A METHODOLOGY FOR ASSESSING THE SEISMIC RISK OF BUILDINGS

by

KATHERINE MARIE THIBERT

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Abstract

Many infrastructure networks rely on each other to deliver utilities and services to the community. In the event of a disaster, these networks can sustain significant damage. It is therefore important to identify interdependencies among networks to mitigate the disaster consequences. In 2003, Public Safety Canada (PSC) and NSERC initiated the Joint Infrastructure Interdependencies Research Program (JIIRP) for this purpose. The research was carried out at six Universities across Canada including the University of British Columbia (UBC). The aim of JIIRP at UBC was to study infrastructure interdependencies during disasters in order to aid in decision making. This involved the development disaster simulation methodology and tool, and the implementation of a case study. UBC's Point Grey campus was used as case study. The campus is located in southwestern British Columbia, a known seismic zone, therefore earthquake disaster scenario was chosen.

Reasonable estimations of the expected seismic damage and losses are required in order to simulate a realistic disaster scenario. For this reason, in this thesis, seismic risk assessment was carried out for the buildings at UBC. This involved the development of a building database, the assessment of the expected level of damage to the structural and nonstructural building components, and the estimation of monetary, human and functionality losses. Buildings in the database were classified into prototypes and the damage was estimated for several levels of intensity using damage probability matrices. As expected, the most vulnerable buildings on campus were those containing unreinforced masonry. These buildings make up 7% of the buildings on campus. The least vulnerable buildings were multi-family residential wood buildings which account for 27% of the buildings on campus. Losses were estimated following the damage assessments. Casualties were estimated for three times of day. 2PM was determined to be the critical time of day the campus population is the greatest at this time.

Monetary loss and functionality trends were examined with respect to earthquake intensity and it was shown that for moderate intensity earthquakes, the losses depend primarily on nonstructural damage, while structural damage plays the most important role for higher intensities.

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Dedication

To my parents,

Thank you for all your love and support.

1 Introduction

Southwestern British Columbia lies in one of the most seismically active regions in Canada. With a population of approximately 2.5 million it is important to understand the possible damage and loss that could occur as the result of future earthquakes in order to reduce or eliminate the potential for catastrophic effects.

Many infrastructure networks rely on each another to deliver utilities and services to the community. For example, water is distributed to the public by pumps located in a station. The pumps require electricity and shelter from the elements in order to operate normally. In the event of a disaster, such as an earthquake, infrastructure networks can sustain significant damage. It is therefore important to identify interdependencies among various critical infrastructures in order to mitigate the consequences of a disaster. For these reasons Public Safety Canada (PSC) and the Natural Sciences and Engineering Research Council (NSERC) initiated the Joint Infrastructure Interdependencies Research Program (JIIRP) in 2003. The aim of the research program was to develop knowledge to “secure and protect Canada’s critical infrastructure” (PSC, 2005). The research was carried out at the University of British Columbia (UBC) in conjunction with York University, The University of Saskatchewan, École Polytechnique, the University of Toronto and the University of Guelph. UBC was responsible for the investigation of “decision making for critical linkages in infrastructure networks” (PSC, 2005). A disaster simulation tool was developed in order to identify the interdependencies among critical infrastructures and UBC’s Point Grey campus was used as case study for the simulator. The campus is located in southwestern British Columbia, in a known seismic zone, enabling earthquake disaster scenarios to be modeled. The infrastructure networks included in the case study are the buildings, water, electrical, natural gas, communications and transportation lifeline systems.

Reasonable estimations of the expected seismic damage and losses are required in order to simulate a realistic disaster scenario. For this reason, a seismic risk assessment was carried out for the building and lifeline networks on campus. This thesis is one of two studies conducted on seismic risk assessment at UBC. In this study, a seismic risk assessment methodology for buildings in British Columbia is improved by updating damage assessment methods and developing methods to estimate earthquake casualties and loss of function, and was implemented for a case study. The companion thesis, by H. Juarez, (Juarez, 2008) examines the seismic risk of lifelines.

1.1 Background

Seismic Risk Assessment (SRA) involves determining the adverse consequences that people and society might suffer as a result of future earthquakes (EERI Committee on Seismic Risk, 1989). There are three components to seismic risk assessment: the seismic hazard, the vulnerability of structures in the region and the expected losses that result from damage.

Seismic hazard assessment methodologies are used to estimate the expected level of ground shaking at a given location. The ground shaking level depends on the earthquake source, the effects of the wave travel path and the local site conditions. Source characteristics that affect the ground shaking include the magnitude and type of fault. Travel effects include the distance from the earthquake source to the sight of interest and the geology through which the seismic waves travel. The effects of local site conditions depend on the geology at the site and include soil amplification, liquefaction and landslides.

Regional building stock data must be collected and stored in a building inventory. Data required to perform seismic risk assessment includes the name, address and use of the building as well as structural considerations such as height, age, material and lateral force resisting system. In order to manage the vast amount of data, a Geographical Information Systems (GIS) must be used. GIS programs have graphical and database components which are linked providing a convenient way of storing and visualizing the data.

For the purpose of estimating damage, buildings in the database are classified into groups of similar structural traits, since it is impractical to perform detailed analysis of every building in the database. Motion damage relationships developed for these building prototypes are used to determine the expected amount of structural and nonstructural damage sustained by the building for a given earthquake level.

Losses are estimated based on the result of the damage assessment. Monetary losses are calculated based on structural and nonstructural damage and the replacement value of the building. The value of the structural components, the nonstructural components and the building contents, depend on the use of the facility. In general, the nonstructural components and contents make up the most significant portion of the replacement value and hence the economic losses that result from earthquake damage.

The number of casualties is determined based on the structural damage and the number of occupants present in the building at the time of the earthquake. Casualties are estimated for three times of day: 2AM, 2PM and 5PM to represent a population at home, at work and commuting respectively.

Functionality is defined as the buildings ability to operate after the earthquake has occurred. Buildings are placed into functionality categories based on the results of the structural and nonstructural damage assessments. It is these loss estimations that will be used as input for the JIIRP simulator with similar results for the lifeline systems for the identification of infrastructure interdependencies.

1.2 Goals, Purpose, Objectives and Tasks

The goal of this thesis is to contribute to the knowledge and understanding of the effects of earthquake related disasters. This knowledge will improve both short and long term disaster planning as well as community awareness. These improvements will help to mitigate the negative consequences of potential seismic events.

The purpose of this study is to supply the JIIRP at UBC with seismic damage estimations of buildings so realistic disaster simulations can be performed and critical infrastructure interdependencies can be identified.

The objectives of the thesis are to: 1) to improve knowledge on seismic risk assessment; 2) apply this knowledge to the hazard setting and construction practices of British Columbia; 3) improve an existing methodology for seismic risk assessment in British Columbia; 4) assess the validity of the methodology through the use of a case study; and 5) provide documentation on how the risk estimates should be implemented by JIIRP at UBC.

In order to satisfy these objectives, the following tasks were performed:

- Updated existing damage estimation methodologies for BC
- Updated existing monetary loss estimation methodologies for BC
- Developed a methodology for estimating casualties in BC
- Developed a methodology for estimating functionality of buildings after the earthquake.

- Implemented the methodology on a case study for several levels of earthquake intensity
- Investigated the loss and damage trends with respect to intensity
- Performed a cost benefit analysis for retrofit of buildings

1.3 Scope

This thesis focuses on the application of regional seismic risk assessment (SRA) methodologies. While most methodologies are appropriate for any region, the work presented in this thesis is specific to seismic risk assessment in British Columbia. Modification to the motion-damage relationships implemented in this study is required for the methodologies use in other regions.

With regards to the assessment of structural and nonstructural damage several assumptions were made:

- The damage assessments are limited to the damage induced by seismic shaking of buildings. While collateral hazards such as landslide, liquefaction and earthquake induced fires and flooding are important factors when assessing earthquake damage these were not included in this study due to lack of time and available resources

- The methodology is for regional assessment and, due to the number of buildings to be assessed and the amount of time required; detailed structural analyses were not performed. The buildings are classified into one of thirty one prototypes for which motion damage relationships were developed. Uncertainties in the damage estimations are therefore introduced because of this simplification.

- Nonstructural components are separated into displacement sensitive, acceleration sensitive and building contents for their damage assessment. This results in generalized damage estimates of all components in the building. The damage to specific components or systems of components, such as the mechanical, electrical and plumbing, is not attainable with this methodology.

The monetary losses do not include the indirect losses due to business interruption. The calculation of indirect losses depends not only on the damage to a building, but involves the calculation of downtime. Downtime depends on the time for the repair of damage and, additionally, the upstream and downstream effects of the earthquake. Due to this complexity, and the lack of time and resources, monetary losses were calculated for direct losses due to damage only. The estimation of downtimes and recovery is limited to the exploration of the concept and possible methods for its estimation.

There are many uncertainties involved in the estimation of earthquake casualties. The estimation depends on the structural damage assessment, the relationships between casualties and the damage state (casualty rate) and the number of people in the building at the time of the event. As previously mentioned the structural damage is determined for building prototypes and may not represent all of the characteristics of a building. The casualty rates used for this study were obtained from HazUS, which is the current state of the art methodology for seismic risk assessment in the United State (FEMA/NIBS, 2005). These rates were determined based on observed deaths and injuries in recent California earthquakes and may not be suitable for British Columbia. However, at this time, there is no earthquake casualty data available for BC and the HazUS casualty rates are the most suitable estimates available.

Introductory research has been done in the area of estimating the functionality of a building after an earthquake has occurred. The methodology presented in this thesis represents a good start, but further research is needed in order to develop confidence in the results.

The methodology was applied to a case study on the University of British Columbia Point Grey campus; however, not all of the buildings on campus were included. Single family homes not belonging to the university and storage sheds were not included. Also, the assessment was completed for the condition of UBC campus in the summer of 2006. New construction, demolition or seismic upgrades accomplished since that time were not included.

1.4 Organization of the Thesis

The following topics are discussed in this thesis and are listed in the order in which they are presented. Chapter 2 briefly reviews past and current research on seismic risk assessment. Chapter 3 describes the JIIRP project including a brief description of its components and how SRA fits in. Chapter 4 presents an overview of seismic risk assessment. The four requirements for risk are discussed and a road map for the performance of the SRA methodology is presented. Chapter 5 discusses the components of seismic risk assessment. This includes a brief discussion of seismic hazard analysis and the effect of local soil conditions as well as damage assessment and the estimation of losses. The damage assessment is for both structural and nonstructural damage. Here, the classification system for British Columbia and the intensity based damage matrices are presented. Loss estimation includes monetary, human and functionality losses. The concept of downtime is also discussed. In Chapter 6 the University of British Columbia case study is described, a building inventory database was constructed and the damage assessments and loss estimations were performed. The results are presented in the form of maps developed using a GIS platform. Chapter 7 presents a discussion of the results as well as a cost benefit analysis and a discussion of the value of the methodology. In Chapter 8, conclusions on the methodology and recommendations for further research are made.

2 Literature Review

In this Chapter a summary of seismic risk assessment studies carried out in British Columbia and various areas in the world is presented. General seismic risk assessment studies are first presented followed by nonstructural component studies, monetary loss estimations, casualty estimations and functionality studies. Each section is divided by region.

2.1 Seismic Risk Assessment

This section presents general seismic risk assessment studies performed in the United States, British Columbia, and Europe. This review is by no means extensive, but it can give the reader a sense of the type of work that has been done in these regions.

2.1.1 United States

Seismic risk assessment has been investigated in the United States, particularly in California for many years. The summaries of three important studies: ATC-13 (ATC 1985), FEMA 154 (2002) and HazUS (FEMA/NIBS, 1997) are presented.

In 1985, the Applied Technology Council released "ATC 13 - Earthquake Damage Evaluation Data for California" (ATC 1985). The document introduced a classification system for facilities and provides an estimate of damage for each class. It organized all structures and infrastructures into 91 different facility classes, 40 of which were buildings. The expected seismic damage sustained by a building is related to ground shaking intensity through Damage Probability Matrices (DPMs). For each facility class, the DPM expresses the probability of being in a certain damage state given the Modified Mercalli shaking intensity (MMI). There are seven damage states, each of which is associated with a range of Damage Factors (DFs) and Central

Damage Factors (CDF). These damage factors signify the ratio of dollars lost due to damage to the total replacement value of the structure.

FEMA 154: Rapid Visual Screening of Buildings for Potential Seismic Hazards was developed in 1989 by the Federal Emergency Management Agency and updated in 2002 (FEMA, 2002) in order to perform seismic vulnerability assessment from rapid visual screening. Buildings are classified into one of ten prototypes and seismic vulnerability is described in terms of a structural score. This score is determined through the addition of the prototype Basic Structural Score (BSH) and the Score Modifiers (SM). The Basic Structural Score represents the negative log of the probability of collapse of the building given the Most Credible Earthquake (MCE) for the region. Score modifiers are used to account for irregularities characteristics that affect the seismic performance of buildings: the height, vertical and horizontal irregularities, the age of the building and the soil type on which it is founded.

HazUS (FEMA/NIBS, 2005) is a loss estimation software package developed by the Federal Emergency Management Agency (FEMA) and the National Institute of Building Science (NIBS) developed in 1997 and updated in 2005. The methodology relates the expected building damage to the spectral acceleration and displacement. Demand spectra are used to describe the input ground motions and the seismic performance of buildings is represented through the use of capacity curves. The level of spectral displacement and acceleration experienced by a building is determined from the intersection of the capacity and demand curves. Five damage states are define for each building prototype and the probability of being in or exceeding each certain damage state given spectral displacement is determined from fragility curves.

In 2001, seismic risk assessment study was conducted for hospitals and other essential buildings in Clark County, Nevada (Sack et al., 2006) using both the FEMA 154 and

FEMA/NIBS approaches. The studies were carried out using two independent deterministic earthquake scenarios that had the same probability of exceedance. The results of both methods indicated that a large number of essential buildings would be severely damaged to the point of failure for the given scenarios. A comparison of the results indicated that the FEMA 154 results were more conservative.

2.1.2 British Columbia

Southwestern British Columbia is a high seismicity zone and seismic risk assessment has been investigated in the area for some time. The summaries of four important studies: the National Research Council of Canada’s “Manual for Seismic Screening of Buildings for Seismic Investigation” (NRCC, 1992), Bell (1998), Blanquera (1999) and Onur (2001) are presented.

NRCC’s “Manual for Seismic Screening of Buildings for Seismic Investigation” (NRCC, 1992) was developed based ATC 13 (1985) for the purpose of ranking buildings in a region according to their ability to resist seismic shaking. The screening procedure included the examination of structural prototype, building irregularities, seismicity, soil conditions, building occupancy and nonstructural damages. Buildings were ranked to have either low, medium or high seismic risk and those with medium or high risk were recommended for further investigation.

In response to the needs of the insurance industry and local governments, the University of British Columbia and Bell (1998) investigated various seismic risk assessment methodologies and developed a classification system and Modified Mercalli Intensity (MMI) based damage relationships for BC buildings. The classification system, named BC 31, included 31 prototypes based on construction practices in the province. The damage relationships were developed by adapting the ATC 13 (ATC, 1985) damage probability matrices (DPM) to account for British Columbia construction practices.

In 1999, Blanquera (1999) used the BC 31 classification system and damage probability matrices to perform a seismic risk assessment for the City of New Westminster, BC. Seismic hazard assessment was carried out and MMI VII and VIII were used to estimate the building damage. A comprehensive building database was assembled and the expected damage was estimated using the damage probability matrices initially developed by Bell (1998) and subsequently modified and refined by Ventura, Onur and Finn (Ventura, 2005). The results were presented in terms of the mean damage factor on block by block basis using a geographic information software (GIS) software platform.

In 2001, a study was conducted by Tuna Onur (Onur, 2001) under the direction of Ventura and Finn (2005) to estimate the potential damage and subsequent monetary losses that would result from seismic shaking in the Cities of New Westminster, Victoria and Vancouver. The assessments included seismic hazard assessment, the development of comprehensive building databases, and the assessment of structural and nonstructural damages for the hazard level and the estimation of direct monetary losses. Probabilistic seismic hazard assessment was carried out and MMI VIII was determined to be the appropriate intensity level for all three study areas. Comprehensive building databases were assembled from city databases, rapid visual screening and inference schemes. The databases contained approximately 8000 buildings in New Westminster, 13,000 in Victoria and 20,000 in Vancouver. Structural damage was estimated using the damage probably matrices developed by Ventura, Onur and Finn (2005) and the results were mapped on a block by block basis using GIS software. Nonstructural damage and monetary losses were also estimated for the study areas. The methods are presented in sections 2.2.2 and 2.3.2.

Onur’s study also investigated the use of spectral displacement based damage functions instead of Modified Mercalli Intensity (Ventura, Onur and Finn, 2002). Capacity and fragility curves were developed for three BC prototypes: unreinforced low-rise masonry buildings, single family homes and concrete high-rise shear wall buildings. The resulting damages were compared to those from the intensity based DPMs and were determined to be similar.

2.1.3 Europe

Many seismic risk assessment studies in Europe are currently being performed based in the 1998 European Macroseismic Scale (EMS), (Grunthal, 1998). This 12 degree scale defines the earthquake intensity at a particular location based on the input of the shaking effect on humans, objects and building damage. “The major difference between the EM-98 Scale and other intensity scales is the detail with which different terms, such as the building types and vulnerability class, the damage grades and quantities are defined “(Grunthal, 1998).

The vulnerability classification consists of six categories; defined as the “vulnerability classes” A to F. Classes A through C represent buildings with high seismic vulnerabilities, for example, Adobe and rubble stone construction typically fall into class A, unreinforced masonry structures fall into class B and non-ductile reinforced concrete structures are classified as C. Classes D and E represent buildings with low and moderate earthquake resistant design and class F is for buildings with high earthquake resistant design, like base isolation.

Damage grades are used to describe the level of damage sustained by a building due to seismic shaking. Five damage grades are defined for each building construction type to account for the different damage and failure modes. Damage grade 1 represents slight damage, while grade 5 describes the full collapse.

The intensity at a location is described in terms of the quantity of buildings from each vulnerability class expected to be in each damage grade. The quantities are “few”, “many” and most”. An example of this intensity definition is presented for EM-98 Intensity which describes building damage as:

> Many buildings of vulnerability class A suffer damage of grades; a few damage grade 4.
>
> Many buildings of vulnerability class B suffer damage of grade 2; a few of damage grade 3.
>
> A few buildings of vulnerability class C sustain damage of grade 2.
>
> A few buildings of vulnerability class d sustain damage of grade 1.

While this document was developed in order to classify the intensity at a particular location, since vulnerability classes, damage grade and statistical quantities were defined, it can be used to develop damage probability matrices and estimate the seismic risk in European regions. This was done in the studies by Schwarz et al, (2004), Tyagunov et al. (2004) and Langhammer et al. (2006) presented below.

The purpose of the 2004 “Vulnerability and Risk Assessment for Earthquake Prone Cities” by Tyagunov et al (Tyagunov, 2004) was the assessment and mapping of the seismic risk for Germany. Because of the large scale of the study area, the risk was estimated on a community basis. The communities were separated into one of five population classes and vulnerability was assigned on a community based on the data from representative communities and the EMS-98 Scale Damage Probability matrices were developed from the EMS vulnerability classes, damage grades and quantities. Damage was predicted for the country’s seismic hazard. The results were mapped using GIS software in terms of the separate damage.

A more refined seismic risk assessment was concluded for the city of Cologne, Germany (Schwarz, 2004) in conjunction with Tyagunov’s study. Both deterministic and probabilistic seismic hazard assessments were conducted for the region. This included local soil profile investigations to determine the potential for ground motion amplification. A building inventory was collected and each building was classified using the EMS 1998 vulnerability classes. The damage was estimated on a building by building bases using similar motion damage relationships used in Tyagunov's study. The assessment was conducted for three levels of detail in order to determine the effects of site properties and dynamic characteristics of the buildings on the overall damage to the city. Monetary losses based on the expected damage were also estimated.

A deterministic EMS 98 based seismic risk assessment study was performed on the City of Aigio, Greece (Langhammer, 2006). The study used the 1995 Aigio earthquake scenario and condition of the building stock at that time in order to compare the results of the assessment with actual observed damages. The results achieved using EMS 98 based damage matrices compared well. The city was also assessed for its 2005 state under the same earthquake scenario. The results indicated an improvement in the city's overall earthquake vulnerability due to new construction and retrofits that have occurred.

2.2 Nonstructural Components

This section presents nonstructural component seismic risk assessment studies performed in the United States, British Columbia and Iran. This review is by no means extensive, but it can give the reader a sense of the type of work that has been done in these regions.

2.2.1 United States

As mentioned above, the ATC-13 (ATC 1985) and HazUS (FEMA/NIBS, 1997) methodologies include nonstructural damage assessment. These and two studies by Taghavi and Miranda (2003) are presented in this section.

The ATC 13 (ATC 1985) nonstructural component damage assessment methodology is similar to that for buildings; the expected damage is evaluated through the use of damage probability matrices. Nonstructural components are grouped into six facility classes: residential equipment, office equipment and furniture, electrical equipment, mechanical equipment, high technology equipment and laboratory equipment. A building would be assessed for each nonstructural component class it contains.

The FEMA/NIBS (2005) methodology for estimating nonstructural component damage is similar to that for estimating structural damage except that HazUS separates nonstructural components into two categories: displacement sensitive nonstructural components and acceleration sensitive nonstructural components. Displacement sensitive components include partition walls, exterior wall panels, architectural finishes, piping, cladding and penthouses. Acceleration sensitive components consist of electrical and mechanical equipment, piping, cantilever elements, parapets and racks. This methodology uses fragility curves based on inter-storey drift and peak floor accelerations to determine the damage to displacement sensitive and acceleration sensitive components respectively.

The 2003 Pacific Earthquake Engineering Research center (PEER) report entitled "Response Assessment of Nonstructural Components" (Taghavi and Miranda, 2003) presented a database of the seismic performance of building nonstructural components and contents. The database included a nonstructural component classification system, component replacement values and installation costs and seismic performance information. Performance information was gathered from observed damages that resulted from previous California earthquakes. Also included in the report are the contributions of nonstructural components and contents to the overall replacement value of various building types. This is further discussed in section 2.3.1.

Another study by Miranda and Taghavi (2003) investigated acceleration demands on nonstructural components and the parameters that affect these demands in order to develop simplified methods for their estimation. A simple model was developed and subjected to acceleration time histories. This model consisted of a flexure and shear beam connected by axially rigid links which depends wholly on the first natural period and the damping of the building as well as an α factor which controls the participation of flexure. The results of the modeling were compared to acceleration recordings from real buildings, in particular a 52 storey structure located in Los Angeles, and finites element models and the simple model compared well with both.

Parametric studies were conducted models with various natural periods and α factors. It was found that both had an influence over the response of the building, natural period having a more significant influence. Overall it was discovered that higher modes and natural period have a significant influence on acceleration demand.

2.2.2 British Columbia

In British Columbia, two studies that have included the assessment of nonstructural components damage as part of seismic risk assessment are the 1999 study by Cook and the 2001 study by Onur which was introduced in section 2.1.2. The 1998 NRC report (NRC 1998) also included nonstructural damage assessment, however since the methodology is similar to that of ATC 13 (ATC 1985), it will not be discussed here

In an accompanying study to Blanquera (1999), Cook (1999) investigated nonstructural component and building content damage. For the estimation of nonstructural damage in British Columbia, damage probability matrices were developed from the nonstructural fragility curves that were presented in FEMA/NIBS (1997) displacement sensitive components, acceleration sensitive components and building contents. Cook added building contents under the assumption that they were acceleration sensitive, but had different damage states. These damage probability matrices were applied to the City of New Westminster using the same database collected by Blanquera (1999).

The nonstructural damage probability matrices developed by Cook (1999) under the direction of Ventura and Finn, were used to evaluate nonstructural damage in Onur's (2001) study. The expected displacement sensitive components, acceleration sensitive components and building contents damage was estimated for all three study areas: New Westminster, Victoria and Vancouver for MMI VIII. The damage to displacement sensitive components was significantly higher than that for acceleration sensitive components and building contents.

2.2.3 Iran

The 2006 paper by Eshghi and Razzighi entitled "Rapid Seismic Safety Evaluation of Existing Liquid Storage Tanks" involved the development of a rapid visual screening (RVS) process for on grade liquid storage tanks. The methodology examined three types of tank vulnerability: damage to the shell, damage to the roof and damage to the nozzles and pipes. The effects of the tank height, diameter and whether the tank was full or empty were also investigated. The methodology was applied to a number of liquid storage tanks in Iran and the results were compared to results achieved through detailed structural analysis and FEMA/NIBS (2005) fragility curves. The RVS method was determined to be conservative when compared to structural analysis; however, it was determined to be more appropriate than the FEMA/ NIBS (2005) method, which does not take tank size and fullness into account.

2.3 Monetary Losses

Studies in the United States and British Columbia that were introduced above are further discussed in terms of monetary loss estimation.

2.3.1 United States

ATC 13 (ATC, 1985) used a simple method to estimate the monetary losses associated with earthquake damage. Since the mean damage factors represent the ratio of dollars lost to the replacement value of the building, monetary losses can be estimated by multiplying the mean damage factor and the replacement value. Replacement values are estimated from constructions cost per square foot and the floor area of the building.

The 2003 Pacific Earthquake Engineering Research center (PEER) report entitled "Response Assessment of Nonstructural Components" (Taghavi and Miranda, 2003) illustrated the importance of considering the use of a building when estimating building replacement values and monetary losses. It was shown that for most building types, (offices, hotels, etc…) structural components make up about 10% to 20% of the total replacement value, while nonstructural components make up 60% to 70% and contents, 10% to 20%. This is significantly different for high importance or high technology buildings such as hospitals or research labs. Here, it was discovered that contents can make up a much as 45% of the buildings total replacement value.

The FEMA/NIBS (2005) methodology takes into account the use of the building when estimating monetary losses that result from shaking damage. Buildings are further classified into 1 of 33 building use classes. Here the total replacement value of the structure is determined from the summation of the construction cost of the building and the replacement value of its contents. The construction cost is distributed to the structural, displacement sensitive and acceleration sensitive components by means of the repair cost ratios. These ratios represent the fraction of the construction cost that is attributed to each of the three types of components. Monetary losses are determined by multiplying the structural and nonstructural damages by the replacement values of the components and contents.

2.3.2 British Colombia

In British Columbia, two studies, Onur (2001) and a report by Munich Re (1990), estimated monetary losses resulting from structural and nonstructural earthquake damage.

In 1990, Munich Re conducted a study on the economic impact of a scenario earthquake in Vancouver. The scenario chosen was a Richter Magnitude 6.5 earthquake with an epicenter in the Straight of Georgia. The ground shaking level was converted to the Modified Mercalli Intensity scale for loss estimation using Munich Re loss ratios. The study did not incorporate the use of comprehensive database as, at the time, a building inventory methodology was not available. Instead, replacement costs were determined based on square footage and extrapolation loss estimates from in depth examination of all buildings in Vancouver's downtown core. The study recommended the development of a building inventory methodology in order to achieve more reliable loss estimates.

Since damages were estimated using damage probability matrices in Onur's study (2001), an ATC 13 loss estimation approach was used. Building replacement values were estimated by multiplying the building floor area by construction costs per square meter for each building prototype. It was assumed that 25% of the replacement value is attributed to structural components and the remaining 75% is split equally between the displacement sensitive and acceleration sensitive nonstructural components. The replacement value of the contents was not included. Monetary losses were calculated by multiplying the replacement values of each set of components by their respective mean damage factors.

2.4 Casualty Estimation

Several methodologies are currently available for the estimation of earthquake related casualties. This section examines some of the studies conducted in the United States and Asia. Casualty estimation studies have also been conducted in Europe; however they are not discussed here.

2.4.1 United States

In the ATC 13 methodology, casualties are estimated based on the mean damage factor of the building, the casualty fraction and the number of people in the building. For each of the seven damage states, the fraction of people with minor injuries, serious injuries and the fraction of people dead are given. These fractions were developed based observed deaths and injuries from previous California earthquakes. Based on the mean damage factor of the building, the casualty fraction is selected from a table and multiplied by the number of occupants in order to determine the expected number of building casualties.

The FEMA/ NIBS (2005) methodology estimates the number of casualties based on the structural damage to the building and the number of occupants present inside and outside of the building at the time of the event. In order determine the number of casualties the population in the building is multiplied by the probability of being in a certain damage given the size of the earthquake and the probability of an injury of a certain severity occurring given the damage state (casualty rates).

For the purpose of casualty estimation, FEMA/NIBS defined five damage states: slight, moderate, extensive, and complete with or without collapse. This varies from the original four damage states to highlight the influence of building collapse and partial collapse on deaths and injuries. Four levels of injury severity are defined. They range from injuries requiring the assistance of paraprofessionals, such as stitches and concussions, to instantaneous death. The casualty rates are given in form of tables for each damage state.

Casualties are estimated at three specific times of day: 2 am, 2 pm and 5 pm. These scenarios represent the times when the population is typically at home, at work or school and commuting respectively. The number of occupants inside and outside the building at these three times is first determined and the number of casualties in each severity level is determined by multiplying ht number of occupants by the probability of damage and the appropriate casualty rate.

2.4.2 Asia

Zhao et al. (2004) proposed a method for seismic casualty estimation name the "Dynamic Method". This method not only considers the "initial" injuries due to seismic damage, but also the injury development over time of those who are trapped. The method has three steps: determining the distribution of local trapped surroundings, injury development and computing the final injury numbers. The first step involves the calculation of the "Initial Casualty Matrix" which is based on structural damage and injury severity. The severity of the "trapped surrounding" is also determined in this step. These are made time dependent through the "state function" which is the time-dependent function for injury development. The final casualty numbers are determined by plugging in the time it takes for rescue into the state function. As an example, this method was applied for the Tangshan earthquake and the results were compared to the real casualty data.

2.5 Functionality Estimation

Currently there are few studies that examine the loss of building function after an earthquake. This topic is briefly discussed in the 2000 report by the Pan American Health Association (PAHO) and the World Health Organization (WHO entitled "Principles of Disaster Mitigation in Health Facilities" (PAHO/WHO, 2000) and the 1994 EERI report, "Expected Seismic Performance of Buildings" (EERI, 2004).

The PAHO/WHO report investigated the past seismic performance of health care facilities and made recommendations for the evaluation of vulnerabilities in existing buildings. Structural, nonstructural and administration/ operational vulnerabilities were considered. From these vulnerability assessments, the buildings were placed into one of four seismic safety levels: fully functional, operational, life safe and near collapse. These categories are described in terms of the buildings ability to operate post earthquake. Of the four categories only fully functional and operational health facilities are able to perform after the earthquake. The life safety category discusses the functionality in terms of building evacuation routes.

"Expected Seismic Performance of Buildings" (EERI, 1994) was developed for the purpose of educating the public, particularly building owners and government policy makers, about the damage in buildings that is likely to arise as the result of seismic shaking. Five "standardized" damage states are presented in order to classify the various levels of expected building damage: none, slight moderate, extensive and complete. These categories describe the overall status of the building based on structural, nonstructural and contents damage and also give a rough estimate of the amount of time it will take to recover from this damage.

3 Joint Infrastructure Interdependencies Research Program

The Joint Infrastructure Interdependencies Research Program (JIIRP) is part of an "ongoing national effort to secure and protect Canada's critical infrastructure" (Gov. of Canada, 2005). The program was co-funded by Public Safety Canada and the Natural Sciences and Engineering Research Council (NSERC). Six universities across the country were involved: York University, École Polytechnique, the University of Saskatchewan, The University of Toronto (U of T), The University of Guelph, and The University of British Columbia (UBC). The research that was conducted at York University involved modeling interdependencies for emergency management using geographic decision support systems. École Polytechnique studied interdependencies and domino effects in life support systems. The University of Saskatchewan developed models to simulate critical infrastructure networks. U of T developed a model of infrastructure interdependencies through the analysis of stake holder needs. The University of Guelph studied was to improve the resilience of water infrastructure and health response systems against waterborne disease. UBC studied decision making for critical linkage in infrastructure networks. This chapter briefly describes the JIIRP project at UBC and how Seismic Risk Assessment plays a role in the project.

3.1 JIIRP UBC

Infrastructure networks are important to the overall function and quality of life of the public. These networks are complex systems within themselves and rely on many factors in order to operate. A water network for example, is actually made up of three separate networks: drinking water, waste water and storm sewers. In the city of Vancouver, drinking water is supplied to the city from two main reservoirs. Water is pumped from the reservoirs to a treatment plant, where it is made suitable for consumption. From the treatment plant, it is pumped along main pipes to water stations, which then distribute water to using a complex network of secondary pipes the public in their area. Water is collected and returned to the treatment plants through the waster water network after it has been used. A disruption in any one of these components could cause problems.

In a city, there are many infrastructure networks which interact and rely on each another to deliver utilities and services to the community. For example, pumping stations and water treatment facilities rely on electricity and shelter from the elements in order to deliver safe drinking water to the public. A disruption in electricity could potentially interrupt water services in an area.

In the event of a disaster, such as an earthquake or storm, infrastructure networks can sustain significant damage. It is therefore important to identify interdependencies among various critical infrastructures in order to assist decision makers to mitigate the consequences of a disaster.

“The Joint Infrastructure Interdependencies Research Project of the University of British Columbia is an effort to assess the impact of physical and temporal interdependencies among multiple infrastructure systems, during the development of large disaster events.” (Martí, et. al. 2008). The project is multidisciplinary and has twelve researchers from various departments on UBC campus and Simon Fraser University (SFU) including: electrical engineering, civil engineering, software engineering, computer science, business administration, geography and psychology. Because of the complexity of the problem, JIIRP UBC centers around the development of real time disaster simulator to play out multi-hazard disaster scenarios, identify independencies and functionality conditions of infrastructure networks.

3.2 Infrastructure Interdependencies Simulator

JIIRP UBC aims to model the real time effects of a disaster and identify the interdependencies among the critical infrastructure networks. There are six principal components of the projects architecture: the physical layers, damage assessment, human layers, database (I2DB), the infrastructure interdependencies simulator (I2Sim) and visualization. Figure 3-1 displays these components.

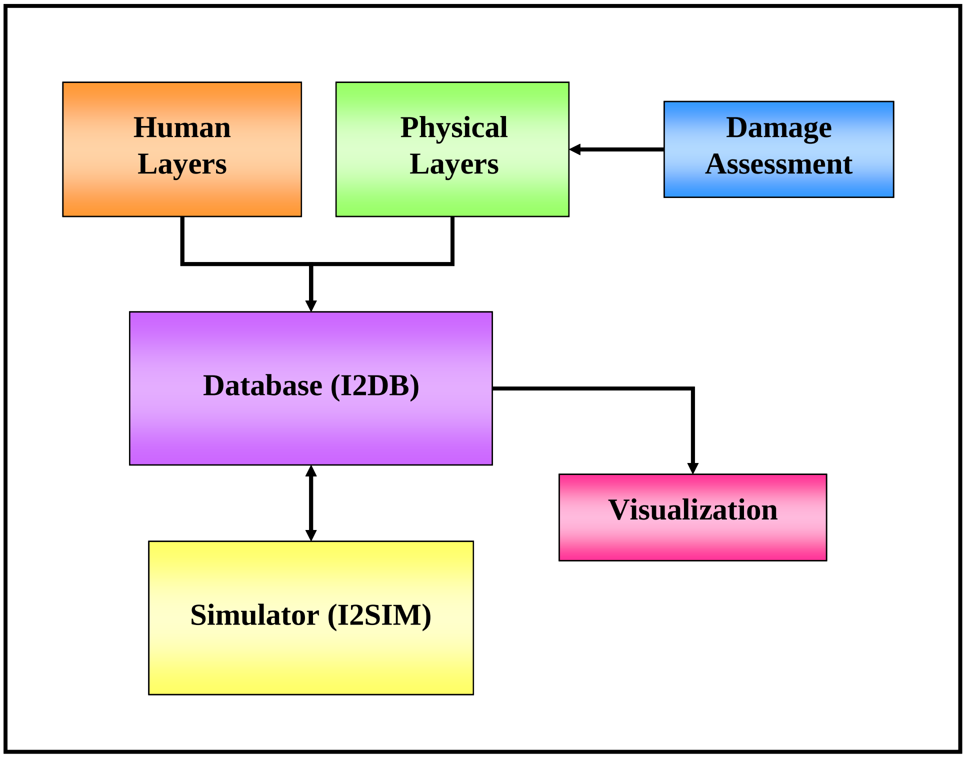

Figure 3-1 UBC JIIRP Project

The physical layers represent the physical attributes of each infrastructure network in the study space. For example, water, gas, electrical, transportation and building networks are represented by individual physical layers. Each layer contains data such as the geographic locations of network components, physical properties such as age and material, the hierarchy of components and the direction of "flow" for the lifeline networks. The water network for example is made up of reservoirs, pumping stations and various pipelines. Each of these components has a geographic location and physical properties and the hierarchy is defined in terms of main and secondary water lines. The water flows from the reservoir to the pumping station through a water main. From the pumping station, it is distributed to the users through main and secondary pipelines. Known interdependencies between the infrastructure networks are also included in the human layers. For example, electricity is needed in order for water pumps in the pumping station to function.

In order to simulate a disaster event, it is necessary to determine the expected level of damage sustained by the infrastructure networks as the result of the disaster. Disasters include natural hazards such as earthquakes, floods, hurricanes and wildfires and man made disasters such as terrorism. The damage assessment module involves the estimation of physical damage to the component, the number of casualties, the amount of economic loss and the loss of function that results from this damage.

Human beings play an important role in disaster planning and response. For this reason, human layers are included in the UBC JIIRP project. The human layers include people flow, disaster victim behaviour, first responder actions and decision maker roles. People flow can be viewed on two levels: the micro scale and the macro scale. The micro scale level models evacuation routes in individual buildings: taking into account that high-rise buildings will take longer to evacuate. The macro scale models where people will go once outside of the building and includes displaced people, emergency shelters and hospital.

The first responder layer models the flow of first responders and investigates psychological effects such as post-traumatic stress disorder.

Behaviour and psychological factors affecting disaster victims is evaluated in terms of five factors: perceived vulnerability, panic, identity and family, grieving and social and antisocial behaviours. Perceived vulnerability evaluates the “preparedness” of a community for disasters. Communities which are more prepared will respond better to a stressful situation and will be less likely to panic. Identity and family takes into account human behaviour regarding loved ones in disaster events. Social behaviours include community outreach and people helping each other while antisocial behaviour takes into account common problems like looting and civil unrest.

Decision makers play significant roles in disaster events and are taken into account in the human layers through the use of software agents. These agents perform two functions. The first is to capture and test emergency management policies already in place in the study area. Secondly, they provide support to emergency personnel. This support includes diagnosis of root causes of system failures and the evaluation of the effects of decisions through the I2Sim simulator.

The data generated in the human and physical layers are aggregated into a database (I2DB). This database provides a common platform for data storage and is set up to feed the data to the simulator directly and receive the output of the simulation. The database updates the system sate from this output for visualization and user interaction.

The results of the simulation can be viewed both statically and dynamically. Static visualization provides “snapshots” of the state of the whole study area at certain moments in time. This is accomplished by mapping the data using a geographical information system (GIS) platform. Dynamic visualization allows the monitoring of individual buildings or components in the study area. The functionality or output of these components is plotted with respect to time.

The simulator model is made up of three primary components: tokens, channels and cells. Tokens are defined as the goods and services that are being produced or consumed by the population; for example water, food, electric and medical services. Channels are units which transport tokens from one location to another. They are used to model lifeline systems such as roads, water pipelines and electrical wires. In order to get a realistic model of lifeline systems, the amount of tokens that can be transported are limited by the capacity of the lifeline component. A time delay is included to account for real life travel times. Cells are entities which perform a function and are used to model buildings in the system. Cells required input of certain tokens in order to perform their functions and produce their output tokens. A hospital, for example, requires water, electricity, doctors, nurses and medical supplies in order to provide health services. There are many types of cells that perform different functions (hospital, residence, classroom) and models need to be developed to represent the internal function of each type.

Damage as the result of a disaster event affects the cells and channels ability to produce and transport tokens respectively. Damage to a cell affects its overall functionality and reduces the output it's of tokens regardless of the damage to its surroundings. Damage to the channels reduces the number of tokens they are able to transport and increases the time delay. Channel damage also affects the cell functionality by reducing the number of input tokens.

3.3 UBC Test Case

A case study of the University of British Columbia's Point Grey campus was performed as an implementation of the simulator methodology. The campus' geographical location, infrastructure complexity, and the diversity of its population made it an ideal test case to develop, test and validate I2Sim. The University has a population of approximately 10,000 full time residents and 47, 000 transitory occupants and most of the utility systems are managed internally. As such, it shares many of the attributes of a small city.

The infrastructure networks to be modeled are the buildings, water, electrical, natural gas, communications and transportation lifeline systems. The lifeline systems are to be modeled with channels and the buildings, as cells. UBC campus contains a variety of buildings that perform many different functions. Currently, there are 19 different cell models being used in the case study which are listed in table 3-1.

Table 3-1 UBC Cell Types

Cell Number	Cell Name
1	Hospitals
2	Fire Halls
3	Ambulance Stations
4	Police Stations
5	Classroom and Library
6	Research Labs and museum
7	Residences
8	Parking
9	Recreational and Society
10	Electrical substation
11	Water station
12	Telecommunications Generators
13	Transportation
14	Food Services
15	Commercial
16	Administration
17	Services and Utilities
18	Power Station
19	Steam Station

Based on the British Columbia Provincial Emergency Program's (PEP) risk matrix (PEP, 2007), a ranking of critical events for UBC campus was developed An earthquake scenario was selected as the disaster to be simulated in the test case based on this ranking.

Realistic estimates of the damage done to buildings and lifeline systems are required in order to carry out an accurate disaster simulation. Due to the size of the study area and the amount of time and resources available, Risk Assessment was deemed to be the most appropriate method of determining the probably seismic damage. Seismic risk assessment (SRA) was carried out for the buildings and lifeline networks on campus. This thesis is one of two studies conducted on of seismic risk assessment in British Columbia. In this study, seismic risk assessment methodology was implemented for buildings while the companion thesis, by H. Juarez, (Juarez, 2008) examines the seismic risk of infrastructure, multi-hazard assessment and infrastructure interdependencies. Building seismic risk assessment includes the assessment of both structural and nonstructural damage and the estimation of casualties, monetary losses and functionality.

4 Seismic Risk Assessment

4.1 Background

In terms of natural disasters, risk refers to the expected losses from a given hazard to a given element at risk, over a specified future time (UNDRO, 1979). Seismic risk**,** therefore**,** refers to expected losses due to future earthquakes. It is comprised of four elements: hazards, location, exposure and vulnerability. In order for the seismic risk to exist, all four elements must be present. Figure 4-1 illustrates this concept.

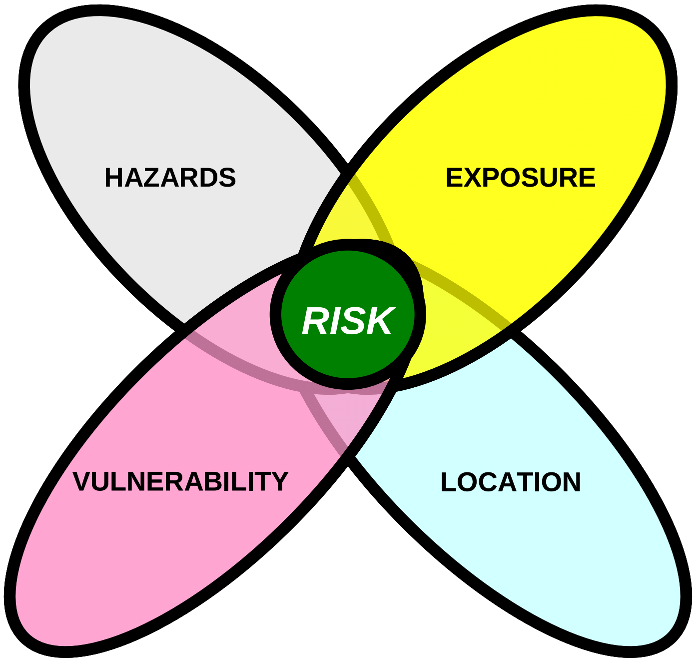

Figure 4-1 Components of Seismic Risk (FEMA, 2007)

Seismic hazard is defined as the study of expected earthquake ground motions at any point on earth. The expected level of shaking at the site or region of interest is calculated based on the characteristics of the areas seismic sources, the attenuation of seismic waves from the epicenter to the site and the local site conditions (location). Seismic hazard assessment can be either deterministic or probabilistic. Deterministic Seismic Hazard Assessments (DSHA) are scenario studies conducted to determine the effects of a single earthquake. Probabilistic Seismic Hazard Assessment (PSHA) takes into account all possible earthquakes that can occur in the region from various sources using Magnitude-Recurrent relationships. These relationships describe the distribution of earthquake magnitudes for a given period of time for each earthquake source zone. Results of PSHA are typically presented in the form of a curve displaying the probability of annually exceeding a given ground motion level.

Seismic hazard assessment uses “reference” ground conditions, typically rock or firm soil, to determine the attenuation of ground motions. Local site conditions can have a significant effect on the level and characteristics of seismic shaking. For this reason, the location of a site or region of interest needs to be factored into the calculation of seismic risk. Site conditions refer to the geologic, topographic and soil characteristics that can have an influence on the amplitude, frequency content and duration of the seismic shaking. Local site conditions are also necessary to determine the liquefaction and landslide potential.

Exposure is defined as the valuables that could suffer losses as the result of earthquake shaking. These valuables can be either economic or social and include human lives, infrastructure and business revenue. For example, a grocery store has its occupants, the value of the building, the value of its contents and potential revenue exposed to the natural hazard present in the region. Risk assessments for large areas require a comprehensive inventory to store exposure data and classify structures into groups according to their use, structural characteristics and importance.

The seismic vulnerability of a structure refers to how well it will perform under earthquake loading. It is essentially the sensitivity of the exposed structures to the expected seismic hazard in a region. Structural vulnerability is typically defined by motion-damage relationships which define the probability of damage to a structure given the level of ground shaking. These relationships can be grouped into two categories: intensity based and engineering parameter based. Intensity base relationships are typically developed based on expert opinion and express the probability of damage given the earthquake intensity using damage probability matrices (DPM). Engineering parameter based methodologies typically use spectral acceleration or spectral displacement in the form of demand spectra to describe the input ground motions. The building characteristics are represented by capacity curves and the building vulnerability is predicted though the use of fragility curves. Both methods are discussed in section 5.3 of this thesis.

4.2 British Columbia Seismic Risk Assessment Methodology

The British Columbia Seismic Risk Assessment Methodology incorporates all four elements of seismic risk. The main components are earthquake hazard, location, exposure, vulnerability, collateral hazards, direct damage, indirect damage, direct losses, downtime, indirect losses, consequence and the final risk level. Figure 4-2 presents a flow diagram of the methodology.

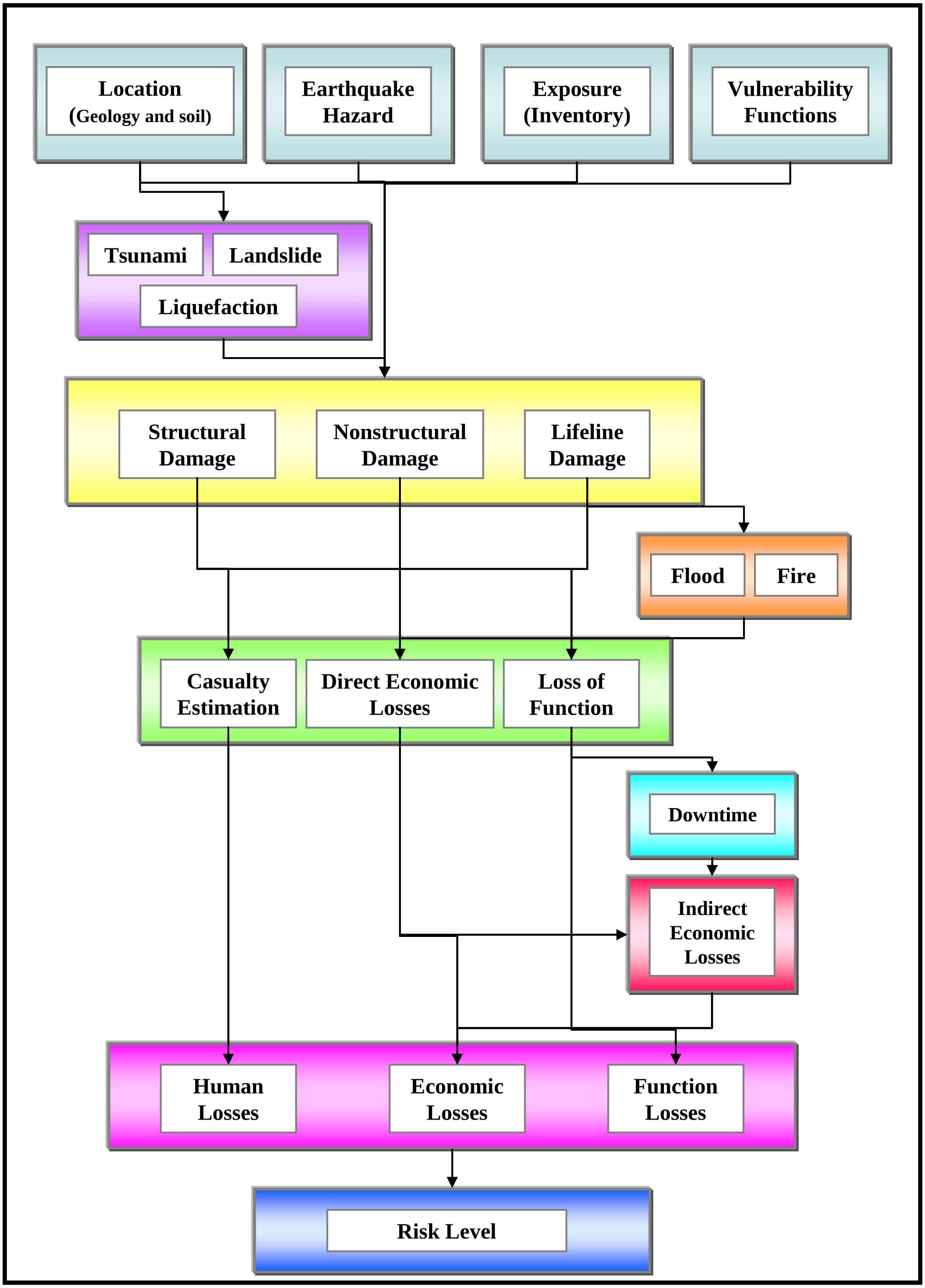

Figure 4-2 BC Seismic Risk Assessment Methodology

The four main components of risk assessment presented in the previous section are displayed in grey in figure 4-2. It should be noted that while the methodology can account for the damage to lifeline systems, this thesis is concerned with seismic risk assessment of buildings and the procedures and components presented are for buildings only. The procedures for determining the expected level of seismic shaking and soil amplification are presented in section 5.1. The assessment of collateral hazards (purple block) such as liquefaction, landslide and tsunami require separate assessment in order to account for their effects. While collateral hazards are important factors when assessing earthquake damage they were not included in this study due to lack of time and available resources. The exposure includes inventory collection and the structural classification system. Currently there are 31 British Columbia building prototypes. Inventory collection is discussed in more detail in section 5.2.

The vulnerability functions are intensity based damage probability matrices. They were developed for the 31 prototypes are based on expert opinion. While it is recognized that engineering parameter based vulnerability relationships are the current state of the art method for the assessment of seismic damage**,** at this time there is great uncertainty in the fragilities and insufficient data to develop these curves for BC. The damage probability matrices are already developed for BC (Ventura, 2005) and offer and more convenient and refined estimations for the study area.

The yellow block contains the estimation of direct damage to buildings and lifeline systems based on the vulnerability, exposure, hazard and location. The direct damage includes estimates of the damage sustained by the building structural components and nonstructural components as well as damage to lifeline systems. Damage is expressed in terms of the mean damage factor (MDF)**,** which is calculated from the prototype damage probability matrices for a given instrumental intensity. The mean damage factor is defined as the ratio of the cost of damage to the replacement value of the building. Procedures for determining the structural and nonstructural damage sustained by a building are given in sections 5.3 and 5.4 respectively. The assessment of lifelines is not discussed in this thesis.

Indirect damage is the result of the additional hazard created by the direct damage sustained to the buildings and lifeline affected by the earthquake. Fires and flooding caused by the rupture of natural gas and water pipelines are common forms of indirect damage. While it is acknowledged that these additional hazards can have a significant effect on the overall damage and loss sustained by a community, procedures to evaluate their effects are not included due to time and funding constraints.

Direct losses (green block) are the result of earthquake damage and include the estimation of human losses, monetary losses and the loss of building function. The BC seismic risk assessment methodology defines casualties as injuries and fatalities that result from earthquake building damage. The number of casualties is determined based on the level of structural damage suffered by a building and the number of occupants at the time of the earthquake. Casualty estimations are performed for three times of day: 2am, 2pm and 5pm. The methodology is discussed in section 5.6. Direct economic losses are incurred from the repair and replacement of damaged building components. Monetary losses are determined based on the replacement value of the building and the damage to its structural and nonstructural components. Section 5.5 presents the procedures for their estimation. Loss of function refers to the buildings ability to operate given the level damage it has sustained from a seismic event. Buildings are placed into one of five functionality categories base on the structural and nonstructural damage assessments. Functionality is discussed in section 5.7 of this thesis.

Downtime refers to the amount of time required to bring a building back to a fully functional state. It depends not only on the time required for damage repair but also on a number of additional factors such as the availability of funding and resources. Due to the complexity involved in calculating indirect losses, only direct losses will be considered in this thesis. Downtime estimation is discussed further in section 5.8. Indirect economic losses are the losses incurred due to business interruption and depend directly on the estimation of downtime. Since the estimation of downtime has not yet been included in the BC seismic risk assessment methodology, the estimation of indirect losses has also not been integrated.

The magenta block defines the final result of seismic risk assessment: the consequences of a given seismic event. The consequences include the total number of casualties, the direct and indirect economic losses and the loss of function. The consequences determine the level of risk associated with a particular seismic event. This risk level should be evaluated by policy makers and government officials to determine if the level is acceptable.

5 Components of Seismic Risk Assessment

As discussed in chapter 4, there are many components to seismic risk assessment. In this chapter seismic hazard assessment, building inventory collection, structural damage assessment, nonstructural damage assessment, monetary losses, casualty estimation and the assessment of functionality are examined. The estimation of recovery times was explored and possible methods were recommended. This chapter details the methodologies used for each of the components listed above.

5.1 Seismic Hazard Assessment

5.1.1 Overview

Seismic hazard is defined as "the likelihood of earthquakes occurring at a location of interest or the level of ground shaking at a specified location due to future earthquakes." There are two methods for calculating the seismic hazard at a site: Deterministic Seismic Hazard Assessment (DSHA) and Probabilistic Seismic Hazard Assessment (PSHA). These are briefly described in the section below. For a more detailed explanation of seismic hazard assessment please refer to Dowrick, 2003.

DSHA is generally used for discrete "scenario" assessments where the magnitude of the earthquake and the distance from the epicenter to the site of interest are known. The magnitude selected depends on the scope of the problem and is typically related to the Maximum Design Earthquake (MDE) or the Maximum Considered Earthquake (MCE) for the tectonic setting. The MCE is the largest earthquake that a given seismic source can produce under its tectonic setting and the MDE is the earthquake level used in the design of a structure. Attenuation equations are applied in order to determine the ground motions at the site. These equations take into account the effects of earthquake waves traveling from the epicenter to the site on the ground motions. Local site conditions also need to be considered. DSHA results in an estimation of the ground motion at the site of interest due to the specified scenario earthquake.

PSHA takes into account all possible earthquakes which have occurred or can occur in the specified region. The first step of the assessment is the identification of seismic “faults and source zones”. The source zones represent areas of similar seismicity. Each of these source zones has an associated magnitude recurrence relationship which defines the probability of exceeding a given magnitude for that source zone. Attenuation relationships are applied for each source zone and the total hazard is calculated by the integration of the contributions of each of these zones. The result is a plot of the annual probability of exceedance of accelerations. Figure 5-1 displays an example of a hazard curve. It describes the annual frequency of earthquakes that produce a peak ground acceleration amplitude larger than a selected PGA at the location of interest. For example the annual frequency of exceedance for a PGA of 20% g is approximately 0.00009 or 1 in 11,000 years.

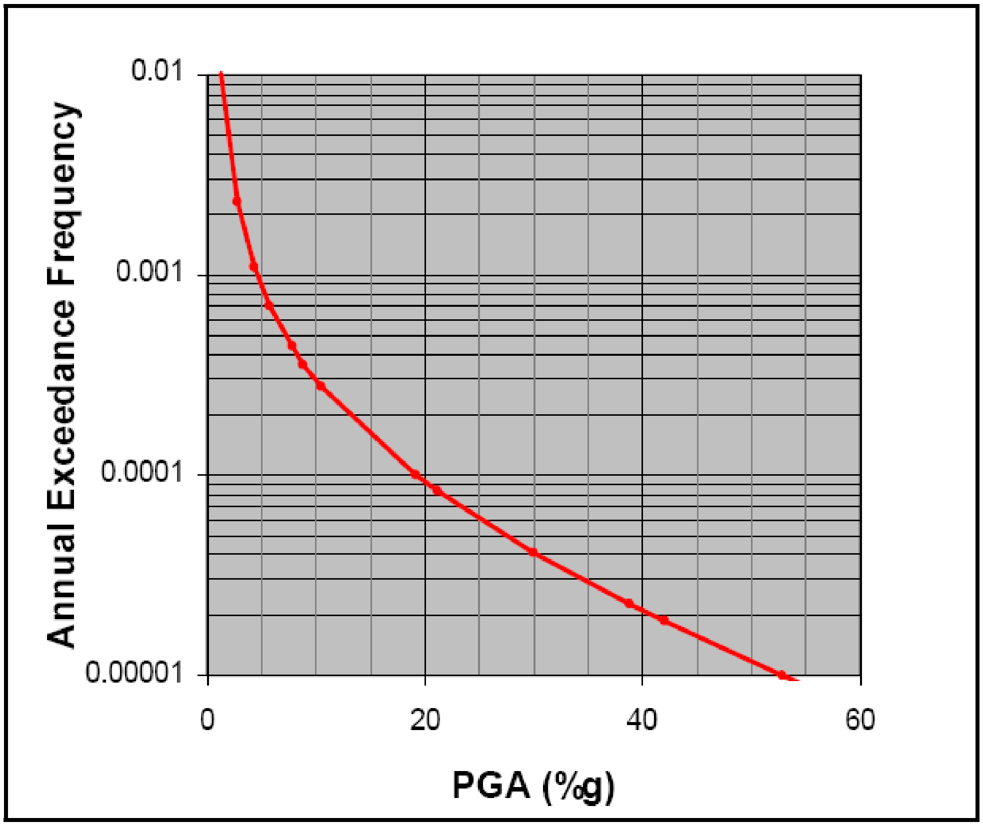

Figure 5-1 Example of a Probabilistic Hazard Curve

5.1.2 Seismic Setting of Southwestern British Columbia

Southwestern British Columbia is an active seismic region of the world with a complex tectonic setting. It lies over the Cascadia subduction zone where the Juan de Fuca and the Explorer oceanic plates are being subducted beneath the North America plate. Figure 5-2 displays the tectonic setting. There are three distinct types of earthquakes that occur in this region due to the tectonic setting: crustal earthquakes, subcrustal earthquakes and subduction earthquakes. Crustal earthquakes are shallow local earthquakes that occur in the North America Plate. These earthquakes typically occur at a depth of 20 km below the surface. Subcrustal earthquakes are deep earthquakes which occur within the subducting Juan de Fuca plate at depths of approximately 60km. Subduction earthquakes occur at the interface between the Juan de Fuca and the North America plates; however, these are rare events that produce extremely large magnitudes. A detailed description of each type of earthquake is available in Clague and Turner (2003).

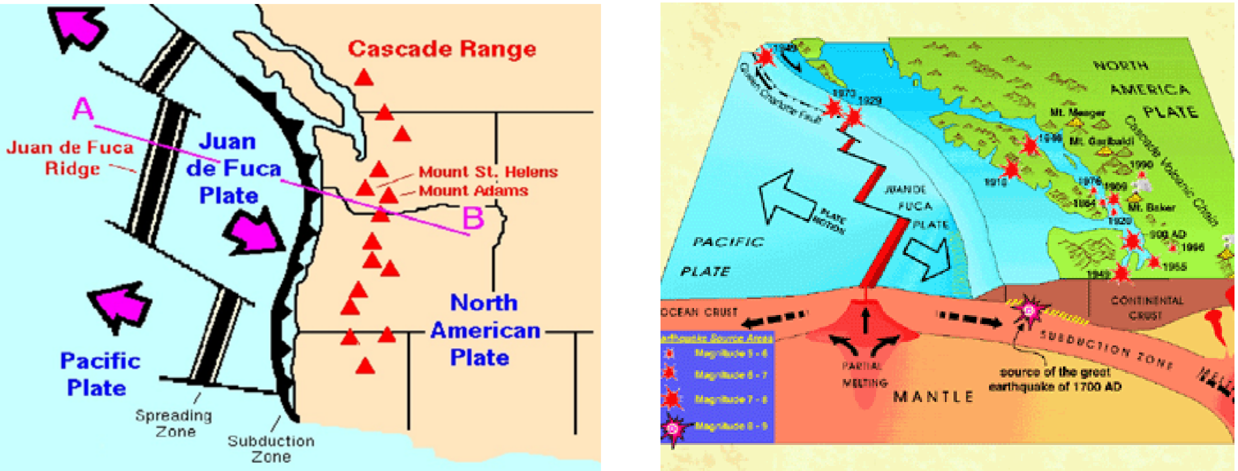

Figure 5-2 Cascadia Subduction Zone (USGS, 2007 and NRCAN, 2007)

5.1.3 Ground Motion Parameters and Instrumental Intensity

In order to perform intensity based damage assessments, ground motion information, such as peak ground acceleration (PGA) and peak ground velocity (PGV), must first be converted to an earthquake Intensity scale. Intensity is a measure of the effects of an earthquake on the built environment. It differs from magnitude scale (Richter Magnitude, Moment Magnitude, etc.) in that magnitude is a quantitative measure of the energy released at the hypocenter of the earthquake while intensity is a qualitative measure of the damage. Onur's study used the Modified Mercalli Intensity scale (MMI) for British Columbia damage assessment and since then, there has been a important research conducted on the relationships between ground shaking and intensity scales. Wald's paper entitled "Relationships between Peak Ground Acceleration, peak ground velocity and Modified Mercalli Intensity" (Wald 1999) compared earthquake intensity in terms of MMI to strong motion records from eight California earthquakes with the purpose of updating existing relationships between intensity and ground motion parameters. The relationships are presented in equations 5-1 and 5-2. (II is the Instrumental Intensity), where PGA is in cm/s^2 and PGV is in cm/s.

For intensities smaller than VII it is recommended using a relationship that follows acceleration and for those greater than VII one that follows velocity should be used.

$$\mathbf{II = 3.66\log(PGA) - 1.66} \qquad \mathbf{(5\text{-}1)}$$

$$\mathbf{II = 3.47\log(PGV) + 2.35} \qquad \mathbf{(5\text{-}2)}$$

These equations result in the table presented below (5-1) which is used for quick conversion from PGA or PGV to the intensity scale, named the Instrumental Intensity scale since the relationships are based on strong motion instrument recordings. The Instrumental Intensity scale has the same meaning and terms as the Modified Mercalli Intensity scale, the difference being the equations used. The Intensity scale is presented in Appendix A.

Table 5-1 Instrumental Intensity Scale (Wald, 1999)

Perceived Shaking	Not Felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
Potential Damage	None	None	None	Very Light	Light	Moderate	Moderate/ Heavy	Heavy	Very Heavy
Peak ACC. (%g)	**< 0.17**	**0.17-1.4**	**1.4-3.9**	**3.9-9.2**	**9.2-18**	18-34	34-65	65-124	> 124
Reach VEL (cm/s)	< 0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	**16-31**	**31-60**	**60-116**	**> 116**
Instrumental Intensity	**I**	**II - III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X+**

It should be noted that these relationships were developed for California crustal earthquakes and may not correlate with the southwestern British Columbia seismic setting. California crustal earthquakes tend to occur within the top ten kilometers of the crust. Surface faulting is often seen and aftershocks are more common than crustal earthquakes in BC (Onur, 2001). Also, subcrustal and subduction earthquakes are not represented in these relationships. While intensity to peak ground motion relationships were developed for many regions, there are none currently available for British Columbia. A relationship based on strong motion relationships from another region must be used. Several relationships have been developed from California strong motion data: Neumann (1945), Trifunac and Brady (1975), McCormack and Rad (1997) and Wald (1999). The instrumental intensity relationships proposed by Wald (equations 5-1 and 5-2) are currently being used by the United States Geological Survey (USGS) for the rapid generation of earthquake intensity maps ("SHAKEMAP") for earthquakes around the world.

5.1.4 Soil Amplification

Many past earthquakes have shown that local soil conditions can have a considerable influence on seismic response and the amount of damage seen at a site. It is for this reason that their effects should be evaluated. Notable sources of damage apart from ground shaking are liquefaction, landslides and soil amplification. Liquefaction and landslide damage are usually determined in separate geotechnical analyses and while they are important components of seismic risk assessment, due to lack of time and resources, are out of the scope of this thesis. Soil amplification, however, is directly related to the ground motion amplitude at a site. It occurs when soil layers overlying the bedrock have dynamic properties that tend to intensify the bedrock ground motions.

There are several methods to determine the level of soil amplification. The first method is numerical modeling using a software package such as SHAKE (Schnabel, 1972). The second is the empirical multiplication factors proposed by the National Earthquake Hazards Reduction Production Program (NEHRP) (BSSC, 1995) and adopted by the National Building Code of Canada (NBCC 2005) (NRC, 2005). Numerical modeling requires extensive knowledge of the soil profile and is time and resource consuming. The empirical method is preferred for the purpose of this study. Table 5-2 displays the site classes defined in NBCC 2005. The classes range from A to F: A being hard rock and F being peat, which requires site specific analysis. These are the same as those defined in NEHRP with the only difference being the reference soil condition. The NEHRP reference condition is site class “B”, while NBCC 2005 uses site class “C”. Also displayed in this table are the short period amplification factors, F_a. The peak ground acceleration determined through seismic hazard analysis should be multiplied by these factors before being converted to the instrumental intensity scale.

Table 5-2 NBCC 2005 Soil Classes and Acceleration Amplification Factors (NBCC, 2005)

Site Class	**Ground Profile Name**	**Average Properties in Top 30m, as per appendix A**			**Fa (Sa(0.2)<0.25)**
		Average Shear Wave Velocity, V_s (m/s)	Average Standard Penetration Resistance, N_{60}	Soil Undrained Shear Strength, s_u	
A	Hard Rock	$V_s > 1500$	n/a	n/a	0.7
B	Rock	$760 < V_s \leq 1500$	n/a	n/a	0.8
C	Very dense soil and soft rock	$360 < V_s < 760$	$N_{60} > 50$	$s_u > 100$ kPa	1
D	Stiff soil	$180 < V_s < 360$	$15 \leq N_{60} \leq 50$	$50 \text{ kPa} < s_u \leq 100 \text{kPa}$	1.3
E	Soft soil	$V_s < 180$	$N_{60} < 15$	$s_u < 50$ kPa	2.1
		Any profile with more than 3 m of soil with the following characteristics: plasticity index: PI >20 moisture content: w ≥ 40%, and undrained shear strength: $s_u < 25$kPa			
F	Other soils	Site-specific evaluation required			

The shear wave velocity, V_s, the standard penetration resistance, and the undrained shear strength are the average of the top 30 m of the soil layer.

5.2 Building Inventory Collection

Data collection is a very important and time consuming step of seismic risk assessment as results of the assessment depend on its accuracy. Typical building inventories contain the name, address, year of construction, primary use, number of stories, structural material, lateral force resisting system (LFRS) and the soil class. There are a number of resources from which data can be gathered. Local and provincial governments and the private sector typically have large databases. For those buildings which no data is available side walk surveys can be conducted.

Once the data has been gathered it is important to put it together in a standardized database. Geographic Information Systems (GIS) can be used for this purpose.

5.3 Structural Damage Assessment

5.3.1 Overview

Seismic Risk Assessment methodologies can be grouped into two types, depending on the parameter used to portray the expected ground motion: engineering parameter based and intensity based. Engineering parameter based methodologies, such as HazUS (FEMA/NIBS 2005) typically use spectral acceleration or spectral displacement in the form of demand spectra to describe the input ground motions. The building characteristics are represented by capacity curves and the building vulnerability is predicted though the use of fragility curves. The HazUS methodology was developed specifically for the United States based on earthquake damage data and cannot be used for BC seismic risk assessment without modification. It is recognized that engineering parameter based methodologies are the current state of the art method for seismic risk assessment; however at this time there is great uncertainty in the fragilities and insufficient data to develop these curves for BC. Intensity based damage probability matrices are already developed for BC (CCE) and offer a more convenient and refined estimation for the study area.

Intensity based methodologies are a common technique for the estimation of damage. In 1985, the Applied Technology Council released "ATC 13 - Earthquake Damage Evaluation Data for California" (ATC 1985). The document introduces a classification system for facilities and provides an estimate of damage for each class. It has organized all structures and infrastructures into 91 different facility classes, 40 of which are buildings. The expected seismic damage sustained by a building is related to ground shaking intensity through Damage Probability Matrices (DPMs). For each class, the DPM expresses the probability of being in a certain damage state given the Modified Mercalli shaking intensity (MMI). There are seven damage states, each of which is associated with a range of Damage Factors (DFs) and Central Damage Factors (CDF). These damage factors signify the ratio of dollars lost due to damage to the total replacement value of the structure. Table 5-3 presents the damage states, their description and their corresponding DF ranges and CDFs. ATC has also released other documents that pertain to the seismic evaluation of buildings and lifelines. The 1987 "Evaluation of the Seismic Resistance of Existing Buildings" provided techniques for the detailed assessment of seismic resistance of individual buildings (ATC, 1987) and ATC 25 "Seismic Vulnerability and Impact of the Disruption of Lifelines in the Conterminous United States" provides an improved method for estimating lifeline damage (ATC, 1991). While these methods provide a more accurate estimation of seismic damage to buildings and lifelines, for the purpose of this thesis, an ATC 13 type assessment is preferred since ATC 14 is not suitable for regional seismic risk assessment.

Table 5-3 ATC 13 Damage States

Damage States		**Description**	**DF Range (%)**	**CDF (%)**
1	None	No Damage	0	0.0
2	Slight	Limited localized minor damage not requiring repair	0 - 1	0.5
3	Light	Significant localized damage of some components generally not requiring repair	1-10	5.0
4	Moderate	Significant localized damage of many components requiring repair	10-30	20.0
5	Heavy	Extensive damage requiring major repairs	30-60	45.0
6	Major	Major widespread damage that may result in the facility being destroyed or repaired	60-100	80.0
7	Destroyed	Total destruction of the majority of the facility	100	100.0

The DPMs were developed based on expert opinion; the Applied Technology Council surveyed 71 earthquake engineering experts. They were asked to provide their low, high and best estimates of the damage for each facility class at intensities VI through XII. There were three rounds of questionnaires and the results were fit to a beta distribution to get the final matrices. An example DPM for facility class 41 (underground liquid storage tank) is displayed in Table 5-4. The matrix is used in the following manner: if the earthquake intensity to be evaluated is VIII, there would be a 3% probability of no damage, 81% probability of slight damage, 14% probability of light damage and 2% of moderate damage.

Table 5-4 ATC 13 DPM for Underground Storage Tanks (%)

ATC13 -41							
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	93.6	92.7	2.8				
0.5	6.4	7.3	80.8				
5.0	0.0	0.0	14.4	98.0	87.9	4.5	
20.0		0.0	2.0	2.0	12.1	90.2	65.7
45.0			0.0	0.0	0.0	5.3	34.0
80.0					0.0	0.0	0.3
100.0							

The results of the damage assessment are presented in terms of the Mean Damage Factor (MDF). The MDF is the ratio of dollar loss to the replacement cost of the building and describes the total expected level of damage in a building for the given level of II intensity. The MDF can be calculated from the following equation:

$$\mathbf{MDF_{II,\,prototype} = \frac{1}{100}\sum_{i=1}^{7}(CDF_i * P(DS_i))} \qquad \textbf{(5-3)}$$

Where CDF_i is the Central Damage Factor and P (DS_i) is the probability of a given building prototype being in that damage state given the Modified Mercalli Intensity. Again using the example of an intensity VIII earthquake, the Mean Damage Factor for an underground storage tank would be:

$$\mathbf{MDF_{VIII,41} = \frac{1}{100} * (0.0 * 2.8 + 0.5 * 80.8 + 5.0 * 14.4 + 20.0 * 2.0) = 1.5\%} \qquad \mathbf{(5\text{-}4)}$$

5.3.2 BC 31 Classification System

ATC-13 has 40 building facility classes. These classes are based on California design and construction practices and are not applicable in British Columbia. In 1998, a classification system based on ATC-13 was developed for British Columbia construction practices (Ventura, 2005) where buildings were grouped into 31 prototypes based on material, the number of stories, lateral force resisting systems and age. Table 5-5 displays the BC-31 prototypes and each one is described in detail in Appendix B. Low-rise, mid-rise and high-rise represent buildings with one to three stories, four to seven stories and over eight stories respectively.

Table 5-5 BC 31 Building Prototypes

Number	Material	Building Prototype	Code
1	**Wood**	Wood Light Frame Residential	WLFR
2		Wood Light Frame Low Rise Commercial/ Institutional	WLFCI
3		Wood Light Frame Low Rise Residential	WLFLR
4		Wood and Post Beam	WPB
5	**Steel**	Light Metal Frame	LMF
6		Steel Moment Frame Low Rise	SMRLR
7		Steel Moment Frame Medium Rise	SMFMR
8		Steel Moment Frame High Rise	SMFHR
9		Steel Braced Frame Low Rise	SBFLR
10		Steel Braced Frame Medium Rise	SBFMR
11		Steel Braced Frame High Rise	SBRHR
12		Steel Frame with Concrete Walls Low Rise	SFCWLR
13		Steel Frame with Concrete Walls Medium Rise	SFCWMR
14		Steel Frame with Concrete Walls High Rise	SFCWHR
15		Steel Frame with Concrete Infill Walls	SFCI
16		Steel Frame with Masonry Infill Walls	SFMI
17	**Concrete**	Concrete Frame with Concrete Walls Low Rise	CFCWLR
18		Concrete Frame with Concrete Walls Medium Rise	CFCWMR
19		Concrete Frame with Concrete Walls High Rise	CFCWHR
20		Reinforced Concrete Moment Frame Low Rise	CMFLR
21		Reinforced Concrete Moment Frame Medium Rise	CMFMR
22		Reinforced Concrete Moment Frame High Rise	CMFHR
23		Reinforced Concrete Frame with Infill Walls	CFIW
24	**Masonry**	Reinforced Masonry Shear Wall Low Rise	RMLR
25		Reinforced Masonry Shear Wall Medium Rise	RMMR
26		Unreinforced Masonry Bearing Wall Low Rise	URMLR
27		Unreinforced Masonry Bearing Wall Medium Rise	URMMR
28	**Tilt Up**	Tilt Up	TU
29	**Precast**	Precast Concrete Low Rise	PCLR
30		Precast Concrete Medium Rise	PCMR
31	**Mobile**	Mobile Homes	MH

Damage Probability Matrices for the 31 prototypes were developed using the same principles as ATC-13. The matrices express the probability of being in a certain damage state given the Modified Mercalli Intensity and the methodology uses the same seven damage states and damage factors as ATC 13. The DPMs for all 31 prototypes can be seen in Appendix C. Table 5-6 presents the Mean Damage Factors for all 31 prototypes. Conversion to the

Instrumental Intensity scale does not affect the Damage Probability Matrices themselves. It alters only the selection of the appropriate intensity to be used to estimate the damage.

Table 5-6 BC Mean Damage Factors

		Mean Damage Factor (%)						
Number	**Prototype**	**II VI**	**II VII**	**II VIII**	**II IX**	**II X**	**II XI**	**II XII**
1	**WLFR**	1.2	4.1	6.2	12.0	22.7	28.4	37.7
2	**WLFCI**	1.2	5.5	9.1	14.5	27.4	36.9	44.1
3	**WLFLR**	1.0	3.8	4.9	11.6	18.8	28.1	37.4
4	**WPB**	1.4	6.4	11.8	18.9	31.6	39.1	45.9
5	**LMF**	0.5	2.7	4.1	7.0	18.8	23.9	36.7
6	**SMRLR**	0.6	3.2	5.0	6.3	17.3	23.4	36.1
7	**SMFMR**	0.7	3.7	5.1	8.7	20.6	31.7	42.8
8	**SMFHR**	0.7	4.5	5.8	17.2	23.6	37.4	44.8
9	**SBFLR**	0.9	2.6	6.9	12.3	22.4	31.4	40.6
10	**SBFMR**	1.6	4.5	10.1	14.8	22.1	32.5	38.3
11	**SBRHR**	1.6	5.9	10.5	16.0	23.8	39.6	48.4
12	**SFCWLR**	0.9	4.5	6.2	15.6	22.2	36.0	46.5
13	**SFCWMR**	1.3	4.7	7.7	19.3	29.1	42.2	51.1
14	**SFCWHR**	1.3	4.7	9.3	22.8	32.8	49.3	57.0
15	**SFCI**	1.1	4.6	8.5	18.4	30.3	47.9	53.4
16	**SFMI**	3.1	7.5	16.5	36.2	45.8	64.0	69.2
17	**CFCWLR**	0.9	4.7	5.0	13.9	21.0	36.9	49.4
18	**CFCWMR**	0.9	3.6	7.9	16.8	23.8	39.1	51.2
19	**CFCWHR**	1.1	4.0	11.3	22.9	30.4	43.2	54.2
20	**CMFLR**	3.0	5.5	13.8	21.0	37.9	48.9	54.5
21	**CMFMR**	3.0	5.8	13.6	22.3	41.0	55.3	60.3
22	**CMFHR**	3.4	4.9	15.7	25.5	41.6	60.1	67.4
23	**CFIW**	2.9	7.7	15.6	30.4	39.6	60.6	67.5
24	**RMLR**	0.7	4.0	5.9	16.6	31.5	43.4	58.3
25	**RMMR**	0.9	4.6	8.0	26.7	35.3	47.8	67.3
26	**URMLR**	2.8	10.2	23.4	34.9	51.7	65.8	80.0
27	**URMMR**	4.3	12.2	26.9	38.2	53.8	70.0	83.7
28	**TU**	0.8	3.7	9.0	18.8	34.0	50.5	65.6
29	**PCLR**	2.3	4.8	11.3	25.0	39.2	51.7	66.6
30	**PCMR**	2.7	6.1	13.0	28.4	38.0	53.0	69.1
31	**MH**	1.8	5.6	13.5	18.8	31.8	45.0	56.7

5.3.3 Damage Modification Factors

5.3.3.1 Overview

The damage probability matrices were developed under the assumption that the buildings being assessed were “regular”. A “regular” building was defined as one that has standard geometry, is without soft stories and short columns, is in good state of repair and has not been seismically retrofitted. Many buildings, however, are not regular and structural damage modification factors are required in order to account for the change in behaviour caused by the above issues.

There are several current seismic risk assessment methodologies that use modification factors. One such methodology is FEMA 154: Rapid Visual Screening of Buildings for Potential Seismic Hazards (2002). Here a building’s vulnerability is described in terms of a structural score (S) which is determined through the addition of the prototype Basic Structural Score (BSH) and the Score Modifiers (SM) that account for irregularities (see equation 5-4). Here, the higher the score, the better the performance. This methodology has the advantage of being easily adaptable for use with the BC structural damage assessment. The FEMA BSHs are similar in concept to the BC mean damage factors. Normalizing these scales could allow the use of the SMs for British Columbia. The following paragraphs describe the FEMA methodology in more detail including the building prototypes, the ground motion parameter used and the building irregularities that the SMs were developed for. Section 5.3.3.2 describes the adaptation of this methodology for BC.

$$\mathbf{S = BSH \pm SM} \qquad \mathbf{(5\text{-}5)}$$

The building classification system is made for the ten building prototypes listed in table 5-7. Unlike the BC 31 classification system, there are no separate prototypes to account for the number of stories of the building. Instead, all prototypes are assumed to be low-rise and score modifiers are used for mid-rise and high-rise buildings.

The FEMA basic structural score and score modifiers were developed for three levels of seismicity. Regions of high, moderate and low seismicity were determined by the United States Geological Survey (USGS) through the use of seismic hazard maps for ground motions with a 2% probability in 50 years of occurrence.

The Basic Structural Score represents the negative log of the probability of collapse of the building given the Most Credible Earthquake (MCE) for the region (equation 5-5). This probability of collapse (P (collapse)) is determined though the use of the MCE demand spectrum, building prototype capacity curves and fragility curves. Since the negative log is applied, the higher the structural score, the less vulnerable the building is to damage.

$$\mathbf{BSH = -\log_{10} * [P(collapse, MCE)]} \qquad \mathbf{(5\text{-}6\ )}$$

Table 5-7 displays the Basic Structural Score of all ten prototypes for all three seismicity levels (Low, moderate and high). For a concrete moment frame building (C1) the BSH for low, moderate and high seismicity is 4.4, 3.0 and 2.5 respectively.

Table 5-7 FEMA 154 Prototypes and Basic Scores

Code	Class	Basic Score (BSH) Low	Basic Score (BSH) Moderate	Basic Score (BSH) High
W1	Small Wood Frame	7.4	5.2	4.4
W2	Large Wood Frame	6.0	4.8	3.8
S1	Steel Moment Frame	4.6	3.6	2.8
S2	Steel Braced Frame	4.8	3.6	3.0
S3	Light Metal Frame	4.6	3.8	3.2
S4	Steel Frame Concrete Wall	4.8	3.6	2.8
S5	Steel Frame Infill Wall	5.0	3.6	2.0
C1	Concrete Moment Frame	4.4	3.0	2.5
C2	Concrete Shear Wall	4.8	3.6	2.8
C3	Concrete Frame Infill Wall	4.4	3.2	1.6
PC1	Tilt Up	4.4	3.2	2.6
PC2	Precast Concrete Frame	4.6	3.2	2.4
RM1	Reinforced Masonry Flexible Diaphragm	4.8	3.6	2.8
RM2	Reinforced Masonry Rigid Diaphragm	4.6	3.4	2.8
URM	Unreinforced Masonry	4.6	3.4	1.8

Score modifiers are used to account for four characteristics that generally affect the seismic response of buildings: the height, vertical and horizontal irregularities, the design and construction year of the building and the soil type it is founded on. The height modifiers, as mentioned above, include mid-rise and high-buildings. Vertical and horizontal irregularities account for building geometry and earthquake resisting deficiencies such as soft stories or short columns. "Design and construction year modifiers are used to represent buildings that were constructed prior to the enforcement and adoption of seismic codes (precode) and those constructed after the adoption of significantly improved seismic codes (post benchmark)"(FEMA 155). Finally the soil type modifiers account for the amplification of soft soils. Table 5-8 displays the score modifiers for the moderate seismicity level. The SMs were developed in a similar manner as the Basic Structural Scores. It can be seen from this table that the mid-rise, high-rise and post benchmark score modifiers work to improve the performance of the building while the remaining modifiers decrease its performance. The mid-rise and high-rise SMs are positive since it was assumed that they would perform better than low-rise buildings due to their superior design and construction

Table 5-8- FEMA 154 Score Modifiers for Moderate Seismicity

Moderate Seismicity										
Class	Basic Scores	Mid-Rise	High-Rise	Vertical Irregularity	Plan Irregularity	Precode	Post Benchmark	Soil Type C	Soil Type D	Soil Type E
W1	5.2	0.0	0.0	-2.5	-0.5	0.0	2.4	-0.2	-0.6	-1.2
W2	4.8	0.0	0.0	-2.0	-0.5	-1.0	2.4	-0.8	-1.2	-1.8
S1	3.6	0.4	1.4	-1.0	-0.5	-1.0	1.4	-0.6	-1.0	-1.6
S2	3.6	0.4	1.4	-1.5	-0.5	-0.8	1.4	-0.8	-1.2	-1.6
S3	3.8	0.0	0.0	0.0	-0.5	-0.6	0.0	-0.6	-1.0	-1.6
S4	3.6	0.4	1.4	-1.0	-0.5	-0.8	1.6	-0.8	-1.2	-1.6
S5	3.6	0.4	0.8	-1.0	-0.5	-0.2	0.0	-0.8	-1.2	-1.6
C1	3.0	0.2	0.5	-1.5	-0.5	-1.2	1.4	-0.6	-1.0	-1.6
C2	3.6	0.4	0.8	-1.0	-0.5	-1.0	2.4	-0.8	-1.2	-1.6
C3	3.2	0.2	0.4	-1.0	-0.5	-0.2	0.0	-0.6	-1.0	-1.6
PC1	3.2	0.0	0.0	0.0	-0.5	-0.8	2.4	-0.6	-1.0	-1.6
PC2	3.2	0.4	0.6	-1.0	-0.5	-0.8	0.0	-0.6	-1.2	-1.6
RM1	3.6	0.4	0.0	-1.0	-0.5	-1.0	2.8	-0.8	-1.2	-1.6
RM2	3.4	0.4	0.6	-1.0	-0.5	-0.8	2.6	-0.6	-1.2	-1.6
URM	3.4	-0.4	0.0	-1.0	-0.5	-0.2	0.0	-0.4	-0.8	-1.6

5.3.3.2 BC Modifiers

Modification factors for British Columbia structural damage assessment were developed based on the methodology used in FEMA 154. Three steps were involved in their development. First, characteristics which are known to affect the amount of structural damage subjected on a building during an earthquake were identified and selected as modifiers. Next, matching schemes between FEMA 154 and the BC SRA methodology were developed and, lastly, the normalization of the FEMA basic scores and the calculation of the final BC modification factors were performed. These three steps are described in the following paragraphs and detailed description of the calculations is presented in Appendix D.

FEMA score modifiers represent the effects of the building height, the soil type on which it is founded, geometrical irregularities and age on seismic response of a building. For the BC methodology, the effect of building height is accounted for by the prototype mean damage factors and the soil amplification is taken into account by the soil factors discussed in section 5.1.4. Therefore, only geometry, age, maintenance and retrofits where taken into consideration. Modification factors were developed for plan and vertical irregularities, the current state of repair, pounding, soft stories, openings, short column effects, pre-code construction, construction after the benchmark code and retrofits. Each of the modifiers is described below in table 5-9. Note LFRS stands for Lateral Force Resisting System.

Table 5-9 BC Modifiers

Modifier	Description
Plan Irregularity	The presence of irregularities and unsymmetrical layout of the building's plan geometry and LFRS
Vertical Irregularity	The presence of irregularities in the plan profile and LFRS at each storey
State of Repair	The overall condition of the building relating to pre-existing damage and deterioration
Pounding	Damage that is induced due to the relative displacement between adjacent buildings
Soft Story	The presence of a local reduction in stiffness of a particular storey of a building
Openings	The presence of large openings in LFRS shear walls
Short Columns	The presence of short columns which are the results of partial height infill walls or deep beams. The effect is a decrease in the shear resistance
Precode	A building constructed before the enforcement of seismic design provisions in the building code, 1967 for Vancouver
Post Benchmark	A building constructed after the benchmark code year, 1990 for Vancouver
Retrofit	A building that has had partial or full upgrading of its structural system

The BC 31 and FEMA 154 building prototypes were matched according to material and the primary lateral force resisting system. Table 5-10 presents the matching scheme. Two reinforced masonry prototypes are available in FEMA 154: reinforced masonry with flexible diaphragm (RM1) and reinforced masonry with rigid diaphragm (RM2). It was decided to use the flexible diaphragm prototype (RM1) since it represents the worst case of the two. The only BC 31 prototype not considered is Mobile Home (MH). Mobile homes are typically regular buildings in geometry and the arrangement of the LFRS does not require modification factors.

Table 5-10 Prototype Matching between FEMA and BC

FEMA 154	BC 31
W1	WLFR
W2	WLFCI, WLFLR, WPB
S1	SMFLR, SMFMR, SMFHR
S2	SBFLR, SBFMR, SBFHR
S3	LMF
S4	SFCWLR, SFCWMR, SFCWHR
S5	SFCI, SFMI
C1	CMFLR, CMFMR, CMFHR
C2	CFCWLR, CFCWMR, CFCWHR
C3	CFIW
PC1	TU
PC2	PCLR, PCMR
RM1	RMLR, RMMR
RM2	
URM	URMLR, URMMR

The BC damage assessment methodology proposed here introduces the use of the Instrumental Intensity scale. Translation from the FEMA seismicity levels to the intensity scale is therefore necessary. Each of the FEMA 154 seismicity levels is associated with ranges of spectral parameters (ref FEMA 155). These were converted to the intensity scale through the equations presented in section 5-1. Table 5-11 displays the results of this calculation.

Table 5-11 Intensity Matching Scheme

FEMA Seismicity Level	Short Period Spectral Acceleration (g)	Instrumental Intensity
Low	< 0.167	VI
Moderate	0.167 to 0.5	VII, VIII
High	> 0.5	IX, X, XI, XII

The FEMA 154 and BC modifiers differ in number; therefore a matching scheme between the two had to be developed in order to determine the appropriate factors. Plan irregularity, vertical irregularity, precode and post benchmark modifiers were related with their corresponding FEMA modifiers. Openings and short columns are forms of plan irregularity and therefore were associated with the FEMA plan irregularity modifier. For the same reason, soft stories were linked to the vertical irregularity score modifier. The effect of pound on a building was considered to be similar to a vertical irregularity and these factors were used. The state of repair and retrofit modifiers could not be matched with FEMA 154 SMs. It was rationalized that poor state of repair would affect the performance of a building by 60% regardless of the prototype and the intensity of the shaking. However, this modifier should only be included in the damage assessment if the building shows signs of severe damage and deterioration such as significant cracking or spalling of concrete or corrosion in steel. Accounting for the effects of retrofits is discussed later in this section.

The modification factors for the BC structural damage assessment were calculated by normalizing the FEMA score modifiers (SM) with respect to the Basic Scores (BSH) for each FEMA prototype. These normalized factors were then multiplied by the BC MDFs for each prototype and intensity level in order to determine the final modifiers. Appendix D presents a detailed description of these calculations. As an illustration, table 5-12 presents the normalized modification factors for the single family home (WLFR) prototype. These factors represent the fraction by which the MDF should be adjusted if the "irregularity" is present in the building. For example, a plan irregularity would increase the MDF by 7% for an intensity VI earthquake.

Table 5-12 Normalized BC Modification Factors for WLFR (%)

Class :1 WLFR		Modifiers								
II	MDF	Plan Irregularity	Vertical Irregularity	state of Repair	Pounding	Soft Storey	openings	Short Columns	Precode	Post Benchmark
6	1.2	7.0	34.0	60.0	34.0	34.0	7.0	7.0	0.0	-16.0
7	4.4	10.0	48.0	60.0	48.0	48.0	10.0	10.0	0.0	-23.0
8	7.4	10.0	48.0	60.0	48.0	48.0	10.0	10.0	0.0	-23.0
9	12.0	11.0	57.0	60.0	57.0	57.0	11.0	11.0	0.0	-27.5
10	25.4	11.0	57.0	60.0	57.0	57.0	11.0	11.0	0.0	-27.5
11	29.9	11.0	57.0	60.0	57.0	57.0	11.0	11.0	0.0	-27.5
12	37.7	11.0	57.0	60.0	57.0	57.0	11.0	11.0	0.0	-27.5

Table 5-13 displays the modifiers for WLFR. The modifiers are the result of multiplying the factors in table 5-12 by the MDFs for the prototype. Looking again at the case of a single family home with a plan irregularity at intensity VI, the final modifier is 7% of the MDF (1.2). The modifiers in table 5-13 are applied through the following equation. (The modifier tables for each prototype are available in Appendix D.)

$$\mathbf{MDF_F = MDF + \sum SM} \qquad \mathbf{(5\text{-}7)}$$

Where MDF_F is the final structural mean damage factor, MDF is the base mean damage factor and ΣSM is the summation of all of the applicable modifiers. For example: the final MDF for a post benchmark single family home with a plan irregularity and openings in the shear walls at intensity IX would be:

$$\mathbf{MDF_F = 12 + (1.3 + 1.3 + (-3.3)) = 11.3} \qquad \mathbf{(5\text{-}8)}$$

Table 5-13 Final Modifiers for WLRF

Class :1 WLFR		Modifiers (SM)								
II	MDF	Plan Irregularity	Vertical Irregularity	state of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
6	1.2	0.1	0.4	0.7	0.4	0.4	0.1	0.1	0.0	-0.2
7	4.4	0.4	2.1	2.6	2.1	2.1	0.4	0.4	0.0	-1.0
8	7.4	0.7	3.6	4.4	3.6	3.6	0.7	0.7	0.0	-1.7
9	12.0	1.3	6.8	7.2	6.8	6.8	1.3	1.3	0.0	-3.3
10	25.4	2.8	14.5	15.2	14.5	14.5	2.8	2.8	0.0	-7.0
11	29.9	3.3	17.0	17.9	17.0	17.0	3.3	3.3	0.0	-8.2
12	37.7	4.1	21.5	22.6	21.5	21.5	4.1	4.1	0.0	-10.4

The method for assessing seismically upgraded buildings is different from that presented above. Buildings are retrofitted to a given performance level, typically “life safety”. At this level, the building is expected to sustain some damage but avoid collapse allowing the occupants to escape safely. Since the expected level of damage is known, the expected MDFs can be predicted for each intensity level regardless of the prototype. The mean damage factors for retrofitted and partially retrofitted building were developed based on the opinion of the author and are presented below in table 5-14. These factors function as an "override" to the original MDFs and modifiers for buildings that have been retrofit. They apply to every BC building prototype. These "new MDFs" apply to all 31 prototypes but should only be applied if they are less than the final MDF (equation 5-7) of the building.

Table 5-14 Mean Damage Factors for Retrofitted and Partially Retrofitted Buildings

Retrofit and Partial Retrofit MDFs (%)							
	VI	VII	VIII	IX	X	XI	XII
Retrofit	0	10	20	30	45	50	60
Partial Retrofit	10	20	30	45	50	60	80

In order to evaluate the effect of the proposed modification factors, the structural damage was estimated for several test cases and plotted against the instrumental intensity. For each prototype, the base, the worst, the best and a likely building case was calculated. The base case represents a regular building for which no modification factors are required. The likely case is an irregular building for which one or two of the modification factors apply. The appropriate modifiers were chosen in order to reflect common traits of a particular prototype. Worst case buildings are those for which all of the modification factors that have the effect of increasing the structural damage apply. These are plan irregularity (PI), vertical irregularity (VI), poor state of repair (SR), pounding (PO), soft storey (SS), openings (OP), short columns (SC) and precode buildings (PC). Although these are unlikely buildings, it was of interest to plot them in order to define the maximum possible damage boundary for each prototype. The best case represents a building that was constructed post benchmark (PB) or has been retrofitted.

Figure 5-3 displays this assessment for a wood light frame commercial/ institutional building (WLCI). In this figure, the “best case” is a building constructed post benchmark. The range of possible MDFs is bounded by best and worst cases of the building. Commercial buildings of this type tend to be grouped together in the form of streetscapes and corner buildings may be severely damaged by pounding. Also, many of these buildings have storefronts and suffer the effects of a soft storey. The likely case was therefore chosen to be a commercial building with a soft storey and pounding. At low intensities, the modification factors have little effect on the total structural damage, but as the intensity increases they play a much more important role. For an intensity X earthquake, using the “base” mean damage factor only, the building is expected to have moderate damage (MDF = 27%). However, if the modifiers are included, the damage would be heavy (56%).

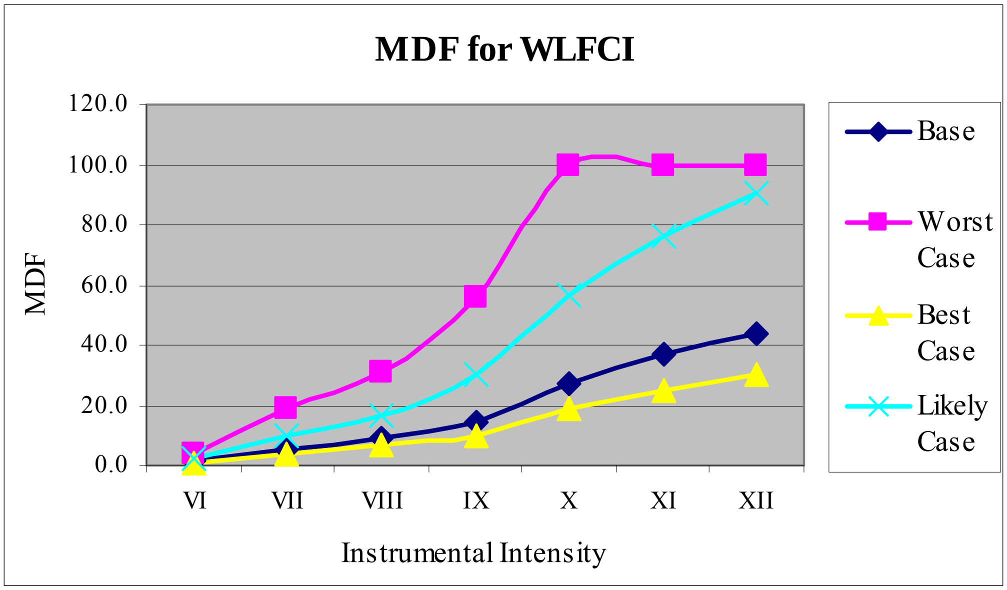

Figure 5-3 Effect of Modifiers on Mean Damage Factors for WLFCI

The result of a similar assessment conducted for low-rise unreinforced masonry buildings (URMLR) is presented in figure 5-4. These buildings were a common form of low-rise construction for commercial and industrial buildings until 1973 when the National Building

Code of Canada required all masonry to be reinforced. For this reason, the best case building is one that has been retrofitted. Many of these commercial buildings of this construction have storefronts and were constructed precode. The likely case is therefore, a precode building with a soft first storey. Similar to the WLFCI building, the effect of the modification factors is minimal at lower intensities and becomes more significant as the intensity increases. At intensity X, the base case predicts a MDF of 52%, placing the building in the heavy damage state. Applying the modification factors, results in a MDF of 86%, implying that major damage has occurred.

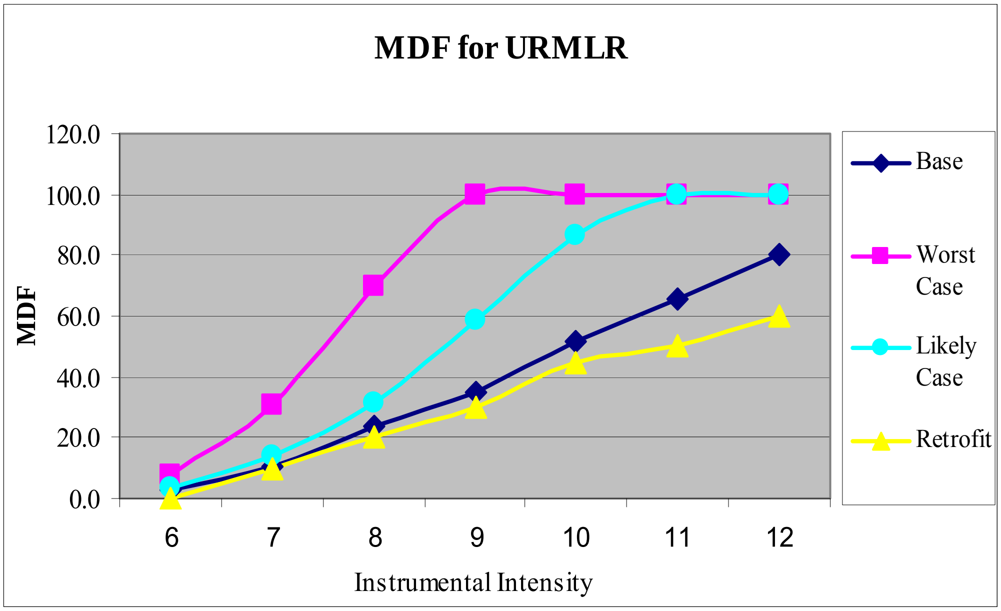

Figure 5-4 Effect of Modifiers Mean Damage Factors for URMLR

An intensity X earthquake is described as one that would result in "some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent." (MMI Scale, Appendix A) The mean damage factors calculated using the modification factors complement this description better than the base MDFs. For these particular cases, their use provides a more rational assessment of the damage.

5.4 Nonstructural Damage Assessment

5.4.1 Overview of Nonstructural Damage Assessment

It has been observed in a number of recent earthquakes that while disastrous losses and casualties are attributed to structural damage, economic losses are dominated by the damage to nonstructural components (NSC). It is therefore of interest to estimate the damage to NSCs as well as structural damage when performing seismic risk assessment.

ATC 13 was the first study to address the damage to nonstructural components. The methodology is similar to that for buildings; the expected damage is evaluated through the use of damage probability matrices. Nonstructural components are grouped into six facility classes: residential equipment, office equipment and furniture, electrical equipment, mechanical equipment, high technology equipment and laboratory equipment. The DPMs were developed from expert opinion using the seven damage states discussed in section 5.3.1.

Recent studies (HazUS, 2005) separate nonstructural components into two categories: displacement sensitive components and acceleration sensitive components. Displacement sensitive components include partition walls, exterior wall panels, architectural finishes, piping, cladding and penthouses. Acceleration sensitive components consist of electrical and mechanical equipment, piping, cantilever elements, parapets and racks. Building contents such as shelving and furniture are also deemed to be acceleration sensitive.

In 1997, FEMA/NIBS (HazUS) developed a methodology for nonstructural damage assessment which considers the dissimilar behaviour of the two categories of components (FEMA/NIBS, 1997) This methodology uses fragility curves based on inter-storey drift and peak floor accelerations to determine the damage to displacement sensitive and acceleration sensitive components respectively. The fragility curves describe the probability of exceeding the damage state given the spectral displacement or acceleration. They are used in conjunction with building prototype capacity curves and demand spectra in order to determine the level of component damage

Here, the damage states for non structural components are defined for the component, not the building prototype. This is because the damage depends primarily on the floor accelerations and the inter-storey drift which can be achieved in any type of structure. The HazUS damage states for displacement sensitive components and acceleration sensitive components are presented in Appendix E.

Each damage state is related to a range of damage factors (DF) and central damage factors (CDF) which represent the ratio of dollars lost to the replacement cost of the component. The CDFs for displacement sensitive components, acceleration sensitive components and building contents are presented in table 5-5. While buildings contents are acceleration sensitive, their CDFs are half of those for acceleration sensitive components.

Table 5-15 Central Damage Factors for Nonstructural Components

Damage state	**Central Damage Factors**		
	Displacement-Sensitive	**Acceleration - Sensitive**	**Building Contents**
None	0%	0%	0%
Slight	2%	2%	1%
Moderate	10%	10%	5%
Extensive	50%	50%	25%
Complete	80%	80%	40%

5.4.2 BC 31 Nonstructural Assessment

For the estimation of nonstructural damage in British Columbia, damage probability matrices were developed from the nonstructural fragility curves and building capacity curves in

HazUS by Cook (1999). This involved first matching the BC prototypes to those in FEMA/ NIBS and converting spectral displacement and acceleration to the Modified Mercalli Intensity scale. The particulars of these computations can be seen in Cook (1999). The resulting DPMs were updated with the instrument intensity scale and are presented in Appendix E. The mean damage factors for displacement sensitive and acceleration sensitive nonstructural components, and building contents are displayed in tables 5-16 through 5-18.

Table 5-16 Mean Damage Factors for Displacement Sensitive Components

Displacement-sensitive components							
CDF %	**Damage Probability (%) at II**						
	VI	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
1-WFLR	10.0	15.3	17.0	22.7	27.6	32.2	35.8
2-WLFCI	8.1	14.8	15.8	20.3	24.4	27.5	30.5
3-WLFLR	10.0	15.3	16.9	22.7	28.3	32.2	35.8
4-WPB	10.0	15.3	16.9	22.7	28.3	32.2	35.8
5-LMF	10.7	18.2	18.8	26.4	30.9	34.7	37.5
6-SMFLR	7.1	15.9	16.7	20.7	25.4	28.5	32.4
7-SMFMR	7.3	16.2	16.8	18.1	22.4	24.7	35.3
8-SMFHR	7.0	7.5	8.5	15.7	20.4	25.0	29.2
9-SBFLR	7.3	14.0	15.6	21.1	25.0	28.7	31.5
10-SBFMR	7.1	13.3	14.6	15.3	18.4	21.8	24.6
11-SBFHR	5.3	9.8	11.0	13.3	18.3	22.0	25.6
12-SFCWLR	8.0	16.9	17.1	21.7	26.0	29.4	31.9
13-SFCWMR	6.1	14.6	15.1	15.7	18.5	22.5	25.7
14-SFCWHR	5.6	11.3	11.7	13.1	17.5	23.4	26.8
15-SFCI	8.0	16.3	17.1	21.7	26.0	29.4	31.9
16-SFMI	8.0	16.3	16.7	21.7	26.0	29.4	31.9
17-CFCWLR	9.0	16.7	17.3	21.8	26.9	29.8	33.0
18-CFCWMR	5.0	11.0	11.3	13.8	17.2	20.0	22.2
19-CFCWHR	5.8	10.7	11.1	13.1	15.9	18.2	21.2
20-CMFLR	8.4	17.2	17.7	23.3	27.5	31.2	33.6
21-CMFMR	6.9	15.4	15.8	17.4	20.6	24.0	27.1
22-CMFHR	7.5	15.0	15.6	18.4	23.8	28.2	32.2
23-CFIW	8.7	18.6	19.1	26.1	32.3	38.1	49.8
24-RMLR	10.5	13.7	14.5	22.3	27.0	30.0	32.9
25-RMMR	5.2	8.8	9.2	13.7	17.0	19.8	22.2
26-URMLR	12.1	21.2	22.8	32.2	31.0	34.8	37.5
27-URMMR	7.7	13.8	14.2	17.2	21.2	24.9	27.7
28-TU	11.4	15.7	16.5	24.3	29.7	33.2	35.6
29-PCLR	9.0	16.7	17.3	22.9	27.3	31.0	33.8
30-PCMR	5.6	11.2	11.5	15.5	19.0	21.7	25.7
31-MH	12.2	21.6	22.2	29.3	34.3	37.5	43.7

Table 5-17 Mean Damage Factors for Acceleration Sensitive Components

Acceleration-sensitive components							
CDF %	**Damage Probability (%) at II**						
	VI	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
1-WFLR	1.0	3.3	5.5	8.8	14.3	18.2	20.7
2-WLFCI	0.9	3.1	3.3	6.2	8.3	9.9	10.7
3-WLFLR	1.0	3.1	4.8	8.8	14.3	18.2	20.7
4-WPB	1.0	3.1	4.8	8.8	14.3	18.2	20.7
5-LMF	0.6	2.3	2.7	4.9	6.3	6.7	7.5
6-SMFLR	0.3	1.7	2.1	3.2	4.1	5.1	5.9
7-SMFMR	0.0	0.4	0.3	0.7	1.2	2.4	2.8
8-SMFHR	0.0	0.0	0.0	0.1	0.4	0.5	0.5
9-SBFLR	0.7	3.0	3.6	5.3	6.8	7.1	7.9
10-SBFMR	0.1	0.4	1.1	1.6	2.6	3.1	3.7
11-SBFHR	0.0	0.2	0.3	0.4	0.9	1.4	2.1
12-SFCWLR	1.2	2.0	2.8	5.1	5.8	6.6	6.6
13-SFCWMR	0.1	1.4	1.2	2.3	3.1	3.7	3.9
14-SFCWHR	0.0	0.3	0.4	0.5	1.3	2.1	2.4
15-SFCI	1.1	1.9	2.7	5.1	5.8	6.5	6.5
16-SFMI	1.1	1.8	2.6	4.9	5.6	6.3	6.3
17-CFCWLR	0.7	3.3	3.6	7.1	9.5	10.7	11.6
18-CFCWMR	0.3	1.7	2.1	3.8	5.1	6.5	7.4
19-CFCWHR	0.0	0.5	0.8	0.9	1.8	2.3	3.4
20-CMFLR	0.4	1.9	2.1	4.1	5.4	6.1	6.8
21-CMFMR	0.1	0.7	0.9	1.8	2.4	3.3	3.8
22-CMFHR	0.0	0.1	0.2	0.4	0.5	0.7	0.9
23-CFIW	0.6	3.0	3.3	3.6	3.6	3.6	3.6
24-RMLR	1.0	3.9	4.2	7.7	10.2	11.5	12.8
25-RMMR	0.3	1.9	2.4	4.1	5.8	7.4	8.5
26-URMLR	2.1	5.5	5.9	9.3	10.8	11.9	11.9
27-URMMR	0.6	2.9	4.8	9.6	11.1	12.1	12.1
28-TU	1.3	3.0	3.7	8.0	11.2	13.9	14.2
29-PCLR	1.1	2.3	2.7	5.6	6.7	7.0	7.9
30-PCMR	0.3	1.6	1.8	3.1	3.9	4.6	5.3
31-MH	1.0	2.2	2.5	3.9	4.2	4.5	4.5

Table 5-18 Mean Damage Factors for Building Contents

Building contents							
CDF %	**Damage Probability (%) at II**						
	VI	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
1-WFLR	0.5	1.6	2.7	4.4	7.1	9.1	10.4
2-WLFCI	0.4	1.5	1.7	3.1	4.2	5.0	5.4
3-WLFLR	0.5	1.5	2.4	4.4	7.1	9.1	10.4
4-WPB	0.5	1.5	2.4	4.4	7.1	9.1	10.4
5-LMF	0.3	1.1	1.3	2.4	3.2	3.4	3.7
6-SMFLR	0.1	0.9	1.1	1.6	2.1	2.6	2.9
7-SMFMR	0.0	0.2	0.2	0.3	0.6	1.2	1.4
8-SMFHR	0.0	0.0	0.0	0.0	0.2	0.2	0.3
9-SBFLR	0.3	1.5	1.8	2.6	3.4	3.6	3.9
10-SBFMR	0.1	0.2	0.5	0.8	1.3	1.5	1.8
11-SBFHR	0.0	0.1	0.1	0.2	0.4	0.7	1.0
12-SFCWLR	0.6	1.0	1.4	2.6	2.9	3.3	3.3
13-SFCWMR	0.1	0.7	0.6	1.1	1.5	1.8	2.0
14-SFCWHR	0.0	0.1	0.2	0.3	0.7	1.0	1.2
15-SFCI	0.6	1.0	1.3	2.5	2.9	3.2	3.2
16-SFMI	0.5	0.9	1.3	2.4	2.8	3.2	3.2
17-CFCWLR	0.3	1.6	1.8	3.6	4.7	5.4	5.8
18-CFCWMR	0.1	0.8	1.0	1.9	2.5	3.3	3.7
19-CFCWHR	0.0	0.3	0.4	0.4	0.9	1.1	1.7
20-CMFLR	0.2	1.0	1.0	2.1	2.7	3.1	3.4
21-CMFMR	0.1	0.4	0.5	0.9	1.2	1.6	1.9
22-CMFHR	0.0	0.1	0.1	0.2	0.3	0.4	0.4
23-CFIW	0.3	1.5	1.6	1.8	1.8	1.8	1.8
24-RMLR	0.5	2.0	2.1	3.9	5.1	5.7	6.4
25-RMMR	0.1	1.0	1.2	2.0	2.9	3.7	4.3
26-URMLR	1.1	2.7	3.0	4.7	5.4	5.9	5.9
27-URMMR	0.3	1.5	2.4	4.8	5.5	6.1	6.1
28-TU	0.7	1.5	1.9	4.0	5.6	6.9	7.1
29-PCLR	0.5	1.1	1.3	2.8	3.4	3.5	3.9
30-PCMR	0.1	0.8	0.9	1.5	2.0	2.3	2.6
31-MH	0.5	1.1	1.3	2.0	2.1	2.3	2.3

For the purpose of comparing the expected damage to displacement sensitive components, acceleration sensitive components and building contents the mean damage factors were plotted against instrumental intensity. Figure 5-5 presents the plots for four building prototypes that were examined: Wood Light Frame Residential (WLFR), Steel Moment Frame

Low Rise (SMFLR), Concrete Frame with Concrete Shear Walls Low Rise (CFCWLR) and Unreinforced Masonry Low Rise (URMLR).

5.5 Monetary Losses

The estimation of losses is the next step in a seismic risk assessment. As described in chapter 4, there are three forms of loss: monetary loss, human loss and the loss of building function. Monetary losses are described as any financial losses incurred as the result of an earthquake and these can be divided into direct and indirect losses. Direct monetary losses result from the damage sustained to the building due to ground shaking. Indirect losses are those resulting from collateral hazards (tsunami, landslide, liquefaction, fire following) as well as those incurred due to business interruption. As discussed in section 5.3 and 5.4, the structural and nonstructural damage sustained from collateral hazards was not estimated and**,** therefore, their associated economic losses are not calculated. Estimating the losses due to business interruption involves the assessment of downtime. Downtime is defined as the amount of time it takes for a business to fully recover after a disaster. It depends not only on the time required for damage repair but also on a number of additional factors such as the availability of funding and resources. Due to the complexity involved in calculating indirect losses, only direct losses will be considered in this thesis. Downtime estimation is discussed further in section 5.8.

Monetary losses are calculated by summation of the losses incurred from structural, displacement sensitive nonstructural components, acceleration sensitive nonstructural components and building contents damage. Since the mean damage factor (MDF), which expresses the amount of damage done to each component, is the ratio of dollars lost to the replacement value of the building, monetary losses can be calculated by multiplying the MDFs by the replacement values. This is demonstrated in equations 5-9 and 5-10, where the structural and nonstructural MDFs are multiplied by their respective values and the total replacement value of the building is simply their sum.

$$\mathbf{ML = R_S * MDF_S + R_A * MDF_A + R_D * MDF_D + R_C * MDF_C} \quad \textbf{(5-9)}$$

$$\mathbf{R = R_S + R_A + R_D + R_C} \quad \textbf{(5-10)}$$

Where: ML is the total monetary loss for the building
MDF_S is the structural Mean Damage Factor
MDF_D is the displacement sensitive Mean Damage Factor
MDF_A is the acceleration sensitive Mean Damage Factor
MDF_C is the building contents Mean Damage Factor
R_S is the replacement value of the structural components
R_A is the replacement value of the acceleration sensitive NSCs
R_D is the replacement value of the displacement sensitive NSCs
R_C is the replacement value of the building contents
R is the total replacement value of the building

The nonstructural damage is determined based on inter-storey drift and floor accelerations only and does not take into account additional issues caused by major structural damage (MDF < 60%). For example, a certain piece of electrical equipment is expected to suffer damage when the floor acceleration reaches a given level, however it is located in a building that is expected to partially collapse well before this threshold is reached. The damage induced on the equipment from the partial collapse of the building is much higher than if it were subjected to the floor accelerations alone. For this reason, the monetary losses of buildings that have a structural mean damage factor greater than or equal to 60% should be calculated from structural damage only (equation 5-8).

$$\textbf{If MDFS} > \textbf{60}, \quad \mathbf{M_L = R_S * MDF_S + R_A * MDF_S + R_D * MDF_S + R_C * MDF_S} \quad \textbf{(5-11)}$$

Replacement values were estimated based on the cost of construction per square meter on a building prototype basis. These values are based on the expert opinion of practicing engineers in BC and summarized by Dr. Tim White, P.Eng of the firm Bush, Bohlman, and Partners and are presented in table 5-19 in terms of 2007 Canadian dollars.

The replacement values of the structural components (R_S), displacement sensitive components (R_D), acceleration sensitive components (R_A) and building contents (R_C) need to be determined. This thesis presents two approaches for the distribution of building value and hence the estimation of monetary losses: The Facility Independent (FI) and Facility Dependent (FD) methods. Both are described in detail below.

Table 5-19 Construction Costs for BC 31 Prototypes

Prototype	**2007 Construction Costs ($CAD/m^2)**
WLFR	1610
WLFCI	1350
WLFLR	1350
WPB	2150
LMF	1210
SMRLR	2150
SMFMR	2690
SMFHR	3500
SBFLR	2150
SBFMR	2690
SBRHR	3500
SFCWLR	2420
SFCWMR	2960
SFCWHR	3770
SFCI	2960
SFMI	2960
CFCWLR	2420
CFCWMR	2960
CFCWHR	3630
CMFLR	2420
CMFMR	2960
CMRHR	3630
CFIW	2960
RMLR	1880
RMMR	2420
URMLR	1880
URMMR	2420
TU	2150
PCLR	1880
PCMR	2420
MH	1350

5.5.1 Facility Independent Estimation

The Facility Independent methodology is a rapid and convenient way of estimating monetary losses that result from earthquake damage. Here it is assumed that 25% of the buildings replacement value be attributed to its structural components and the remaining 75% is divided equally between the nonstructural components and building contents regardless of the use of the building. Onur (2001) used this methodology to estimate the monetary losses for the cities of New Westminster, Vancouver and Victoria.

The total replacement value of the building, R, is determined by multiplying the values in table 5-19 by the total floor area of the building. Substituting the 25% replacement value for the structural components and the 75% for the nonstructural components and building contents, equations 5-9 and 5-11 become:

$$\mathbf{ML = 0.25 * R * MDF_S + 0.25 * R * MDF_A + 0.25 * R * MDF_D + 0.25 * R * MDF_C} \tag{5-12}$$

$$\mathbf{ML = 0.25 * R * MDF_S + 0.25 * R * MDF_s + 0.25 * R * MDF_s + 0.25 * R * MDF_s} \tag{5-13}$$

Equation 5-12 and 5-13 are used in conjunction with the building replacement value and structural and nonstructural mean damage factors in order to calculate Facility Independent monetary losses. This can be illustrated with the following example.

A large 5 story building with a total floor area of 45,000 square meters is to be assessed for an earthquake of Instrumental Intensity IX. The building is classified to be prototype 18 (CFCWMR) and the MDFs for its structural components, displacement sensitive components, acceleration sensitive component were determined and are presented in table 5-20. Since the structural MDF is less than 60%, equation 5-12 is used to calculate the expected monetary losses. The building replacement value is determined by multiplying the total floor area by the appropriate values from table 5-19. For CFCWMR, this value is \$2,960 dollars per square meter and the total replacement value is determined to be in the order of \$131 million dollars. As demonstrated by table 5-20 the expected monetary losses are approximately \$14 million dollars or 11% of the replacement value with the cost of structural damage making up over half of the dollars lost.

Table 5-20 Building 3 Facility Independent Monetary Losses

Building # 3 (II IX)			
	Total Replacement Value (R)	MDF	\$ Losses
Structural	130,800,000	22.8	7,500,000
NSC Displacement	130,800,000	13.8	4,500,000
NSC Acceleration	130,800,000	3.8	1,200,000
NSC Contents	130,800,000	2.2	700,000
Total			13,900,000

5.5.2 Facility Dependent Estimation

More recent studies have demonstrated the importance of considering the building use when determining its replacement value and expected monetary losses due to seismic shaking. One such study by Taghavi and Miranda entitled “Response Assessment of Nonstructural Components” (Taghavi, 2003) examined the seismic performance of nonstructural components. Data collected included observed earthquake damage as well as the cost of various building components. Figure 5-5 displays the breakdown of component values for three types of buildings. For all three buildings, it can be seen that the nonstructural components and building contents make up the majority of the buildings value. Also, for buildings that house specialized and sensitive equipment, such as hospitals, the value of the contents can be as much as 50% of the total building value. It is therefore more desirable to take into account the use of a facility when estimating monetary losses.

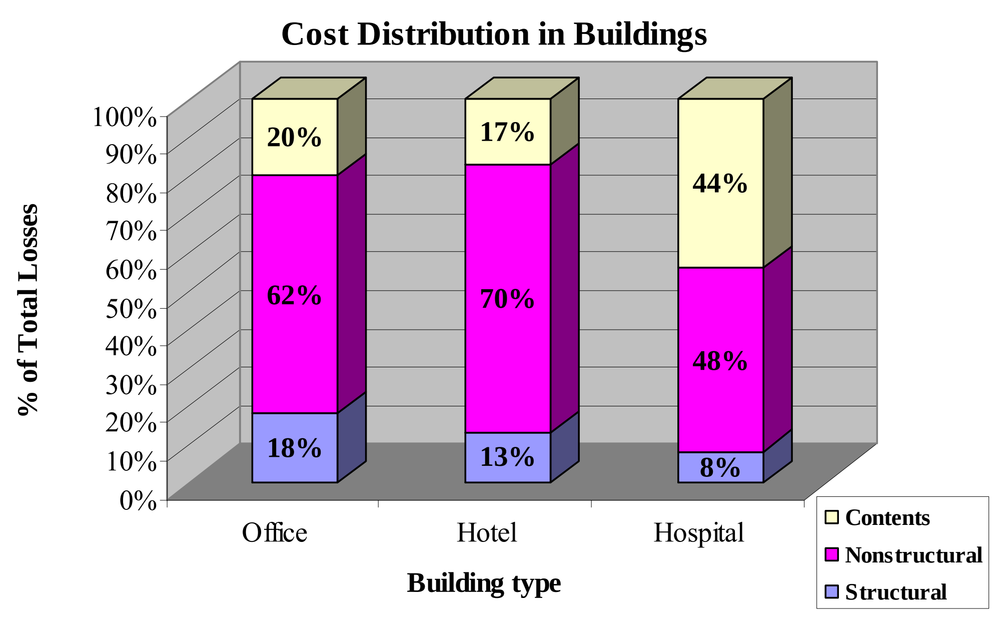

Figure 5-5 Cost Distribution for Offices, Hotel and Hospitals (Taghavi, 2003)

The methodology proposed by HazUS (FEMA/NIBS, 2005) takes the facility type into account when estimating building replacement values and expected monetary losses due to seismic shaking. Here the total replacement value of the structure is determined from the summation of the construction cost of the building and the replacement value of its contents. This is represented in equation 5-14 where R is the total replacement value of the building, RCONS is the construction cost and RCONT is the value of the contents.

$$\mathbf{R = Rcons + Rcont} \qquad \textbf{(5-14)}$$

The building construction cost includes the value of the structural components, the displacement sensitive nonstructural components and the acceleration sensitive nonstructural components. It is calculated by multiplying the building floor area by the appropriate value in table 5-19. The replacement value of the building contents is determined from the construction cost using equation 5-14, where γ is the contents value ratio.

$$\mathbf{R_{CONT}} = \frac{\gamma}{\gamma - \mathbf{1}}\mathbf{R_{CONS}} \tag{5-15}$$

The contents value ratios were developed based on building cost distribution data collected by Taghavi and Miranda (2003) and are presented in table 5-21. They represent the fraction of the total building value taken up by its contents (figure 5-5). The ratios range from 0.15 for single family homes to 0.45 for hospitals.

The construction cost is distributed to the structural, displacement sensitive and acceleration sensitive components by means of the repair cost ratios: αs, αd, and αa respectively. These ratios represent the fraction of the construction cost that is attributed to each of the three types of components. These values depend on the use of the facility and are displayed in table 5-21 along with the contents value ratios described above. The fifteen building types listed are a simplified set of the thirty three types available in HazUS. The ratios add up to 1.0 and vary greatly from building type to building type. The structural repair cost ratios range from 0.14 for hospitals to 0.66 for parking structures and have an average of 0.24. The displacement sensitive ratios range from 0.07 for agricultural buildings to 0.5 for single family homes and have an average of 0.34. Finally the acceleration sensitive ratios have an average of 0.41 and range from 0.18 for parking structure to 0.7 of industrial buildings. Overall, most of the construction cost lies in the nonstructural components. There is also a factor used for the building contents: αc, the contents damage ratio. This ratio is constant over all building types and is equal to 0.5 as HazUS assumes that "even in the complete damage state some percentage of contents, set at 50%, can be retrieved" (FEMA/NIBS, 2005)

Table 5-21 Repair Cost Ratios and Building Content Ratios

#	Type	Name	Structural Repair Cost Ratio α_s	Displacement Sensitive Repair Cost Ratio α_d	Acceleration Sensitive Repair Cost Ratio, α_a	Building Contents Value Ratio, γ
1	Res	Single Family Home	0.25	0.50	0.25	0.15
2	Res	Mobile Home	0.22	0.42	0.36	0.20
3	Res	Multi Family Dwelling	0.15	0.45	0.40	0.20
4	Res	Institutional Dormitory	0.20	0.42	0.38	0.17
5	Com	Retail/ Wholesale	0.32	0.29	0.39	0.25
6	Com	Services	0.21	0.35	0.44	0.25
7	Com	Banks	0.15	0.37	0.48	0.30
8	Com	Hospital / Clinics	0.14	0.38	0.48	0.45
9	Com	Entertainment/ Theaters/ Recreation	0.14	0.37	0.49	0.25
10	Com	Parking	0.66	0.18	0.18	0.25
11	Ind	All Industrial	0.18	0.12	0.70	0.40
12	Agr	Agriculture	0.47	0.07	0.46	0.15
13	Rel	Religious	0.20	0.36	0.44	0.15
14	Gov	General Services and Emergency Response	0.16	0.37	0.47	0.35
15	Edu	Schools / Libraries / Colleges	0.20	0.50	0.30	0.35

Subbing these values into equations 5-9 and 5-10 we get:

$$\mathbf{ML = \alpha_S * R_{CONS} * MDF_S + \alpha_A * R_{CONS} * MDF_A + \alpha_D * R_{CONS} * MDF_D + 0.5 * R_{CONT} * MDF_C} \qquad \textbf{(5-16)}$$

$$\mathbf{ML = \alpha_S * R_{CONS} * MDF_S + \alpha_A * R_{CONS} * MDF_S + \alpha_D * R_{CONS} * MDF_S + 0.5 * R_{CONT} * MDF_S} \qquad \textbf{(5-17)}$$

These are the equations to be used in conjunction with table 5-21 for Facility Dependent direct monetary losses due to earthquake shaking. Using the same example of a large concrete building located on UBC campus, the construction cost, R_{CONS}, was determined to be \$131 million dollar. This building is a hospital. From table 5-21 γ is 0.45 and the replacement value of the contents, R_{CONT}, is calculated to be \$107 million dollars from equation 5-15. The total replacement value of the building, R, is therefore \$238 million dollars.

Table 5-22 displays the structural , displacement sensitive NSCs, acceleration sensitive NSCs and building contents MDFs as well as the appropriate repair cost and contents damage ratios taken from table 5-21. For a hospital, α_s is equal to 0.14, α_d is equal to 0.38, α_a is equal to 0.48 and α_c is the constant 0.5. Since the structural MDF is less than 60%, equation 5-16 is used to calculate a monetary loss of $14.9 million dollars or 6% of the total building value. Unlike the results from the Facility Independent method, the highest amount of dollars lost is attributed to the displacement sensitive nonstructural components.

Table 5-22 Facility Dependent Monetary Losses of Building 3 for II IX

Building # 3 (II IX)				
	Total Replacement Value (R)	MDF	α factor	$ Losses
Structural	130,800,000	22.8	0.14	4,200,000
NSC Displacement	130,800,000	13.8	0.38	6,900,000
NSC Acceleration	130,800,000	3.8	0.48	2,400,000
NSC Contents	107,000,000	2.2	0.5	1,400,000
Total				14,900,000

For the same building, assessed for an intensity XII earthquake, the structural mean damage factor is 69.6% (table 5-22). Since the structural MDF is greater than 60% equation 5-17 is used to calculate the monetary losses, which are determined to be in the order of $130 million dollars.

Table 5-23 Facility Dependent Monetary Losses of Building 3 for II XII

Building # 3 (II XII)				
	Total Replacement Value (R)	MDF	α factor	$ Losses
Structural	130,800,000	69.6	0.14	12,700,000
NSC Displacement	130,800,000	69.6	0.38	34,600,000
NSC Acceleration	130,800,000	69.6	0.48	43,700,000
NSC Contents	107,000,000	69.6	0.5	37,200,000
Total				128,200,000

5.6 Casualty Estimation

5.6.1 Overview of Casualty Estimation

The major aim in performing seismic risk assessment is the protection of human lives. One of the most important aspects of seismic risk assessment is the estimation of casualties. Here, casualties are defined as a people who are injured or killed as a result of an earthquake.

The number of causalities varies greatly from earthquake to earthquake and casualties can occur in a number of ways. They are attributable to structural and nonstructural damage, collateral hazards (tsunami, landslide, etc) heart attacks, car accidents and a variety of other causes. Coburn and Spence's book, "Earthquake Protection", (2002) states that "Over 75% of [earthquake] deaths are caused by building collapse and if secondary disasters are excluded, building collapse causes almost 90% of earthquake-related deaths", where "secondary disasters" are the collateral hazards. It is reasonable therefore, to estimate earthquake casualties based on structural damage alone.

There are several methodologies currently in use for the estimation of earthquake casualties. One is the Direct Social Losses module of HazUS 2005 (FEMA/ NIBS). The methodology estimates the number of casualties based on the structural damage to the building and the number of occupants present at the time of the event. The model is an extension of the event tree model proposed by Stojanovski and Dong (1994). The tree begins with the scenario earthquake and branches out to follow every possible path that leads to the occurrence of casualties. In order to determine the number of casualties the population in the building is multiplied by the probability of being in a certain damage given the size of the earthquake and the probability of an injury of a certain severity occurring given the damage state. An example event tree**,** which is presented in HazUS 2005**,** is displayed in figure 5-6. Here, the purpose is to determine the number of people killed as a result of a scenario earthquake.

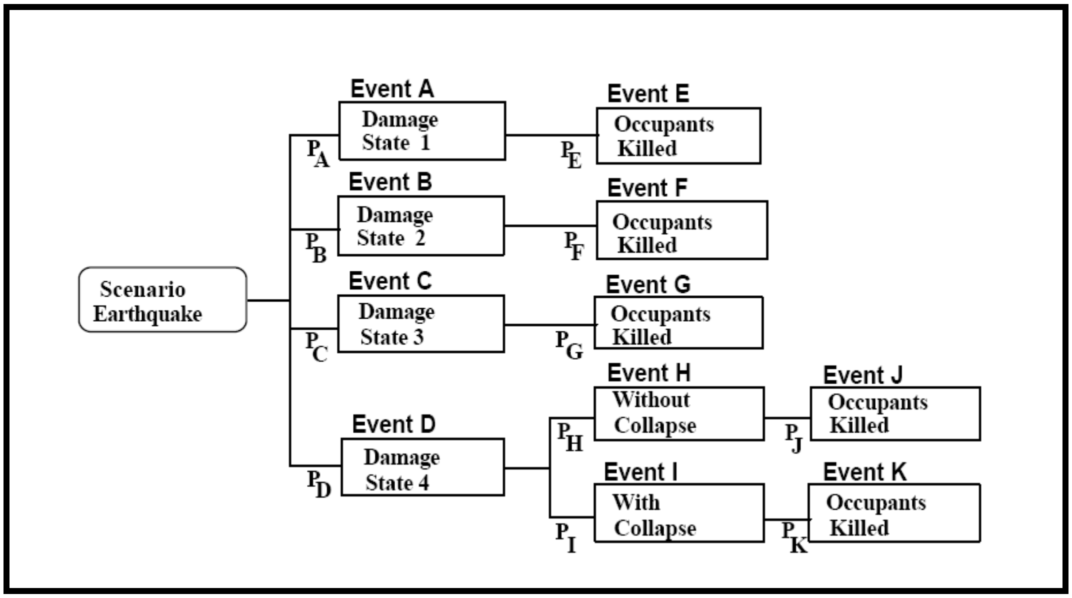

Figure 5-6 Example of Casualty Event Tree (FEMA/NIBS 2005)

For the purpose of casualty estimation, HazUS defines five damage states: slight, moderate, extensive, and complete with or without collapse (described as events A, B, C, D, H and I in figure 5-6). The probability of being in a certain damage state given the size of the earthquake is determined from structural damage assessment through the use of fragility curves. The fragility curves express the probability of exceeding a damage state given the spectral displacement or acceleration. The probability of fatalities as the result of the given damage state (events E, F, G, J and K) is defined by the casualty rates available in the module. The probability of fatalities for this example is calculated as follows:

$$P_{killed} = P_A * P_E + P_B * P_F + P_C * P_G + P_D * (P_H * P_J + P_I * P_K) \qquad \textbf{(5-18)}$$

The total number of people killed is determined by multiplying the number of occupants in the building at the time of the earthquake by this probability.

It is of interest to estimate the number of people injured, as well as those killed, as a result of the scenario earthquake. The methodology classifies injuries into four different severity levels ranging from minor injuries that require medical attention to instantaneous death. A description of each severity level is presented in table 5-24.

Table 5-24 Injury Severity (FEMA/NIBS 2005)

Injury Severity Level	Injury Description
1	Injuries requiring basic medical aid that could be administered by paraprofessionals. These types of injuries would require bandages or observation. Some examples are: a sprain, a severe cut requiring stitches, a minor burn (first degree or second degree on a small part of the body), or a bump on the head without loss of consciousness. Injuries of a lesser severity that could be self treated are not estimated by HazUS.
2	Injuries requiring a greater degree of medical care and use of medical technology such as x-rays or surgery, but not expected to progress to a life threatening status. Some examples are third degree burns or second degree burns over large parts of the body, a bump on the head that causes loss of consciousness, fractured bone, dehydration or exposure.
3	Injuries that pose an immediate life threatening condition if not treated adequately and expeditiously. Some examples are: uncontrolled bleeding, punctured organ, other internal injuries, spinal column injuries, or crush syndrome.
4	Instantaneously killed or mortally injured

The HazUS casualty rates take into account people inside and outside of the building at the time of the event. Outdoor casualties are caused by falling hazards, for example parapet failures. It should be noted that only three damage states are considered for outdoor injuries: moderate, extensive and complete since it is unlikely that falling injuries will occur with slight damage. Indoor and outdoor casualty rates for moderate damage of the FEMA / NIBS prototypes are presented in tables 5-25 and 5-26. The tables for the remaining damage states are available in appendix F. Note that “0” means an insignificant percentage. It can be observed that for all damage states, the indoor casualty rates are much higher than those for outdoor and there is a greater probability for less severe injuries. Unreinforced buildings are expected to have a highest number of both indoor and outdoor casualties.

Table 5-25 Indoor Casualty Rates for Moderate Damage (FEMA/NIBS 2005)

#	Building Type	Casualty Severity Level			
		Severity 1(%)	Severity 2 (%)	Severity 3 (%)	Severity 4 (%)
1	W1	0.25	0.03	0	0
2	W2	0.20	0.025	0	0
3	S1L	0.20	0.025	0	0
4	S1M	0.20	0.025	0	0
5	S1H	0.20	0.025	0	0
6	S2L	0.20	0.025	0	0
7	S2M	0.20	0.025	0	0
8	S2H	0.20	0.025	0	0
9	S3	0.20	0.025	0	0
10	S4L	0.25	0.03	0	0
11	S4M	0.25	0.03	0	0
12	S4H	0.25	0.03	0	0
13	S5L	0.20	0.025	0	0
14	S5M	0.20	0.025	0	0
15	S5H	0.20	0.025	0	0
16	C1L	0.25	0.03	0	0
17	C1M	0.25	0.03	0	0
18	C1H	0.25	0.03	0	0
19	C2L	0.25	0.03	0	0
20	C2M	0.25	0.03	0	0
21	C2H	0.25	0.03	0	0
22	C3L	0.20	0.025	0	0
23	C3M	0.20	0.025	0	0
24	C3H	0.20	0.025	0	0
25	PC1	0.25	0.03	0	0
26	PC2L	0.25	0.03	0	0
27	PC2M	0.25	0.03	0	0
28	PC2H	0.25	0.03	0	0
29	RM1L	0.20	0.025	0	0
30	RM1M	0.20	0.025	0	0
31	RM2L	0.20	0.025	0	0
32	RM2M	0.20	0.025	0	0
33	RM2H	0.20	0.025	0	0
34	URML	0.35	0.04	0.001	0.001
35	URMM	0.35	0.04	0.001	0.001
36	MH	0.25	0.03	0	0

Table 5-26 Outdoor Casualty Rates for Moderate Damage (FEMA/NIBS 2005)

#	Building Type	Casualty Severity Level			
		Severity 1(%)	Severity 2 (%)	Severity 3 (%)	Severity 4 (%)
1	W1	0.05	0.005	0.0001	0.0001
2	W2	0.05	0.005	0	0
3	S1L	0.05	0.005	0	0
4	S1M	0.05	0.005	0	0
5	S1H	0.05	0.005	0	0
6	S2L	0.05	0.005	0	0
7	S2M	0.05	0.005	0	0
8	S2H	0.05	0.005	0	0
9	S3	0	0	0	0
10	S4L	0.05	0.005	0	0
11	S4M	0.05	0.005	0	0
12	S4H	0.05	0.005	0	0
13	S5L	0.05	0.005	0	0
14	S5M	0.05	0.005	0	0
15	S5H	0.05	0.005	0	0
16	C1L	0.05	0.005	0	0
17	C1M	0.05	0.005	0	0
18	C1H	0.05	0.005	0	0
19	C2L	0.05	0.005	0	0
20	C2M	0.05	0.005	0	0
21	C2H	0.05	0.005	0	0
22	C3L	0.05	0.005	0	0
23	C3M	0.05	0.005	0	0
24	C3H	0.05	0.005	0	0
25	PC1	0.05	0.005	0	0
26	PC2L	0.05	0.005	0	0
27	PC2M	0.05	0.005	0	0
28	PC2H	0.05	0.005	0	0
29	RM1L	0.05	0.005	0	0
30	RM1M	0.05	0.005	0	0
31	RM2L	0.05	0.005	0	0
32	RM2M	0.05	0.005	0	0
33	RM2H	0.05	0.005	0	0
34	URML	0.15	0.015	0.0003	0.0003
35	URMM	0.15	0.015	0.0003	0.0003
36	MH	0	0	0	0

FEMA/NIBS (2005) recommends estimating casualties at three specific times of day: 2AM, 2PM and 5PM. These scenarios represent the times when the population is typically at home, at work or school and commuting respectively. The process to calculate the number of people located in various types of buildings is presented in table 5-27.

Table 5-27 Number of Occupants at Three Times of Day (FEMA/NIBS 2005)

Occupancy	2:00 AM	2:00 PM	5:00 PM
Indoors			
Residential	(0.999)0.99(NRES)	(0.7)0.75(DRES)	(0.7)0.5(NRES)
Commercial	(0.999)0.02(COMW)	(0.99)0.98(CONW) + (0.8)0.2(DRES) + 0.8(HOTEL) + 0.8(VISIT)	0.98[0.5(CONW) + 0.1(NRES) + 0.7(HOTEL)
Educational		(0.9)0.8(GRADE) + 0.8(COLLEDGE)	(0.8)0.5(COLLEDGE
Industrial	(0.999)0.1(INDW)	(0.9)0.8(INDW)	(.09)0.5(INDW)
Hotels	0.999(HOTEL)	0.19(HOTEL)	0.299(HOTEL)
Outdoors			
Residential	(0.001)0.99(NRES)	(0.3)0.75(DRES)	(0.3)0.5(NRES)
Commercial	(0.001)0.02(CONW)	(0.01)0.98(CONW) + (0.2)0.2(DRES) + (0.2)VISIT + 0.5(1-PRFIL)0.05(POP)	0.02[0.5(CONW) + 0.1(NRES) + 0.7(HOTEL)] + 0.5(1-PRFIL)[0.05(POP) + 1(COMM)]
Educational		(0.1)0.8(GRADE) + (0.2)COLLEDGE	(0.2)0.5(COLLEDGE)
Industrial	(0.001)0.1(INDW)	(0.1)0.8(INDW)	(0.1)0.5(INDW)
Hotels	0.001(HOTEL)	0.01(HOTEL)	0.001(HOTEL)
Commuting			
Cars	0.005(POP)	(PRFIL)0.05(POP)	(PRFIL)[0.05(POP) + 1(COMM)
Other		0.5(1-PRFIL)0.05(POP)	0.5(1-PRFIL)[0.05(POP) + 1(COMM)

Where: POP is the total population is the census tract
DRES is the daytime residential population
NRES is the nighttime residential population
COMM is the number of people commuting
COMW is the number of people employed in the commercial sector
INDW is the number of people employed in the industrial sector
GRADE is the number of students grades K- 12
COLLEGE is the number of university and college students
HOTEL is the number of people in hotels
PRFIL is the ratio of commuters using cars (0.6 dense urban and 0.8 as default)
VISIT is the number of people that do no live in the census tract

In order to illustrate the use of this table, the case of a residential building at 2am is examined. The formulas for determining the number of indoor (O_{RI}) and outdoor (O_{RO}) occupants are:

$$O_{RI} = 0.999 * 0.99 * NRES \qquad (5\text{-}19)$$

$$O_{RO} = 0.001 * 0.99 * NRES \qquad (5\text{-}20)$$

These equations state that 99% of night time residents are expected to be at home. 99.9% of these occupants are expected to be indoors and the remaining 0.1% is expected to be outdoors. While this table was developed for HazUS on a census tract basis, these formulas could be applied on a building basis provided that building population data is available.

5.6.2 BC Casualty Estimation

The HazUS casualty estimation methodology can be easily adapted for British Columbia. This is done by using the BC damage probability matrices instead of HazUS fragility curves in conjunction with the casualty rates. In order to accomplish this, a matching scheme between the HazUS and BC building prototypes needs to be developed. The prototypes were matched according to height, material and lateral force resisting system. The matching scheme is presented in table 5-28.

The HazUS casualty rates are available for five damage states: slight, moderate, extensive, complete without collapse and complete with collapse. Seven damage states were used in the development of the BC damage probability matrices. In order to determine the probability of casualties, modification of the damage probability matrices is required. The damage states were matched according to their respective descriptions and the matching scheme is displayed in table 5-29. The BC “destroyed” damage state matched the HazUS “complete with collapse” damage state; the BC “major” to HazUS “complete without collapse”; the “heavy” to “extensive” and moderate to moderate. The damage probabilities for the BC “none”, “slight” and “light” damage states were first summed and then matched to the HazUS “slight” damage state**.**

Table 5-28 Building Prototype Matching Scheme

BC-31	HazUS
1-WLFR	1-W1
2-WLFCI	2-W2
3-WLFLR	2-W2
4-WPB	2-W2
5-LMF	9-S3
6-SMFLR	3-S1L
7-SMFMR	4-S1M
8-SMFHR	5-S1H
9-SBFLR	6-S2L
10-SBFMR	7-S2M
11-SBFHR	8-S2H
12-SFCWLR	10-S4L
13-SFCWMR	11-S4M
14-SFCWHR	12-S4H
15-SFCI	14-S5M
16-SFMI	14-S5M
17-CFCWLR	19-C2L
18-CFCWMR	20-C2M
19-CFCWHR	21-C2H
20-CFLR	16-C1L
21-CFMR	17-C1M
22-CFHR	18-C1H
23-CFIW	23-C3M
24-RMLR	31-RM2L
25-RMMR	32-RM2M
26-URMLR	34-URML
27-URMMR	35-URMM
28-TU	25-PC1
29-PCLR	26-PC2L
30-PCMR	27-PC2M
31-MH	36-MH

Table 5-29 Damage States Matching Scheme

HazUS Damage States	BC Damage States
Slight	None, Slight, Light
Moderate	Moderate
Extensive	Heavy
Complete (no Collapse)	Major
Complete (Collapse)	Destroyed

Table 5-30 displays the DPM for single family homes (1 WLFR). The damage probabilities for the “none”, “slight” and “light” damage states were summed and the damage states were matched to those for HazUS to achieve the adapted DPM seen in table 5-31. This was done for all 31 prototypes and was used in conjunction with the casualty rates to calculate the probability of casualties given the building prototype and instrument intensity, $\mathbf{P(Sev, II)_{prototype}}$.

Table 5-30 DPM for the Single Family Home Prototype (%) (1 WLFR)

1-WLFR							
BC Damage States	VI	VII	VIII	IX	X	XI	XII
None	8.0	4.0	1.0				
Slight	75.0	28.0	6.0	1.0			
Light	17.0	64.0	86.0	69.0	10.0	2.0	
Moderate		4.0	5.0	20.0	76.0	69.0	42.0
Heavy			2.0	10.0	12.0	25.0	50.0
Major					2.0	4.0	6.0
Destroyed							2.0

Table 5-31 Casualty Estimation Adapted Single Family Home Prototype (%)

1-WLFR							
HazUS Damage States	VI	VII	VIII	IX	X	XI	XII
Slight	100.0	96.0	93.0	70.0	10.0	2.0	0.0
Moderate		4.0	5.0	20.0	76.0	69.0	42.0
Extensive			2.0	10.0	12.0	25.0	50.0
Complete (no Collapse)					2.0	4.0	6.0
Complete (Collapse)							2.0

This calculation is simplified by arranging the casualty rate value from tables F1 through F8 on a prototype basis as seen in table 5-32. Both the indoor and outdoor casualty rates are presented. The probability of casualties, given the prototype and instrument intensity, is calculated by first determining the indoor and outdoor probabilities for each injury severity level. This is calculated by summing the multiplication of the probability of damage from the DPM and the casualty rate for every damage state. The indoor and outdoor probabilities are then summed.

Table 5-32 Casualty Rates for WLFR

Building Prototype: 1-WLFR								
	Indoor				Outdoor			
Damage State	Severity 1 (%)	Severity 2 (%)	Severity 3 (%)	Severity 4 (%)	Severity 1 (%)	Severity 2 (%)	Severity 3 (%)	Severity 4 (%)
Slight	0.05	0	0	0	0	0	0	0
Moderate	0.25	0.03	0	0	0.05	0.005	0.0001	0.0001
Extensive	1	0.1	0.001	0.001	0.3	0.03	0.0003	0.0003
Complete (no Collapse)	5	1	0.01	0.01	2	0.5	0.1	0.05
Complete (Collapse)	40	20	3	5	0	0	0	0

This is illustrated with the following example for prototype WLFR and instrumental intensity IX. The indoor and outdoor probabilities of the occurrence of severity 1 injuries are:

$$\mathbf{P(Sev1,IX)_{WLFRindoor} = (70*0.05+20*0.25+10*1+0*5+0*40)*10^{-4} = 0.00185} \qquad \mathbf{(5\text{-}21)}$$

$$\mathbf{P(Sev1,IX)_{WLFRoutdoor} = (70*0+20*0.05+10*0.3+0*2)*10^{-4} = 0.0004} \qquad \mathbf{(5\text{-}22)}$$

The total probability of severity 1 injuries is 0.002.

$$\mathbf{P(Sev1,IX)_{WLFR} = 0.00185+0.0004 = 0.00225} \qquad \mathbf{(5\text{-}23)}$$

This was done for all four severity levels and the resulting probabilities were summed to get the total probability of casualties for each prototype at each level of earthquake intensity. The values presented in table 5-33 should be multiplied by the number of occupants at the time of the earthquake to get the total number of expected casualties for the building.

Table 5-33 Casualty Probabilities

BC 31 Class	BC Probability of Casualties given Building Prototype and II						
	VI	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
1	0.001	0.001	0.001	0.002	0.006	0.009	0.027
2	0.001	0.001	0.002	0.004	0.011	0.039	0.059
3	0.001	0.001	0.001	0.002	0.003	0.009	0.022
4	0.001	0.001	0.004	0.029	0.041	0.055	0.074
5	0.001	0.001	0.001	0.001	0.002	0.004	0.011
6	0.001	0.001	0.001	0.001	0.002	0.004	0.011
7	0.001	0.001	0.001	0.001	0.003	0.010	0.018
8	0.001	0.001	0.001	0.003	0.005	0.014	0.020
9	0.001	0.001	0.001	0.002	0.006	0.010	0.029
10	0.001	0.001	0.001	0.002	0.004	0.009	0.019
11	0.001	0.001	0.001	0.002	0.005	0.015	0.046
12	0.000	0.001	0.001	0.003	0.006	0.011	0.022
13	0.001	0.001	0.001	0.003	0.008	0.016	0.030
14	0.001	0.001	0.001	0.005	0.010	0.028	0.045
15	0.001	0.001	0.001	0.004	0.010	0.038	0.051
16	0.001	0.001	0.003	0.016	0.031	0.091	0.168
17	0.001	0.001	0.001	0.002	0.005	0.020	0.045
18	0.001	0.001	0.001	0.003	0.005	0.014	0.042
19	0.001	0.001	0.002	0.006	0.010	0.025	0.058
20	0.001	0.001	0.002	0.004	0.013	0.037	0.064
21	0.001	0.001	0.002	0.004	0.016	0.052	0.076
22	0.001	0.001	0.003	0.006	0.018	0.089	0.118
23	0.001	0.001	0.003	0.011	0.023	0.072	0.158
24	0.001	0.001	0.001	0.003	0.012	0.033	0.080
25	0.001	0.001	0.001	0.007	0.020	0.027	0.103
26	0.001	0.003	0.027	0.052	0.110	0.173	0.293
27	0.001	0.004	0.029	0.056	0.109	0.176	0.309
28	0.001	0.001	0.001	0.003	0.012	0.060	0.094
29	0.001	0.001	0.002	0.014	0.037	0.059	0.106
30	0.001	0.001	0.002	0.007	0.015	0.041	0.115
31	0.001	0.001	0.002	0.003	0.009	0.014	0.028

The number of occupants present in the building at the time of the earthquake is calculated for three times of day using the formulas presented in table 5-27. For the BC casualty estimation a hospital occupancy type was included to account for these important post disaster buildings. The number of people occupying a hospital at 2AM, 2PM and 5PM are determined by multiplying the capacity of the building by the appropriate time of day factor. The capacity of the building is estimated by multiplying the floor area by the occupancy density factor of 0.1 people per square meter. The hospital time of day factors are 0.1, 0.4 and 0.2 for 2am, 2pm and 5pm respectively.

It should be noted that since the casualty probabilities were determined from the damage probability matrices the mean damage factor modifiers are not included at this time due to a lack of time and resources. The modifiers have a significant effect on the expected structural damage and should be included in future BC seismic risk assessment studies.

One possible method for their inclusion would be to estimate the probability of casualties based on the final MDF alone. The building would be placed in a damage state category based on table 5-3 and the calculation would be performed using only the casualty rates for that damage state. For example, a single family home was determined to have a MDF of 34% for an instrumental intensity IX earthquake. From table 5-3, this building is in the heavy (extensive, HazUS) damage state. The probability of casualties is determined by the summation of probabilities for each of the injury severity levels. The difference lies in the calculation of these probabilities.

$$\mathbf{P(Sev1, IX)_{WLFR_{indoor}} = (34 * 1) * 10^{-4} = 0.0034} \qquad \mathbf{(5\text{-}24)}$$

$$\mathbf{P(Sev1, IX)_{WLFR_{outdoor}} = (34 * 0.3) * 10^{-4} = 0.001} \qquad \mathbf{(5\text{-}25)}$$

The probability of severity 1 indoor and outdoor casualties for this building is 0.0034 and 0.001 respectively. The total probability of the occurrence of severity 1 injuries is 0.0044 and the total probability of casualties is 0.005. This casualty estimation method is more complex than using the probabilities in table 5-33. It requires a series of calculations for each building rather than simply reading values from a table. The casualty estimation for the UBC case study presented in chapter 6 was performed using table 5-33.

5.7 Functionality Assessment

Loss of function is an important component of seismic risk assessment. It is of interest to investigate functionality particularly for post disaster buildings such as hospitals, emergency response stations and shelters. Also functionality can lead to estimates of downtime and recoverability. In this thesis, functionality is defined as the buildings ability to operate after a seismic event has occurred. It depends on the amount of damage sustained to the structure, the nonstructural components and building contents.

Currently there are few studies that examine the loss of building function after an earthquake. This topic is briefly discussed in the 2000 report by the Pan American Health Association (PAHO) and the World Health Organization (WHO entitled “Principles of Disaster Mitigation in Health Facilities” (PAHO/WHO, 2000) and the 1994 EERI report, “Expected Seismic Performance of Buildings” (EERI, 2004).

The PAHO/WHO report investigated the past seismic performance of health care facilities and made recommendations for the evaluation of vulnerabilities in existing buildings. Structural, nonstructural and administration/ operational vulnerabilities were considered. From these vulnerability assessments, the buildings were placed into one of four seismic safety levels: fully functional, operational, life safe and near collapse. These categories are described in terms of the buildings ability to operate post earthquake. Of the four categories only fully functional and operational health facilities are able to perform after the earthquake. The life safety category discusses the functionality in terms of building evacuation routes.

“Expected Seismic Performance of Buildings” (EERI, 1994) was developed for the purpose of educating the public, particularly building owners and government policy makers, about the damage in buildings that is likely to arise as the result of seismic shaking. Five “standardized” damage states are presented in order to classify the various levels of expected building damage: none, slight, moderate, extensive and complete. These categories describe the overall status of the building based on structural, nonstructural and contents damage and also give a rough estimate of the amount of time it will take to recover from this damage.

Functionality categories were developed for British Columbia seismic risk assessment based on the PAHO seismic safety levels and the EERI standardized damage states. There are five categories ranging from “Fully Functional” to “Near Collapse” and an estimate of the functionality in terms of percentage is presented for each. Table 5-34 lists the categories, their descriptions and functionality percentages.

Table 5-34 Functionality Categories

Category	Title	Description	% Functional
A	Fully Functional	The building remains in a suitable condition for normal use, perhaps with some limitations. No damage, but contents could be shifted. Only incidental hazard.	100
B	Operational	Very limited damage to the structure and non- structural components is seen. Contents are shifted. Clean up and inspection is a necessity. It is possible that repairs will have to be made before normal function can resume. Only incidental hazard. Important buildings, such as hospitals and fire stations, can operate. Less important buildings may be closed for a week for clean-up and minor repairs.	80
C	Moderate	Primarily Non-structural Damage and some minor structural damage. Repairs are required. Important buildings may be able to function, but at reduced capacity (~ 50%). Remote chance of lives threatened.	50
D	Life Safe	Extensive structural or nonstructural damage. Long term closure should be expected due to the amount of repair work or uncertainty of economic feasibility. Localized, life threatening situations would be common.	0
E	Near Collapse	Building may suffer total or partial collapse or structural or non-structural damage that is not economically repairable. Life threatening situations in every building in the category.	0

In order to determine the overall functionality of a building, the structural damage and all three forms of nonstructural damage must first be classified individually into functionality categories. Table 5-35 presents the damage thresholds for each functionality category for each type of damage. These thresholds are based on the damage state ranges presented in table 5-3 for the structural components and 5-15 for the nonstructural components and contents. Buildings are classified into functionality categories based on their final mean damage factors for each component. The overall functionality of the building is taken to be the worst case of the structural, displacement sensitive, acceleration sensitive or contents functionalities.

Table 5-35 Functionality Category Thresholds

Category	Structural	Displacement Sensitive Components	Acceleration Sensitive Components	Building Contents
A	0 to 1%	0	0	0
B	1 to 10	0 to 5	0 to 5	0 to 2
C	10 to 30	5 to 20	5 to 20	2 to 10
D	30 to 60	20 to 80	20 to 80	10 to 40
E	60 to 100	80 to 100	80 to 100	40 to 100

This is illustrated with the following example. The structural and nonstructural components mean damage factors were determined for building #3 given an intensity IX earthquake and are presented in table 5-36. Each MDF was classified into a functionality category based on the ranges presented in table 5-35. The structural and displacement sensitive nonstructural components are classified into category “C”, while acceleration sensitive nonstructural components and building contents fall into category B. “C” is the worst case therefore; the overall functionality for this building given and intensity IX earthquake is C.

Table 5-36 Functionalities for Building 3

Building # 3		
	MDF	Functionality Category
Structural	22.8	C
NSC Displacement	13.8	C
NSC Acceleration	3.8	B
NSC Contents	1.9	B

5.8 Downtime

It is of interest to estimate the amount of time required to repair damage and recover the function of a building after an earthquake. This “downtime” is influenced by many factors and its estimation can be quite complex. The components influencing downtime can be split into two groups: rational and irrational. Rational downtime components are the actual construction costs and repair time while the irrational components include the time for financing the repairs, the mobilizing of labour and materials and other situation specific effects. (Ref)

A study conducted by Comerio in 2006 entitled "Estimating Downtime in Loss Modeling" examined downtime data from past earthquakes as well as its assessment in loss modeling. The case of Stanford University**,** after the Loma Prieta earthquake in 1989**,** was examined in detail. Of the approximately 400 buildings on campus, twenty five had to be closed due to earthquake damage. Many of the buildings, those deemed of high importance, were repaired within two years of the earthquake, while others took four to nine years. There are some in fact, which have yet to be repaired. The reason for this discrepancy was financing. Those completed quickly were funded by the University while the remaining buildings were financed through application to the Federal government. Comerio's study illustrates the complexity involved in estimating downtimes. For this reason, this type of analysis was determined to be outside of the scope of this thesis.

It is recommended that further investigation of this topic be conducted in future seismic risk assessment studies. HazUS has a methodology for estimating downtime. For buildings with low damage, downtime is estimated from construction times only while buildings with higher damage take into consideration the time required for financing, design and obtaining permits. If this methodology could be adopted for British Columbia construction practices, it could present a possible solution to the problem.

5.9 Step by Step BC Seismic Risk Assessment

This section summarizes chapter 5 by giving step by step instructions for the performance of Seismic Risk Assessment in British Columbia. A large hospital building located on UBC campus is used as an example to illustrate the methodology.

5.9.1 Step 1: Seismic Hazard Assessment

The BC seismic risk assessment methodology assumes that ground motions (typically PGA) have been predetermined using deterministic or probabilistic seismic hazard analysis. These processes are described in detail in Onur, 2000. The next step is to determine if the site will be affected by soil amplification and if so, apply the appropriate amplification factors. Table 5-2 lists the NBCC 2005 soils types and acceleration amplification factors by which the expected peak ground acceleration should be multiplied. In order to classify the site, soil properties such as shear wave velocity (Vs) and undrained shear strength (su) should be determined through geotechnical investigations.

The ground motions need to be converted to the Instrumental Intensity Scale in order to perform the structural and nonstructural damage assessments. This is accomplished through the use of equations 5-1 or 5-2 and table 5-1.

As stated above, the example building is a large hospital located on the University of British Columbia's Point Grey Campus. Seismic hazard assessment indicates that the expected peak ground acceleration is 0.46g. Geotechnical investigations have determined the soil underlying the building to be site class "C". The amplification factor for this class is 1.0, meaning no amplification is expected. The Instrumental Intensity is determined using equation

5-1. This equation requires the PGA to be in cm/s^2 (0.46g =451 cm/s^2). Therefore this building is to be assessed for an intensity VIII earthquake.

$$\mathbf{II = 3.66 * \log(451) - 1.66 = 8.05} \qquad \mathbf{(5\text{-}26)}$$

5.9.2 Step 2: Data Collection

In order to perform regional seismic risk assessment, a comprehensive building inventory database needs to be developed. The database should contain the name, address, year of construction, primary use, number of stories, footprint area, structural material, the lateral force resisting system (LFRS), the soil class and a database identification number. In addition, modifier data such as the presence of soft stories or irregularities needs to be determined. The list of modifiers is presented in table 5-9. There are a number of resources from which data can be gathered. Local and provincial governments and the private sector typically have large databases. For those buildings where no data is available, side walk surveys can be conducted. Structural drawings may need to be reviewed in order to determine if certain modifying conditions are present in the buildings.

Table 5-37 and 5-38 present the collected data for the example building. The 5 storey hospital was constructed in the late 1970s and has a footprint area of almost 9000 square meters. It is a concrete structure with a shear wall lateral force resisting system. The only modifying condition is the presence of a vertical irregularity in the upper two stories. N refers to no, and Y refers to yes.

Table 5-37 Building "3" General Data

Name	Construction Year	Number of Stories	Footprint Area (m2)	Total Area (m2)	Use	Structural Material	LFRS
Building "3"	1977	5	8850	44250	Hospital	Concrete	Shear Walls

Table 5-38 Building "3" Modifier Data

Modifiers									
Plan Irregularity	Vertical Irregularity	state of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark	Retrofit
N	Y	N	N	N	N	N	N	N	N

5.9.3 Step 3: Direct Damage Assessment

5.9.3.1 Structural Damage Assessment

The first step in the assessment of building structural damage is to classify the building into one of the 31 British Columbia building prototypes presented in table 5-5. Detailed descriptions of each prototype are available in appendix B. The structural mean damage factor (MDF) is determined using equation 5-7 and the base MDF for each prototype is available in table 5-6. The modifier tables for each prototype are available in appendix D.

The example structure is a 5 storey concrete shear wall building with a vertical irregularity. It is classified as a Concrete Frame Concrete Wall Medium Rise building (18 CFCWMR). The base MDF for this prototype for an intensity VII earthquake is determined from table 5-6 to be 7.9% and the appropriate vertical irregularity modifier is 2.2. The final structural mean damage factor for this building given an intensity VIII earthquake calculated from equation 5-27 is therefore 10.1 %.

$$\mathbf{MDF_F = 7.9 + 2.2 = 10.1} \qquad \textbf{(5-27)}$$

5.9.3.2 Nonstructural Damage Assessment

Nonstructural components are separated into displacement sensitive, acceleration sensitive and building contents. The expected damage for each is determined from the nonstructural component damage probability matrices for each building prototype presented in appendix E. The mean damage factors were calculated using equation 5-3 and are presented in tables 5-16, 5-17 and 5-18. Nonstructural damage assessment for a building is performed by selecting the appropriate value from each table. For an intensity VIII earthquake, the example building is expected to have 11.3% displacement sensitive damage, 2.1% acceleration sensitive damage and 1% contents damage.

5.9.4 Step 4: Loss Estimation

5.9.4.1 Monetary Losses

Monetary Losses can be determined using either of the methods presented in section 5.5. The simpler facility independent method is presented first.

5.9.4.1.1 Facility Independent Method

The replacement value, R, of the building must first be determined. This is accomplished by multiplying the total area of the building by the appropriate value in table 5-19. Building # 3 has a total area of 44,250 square meters and is a prototype 18 CFCWMR building. Table 5-19 indicates that the construction cost per square meter in 2007 CDN dollars for this type of building is $2,960. The replacement value of the hospital is therefore $130.8 million dollars Canadian.

Since the structural MDF is less than 60% the monetary losses can be calculated using equation 5-12. The repair cost ratios are all equal to 0.25. The calculation of the monetary losses for building #3 given an intensity VIII earthquake is summed in table 5-39. The expected losses are in the order of $8 million dollars.

Table 5-39 Facility Independent Monetary Losses for Building #3 (II VIII)

Building # 3 (II VIII)				
	Total Replacement Value (R)	MDF	Repair cost Ratio	$ Losses
Structural	130,800,000	10.1	0.25	3,300,000
NSC Displacement	130,800,000	11.3	0.25	3,700,000
NSC Acceleration	130,800,000	2.1	0.25	700,000
NSC Contents	130,800,000	1.0	0.25	300,000
Total				8,000,000

5.9.4.1.2 Facility Dependent Method

The Facility Dependent method takes into account the use of the facility for the calculation of the replacement value of the structure and the expected monetary losses. The replacement value is calculated using equation 5-16 where R_{CONS} is the construction cost of the building and R_{CONT} is the replacement value of the building's contents. The construction cost is then determined by multiplying the total area of the building by the appropriate value in table 5-19. This is the same value used to represent the total replacement value of the building in the Facility Independent method. The replacement value of the contents is calculated from the construction cost using equation 5-21 where the contents value factor, γ, is given in table 5-21 for various building uses.

The construction cost for the example building was determined to be $130.8 million dollars based on the total area of the building and the values given in table 5-19. The contents value factor for a hospital is 0.45. Using equations 5-14 and 5-15 the replacement value of the contents and the total replacement value of the building are:

$$\mathbf{R_{CONT}} = \frac{\mathbf{0.45}}{\mathbf{1-0.45}}\mathbf{130{,}800{,}000 = 107{,}000{,}000} \qquad \textbf{(5-28)}$$

$$\mathbf{R = 130{,}800{,}000 + 107{,}000{,}000 = 238{,}000{,}000} \qquad \textbf{(5-29)}$$

The repair cost ratios are given in table 5-21 for structural, displacement sensitive and acceleration sensitive components. The contents damage ratio is always 0.5. Since the structural MDF is less than 60%, equation 5-16 is used to estimate the monetary losses for UBC hospital given an intensity VIII earthquake. This is summarized in table 5-40. The expected monetary losses are in the order of $9.4 millions dollars.

Table 5-40 Facility Dependent Monetary Losses

Building # 3 (IIVIII)				
	Total Replacement Value (R)	MDF	α factor	$ Losses
Structural	130,800,000	10.1	0.14	1,800,000
NSC Displacement	130,800,000	11.3	0.38	5,600,000
NSC Acceleration	130,800,000	2.1	0.48	1,300,000
NSC Contents	107,000,000	1.0	0.5	700,000
Total				9,400,000

The monetary losses determined using the facility dependent method are $1.4 million dollars higher than those calculated using the facility independent method. This is primarily due to the inclusion of the building contents value. Comparing tables 5-39 and 5-40, it can be seen that the FD nonstructural component and content losses are significantly than those calculated using the FI method.

5.9.4.2 Human Losses

The expected number of casualties in a building depends on the number of occupants at the time of the earthquake and the probability of casualties given the prototype and instrumental intensity. The number of people occupying the building at the three desired times of day (2am, 2pm and 5pm) is calculated using the formulas in table 5-27 or, if the building is a hospital, multiplying its capacity by the time of day factors. The probability of casualties given the prototype and intensity is given in table 5-33.

The example building is a hospital with a floor area of 44,250 square meters. The occupancy density is 0.1 people per square meters; the capacity is therefore 4400 people. The time of day factors are 0.1, 0.4 and 0.2 for 2am, 2pam and 5pm respectively. The number of occupants in the building at these times of day is therefore 442, 1768 and 884.

The probability of casualties given a prototype 18 CFCWMR building at intensity VIII earthquake is 0.001 from table 5-33. The number casualties expected in the building for intensity VIII earthquake at three possible times of day are:

$$\mathbf{CAS_{2am} = 0.001 * 442 = 0.4} \tag{5-30}$$

$$\mathbf{CAS_{2pm} = 0.001 * 1768 = 1.8} \tag{5-31}$$

$$\mathbf{CAS_{5pm} = 0.001 * 884 = 0.8} \tag{5-32}$$

The results of this analysis can be interpreted as follows: If the earthquake were to occur at 2am; no casualties are expected; at 2pm, 2 casualties are expected and at 5pm 1 casualty is expected.

5.9.4.3 Loss of Function

The building functionally is determined based on the damage to the structural components, the displacement sensitive NSCs, the acceleration sensitive NSCs and the building contents. The functionality of each individual component is determined based on table 5-35 and the overall functionality is taken as worst of the four. Table 5-41 presents the component functionalities for the example building. The structural, acceleration sensitive components and building contents are all placed in category B. The displacement sensitive components however are in functionality category C and the overall functionality of the hospital is C or 50% operational.

Table 5-41 Building Functionality for Intensity VIII

Building # 3 (II VIII)		
	MDF	Functionality Category
Structural	10.1	B
NSC Displacement	11.3	C
NSC Acceleration	2.1	B
NSC Contents	1	B

6 Case Study: UBC Campus

This chapter discusses the seismic risk assessment that was carried out for the Vancouver Campus of the University of British Columbia (UBC). This case study involved the collection of data, the construction of a comprehensive building database, the assessment of structural and nonstructural damage, the estimation of monetary and human losses and the determination of the functionality. Here, due to the quantity of data, the results are presented for Instrumental Intensity IX only. Results for the other intensities are presented in Appendix I.

UBC Campus is an ideal location as a test case for the infrastructure interdependencies simulator (I2Sim) because it has all of the attributes of a small city. The campus has distinct residential, commercial and industrial areas and provides a majority of its own utility services. Currently there are over ten thousand full time residents and fifty thousand transitory occupants including students, faculty and staff.

6.1 UBC Campus Overview

The University of British Columbia is located on the Point Grey Peninsula at the Western edge of the City of Vancouver in British Columbia, Canada (See Figure 6-1). It is bounded on the east by Pacific Spirit Park which together with the campus makes up the University Endowment lands. The campus is approximately 4 square kilometers and has a peak elevation of 100 meters above sea level. Along the perimeter of the peninsula, the elevation falls steeply down to sea level and the Straight of Georgia. Sea cliffs are present at the northwestern corner of the campus and there is a risk of landslide, however, no buildings are present in this area. The geology is made up of a thick layer of stiff glacial sediments which is underlain by bedrock and there is no risk for liquefaction.

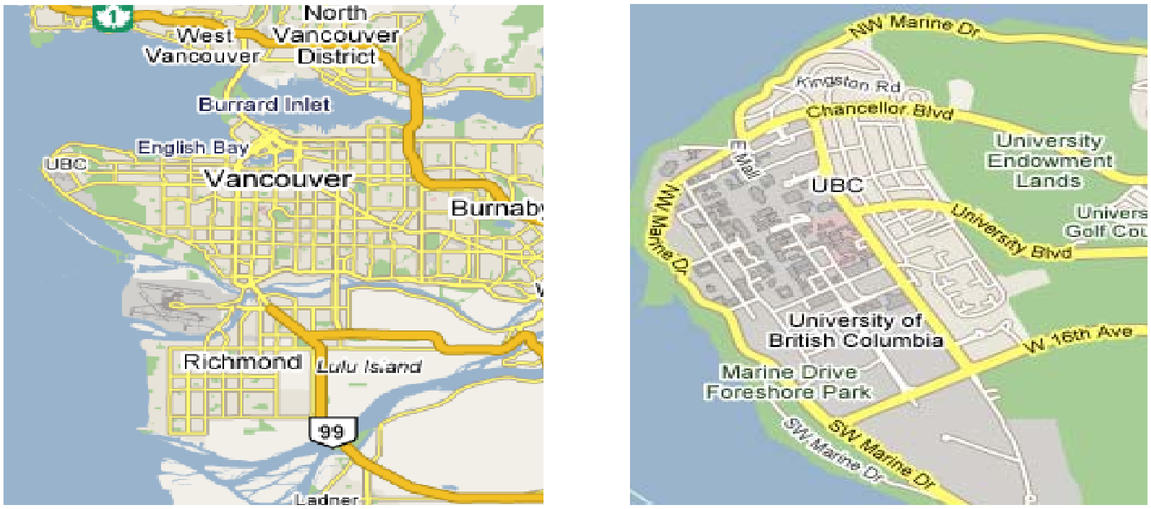

Figure 6-1: The City of Vancouver and UBC Campus (Google Maps, 2008)

The Point Grey campus was opened in 1925, seventeen years after the formation of UBC. Construction began in 1923 with the library, powerhouse, science building (now a wing of the chemistry building) and a few temporary classroom buildings. At this time there were ## buildings on campus and approximately 1200 students enrolled at the University. The campus grew steadily over time with large spikes of construction in the 1960s and the 1980s. Currently there are over 600 buildings on campus and the population has reached roughly 43,500 students, 12,600 faculty and staff and 10,000 full time residents

There are four main roads that connect UBC to the City of Vancouver: Marine Drive, 16th Avenue, University Boulevard and 4th Avenue (Fig. 6-1). The majority of lifelines that supply the campus follow these four routes. The university manages the distribution of water, gas, steam and electricity to all of its buildings through two key buildings, the powerhouse and the electrical substation. These buildings receive water and power respectively and distribute the utilities across campus. The campus also has its own hospital complex as well as fire, police and ambulance stations.

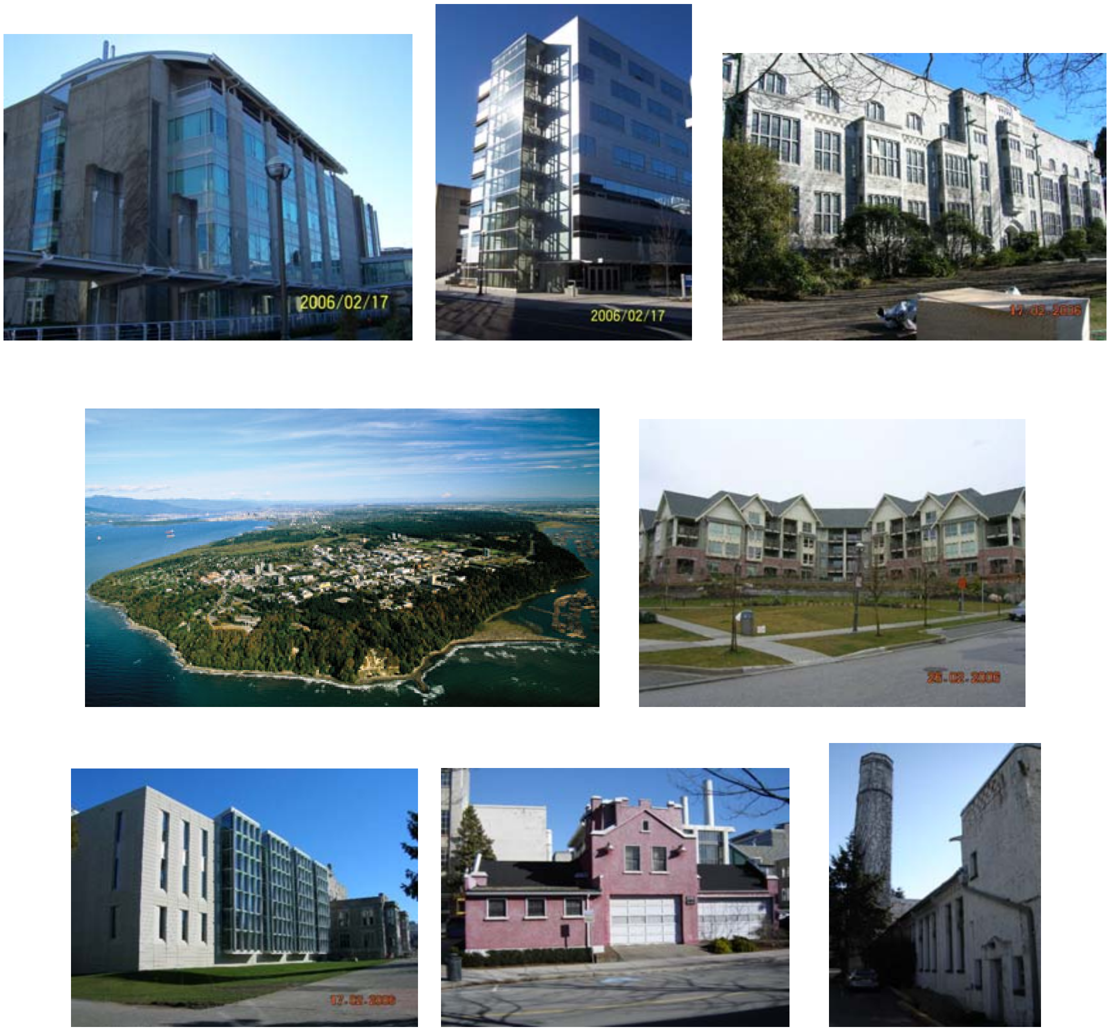

Figure 6-2 UBC Campus Photos

6.2 Seismic Hazard Assessment

Seismic Risk Assessment (SRA) was conducted on UBC campus for seven levels of Instrumental Intensity, VI through XII, in order to cover all possible scenarios for the use of I2Sim. The results for intensity IX are presented in this chapter while those for the remaining intensities are presented in Appendices G through K. Since the campus is founded on firm glacial sediments, the soil can be classified as type “C” and no amplification is required.

6.3 Building Inventory

For the purpose of this study only 364 buildings of the 600 on campus were assessed. Not included in the study were single family homes located outside of the university campus. Also storage sheds, barns and other buildings that do not play a significant role to the university community were not assessed

The inventory collection first involved the identification of existing data sources. Two primary sources used in this study were the UBC Planning Department and Records office. The planning department provided the results of a similar assessment conducted by Delcan in 1995 (Delcan, 1995). This study contained an existing database with the information for approximately 200 of the desired buildings. The UBC records office was instrumental in gathering data for the remaining buildings and updating the database from the Delcan study. Where information was not available in either of these sources, sidewalk surveys were performed and this involved only five buildings in the study area. Information collected for the database included name, address, floor area, number of stories and year of construction of the building as well as structural material, lateral force resisting system and any irregularities. The data was stored using Microsoft Excel spreadsheets.

6.4 Structural Damage Assessment

6.4.1 Classification of Buildings

The buildings were classified into one of the BC 31 building prototypes discussed in section 5.3.2. Figure 6-3 presents the classification of UBC campus on a building by building basis. The majority of buildings on campus are constructed of wood or concrete. These two materials make up 51% and 35% of the total buildings in the study area respectively. The remaining materials, steel, pre-cast concrete, masonry and mobile homes make up less than 7% of the total number of buildings each. The distribution of the construction material is presented in figure 6-4.

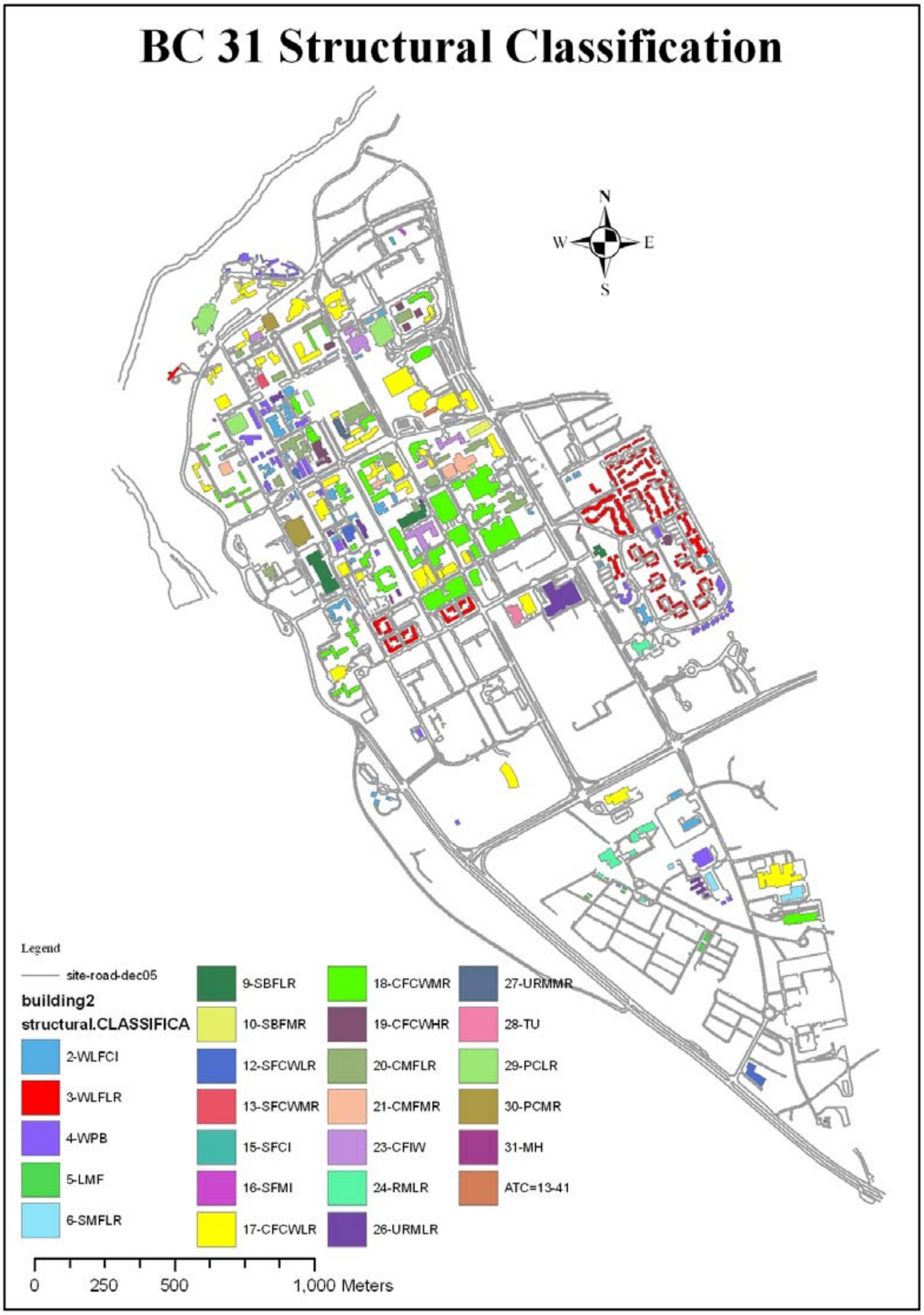

Figure 6-3: Building Prototypes on UBC Campus

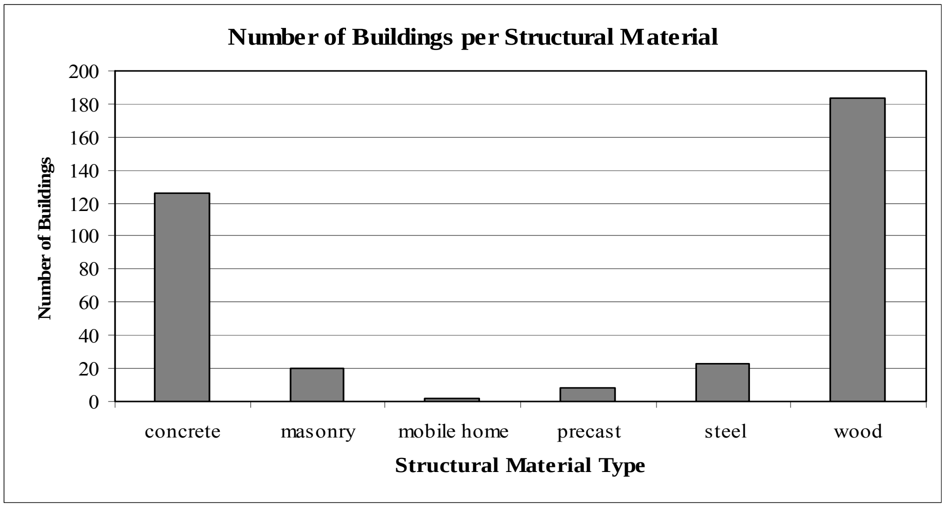

Figure 6-4 Distribution of Construction Material at UBC

The number of buildings of each prototype is presented in figure 6-5. Here the prototypes are represented by their numbers (table 5.5). Unlike the majority of urban areas, the most common building prototype on campus is multi-family wood frame homes (WLFLR), making up 28% of buildings and 55% of the wood buildings. There are, in fact, no single family homes present in the study area. This is due to the unique residential organization of the university campus where high density residential areas are typically desired. The two remaining wood prototypes, light frame commercial/ institutional (WLFCI) and Post and Beam (WPB) make up 11% and 12% of all buildings in the study area. These are typically classroom and office buildings.

Of the highly prevalent concrete buildings, the most common prototypes are low and medium rise concrete shear wall buildings (CFCWLR and CFCWMR). These make up 40% and 35% of concrete buildings and 14% and 12% of the buildings in the study area respectively. These buildings are typically classrooms, laboratories, libraries and offices.

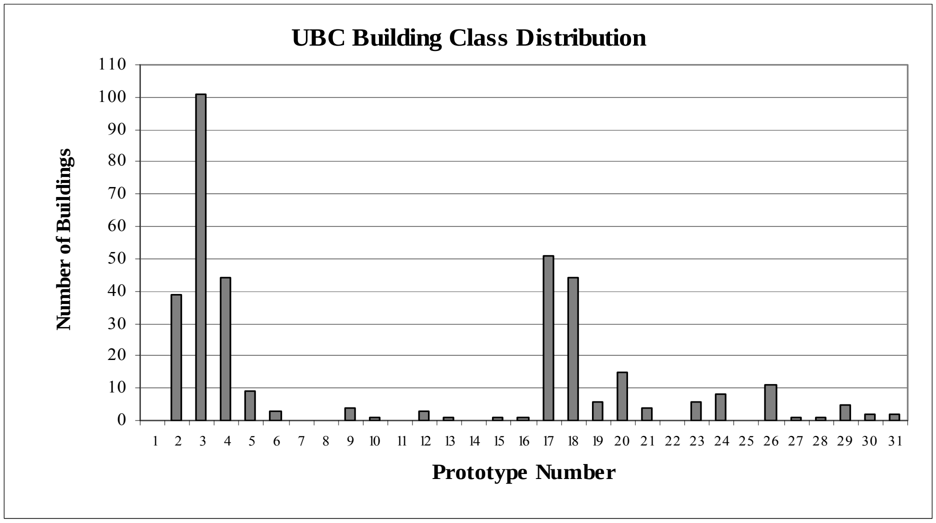

Figure 6-5 Distribution of Building Prototype

6.4.2 Structural Damage

The structural damage estimation was carried out using the intensity based damage matrices and modification factors described in the chapter 5. The results are presented in the form of the Mean Damage Factor (MDF) which was described in section 5.3.1. The assessment was performed twice for all levels on instrumental intensity: the first using only the MDFs calculated from the damage probability matrices without the modifiers and the second, with their addition. This was done in order to evaluate the effects of the modifiers. Figure 6-6 presents the results of the structural damage assessment without the modifiers for II IX. It can be seen from this map that the majority (91%) of buildings fall into the moderate damage state. Few have sustained light (4%) and heavy (5%) damage. Figure 6-8 displays the number of buildings in each damage state for intensity IX.

The addition of the modifiers slightly changes the results of the structural damage assessment. Figure 6-7 presents the results for each building in the study area. The majority (73%) of buildings are still in the moderate damage state; however there is a significant increase in the number of buildings in the light (13%) and heavy (11%) and the major (2%) damage states. The number of buildings in each damage state is presented in figure 6-9. Comparing this histogram to that for the results of the assessment without modifiers, it appears that the modifiers have the effect of spreading out the damage. A detailed discussion of the effects of the modifiers is presented in chapter 7.

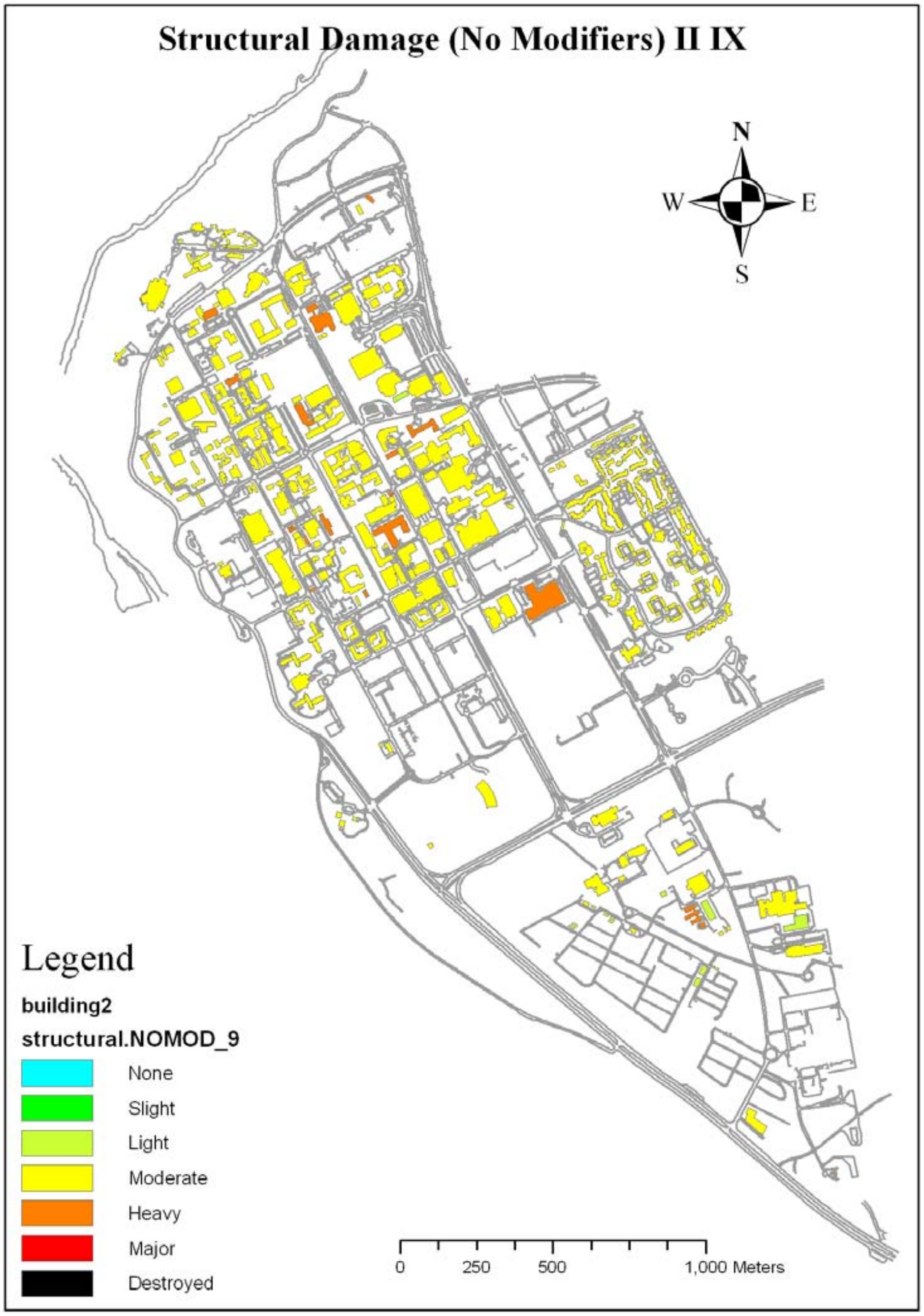

Figure 6-6 Structural Damage without Modifiers for II IX

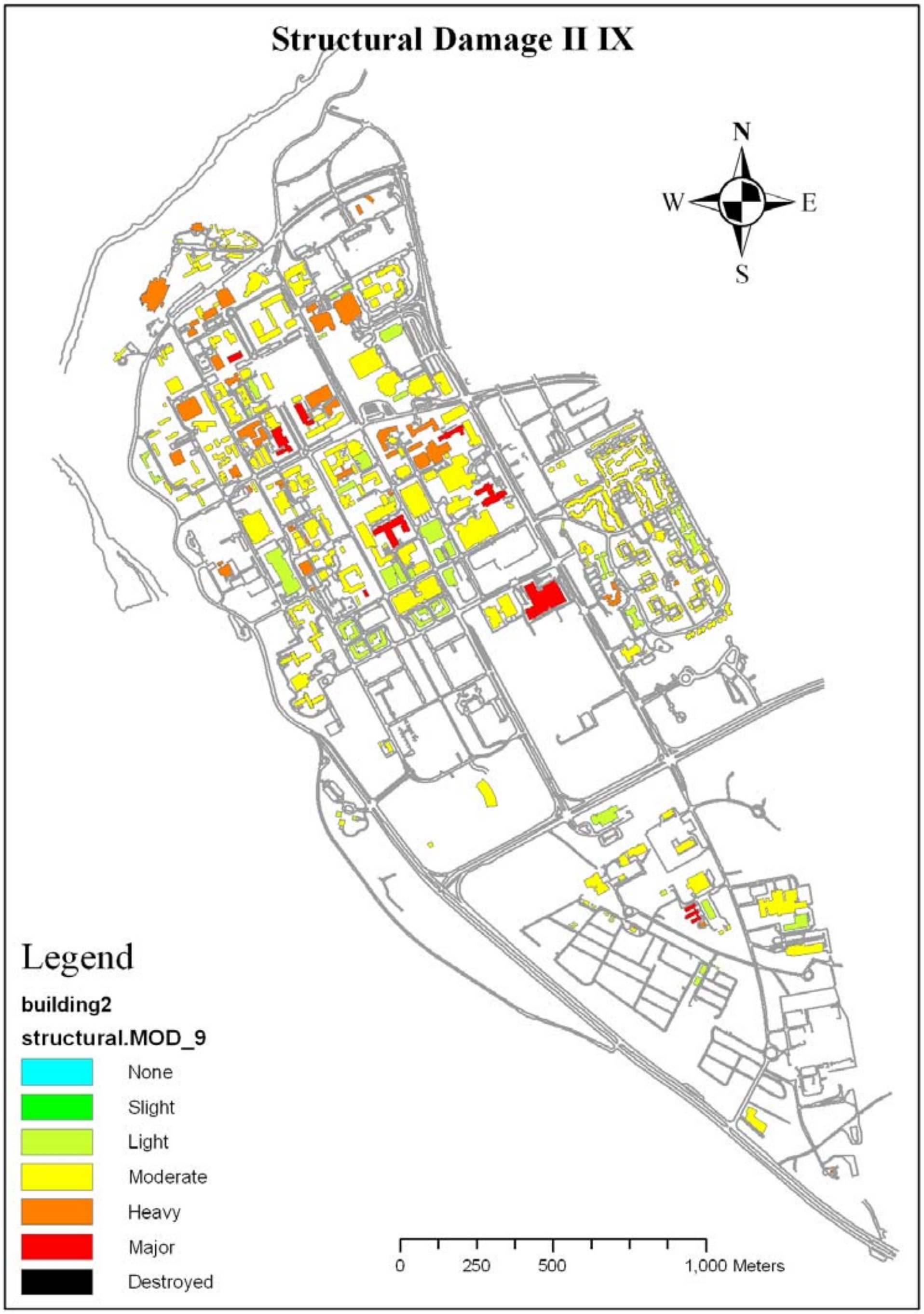

Figure 6-7 Structural Damage with Modifiers for II IX

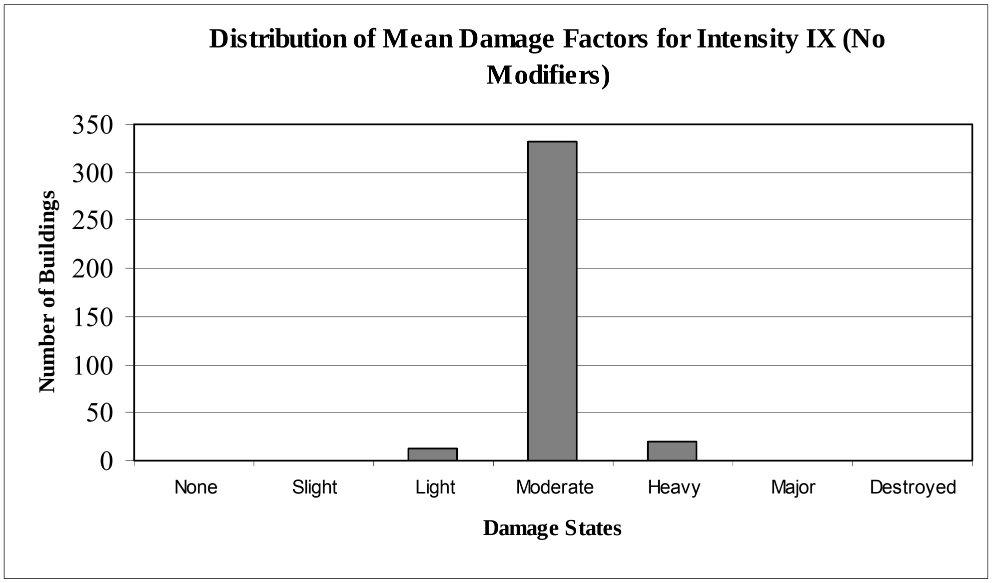

Figure 6-8 Distribution of Structural Damage without Modifiers for II IX

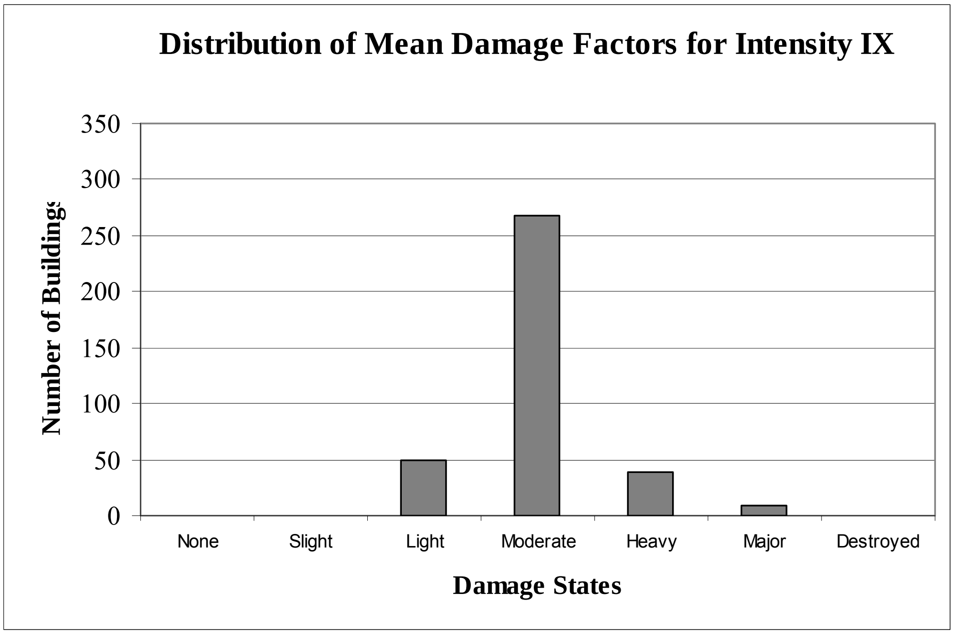

Figure 6-9 Distribution of Structural Damage with Modifiers for II IX

6.5 Nonstructural Damage Assessment

Damage to the nonstructural components was calculated in a similar manner using the Mean Damage Factors (MDFs) presented in tables 5.17, 5.18 and 5.19. The resulting nonstructural damage maps for displacement sensitive components, acceleration sensitive components and building contents are presented in figures 6-10, 6-11 and 6-12.

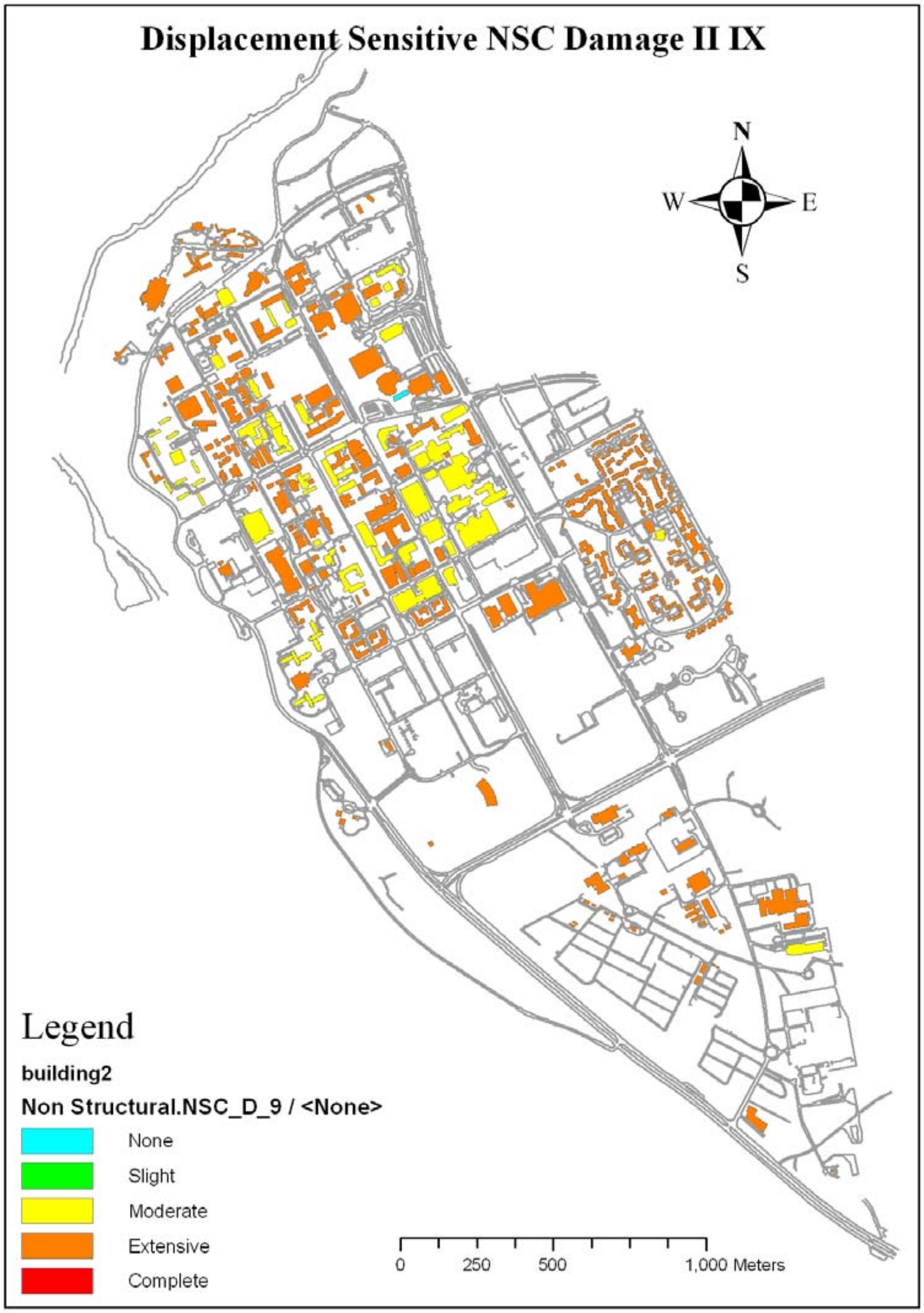

Figure 6-10 Displacement Sensitive Damage for II IX

Damage to the displacement sensitive components was fairly high for intensity IX: 83% of the buildings had extensive damage (MDF between 20% and 80%) and the remaining 17% were expected to suffer moderate damage (MDF between 5% and 20%). The number of buildings in each state is presented in figure 6-13

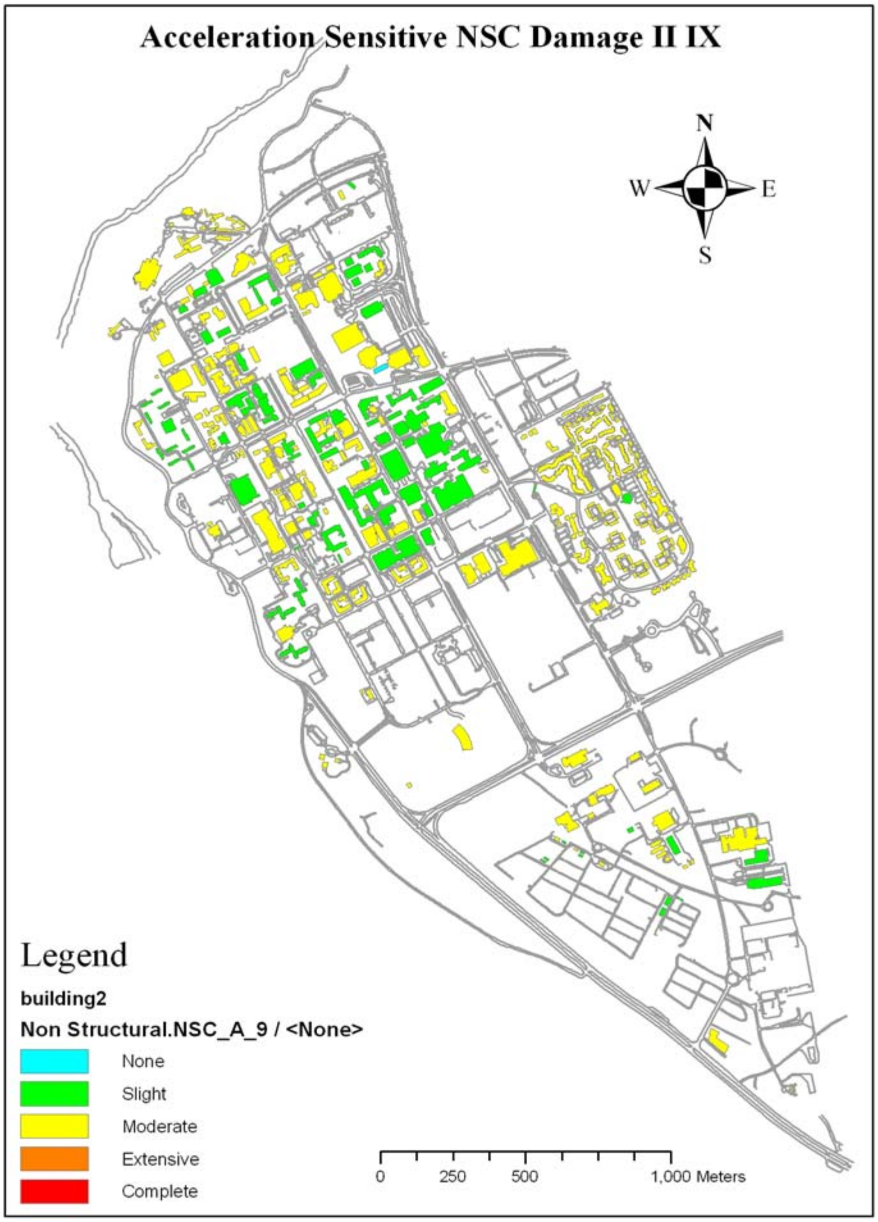

Figure 6-11 Acceleration Sensitive Damage for II IX

The damage to the acceleration sensitive components is lower than for displacement sensitive. For intensity IX, 74% of the buildings in the study area had moderate damage and the remaining 26% were in the slight (0 to 5%) damage state (Figure 6-14). Figure 6-15 displays the results for building contents, 80% of the buildings were in the moderate damage state and 20% in slight.

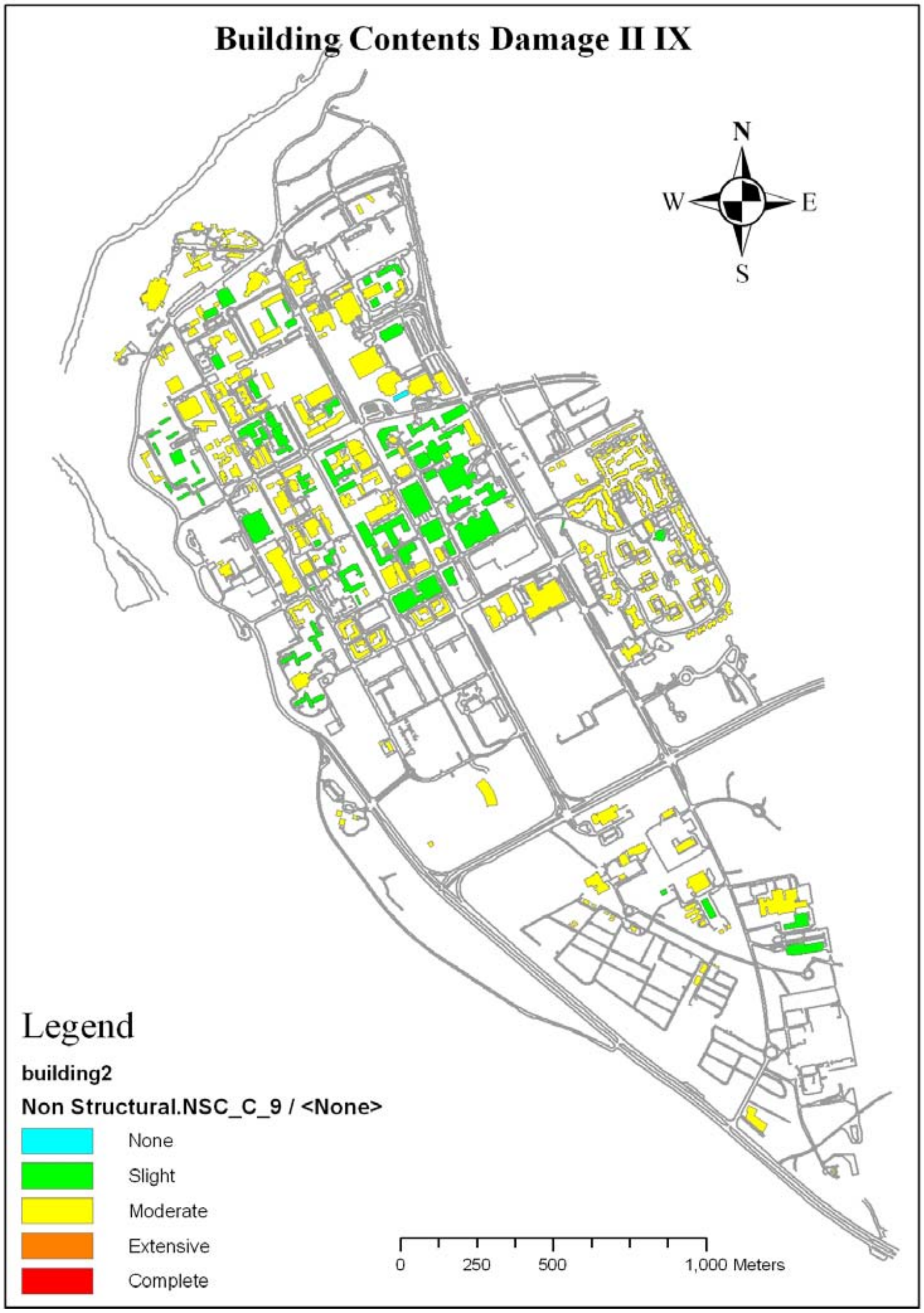

Figure 6-12 Building Contents Damage for II IX

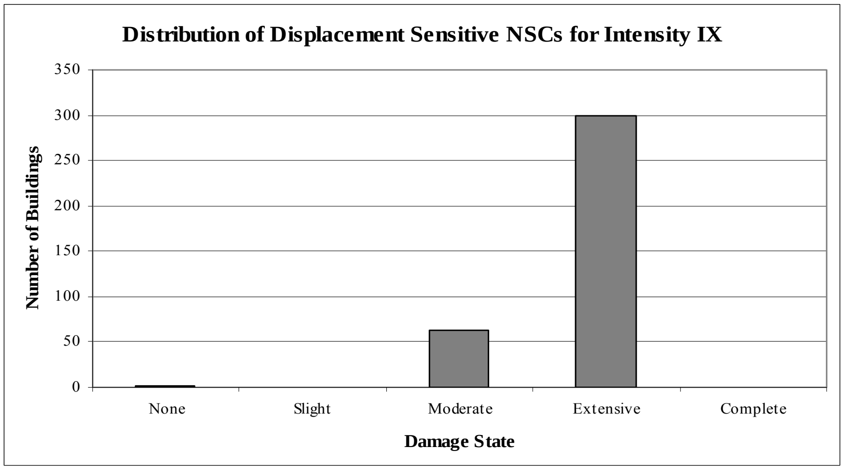

Figure 6-13 Distribution of Displacement Sensitive Damage

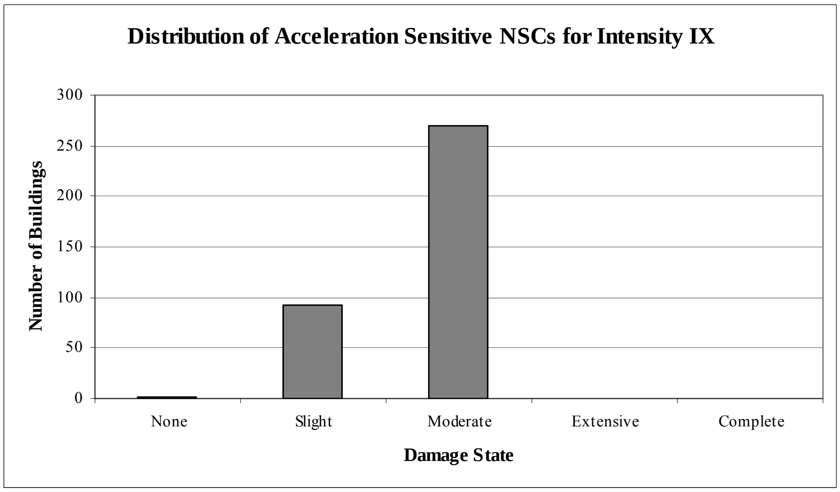

Figure 6-14 Distribution of Acceleration Sensitive Damage

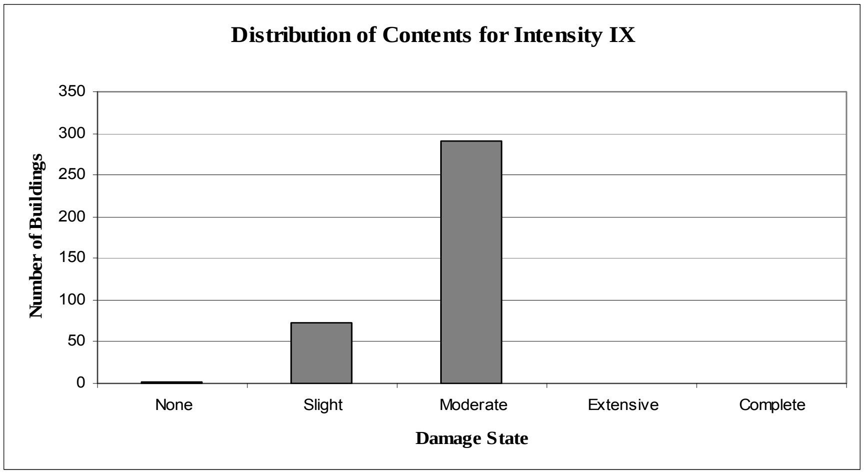

Figure 6-15 Distribution of Building Content Damage

6.6 Monetary Losses

Monetary losses resulting from the structural and nonstructural damage estimates were calculated for UBC campus for each level of instrumental intensity using both the Facility Independent and Facility Dependent methodologies.

6.6.1 Facility Dependent Monetary losses

The replacement values were first determined by multiplying the total area of the buildings by the values given in table 5.20. Figure 6-16 presents the replacement values of the buildings in the study for instrumental intensity IX.

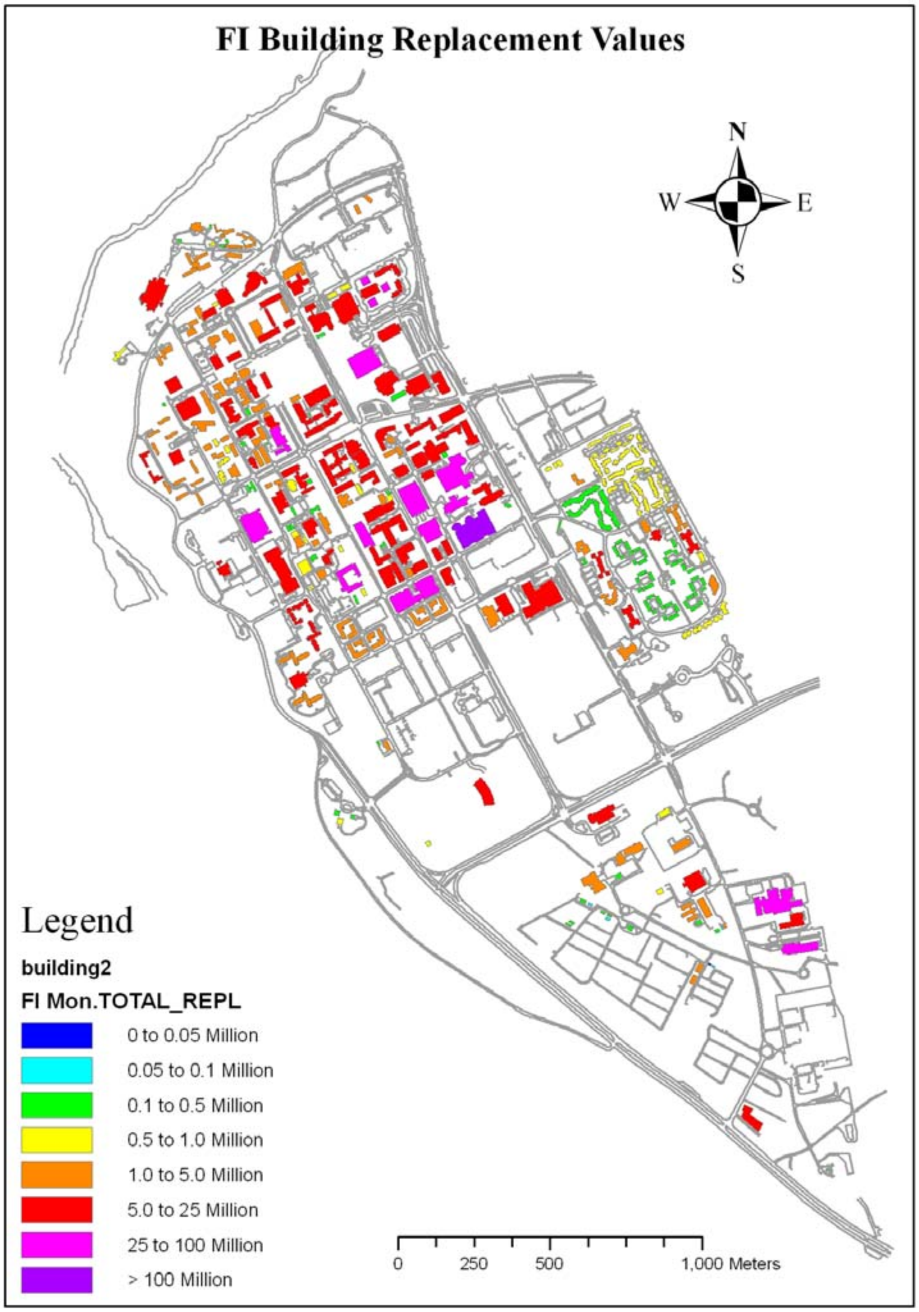

Figure 6-16 Replacement Value of UBC Campus Buildings

The total value of all the building in the study area was determined to be about 2.1 billion dollars with the majority (70%) of being valued at half a million to 25 million dollars. None are worth less than fifty thousand dollars and three (seen in purple in figure 6-16) are valued at over 100 million dollars. Figure 6-17 presents the distribution of the estimated replacement values of the buildings.

The monetary losses were calculated for using equations 5-9 and 5-21 and the results are displayed in figure 6-19. The total monetary losses for an intensity IX earthquake were calculated to be 290 million dollars, 14% of the total replacement value of the study area. The histogram is presented in figure 6-18 shows that 65% of the buildings were suffered losses of less than 500 thousand dollars and 33% between this amount and 5 million dollars.

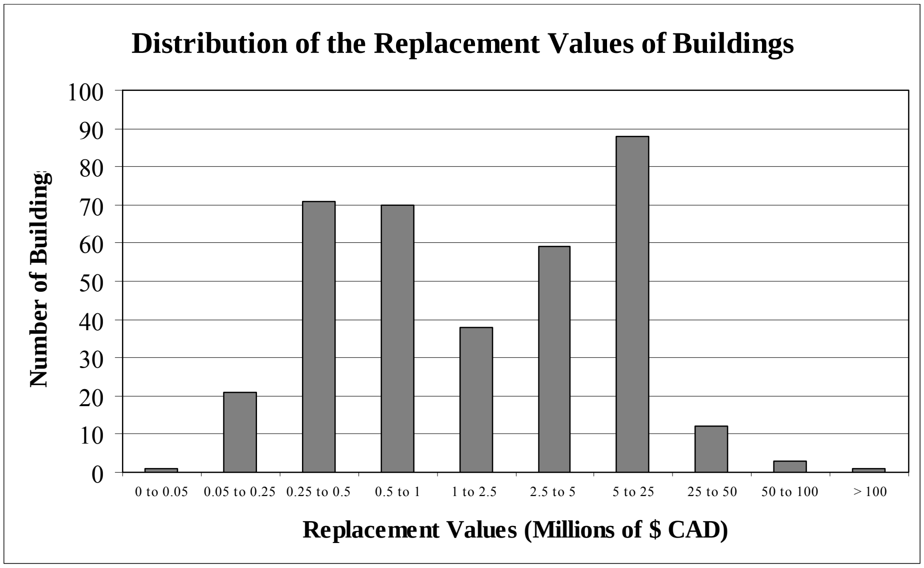

Figure 6-17 Distribution of Building Replacement Value on UBC Campus

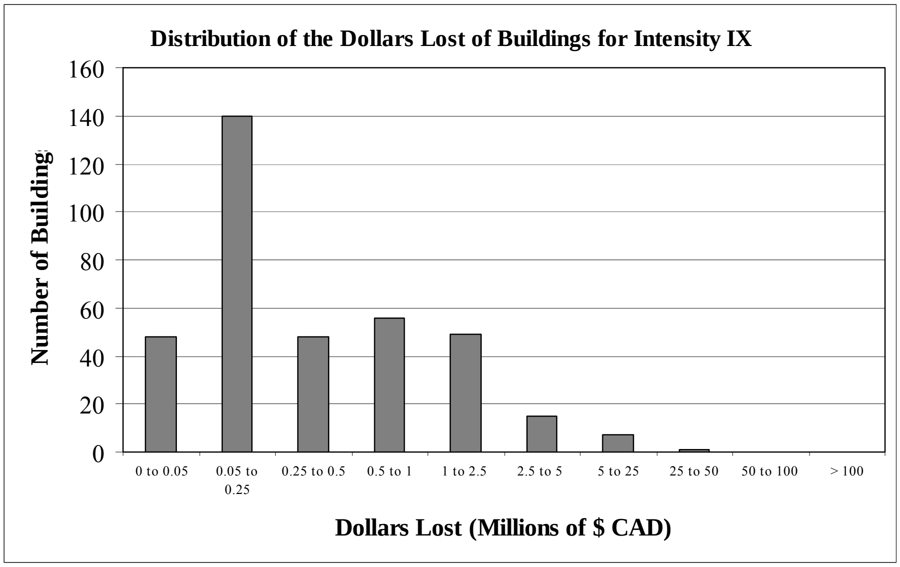

Figure 6-18 Distribution of Dollars Lost for II IX

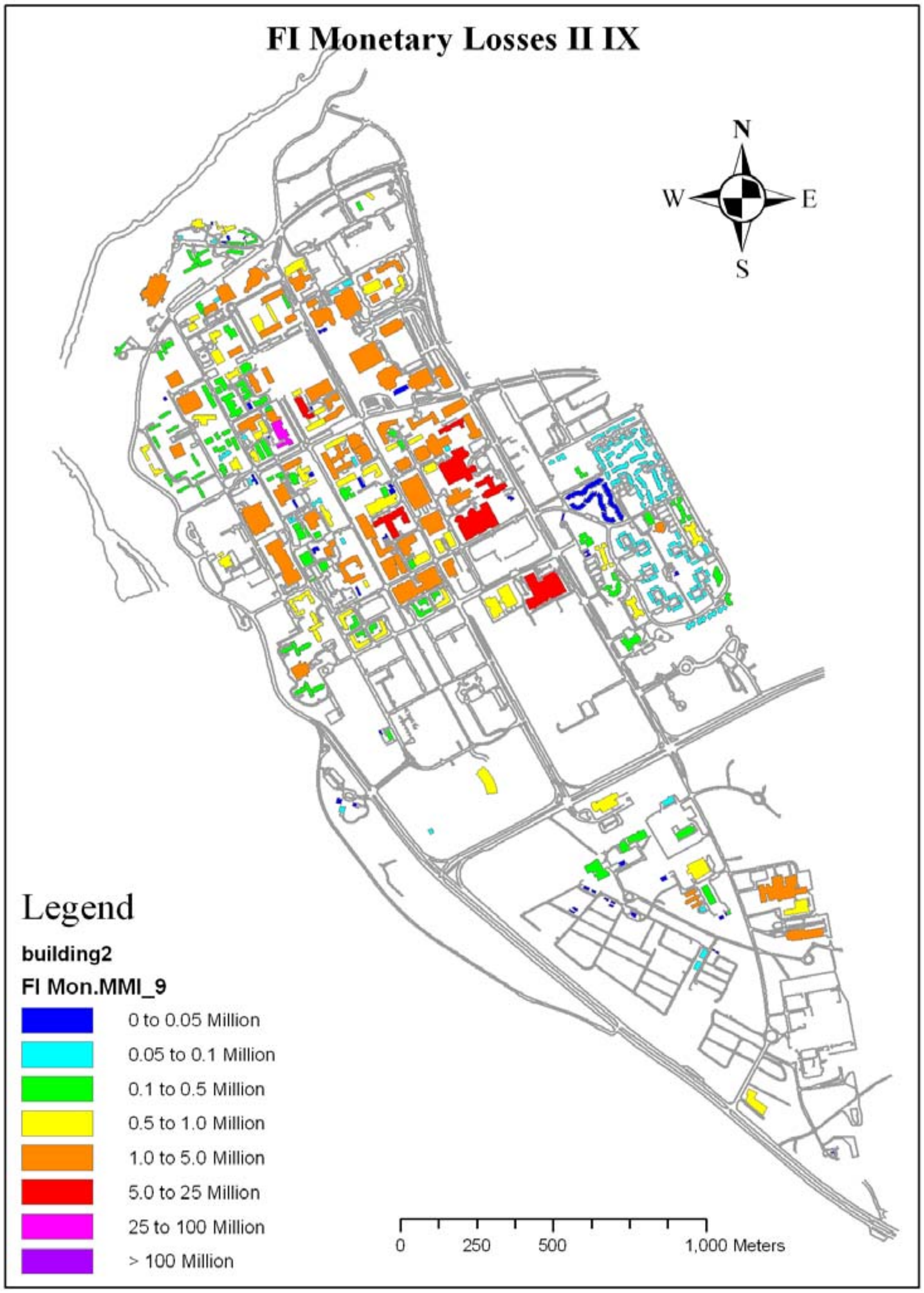

Figure 6-19 Monetary Losses for Intensity IX

6.6.2 Facility Dependent Monetary Losses

The replacement values were first determined using equations 5.15 though 5.20. The repair cost ratios (αs, αd, and αa) and contents value factor (γ) were given in table 5.21. Figure 6-20 presents the replacement values of the buildings in the study for instrumental intensity IX.

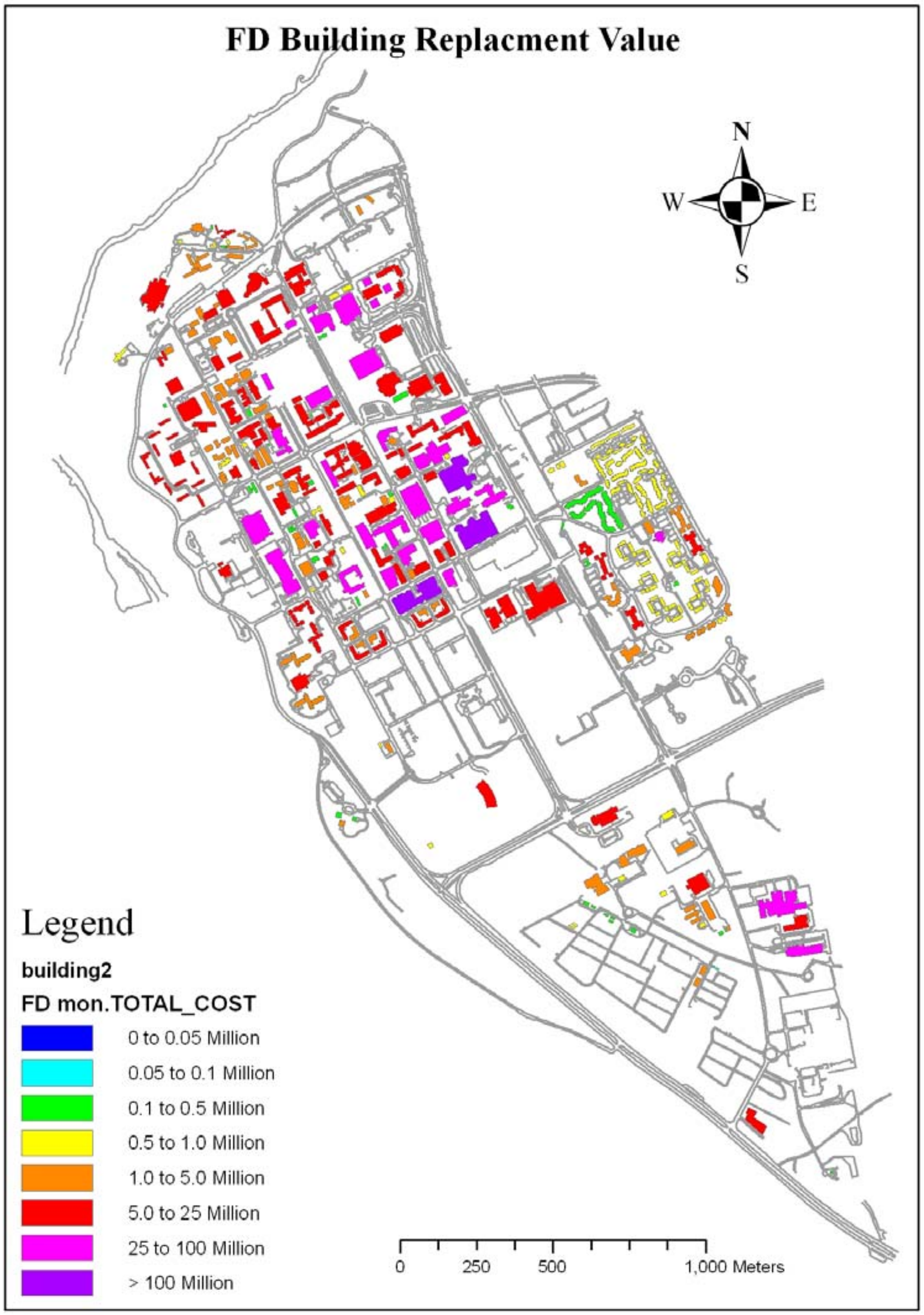

Figure 6-20 Facility Dependent Building Replacement Values

The total value of all the building in the study area was determined to be about three billion dollars with the majority (86%) of being valued at half a million to 50 million dollars. None are worth less than fifty thousand dollars and five (seen in purple in figure 6-20) are valued at over 100 million dollars. Figure 6-21 presents the distribution of the estimated replacement values of the buildings.

The monetary losses were calculated for using equations 5-9 through 5-21 and the results are displayed in figure 6-22. The total monetary losses for an intensity IX earthquake were calculated to be 400 million dollars, 13% of the total replacement value of the study area. The histogram is presented in figure 6-23 shows that 59% of the buildings suffered losses of less than 500 thousand dollars and 97% less than 5 million dollars.

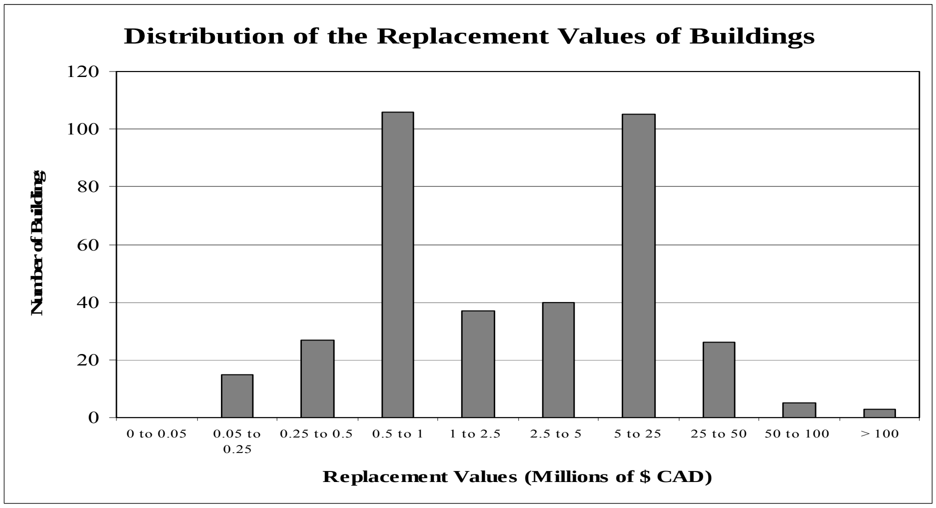

Figure 6-21 Distribution of Facility Dependent Replacement Values

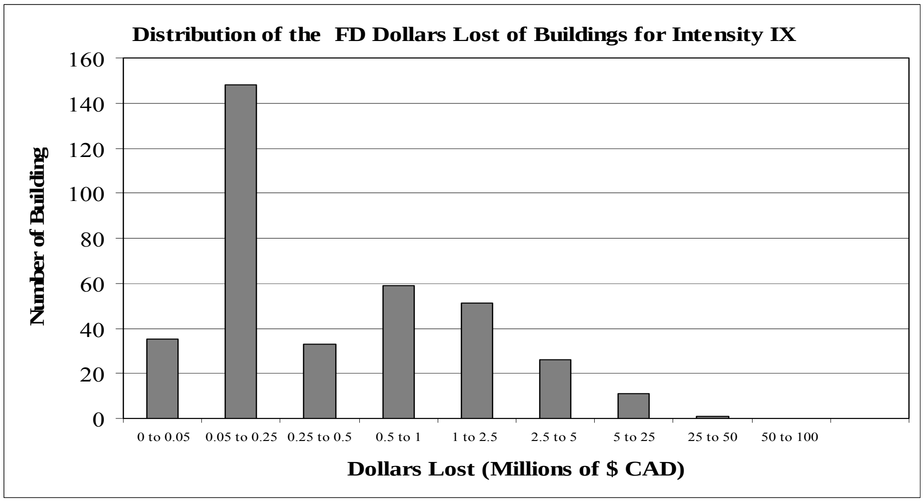

Figure 6-22 Distribution of Facility Dependent Monetary Losses for II IX

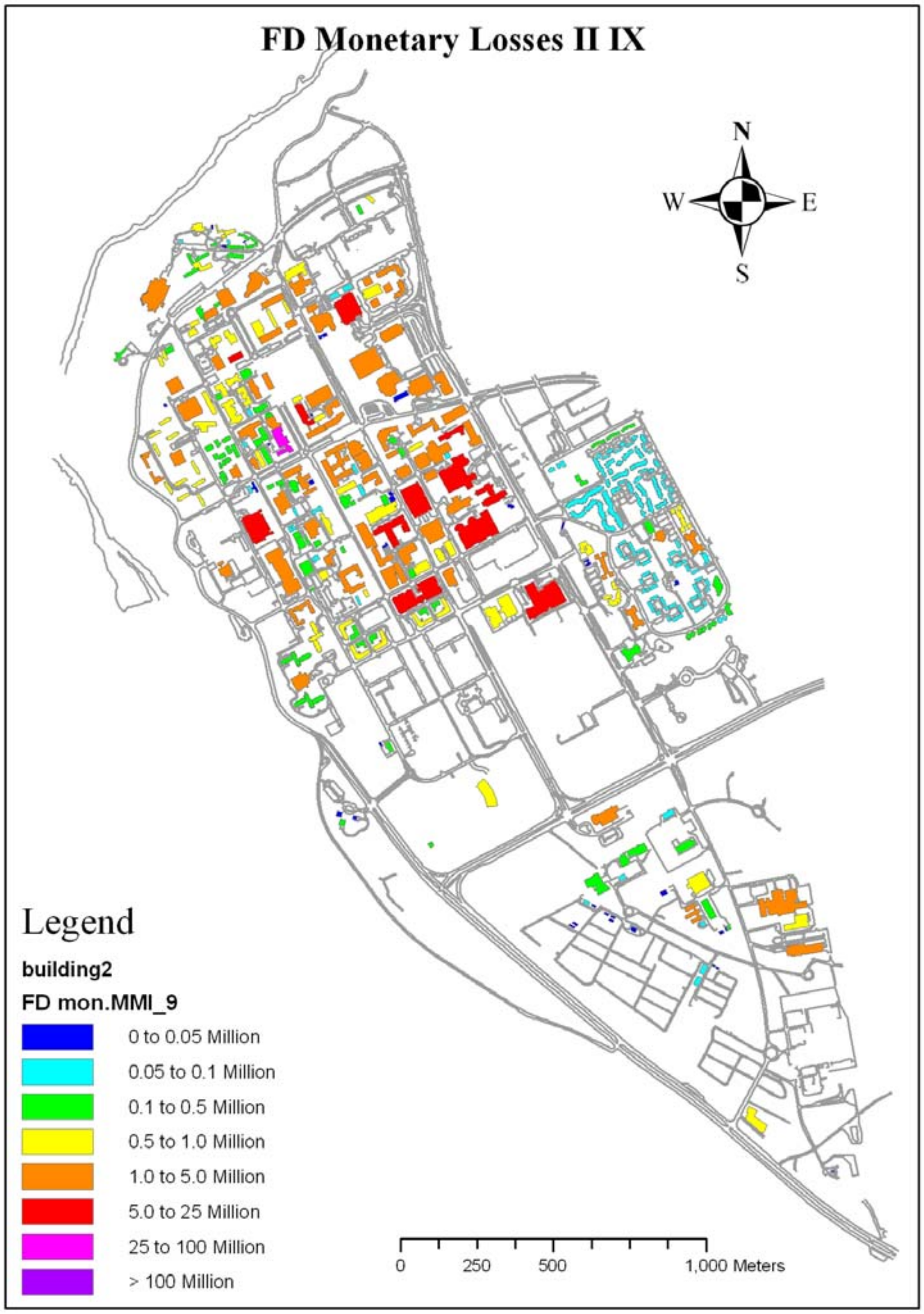

Figure 6-23 Facility Dependent Monetary Losses

6.7 Casualty Assessment

As discussed in section 5.6, the number of earthquake casualties is estimated based on the number of occupants in the building at the time of the event and the structural damage caused by the shaking. The number of occupants depends on the use of the building and the time of day of the event. The 19 cell classes developed by JIIRP (section 3.2) were simplified into six use classes: residential, educational, industrial, commercial, hotels and healthcare in order to use the HazUS occupancy tables presented in table 5.27. Figure 6-24 presents the distribution of building use on UBC campus and figure 6-25 displays their locations. The majority of buildings on campus are educational and residential, making up 55% and 36% respectively. Most of the residential buildings lie on the eastern edge and around the perimeter separated from the educational core of the University.

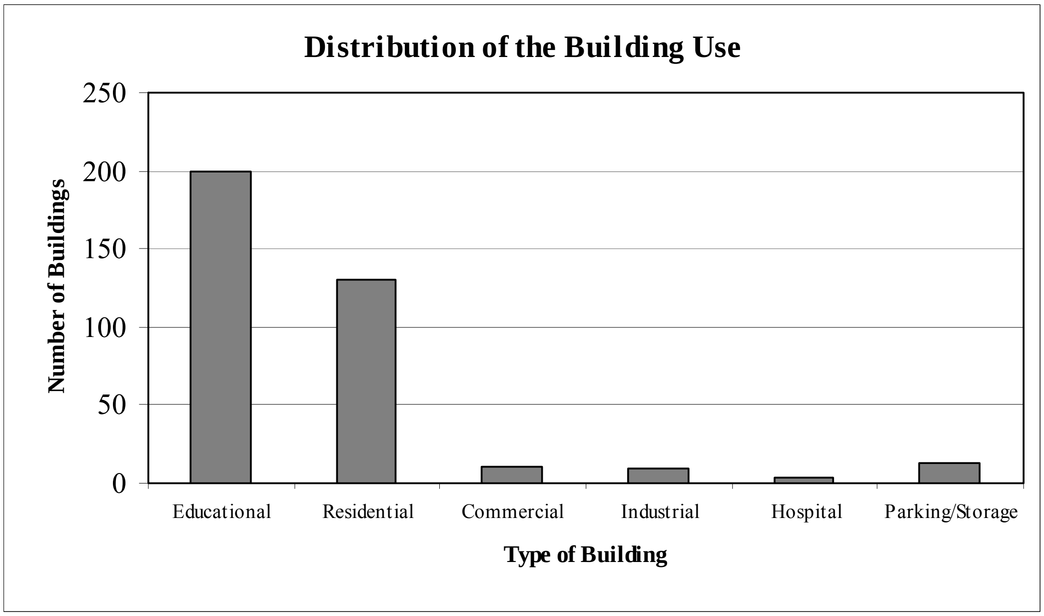

Figure 6-24 Distribution of Building Use on Campus

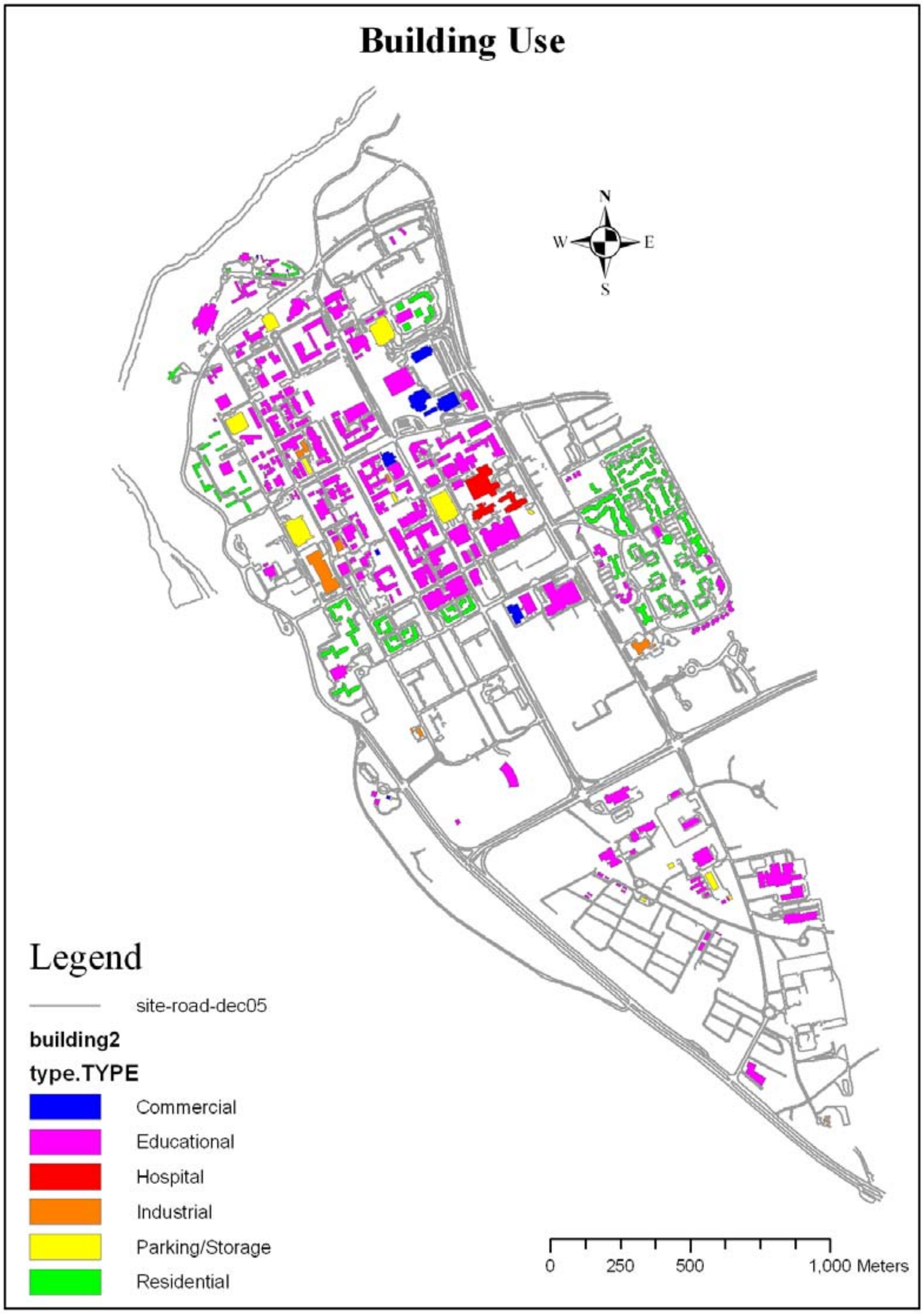

Figure 6-25 Building Use on Campus

The casualty estimation was conducted for three times of day 2AM, 2PM and 5PM. The number of people in each building at those given times was calculated using the tables and procedures described in section 5.6. The HazUS tables were developed for the use of population estimation in terms of census tract population however, for the purpose of this study; the number of casualties was desired on a building by building basis. In order to translate these equations for this purpose, the number of people in each type of building for each time of day was first determined for the campus as a whole. The population was then distributed to each building based on their use and capacity. The total number of people estimated to be on campus at 2am, 2pm and 5pm is 7,000, 40,000 and 21,000 respectively. Figure 6-26 presents the percentage of people in each type of building for the three times of day and their locations are presented in figures 6-27 to 6-29. From these figures it can be seen that at 2AM the majority (85%) of the population is residential with the remaining types of buildings making up less than 10% of the total population each. At 2pm and 5pm the population most of the population is educational although there is significant portion in residential buildings at 5pm.

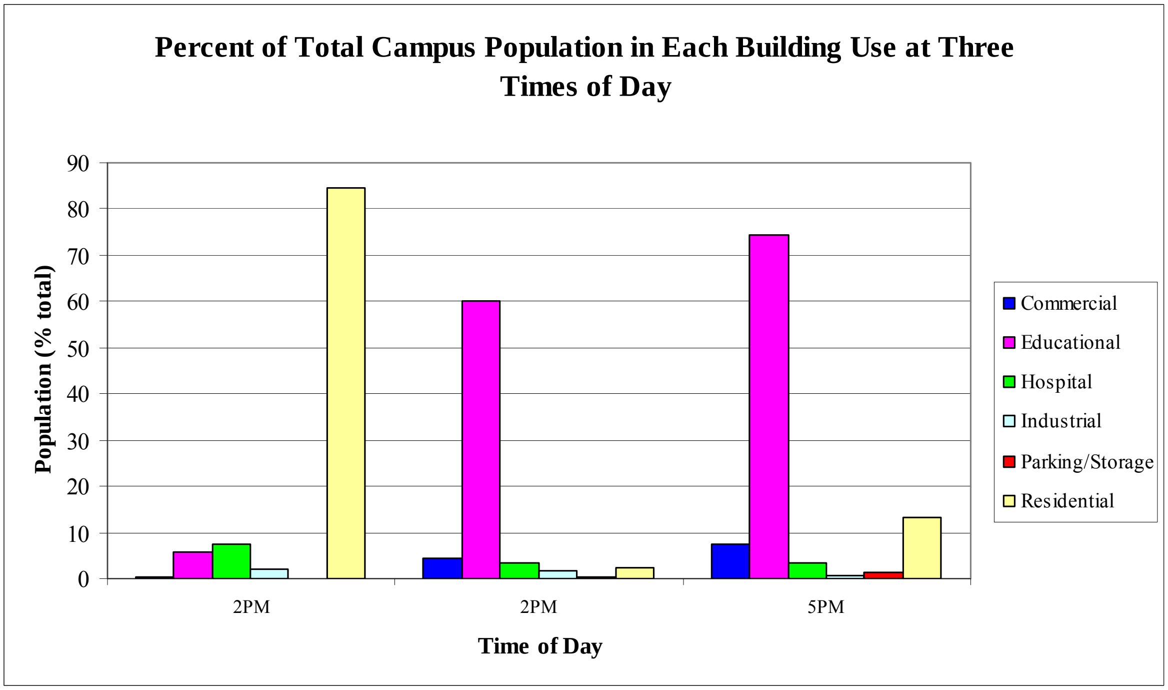

Figure 6-26 Population Distribution on Campus for Three Times of Day

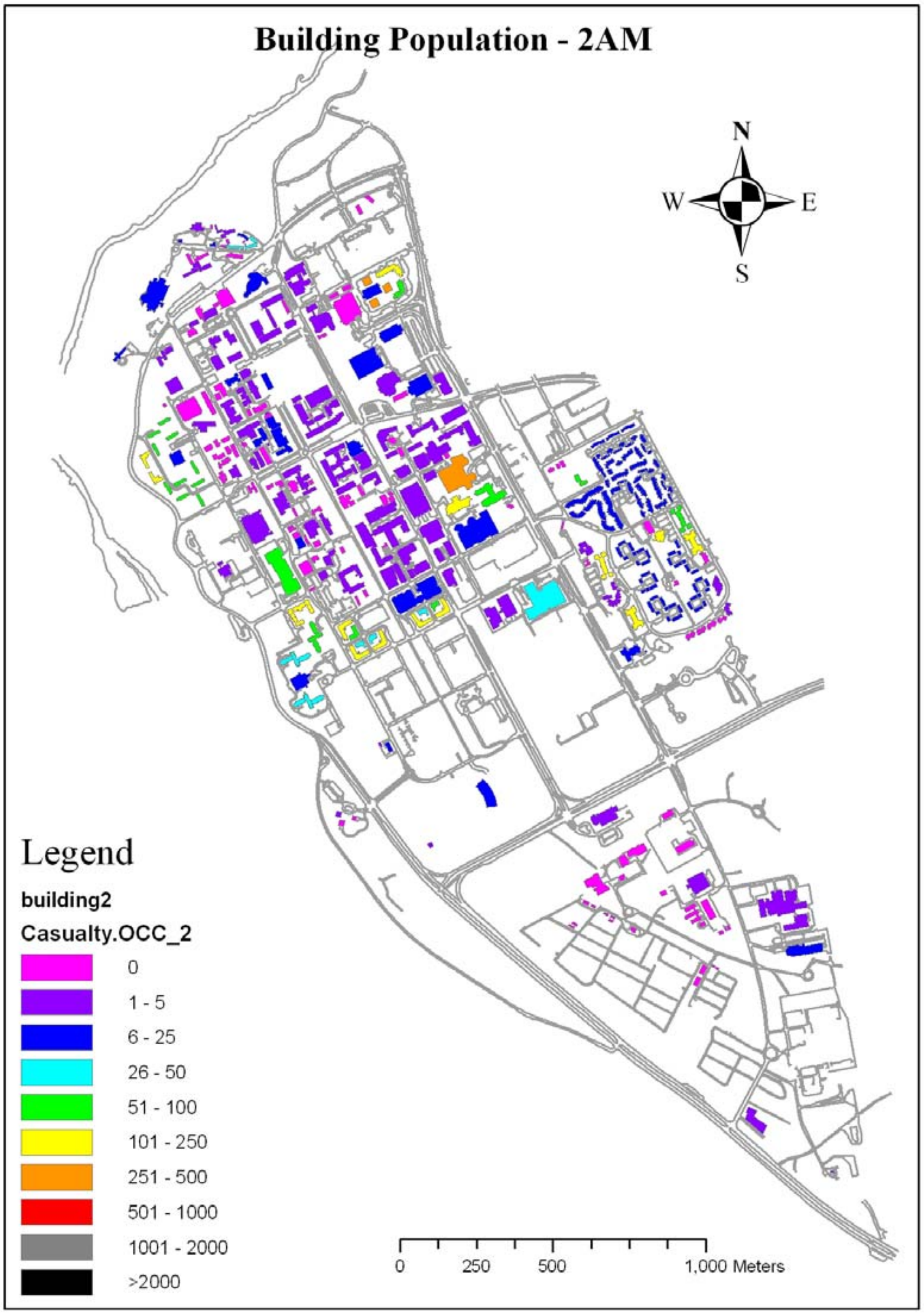

Figure 6-27 Population on Campus at 2AM

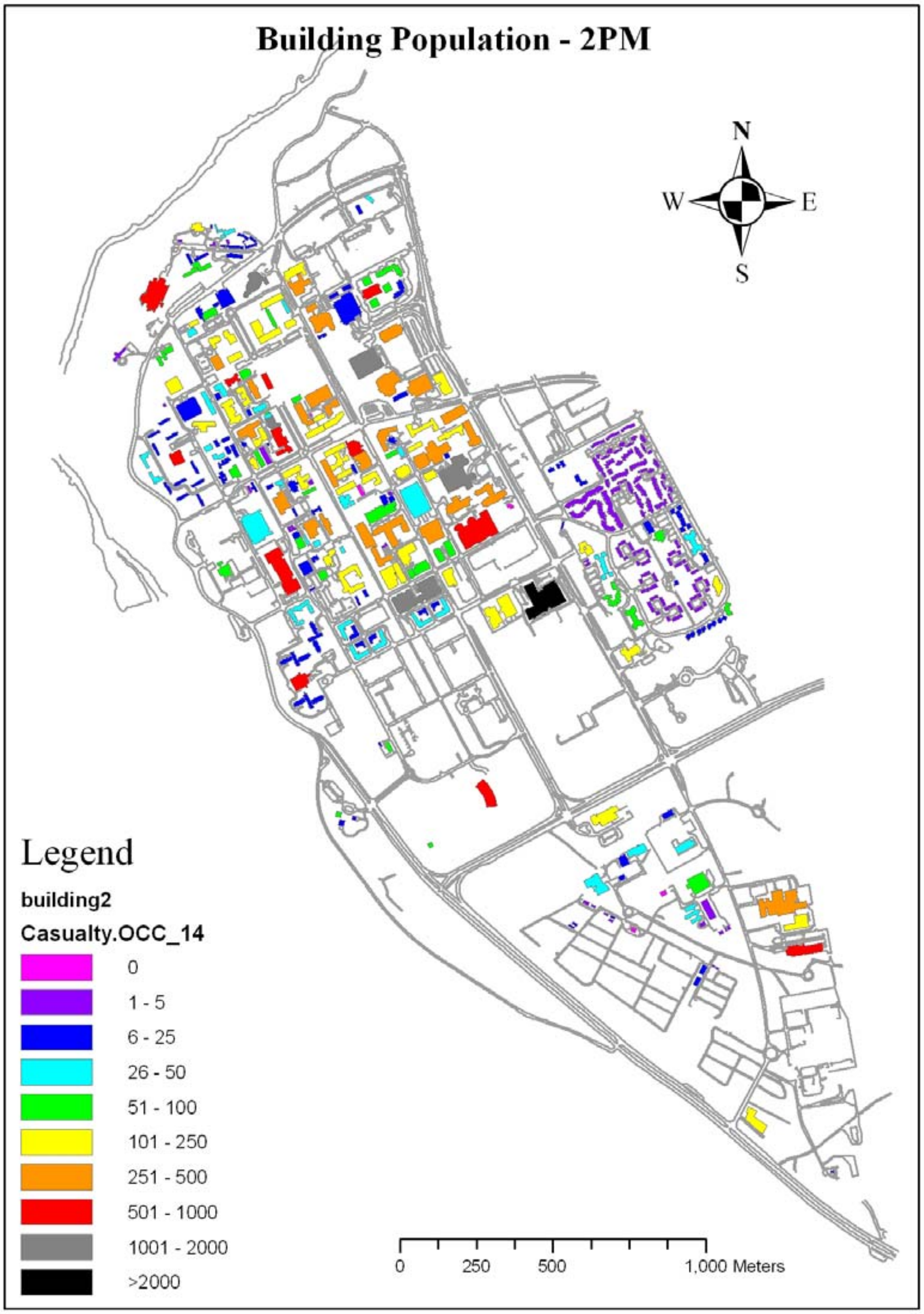

Figure 6-28 Population on Campus at 2PM

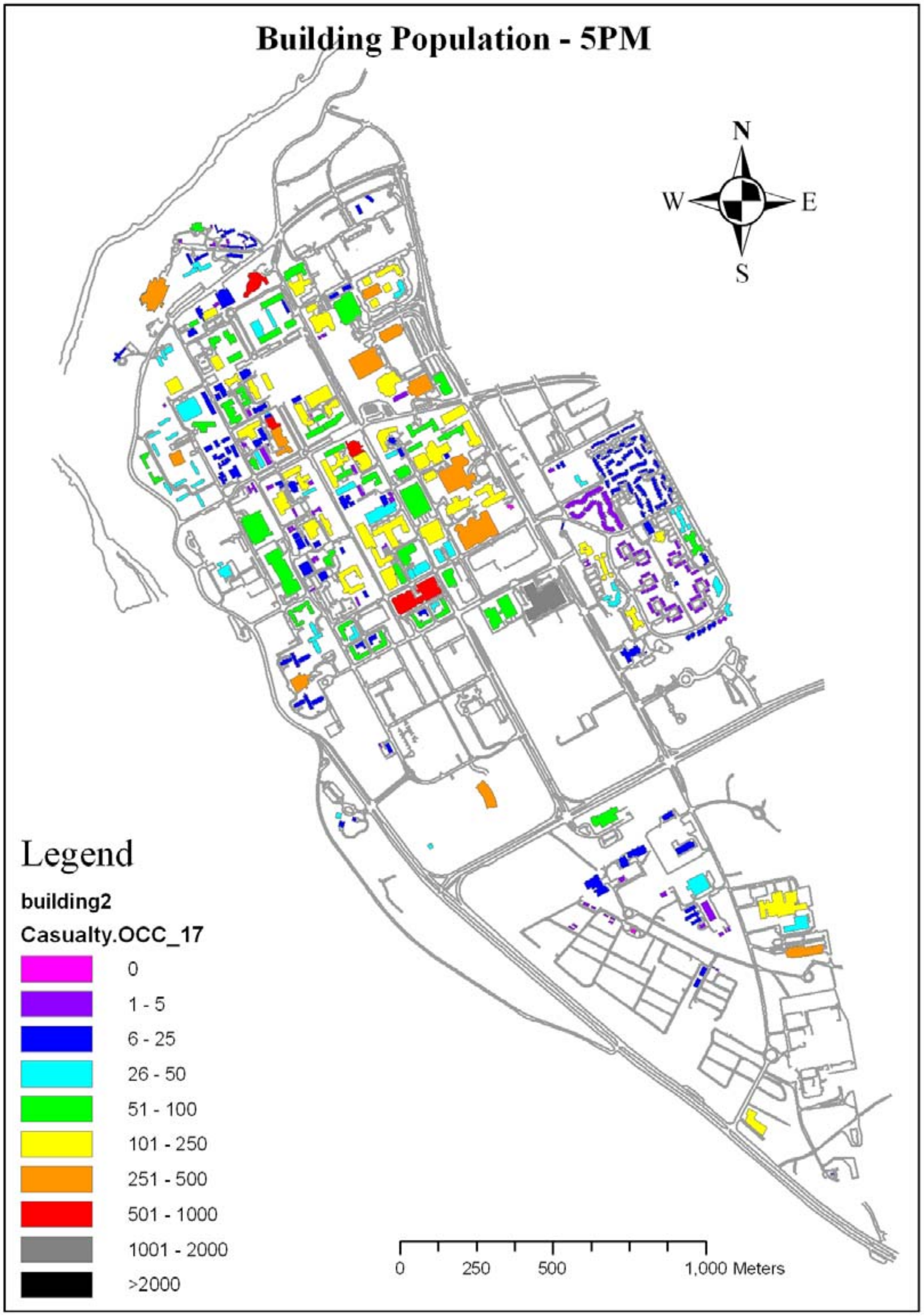

Figure 6-29 Population on Campus at 5PM

The number of casualties was estimated by multiplying the number of people in each building by the values given in table 5.33. Figures 6-30, 6-31 and 6-32 present the results of the casualty estimation at 2AM, 2PM and 5PM respectively for instrumental intensity IX.

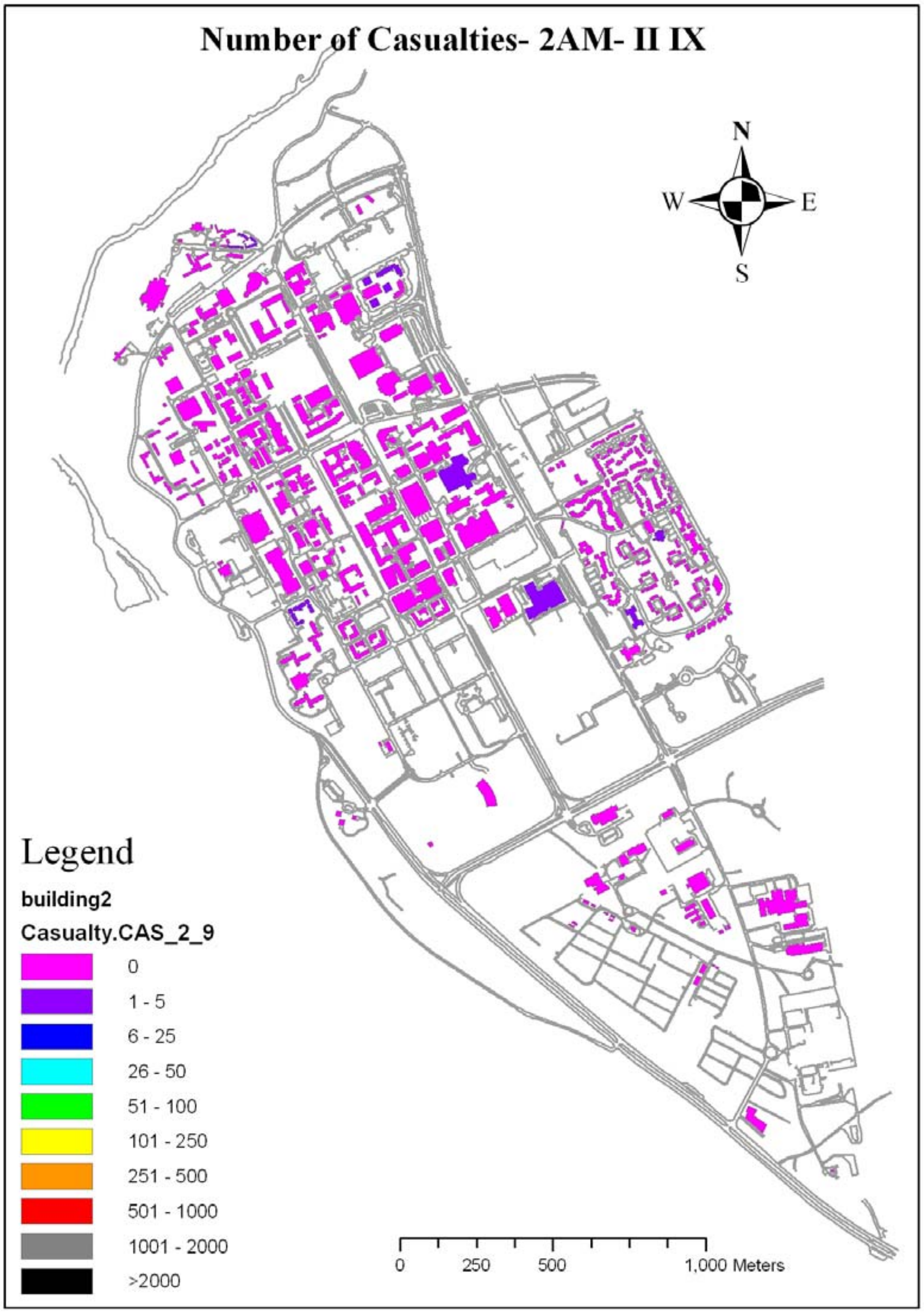

Figure 6-30 Casualties for II IX at 2PM

The total number of casualties estimated for UBC campus for an intensity IX earthquake occurring at 2AM is 30. This number is 0.5% of the population located on campus at the time and represents all levels of injury severity. These casualties are primarily located in residences and hospitals; however there are a few in certain commercial buildings.

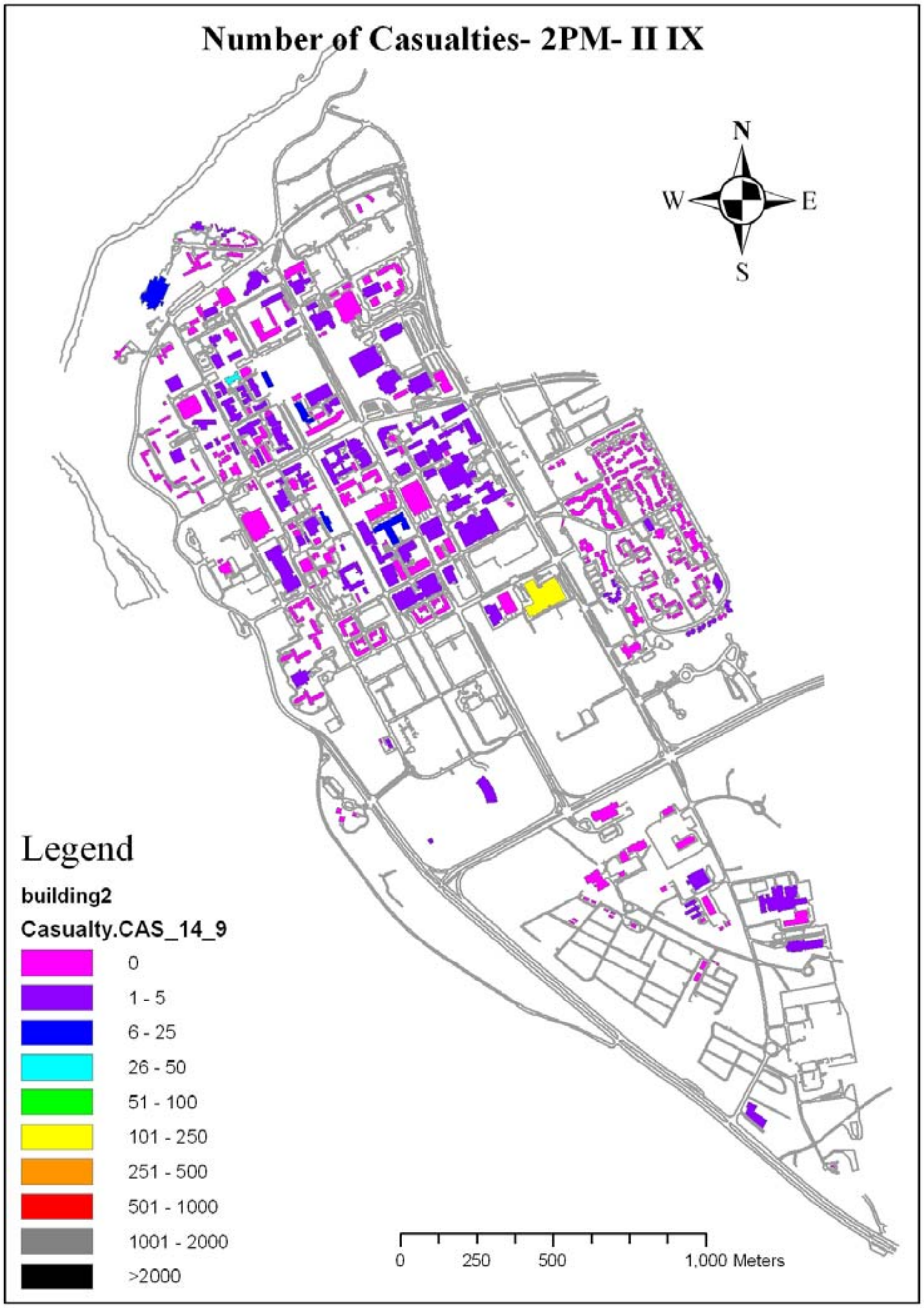

Figure 6-31 Casualties for II IX at 2PM

The total number of casualties estimated for UBC campus for an intensity IX earthquake occurring at 2pm is 416: 1% of the population on campus. These casualties are primarily located in educational, commercial and industrial buildings.

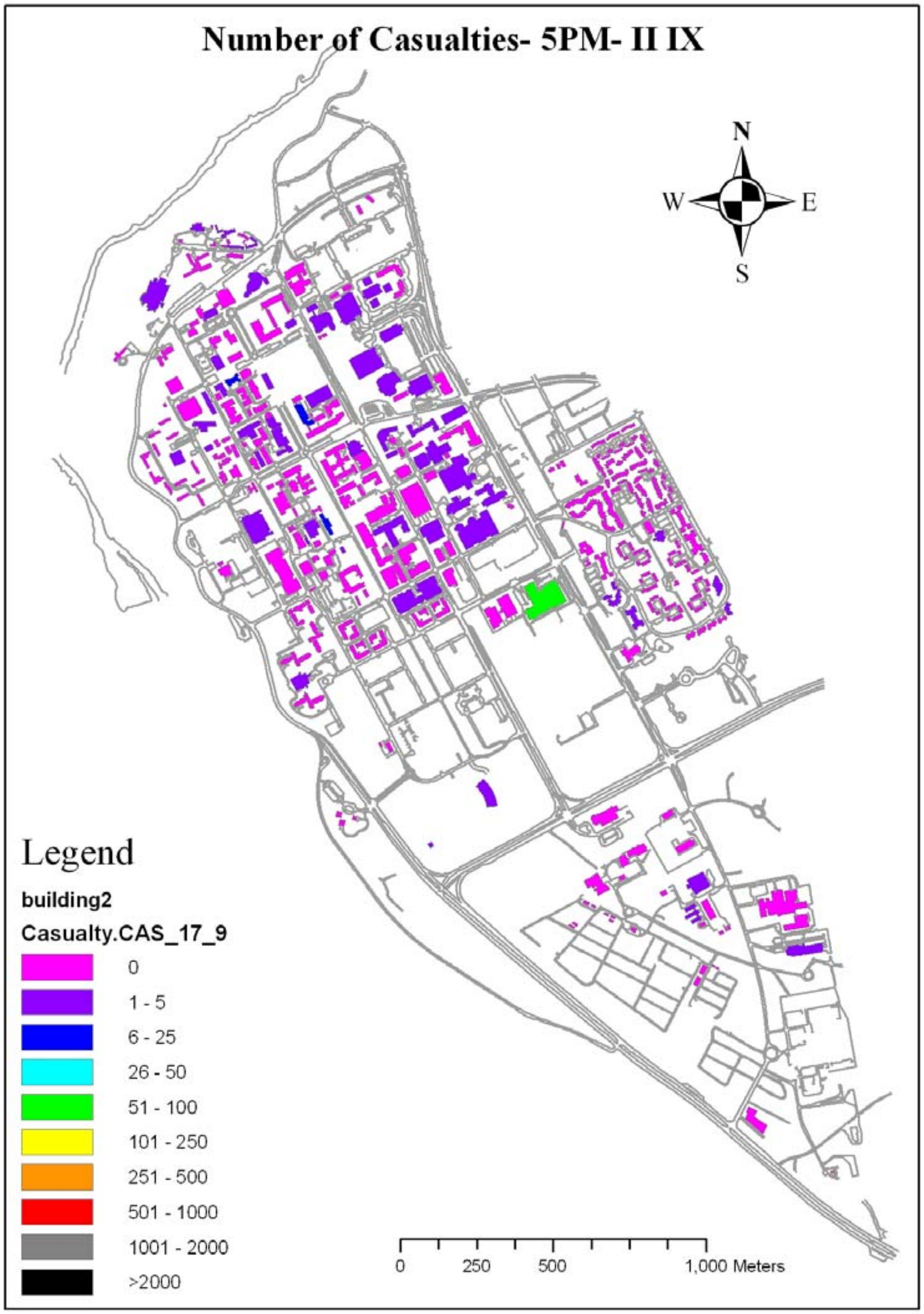

Figure 6-32 Casualties for II IX at 5PM

At 5pm the total number of casualties due to an intensity IX earthquake would be 204; 0.9% of the population. These casualties are primarily located in hospitals and educational, industrial and commercial buildings.

In terms of casualties, the worst case scenario for UBC campus would be an earthquake occurring at 2PM, when the population is the highest. This is a special characteristic of a university campus.

6.8 Functionality

The functionality assessment was performed according to the methodology described in section 5.7. The buildings were categorized into functionality categories for each of the four damage assessments: structural, displacement sensitive components, acceleration sensitive components and building contents. The worst case category was chosen as the overall functionality. Figure 6-33 presents the number of building in each functionality category for II IX and figure 6-34 functionality for each building. 84% of the buildings fall into category D, while 14% and 2% are in categories C and E respectively. This figure strongly resembles the results of the displacement sensitive NSCs damage assessment. Trends of the damage assessments and losses as intensity increases are discussed in detail in Chapter 7

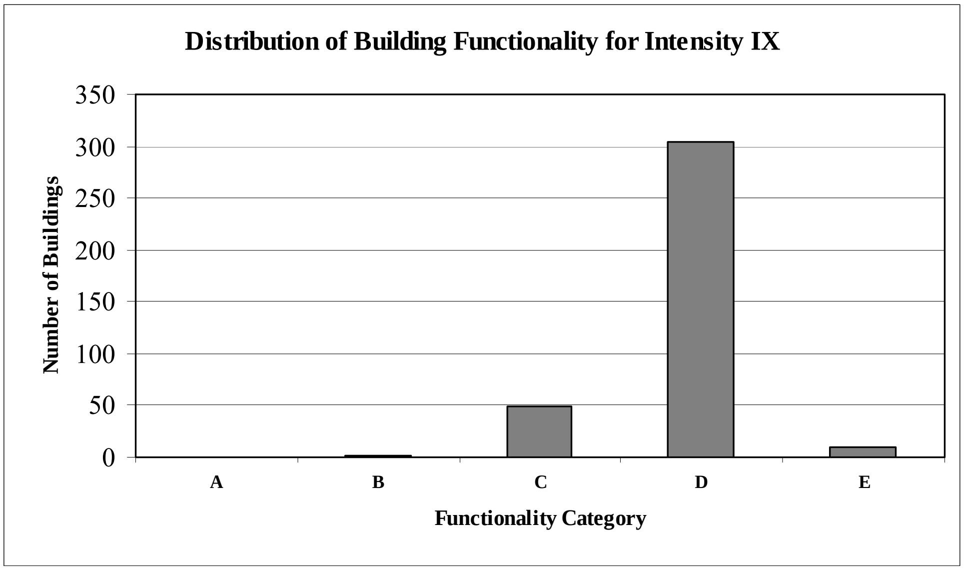

Figure 6-33 Number of Buildings in Each Functionality Category for II IX

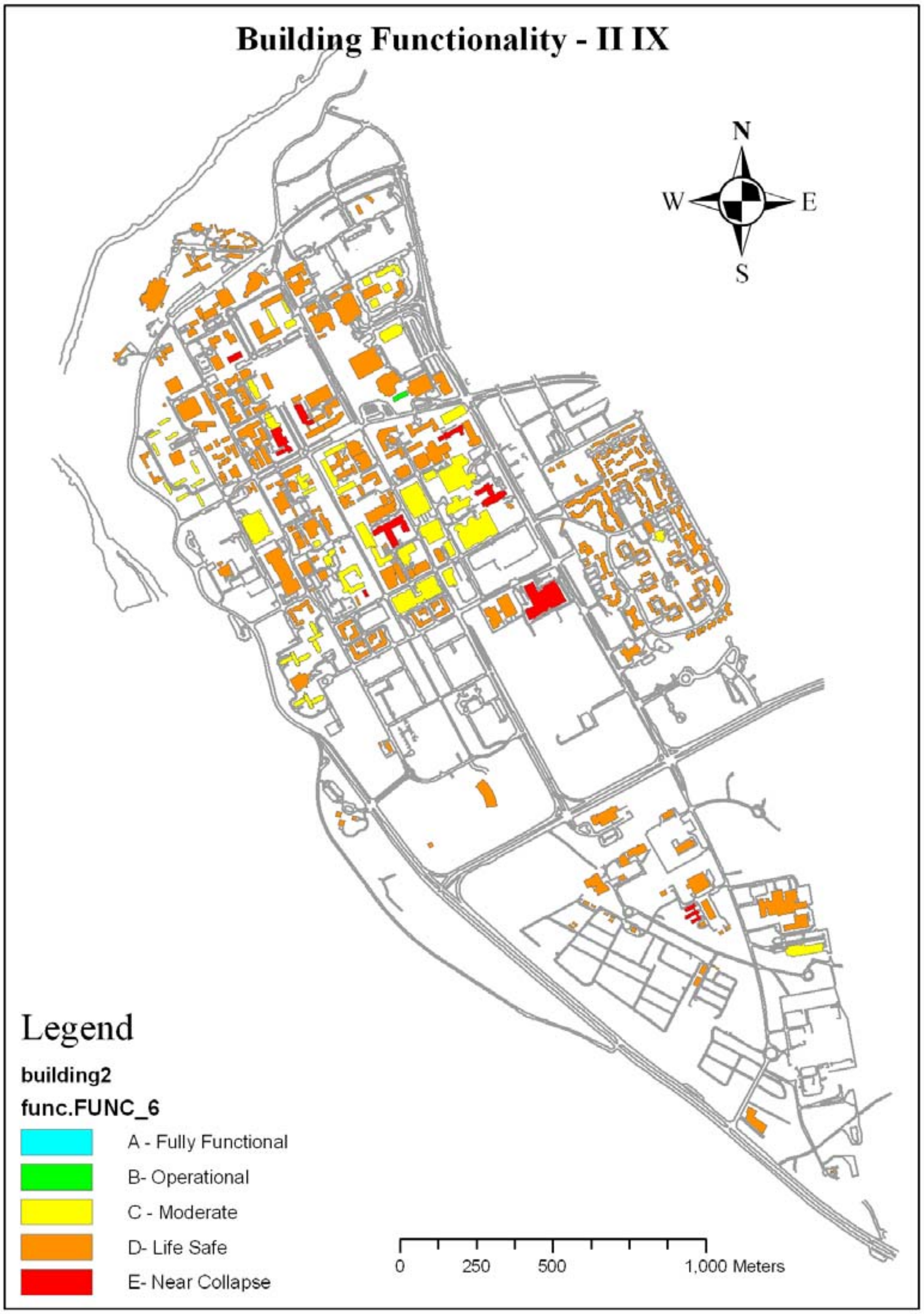

Figure 6-34 Campus Functionality for II IX

7 Discussion

This chapter discusses the results of the seismic risk assessment carried out for UBC campus. The results for all seven levels of intensity are discussed. A seismic retrofit cost benefit analysis was performed for two levels of Instrumental Intensity. The results are presented and discussed in the second section of this chapter. Finally, the value of the work presented in this thesis is discussed in terms of its benefit to the study of seismic risk assessment in British Columbia, the JIIRP project and to the community at large

7.1 Discussion of Results

The UBC test case results are discussed for all seven levels of intensity. The effects of the structural damage modifiers are examined and a comparison of the two monetary loss estimation methodologies, presented in section 5.5, is made. The results of the damage assessments and loss estimations are further examined in terms of their trends with respect to the Instrumental Intensity.

A comparison of the average structural mean damage factors calculated with and without the structural damage modifiers for UBC campus are presented in figure 7-1 for all seven levels of Instrumental Intensity. The two trends have roughly the same shape, with dramatic damage increases after intensity VIII. The structural damage modifiers have the overall affect of increasing the expected structural damage sustained at the UBC campus. The average MDFs, with and without modifiers, are similar for intensities VI through VIII, however, the modifiers have a more significant effect with increasing Instrumental Intensity; the maximum difference being 10% at intensity XII. A large percentage of the buildings in the UBC test case have irregularities and the effect of the modifiers may be less significant for a city where most of the building stock is single family homes.

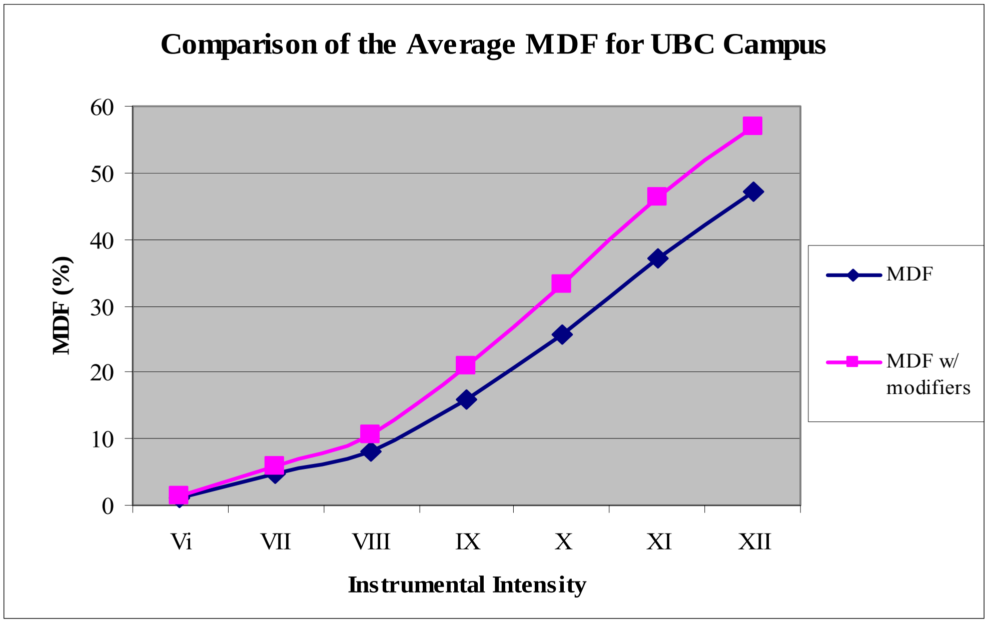

Figure 7-1 Comparison of the Average Mean Damage Factors for UBC Campus

The UBC campus average nonstructural component mean damage factors for all seven levels of intensity are presented in figure 7-2. It is clear from this figure that the displacement sensitive NSCs are expected to suffer a much higher level of damage than the acceleration sensitive components and the building contents. This is expected because the MDFs for displacement sensitive components presented in section 5.4 are much higher than those of the other components. For all three types of components, the damage increases significantly from intensities VI to VII, levels out slightly from VII to VIII and increases more significantly from VII to XII.

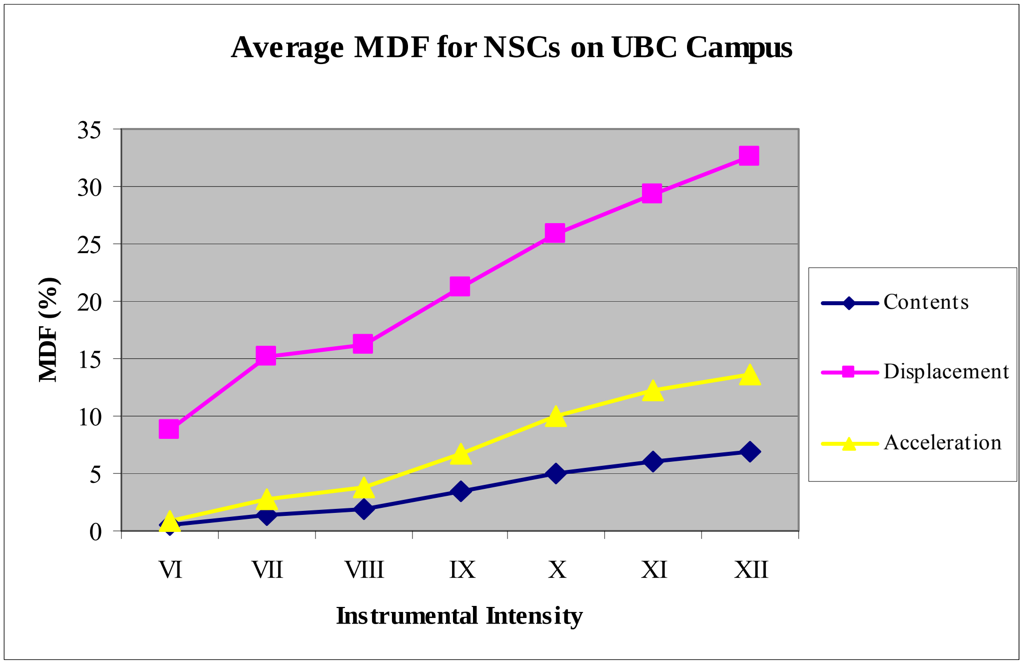

Figure 7-2 Average Nonstructural Mean Damage Factors for UBC Campus

Figure 7-3 presents a comparison of the UBC test case Facility Independent and Facility Dependent monetary loss estimations. The total monetary losses expected for the campus are displayed for each level of intensity. The facility dependent methodology results in higher amounts of loss for the study area. This is expected since, with the inclusion of the building contents, the FD method uses higher replacement values to estimate the losses. The difference in the total losses for both methods is not very significant for intensities VI through VIII; however this difference becomes more pronounced with increasing intensity.

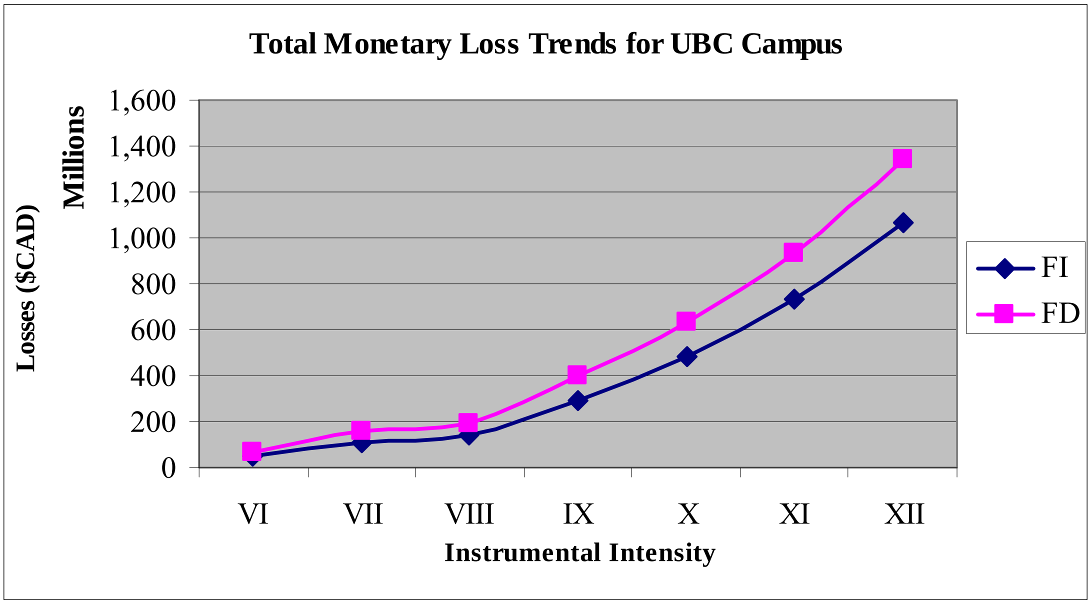

Figure 7-3 Total FI and FD Monetary Losses for UBC Campus

Examining the shape of the trends in figure 7-3, it can be seen that, from intensities VI to VII, the damages increase slightly and seem to level off between intensities VII to VIII. They increase dramatically from intensities VIII to XII. The trends for the first three intensity levels are similar to those seen in figure 7-2 for the nonstructural components damage. The trends for the higher intensity are similar to those for structural damage. It is, therefore of interest to determine the contribution of the structural and nonstructural components to the total expected losses for each intensity level.

Figures 7-4 and 7-5 presents the component losses and total losses calculated for the whole study area using the Facility Independent and Facility Dependant methodologies respectively. The graphs are plotted using the logarithmic scale for clarity as the total losses are a thousand times higher than some of the component losses. For the FI method, it can be seen that the acceleration sensitive components and building contents contribute little to the total losses. For intensities VI through VIII, the displacement sensitive component damage makes up most of the total monetary losses. As the intensity increases the losses due to structural damage become much more important and at intensity XII they account for almost the total loss. The displacement sensitive component losses trend line and structural losses trend line cross each other just after intensity VIII.

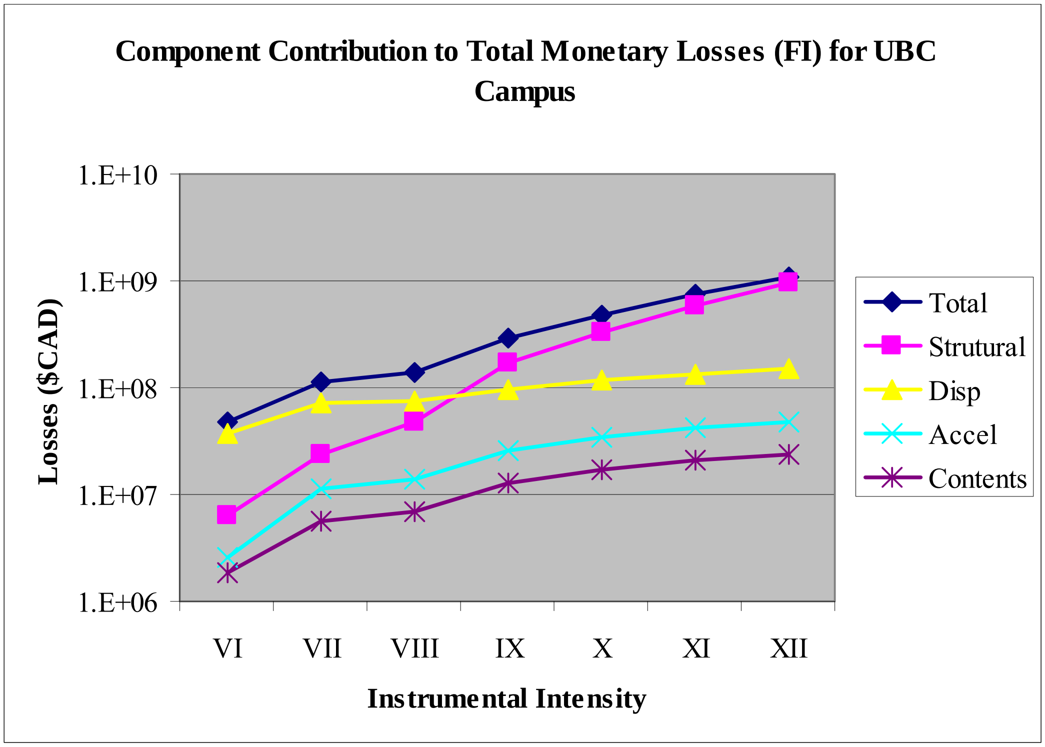

Figure 7-4 FI Component Monetary Losses for UBC Campus

The same contributing trends are seen for the Facility Dependant losses. The displacement sensitive losses are the most significant contributors for the lower intensities and the structural losses become more important for the higher intensities. The main differences between 7-4 and 7-5 are that the losses that result from acceleration sensitive component damages are significantly higher for the FD method and that the intersection of the structural and displacement sensitive trend lines is closer to intensity IX.

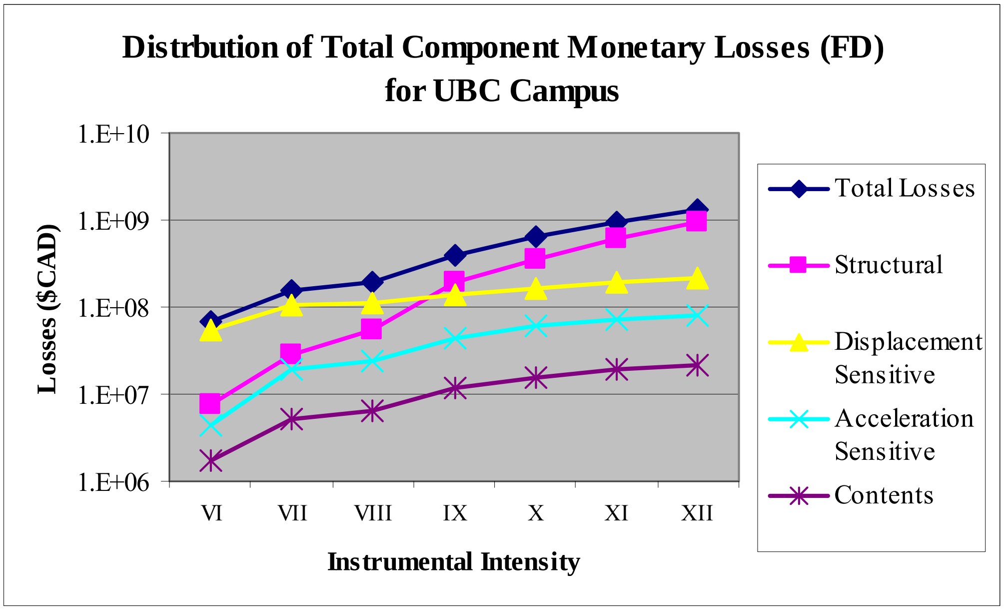

Figure 7-5 FD Component Monetary Losses for UBC Campus

From these figures it can be concluded that for low to moderate levels of intensity (VI to VIII) the damage to displacement sensitive components contribute the most to the total expected direct economic losses. For higher intensities, (IX to XII) the damage to structural components will be the most costly. Contents and acceleration sensitive components can be the most valuable components in a building, depending on its use. However the damages are expected to be quite low and, therefore, contribute only slightly to the total monetary losses.

The total number of casualties expected at UBC campus is presented for all seven levels of intensity in figure 7-6 for three specific times of day. Very few casualties are expected for intensities VI through VIII; however the number increases significantly from intensities IX through XII. The trend is similar to that of the expected structural damage. Since the casualty estimation depends on the structural damage and the number of occupants, this makes sense. For all levels of Instrumental Intensity, the time of 2pm is the most critical earthquake time for UBC campus. This may differ in the case of a city.

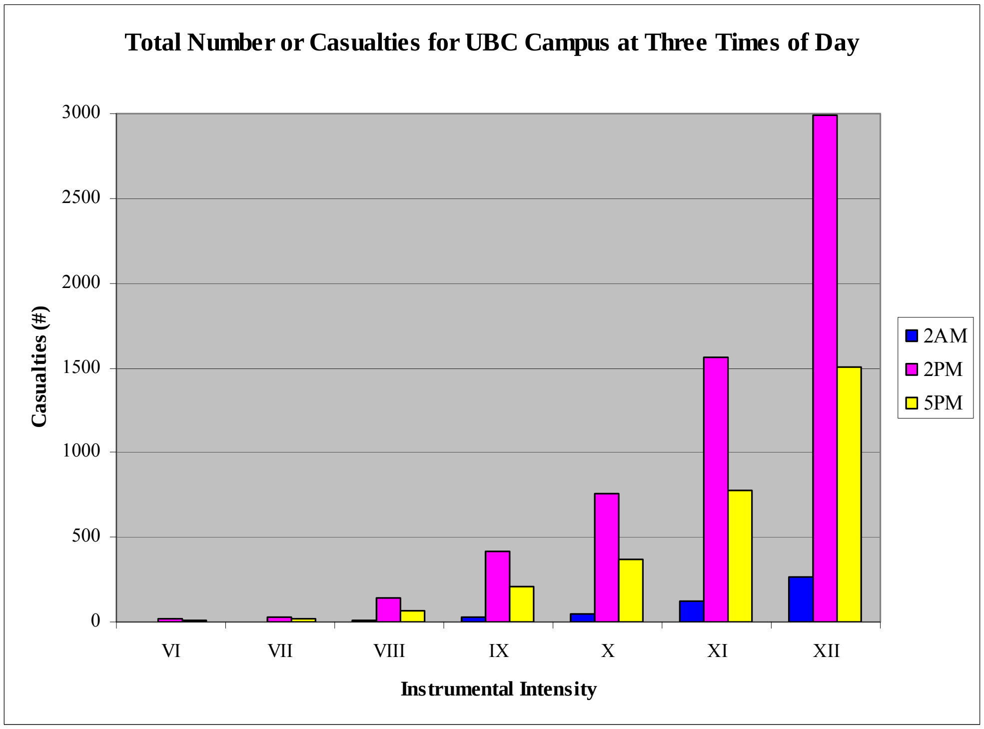

Figure 7-6 Total Number of Expect Casualties for UBC Campus

Figure 7-7 displays the overall functional of buildings in study area for all seven levels of intensity. The functionality is plotted in terms of the number of buildings in each category. For intensities VI through VIII, the majority of buildings fall into category C. The number of buildings in category D increases dramatically at intensity IX and continue to be the most common category through intensity XII. Category E buildings begin to emerge at intensity IX. The number of buildings in this category increase steadily to intensity XII, where they account for one third of the buildings in the study area. Since the overall functionally is determined from the worst case of the structural displacement sensitive, acceleration sensitive and contents functionality. It is of interest to determine which components have the greatest effect for all levels of intensity. Figures 7-8 to 7-11 present the UBC campus component functionality for all seven levels of Instrumental Intensity.

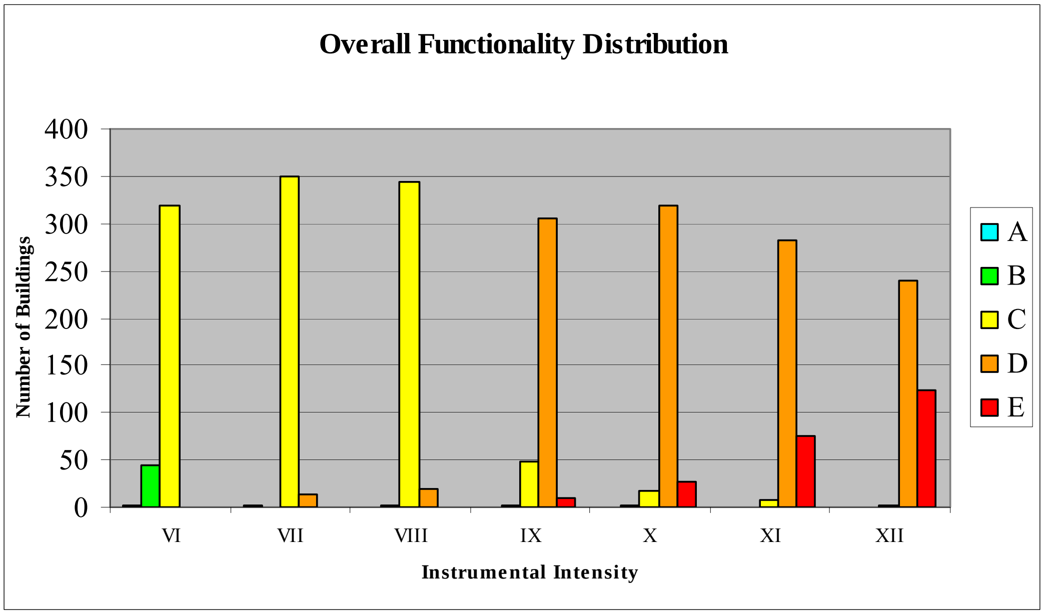

Figure 7-7 Overall Building Functionality for UBC Campus

The structural component functionality is presented in figure 7-8. For intensities VI to VIII most buildings have a structural functionality of category B, with a significant portion being C for intensity VIII. The number of buildings in category C peak at intensity IX and steadily decrease with increasing intensity. The number of buildings in category D increase steadily with increasing intensity. Category E buildings emerge at intensity IX and increase with increasing intensity. At II XII, they account for one third of all buildings in the study area.

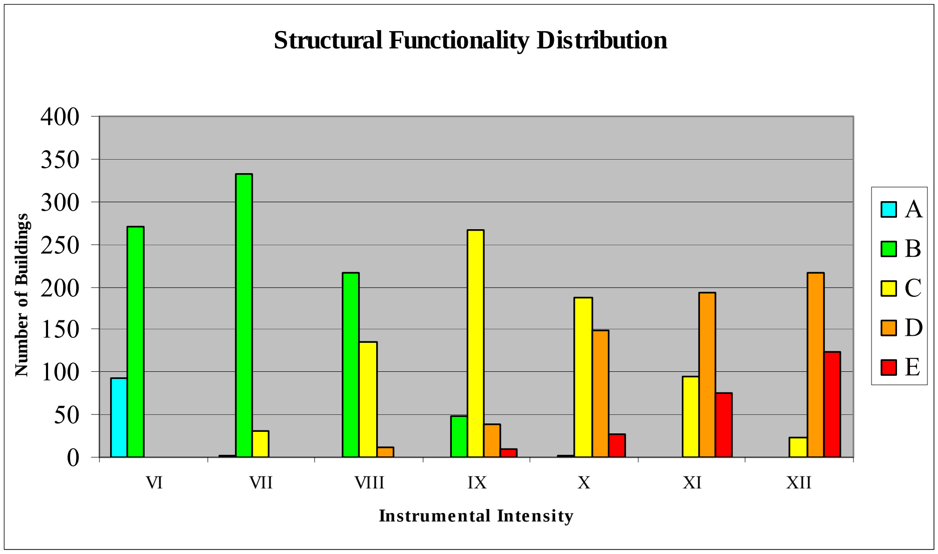

Figure 7-8 Structural Functionality for UBC Campus

The functionality of the displacement sensitive components is presented in figure 9. The functionality is primarily category C for intensities VI to VIII. For intensities IX to XI, the majority of the buildings fall into category D. At XII all of the buildings in the study area are D.

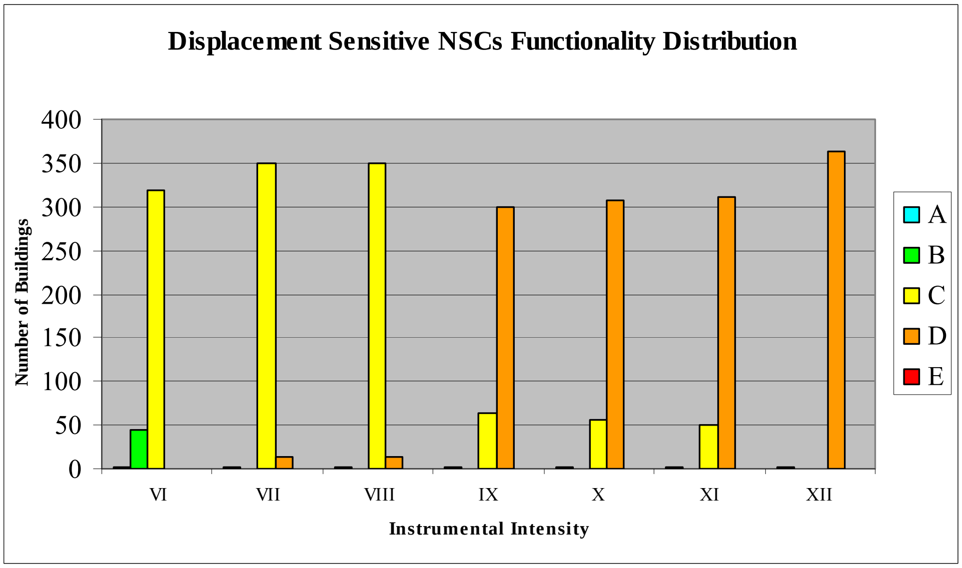

Figure 7-9 Displacement Sensitive NSC Functionality for UBC Campus

The acceleration sensitive components and building contents functionality are presented in figures 7-10 and 7-11 respectively. For both plots, the majority of buildings fall into category B for intensities VI and VII and category C for intensities IX to XII. At intensity VIII, the acceleration components are primarily B and the contents are split equally between category C and D. At intensity XII, the acceleration components and building contents are split equally between category C and D.

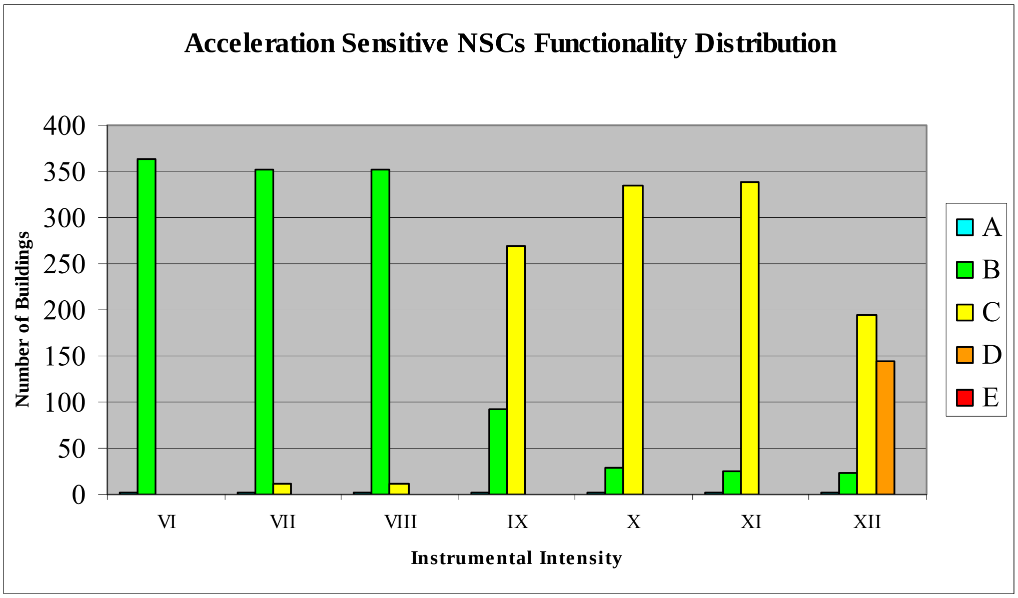

Figure 7-10 Acceleration Sensitive NSC Functionality for UBC Campus

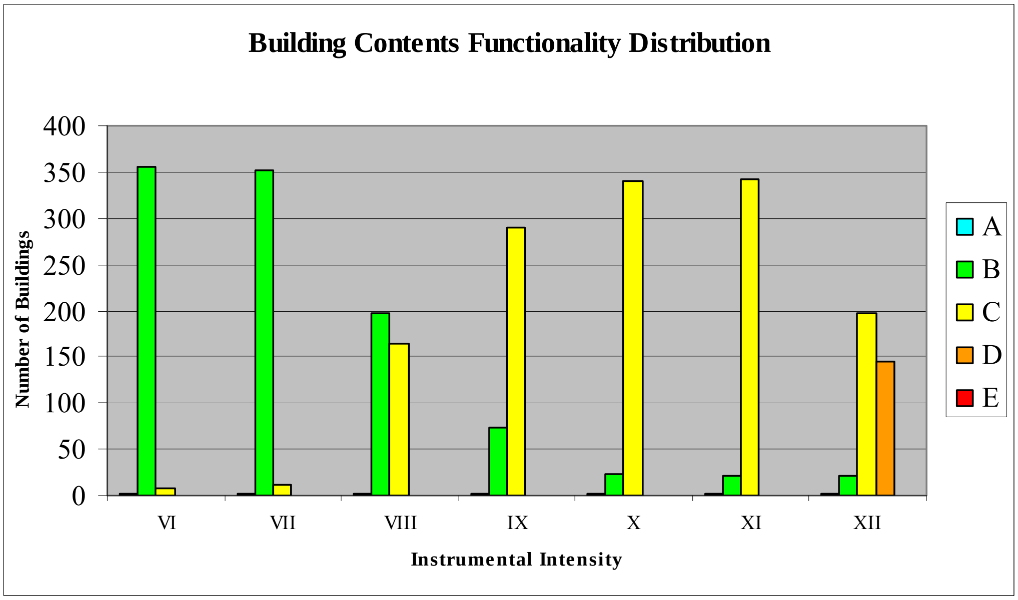

Figure 7-11 Building Contents Functionality for UBC Campus

When comparing the individual component functionalities to the overall functionality, it can be seen that the functionality of a building depends on the damage sustained by its displacement sensitive nonstructural components for intensities VI through VIII and on structural damage for IX to XII. This is a similar conclusion as the monetary losses.

7.2 Value of the Work

This section discusses the seismic risk assessment methodology (SRA) presented in this thesis. The work is discussed in terms of its value to SRA in southwestern British Columbia, the JIIRP simulator and to the community at large.

7.2.1 SRA in Southwestern BC

The enhanced seismic risk assessment methodology (SRA) presented here improves on the methodology used for SRA in southwestern British Columbia in 2000. The enhancements include the modification of existing, and the addition of new, SRA components. The Modified Mercalli Intensity based damage probability matrices were linked to the more recent Instrumental Intensity scale and the inclusion of structural modification factors improved the confidence in the damage assessment. In addition to economic losses, two other forms of loss were incorporated into the methodology: human losses and the loss of function. These allow for a more complete picture of the effects of earthquake damage. The incorporation of the Instrumental Intensity scale in the damage probability matrices modernizes the motion damage relationships and allows for more accurate conversion from peak ground velocity and peak ground acceleration to intensity.

The structural modification factors improve the results of the structural damage assessment. The original damage probability matrices (DPMs) were developed under the assumption that the buildings were simple prototypes. This is not the case for most buildings. The modification factors take this into account by considering structural characteristics which enhance or diminish the building's ability to resist earthquake damage, giving a more rational prediction of building damage and increasing the confidence in the results.

"The first priority in any disaster situation is the preservation of human lives." (Marti, 2005). The estimation of human losses adds greatly to the seismic risk assessment methodology because it takes into account the societal impacts of earthquake damage by allowing the visualization the consequences of earthquake damage. Not only are we estimating the number of casualties, we are also looking at where these casualties occur. This information is especially valuable when assessing buildings that are important to the community such as hospitals or schools.

The loss of function categorization is a valuable data interpretation tool. It simplifies the results of the structural and nonstructural damage assessments into one damage category. It provides an immediate picture of what buildings are functional post-disaster and can lead to the determination of recovery times.

7.2.2 Infrastructure Interdependencies Simulator

Using the Infrastructure Interdependencies Simulator (I2Sim), two components of the SRA can be input directly to perform different infrastructure interdependency analyses: the loss of function categorization and the casualty estimation. In addition, the methodology could be used in conjunction with the simulator to model human factors such as displacement shelters, and response to building damage.

The loss of function assessment was done for the purpose of translating damage assessment results into a single value to be used by the simulator. Each of the 5 functionality categories is associated with a percentage value which indicates to what degree the building is able to function. (See table 7-1) Translated into the JIIRP ontology, the functionality would affect the cells ability to output its tokens. For example, if the hospital cell was damaged to the point where it is in category C, the number of beds output would be reduced by 50%. This does not include the damage to the channels which could further reduce the output capacity of the cell.

Table 7-1 Functionality

Category	Title	% functional
A	Fully Functional	100
B	Operational	80
C	Moderate	50
D	Life Safe	0
E	Near Collapse	0

A direct use of the casualty estimation for the simulator is the modeling of emergency response and recovery efforts. Here the number of casualties in a building could be represented as a property of the cell indicating the demand for emergency responders. The responders would be the tokens traveling along the transportation channel network. The final element would be the hospital as the destination cell for the casualties. The properties of the hospital such as its capacity, the severity of injuries it is able to treat and emergency response procedures would be modeled within the cell.

7.2.3 The Community

The prediction of the expected level of earthquake damages and loss are very valuable to a community. This knowledge would greatly assist with community earthquake risk reduction planning, the development of multiple mitigation strategies, policy development and public education of seismic risk and hazards. Specific examples are the estimation of monetary losses and human casualties.

The estimation of monetary losses could be used to perform economic analyses and could assist with disaster mitigation planning. In the case of UBC, it could help the university develop effective seismic risk reduction plans, evaluate the need for seismic retrofit of existing buildings and implement risk management strategies.

The casualty assessment is useful to first responders and hospital staff who will be reacting to the disaster. The assessment would make them aware of buildings or clusters of buildings that have a high potential for casualties. This knowledge could help with disaster and emergency response planning by giving an estimate of the number of people expected to require treatment. This would assist with disaster planning and aid in answering questions such as: does the hospital have the capacity to treat this many patients, can the hospital treat these types of injuries and where will patients be sent if they cannot receive the treatment they require

The BC Seismic Risk Assessment methodology could be easily adapted to estimate the risk for other hazards such as hurricanes, flooding and terrorism. The Hazard assessment and evaluation of local conditions would be in terms of the hazards themselves and the building inventory would need to take into account building characteristics that have significant effect on the response of the building to those hazards. The motion damage relationships would be modified to reflect the expected behaviour of a building to the hazard. The loss estimation methodologies presented in this thesis would remain the same, they would simply use different values of direct damage to determine the expected losses.

8 Conclusions and Recommendations

8.1 Summary

In this thesis an improvement of the existing seismic risk assessment methodology for British Columbia was made and the assessment was carried out for the University of British Columbia's Point Grey campus. The motion damage relationships were updated to include the use of the Instrumental Intensity Scale. The structural damage assessment methodology was updated with the inclusion of the structural damage modifiers for a more rational prediction of structural damage. The facility dependent monetary loss estimation methodology includes the use of a building to determine its replacement value and therefore updates the existing methodology. A methodology to estimate the number of casualties expected as a result of structural damage was developed and was included into the BC seismic risk assessment methodology. A method to predict the functionality of a building post earthquake based on the structural and nonstructural damage was also developed and included.

An assessment of a seismic risk at UBC campus was carried out for seven levels of Instrumental Intensity. The potential for soil amplification was investigated and determined to be not an issue at the campus location. The structural damage was assessed with and without the use of structural damage modifiers and the damage to nonstructural components was assessed for all seven levels of intensity. The results from the two damage assessments were mapped using a GIS software package and high risk buildings were identified. Monetary losses resulting from structural and nonstructural damages were estimated using two different methodologies: the Facility Independent and the Facility Dependent for all seven levels of intensity. The expected number of casualties at UBC campus was estimated based on structural damage at three different times of day for all seven levels of intensity. Finally the functionality of each building was predicted based on structural and nonstructural damage for all seven levels of intensity. The results of the three loss estimations were mapped using the same GIS software and buildings with high losses were identified.

The results of the structural damage assessment with and without modifiers were compared for all levels of Instrumental Intensity and the structural and nonstructural damage trend were examined. The results of the two monetary loss estimation methodologies were compared and trends were examined. Also the contributions of the structural and nonstructural component damage to the total losses for the entire total number of casualties at UBC were plotted with respect to the Instrumental Intensity and the trends were discussed. Finally the functionality trends on campus were examined and the contributions of the building components to the loss of functionality were investigated.

8.2 Conclusions

The BC seismic risk assessment methodology was carried out for the University of British Columbia Point Grey campus. From the results of this assessment several conclusions can be made.

As expected, the most vulnerable buildings on campus were identified to be unreinforced masonry buildings and those with masonry infill walls. These buildings make up 5% and 2% of the buildings in the study area respectively and are typically located in the educational core of the campus.

The least vulnerable buildings were multi-family residential wood construction buildings (WLFLR). They make up 27% of the buildings in the study area and are typically located on perimeter of the campus.

In terms of economic losses, the educational core, particularly in the hospital complex area, are expected to suffer the highest losses for all levels of intensity. This is due to the replacement value of these buildings and the high value of their contents.

An earthquake occurring at 2PM would cause the highest number of casualties for all levels of Instrumental Intensity. The overall campus population is the highest at this time and the majority of the people are occupying the more vulnerable educational buildings. At 2AM almost 90% of the campus population is located in residential buildings, however the total campus population is lower and the majority of campus residential buildings are low vulnerability wood frame construction.

An examination of the monetary loss and functionality trends revealed that for moderate intensity earthquakes (VI to VIII) the total monetary losses and functionality depend primarily on the damage to displacement sensitive nonstructural components. For higher intensity earthquakes, (IX to XII) structural damage plays the most important role.

8.3 Recommendations

The structural and nonstructural damage was determined for seismic shaking alone. The only local site condition taken into account in the methodology is the potential for soil amplification. Other site conditions that are major causes of damage are liquefaction, landslide and surface rupture. In addition to site conditions, collateral hazards and indirect damage such as tsunamis and earthquake induced fires and floods, can significantly increase the level of damage sustained by a building. It is therefore recommended that these collateral hazards be integrated into the BC seismic risk assessment methodology.

Two methodologies were described in Chapter 5 for the estimation of direct monetary losses based on the expected structural and nonstructural damage in a building. Both methodologies were implemented for the UBC test case and compared in Chapter 7. It is recommended that the Facility Dependent methodology be used in all future seismic risk assessment studies. While it is more complicated than the Facility Independent methodology, it is still easy to implement and results in more rational estimates of the building replacement values and subsequent monetary losses.

The casualty estimation methodology was developed using the structural damage probability matrices and did not include the structural damage modifiers. The modifiers have a significant effect on the expected level of structural damage and should be included in future studies. A methodology to estimate casualties based on the final structural mean damage factor was briefly described at the end of Section 5.6.2. It is recommended that this methodology be further investigated and eventually integrated into the risk assessment methodology.

The BC loss estimation methodology estimates direct monetary losses only. An estimation of down time and the resulting indirect monetary losses were not included. Downtime and indirect economic losses are important factors that need to be estimated. Therefore the development of a method to estimate these components is recommended.

At this time, limited research has been done in the area of estimating the functionality of a building after an earthquake has occurred. The methodology in this thesis represents a good start, but further research of this topic is recommended to develop confidence in their results.

Seismic risk assessment was carried out at UBC campus for 364 buildings. A university campus presents a unique setting where the majority of the population is transitory and very few people reside. There are many cities exposed to seismic hazard that could greatly benefit from the results of a seismic hazard assessment. It is recommended that a seismic risk assessment be carried out for a large British Columbia city in order to evaluate its seismic risk and validate the BC seismic risk assessment methodology.

All components of the methodology need to be validated by comparing their results with real earthquake damage and loss data. At this time, however, no such data exists for British Columbia. It is recommended that when British Columbia data becomes available, the BC seismic risk assessment methodology be validated.

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Appendix A: Modified Mercalli Intensity Scale

I. Not felt except by a very few under especially favorable conditions.

II. Felt only by a few persons at rest, especially on upper floors of buildings.

III. Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.

IV. Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V. Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.

VI. Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.

VII. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.

VIII. Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.

IX. Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.

XI. Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.

XII. Damage total. Lines of sight and level are distorted. Objects thrown into the air.

Appendix B. Description OF BC Building Prototypes

Descriptions of the building prototypes listed in Chapter 5, Table 5.3 are given in the following paragraphs.

1. WLFR (Wood Light Frame residential):

This prototype includes single family detached homes and attached town houses. They are generally one or two stories high with a foot print area in the range of 70 to 350 square meters. The vast majority of buildings in Southwestern BC are of this prototype, usually located in the residential or suburban areas. These buildings usually behave very well (lightweight, low rise, many walls) except when a parking garage is built into the structure creating an equivalent of a weak storefront.

2. WLFCI (Wood Light Frame Low Rise Commercial/ Institutional):

This prototype includes one or two storey commercial and institutional buildings varying in size from 80 to 600 square meters in footprint area. The ground floor usually has extensive areas of glazing creating a storefront. This prototype makes up about 10% of the commercial/institutional building stock. These buildings behave very well if there are less window openings than half the area of the perimeter wall. Commercial buildings with storefronts are subject to extensive damage if they are stand-alone structures.

3. WLFLR (Wood Light Low Frame Rise Residential):

This prototype includes wood frame structures up to four stories in height principally for residential use. The footprint area can be as large as 1500 square meters. They usually have considerable interior load bearing walls and no extensive glazing. Exterior walls may be clad in a variety of materials including wood or vinyl siding, or stucco, brick veneer, and metal. About 90% of all low-rise residential buildings are of this prototype. These structures generally behave well if they do not have a ground level parking area, or if they have concrete underground parking levels.

4. WPB (Wood Post and Beam):

This prototype includes some one or two storey commercial structures. Old high-rise structures (industrial, storage, manufacturing) are also classified as post and beam if the perimeter columns are load bearing and the masonry part is not load bearing. This prototype can be found in “West coast Style” post and beam homes of the 1950’s and 1960’s; one or two storey industrial facilities of the 1920’s to 1950’s; schools, gymnasiums, churches, warehouses as well as some commercial structures of the 1950’s and 1960’s. These buildings generally behave poorly.

5. LMF (Light Metal Frame):

This prototype includes lightweight pre-engineering “Butler” type industrial and agricultural buildings (usually used as warehouses or industrial shops) with rigid frames in the short direction and cross bracing in the other direction. About 5% of the inventory of industrial warehouse type buildings are of this prototype. These buildings are expected to behave well.

6. SMFLR (Steel Moment Frame Low Rise):

This prototype includes steel moment framed structures of one to three stories in height, generally used for institutional facilities or office structures. Moment frames transfer lateral forces from the floors to the foundations in one or both directions. These structures are extremely rare in Southwestern BC and are extremely hard to identify unless portions of the structure are exposed. These are very flexible buildings and will cause extensive non-structural damage due to the flexibility and torsional effects (rigid floor diaphragms with flexible frame).

7. SMFMR (Steel Moment Frame Medium Rise

This prototype includes steel moment framed structures of four to seven stories in height, generally used for institutional facilities or office structures. These structures are very rare in Southwestern BC and are extremely hard to identify unless portions of the structure are exposed. These are very flexible buildings and will cause extensive non-structural damage due to the flexibility and torsional effects (rigid floor diaphragms with flexible frame).

8. SMFHR (Steel Moment Frame High Rise):

This prototype includes steel moment framed structures of over eight stories in height, generally used for institutional facilities or office structures. These structures are very rare in Southwestern BC and are extremely hard to identify unless portions of the structure are exposed. These are flexible buildings and will cause extensive non-structural damage due to the flexibility and torsional effects (rigid floor diaphragms with flexible frame).

9. SBFLR (Steel Braced Frame Low Rise):

This prototype includes structures with steel braced frames in both directions, one to three stories in height, generally used for one or two storey commercial and institutional buildings as well as many low-rise industrial facilities. About one third of older industrial facilities and 5% of the commercial and institutional buildings are of this prototype. They are to identify unless the bracing is exposed. These structures usually have storefronts and flexible diaphragms, which may cause problems as well as connections of the bracing system.

10. SBFMR (Steel Braced Frame Medium Rise):

This prototype includes structures with steel braced frames in both directions, four to seven stories in height, generally found in older office buildings as well in older light manufacturing facilities. Many multi-storey industrial facilities such as pulp and paper mill, boiler plants are also of this prototype. However, other than these structures, this prototype is very rare in Southwestern BC. They are also hard to identify unless the bracing is exposed. These structures are in high risk because of their flexibility coupled with the attachment of a heavy perimeter cladding. They usually behave poorly because of poor connections in the bracing systems.

11. SBFHR (Steel Braced Frame High Rise):

This prototype includes structures with steel braced frames in both directions, over eight stories in height, generally used for office buildings and some very tall industrial buildings such as grain elevators. These structures are very rare in Southwestern BC and hard to identify unless the bracing is exposed. These structures are high in risk because of their flexibility coupled with the attachment of a heavy perimeter cladding. They behave poorly usually because of poor connections in the bracing system.

12. SFCWLR (Steel Frame with Concrete Walls Low Rise):

This prototype includes one and two storey steel framed structures that use concrete shear walls as their vertical elements to transfer seismic forces from roof and floors to the foundations. It is one of the most common forms of steel construction for commercial and institutional buildings, particularly those constructed after 1970's. The steel frame may be hard to identify unless drawings or access is available. These buildings generally behave well, particularly if the walls are well distributed, although structures with storefronts will experience damage

13. SFCWMR (Steel Frame with Concrete Walls Medium Rise):

This prototype includes steel frame structures with concrete shear walls from three to seven stories in height. It is a fairly common form of steel construction for commercial and institutional buildings, making up about 30% of the inventory of medium rise buildings. The steel frame may be hard to identify unless drawings or access to the structure is available. These buildings generally behave well, particularly if the walls are well distributed to minimize torsional effects.

14. SFCWHR (Steel Frame with Concrete Walls High Rise).

This prototype includes steel frames structures with concrete shear walls over eight stories in height, used for commercial and institutional buildings. It was fairly common prior to 1985, however, is now being superseded by concrete frame with concrete shear wall structures (CFHR). About 15% of the pre-1985 office towers and probably less than 10% of post- 1985 towers are of this prototype. The steel frame may be hard to identify unless drawings or access to the structure is available. These buildings generally behave well, particularly if the concrete shear walls are well distributed to minimize torsional effects and have well-detailed connections to the steel frames.

15. SFCIW (Steel Frame with Concrete Infill Walls):

This prototype includes steel framed buildings with concrete infill walls, which were usually built along the sides of the buildings and used as a fire separation between the buildings (not considered as shear walls). This was a common form of construction prior to the 1950's, when offices and some light industrial buildings (up to seven stories) were constructed in this manner. These buildings are to identify unless the adjacent building has been torn down. They are expected to behave reasonably well although extensive damage and partial collapses can be expected if storefronts exist.

16. SFMIW (Steel Frame with Masonry Infill Walls).

This prototype includes steel framed buildings with masonry infill walls, which were usually built along the sides of the building and used as a fire separation between the buildings (not considered as shear walls).This was a common form of construction prior to the 1950's, when offices and some light industrial buildings (up to seven stories) were constructed in this manner. These buildings are to identify unless the adjacent building has been torn down. They were generally not designed for seismic forces, hence they will not behave well, extensive damage and partial collapse can be expected.

17. CFLR (Concrete Frame with Concrete Walls Low Rise)

This prototype includes one to three-storey concrete structure that use concrete shear walls (in one or both directions) as their vertical elements to transfer seismic forces from the roof and floors to the foundations. It is commonly used for commercial and even more commonly for institutional buildings. These buildings generally behave well, particularly if the footprint is rectangular unless the footprint is large enough to cause torsional problems together with inappropriately shear walls.

18. CFMR (Concrete Frame with Concrete Walls Medium Rise):

This prototype includes concrete framed structures with concrete shear walls from four to seven stories in height. It is very common form of construction for medium rise residential, commercial and institutional buildings, making up to more than 50% of the inventory of medium rise buildings. These buildings are usually easy to identify and they generally behave well, particularly if the walls are well distributed to minimize torsional effects.

19. CFHR (Concrete Frame with Concrete Walls High Rise):

This prototype includes concrete framed structures with concrete shear walls eight stories in height. It is an extremely common form of construction for commercial and residential high rises, making up to 90% of the inventory of high rise buildings. These buildings are usually easy to identify and they generally behave well, particularly those built after 1985.

20. RCMFLR (Reinforced Concrete Moment Frame Low Rise):

This prototype includes reinforces concrete moment frame structures of one to three stories in height, generally used for institutional facilities or office structures. The moment frames are used in one or both directions and they replace the shear walls to transfer lateral forces from the floors to the foundation. This form of construction is very rare in Southwestern BC and is extremely hard to identify without drawings. Inadequate detailing of the joints may cause extensive damage in these structures.

21. RCMFMR (Reinforced Concrete Moment Frame Medium Rise):

This prototype includes reinforced concrete moment frame structures of four to seven stories in height, generally used for office structures. This form of construction is extremely rare in Southwestern BC and is very difficult to identify without drawings. Inadequate detailing of the joints may cause extensive damage in these structures.

22. RCMFHR (Reinforced Concrete Moment Frame High Rise):

This prototype includes reinforced concrete moment frame structures of over eight stories in height, generally used for office structures. This form of construction is extremely rare in Southwestern BC and is very difficult to identify without drawings. Inadequate detailing of the joints may cause extensive damage in these structures.

23. RCFIW (Reinforced Concrete Frame with Infill Walls):

This prototype includes reinforced concrete frame buildings with masonry infill walls, which were usually built along the sides of the building and used as a fire separation between the buildings (not considered as shear walls). This was a common form of construction prior to the 1950’s, when offices and some light industrial buildings (up to seven stories) were constructed in this manner. These buildings are difficult to identify unless the adjacent building has been torn down. They were generally not designed for seismic forces, hence they are expected to behave poorly and experience extensive damage.

24. RMLR (Reinforced Masonry Shear Wall Low Rise):

This prototype includes one to three stories high buildings with perimeter load bearing walls of reinforced masonry. Since 1973, when The National Building Code of Canada required that all masonry be reinforced, this has become a very common form of construction for low rise commercial, institutional and industrial buildings. These buildings are usually easy to identify. The walls generally behave well; however, whether or not the roof diaphragm connection to the walls will function adequately is a major concern for these buildings.

25. RMMR (Reinforced Masonry Shear Wall Medium Rise):

This prototype includes buildings with perimeter load bearing walls of reinforced masonry, over three stories in height. In the mid-1970’s, these buildings were constructed to compete with reinforced concrete structures, however, after a small number were built, they were found noncompetitive. Therefore, they are very rare in Southwestern BC. Extensive damage is anticipated in these types of buildings.

26. URMLR (Unreinforced Masonry Bearing Wall Low Rise):

This prototype includes buildings up to three stories in height with perimeter load bearing walls of clay brick, concrete block and hollow clay. This was a very common form of low-rise construction for commercial, institutional buildings unstill 1973, when The National Building Code of Canada required that all masonry be reinforced. These buildings are easy to identify, usually showing extensive areas of red clay brick. They behave very poorly and are considered the most hazardous form of construction in seismic areas

27. URMMR (Unreinforced Masonry Bearing Wall Medium Rise):

This prototype includes three to six storey high buildings with perimeter load bearing walls of mainly clay brick with thickness reaching 750mm. This form of construction was used for commercial and light industrial buildings prior to 1940. These buildings are easy to identify with thick walls and usually extensive areas of red or orange clay brick exposed, often in poor condition. They behave very poorly and are considered as the most hazardous form of construction in seismic areas.

28. TU (Tilt Up):

This prototype includes low-rise structures with walls that are constructed of reinforced concrete panels, which have been cast on site on top of the concrete slab on grade and then tilted into position. It has been commonly used since the late 1970's for warehouses, light manufacturing and research facilities. These buildings are expected to behave reasonably well in BC because of the use of steel roof systems and their superior connections. .

29. PCLR (Precast Concrete Low Rise):

This prototype includes one to three stories high buildings that are constructed of concrete components that have been manufactured off site in a plant and transported to the construction site for installation. Installation consists of lifting and connecting the members together, then pouring a topping over the floors to create a level surface. This form of construction was quite common during the 1960’s and 1970’s for institutional buildings as well as for parking structures. These structures make up a very small portion of the Southwestern BC inventory and behave very poorly, primarily due to the connection failures.

30. PCMR (Precast Concrete Medium Rise):

This prototype includes over four stories high building that are constructed of concrete components that have been manufactured off site in a plant and transported to the construction site for installation. Although this form of construction is common in Canada for commercial and institutional buildings, it has been seldom used in Southwestern BC. These structures make up a very small portion of the Southwestern BC inventory and behave poorly, primarily due to the connection failures.

31. MH (Mobile Homes):

This prototype includes single storey wood framed factory manufactured buildings and school portables. They are generally not more than 33 square meters in area. Individual units behave well if adequately skirted and anchored to a foundation.

Appendix C. BC Structural DPM

Buildings located in southwestern BC were classified into 31 prototypes and damage probability matrices were developed for each of these prototypes. These matrices were developed assuming that the buildings are very nearly regular in shape and they are founded on firm ground, designed to a code prior to 1990. Collateral hazards such as ground failure and fire were not considered (Bell, 1998).

The damage probability matrices (DPMs) for each of the 31 prototypes of buildings are presented below. In these tables, CDF is the Central Damage Factor as defined in Chapter 5, and *** indicates very small probability.

Table C.1. DPM for WLFR (Wood Light Frame Residential)

Description	This prototype includes one or two-storey single family detached homes and attached townhouses. The vast majority of the buildings in southwestern BC are of this prototype.					
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	8.0	4.0	1.0	***	***	***	***
0.5	75.0	28.0	6.0	1.0	***	***	***
5.0	17.0	64.0	86.0	69.0	10.0	2.0	***
20.0	***	4.0	5.0	20.0	76.0	69.0	42.0
45.0	***	***	2.0	10.0	12.0	25.0	50.0
80.0	***	***	***	***	2.0	4.0	6.0
100.0	***	***	***	***	***	***	2.0

Table C.2. DPM for WLFCI (Wood Light Frame Commercial/Institutional)

Description	This prototype includes one or two-storey C/I buildings. This prototype makes up about 10% of the C/I building stock. They often have "storefronts", extensive areas of glazing.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	7.0	1.0	***	***	***	***	***
0.5	77.0	23.0	3.0	1.0	***	***	***
5.0	16.0	69.0	77.0	55.0	9.0	1.0	***
20.0	***	5.0	15.0	35.0	66.0	57.0	40.0
45.0	***	2.0	5.0	7.0	18.0	25.0	37.0
80.0	***	***	***	2.0	7.0	14.0	18.0
100.0	***	***	***	***	***	3.0	5.0

Table C.3. DPM for WLFLR (Wood Light Frame Low Rise Residential)

Description	This prototype includes residential apartment buildings usually up to four stories high. About 90% of all low-rise (multi-family) residential buildings are expected to be of this form.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	7.0	4.0	***	***	***	***	***
0.5	81.0	30.0	12.0	1.0	***	***	***
5.0	12.0	64.0	85.0	65.0	20.0	2.0	***
20.0	***	2.0	3.0	28.0	73.0	70.0	44.0
45.0	***	***	***	6.0	7.0	24.0	47.0
80.0	***	***	***	***	***	4.0	8.0
100.0	***	***	***	***	***	***	1.0

Table C.4. DPM for WPB (Wood Post and Beam)

Description	This prototype includes one or two-storey C/I structures (making up 20% of C/I building stock). Also, industrial plants built between 1920-1950 were commonly of this prototype.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	2.0	1.0	***	***	***	***	***
0.5	77.0	12.0	2.0	***	***	***	***
5.0	21.0	77.0	72.0	60.0	6.0	1.0	***
20.0	***	8.0	17.0	22.0	64.0	54.0	40.0
45.0	***	2.0	7.0	10.0	18.0	25.0	33.0
80.0	***	***	2.0	5.0	8.0	15.0	20.0
100.0	***	***	***	3.0	4.0	5.0	7.0

Table C.5. DPM for LMF (Light Metal Frame)

Description	This prototype includes lightweight pre-engineering industrial and agricultural buildings. It makes up about 5% of the inventory of industrial warehouse type buildings.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	40.0	10.0	2.0	***	***	***	***
0.5	55.0	40.0	17.0	5.0	1.0	***	***
5.0	5.0	50.0	81.0	80.0	15.0	3.0	***
20.0	***	***	***	15.0	79.0	81.0	43.0
45.0	***	***	***	***	5.0	15.0	50.0
80.0	***	***	***	***	***	1.0	7.0
100.0	***	***	***	***	***	***	***

Table C.6. DPM for SMFLR (Steel Moment Frame Low Rise)

Description	This prototype includes SMF structures of one to three stories in height. Extremely rare in BC and hard to identify without drawings, unless portions of the structure are exposed.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	30.0	10.0	2.0	***	***	***	***
0.5	65.0	30.0	5.0	2.0	***	***	***
5.0	5.0	60.0	91.0	89.0	20.0	1.0	***
20.0	***	***	2.0	9.0	79.0	85.0	40.0
45.0	***	***	***	***	1.0	14.0	57.0
80.0	***	***	***	***	***	***	3.0
100.0	***	***	***	***	***	***	***

Table C.7. DPM for SMFMR (Steel Moment Frame Medium Rise)

Description	This prototype includes SMF structures of four to seven stories in height. Extremely rare in BC and difficult to identify without drawings, unless portions of the structure are exposed.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	25.0	8.0	1.0	***	***	***	***
0.5	68.0	20.0	6.0	2.0	***	***	***
5.0	7.0	72.0	90.0	76.0	8.0	1.0	***
20.0	***	***	3.0	20.0	85.0	56.0	20.0
45.0	***	***	***	2.0	7.0	40.0	72.0
80.0	***	***	***	***	***	3.0	8.0
100.0	***	***	***	***	***	***	***

Table C.8. DPM for SMFHR (Steel Moment Frame High Rise)

Description	This prototype includes SMF structures over eight stories in height. Extremely rare in BC and difficult to identify without drawings, unless portions of the structure are exposed.					
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	20.0	5.0	***	***	***	***	***
0.5	73.0	13.0	12.0	***	***	***	***
5.0	7.0	80.0	79.0	32.0	1.0	***	***
20.0	***	2.0	9.0	60.0	84.0	36.0	12.0
45.0	***	***	***	8.0	15.0	60.0	80.0
80.0	***	***	***	***	***	4.0	8.0
100.0	***	***	***	***	***	***	***

Table C.9. DPM for SBFLR (Steel Braced Frame Low Rise)

Description	This prototype includes SBF C/I and industrial structures of one to three stories in height. It is hard to identify. About 33% of older industrial facilities and 5% of C/I buildings are SBFLR.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	20.0	8.0	***	***	***	***	***
0.5	70.0	45.0	5.0	***	***	***	***
5.0	10.0	47.0	81.0	60.0	6.0	1.0	***
20.0	***	***	14.0	35.0	85.0	60.0	31.0
45.0	***	***	***	5.0	6.0	34.0	60.0
80.0	***	***	***	***	3.0	5.0	7.0
100.0	***	***	***	***	***	***	2.0

Table C.10. DPM for SBFMR (Steel Braced Frame Medium Rise)

Description	This prototype includes SBF C/I and industrial structures of four to seven stories in height. It is very rare except some pulp and paper mills, and extremely difficult to identify.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	15.0	2.0	***	***	***	***	***
0.5	60.0	10.0	1.0	***	***	***	***
5.0	25.0	88.0	65.0	40.0	6.0	1.0	***
20.0	***	***	34.0	57.0	82.0	50.0	32.0
45.0	***	***	***	3.0	12.0	48.0	65.0
80.0	***	***	***	***	***	1.0	2.0
100.0	***	***	***	***	***	***	1.0

Table C.11. DPM for SBFHR (Steel Braced Frame High Rise)

Description	This prototype includes SBF structures above eight stories in height. It is very rare and extremely difficult to identify without drawings unless portions of the system are exposed.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	15.0	2.0	***	***	***	***	***
0.5	60.0	2.0	***	***	***	***	***
5.0	25.0	89.0	65.0	32.0	3.0	1.0	***
20.0	***	7.0	34.0	65.0	80.0	27.0	10.0
45.0	***	***	1.0	3.0	17.0	67.0	75.0
80.0	***	***	***	***	***	5.0	12.0
100.0	***	***	***	***	***	***	3.0

Table C.12. DPM for SFCWLR (Steel Frame with Concrete Walls Low Rise)

Description	This prototype includes one or two-storey SF buildings with concrete shear walls in one or both directions. It is very common in C/I buildings but may be hard to identify.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	20.0	3.0	1.0	***	***	***	***
0.5	67.0	15.0	5.0	2.0	***	***	***
5.0	12.0	80.0	84.0	30.0	15.0	1.0	***
20.0	***	***	10.0	66.0	70.0	40.0	15.0
45.0	***	***	***	2.0	13.0	55.0	70.0
80.0	***	***	***	***	2.0	4.0	15.0
100.0	***	***	***	***	***	***	***

Table C.13. DPM for SFCWMR (Steel Frame with Concrete Walls Medium Rise)

Description	This prototype includes three to seven-storey SF buildings with concrete shear walls. It makes up about 30% of the inventory of medium rise C/I buildings. It may be hard to identify.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	15.0	2.0	1.0	***	***	***	***
0.5	65.0	15.0	5.0	1.0	***	***	***
5.0	20.0	80.0	74.0	10.0	2.0	1.0	***
20.0	***	3.0	20.0	85.0	62.0	18.0	5.0
45.0	***	***	***	4.0	35.0	75.0	74.0
80.0	***	***	***	***	1.0	6.0	21.0
100.0	***	***	***	***	***	***	***

Table C.14. DPM for SFCWHR (Steel Frame with Concrete Walls High Rise)

Description	This prototype includes SF C/I buildings higher than 8 stories. About 15% of the pre-1985 office towers and <10% of the post-1985 towers are of this prototype, but hard to identify.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	20.0	3.0	1.0	***	***	***	***
0.5	67.0	15.0	5.0	2.0	***	***	***
5.0	12.0	80.0	84.0	30.0	15.0	1.0	***
20.0	***	***	10.0	66.0	70.0	40.0	15.0
45.0	***	***	***	2.0	13.0	55.0	70.0
80.0	***	***	***	***	2.0	4.0	15.0
100.0	***	***	***	***	***	***	***

Table C.15. DPM for SFCI (Steel Frame with Concrete Infill Walls)

Description	This prototype is a common form of construction for buildings constructed prior to the 1950's (offices and some light industrial buildings up to seven stories). It is very hard to identify.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	10.0	2.0	***	***	***	***	***
0.5	75.0	14.0	3.0	***	***	***	***
5.0	15.0	82.0	73.0	25.0	2.0	***	***
20.0	***	2.0	24.0	68.0	60.0	16.0	3.0
45.0	***	***	***	6.0	35.0	65.0	72.0
80.0	***	***	***	1.0	3.0	18.0	23.0
100.0	***	***	***	***	***	1.0	2.0

Table C.16. DPM for SFMI (Steel Frame with Masonry Infill Walls)

Description	This prototype is a common form of construction for buildings constructed prior to the 1950's (offices and some light industrial buildings up to seven stories). It is very hard to identify.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	6.0	1.0	***	***	***	***	***
0.5	40.0	3.0	***	***	***	***	***
5.0	53.0	80.0	37.0	3.0	***	***	***
20.0	1.0	15.0	55.0	39.0	25.0	3.0	1.0
45.0	***	1.0	8.0	52.0	55.0	43.0	40.0
80.0	***	***	***	6.0	20.0	50.0	45.0
100.0	***	***	***	***	***	4.0	15.0

Table C.17. DPM for CFLR (Concrete Frame with Concrete Walls Low Rise)

Description	This prototype includes one to three-storey CF structures with concrete shear walls. It is common in commercial and institutional buildings and is generally easy to identify.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	20.0	5.0	1.0	***	***	***	***
0.5	70.0	12.0	8.0	2.0	***	***	***
5.0	10.0	80.0	88.0	40.0	15.0	1.0	***
20.0	***	3.0	3.0	57.0	75.0	40.0	10.0
45.0	***	***	***	1.0	8.0	53.0	72.0
80.0	***	***	***	***	2.0	5.0	15.0
100.0	***	***	***	***	***	1.0	3.0

Table C.18. DPM for CFMR (Concrete Frame with Concrete Walls Medium Rise)

Description	This prototype includes CF structures from four to seven stories in height. It is very common for medium rise residential and C/I buildings, and is relatively easy to identify.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	15.0	2.0	***	***	***	***	***
0.5	75.0	40.0	2.0	***	***	***	***
5.0	10.0	55.0	78.0	33.0	8.0	1.0	***
20.0	***	3.0	20.0	60.0	72.0	29.0	5.0
45.0	***	***	***	7.0	20.0	65.0	75.0
80.0	***	***	***	***	***	5.0	18.0
100.0	***	***	***	***	***	***	2.0

Table C.19. DPM for CFHR (Concrete Frame with Concrete Walls High Rise)

Description	This prototype is very common (over 90% of the inventory of high rise structures - virtually every residential tower and majority of the recent commercial towers). It is easy to identify.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	12.0	2.0	***	***	***	***	***
0.5	73.0	30.0	2.0	***	***	***	***
5.0	15.0	65.0	57.0	15.0	1.0	1.0	***
20.0	***	3.0	40.0	66.0	61.0	28.0	5.0
45.0	***	***	1.0	18.0	35.0	55.0	67.0
80.0	***	***	***	1.0	3.0	16.0	25.0
100.0	***	***	***	***	***	***	3.0

Table C.20. DPM for RCMFLR (Reinforced Concrete Moment Frame Low Rise)

Description	This prototype includes one to three-storey RCMF structures, generally used for institutional facilities or office structures. It is very rare in BC and extremely hard to identify.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	5.0	1.0	***	***	***	***	***
0.5	40.0	5.0	1.0	***	***	***	***
5.0	55.0	89.0	45.0	10.0	1.0	***	***
20.0	***	5.0	51.0	80.0	34.0	10.0	1.0
45.0	***	***	3.0	10.0	60.0	73.0	74.0
80.0	***	***	***	***	5.0	15.0	20.0
100.0	***	***	***	***	***	2.0	5.0

Table C.21. DPM for RCMFMR (Reinforced Concrete Moment Frame Medium Rise)

Description	This prototype includes four to seven-storey RCMF structures, generally used for office structures. It is extremely rare in BC and is extremely hard to identify without drawings.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	5.0	1.0	***	***	***	***	***
0.5	40.0	5.0	1.0	***	***	***	***
5.0	55.0	87.0	43.0	5.0	1.0	***	***
20.0	***	7.0	55.0	83.0	23.0	5.0	1.0
45.0	***	***	1.0	12.0	70.0	65.0	58.0
80.0	***	***	***	***	6.0	25.0	35.0
100.0	***	***	***	***	***	5.0	6.0

Table C.22. DPM for RCMFHR (Reinforced Concrete Moment Frame High Rise)

Description	This prototype includes RCMF structures higher than eight-storey, generally used for office structures. It is extremely rare in BC and is extremely hard to identify without drawings.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	2.0	1.0	***	***	***	***	***
0.5	33.0	7.0	***	***	***	***	***
5.0	65.0	90.0	39.0	5.0	1.0	***	***
20.0	***	2.0	55.0	70.0	22.0	2.0	1.0
45.0	***	***	6.0	25.0	70.0	57.0	39.0
80.0	***	***	***	***	7.0	35.0	52.0
100.0	***	***	***	***	***	6.0	8.0

Table C.23. DPM for RCFIW (Reinforced Concrete Frame with Infill Walls)

Description	This prototype is common in buildings (offices and some light industrial buildings up to 7 stories) constructed prior to 1950's. Masonry infill walls are not considered as shear walls.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	6.0	1.0	***	***	***	***	***
0.5	40.0	5.0	***	***	***	***	***
5.0	54.0	76.0	38.0	5.0	2.0	***	***
20.0	***	17.0	57.0	56.0	38.0	5.0	1.0
45.0	***	1.0	5.0	35.0	46.0	48.0	42.0
80.0	***	***	***	4.0	14.0	45.0	43.0
100.0	***	***	***	***	***	2.0	14.0

Table C.24. DPM for RMLR (Reinforced Masonry Shear Wall Low Rise)

Description	This prototype is very common in post-1973 low-rise C/I and industrial buildings. Distinctive pattern of masonry makes it easy to identify.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	30.0	15.0	1.0	***	***	***	***
0.5	63.0	13.0	10.0	2.0	***	***	***
5.0	7.0	70.0	80.0	30.0	2.0	***	***
20.0	***	2.0	9.0	62.0	62.0	25.0	5.0
45.0	***	***	***	6.0	28.0	63.0	57.0
80.0	***	***	***	***	8.0	10.0	32.0
100.0	***	***	***	***	***	2.0	6.0

Table C.25. DPM for RMMR (Reinforced Masonry Shear Wall Medium Rise)

Description	This prototype constitutes an insignificant component of the southwestern BC inventory of buildings. They look very similar to concrete buildings with masonry/glazing cladding.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	15.0	3.0	***	***	***	***	***
0.5	75.0	22.0	***	***	***	***	***
5.0	10.0	70.0	80.0	2.0	***	***	***
20.0	***	5.0	20.0	70.0	60.0	10.0	1.0
45.0	***	***	***	28.0	25.0	75.0	38.0
80.0	***	***	***	***	15.0	15.0	55.0
100.0	***	***	***	***	***	***	6.0

Table C.26. DPM for URMLR (Unreinforced Masonry Bearing Wall Low Rise)

Description	This prototype was a very common form of low-rise construction until 1973 for C/I and industrial buildings. Easy to identify with extensive areas of red clay brick showing.					
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	10.0	***	***	***	***	***	***
0.5	55.0	3.0	***	***	***	***	***
5.0	30.0	65.0	21.0	5.0	1.0	***	***
20.0	5.0	30.0	60.0	47.0	20.0	6.0	2.0
45.0	***	2.0	15.0	40.0	48.0	35.0	8.0
80.0	***	***	2.0	4.0	25.0	51.0	70.0
100.0	***	***	2.0	4.0	6.0	8.0	20.0

Table C.27. DPM for URMMR (Unreinforced Masonry Bearing Wall Medium Rise)

Description	This prototype was used for commercial and light industrial buildings up to six stories in height, constructed principally prior to 1940. It is commonly seen in the older parts of cities.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	2.0	***	***	***	***	***	***
0.5	30.0	2.0	***	***	***	***	***
5.0	63.0	58.0	6.0	***	***	***	***
20.0	5.0	35.0	70.0	43.0	15.0	2.0	***
45.0	***	5.0	20.0	48.0	52.0	28.0	1.0
80.0	***	***	2.0	5.0	28.0	65.0	79.0
100.0	***	***	2.0	4.0	5.0	5.0	20.0

Table C.28. DPM for TU (Tilt Up)

Description	This prototype is commonly used for the construction of warehouses (seldom over 2 stories). RC panel walls are cast on site on top of the concrete slab and then tilted into position.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	30.0	10.0	***	***	***	***	***
0.5	60.0	35.0	12.0	2.0	***	***	***
5.0	10.0	50.0	58.0	12.0	2.0	***	***
20.0	***	5.0	30.0	82.0	48.0	10.0	1.0
45.0	***	***	***	4.0	45.0	70.0	43.0
80.0	***	***	***	***	5.0	15.0	50.0
100.0	***	***	***	***	***	5.0	6.0

Table C.29. DPM for PCLR (Precast Concrete Low Rise)

Description	This prototype was common during 1960's and 1970's for institutional buildings. It has been common for parking structures, but rare otherwise. Easily identified with exposed concrete.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	10.0	3.0	***	***	***	***	***
0.5	50.0	17.0	5.0	***	***	***	***
5.0	40.0	75.0	60.0	5.0	1.0	***	***
20.0	***	5.0	30.0	77.0	38.0	10.0	4.0
45.0	***	***	5.0	15.0	51.0	66.0	35.0
80.0	***	***	***	2.0	7.0	20.0	55.0
100.0	***	***	***	1.0	3.0	4.0	6.0

Table C.30. DPM for PCMR (Precast Concrete Medium Rise)

Description	This prototype is very rare in southwestern BC although it is common in the rest of Canada for commercial and institutional buildings.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	10.0	1.0	***	***	***	***	***
0.5	40.0	5.0	1.0	***	***	***	***
5.0	50.0	85.0	54.0	1.0	***	***	***
20.0	***	9.0	40.0	65.0	35.0	10.0	1.0
45.0	***	***	5.0	34.0	60.0	60.0	33.0
80.0	***	***	***	***	5.0	30.0	60.0
100.0	***	***	***	***	***	***	6.0

Table C.31. DPM for MH (Mobile Homes)

Description	This prototype includes single storey wood framed factory-manufactured buildings and school portables consisting of a number of factory-manufactured modules joined on site.						
CDF	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
0.0	25.0	10.0	***	***	***	***	***
0.5	55.0	10.0	5.0	***	***	***	***
5.0	30.0	70.0	40.0	25.0	***	***	***
20.0	***	10.0	53.0	65.0	60.0	10.0	1.0
45.0	***	***	2.0	10.0	35.0	83.0	65.0
80.0	***	***	***	***	5.0	7.0	34.0
100.0	***	***	***	***	***	***	***

Appendix D: Structural Modifier Tables

The modifier tables described in section 5.3.3.2 for each of the 31 building prototypes are presented below.

D - 1 Modifier Table for 1 WLFR

WLFR	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.1	0.4	0.7	0.4	0.4	0.1	0.1	0.0	-0.2
VII	0.4	2.1	2.6	2.1	2.1	0.4	0.4	0.0	-1.0
VIII	0.7	3.6	4.4	3.6	3.6	0.7	0.7	0.0	-1.7
IX	1.3	6.8	7.2	6.8	6.8	1.3	1.3	0.0	-3.3
X	2.8	14.5	15.2	14.5	14.5	2.8	2.8	0.0	-7.0
XI	3.3	17.0	17.9	17.0	17.0	3.3	3.3	0.0	-8.2
XII	4.1	21.5	22.6	21.5	21.5	4.1	4.1	0.0	-10.4

D - 2 Modifier Table for 2 WLFCI

WLFCI	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.1	0.4	0.7	0.4	0.4	0.1	0.1	0.2	-0.2
VII	0.6	2.3	3.3	2.3	2.3	0.6	0.6	1.2	-1.4
VIII	0.9	3.8	5.5	3.8	3.8	0.9	1.0	1.9	-2.3
IX	1.9	7.7	8.7	7.7	7.7	1.9	1.9	3.8	-4.6
X	3.6	14.5	16.4	14.5	14.5	3.6	3.6	7.1	-8.6
XI	4.8	19.6	22.1	19.6	19.6	4.8	4.8	9.6	-11.6
XII	5.7	23.4	26.5	23.4	23.4	5.7	5.7	11.5	-13.9

D - 3 Modifier Table for 3 WLFLR

WLFLR	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.1	0.3	0.6	0.3	0.3	0.1	0.1	0.2	-0.2
VII	0.4	1.6	2.3	1.6	1.6	0.4	0.4	0.8	-1.0
VIII	0.5	2.1	2.9	2.1	2.1	0.5	0.5	1.0	-1.2
IX	1.5	6.5	7.0	6.1	6.1	1.5	1.5	3.0	-3.7
X	2.5	10.6	11.3	10.0	10.0	2.5	2.5	4.9	-6.0
XI	3.7	15.7	16.9	14.9	14.9	3.7	3.7	7.3	-8.9
XII	4.9	20.9	22.4	19.8	19.8	4.9	4.9	9.7	-11.8

D - 4 Modifier Table for 4 WPB

WPB	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.1	0.5	0.8	0.5	0.5	0.1	0.1	0.2	-0.3
VII	0.6	2.7	3.8	2.7	2.7	0.6	0.6	1.3	-1.6
VIII	1.2	5.0	7.1	5.0	5.0	1.2	1.2	2.5	-3.0
IX	2.5	10.0	11.3	10.0	10.0	2.5	2.5	4.9	-6.0
X	4.1	16.7	19.0	16.7	16.7	4.1	4.1	8.2	-10.0
XI	5.1	20.7	23.5	20.7	20.7	5.1	5.1	10.2	-12.3
XII	6.0	24.3	27.5	24.3	24.3	6.0	6.0	11.9	-14.5

D - 5 Modifier Table for 5 LMF

LMF	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.1	0.0	0.3	0.0	0.0	0.1	0.1	0.1	0.0
VII	0.4	0.0	1.6	0.0	0.0	0.4	0.4	0.4	0.0
VIII	0.5	0.0	2.5	0.0	0.0	0.5	0.5	0.7	0.0
IX	1.1	0.0	4.2	0.0	0.0	1.1	1.1	1.3	0.0
X	3.0	0.0	11.3	0.0	0.0	3.0	3.0	3.6	0.0
XI	3.8	0.0	14.3	0.0	0.0	3.8	3.8	4.5	0.0
XII	5.9	0.0	22.0	0.0	0.0	5.9	5.9	7.0	0.0

D - 6 Modifier Table for 6 SMFLR

SMFLR	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.1	0.1	0.4	0.1	0.1	0.1	0.1	0.1	-0.1
VII	0.4	0.9	1.9	0.9	0.9	0.4	0.4	0.9	-0.6
VIII	0.7	1.4	3.0	1.4	1.4	0.7	0.7	1.4	-1.0
IX	1.1	2.3	3.8	2.3	2.3	1.1	1.1	2.3	-1.6
X	3.1	6.2	10.4	6.2	6.2	3.1	3.1	6.2	-4.3
XI	4.2	8.4	14.0	8.4	8.4	4.2	4.2	8.4	-5.9
XII	6.5	13.0	21.7	13.0	13.0	6.5	6.5	13.0	-9.0

D - 7 Modifier Table for 7 SMFMR

SMFMR	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.1	0.2	0.4	0.2	0.2	0.1	0.1	0.2	-0.1
VII	0.5	1.0	2.2	1.0	1.0	0.5	0.5	1.0	-0.7
VIII	0.7	1.4	3.1	1.4	1.4	0.7	0.7	1.4	-1.0
IX	1.6	3.1	5.2	3.1	3.1	1.6	1.6	3.1	-2.2
X	3.7	7.4	12.4	7.4	7.4	3.7	3.7	7.4	-5.2
XI	5.7	11.4	19.0	11.4	11.4	5.7	5.7	11.4	-7.9
XII	7.7	15.4	25.7	15.4	15.4	7.7	7.7	15.4	-10.7

D - 8 Modifier Table for 8 SMFHR

SMFHR	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.1	0.2	0.4	0.2	0.2	0.1	0.1	0.2	-0.1
VII	0.6	1.3	2.7	1.3	1.3	0.6	0.6	1.3	-0.9
VIII	0.8	1.6	3.5	1.6	1.6	0.8	0.8	1.6	-1.1
IX	3.1	6.2	10.3	6.2	6.2	3.1	3.1	6.2	-4.3
X	4.2	8.5	14.2	8.5	8.5	4.2	4.2	8.5	-5.9
XI	6.7	13.5	22.4	13.5	13.5	6.7	6.7	13.5	-9.4
XII	8.1	16.1	26.9	16.1	16.1	8.1	8.1	16.1	-11.2

D - 9 Modifier Table for 9 SBFLR

SBFLR	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.1	0.3	0.5	0.3	0.3	0.1	0.1	0.2	-0.1
VII	0.4	1.1	1.6	1.1	1.1	0.4	0.4	0.6	-0.5
VIII	1.0	2.9	4.1	2.9	2.9	1.0	1.0	1.5	-1.3
IX	2.1	6.2	7.4	6.2	6.2	2.1	2.1	3.3	-2.9
X	3.8	11.2	13.4	11.2	11.2	3.8	3.8	6.0	-5.3
XI	5.3	15.7	18.8	15.7	15.7	5.3	5.3	8.5	-7.4
XII	6.9	20.4	24.5	20.4	20.4	6.9	6.9	11.0	-9.6

D - 10 Modifier Table for 10 SBFMR

SBFMR	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.2	0.5	1.0	0.5	0.5	0.2	0.2	0.3	-0.2
VII	0.6	1.9	2.7	1.9	1.9	0.6	0.6	1.0	-0.9
VIII	1.4	4.2	6.1	4.2	4.2	1.4	1.4	2.2	-2.0
IX	2.5	7.4	8.9	7.4	7.4	2.5	2.5	4.0	-3.5
X	3.8	11.1	13.3	11.1	11.1	3.8	3.8	6.0	-5.2
XI	5.5	16.3	19.5	16.3	16.3	5.5	5.5	8.8	-7.6
XII	6.5	19.2	23.0	19.2	19.2	6.5	6.5	10.3	-9.0

D - 11 Modifier Table for 11 SBFHR

SBFHR	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.2	0.5	1.0	0.5	0.5	0.2	0.2	0.3	-0.2
VII	0.8	2.5	3.5	2.5	2.5	0.8	0.8	1.3	-1.2
VIII	1.5	4.4	6.3	4.4	4.4	1.5	1.5	2.3	-2.0
IX	2.7	8.0	9.6	8.0	8.0	2.7	2.7	4.3	-3.8
X	4.0	11.9	14.3	11.9	11.9	4.0	4.0	6.4	-5.6
XI	6.7	19.8	23.8	19.8	19.8	6.7	6.7	10.7	-9.3
XII	8.2	24.2	29.0	24.2	24.2	8.2	8.2	13.1	-11.4

D - 12 Modifier Table for 12 SFCWLR

SFCWLR	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.1	0.3	0.5	0.3	0.3	0.1	0.1	0.2	-0.2
VII	0.6	1.3	2.7	1.3	1.3	0.6	0.6	1.0	-1.0
VIII	0.9	1.7	3.7	1.7	1.7	0.9	0.9	1.4	-1.4
IX	2.8	5.6	9.4	5.6	5.6	2.8	2.8	4.5	-4.4
X	4.0	8.0	13.3	8.0	8.0	4.0	4.0	6.4	-6.3
XI	6.5	13.0	21.6	13.0	13.0	6.5	6.5	10.4	-10.3
XII	8.4	16.7	27.9	16.7	16.7	8.4	8.4	13.5	-13.3

D - 13 Modifier Table for 13 SFCWMR

SFCWMR	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.1	0.3	0.8	0.3	0.3	0.1	0.1	0.1	-0.2
VII	0.7	1.3	2.8	1.3	1.3	0.7	0.7	1.0	-1.0
VIII	1.1	2.2	4.6	2.2	2.2	1.1	1.1	1.7	-1.7
IX	3.5	6.9	11.6	6.9	6.9	3.5	3.5	5.6	-5.5
X	5.2	10.5	17.5	10.5	10.5	5.2	5.2	8.4	-8.3
XI	7.6	15.2	25.3	15.2	15.2	7.6	7.6	12.2	-12.0
XII	9.2	18.4	30.7	18.4	18.4	9.2	9.2	14.8	-14.6

D - 14 Modifier Table for 14 SFCWHR

SFCWHR	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.1	0.3	0.8	0.3	0.3	0.1	0.1	0.2	-0.2
VII	0.7	1.3	2.8	1.3	1.3	0.7	0.7	1.0	-1.0
VIII	1.3	2.6	5.6	2.6	2.6	1.3	1.3	2.0	-2.0
IX	4.1	8.2	13.7	8.2	8.2	4.1	4.1	6.6	-6.5
X	5.9	11.8	19.7	11.8	11.8	5.9	5.9	9.5	-9.3
XI	8.9	17.7	29.6	17.7	17.7	8.9	8.9	14.3	-14.1
XII	10.3	20.5	34.2	20.5	20.5	10.3	10.3	16.5	-16.2

D - 15 Modifier Table for 15 SFCI

SFCI	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.1	0.2	0.5	0.2	0.2	0.1	0.1	0.0	0.0
VII	0.5	1.0	2.2	1.0	1.0	0.5	0.5	0.2	0.0
VIII	1.1	2.2	4.7	2.2	2.2	1.1	1.1	0.5	0.0
IX	4.2	8.4	10.1	8.4	8.4	4.2	4.2	1.7	0.0
X	6.0	11.9	14.3	11.9	11.9	6.0	6.0	2.4	0.0
XI	9.8	19.6	23.5	19.6	19.6	9.8	9.8	3.9	0.0
XII	12.8	25.6	30.7	25.6	25.6	12.8	12.8	5.1	0.0

D - 16 Modifier Table for 16 SMFI

SFMI	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.3	0.6	1.9	0.6	0.6	0.3	0.3	0.1	0.0
VII	1.1	2.1	4.5	2.1	2.1	1.1	1.1	0.5	0.0
VIII	2.3	4.6	9.9	4.6	4.6	2.3	2.3	1.0	0.0
IX	9.1	18.1	21.7	18.1	18.1	9.1	9.1	3.6	0.0
X	11.5	22.9	27.5	22.9	22.9	11.5	11.5	4.6	0.0
XI	16.0	32.0	38.4	32.0	32.0	16.0	16.0	6.4	0.0
XII	17.3	34.6	41.5	34.6	34.6	17.3	17.3	6.9	0.0

D - 17 Modifier Table for 17 CFCWLR

CFCWLR	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.1	0.2	0.5	0.2	0.2	0.1	0.1	0.2	-0.2
VII	0.7	1.3	2.8	1.3	1.3	0.7	0.7	1.3	-1.6
VIII	0.7	1.4	3.0	1.4	1.4	0.7	0.7	1.4	-1.7
IX	2.5	5.0	8.3	5.0	5.0	2.5	2.5	5.0	-6.0
X	3.8	7.6	12.6	7.6	7.6	3.8	3.8	7.6	-9.0
XI	6.6	13.3	22.1	13.3	13.3	6.6	6.6	13.3	-15.9
XII	8.9	17.8	29.6	17.8	17.8	8.9	8.9	17.8	-21.2

D - 18 Modifier Table for 18 CFCWMR

CFCWMR	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.1	0.2	0.5	0.2	0.2	0.1	0.1	0.2	-0.2
VII	0.5	1.0	2.2	1.0	1.0	0.5	0.5	1.0	-1.2
VIII	1.1	2.2	4.7	2.2	2.2	1.1	1.1	2.2	-2.6
IX	3.0	6.0	10.1	6.0	6.0	3.0	3.0	6.0	-7.2
X	4.3	8.6	14.3	8.6	8.6	4.3	4.3	8.6	-10.2
XI	7.0	14.1	23.5	14.1	14.1	7.0	7.0	14.1	-16.8
XII	9.2	18.4	30.7	18.4	18.4	9.2	9.2	18.4	-22.0

D - 19 Modifier Table for 19 CFCWHR

CFCWHR	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.1	0.2	0.7	0.2	0.2	0.1	0.1	0.2	-0.3
VII	0.6	1.1	2.4	1.1	1.1	0.6	0.6	1.1	-1.3
VIII	1.6	3.2	6.8	3.2	3.2	1.6	1.6	3.2	-3.8
IX	4.1	8.2	13.7	8.2	8.2	4.1	4.1	8.2	-9.8
X	5.5	10.9	18.2	10.9	10.9	5.5	5.5	10.9	-13.1
XI	7.8	15.6	25.9	15.6	15.6	7.8	7.8	15.6	-18.6
XII	9.8	19.5	32.5	19.5	19.5	9.8	9.8	19.5	-23.3

D - 20 Modifier Table for 20 CMFLR

CMFLR	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.3	1.0	1.8	1.0	1.0	0.3	0.3	0.8	-0.5
VII	0.9	2.8	3.3	2.8	2.8	0.9	0.9	2.2	-1.3
VIII	2.3	6.9	8.3	6.9	6.9	2.3	2.3	5.5	-3.2
IX	4.2	12.6	12.6	12.6	12.6	4.2	4.2	10.1	-5.9
X	7.6	22.7	22.7	22.7	22.7	7.6	7.6	18.2	-10.6
XI	10.0	29.9	29.9	29.9	29.9	10.0	10.0	24.0	-14.0
XII	10.9	32.7	32.7	32.7	32.7	10.9	10.9	26.2	-15.3

D - 21 Modifier Table for 21 CMFMR

CMFMR	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.3	1.0	1.8	1.0	1.0	0.3	0.3	0.8	-0.5
VII	1.0	2.9	3.5	2.9	2.9	1.0	1.0	2.3	-1.4
VIII	2.3	6.8	8.2	6.8	6.8	2.3	2.3	5.4	-3.2
IX	4.5	13.4	13.4	13.4	13.4	4.5	4.5	10.7	-6.2
X	8.2	24.6	24.6	24.6	24.6	8.2	8.2	19.7	-11.5
XI	11.1	33.2	33.2	33.2	33.2	11.1	11.1	26.5	-15.5
XII	12.1	36.2	36.2	36.2	36.2	12.1	12.1	28.9	-16.9

D - 22 Modifier Table for 22 CMFHR

CMFHR	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.4	1.2	2.0	1.2	1.2	0.4	0.4	0.9	-0.5
VII	0.8	2.5	2.9	2.5	2.5	0.8	0.8	2.0	-1.2
VIII	2.7	7.9	9.4	7.9	7.9	2.7	2.7	6.3	-3.7
IX	5.1	15.3	15.3	15.3	15.3	5.1	5.1	12.2	-7.1
X	8.3	25.0	25.0	25.0	25.0	8.3	8.3	20.0	-11.6
XI	12.0	36.1	36.1	36.1	36.1	12.0	12.0	28.8	-16.8
XII	13.5	40.4	40.4	40.4	40.4	13.5	13.5	32.4	-18.9

D - 23 Modifier Table for 23 CFIW

CFIW	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.3	0.7	1.7	0.7	0.7	0.3	0.3	0.1	0.0
VII	1.2	2.4	4.6	2.4	2.4	1.2	1.2	0.5	0.0
VIII	2.5	4.8	9.4	4.8	4.8	2.5	2.5	0.9	0.0
IX	9.4	19.2	18.2	19.2	19.2	9.4	9.4	4.0	0.0
X	12.3	24.9	23.8	24.9	24.9	12.3	12.3	5.1	0.0
XI	18.8	38.2	36.4	38.2	38.2	18.8	18.8	7.9	0.0
XII	20.9	42.5	40.5	42.5	42.5	20.9	20.9	8.8	0.0

D - 24 Modifier Table for 24 RMLR

RMLR	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.1	0.1	0.4	0.1	0.1	0.1	0.1	0.1	-0.2
VII	0.6	1.1	2.4	1.1	1.1	0.6	0.6	1.1	-1.6
VIII	0.8	1.7	3.5	1.7	1.7	0.8	0.8	1.7	-2.3
IX	3.0	6.0	10.0	6.0	6.0	3.0	3.0	6.0	-8.3
X	5.7	11.3	18.9	11.3	11.3	5.7	5.7	11.3	-15.8
XI	7.8	15.6	26.0	15.6	15.6	7.8	7.8	15.6	-21.7
XII	10.5	21.0	35.0	21.0	21.0	10.5	10.5	21.0	-29.2

D - 25 Modifier Table for 25 RMMR

RMMR	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.1	0.2	0.5	0.2	0.2	0.1	0.1	0.2	-0.3
VII	0.6	1.3	2.8	1.3	1.3	0.6	0.6	1.3	-1.8
VIII	1.1	2.2	4.8	2.2	2.2	1.1	1.1	2.2	-3.1
IX	4.8	9.6	16.0	9.6	9.6	4.8	4.8	9.6	-13.4
X	6.4	12.7	21.2	12.7	12.7	6.4	6.4	12.7	-17.7
XI	8.6	17.2	28.7	17.2	17.2	8.6	8.6	17.2	-23.9
XII	12.1	24.2	40.4	24.2	24.2	12.1	12.1	24.2	-33.7

D - 26 Modifier Table for 26 URMLR

URM LR	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.3	0.6	1.7	0.6	0.6	0.3	0.3	0.1	0.0
VII	1.5	3.0	6.1	3.0	3.0	1.5	1.5	0.6	0.0
VIII	3.5	6.8	14.0	6.8	6.8	3.5	3.5	1.4	0.0
IX	9.8	19.5	20.9	19.5	19.5	9.8	9.8	3.8	0.0
X	14.5	29.0	31.0	29.0	29.0	14.5	14.5	5.7	0.0
XI	18.4	36.8	39.5	36.8	36.8	18.4	18.4	7.2	0.0
XII	22.4	44.8	48.0	44.8	44.8	22.4	22.4	8.8	0.0

D - 27 Modifier Table for 27 URMMR

URMM R	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.5	0.9	2.6	0.9	0.9	0.5	0.5	0.2	0.0
VII	1.8	3.5	7.3	3.5	3.5	1.8	1.8	0.7	0.0
VIII	4.0	7.8	16.1	7.8	7.8	4.0	4.0	1.6	0.0
IX	10.7	21.4	22.9	21.4	21.4	10.7	10.7	4.2	0.0
X	15.1	30.1	32.3	30.1	30.1	15.1	15.1	5.9	0.0
XI	19.6	39.2	42.0	39.2	39.2	19.6	19.6	7.7	0.0
XII	23.4	46.9	50.2	46.9	46.9	23.4	23.4	9.2	0.0

D - 28 Modifier Table for 28 TU

TU	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.1	0.0	0.5	0.0	0.0	0.1	0.1	0.1	-0.2
VII	0.6	0.0	2.2	0.0	0.0	0.6	0.6	0.9	-1.4
VIII	1.4	0.0	5.4	0.0	0.0	1.4	1.4	2.3	-3.4
IX	3.6	0.0	11.3	0.0	0.0	3.6	3.6	5.8	-8.6
X	6.5	0.0	20.4	0.0	0.0	6.5	6.5	10.5	-15.6
XI	9.6	0.0	30.3	0.0	0.0	9.6	9.6	15.7	-23.2
XII	12.5	0.0	39.4	0.0	0.0	12.5	12.5	20.3	-30.2

D - 29 Modifier Table for 29 PCLR

PCLR	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.3	0.5	1.4	0.5	0.5	0.3	0.3	0.4	0.0
VII	0.8	1.5	2.9	1.5	1.5	0.8	0.8	1.2	0.0
VIII	1.8	3.5	6.8	3.5	3.5	1.8	1.8	2.8	0.0
IX	5.3	10.5	15.0	10.5	10.5	5.3	5.3	8.3	0.0
X	8.2	16.5	23.5	16.5	16.5	8.2	8.2	12.9	0.0
XI	10.9	21.7	31.0	21.7	21.7	10.9	10.9	17.1	0.0
XII	14.0	28.0	40.0	28.0	28.0	14.0	14.0	22.0	0.0

D - 30 Modifier Table for 30 PCMR

PCMR	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.3	0.6	1.6	0.6	0.6	0.3	0.3	0.5	0.0
VII	1.0	1.9	3.7	1.9	1.9	1.0	1.0	1.5	0.0
VIII	2.1	4.0	7.8	4.0	4.0	2.1	2.1	3.3	0.0
IX	6.0	11.9	17.0	11.9	11.9	6.0	6.0	9.4	0.0
X	8.0	16.0	22.8	16.0	16.0	8.0	8.0	12.5	0.0
XI	11.1	22.3	31.8	22.3	22.3	11.1	11.1	17.5	0.0
XII	14.5	29.0	41.4	29.0	29.0	14.5	14.5	22.8	0.0

D - 31 Modifier Table for 31 MH

MH	Modifiers								
II	Plan Irregularity	Vertical Irregularity	State of Repair	Pounding	Soft Storey	Openings	Short Columns	Precode	Post Benchmark
VI	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VII	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
VIII	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IX	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
X	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
XI	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
XII	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Appendix E. Nonstructural DPMs

For the estimation of non-structural damage in BC, damage matrices were developed in terms of MMI (Cook, 1999). These non-structural damage matrices are given for each of the 31 building prototypes of southwestern BC. In these tables, CDF is the Central Damage Factor as defined in Chapter 5. It can be noted that the damage probabilities of the building contents are the same as those of acceleration-sensitive components. The only difference between the two is their central damage factors.

Table E.1. Non-Structural Damage Probability Matrices for WLFR

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	66.0	54.2	51.0	41.2	32.7	28.1	24.2
2.0	10.0	11.6	11.9	12.3	12.3	11.5	11.0
10.0	12.7	16.0	16.8	18.6	18.6	19.5	19.3
50.0	1.8	3.5	4.0	5.8	5.8	8.7	9.6
80.0	9.5	14.7	16.3	22.1	28.3	32.1	36.0
Acceleration-sensitive components							
0.0	73.0	47.9	35.2	23.9	14.0	9.9	7.9
2.0	22.4	35.3	37.8	36.3	30.4	25.9	23.1
10.0	4.4	14.6	22.2	30.1	37.0	38.9	39.2
50.0	0.3	2.1	4.7	9.0	16.4	21.5	24.7
80.0	0.0	0.1	0.2	0.7	2.2	3.8	5.0
Building Contents							
0.0	73.0	47.9	35.2	23.9	14.0	9.9	7.9
1.0	22.4	35.3	37.8	36.3	30.4	25.9	23.1
5.0	4.4	14.6	22.2	30.1	37.0	38.9	39.2
25.0	0.3	2.1	4.7	9.0	16.4	21.5	24.7
40.0	0.0	0.1	0.2	0.7	2.2	3.8	5.0

Table E.2. Non-Structural Damage Probability Matrices for WLFCI

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	70.6	55.2	53.2	45.3	38.8	34.7	30.7
2.0	8.0	10.4	10.6	11.3	11.5	11.5	11.3
10.0	10.5	14.5	14.9	16.4	17.3	17.6	17.8
50.0	6.2	9.2	9.5	10.8	11.5	11.9	12.1
80.0	4.7	10.7	11.7	16.3	20.9	24.4	28.1
Acceleration-sensitive components							
0.0	77.4	50.0	47.7	31.8	24.5	20.3	18.5
2.0	19.0	35.0	35.8	39.2	38.6	37.3	36.5
10.0	3.4	13.0	14.1	23.1	28.1	31.1	32.4
50.0	0.3	2.0	2.2	5.4	8.0	10.1	11.1
80.0	0.0	0.1	0.1	0.5	0.9	1.3	1.5
Building Contents							
0.0	77.4	50.0	47.7	31.8	24.5	20.3	18.5
1.0	19.0	35.0	35.8	39.2	38.6	37.3	36.5
5.0	3.4	13.0	14.1	23.1	28.1	31.1	32.4
25.0	0.3	2.0	2.2	5.4	8.0	10.1	11.1
40.0	0.0	0.1	0.1	0.5	0.9	1.3	1.5

Table E.3. Non-Structural Damage Probability Matrices for WLFLR

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	66.0	54.2	51.0	41.2	32.7	28.1	24.2
2.0	10.0	11.6	11.9	12.3	12.0	11.5	11.0
10.0	12.7	16.0	16.8	18.6	16.5	19.5	19.3
50.0	1.8	3.5	4.0	5.8	7.6	8.7	9.6
80.0	9.5	14.7	16.3	22.1	28.3	32.1	36.0
Acceleration-sensitive components							
0.0	73.0	50.0	38.4	23.9	14.0	9.9	7.9
2.0	22.4	34.6	37.5	36.3	30.4	25.9	23.1
10.0	4.4	13.5	20.1	30.1	37.0	38.9	39.2
50.0	0.3	1.9	3.8	9.0	16.4	21.5	24.7
80.0	0.0	0.1	0.2	0.7	2.2	3.8	5.0
Building Contents							
0.0	73.0	50.0	38.4	23.9	14.0	9.9	7.9
1.0	22.4	34.6	37.5	36.3	30.4	25.9	23.1
5.0	4.4	13.5	20.1	30.1	37.0	38.9	39.2
25.0	0.3	1.9	3.8	9.0	16.4	21.5	24.7
40.0	0.0	0.1	0.2	0.7	2.2	3.8	5.0

Table E.4. Non-Structural Damage Probability Matrices for WPB

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	66.0	54.2	51.0	41.2	32.7	28.1	24.2
2.0	10.0	11.6	11.9	12.3	12.0	11.5	11.0
10.0	12.7	16.0	16.8	18.6	19.5	19.5	19.3
50.0	1.8	3.5	4.0	5.8	7.6	8.7	9.6
80.0	9.5	14.7	16.3	22.1	28.3	32.1	36.0
Acceleration-sensitive components							
0.0	73.0	47.9	35.2	23.9	14.0	9.9	7.9
2.0	22.4	35.3	37.8	36.3	30.4	25.9	23.1
10.0	4.4	14.6	22.2	30.1	37.0	38.9	39.2
50.0	0.3	2.1	4.7	9.0	16.4	21.5	24.7
80.0	0.0	0.1	0.2	0.7	2.2	3.8	5.0
Building Contents							
0.0	73.0	47.9	35.2	23.9	14.0	9.9	7.9
1.0	22.4	35.3	37.8	36.3	30.4	25.9	23.1
5.0	4.4	14.6	22.2	30.1	37.0	38.9	39.2
25.0	0.3	2.1	4.7	9.0	16.4	21.5	24.7
40.0	0.0	0.1	0.2	0.7	2.2	3.8	5.0

Table E.5. Non-Structural Damage Probability Matrices for LMF

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	65.1	49.7	48.5	36.5	30.4	25.9	22.9
2.0	9.0	11.0	11.1	11.5	11.4	11.0	10.6
10.0	11.7	15.4	15.6	17.4	17.8	17.9	17.7
50.0	6.7	9.3	9.4	10.9	11.3	11.4	11.4
80.0	7.5	14.7	15.4	23.7	29.1	33.7	37.3
Acceleration-sensitive components							
0.0	80.7	55.0	52.4	35.6	29.3	27.9	25.3
2.0	16.7	33.1	34.3	39.4	39.8	39.7	39.3
10.0	2.6	10.8	11.9	21.0	25.1	26.1	28.0
50.0	0.1	1.1	1.4	3.7	5.4	5.8	6.8
80.0	0.0	0.0	0.1	0.2	0.4	0.5	0.6
Building Contents							
0.0	80.7	55.0	52.4	35.6	29.3	27.9	25.3
1.0	16.7	33.1	34.3	39.4	39.8	39.7	39.3
5.0	2.6	10.8	11.9	21.0	25.1	26.1	28.0
25.0	0.1	1.1	1.4	3.7	5.4	5.8	6.8
40.0	0.0	0.0	0.1	0.2	0.4	0.5	0.6

Table E.6. Non-Structural Damage Probability Matrices for SMFLR

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	68.1	48.2	46.7	40.2	33.6	29.7	25.3
2.0	10.9	13.0	13.1	13.0	12.5	12.1	11.3
10.0	13.1	19.5	19.8	21.1	21.8	21.9	21.6
50.0	2.4	5.7	6.0	7.5	9.0	9.9	11.0
80.0	5.5	13.5	14.3	18.2	23.1	26.4	30.7
Acceleration-sensitive components							
0.0	89.0	63.0	57.6	47.7	41.2	35.6	32.3
2.0	9.9	28.7	31.8	36.2	38.3	39.4	39.7
10.0	1.0	7.4	9.5	13.9	17.2	20.5	22.6
50.0	0.0	0.8	1.1	2.1	3.0	4.1	5.0
80.0	0.0	0.0	0.0	0.1	0.2	0.3	0.4
Building Contents							
0.0	89.0	63.0	57.6	47.7	41.2	35.6	32.3
1.0	9.9	28.7	31.8	36.2	38.3	39.4	39.7
5.0	1.0	7.4	9.5	13.9	17.2	20.5	22.6
25.0	0.0	0.8	1.1	2.1	3.0	4.1	5.0
40.0	0.0	0.0	0.0	0.1	0.2	0.3	0.4

Table E.7. Non-Structural Damage Probability Matrices for SMFMR

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	73.2	49.9	48.8	45.9	37.8	33.9	19.4
2.0	10.0	14.4	14.5	14.7	15.0	14.9	12.9
10.0	8.2	15.8	16.2	17.1	19.4	20.4	22.8
50.0	2.0	5.0	5.2	5.7	7.0	7.7	10.5
80.0	6.6	14.8	15.3	16.6	20.8	23.1	34.4
Acceleration-sensitive components							
0.0	98.5	86.7	89.3	81.0	72.1	55.0	52.5
2.0	1.5	11.6	9.5	16.1	22.6	32.7	33.9
10.0	0.1	1.6	1.1	2.7	5.0	10.9	12.0
50.0	0.0	0.1	0.0	0.2	0.4	1.4	1.6
80.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Building Contents							
0.0	98.5	86.7	89.3	81.0	72.1	55.0	52.5
1.0	1.5	11.6	9.5	16.1	22.6	32.7	33.9
5.0	0.1	1.6	1.1	2.7	5.0	10.9	12.0
25.0	0.0	0.1	0.0	0.2	0.4	1.4	1.6
40.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1

Table E.8. Non-Structural Damage Probability Matrices for SMFHR

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	73.9	72.4	69.3	50.8	41.2	33.2	27.0
2.0	9.8	10.2	11.0	14.3	15.0	14.9	14.3
10.0	8.2	8.7	9.8	15.8	18.7	20.8	22.0
50.0	1.7	1.9	2.2	4.6	6.2	7.6	8.9
80.0	6.4	6.8	7.7	14.4	18.9	23.5	27.8
Acceleration-sensitive components							
0.0	99.9	99.3	98.5	97.3	89.3	86.7	83.9
2.0	0.1	0.7	1.4	2.5	9.4	11.5	13.7
10.0	0.0	0.0	0.1	0.2	1.2	1.7	2.2
50.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
80.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Building Contents							
0.0	99.9	99.3	98.5	97.3	89.3	86.7	83.9
1.0	0.1	0.7	1.4	2.5	9.4	11.5	13.7
5.0	0.0	0.0	0.1	0.2	1.2	1.7	2.2
25.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
40.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table E.9. Non-Structural Damage Probability Matrices for SBFLR

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	72.0	56.3	53.3	43.6	37.6	32.7	29.3
2.0	7.5	10.2	10.6	11.4	11.6	11.6	11.5
10.0	11.1	15.2	15.9	17.5	18.0	18.2	18.2
50.0	4.6	7.5	8.1	9.6	10.5	11.0	11.3
80.0	4.7	10.7	12.2	17.9	22.2	26.4	29.7
Acceleration-sensitive components							
0.0	81.0	50.0	45.4	35.4	29.0	27.6	25.0
2.0	16.3	35.3	37.1	39.6	40.0	40.0	39.6
10.0	2.5	12.6	14.8	20.3	24.3	25.2	27.0
50.0	0.2	2.0	2.5	4.3	6.1	6.5	7.5
80.0	0.0	0.1	0.2	0.4	0.6	0.7	0.8
Building Contents							
0.0	81.0	50.0	45.4	35.4	29.0	27.6	25.0
1.0	16.3	35.3	37.1	39.6	40.0	40.0	39.6
5.0	2.5	12.6	14.8	20.3	24.3	25.2	27.0
25.0	0.2	2.0	2.5	4.3	6.1	6.5	7.5
40.0	0.0	0.1	0.2	0.4	0.6	0.7	0.8

Table E.10. Non-Structural Damage Probability Matrices for SBFMR

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	73.3	56.7	53.7	52.0	45.8	39.4	34.7
2.0	10.6	13.8	14.1	14.2	14.6	14.6	14.3
10.0	7.9	13.6	14.6	15.2	17.2	19.1	20.4
50.0	1.7	3.8	4.2	4.5	5.5	6.6	7.4
80.0	6.5	12.2	13.4	14.1	17.0	20.4	23.2
Acceleration-sensitive components							
0.0	95.8	86.7	72.1	63.2	52.5	47.6	43.2
2.0	4.0	11.9	23.1	28.8	34.6	36.6	38.2
10.0	0.2	1.4	4.5	7.3	11.5	13.8	16.1
50.0	0.0	0.1	0.3	0.6	1.4	1.8	2.4
80.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
Building Contents							
0.0	95.8	86.7	72.1	63.2	52.5	47.6	43.2
1.0	4.0	11.9	23.1	28.8	34.6	36.6	38.2
5.0	0.2	1.4	4.5	7.3	11.5	13.8	16.1
25.0	0.0	0.1	0.3	0.6	1.4	1.8	2.4
40.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1

Table E.11. Non-Structural Damage Probability Matrices for SBFHR

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	77.3	63.7	60.5	55.2	44.5	37.6	31.9
2.0	9.4	12.7	13.3	14.1	14.9	14.9	14.5
10.0	7.5	12.4	13.5	15.4	18.8	20.7	22.0
50.0	0.6	1.9	2.3	3.1	4.8	6.1	7.3
80.0	5.1	9.2	10.3	12.4	17.1	20.7	24.3
Acceleration-sensitive components							
0.0	99.9	92.1	89.7	87.1	75.4	66.4	57.8
2.0	0.1	7.3	9.3	11.5	20.6	26.8	31.9
10.0	0.0	0.6	1.0	1.4	3.7	6.3	9.3
50.0	0.0	0.0	0.0	0.1	0.2	0.5	1.0
80.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Building Contents							
0.0	99.9	92.1	89.7	87.1	75.4	66.4	57.8
1.0	0.1	7.3	9.3	11.5	20.6	26.8	31.9
5.0	0.0	0.6	1.0	1.4	3.7	6.3	9.3
25.0	0.0	0.0	0.0	0.1	0.2	0.5	1.0
40.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table E.12. Non-Structural Damage Probability Matrices for SFCWLR

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	70.6	51.8	51.4	44.0	37.8	33.4	30.5
2.0	7.3	10.1	10.1	10.7	10.9	10.8	10.7
10.0	12.0	16.2	16.3	17.2	17.5	17.5	17.3
50.0	4.6	8.0	8.0	9.2	10.1	10.6	10.8
80.0	5.4	13.9	14.1	18.9	23.7	27.7	30.7
Acceleration-sensitive components							
0.0	67.7	55.5	47.4	30.8	27.7	24.9	24.9
2.0	27.2	35.1	39.3	44.2	44.4	44.2	44.2
10.0	4.7	8.5	11.8	20.7	22.8	24.9	24.9
50.0	0.4	0.9	1.5	3.9	4.7	5.6	5.6
80.0	0.0	0.0	0.1	0.3	0.4	0.5	0.5
Building Contents							
0.0	67.7	55.5	47.4	30.8	27.7	24.9	24.9
1.0	27.2	35.1	39.3	44.2	44.4	44.2	44.2
5.0	4.7	8.5	11.8	20.7	22.8	24.9	24.9
25.0	0.4	0.9	1.5	3.9	4.7	5.6	5.6
40.0	0.0	0.0	0.1	0.3	0.4	0.5	0.5

Table E.13. Non-Structural Damage Probability Matrices for SFCWMR

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	80.1	57.4	56.4	55.0	48.9	41.1	35.4
2.0	7.5	12.5	12.6	12.8	13.4	13.9	13.8
10.0	5.0	12.0	12.3	12.8	14.6	16.8	18.3
50.0	1.7	4.4	4.6	4.8	5.6	6.7	7.6
80.0	5.7	13.7	14.1	14.7	17.5	21.5	24.8
Acceleration-sensitive components							
0.0	94.2	66.4	69.3	55.1	47.6	43.1	41.0
2.0	5.4	26.8	24.9	33.3	36.7	38.3	38.9
10.0	0.4	6.3	5.4	10.4	13.8	16.1	17.3
50.0	0.0	0.5	0.4	1.1	1.8	2.4	2.7
80.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
Building Contents							
0.0	94.2	66.4	69.3	55.1	47.6	43.1	41.0
1.0	5.4	26.8	24.9	33.3	36.7	38.3	38.9
5.0	0.4	6.3	5.4	10.4	13.8	16.1	17.3
25.0	0.0	0.5	0.4	1.1	1.8	2.4	2.7
40.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1

Table E.14. Non-Structural Damage Probability Matrices for SFCWHR

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	81.9	65.3	64.2	60.7	50.0	38.3	32.5
2.0	5.5	10.0	10.2	11.0	13.1	14.4	14.7
10.0	5.8	10.8	11.1	12.1	15.1	17.9	19.1
50.0	1.8	3.7	3.8	4.3	5.6	7.3	8.2
80.0	5.0	10.2	10.6	11.9	16.2	22.1	25.6
Acceleration-sensitive components							
0.0	99.6	89.7	87.1	84.3	69.3	57.8	55.1
2.0	0.4	9.2	11.4	13.7	24.6	31.5	32.9
10.0	0.0	1.0	1.5	2.0	5.6	9.6	10.7
50.0	0.0	0.0	0.1	0.1	0.5	1.0	1.2
80.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Building Contents							
0.0	99.6	89.7	87.1	84.3	69.3	57.8	55.1
1.0	0.4	9.2	11.4	13.7	24.6	31.5	32.9
5.0	0.0	1.0	1.5	2.0	5.6	9.6	10.7
25.0	0.0	0.0	0.1	0.1	0.5	1.0	1.2
40.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1

Table E.15. Non-Structural Damage Probability Matrices for SFCI

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	70.6	53.0	51.4	44.0	37.8	33.4	30.5
2.0	7.3	9.9	10.1	10.7	10.9	10.8	10.7
10.0	12.0	16.0	16.3	17.2	17.5	17.5	17.3
50.0	4.6	7.8	8.0	9.2	10.1	10.6	10.8
80.0	5.4	13.2	14.1	18.9	23.7	27.7	30.7
Acceleration-sensitive components							
0.0	72.1	60.4	52.5	35.4	32.1	29.0	29.0
2.0	22.8	30.1	34.2	39.6	40.0	40.0	40.0
10.0	4.7	8.5	11.8	20.7	22.8	24.9	24.9
50.0	0.4	0.9	1.5	3.9	4.7	5.6	5.6
80.0	0.0	0.0	0.1	0.3	0.4	0.5	0.5
Building Contents							
0.0	72.1	60.4	52.5	35.4	32.1	29.0	29.0
1.0	22.8	30.1	34.2	39.6	40.0	40.0	40.0
5.0	4.7	8.5	11.8	20.7	22.8	24.9	24.9
25.0	0.4	0.9	1.5	3.9	4.7	5.6	5.6
40.0	0.0	0.0	0.1	0.3	0.4	0.5	0.5

Table E.16. Non-Structural Damage Probability Matrices for SFMI

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	70.6	53.0	52.2	44.0	37.8	33.4	30.5
2.0	7.3	9.9	10.0	10.7	10.9	10.8	10.7
10.0	12.0	16.0	16.2	17.2	17.5	17.5	17.3
50.0	4.6	7.8	7.9	9.2	10.1	10.6	10.8
80.0	5.4	13.2	13.7	18.9	23.7	27.7	30.7
Acceleration-sensitive components							
0.0	72.4	60.6	52.5	35.2	31.8	28.7	28.7
2.0	22.8	30.3	34.6	40.2	40.5	40.6	40.6
10.0	4.5	8.3	11.5	20.6	22.8	24.9	24.9
50.0	0.3	0.8	1.4	3.7	4.5	5.4	5.4
80.0	0.0	0.0	0.1	0.2	0.3	0.4	0.4
Building Contents							
0.0	72.4	60.6	52.5	35.2	31.8	28.7	28.7
1.0	22.8	30.3	34.6	40.2	40.5	40.6	40.6
5.0	4.5	8.3	11.5	20.6	22.8	24.9	24.9
25.0	0.3	0.8	1.4	3.7	4.5	5.4	5.4
40.0	0.0	0.0	0.1	0.2	0.3	0.4	0.4

Table E.17. Non-Structural Damage Probability Matrices for CFLR

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	70.3	53.2	52.2	44.3	36.7	32.6	28.7
2.0	8.1	10.5	10.6	11.1	11.2	11.0	10.8
10.0	9.4	13.7	14.0	15.5	16.7	17.1	17.3
50.0	6.6	9.6	9.7	10.7	11.4	11.5	11.6
80.0	5.7	12.9	13.5	18.4	24.1	27.7	31.6
Acceleration-sensitive components							
0.0	80.3	47.7	45.5	28.2	21.3	18.5	16.9
2.0	17.0	36.2	37.0	39.4	37.8	36.5	35.6
10.0	2.5	13.7	14.8	25.2	30.2	32.3	33.5
50.0	0.2	2.2	2.5	6.5	9.5	11.1	12.2
80.0	0.0	0.1	0.2	0.7	1.2	1.5	1.8
Building Contents							
0.0	80.3	47.7	45.5	28.2	21.3	18.5	16.9
1.0	17.0	36.2	37.0	39.4	37.8	36.5	35.6
5.0	2.5	13.7	14.8	25.2	30.2	32.3	33.5
25.0	0.2	2.2	2.5	6.5	9.5	11.1	12.2
40.0	0.0	0.1	0.2	0.7	1.2	1.5	1.8

Table E.18. Non-Structural Damage Probability Matrices for CFMR

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	77.7	61.1	60.4	55.0	48.3	43.5	39.9
2.0	9.3	12.4	12.5	13.0	13.2	13.1	12.9
10.0	7.9	14.0	14.3	16.1	18.0	19.3	20.1
50.0	0.3	2.0	2.1	2.9	4.0	5.0	5.8
80.0	4.8	10.4	10.7	13.1	16.4	19.1	21.3
Acceleration-sensitive components							
0.0	90.2	63.0	57.6	43.3	35.6	29.3	26.6
2.0	9.0	29.3	32.5	38.5	40.1	40.3	40.0
10.0	0.7	6.8	8.8	15.4	19.8	24.0	26.0
50.0	0.0	0.8	1.1	2.7	4.1	5.8	6.8
80.0	0.0	0.0	0.0	0.2	0.3	0.5	0.7
Building Contents							
0.0	90.2	63.0	57.6	43.3	35.6	29.3	26.6
1.0	9.0	29.3	32.5	38.5	40.1	40.3	40.0
5.0	0.7	6.8	8.8	15.4	19.8	24.0	26.0
25.0	0.0	0.8	1.1	2.7	4.1	5.8	6.8
40.0	0.0	0.0	0.0	0.2	0.3	0.5	0.7

Table E.19. Non-Structural Damage Probability Matrices for CFHR

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	79.2	65.0	64.1	58.9	52.6	47.2	41.5
2.0	8.1	11.7	11.9	12.8	13.7	14.2	14.5
10.0	5.8	10.3	10.6	12.3	14.3	16.0	17.7
50.0	1.5	3.1	3.2	3.9	4.8	5.5	6.4
80.0	5.4	9.9	10.2	12.1	14.7	17.0	19.9
Acceleration-sensitive components							
0.0	98.9	83.9	78.1	75.1	60.4	55.0	45.4
2.0	1.1	14.2	18.7	21.0	30.5	33.4	37.5
10.0	0.0	1.8	3.0	3.7	8.3	10.4	15.0
50.0	0.0	0.1	0.2	0.2	0.8	1.1	2.1
80.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Building Contents							
0.0	98.9	83.9	78.1	75.1	60.4	55.0	45.4
1.0	1.1	14.2	18.7	21.0	30.5	33.4	37.5
5.0	0.0	1.8	3.0	3.7	8.3	10.4	15.0
25.0	0.0	0.1	0.2	0.2	0.8	1.1	2.1
40.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1

Table E.20. Non-Structural Damage Probability Matrices for RCMFLR

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	68.1	49.4	48.5	39.6	33.8	29.3	26.6
2.0	8.9	11.2	11.3	11.5	11.4	11.1	10.8
10.0	12.1	16.8	17.0	18.2	18.6	18.7	18.5
50.0	5.7	9.3	9.5	10.9	11.6	12.0	12.1
80.0	5.2	13.3	13.8	19.7	24.5	28.9	31.9
Acceleration-sensitive components							
0.0	86.3	60.3	57.6	41.2	33.9	30.8	27.9
2.0	12.1	30.3	31.8	38.3	39.6	39.8	39.7
10.0	1.5	8.5	9.6	17.4	21.8	23.9	25.8
50.0	0.1	0.9	1.0	2.9	4.3	5.2	6.1
80.0	0.0	0.0	0.0	0.2	0.3	0.4	0.5
Building Contents							
0.0	86.3	60.3	57.6	41.2	33.9	30.8	27.9
1.0	12.1	30.3	31.8	38.3	39.6	39.8	39.7
5.0	1.5	8.5	9.6	17.4	21.8	23.9	25.8
25.0	0.1	0.9	1.0	2.9	4.3	5.2	6.1
40.0	0.0	0.0	0.0	0.2	0.3	0.4	0.5

Table E.21. Non-Structural Damage Probability Matrices for RCMFMR

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	74.0	52.7	51.7	48.6	42.6	36.7	31.9
2.0	10.4	13.9	13.9	14.1	14.2	13.9	13.4
10.0	7.5	14.7	15.1	16.1	17.9	19.6	20.7
50.0	1.7	4.4	4.6	5.1	6.1	7.1	8.0
80.0	6.4	14.3	14.7	16.2	19.3	22.8	26.0
Acceleration-sensitive components							
0.0	95.8	78.1	75.1	60.4	52.5	45.4	41.1
2.0	4.0	18.7	21.0	30.5	34.6	37.5	38.8
10.0	0.2	3.1	3.8	8.4	11.8	15.3	17.6
50.0	0.0	0.1	0.2	0.6	1.1	1.8	2.4
80.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
Building Contents							
0.0	95.8	78.1	75.1	60.4	52.5	45.4	41.1
1.0	4.0	18.7	21.0	30.5	34.6	37.5	38.8
5.0	0.2	3.1	3.8	8.4	11.8	15.3	17.6
25.0	0.0	0.1	0.2	0.6	1.1	1.8	2.4
40.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1

Table E.22. Non-Structural Damage Probability Matrices for RCMFHR

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	76.2	56.4	54.8	48.8	38.1	30.7	24.9
2.0	7.9	12.4	12.6	13.5	14.3	14.3	13.8
10.0	6.7	12.7	13.1	14.9	17.7	19.5	20.5
50.0	2.2	4.6	4.8	5.6	7.1	8.2	9.1
80.0	7.0	14.0	14.6	17.3	22.7	27.3	31.7
Acceleration-sensitive components							
0.0	99.6	96.0	94.2	87.1	84.3	79.9	78.4
2.0	0.4	3.7	5.3	11.3	13.5	16.9	18.0
10.0	0.0	0.3	0.5	1.6	2.1	3.0	3.4
50.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2
80.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Building Contents							
0.0	99.6	96.0	94.2	87.1	84.3	79.9	78.4
1.0	0.4	3.7	5.3	11.3	13.5	16.9	18.0
5.0	0.0	0.3	0.5	1.6	2.1	3.0	3.4
25.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2
40.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table E.23. Non-Structural Damage Probability Matrices for RCFIW

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	67.4	45.7	44.9	34.0	26.0	19.9	10.5
2.0	9.7	12.5	12.5	12.7	12.1	11.1	8.3
10.0	11.9	17.6	17.8	19.5	19.9	19.5	16.9
50.0	5.1	8.9	9.1	10.8	11.7	12.2	11.7
80.0	5.9	15.2	15.7	23.1	30.3	37.3	52.6
Acceleration-sensitive components							
0.0	82.1	50.0	47.0	44.2	44.2	44.2	44.2
2.0	15.2	35.0	36.2	37.2	37.2	37.2	37.2
10.0	2.6	13.3	14.7	16.1	16.1	16.1	16.1
50.0	0.1	1.7	2.0	2.4	2.4	2.4	2.4
80.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1
Building Contents							
0.0	82.1	50.0	47.0	44.2	44.2	44.2	44.2
1.0	15.2	35.0	36.2	37.2	37.2	37.2	37.2
5.0	2.6	13.3	14.7	16.1	16.1	16.1	16.1
25.0	0.1	1.7	2.0	2.4	2.4	2.4	2.4
40.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1

Table E.24. Non-Structural Damage Probability Matrices for RMLR

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	68.2	61.0	59.4	45.1	37.9	33.8	30.1
2.0	7.7	8.9	9.1	10.5	10.8	10.8	10.6
10.0	9.8	11.5	11.9	14.7	15.7	16.1	16.4
50.0	7.0	8.2	8.5	10.2	10.8	10.9	10.9
80.0	7.3	10.4	11.1	19.4	24.8	28.4	32.0
Acceleration-sensitive components							
0.0	74.4	43.4	41.4	25.7	19.4	16.9	14.7
2.0	21.1	37.3	37.8	38.8	36.9	35.6	34.1
10.0	4.1	16.5	17.6	27.5	32.1	33.9	35.4
50.0	0.3	2.7	3.0	7.3	10.4	12.0	13.7
80.0	0.0	0.2	0.2	0.7	1.3	1.7	2.1
Building Contents							
0.0	74.4	43.4	41.4	25.7	19.4	16.9	14.7
1.0	21.1	37.3	37.8	38.8	36.9	35.6	34.1
5.0	4.1	16.5	17.6	27.5	32.1	33.9	35.4
25.0	0.3	2.7	3.0	7.3	10.4	12.0	13.7
40.0	0.0	0.2	0.2	0.7	1.3	1.7	2.1

Table E.25. Non-Structural Damage Probability Matrices for RMMR

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	76.6	66.2	65.3	55.3	49.1	44.3	40.6
2.0	9.2	11.3	11.4	12.4	12.6	12.6	12.4
10.0	8.9	12.8	13.1	16.4	18.1	19.2	19.9
50.0	0.5	1.5	1.6	3.1	4.2	5.1	6.0
80.0	4.8	8.2	8.6	12.8	16.0	18.8	21.2
Acceleration-sensitive components							
0.0	90.2	60.3	55.0	41.2	32.3	26.6	23.0
2.0	9.0	31.0	33.8	39.0	40.3	40.0	39.2
10.0	0.7	7.8	9.8	16.5	22.0	26.0	28.7
50.0	0.0	1.0	1.4	3.0	5.0	6.8	8.3
80.0	0.0	0.0	0.1	0.2	0.4	0.7	0.9
Building Contents							
0.0	90.2	60.3	55.0	41.2	32.3	26.6	23.0
1.0	9.0	31.0	33.8	39.0	40.3	40.0	39.2
5.0	0.7	7.8	9.8	16.5	22.0	26.0	28.7
25.0	0.0	1.0	1.4	3.0	5.0	6.8	8.3
40.0	0.0	0.0	0.1	0.2	0.4	0.7	0.9

Table E.26. Non-Structural Damage Probability Matrices for URMLR

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	64.5	47.7	45.2	32.2	33.7	29.1	26.1
2.0	7.9	9.7	9.9	10.0	10.1	9.9	9.7
10.0	10.9	14.1	14.5	15.5	15.5	15.6	15.5
50.0	8.3	10.7	10.9	11.2	11.2	11.0	10.8
80.0	8.4	17.8	19.6	31.0	29.5	34.4	37.9
Acceleration-sensitive components							
0.0	56.2	32.9	31.0	20.5	17.3	15.4	15.4
2.0	32.9	39.8	39.8	37.6	35.9	34.6	34.6
10.0	9.9	22.5	23.8	31.7	34.3	35.7	35.7
50.0	1.0	4.4	4.9	9.2	11.3	12.7	12.7
80.0	0.0	0.3	0.4	1.0	1.3	1.6	1.6
Building Contents							
0.0	56.2	32.9	31.0	20.5	17.3	15.4	15.4
1.0	32.9	39.8	39.8	37.6	35.9	34.6	34.6
5.0	9.9	22.5	23.8	31.7	34.3	35.7	35.7
25.0	1.0	4.4	4.9	9.2	11.3	12.7	12.7
40.0	0.0	0.3	0.4	1.0	1.3	1.6	1.6

Table E.27. Non-Structural Damage Probability Matrices for URMMR

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	72.2	58.4	57.6	52.2	45.2	39.7	35.9
2.0	10.1	11.7	11.7	11.8	11.6	11.2	10.7
10.0	8.3	12.8	13.0	14.6	16.3	17.5	18.2
50.0	2.7	4.8	4.9	5.8	6.9	7.8	8.5
80.0	6.6	12.4	12.8	15.7	19.9	23.8	26.8
Acceleration-sensitive components							
0.0	82.5	50.0	36.4	19.1	15.8	13.9	13.9
2.0	15.0	35.3	39.8	38.9	37.3	36.1	36.1
10.0	2.4	12.9	19.9	31.5	33.9	35.3	35.3
50.0	0.1	1.7	3.7	9.5	11.5	12.9	12.9
80.0	0.0	0.1	0.2	1.1	1.5	1.8	1.8
Building Contents							
0.0	82.5	50.0	36.4	19.1	15.8	13.9	13.9
1.0	15.0	35.3	39.8	38.9	37.3	36.1	36.1
5.0	2.4	12.9	19.9	31.5	33.9	35.3	35.3
25.0	0.1	1.7	3.7	9.5	11.5	12.9	12.9
40.0	0.0	0.1	0.2	1.1	1.5	1.8	1.8

Table E.28. Non-Structural Damage Probability Matrices for TU

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	66.4	57.0	55.3	41.4	33.5	28.8	25.9
2.0	8.7	10.1	10.3	11.4	11.4	11.1	10.9
10.0	10.6	13.0	13.4	16.1	17.2	17.5	17.6
50.0	4.4	5.8	6.0	7.9	8.9	9.4	9.6
80.0	9.9	14.1	15.0	23.2	29.1	33.2	36.0
Acceleration-sensitive components							
0.0	68.5	50.0	43.4	24.5	16.9	12.9	12.3
2.0	25.1	35.0	37.3	38.6	35.6	32.6	32.0
10.0	5.9	13.3	16.7	28.7	34.3	37.0	37.4
50.0	0.5	1.7	2.5	7.5	11.8	15.2	15.7
80.0	0.0	0.1	0.1	0.7	1.5	2.4	2.5
Building Contents							
0.0	68.5	50.0	43.4	24.5	16.9	12.9	12.3
1.0	25.1	35.0	37.3	38.6	35.6	32.6	32.0
5.0	5.9	13.3	16.7	28.7	34.3	37.0	37.4
25.0	0.5	1.7	2.5	7.5	11.8	15.2	15.7
40.0	0.0	0.1	0.1	0.7	1.5	2.4	2.5

Table E.29. Non-Structural Damage Probability Matrices for PCLR

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	69.5	53.1	52.1	42.8	36.5	31.8	28.4
2.0	7.5	9.9	10.0	10.6	10.8	10.7	10.5
10.0	10.5	14.3	14.5	15.9	16.5	16.7	16.7
50.0	7.2	10.3	10.5	11.6	12.0	12.1	12.0
80.0	5.3	12.4	13.0	19.1	24.3	28.8	32.4
Acceleration-sensitive components							
0.0	72.1	55.0	52.5	32.1	27.6	26.3	23.8
2.0	22.8	33.0	34.2	40.0	40.0	39.8	39.4
10.0	4.8	10.8	11.9	23.1	26.1	27.0	28.8
50.0	0.3	1.1	1.4	4.5	5.8	6.3	7.3
80.0	0.0	0.0	0.1	0.3	0.5	0.5	0.7
Building Contents							
0.0	72.1	55.0	52.5	32.1	27.6	26.3	23.8
1.0	22.8	33.0	34.2	40.0	40.0	39.8	39.4
5.0	4.8	10.8	11.9	23.1	26.1	27.0	28.8
25.0	0.3	1.1	1.4	4.5	5.8	6.3	7.3
40.0	0.0	0.0	0.1	0.3	0.5	0.5	0.7

Table E.30. Non-Structural Damage Probability Matrices for PCMR

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	78.2	63.3	62.5	53.9	46.9	42.4	36.2
2.0	8.8	11.8	11.9	12.7	12.9	12.9	12.5
10.0	6.4	11.3	11.6	14.3	16.3	17.5	19.0
50.0	1.7	3.6	3.8	5.0	6.1	6.9	8.0
80.0	4.9	10.0	10.3	14.1	17.6	20.3	24.4
Acceleration-sensitive components							
0.0	89.7	63.4	60.6	47.6	41.0	37.0	33.5
2.0	9.3	28.6	30.3	36.7	38.9	39.9	40.4
10.0	1.0	7.3	8.3	13.8	17.3	19.5	21.7
50.0	0.0	0.6	0.8	1.8	2.7	3.4	4.1
80.0	0.0	0.0	0.0	0.1	0.1	0.2	0.3
Building Contents							
0.0	89.7	63.4	60.6	47.6	41.0	37.0	33.5
1.0	9.3	28.6	30.3	36.7	38.9	39.9	40.4
5.0	1.0	7.3	8.3	13.8	17.3	19.5	21.7
25.0	0.0	0.6	0.8	1.8	2.7	3.4	4.1
40.0	0.0	0.0	0.0	0.1	0.1	0.2	0.3

Table E.31. Non-Structural Damage Probability Matrices for MH

CDF (%)	Damage Probability (%) at MMI:						
	VI	VII	VIII	IX	X	XI	XII
Displacement-sensitive components							
0.0	62.5	44.6	43.7	33.3	27.1	23.5	17.6
2.0	8.4	10.8	10.9	11.3	11.2	10.9	10.1
10.0	12.2	15.6	15.7	16.7	16.8	16.6	15.9
50.0	8.7	11.4	11.5	12.1	11.9	11.6	10.7
80.0	8.1	17.7	18.3	26.7	33.0	37.3	45.7
Acceleration-sensitive components							
0.0	75.4	57.8	55.1	43.1	41.0	39.0	39.0
2.0	20.2	31.2	32.6	37.6	38.2	38.8	38.8
10.0	4.1	9.8	10.9	16.5	17.6	18.7	18.7
50.0	0.3	1.1	1.4	2.7	3.0	3.4	3.4
80.0	0.0	0.0	0.1	0.2	0.2	0.2	0.2
Building Contents							
0.0	75.4	57.8	55.1	43.1	41.0	39.0	39.0
1.0	20.2	31.2	32.6	37.6	38.2	38.8	38.8
5.0	4.1	9.8	10.9	16.5	17.6	18.7	18.7
25.0	0.3	1.1	1.4	2.7	3.0	3.4	3.4
40.0	0.0	0.0	0.1	0.2	0.2	0.2	0.2

Appendix F: Casualty Tables

The HazUS 2005 Casualty rates presented in section 5.6.1 are presented below for each of the HazUS building prototypes.

F - 1 HazUS (2005) Indoor Casualty Rates for Slight Damage

Damage Level = Slight, Location = indoors					
		Casualty Severity Level			
#	Building Type	Severity 1(%)	Severity 2 (%)	Severity 3 (%)	Severity 4 (%)
1	W1	0.05	0	0	0
2	W2	0.05	0	0	0
3	S1L	0.05	0	0	0
4	S1M	0.05	0	0	0
5	S1H	0.05	0	0	0
6	S2L	0.05	0	0	0
7	S2M	0.05	0	0	0
8	S2H	0.05	0	0	0
9	S3	0.05	0	0	0
10	S4L	0.05	0	0	0
11	S4M	0.05	0	0	0
12	S4H	0.05	0	0	0
13	S5L	0.05	0	0	0
14	S5M	0.05	0	0	0
15	S5H	0.05	0	0	0
16	C1L	0.05	0	0	0
17	C1M	0.05	0	0	0
18	C1H	0.05	0	0	0
19	C2L	0.05	0	0	0
20	C2M	0.05	0	0	0
21	C2H	0.05	0	0	0
22	C3L	0.05	0	0	0
23	C3M	0.05	0	0	0
24	C3H	0.05	0	0	0
25	PC1	0.05	0	0	0
26	PC2L	0.05	0	0	0
27	PC2M	0.05	0	0	0
28	PC2H	0.05	0	0	0
29	RM1L	0.05	0	0	0
30	RM1M	0.05	0	0	0
31	RM2L	0.05	0	0	0
32	RM2M	0.05	0	0	0
33	RM2H	0.05	0	0	0
34	URML	0.05	0	0	0
35	URMM	0.05	0	0	0
36	MH	0.05	0	0	0
B1	Major Bridge	N/A	N/A	N/A	N/A
B2	Continuous Bridge	N/A	N/A	N/A	N/A
B3	S.S. Bridge	N/A	N/A	N/A	N/A

F - 2 HazUS (2005) Indoor Casualty Rates for Moderate Damage

Damage Level = Moderate, Location = indoors					
		Casualty Severity Level			
#	Building Type	Severity 1(%)	Severity 2 (%)	Severity 3 (%)	Severity 4 (%)
1	W1	0.25	0.03	0	0
2	W2	0.2	0.025	0	0
3	S1L	0.2	0.025	0	0
4	S1M	0.2	0.025	0	0
5	S1H	0.2	0.025	0	0
6	S2L	0.2	0.025	0	0
7	S2M	0.2	0.025	0	0
8	S2H	0.2	0.025	0	0
9	S3	0.2	0.025	0	0
10	S4L	0.25	0.03	0	0
11	S4M	0.25	0.03	0	0
12	S4H	0.25	0.03	0	0
13	S5L	0.2	0.025	0	0
14	S5M	0.2	0.025	0	0
15	S5H	0.2	0.025	0	0
16	C1L	0.25	0.03	0	0
17	C1M	0.25	0.03	0	0
18	C1H	0.25	0.03	0	0
19	C2L	0.25	0.03	0	0
20	C2M	0.25	0.03	0	0
21	C2H	0.25	0.03	0	0
22	C3L	0.2	0.025	0	0
23	C3M	0.2	0.025	0	0
24	C3H	0.2	0.025	0	0
25	PC1	0.25	0.03	0	0
26	PC2L	0.25	0.03	0	0
27	PC2M	0.25	0.03	0	0
28	PC2H	0.25	0.03	0	0
29	RM1L	0.2	0.025	0	0
30	RM1M	0.2	0.025	0	0
31	RM2L	0.2	0.025	0	0
32	RM2M	0.2	0.025	0	0
33	RM2H	0.2	0.025	0	0
34	URML	0.35	0.04	0.001	0.001
35	URMM	0.35	0.04	0.001	0.001
36	MH	0.25	0.03	0	0
B1	Major Bridge	N/A	N/A	N/A	N/A
B2	Continuous Bridge	N/A	N/A	N/A	N/A
B3	S.S. Bridge	N/A	N/A	N/A	N/A

F - 3 HazUS (2005) Indoor Casualty Rates for Extensive Damage

Damage Level = Extensive, Location = indoors					
		Casualty Severity Level			
#	Building Type	Severity 1(%)	Severity 2 (%)	Severity 3 (%)	Severity 4 (%)
1	W1	1	0.1	0.001	0.001
2	W2	1	0.1	0.001	0.001
3	S1L	1	0.1	0.001	0.001
4	S1M	1	0.1	0.001	0.001
5	S1H	1	0.1	0.001	0.001
6	S2L	1	0.1	0.001	0.001
7	S2M	1	0.1	0.001	0.001
8	S2H	1	0.1	0.001	0.001
9	S3	1	0.1	0.001	0.001
10	S4L	1	0.1	0.001	0.001
11	S4M	1	0.1	0.001	0.001
12	S4H	1	0.1	0.001	0.001
13	S5L	1	0.1	0.001	0.001
14	S5M	1	0.1	0.001	0.001
15	S5H	1	0.1	0.001	0.001
16	C1L	1	0.1	0.001	0.001
17	C1M	1	0.1	0.001	0.001
18	C1H	1	0.1	0.001	0.001
19	C2L	1	0.1	0.001	0.001
20	C2M	1	0.1	0.001	0.001
21	C2H	1	0.1	0.001	0.001
22	C3L	1	0.1	0.001	0.001
23	C3M	1	0.1	0.001	0.001
24	C3H	1	0.1	0.001	0.001
25	PC1	1	0.1	0.001	0.001
26	PC2L	1	0.1	0.001	0.001
27	PC2M	1	0.1	0.001	0.001
28	PC2H	1	0.1	0.001	0.001
29	RM1L	1	0.1	0.001	0.001
30	RM1M	1	0.1	0.001	0.001
31	RM2L	1	0.1	0.001	0.001
32	RM2M	1	0.1	0.001	0.001
33	RM2H	1	0.1	0.001	0.001
34	URML	2	0.2	0.002	0.002
35	URMM	2	0.2	0.002	0.002
36	MH	1	0.1	0.001	0.001
B1	Major Bridge	N/A	N/A	N/A	N/A
B2	Continuous Bridge	N/A	N/A	N/A	N/A
B3	S.S. Bridge	N/A	N/A	N/A	N/A

F - 4 HazUS (2005) Indoor Casualty Rates for Complete Damage without Collapse

Damage Level = Complete without Collapse, Location = indoors					
#	Building Type	Casualty Severity Level			
		Severity 1(%)	Severity 2 (%)	Severity 3 (%)	Severity 4 (%)
1	W1	5	1	0.01	0.01
2	W2	5	1	0.01	0.01
3	S1L	5	1	0.01	0.01
4	S1M	5	1	0.01	0.01
5	S1H	5	1	0.01	0.01
6	S2L	5	1	0.01	0.01
7	S2M	5	1	0.01	0.01
8	S2H	5	1	0.01	0.01
9	S3	5	1	0.01	0.01
10	S4L	5	1	0.01	0.01
11	S4M	5	1	0.01	0.01
12	S4H	5	1	0.01	0.01
13	S5L	5	1	0.01	0.01
14	S5M	5	1	0.01	0.01
15	S5H	5	1	0.01	0.01
16	C1L	5	1	0.01	0.01
17	C1M	5	1	0.01	0.01
18	C1H	5	1	0.01	0.01
19	C2L	5	1	0.01	0.01
20	C2M	5	1	0.01	0.01
21	C2H	5	1	0.01	0.01
22	C3L	5	1	0.01	0.01
23	C3M	5	1	0.01	0.01
24	C3H	5	1	0.01	0.01
25	PC1	5	1	0.01	0.01
26	PC2L	5	1	0.01	0.01
27	PC2M	5	1	0.01	0.01
28	PC2H	5	1	0.01	0.01
29	RM1L	5	1	0.01	0.01
30	RM1M	5	1	0.01	0.01
31	RM2L	5	1	0.01	0.01
32	RM2M	5	1	0.01	0.01
33	RM2H	5	1	0.01	0.01
34	URML	10	2	0.02	0.02
35	URMM	10	2	0.02	0.02
36	MH	5	1	0.01	0.01
B1	Major Bridge	N/A	N/A	N/A	N/A
B2	Continuous Bridge	N/A	N/A	N/A	N/A
B3	S.S. Bridge	N/A	N/A	N/A	N/A

F - 5 HazUS (2005) Indoor Casualty Rates for Complete Damage with Collapse

Damage Level = Complete with Collapse, Location = indoors					
		Casualty Severity Level			
#	Building Type	Severity 1(%)	Severity 2 (%)	Severity 3 (%)	Severity 4 (%)
1	W1	40	20	3	5
2	W2	40	20	3	10
3	S1L	40	20	5	10
4	S1M	40	20	5	10
5	S1H	40	20	5	10
6	S2L	40	20	5	10
7	S2M	40	20	5	10
8	S2H	40	20	5	10
9	S3	40	20	5	5
10	S4L	40	20	5	10
11	S4M	40	20	5	10
12	S4H	40	20	5	10
13	S5L	40	20	5	10
14	S5M	40	20	5	10
15	S5H	40	20	5	10
16	C1L	40	20	5	10
17	C1M	40	20	5	10
18	C1H	40	20	5	10
19	C2L	40	20	5	10
20	C2M	40	20	5	10
21	C2H	40	20	5	10
22	C3L	40	20	5	10
23	C3M	40	20	5	10
24	C3H	40	20	5	10
25	PC1	40	20	5	10
26	PC2L	40	20	5	10
27	PC2M	40	20	5	10
28	PC2H	40	20	5	10
29	RM1L	40	20	5	10
30	RM1M	40	20	5	10
31	RM2L	40	20	5	10
32	RM2M	40	20	5	10
33	RM2H	40	20	5	10
34	URML	40	20	5	10
35	URMM	40	20	5	10
36	MH	40	20	3	5
B1	Major Bridge	N/A	N/A	N/A	N/A
B2	Continuous Bridge	N/A	N/A	N/A	N/A
B3	S.S. Bridge	N/A	N/A	N/A	N/A

F - 6 HazUS (2005) Outdoor Casualty Rates for Moderate Damage

Damage Level = Moderate, Location = outdoors					
		Casualty Severity Level			
#	Building Type	Severity 1(%)	Severity 2 (%)	Severity 3 (%)	Severity 4 (%)
1	W1	0.05	0.005	0.0001	0.0001
2	W2	0.05	0.005	0	0
3	S1L	0.05	0.005	0	0
4	S1M	0.05	0.005	0	0
5	S1H	0.05	0.005	0	0
6	S2L	0.05	0.005	0	0
7	S2M	0.05	0.005	0	0
8	S2H	0.05	0.005	0	0
9	S3	0	0	0	0
10	S4L	0.05	0.005	0	0
11	S4M	0.05	0.005	0	0
12	S4H	0.05	0.005	0	0
13	S5L	0.05	0.005	0	0
14	S5M	0.05	0.005	0	0
15	S5H	0.05	0.005	0	0
16	C1L	0.05	0.005	0	0
17	C1M	0.05	0.005	0	0
18	C1H	0.05	0.005	0	0
19	C2L	0.05	0.005	0	0
20	C2M	0.05	0.005	0	0
21	C2H	0.05	0.005	0	0
22	C3L	0.05	0.005	0	0
23	C3M	0.05	0.005	0	0
24	C3H	0.05	0.005	0	0
25	PC1	0.05	0.005	0	0
26	PC2L	0.05	0.005	0	0
27	PC2M	0.05	0.005	0	0
28	PC2H	0.05	0.005	0	0
29	RM1L	0.05	0.005	0	0
30	RM1M	0.05	0.005	0	0
31	RM2L	0.05	0.005	0	0
32	RM2M	0.05	0.005	0	0
33	RM2H	0.05	0.005	0	0
34	URML	0.15	0.015	0.0003	0.0003
35	URMM	0.15	0.015	0.0003	0.0003
36	MH	0	0	0	0

F - 7 HazUS (2005) Outdoor Casualty Rates for Extensive Damage

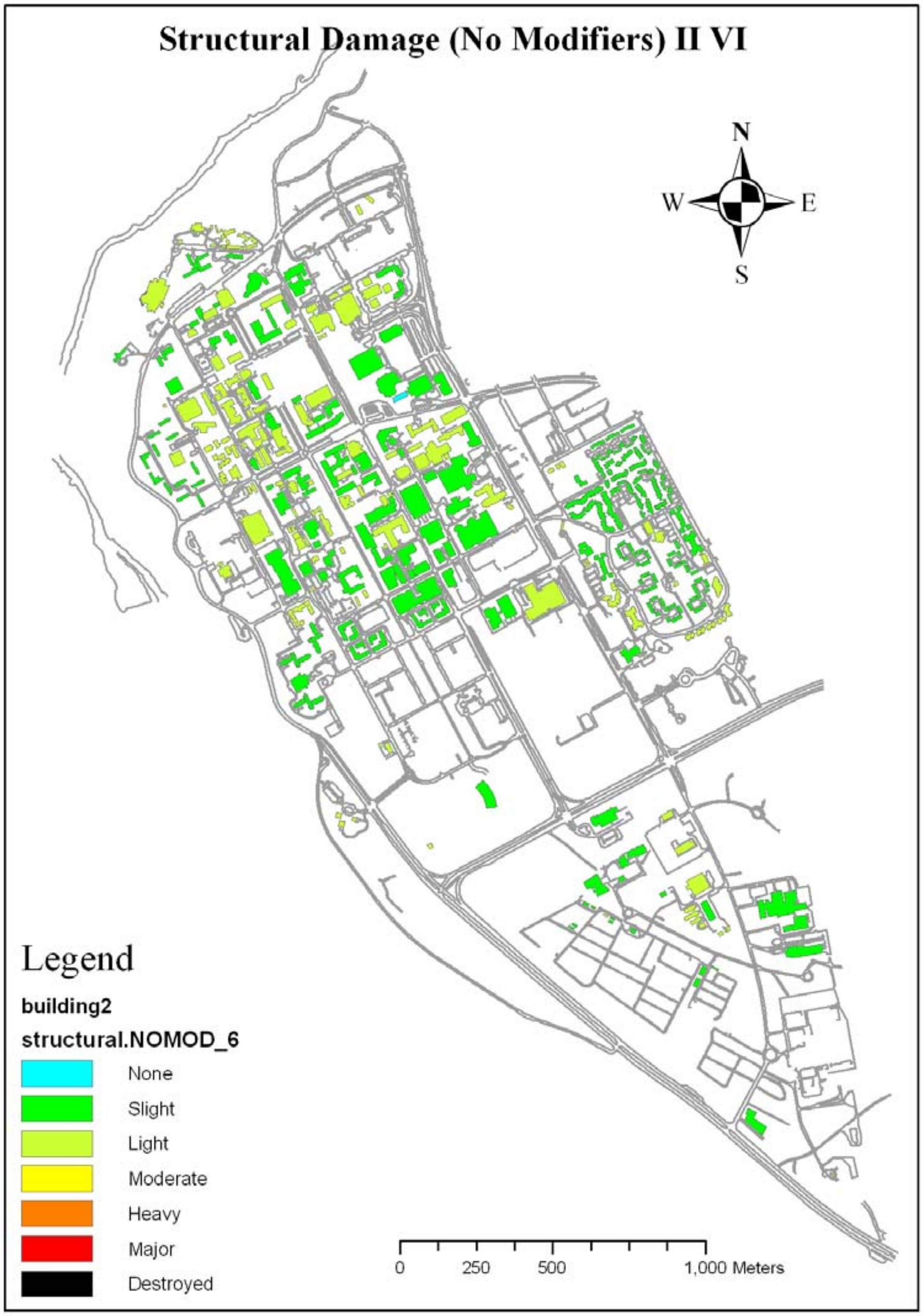
Damage Level = Extensive, Location = outdoors					
		Casualty Severity Level			
#	Building Type	Severity 1(%)	Severity 2 (%)	Severity 3 (%)	Severity 4 (%)
1	W1	0.3	0.03	0.0003	0.0003
2	W2	0.3	0.03	0.0003	0.0003
3	S1L	0.1	0.01	0.0001	0.0001
4	S1M	0.2	0.02	0.0002	0.0002
5	S1H	0.3	0.03	0.0003	0.0003
6	S2L	0.1	0.01	0.0001	0.0001
7	S2M	0.2	0.02	0.0002	0.0002
8	S2H	0.3	0.03	0.0003	0.0003
9	S3	0	0	0	0
10	S4L	0.1	0.01	0.0001	0.0001
11	S4M	0.2	0.02	0.0002	0.0002
12	S4H	0.3	0.03	0.0003	0.0003
13	S5L	0.2	0.02	0.0002	0.0002
14	S5M	0.4	0.04	0.0004	0.0004
15	S5H	0.6	0.06	0.0006	0.0006
16	C1L	0.1	0.01	0.0001	0.0001
17	C1M	0.2	0.02	0.0002	0.0002
18	C1H	0.3	0.03	0.0003	0.0003
19	C2L	0.1	0.01	0.0001	0.0001
20	C2M	0.2	0.02	0.0002	0.0002
21	C2H	0.3	0.03	0.0003	0.0003
22	C3L	0.2	0.02	0.0002	0.0002
23	C3M	0.4	0.04	0.0004	0.0004
24	C3H	0.6	0.06	0.0006	0.0006
25	PC1	0.2	0.02	0.0002	0.0002
26	PC2L	0.1	0.01	0.0001	0.0001
27	PC2M	0.2	0.02	0.0002	0.0002
28	PC2H	0.3	0.03	0.0003	0.0003
29	RM1L	0.2	0.02	0.0002	0.0002
30	RM1M	0.3	0.03	0.0003	0.0003
31	RM2L	0.2	0.02	0.0002	0.0002
32	RM2M	0.6	0.06	0.0006	0.0006
33	RM2H	0.6	0.06	0.0006	0.0006
34	URML	0.6	0.06	0.0006	0.0006
35	URMM	0.6	0.06	0.0006	0.0006
36	MH	0	0	0	0

F - 8 HazUS (2005) Outdoor Casualty Rates for Complete Damage

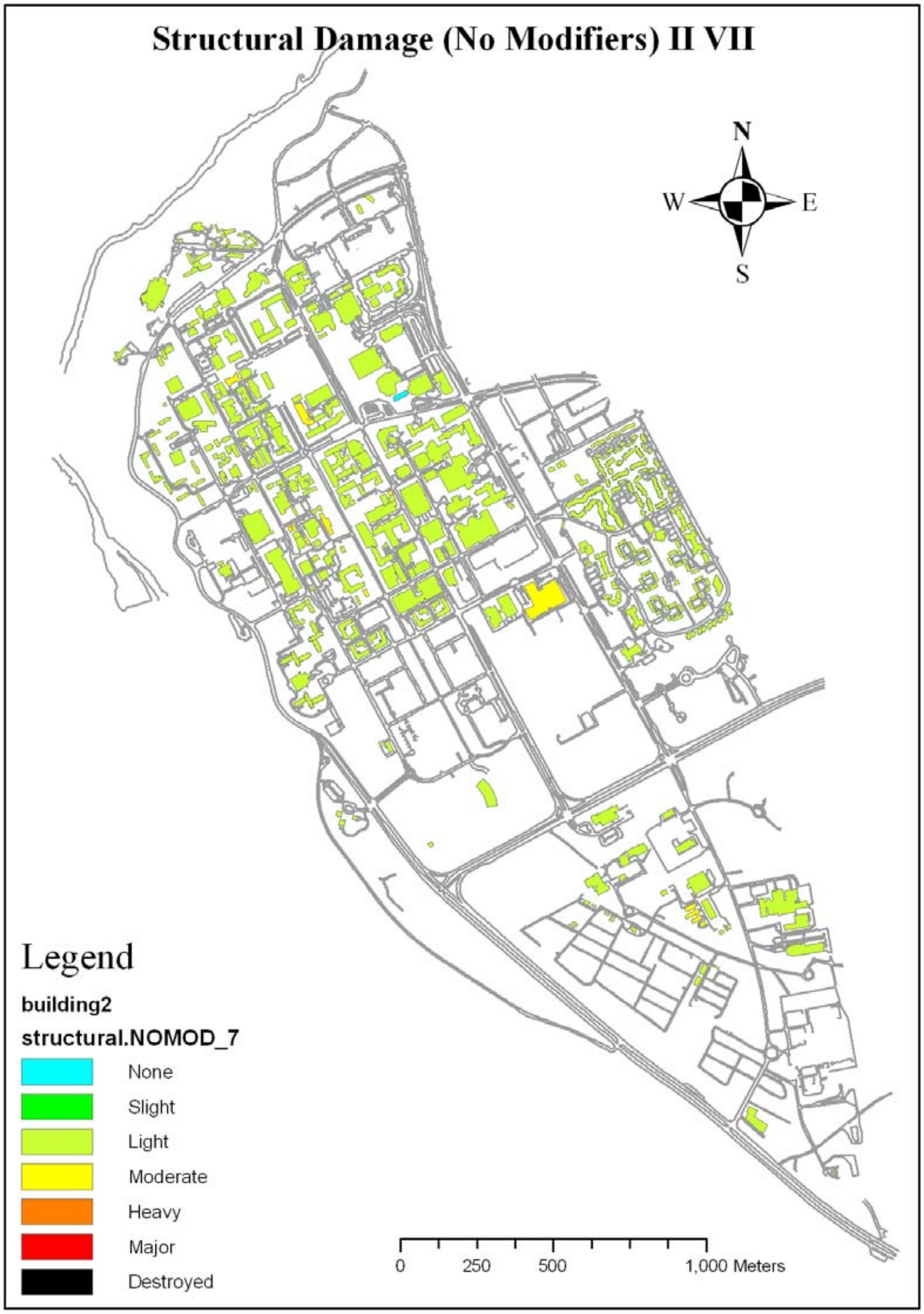
Damage Level = Complete, Location = outdoors					
		Casualty Severity Level			
#	Building Type	Severity 1(%)	Severity 2 (%)	Severity 3 (%)	Severity 4 (%)
1	W1	2	0.5	0.1	0.05
2	W2	2	0.5	0.1	0.05
3	S1L	2	0.5	0.1	0.05
4	S1M	2.2	0.7	0.2	0.2
5	S1H	2.5	1	0.3	0.3
6	S2L	2	0.5	0.1	0.05
7	S2M	2.2	0.7	0.2	0.2
8	S2H	2.5	1	0.3	0.3
9	S3	0.01	0.001	0.001	0.01
10	S4L	2	0.5	0.1	0.05
11	S4M	2.2	0.7	0.2	0.2
12	S4H	2.5	1	0.3	0.3
13	S5L	2.7	1	0.2	0.3
14	S5M	3	1.2	0.3	0.4
15	S5H	3.3	1.4	0.4	0.6
16	C1L	2	0.5	0.1	0.05
17	C1M	2.2	0.7	0.2	0.2
18	C1H	2.5	1	0.3	0.3
19	C2L	2	0.5	0.1	0.05
20	C2M	2.2	0.7	0.2	0.2
21	C2H	2.5	1	0.3	0.3
22	C3L	2.7	1	0.2	0.3
23	C3M	3	1.2	0.3	0.4
24	C3H	3.3	1.4	0.4	0.6
25	PC1	2	0.5	0.1	0.1
26	PC2L	2.7	1	0.2	0.3
27	PC2M	3	1.2	0.3	0.4
28	PC2H	3.3	1.4	0.4	0.6
29	RM1L	2	0.5	0.1	0.05
30	RM1M	2.2	0.7	0.2	0.2
31	RM2L	2	0.5	0.1	0.05
32	RM2M	2.2	0.7	0.2	0.2
33	RM2H	2.5	1	0.3	0.3
34	URML	5	2	0.4	0.6
35	URMM	5	2	0.4	0.6
36	MH	0.01	0.001	0.001	0.01

Appendix G: UBC Structural Damage Results

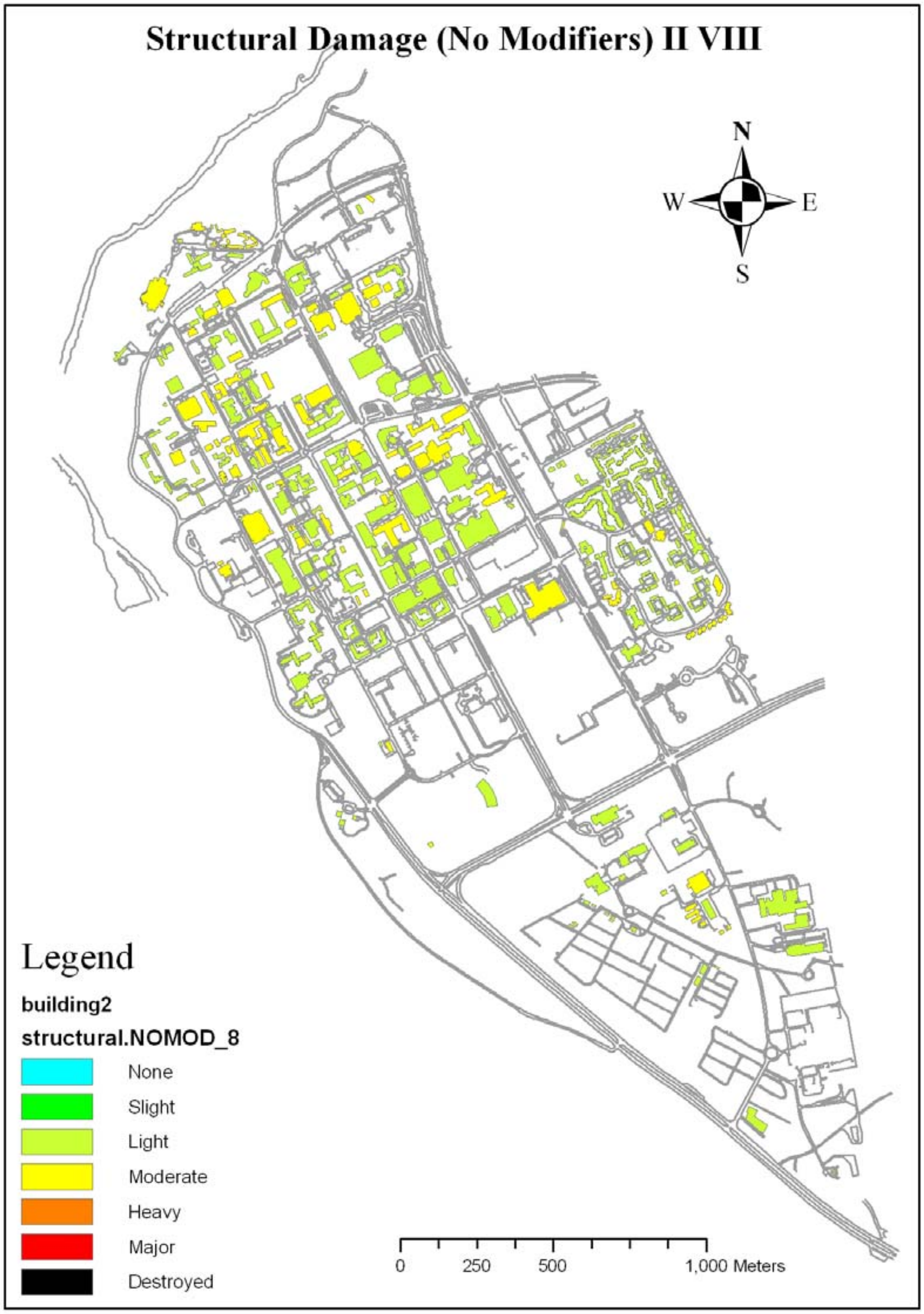
This appendix presents the UBC structural damage results, without and with modifiers, for all seven levels of Instrumental intensity.



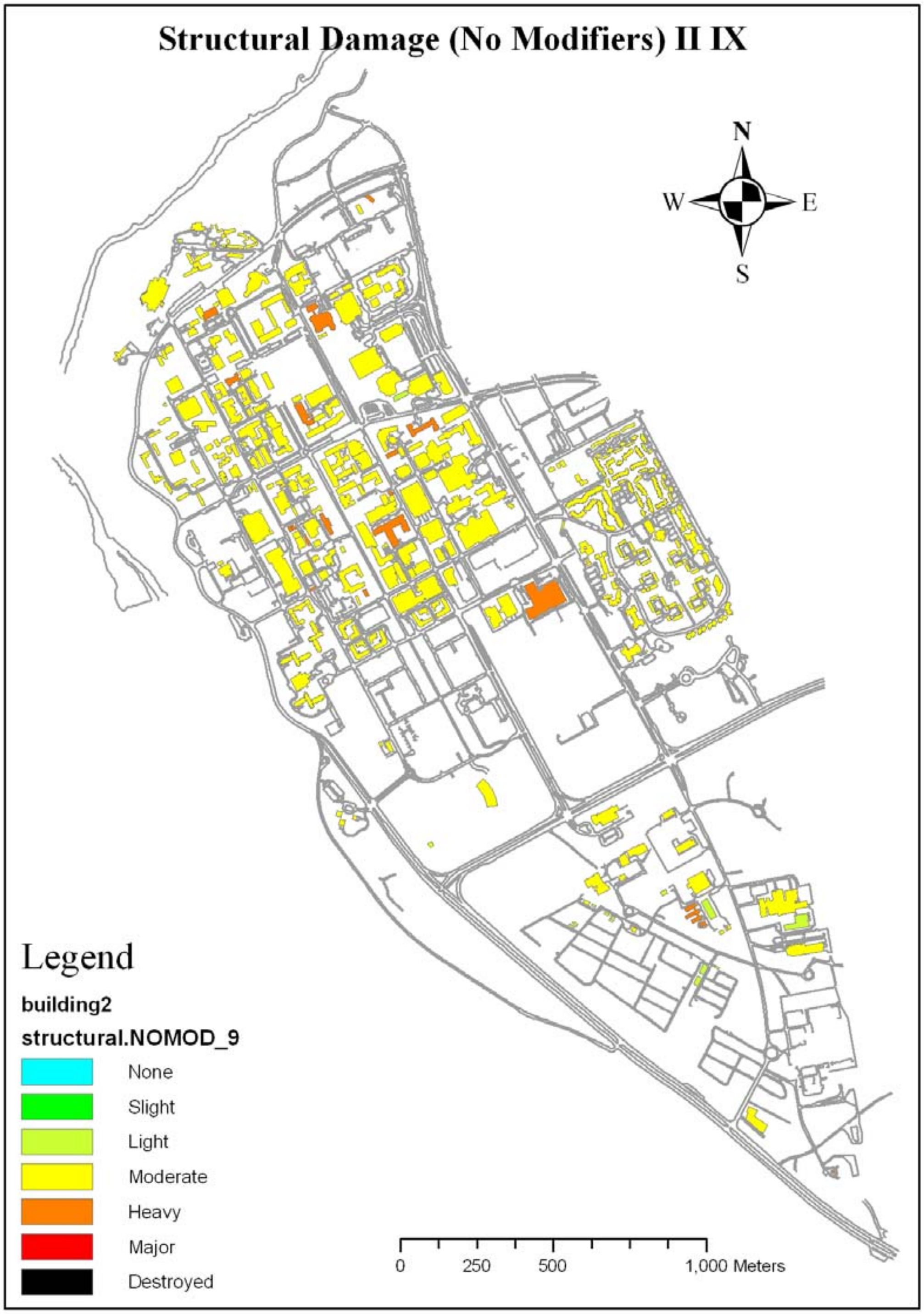
G - 1 UBC Structural Damage without Modifiers – II VI



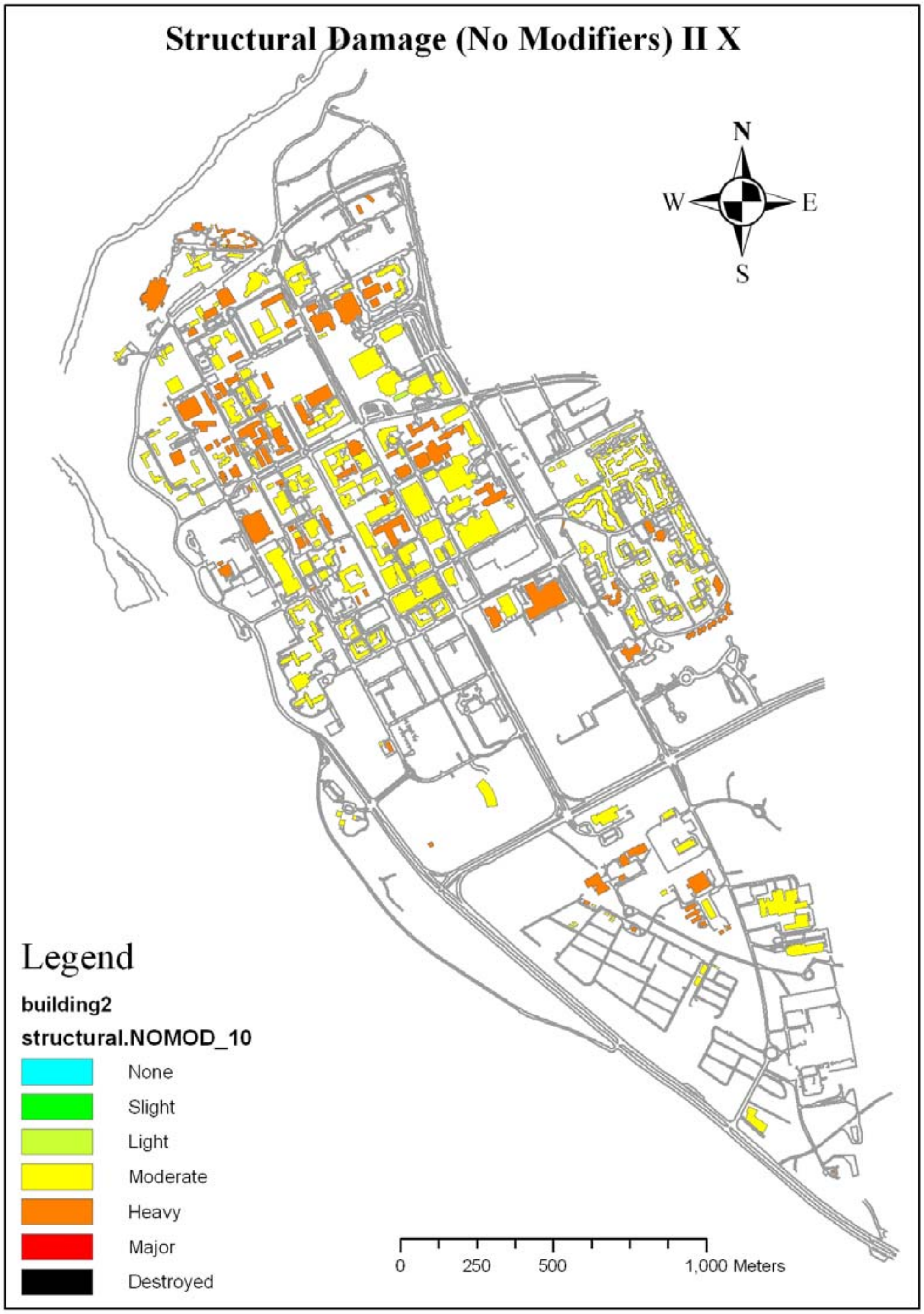
G - 2 UBC Structural Damage without Modifiers – II VII



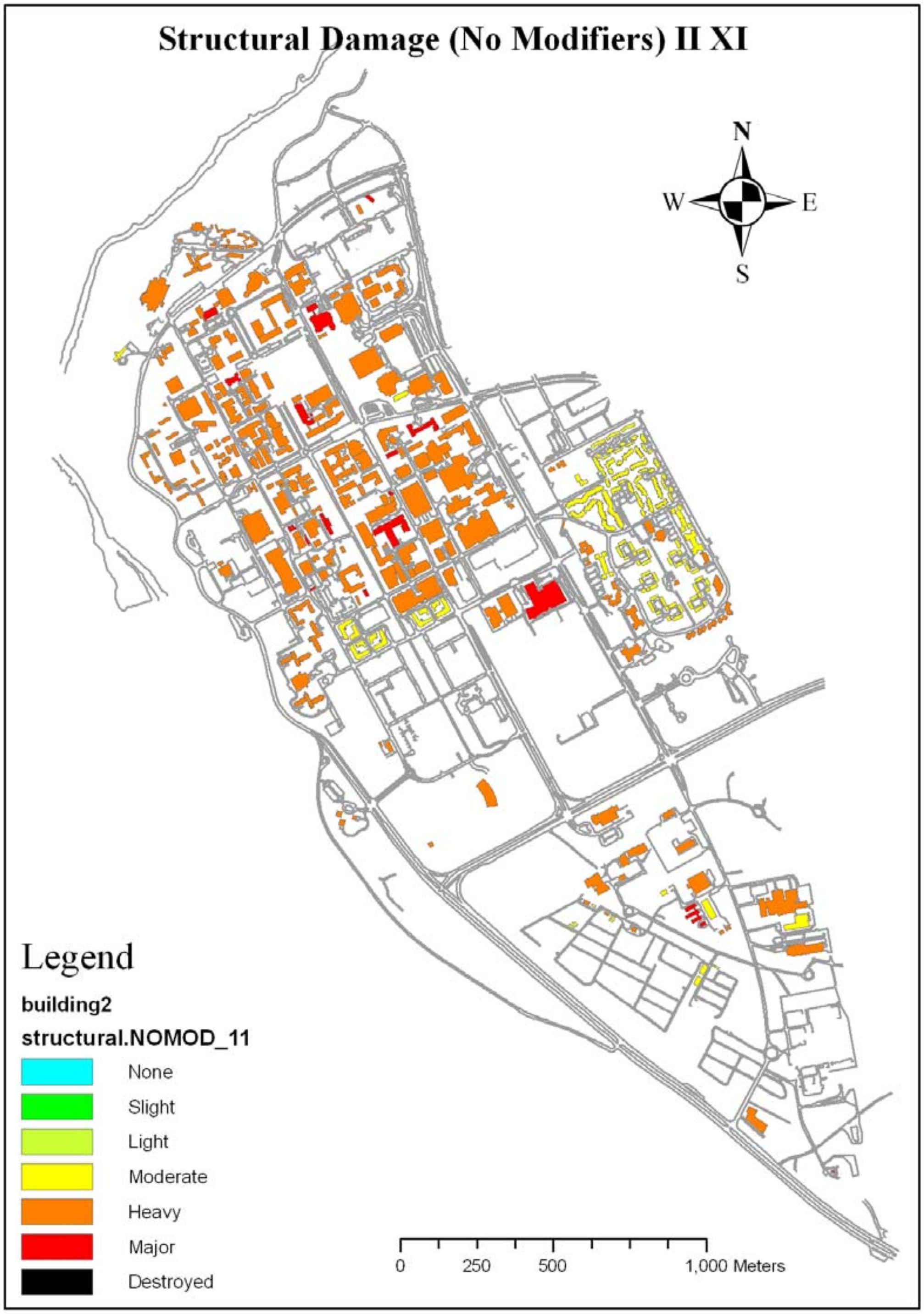
G - 3 UBC Structural Damage without Modifiers – II VIII



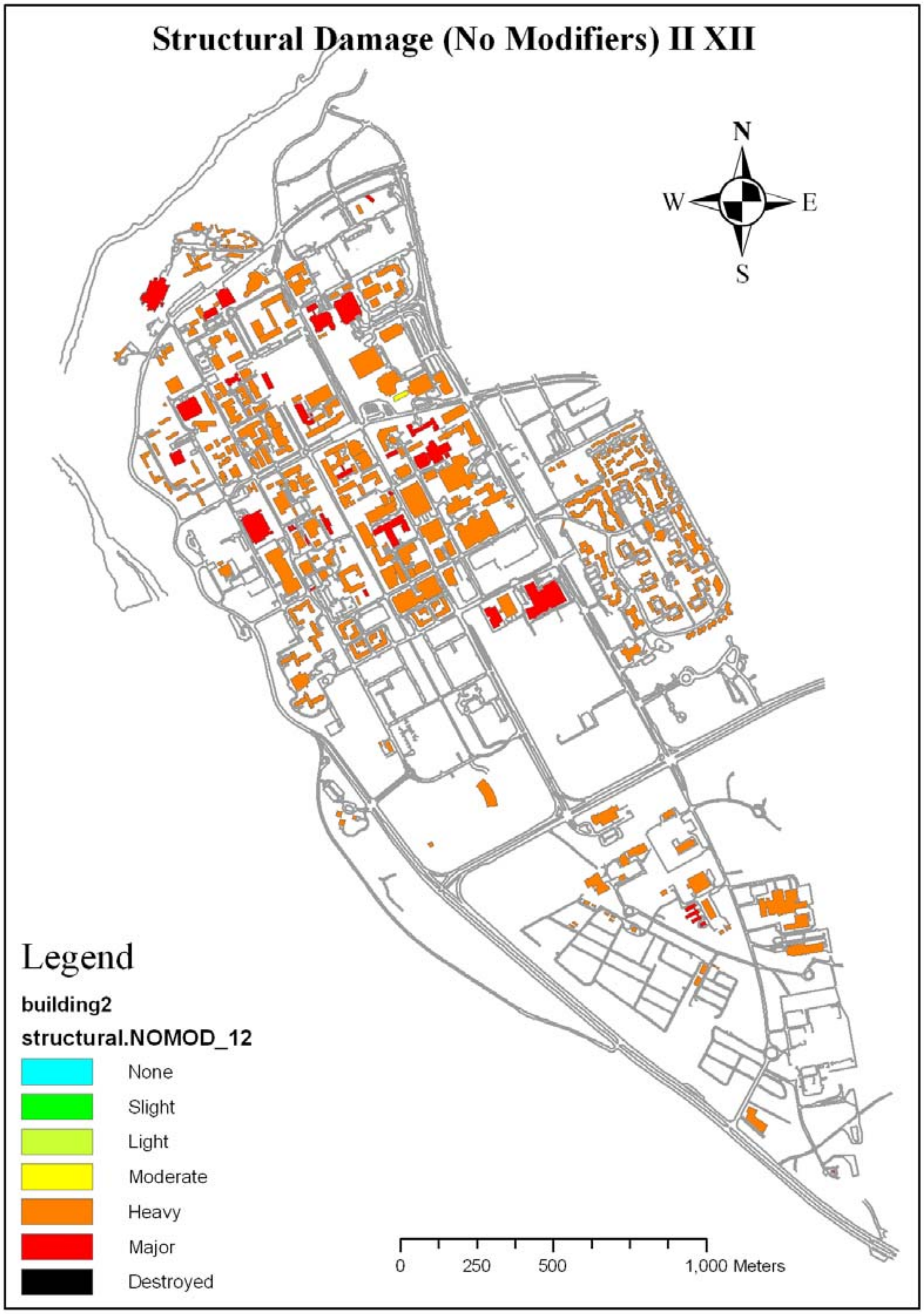
G - 4 UBC Structural Damage without Modifiers – II IX



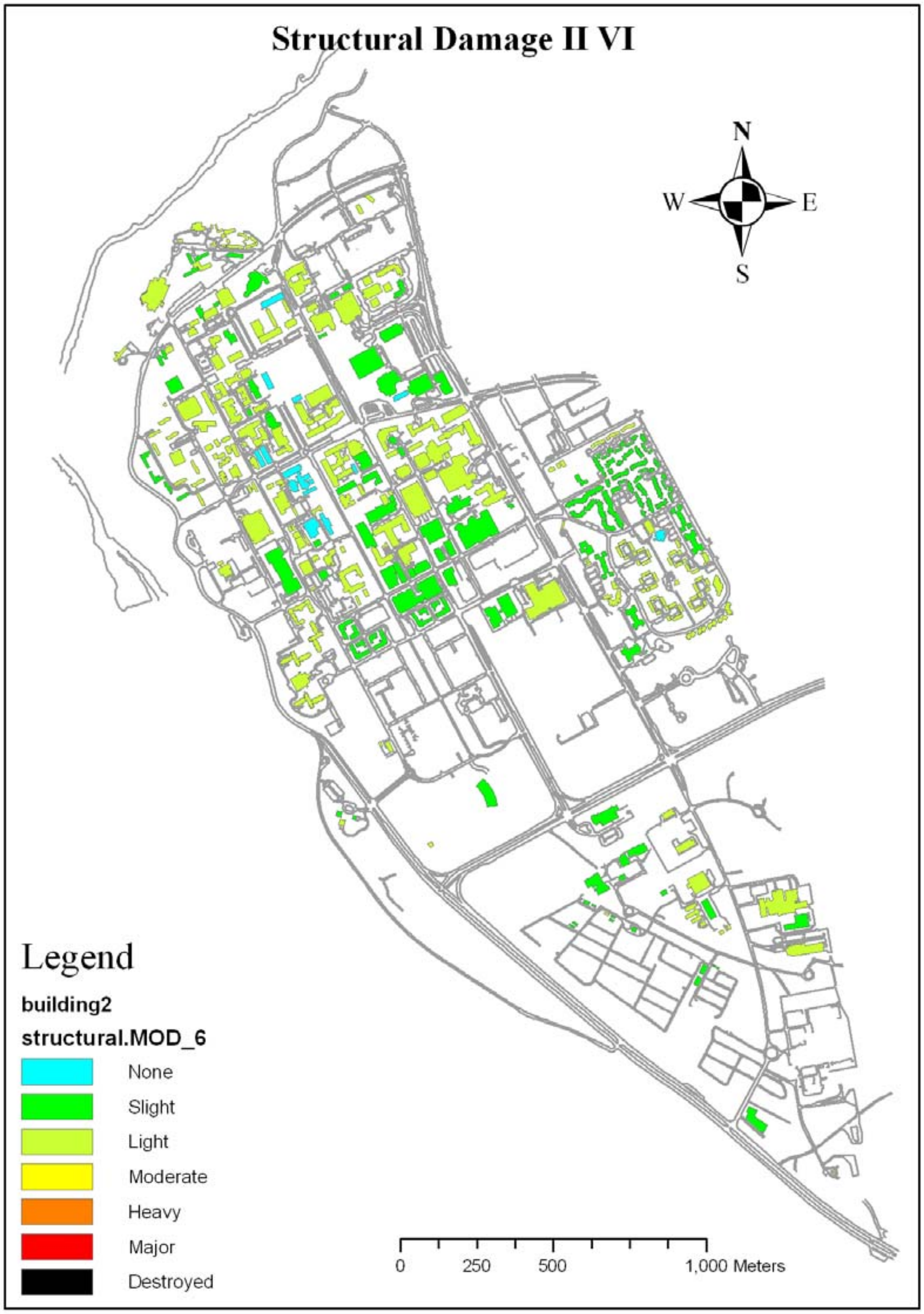
G - 5 UBC Structural Damage without Modifiers – II X



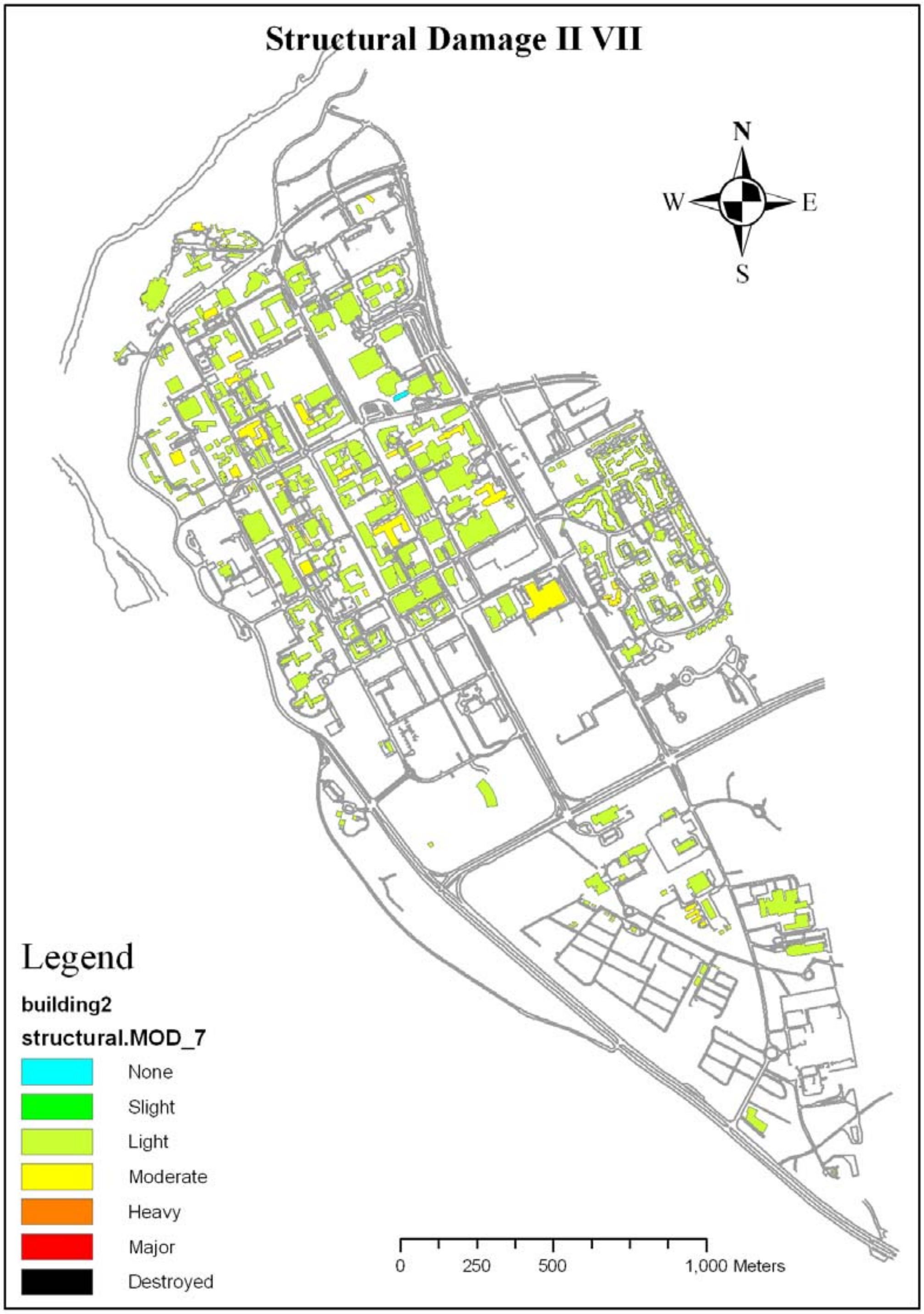
G - 6 UBC Structural Damage without Modifiers – II XI



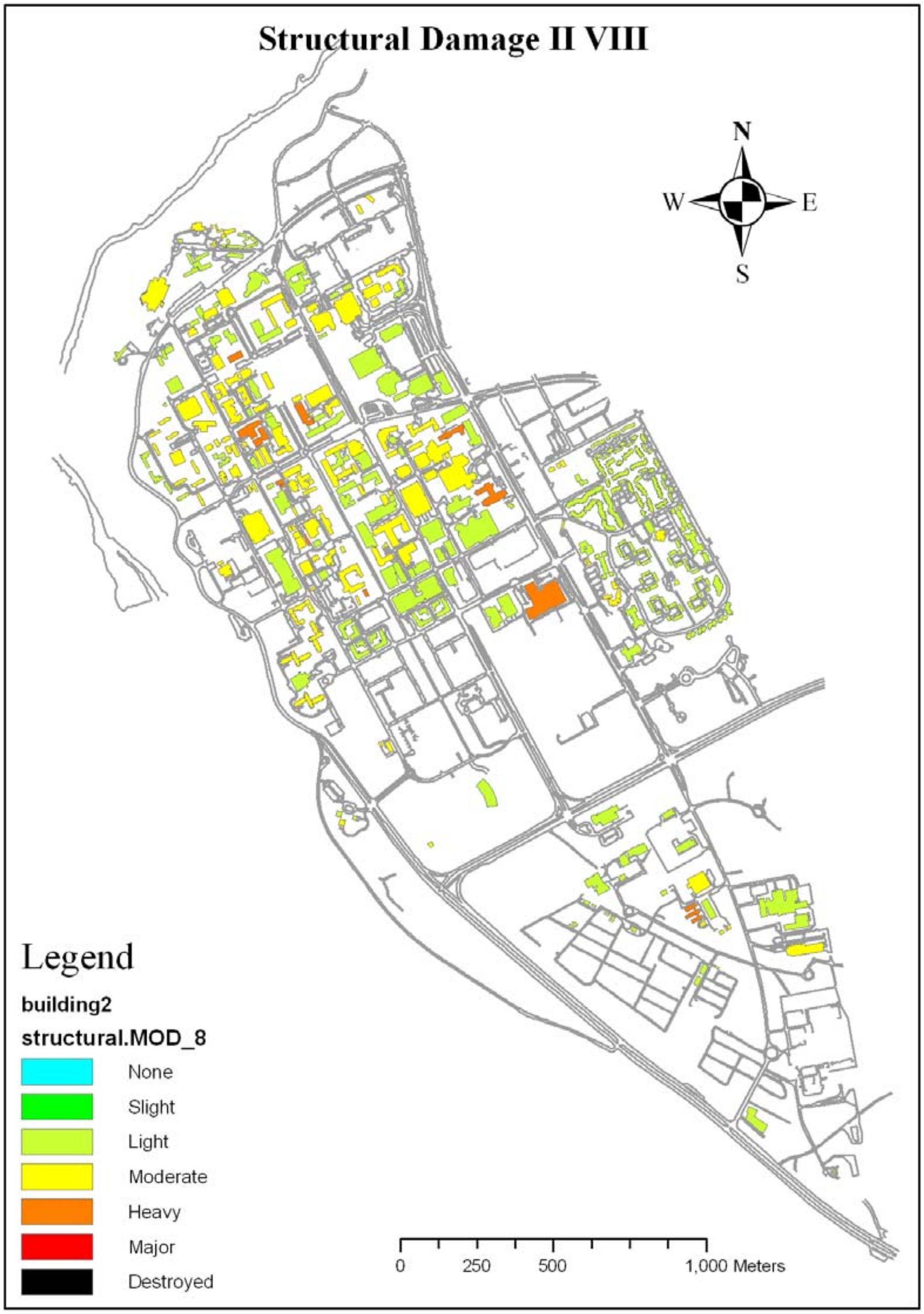
G - 7 UBC Structural Damage without Modifiers – II XII



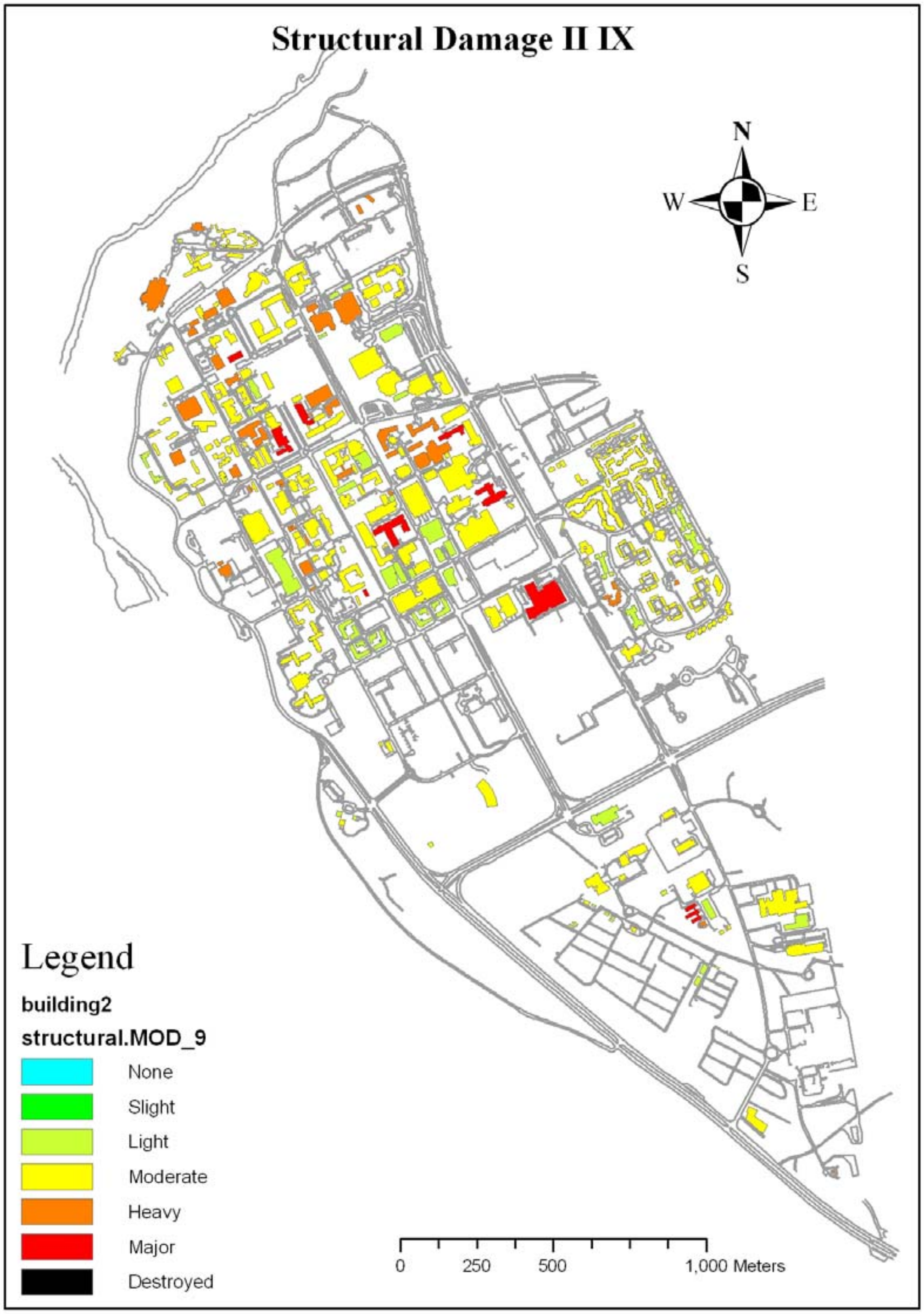
G - 8 UBC Structural Damage with Modifiers – II VI



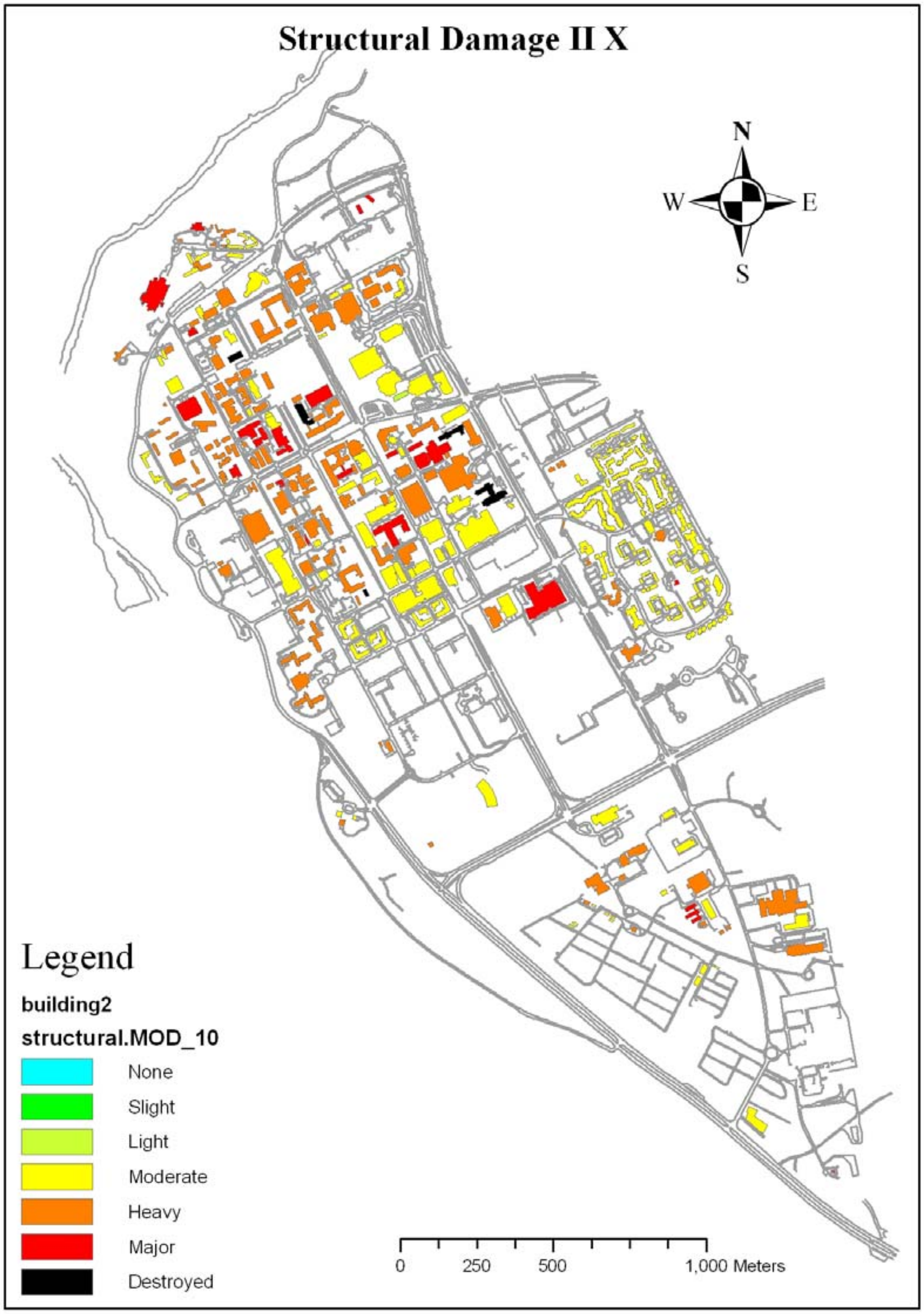
G - 9 UBC Structural Damage with Modifiers – II VII



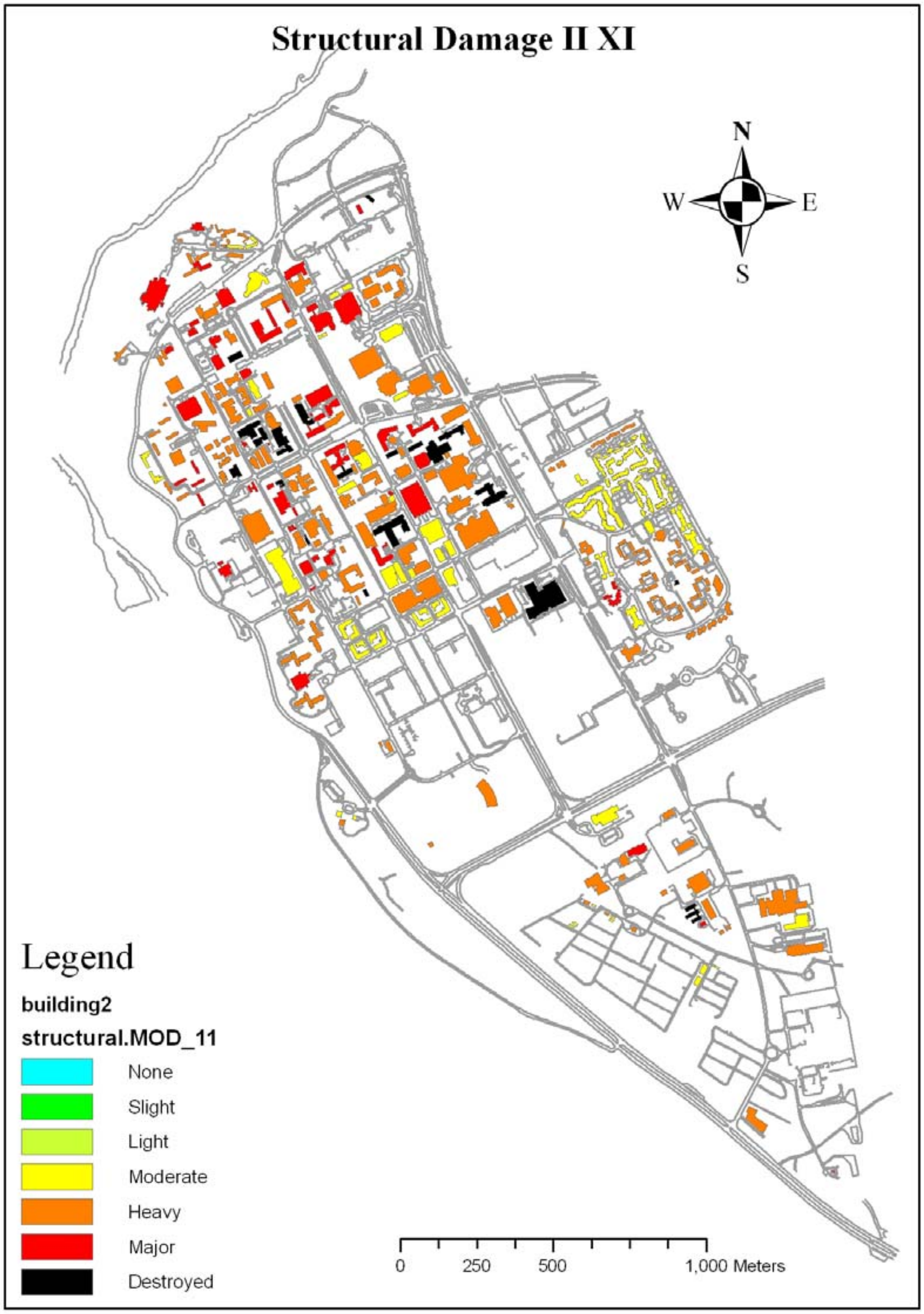
G - 10 UBC Structural Damage with Modifiers – II VIII



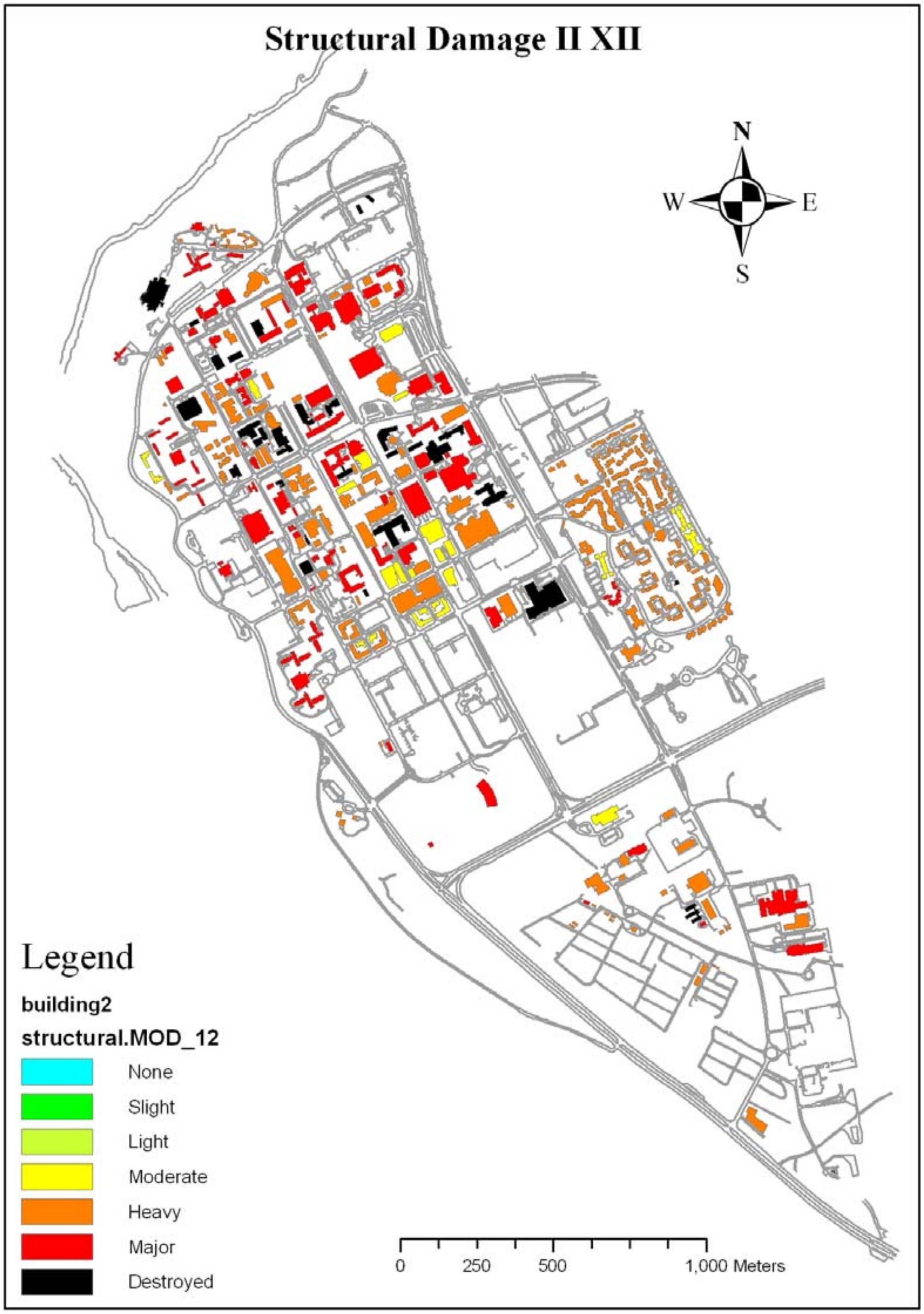
G - 11 UBC Structural Damage with Modifiers – II IX



G - 12 UBC Structural Damage with Modifiers – II X



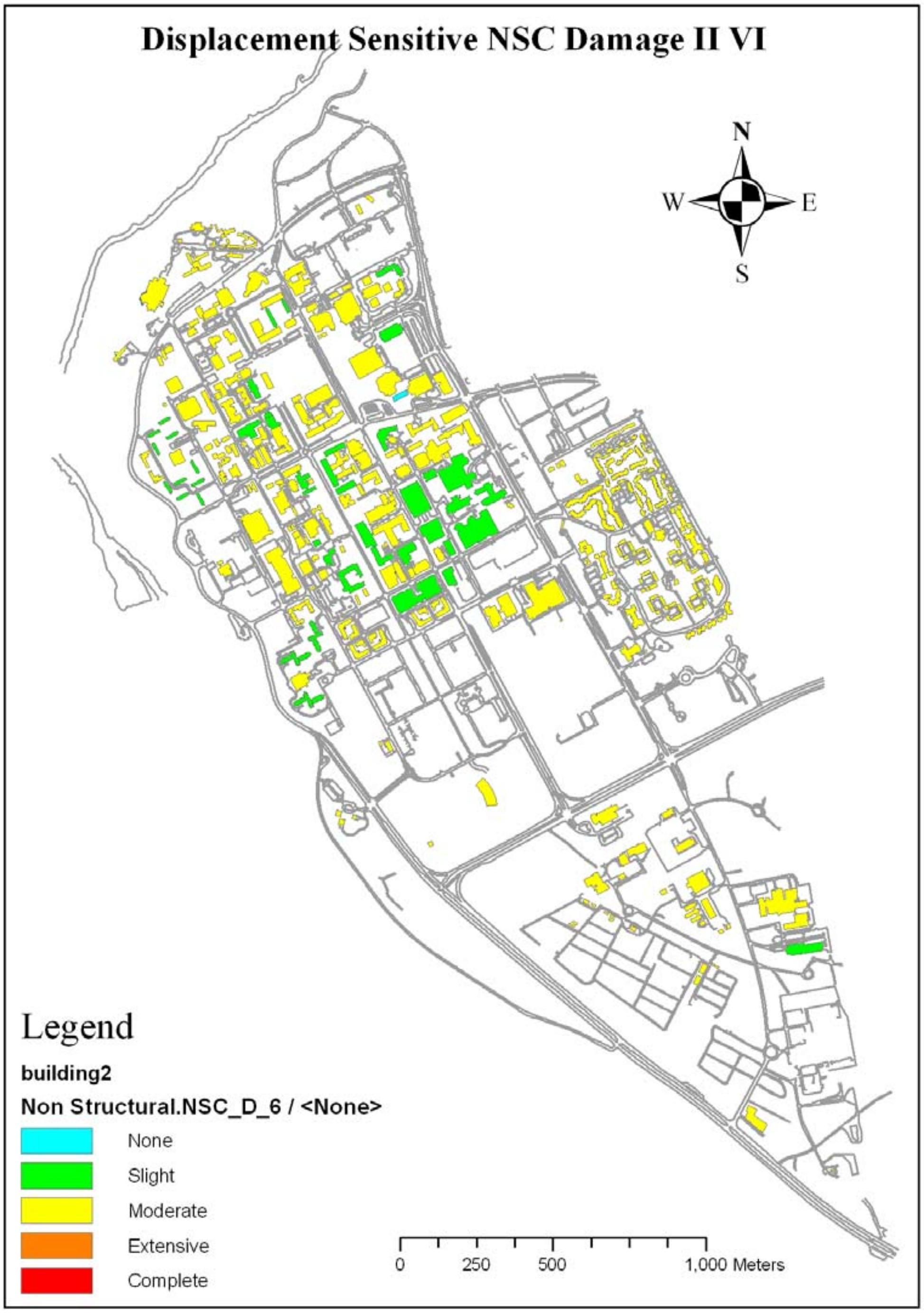
G - 13 UBC Structural Damage with Modifiers – II XI



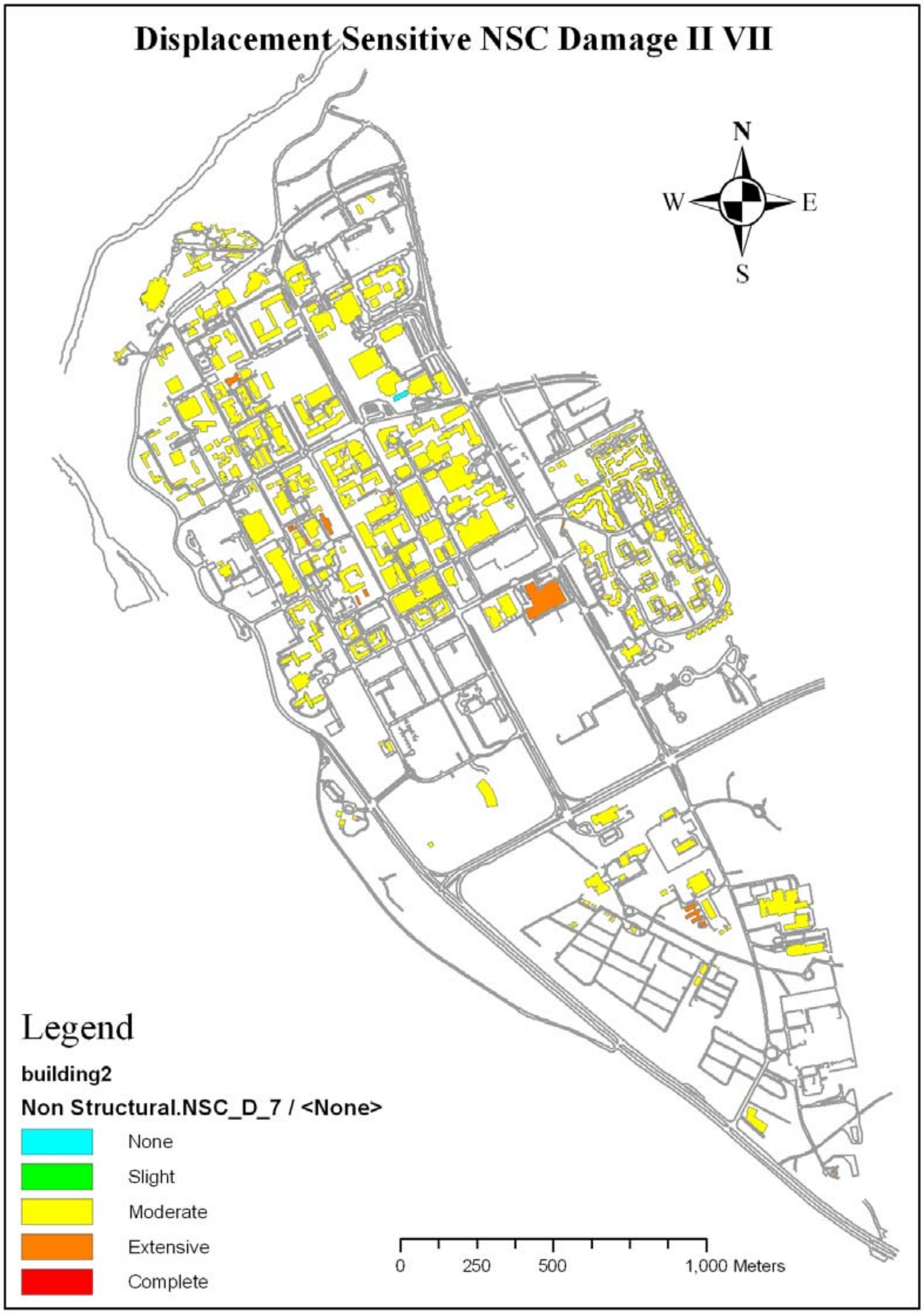
G - 14 UBC Structural Damage with Modifiers – II XII

Appendix H: UBC Nonstructural Damage Results

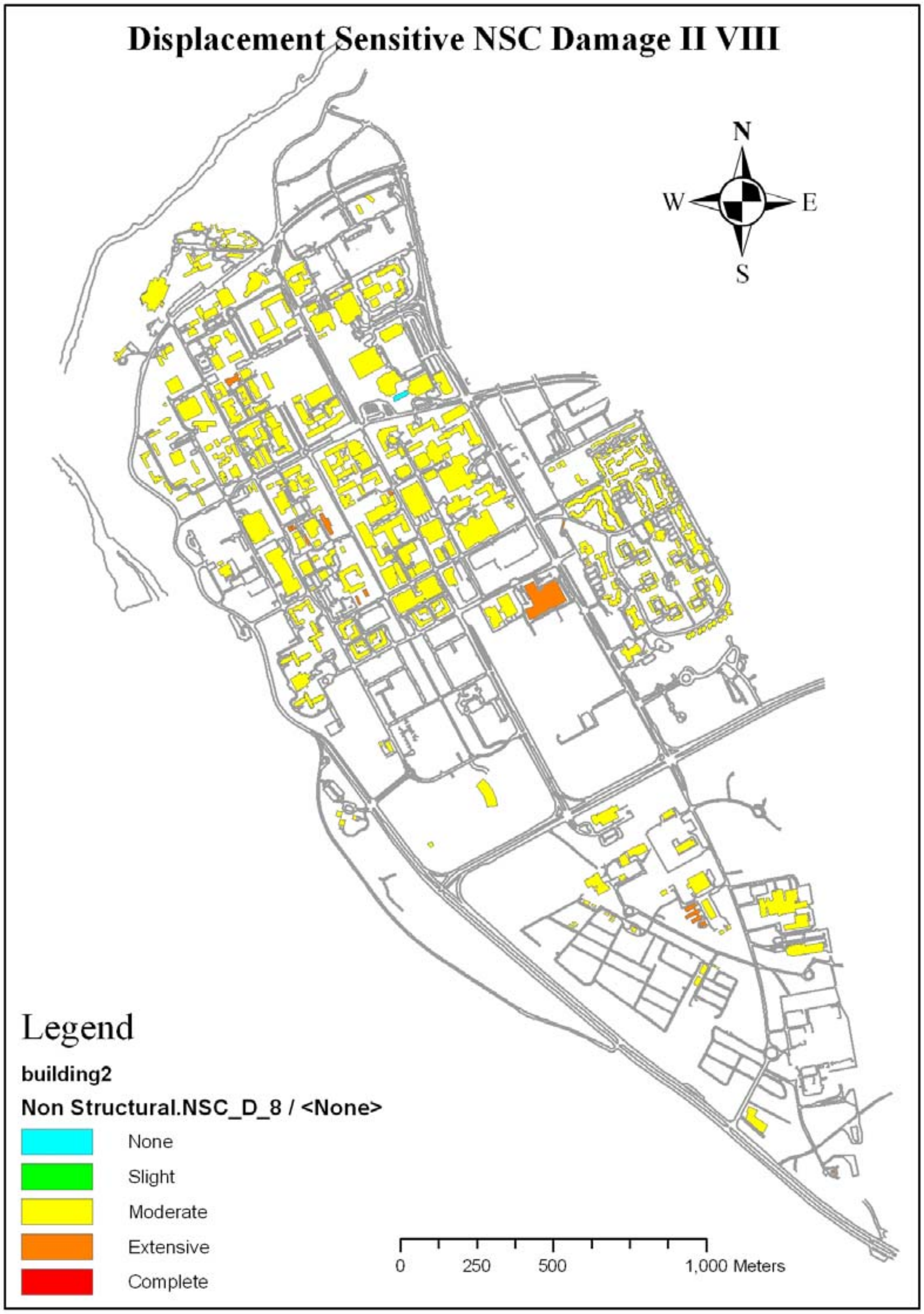
This appendix presents the UBC nonstructural damage results for all seven levels of Instrumental intensity.



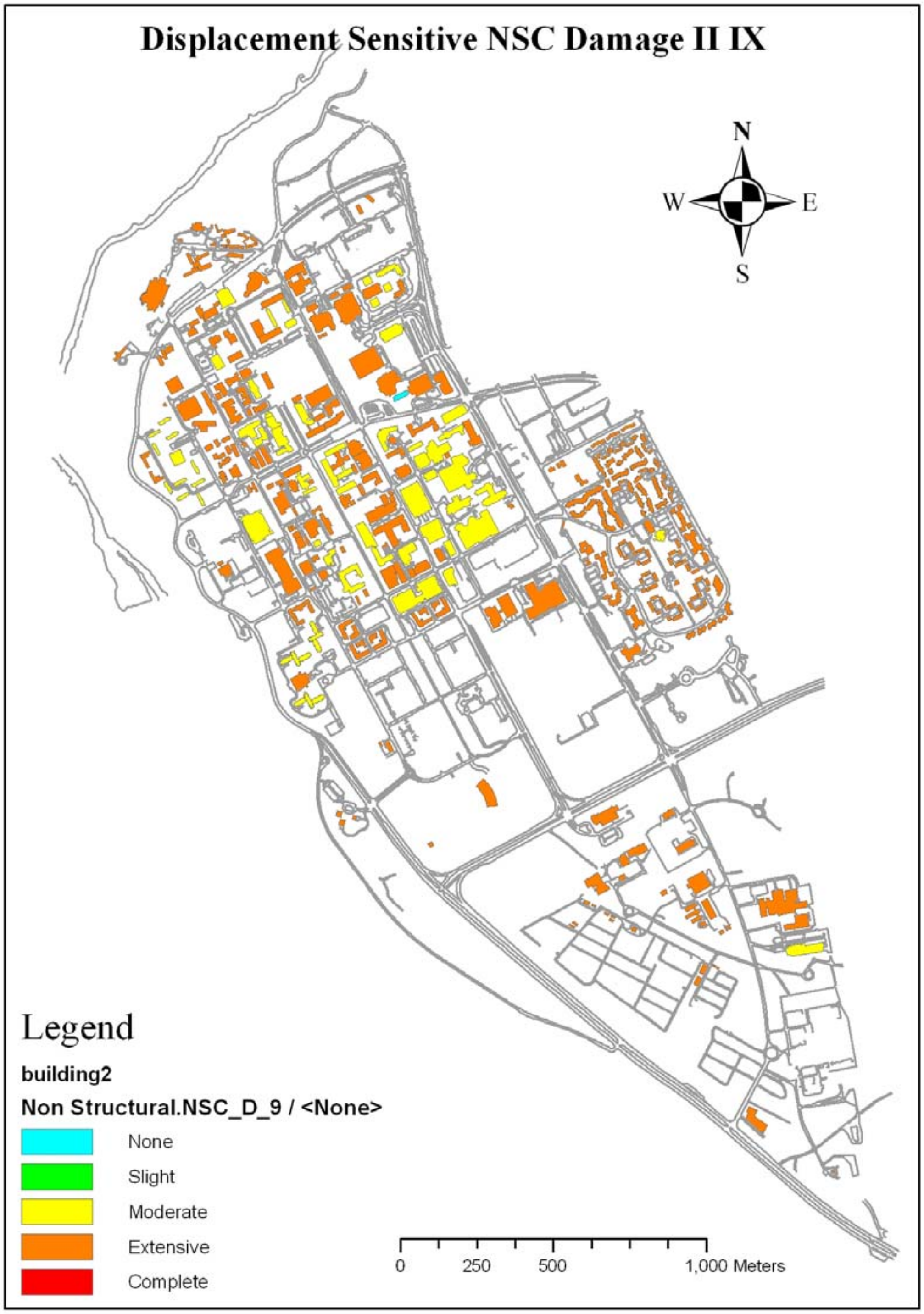
H - 1 UBC Displacement Sensitive Damage - II VI



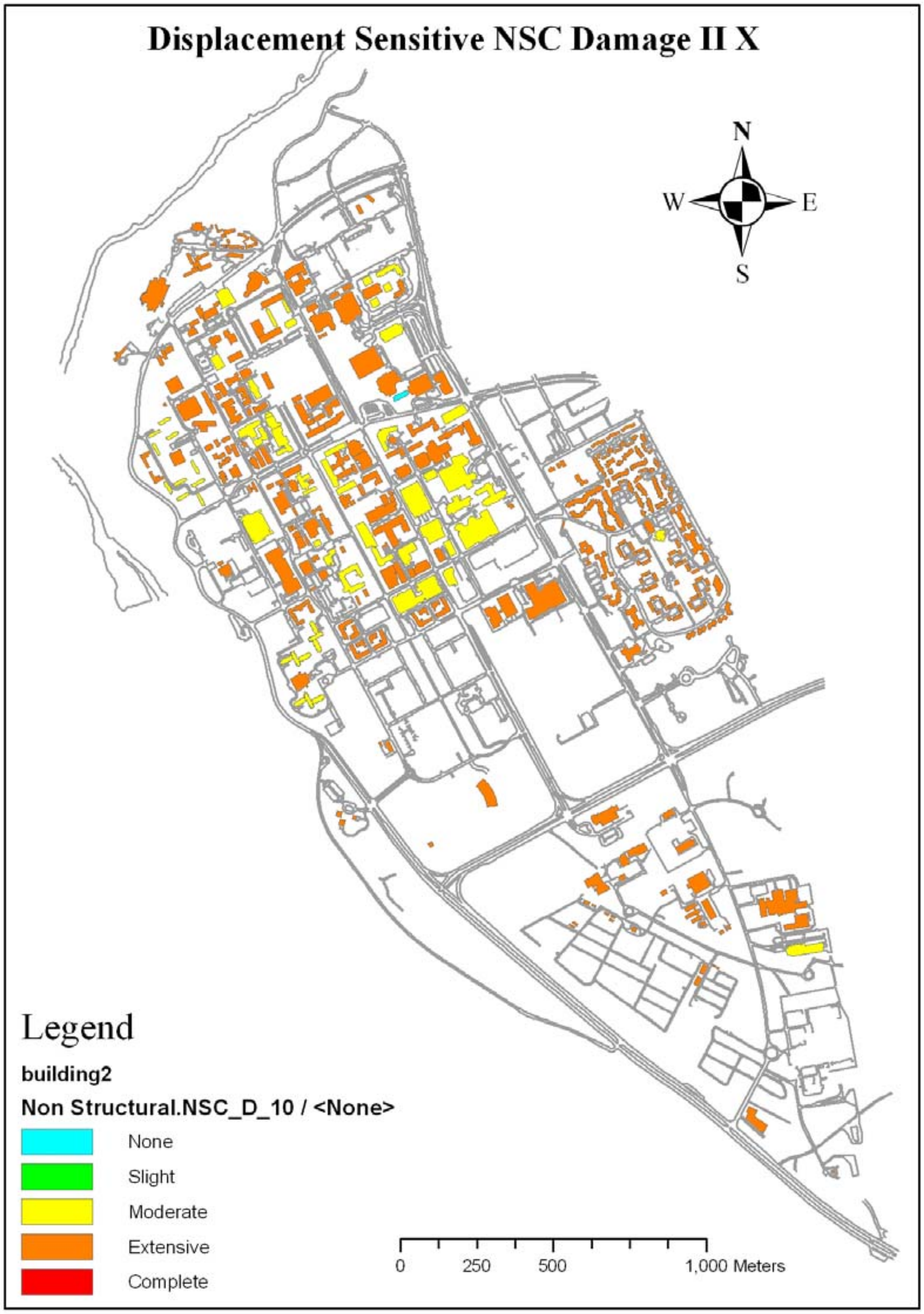
H - 2 UBC Displacement Sensitive Damage - II VII



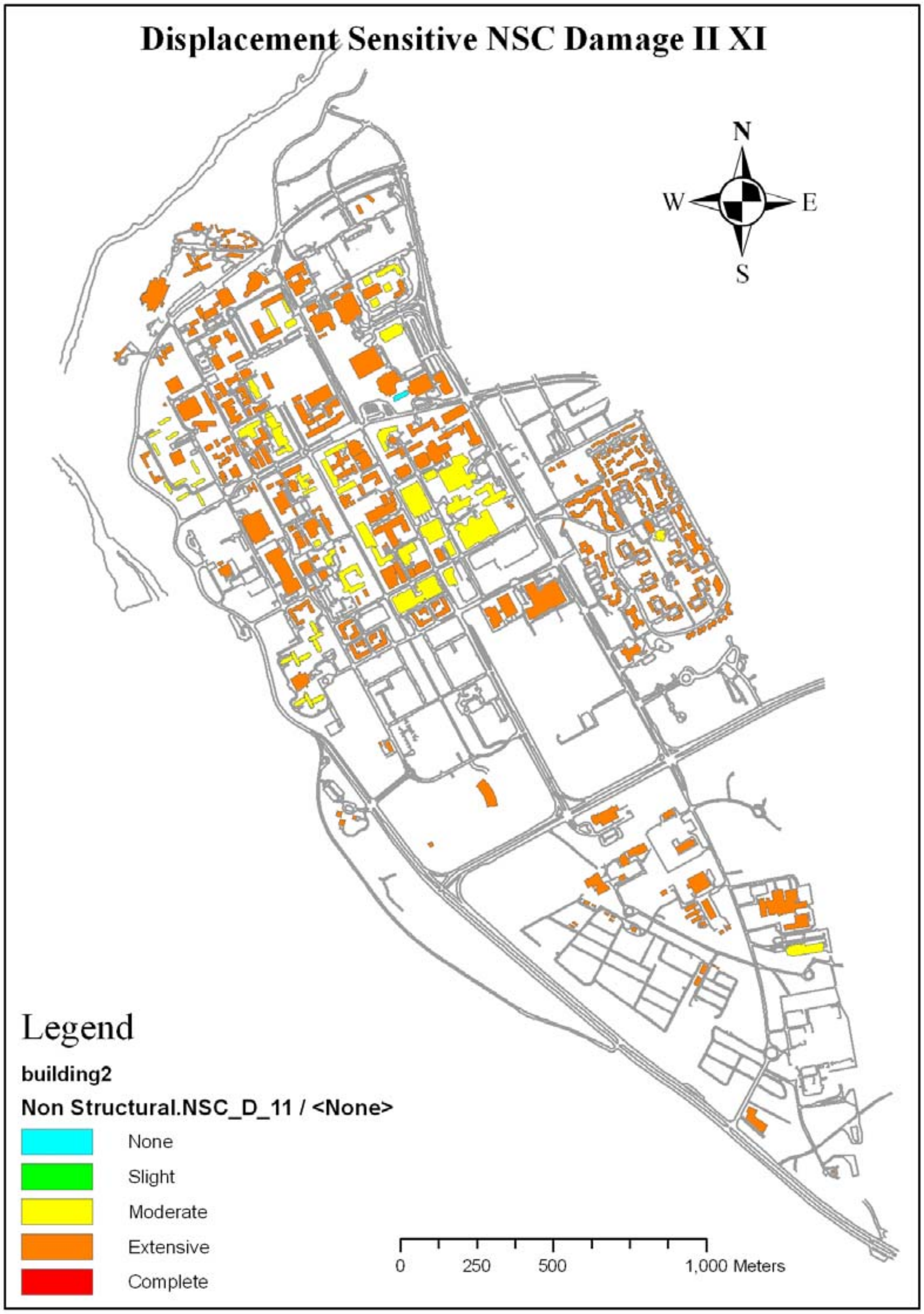
H - 3 UBC Displacement Sensitive Damage - II VIII



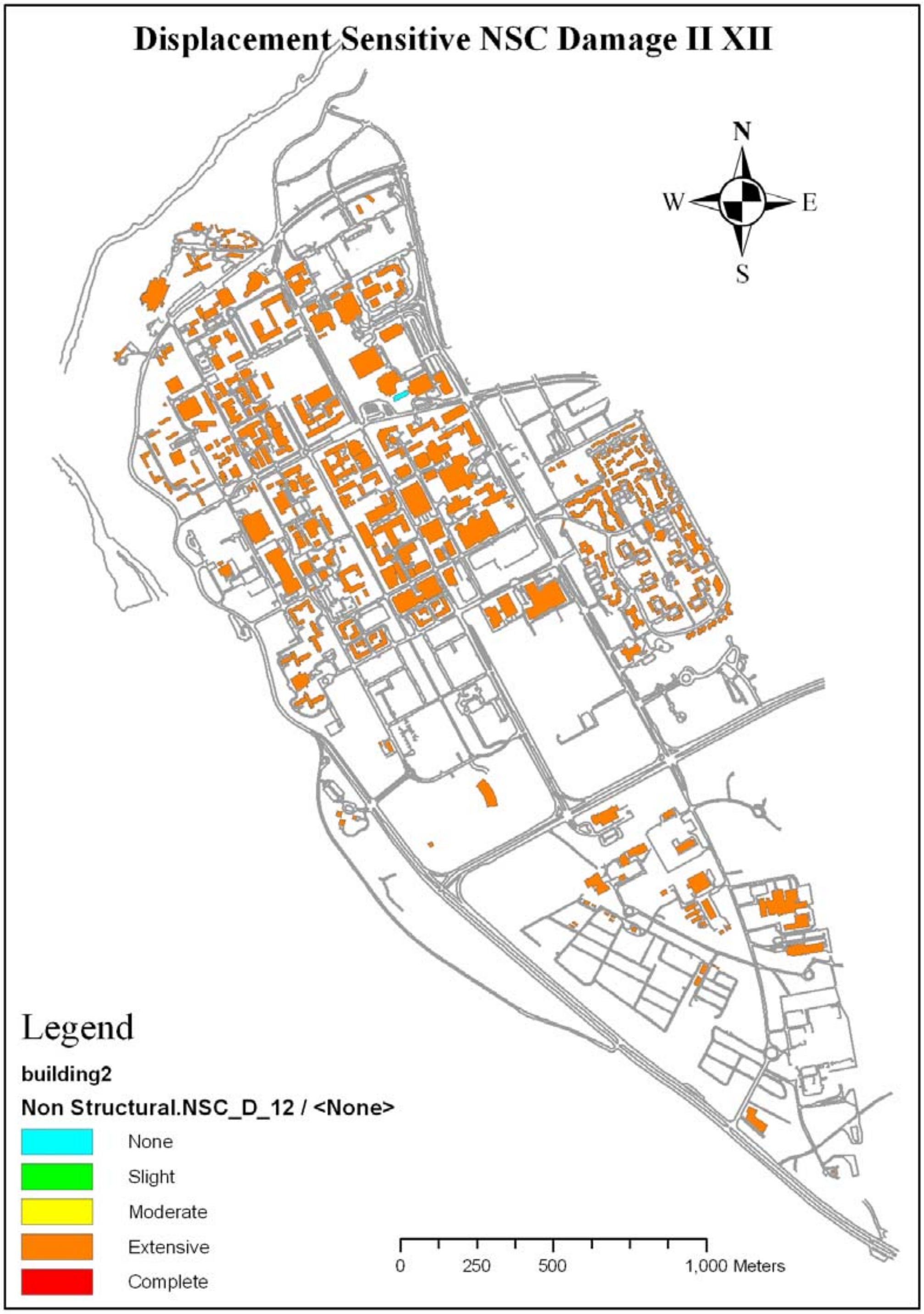
H - 4 UBC Displacement Sensitive Damage - II IX



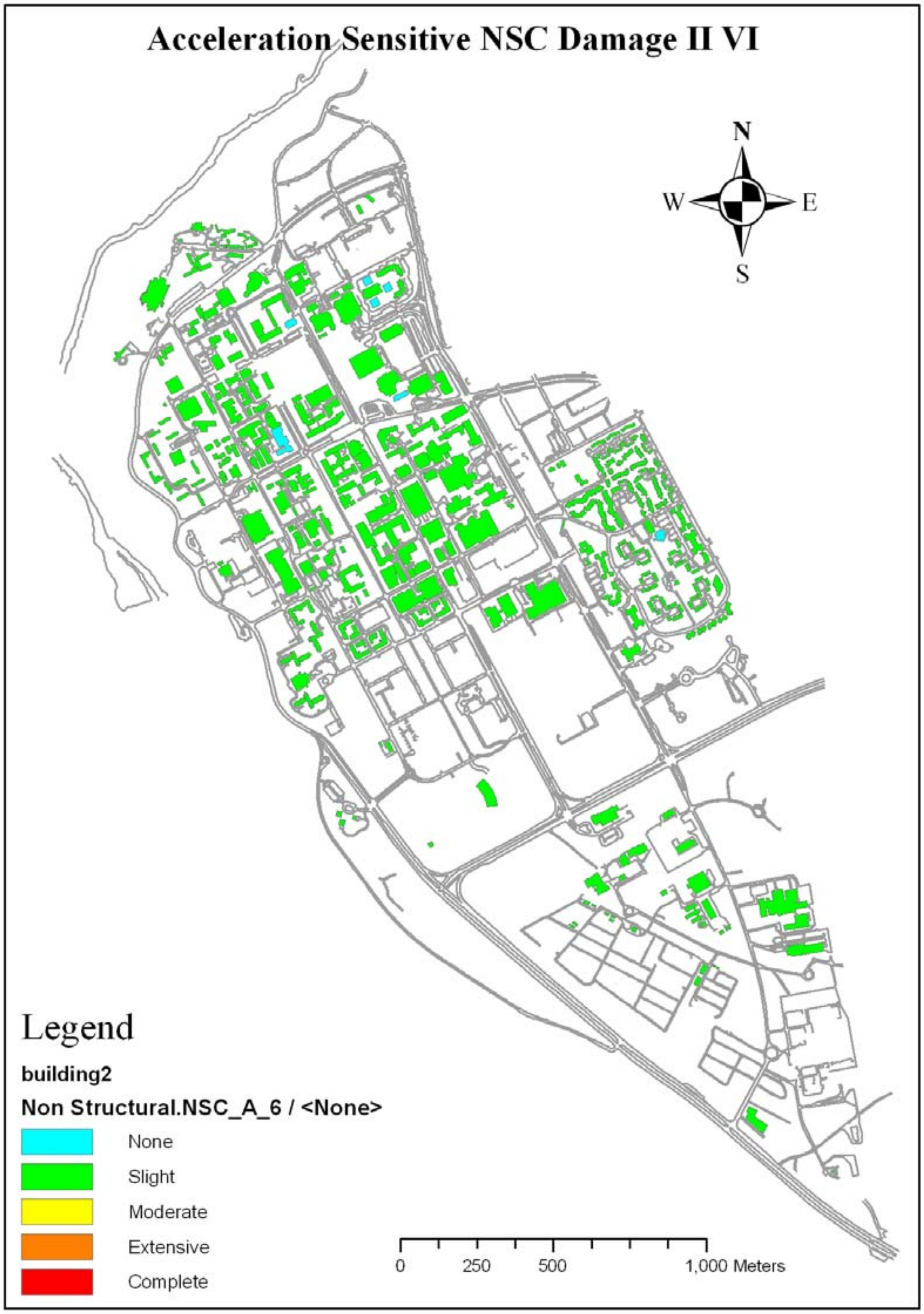
H - 5 UBC Displacement Sensitive Damage - II X



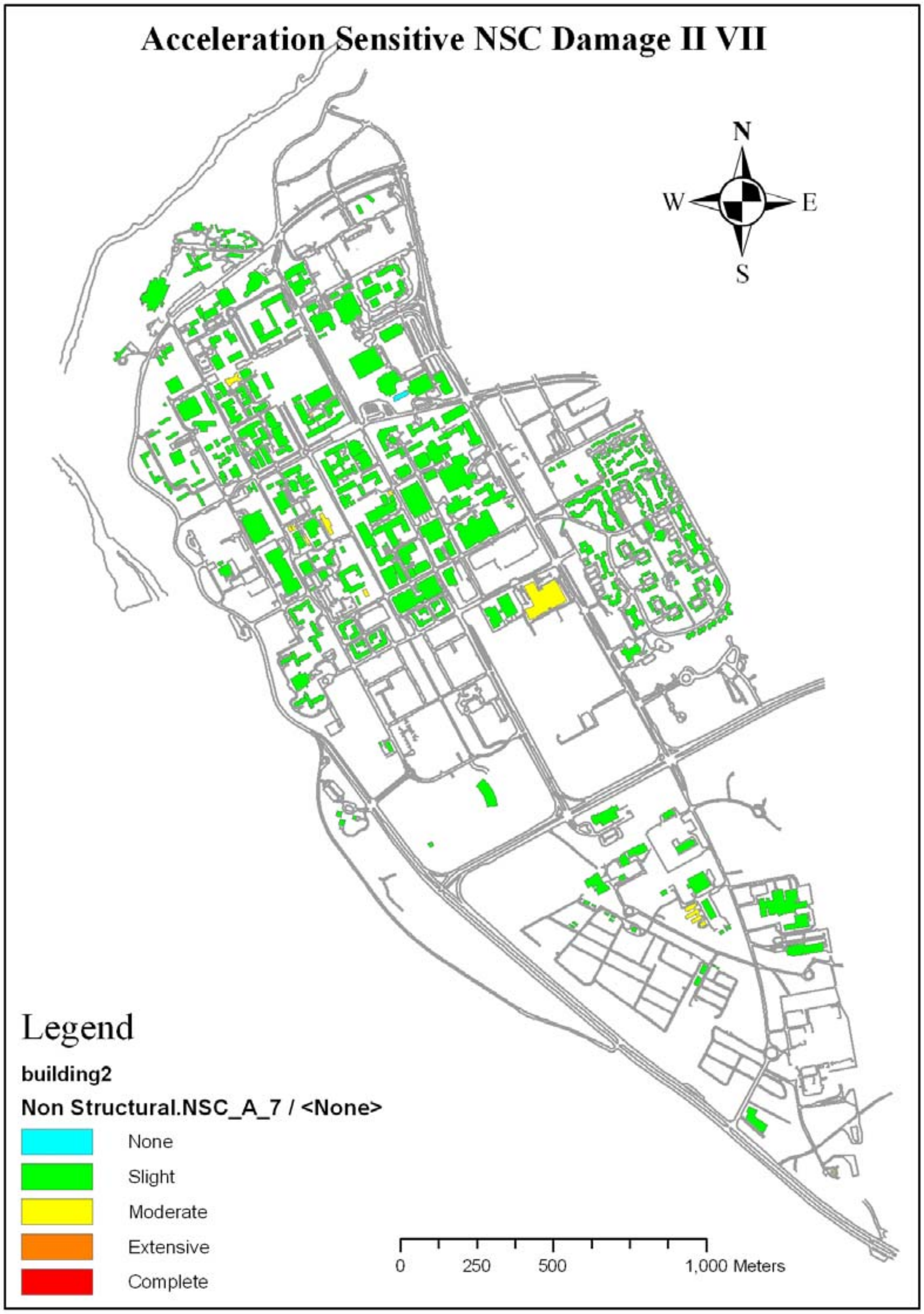
H - 6 UBC Displacement Sensitive Damage - II XI



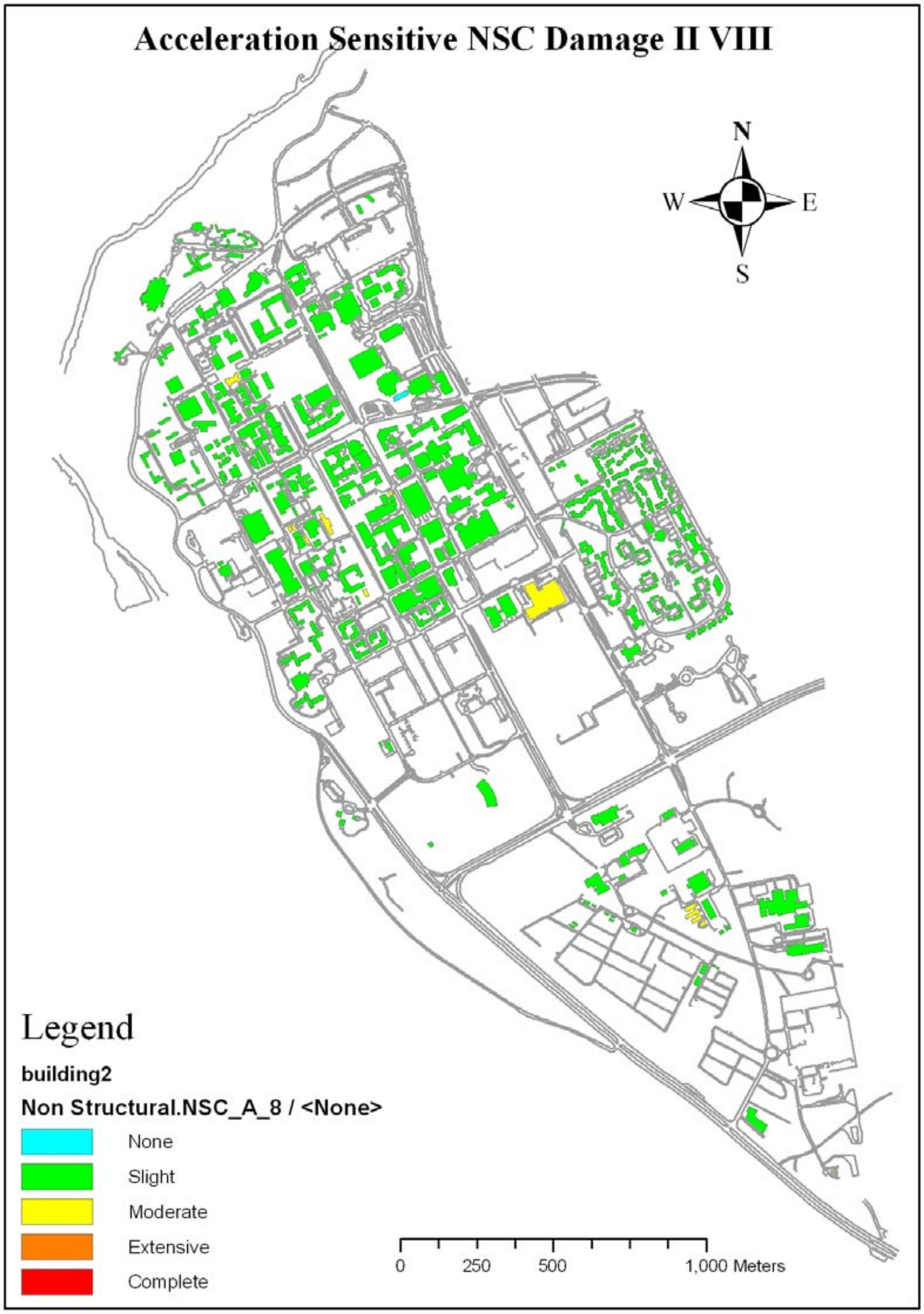
H - 7 UBC Displacement Sensitive Damage - II XII



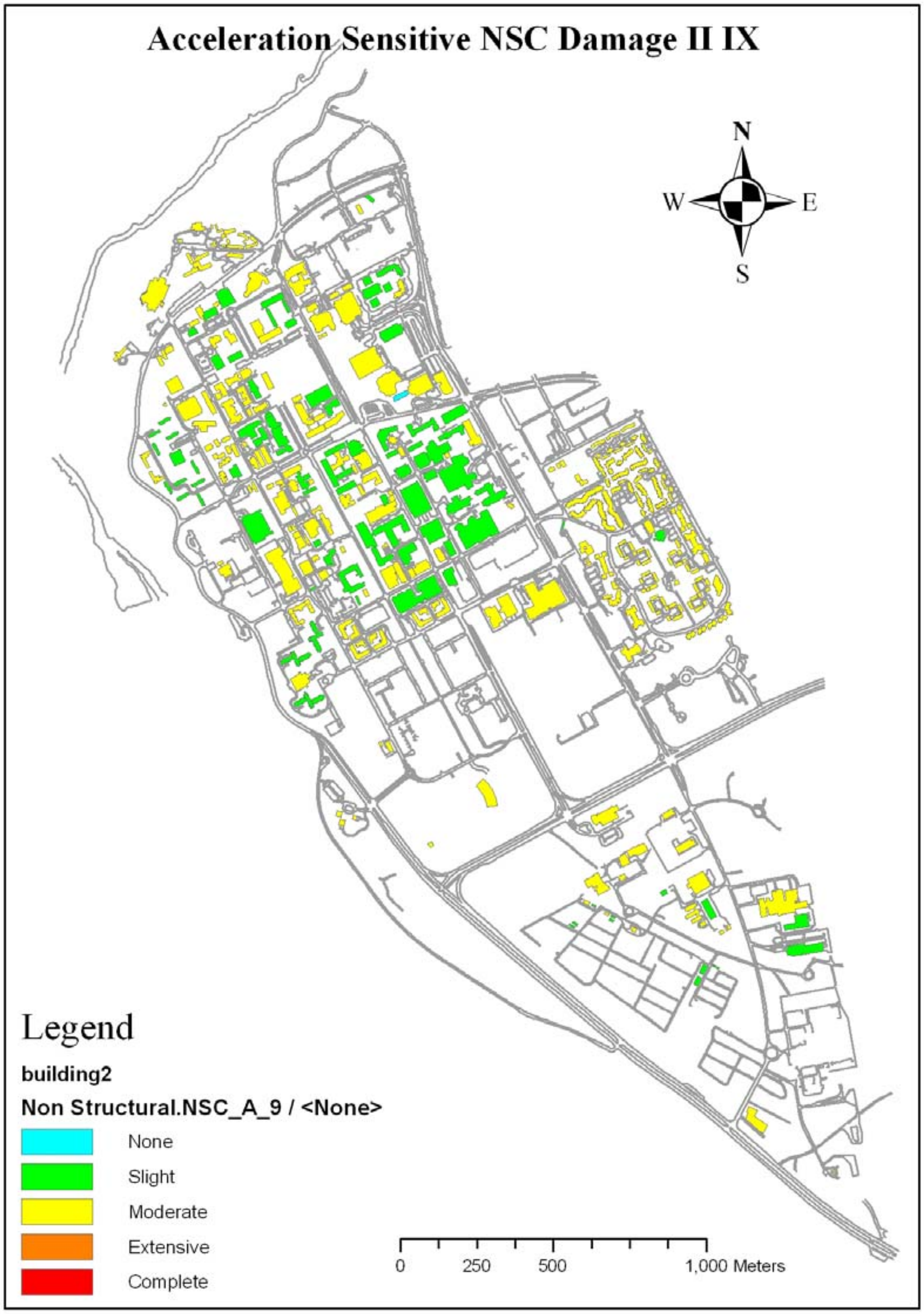
H - 8 UBC Acceleration Sensitive Damage - II VI



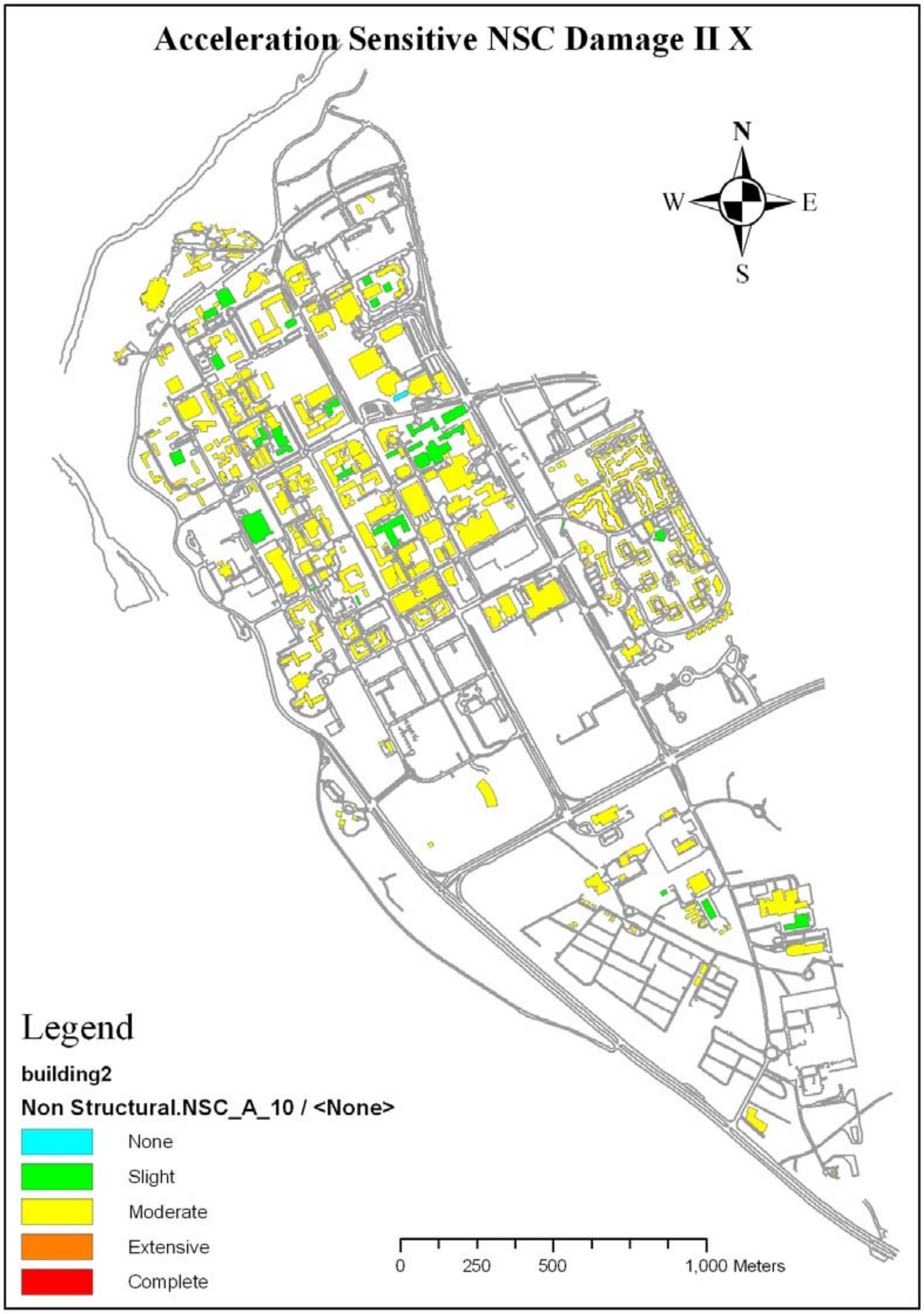
H - 9 UBC Acceleration Sensitive Damage - II VII



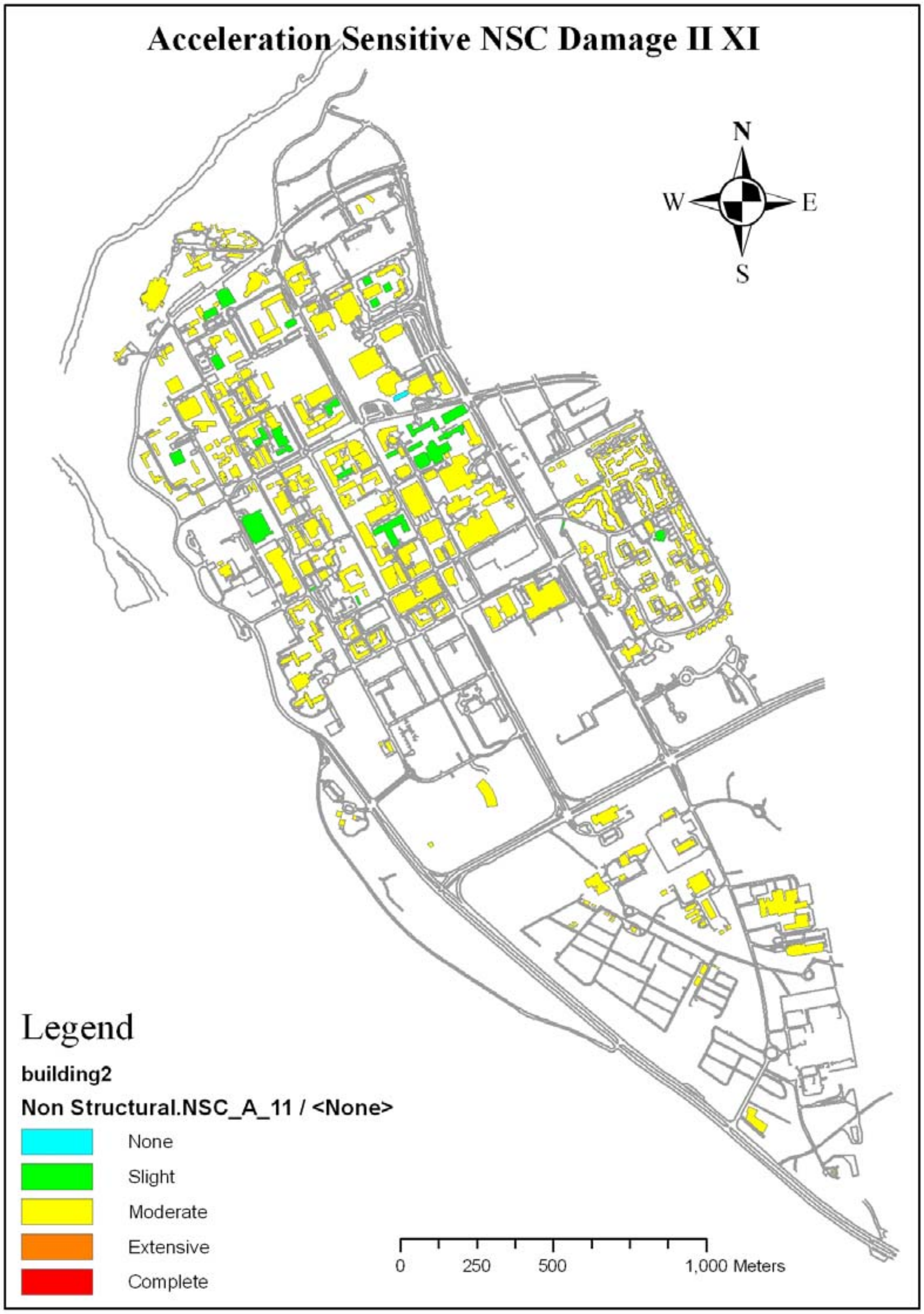
H - 10 UBC Acceleration Sensitive Damage - II VIII



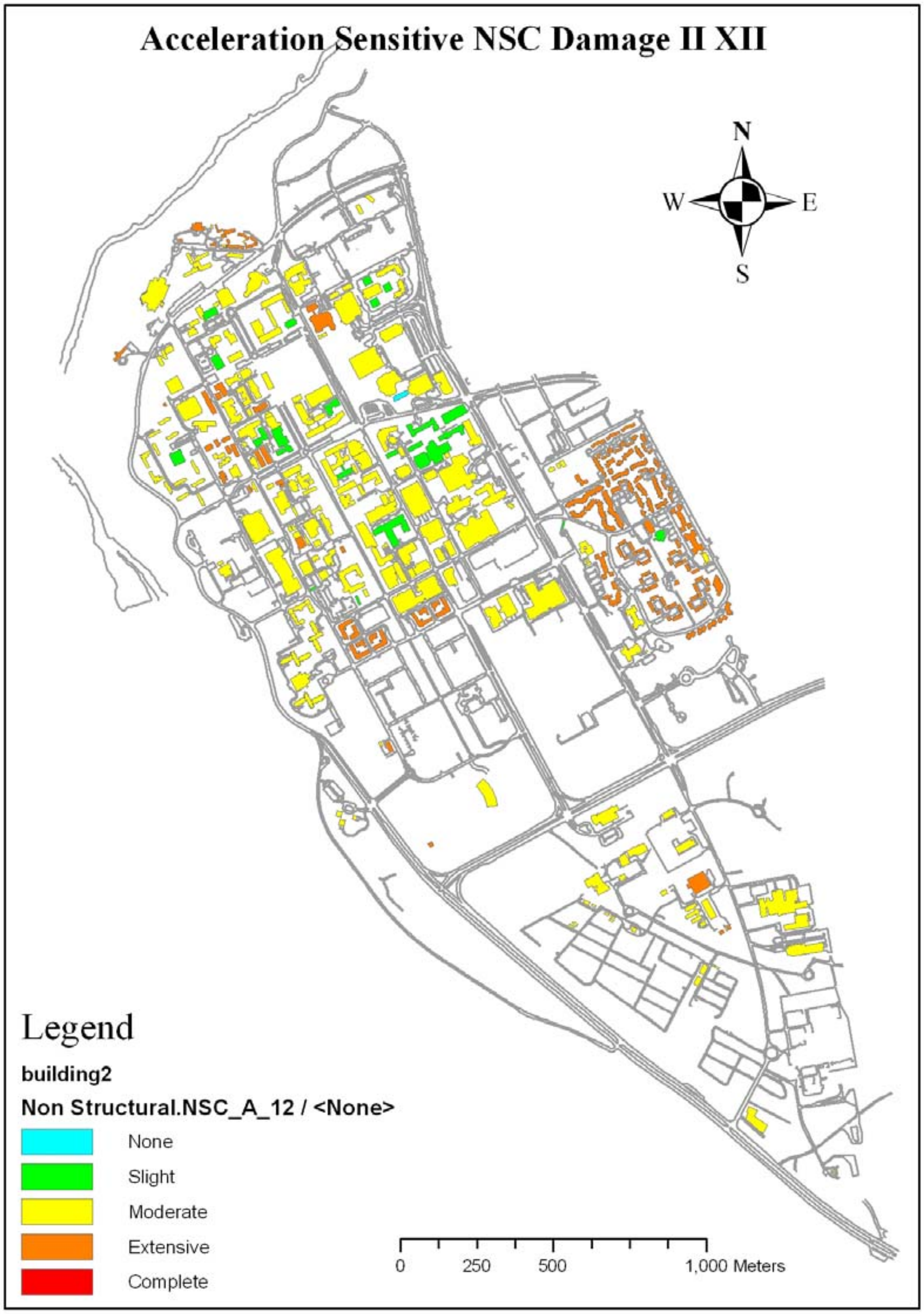
H - 11 UBC Acceleration Sensitive Damage - II IX



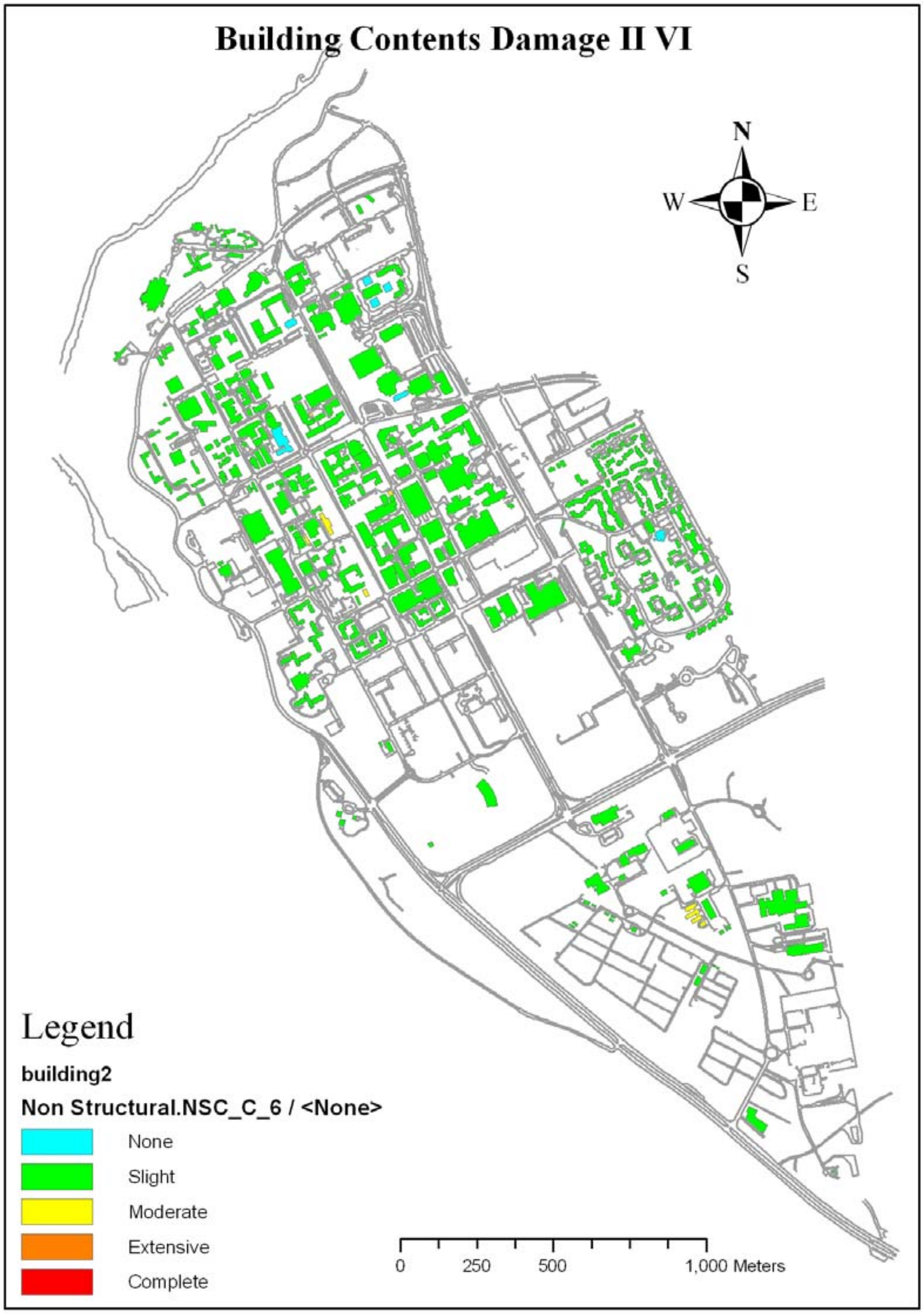
H - 12 UBC Acceleration Sensitive Damage - II X



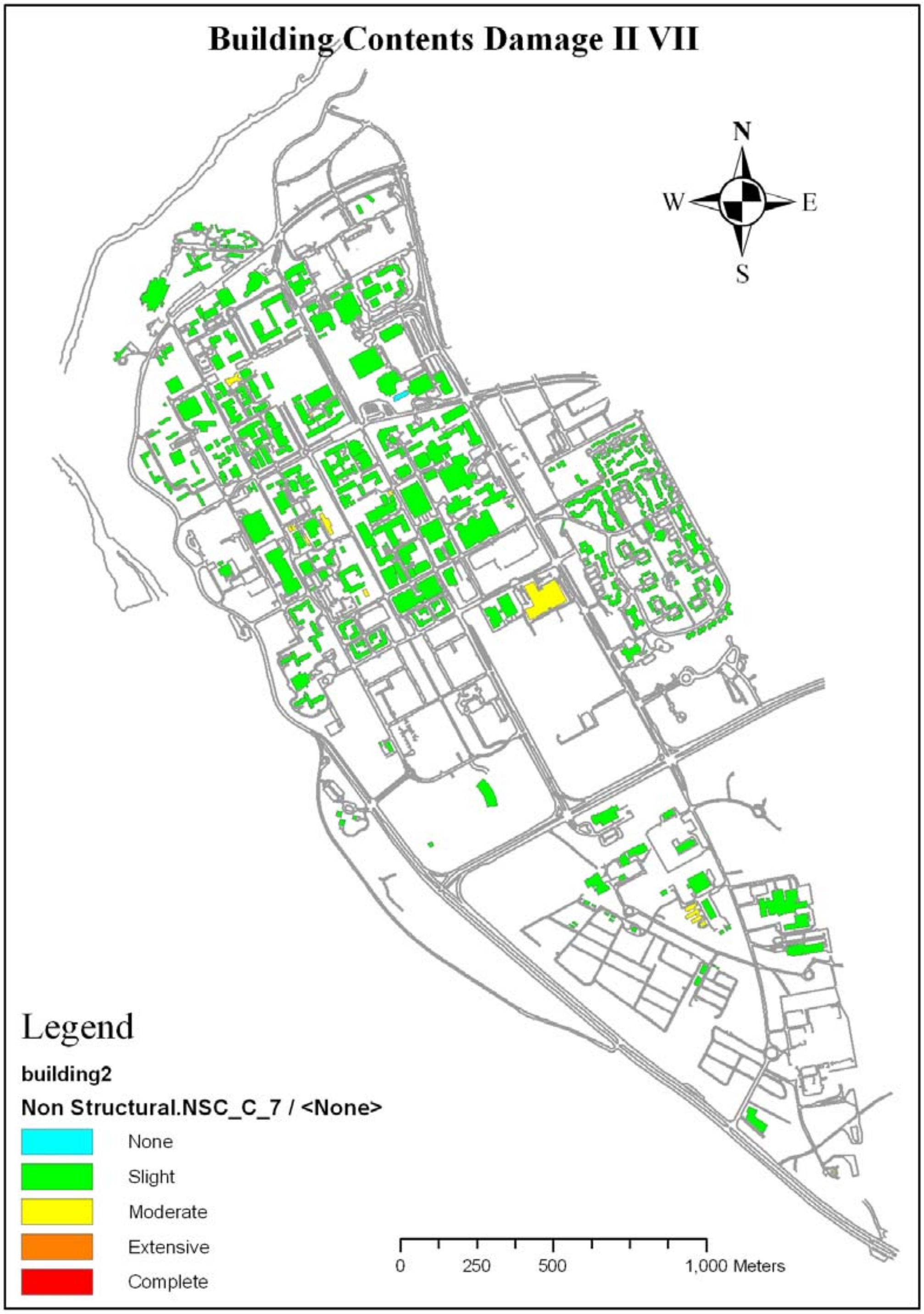
H - 13 UBC Acceleration Sensitive Damage - II XI



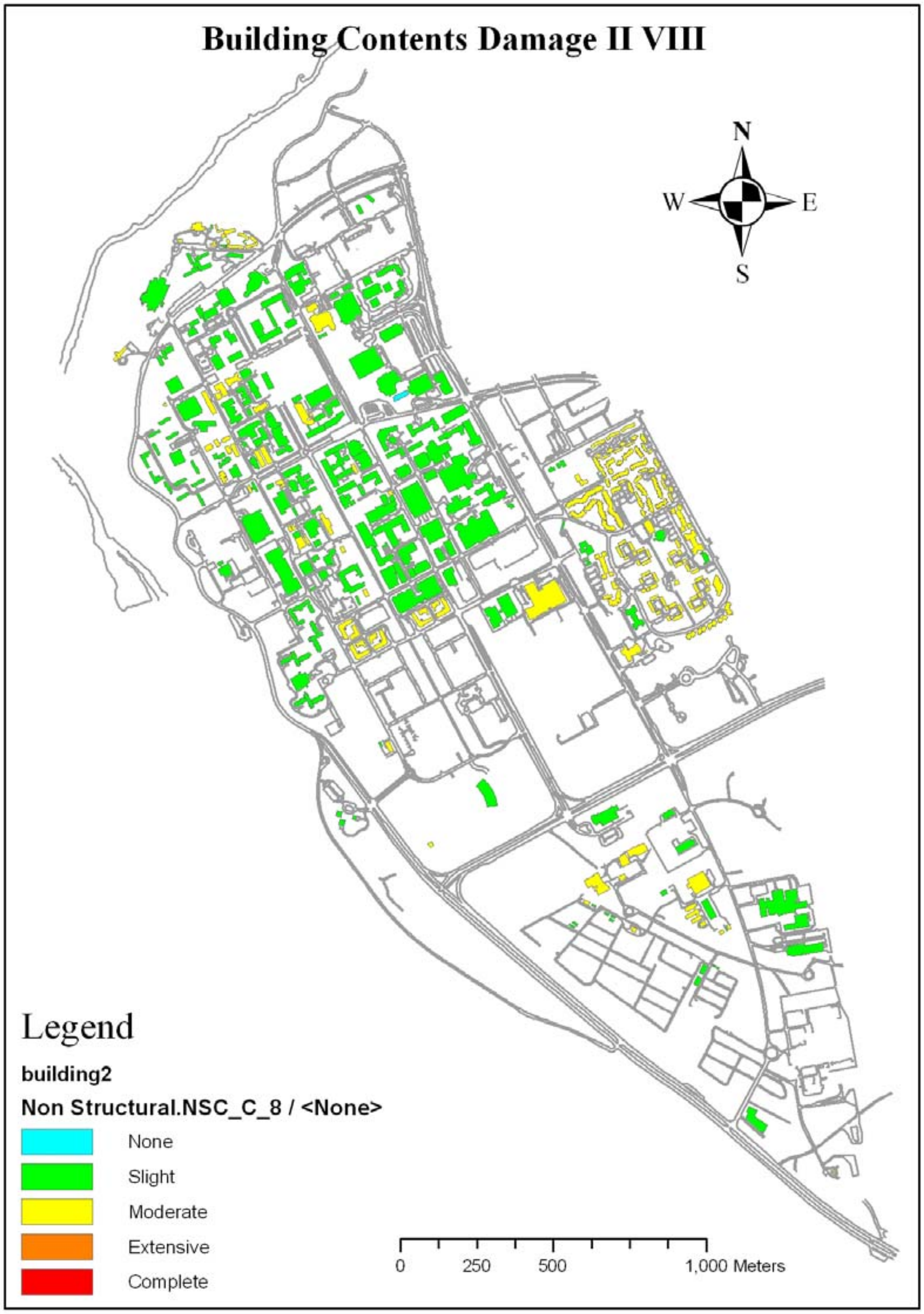
H - 14 UBC Acceleration Sensitive Damage - II XII



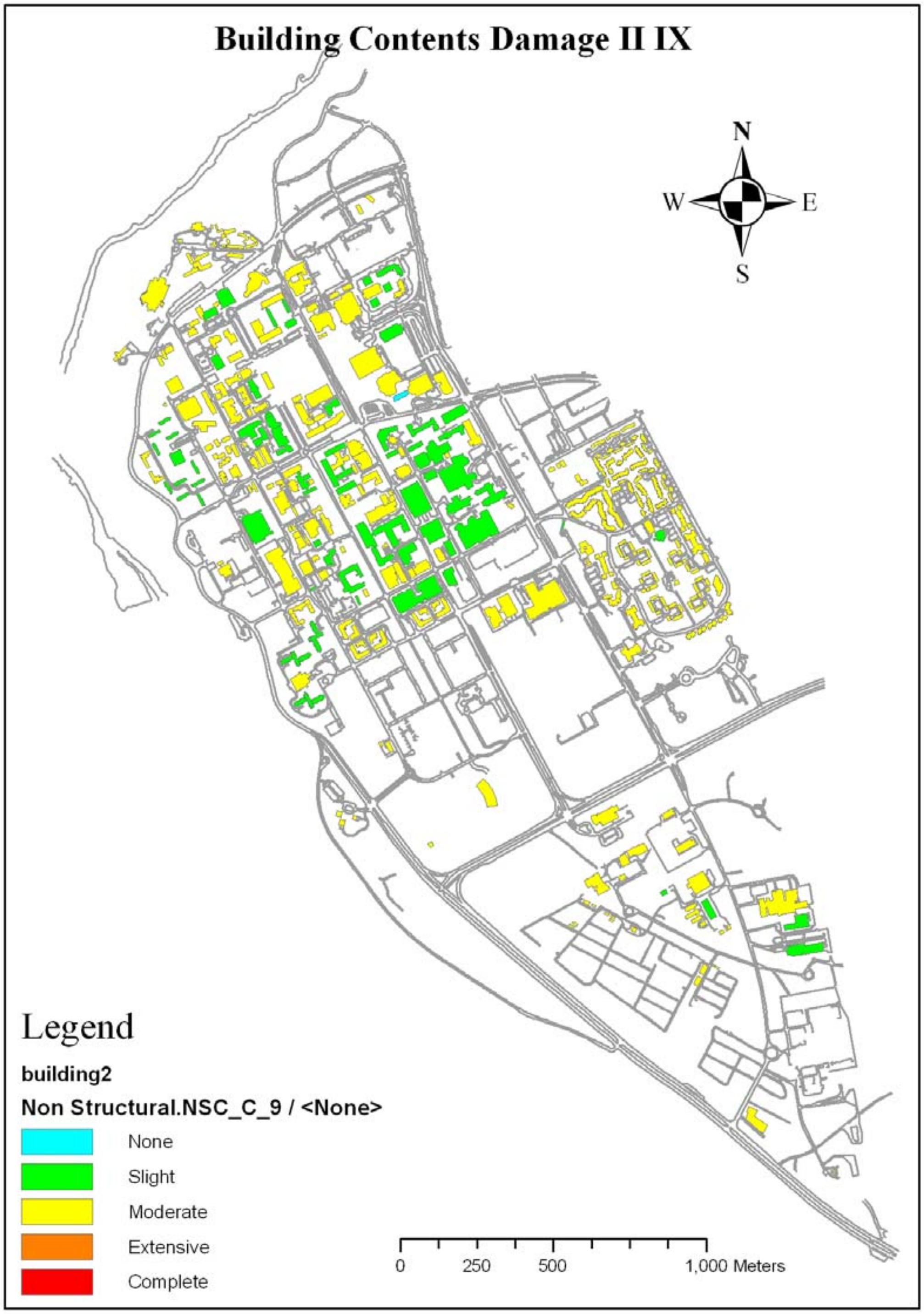
H - 15 UBC Building Contents Damage - II VI



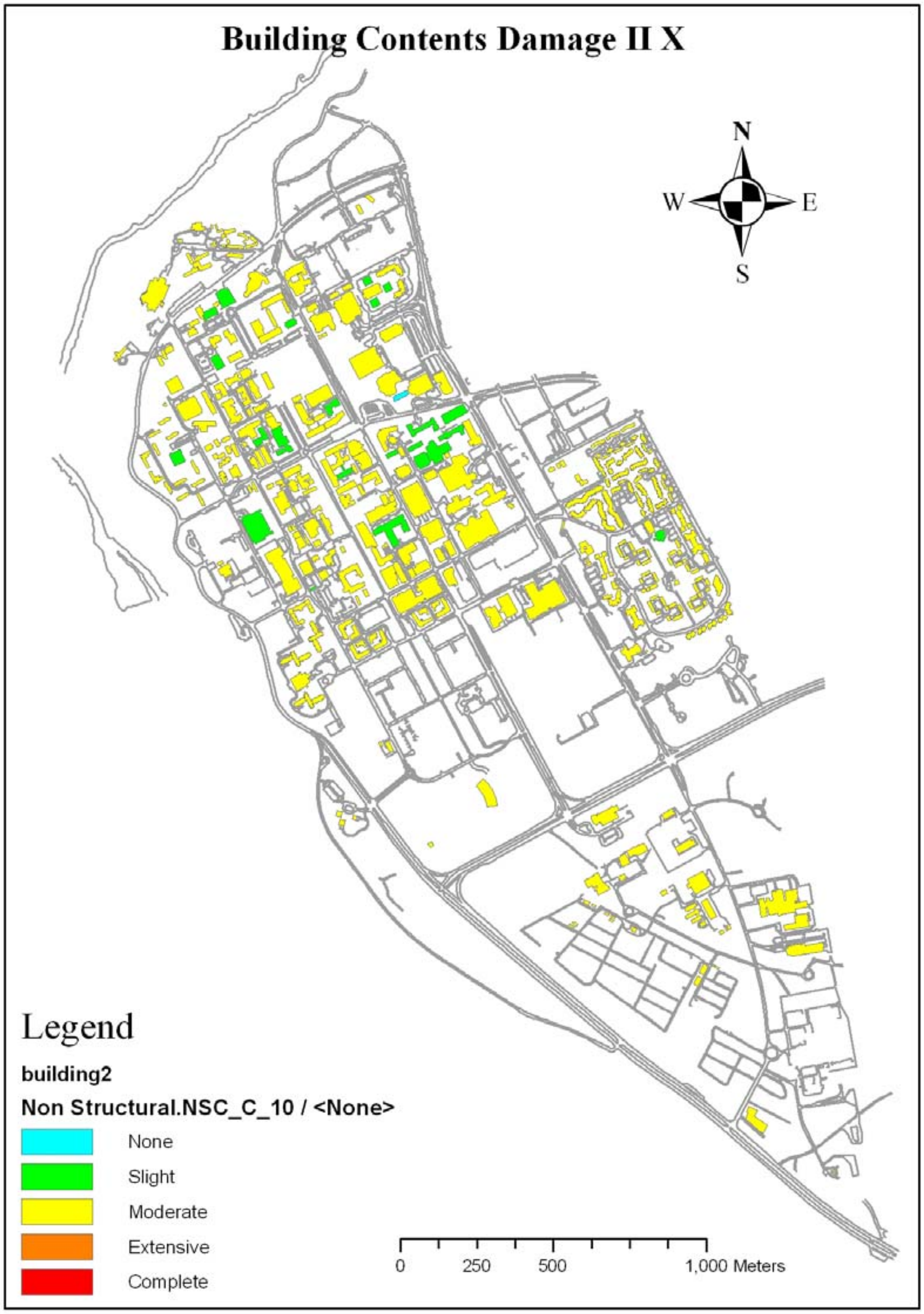
H - 16 UBC Building Contents Damage - II VII



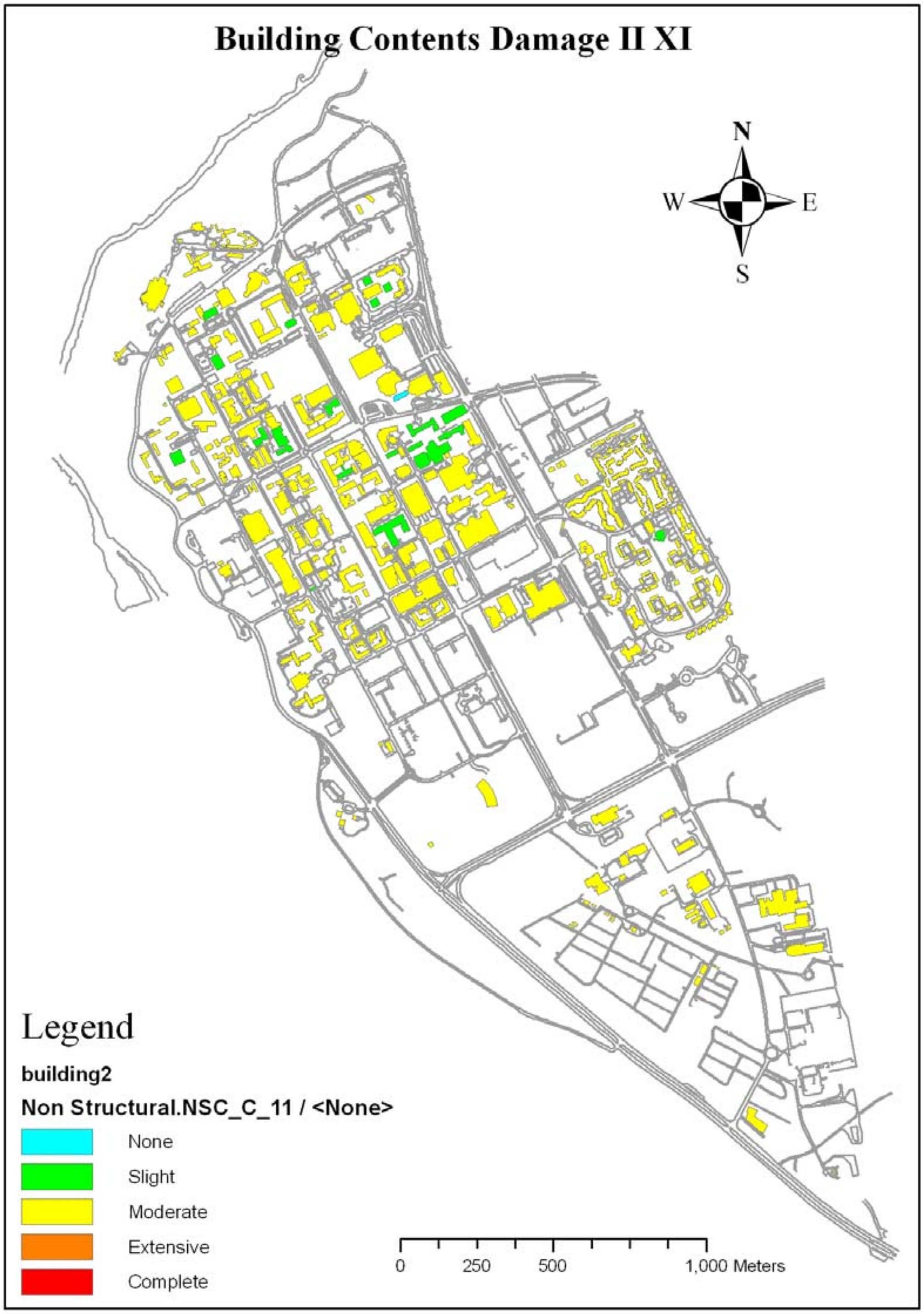
H - 17 UBC Building Contents Damage - II VIII



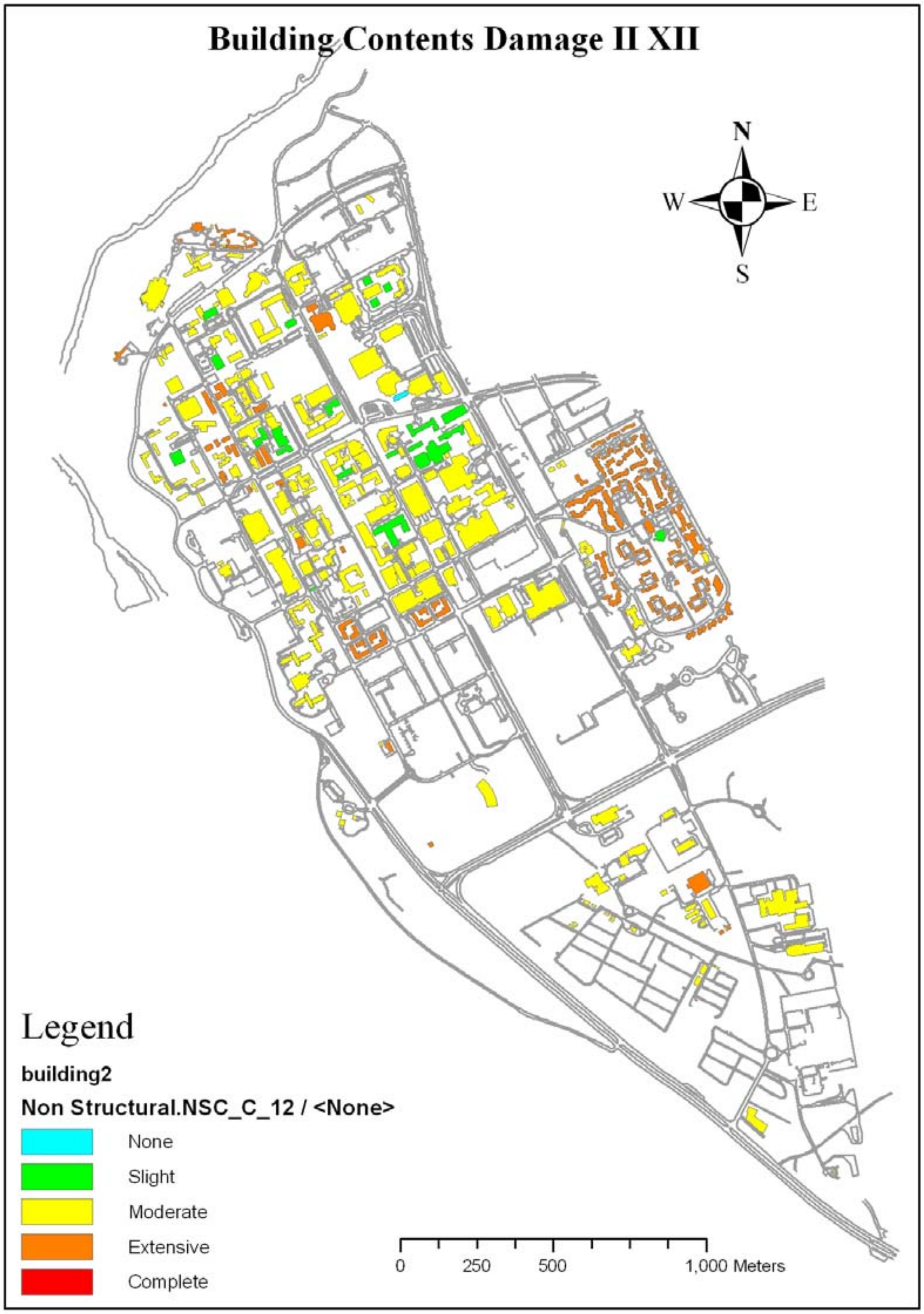
H - 18 UBC Building Contents Damage - II IX



H - 19 UBC Building Contents Damage - II X



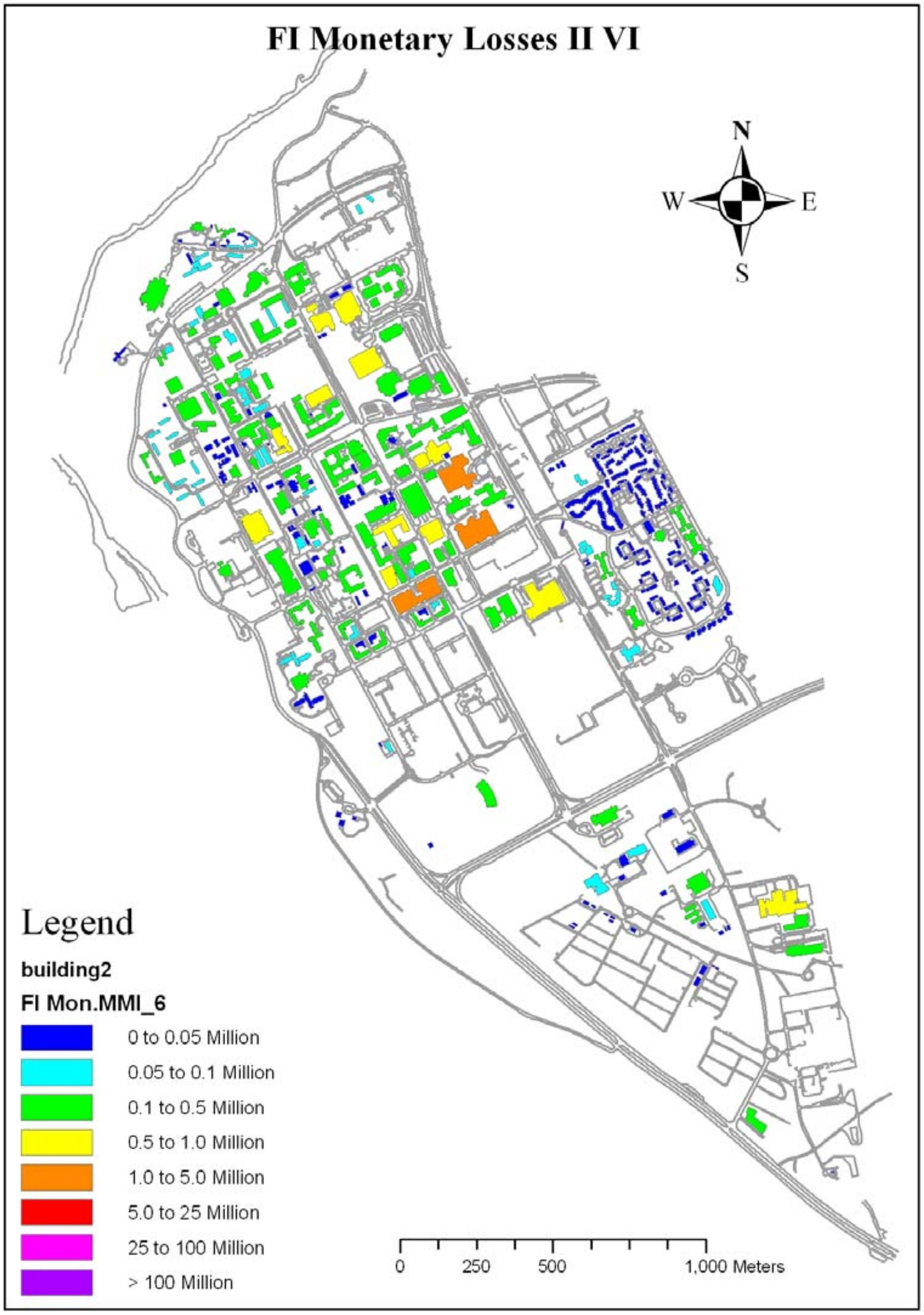
H - 20 UBC Building Contents Damage - II XI



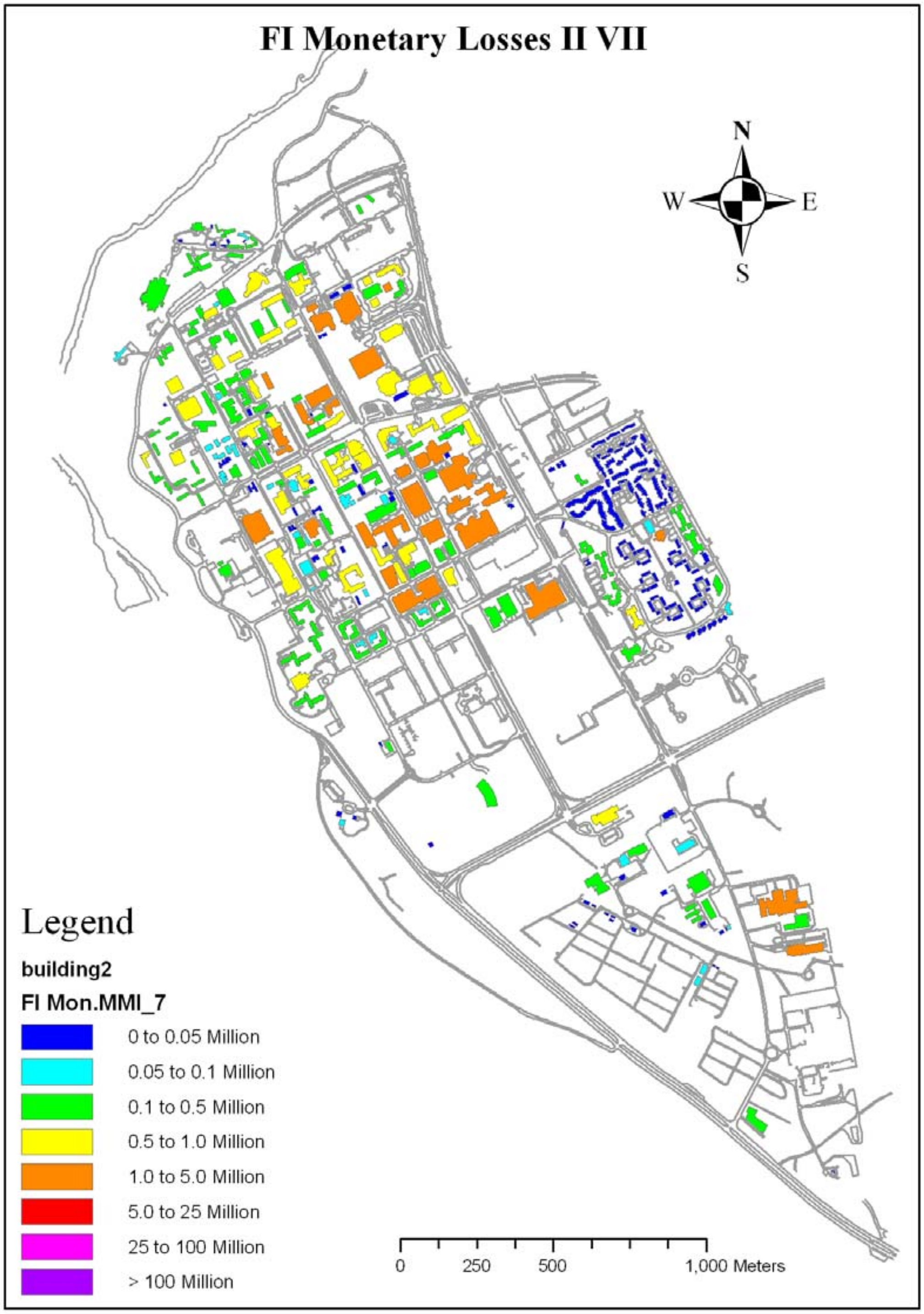
H - 21 UBC Building Contents Damage - II XII

Appendix I: UBC Monetary Loss Results

This appendix presents the Facility Independent and Facility Dependent UBC monetary loss results for all seven levels of Instrumental intensity.

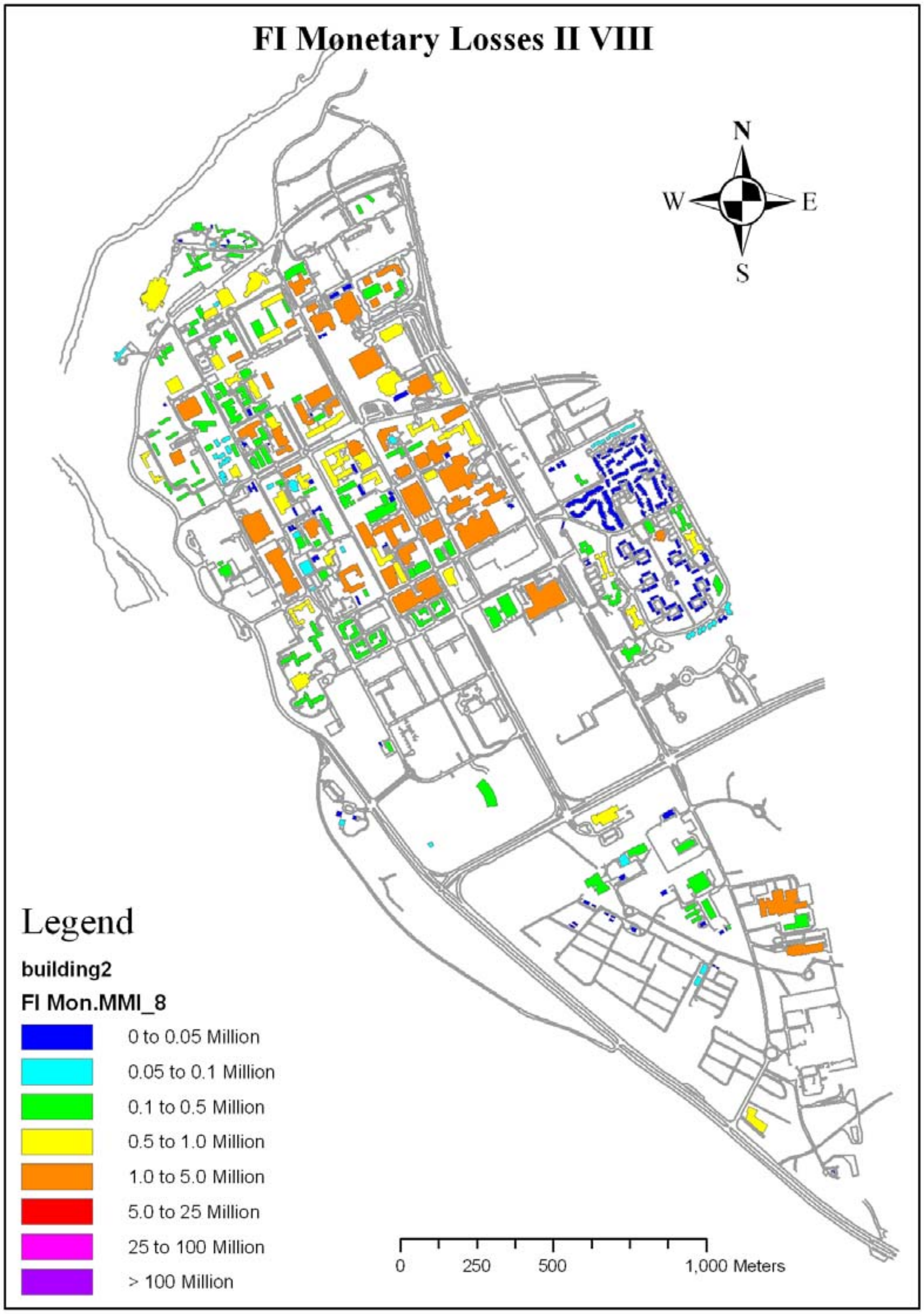


I - 1 UBC FI Monetary Losses – II VI

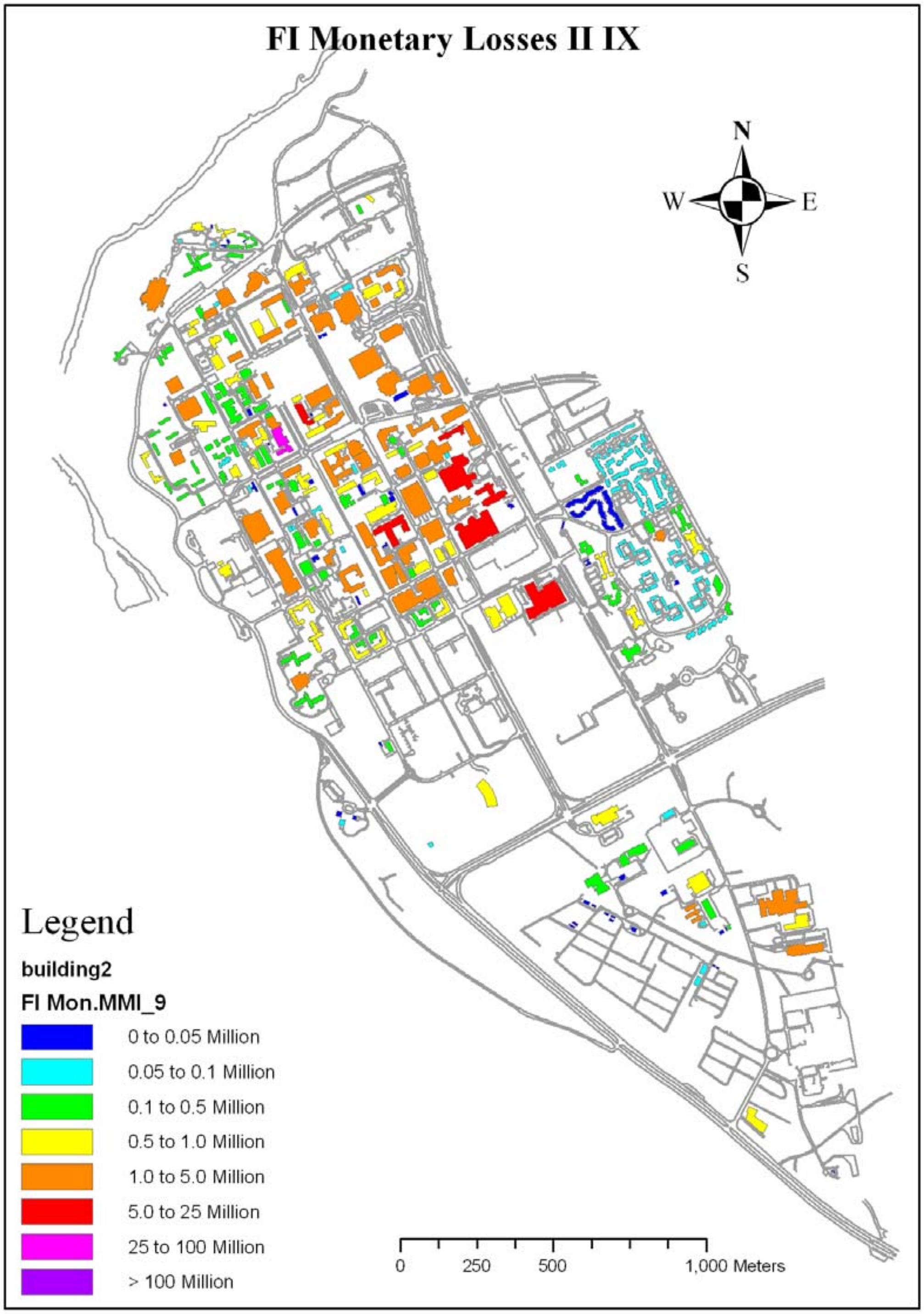


FI Monetary Losses II VII

I - 2 UBC FI Monetary Losses – II VII



I - 3 UBC FI Monetary Losses – II VIII



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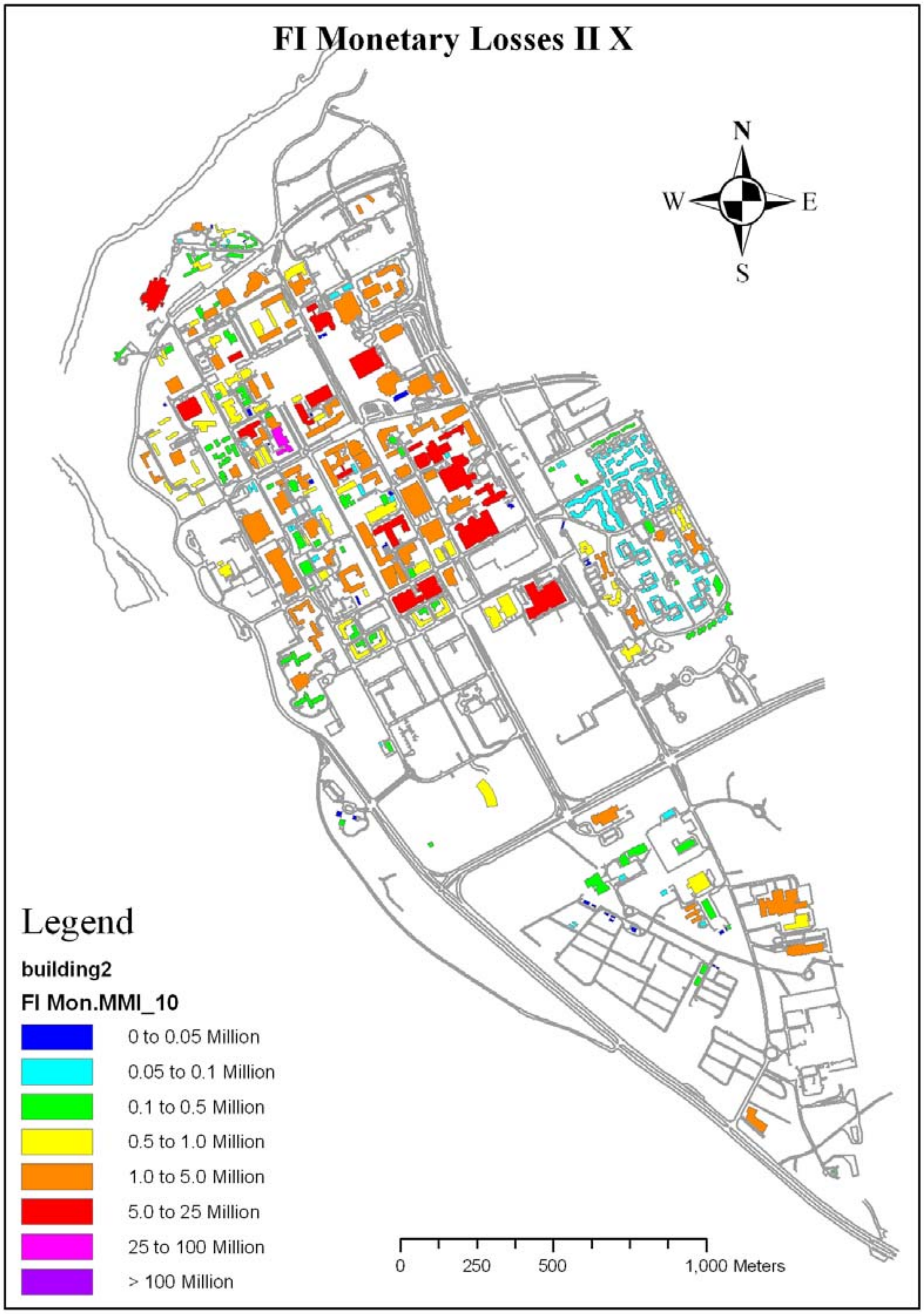

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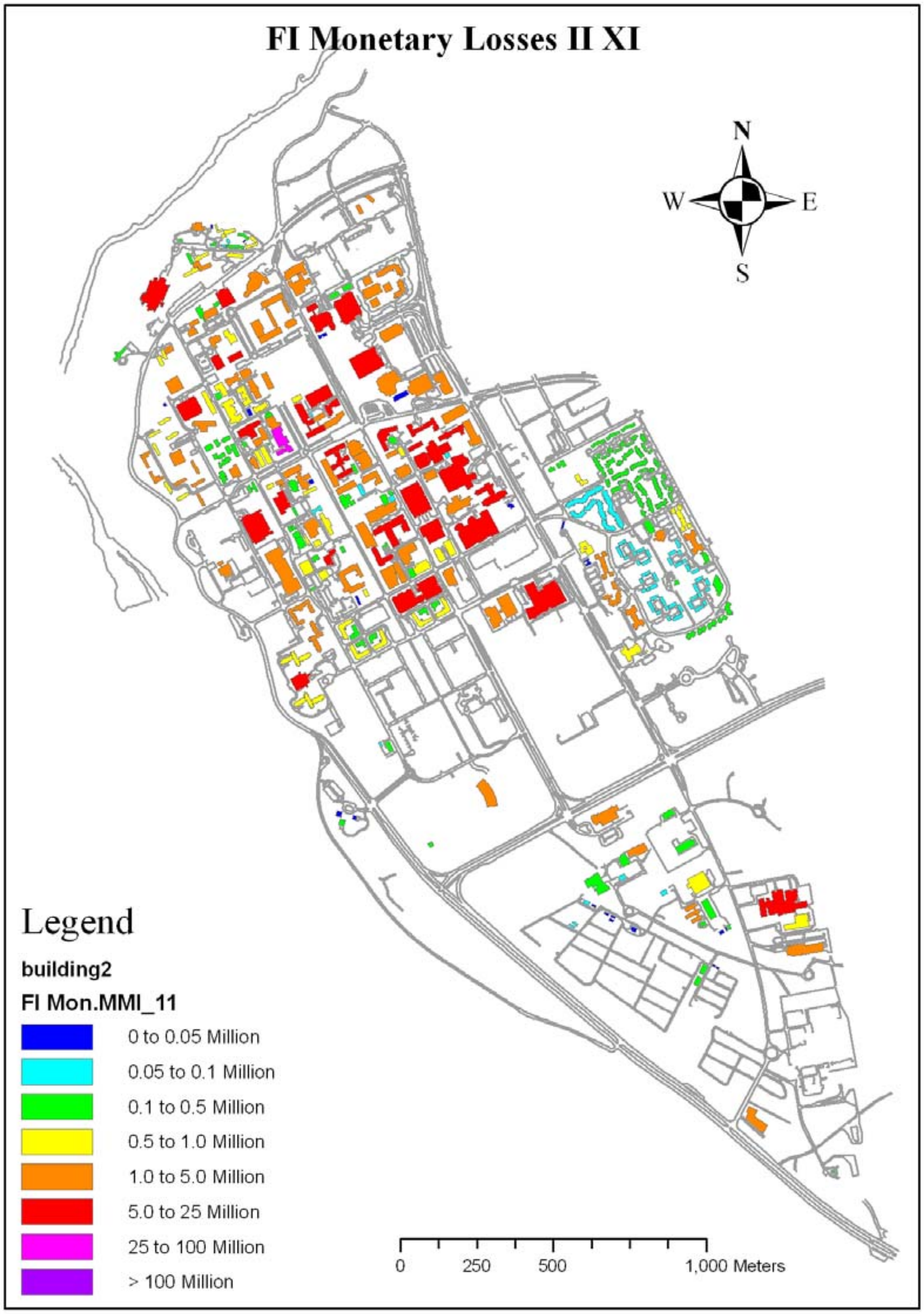
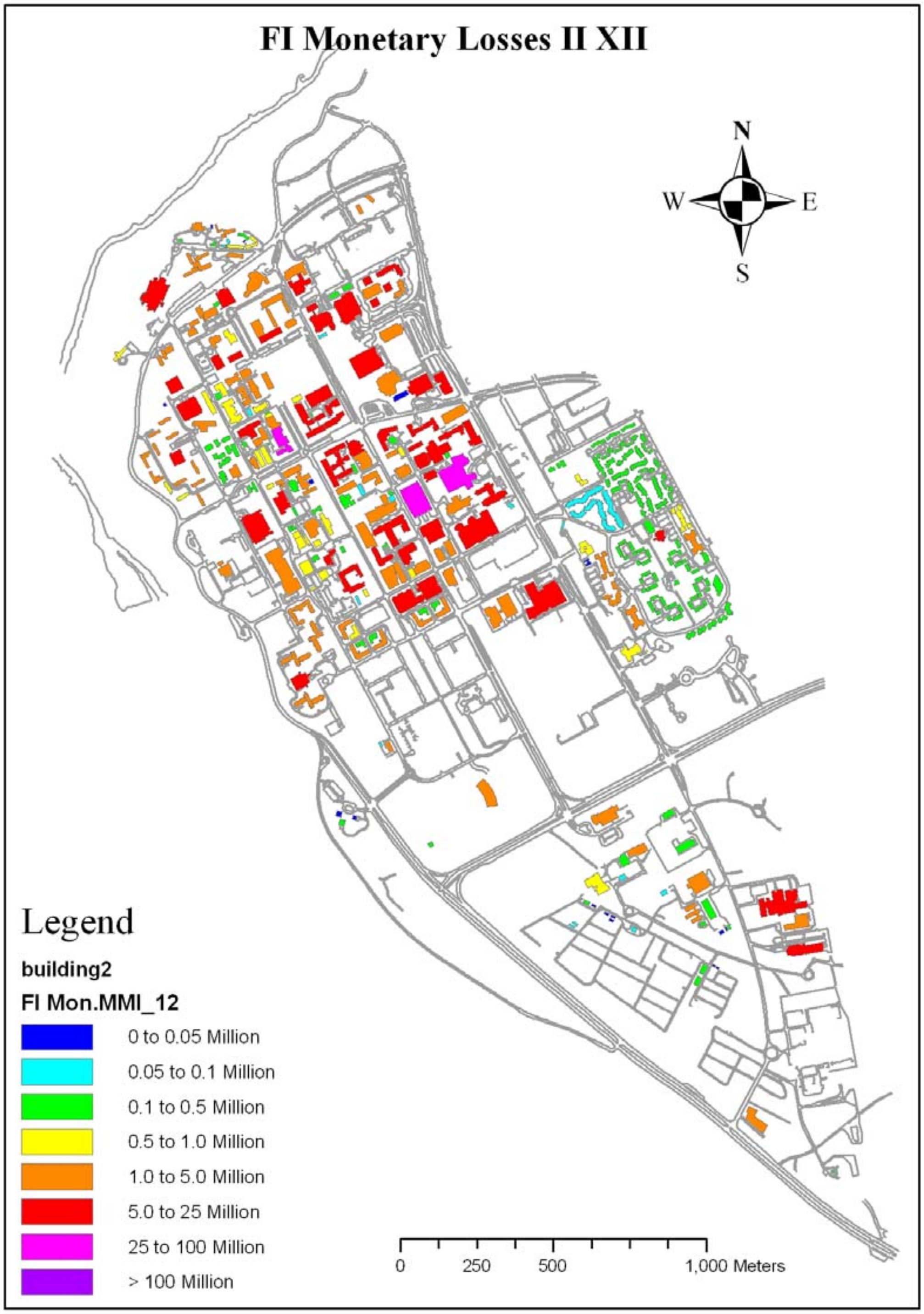
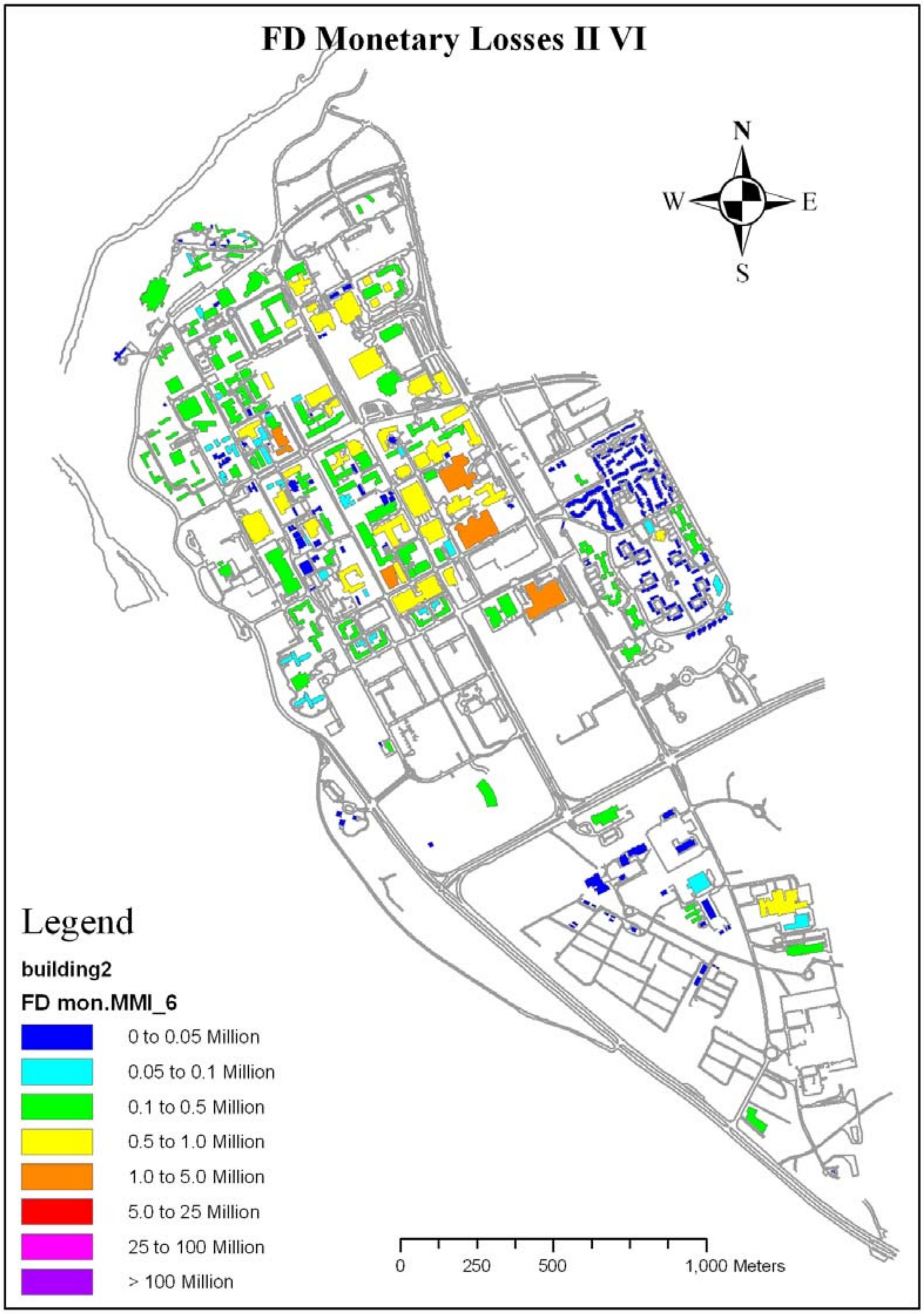


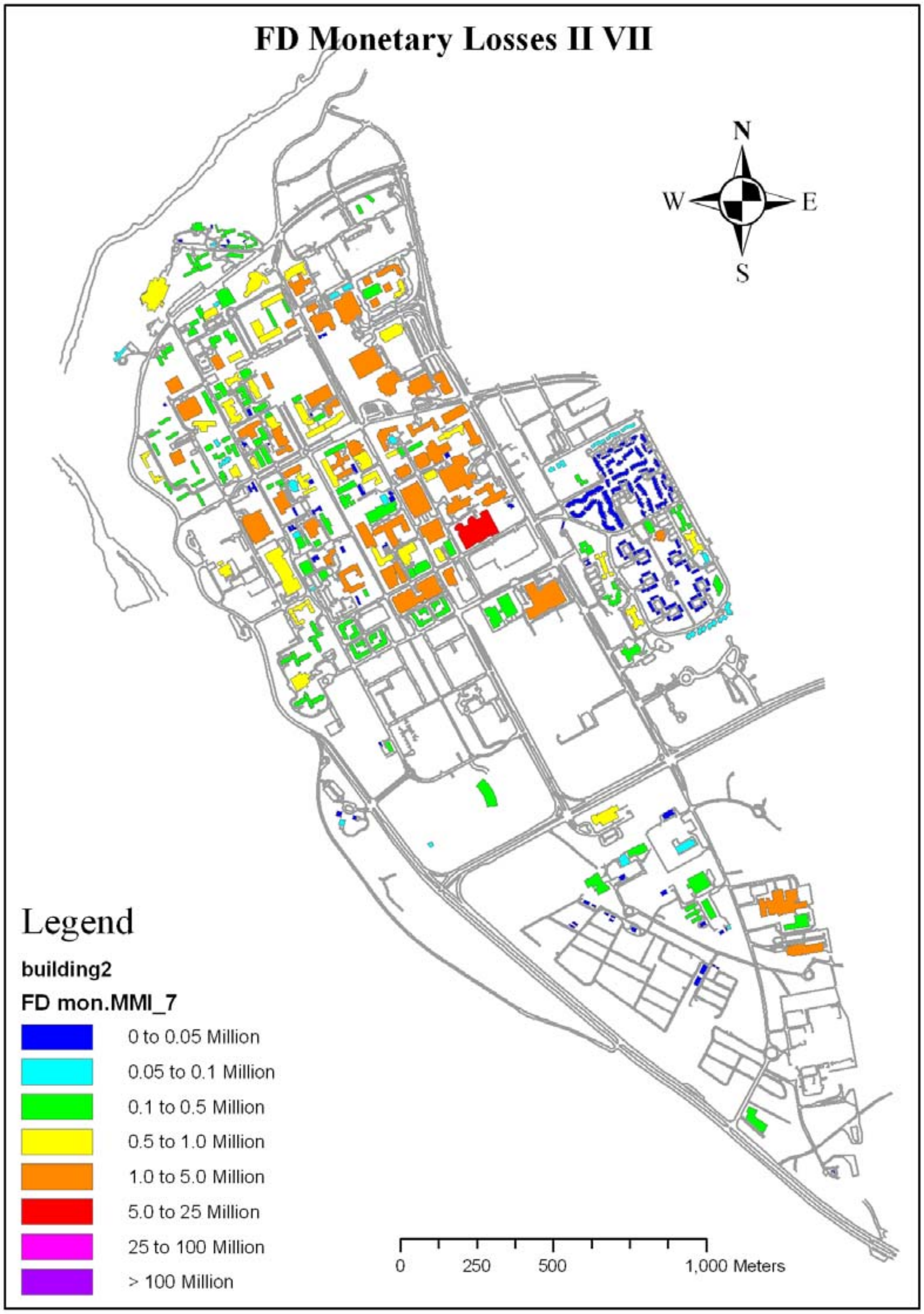
I - 6 UBC FI Monetary Losses – II XI



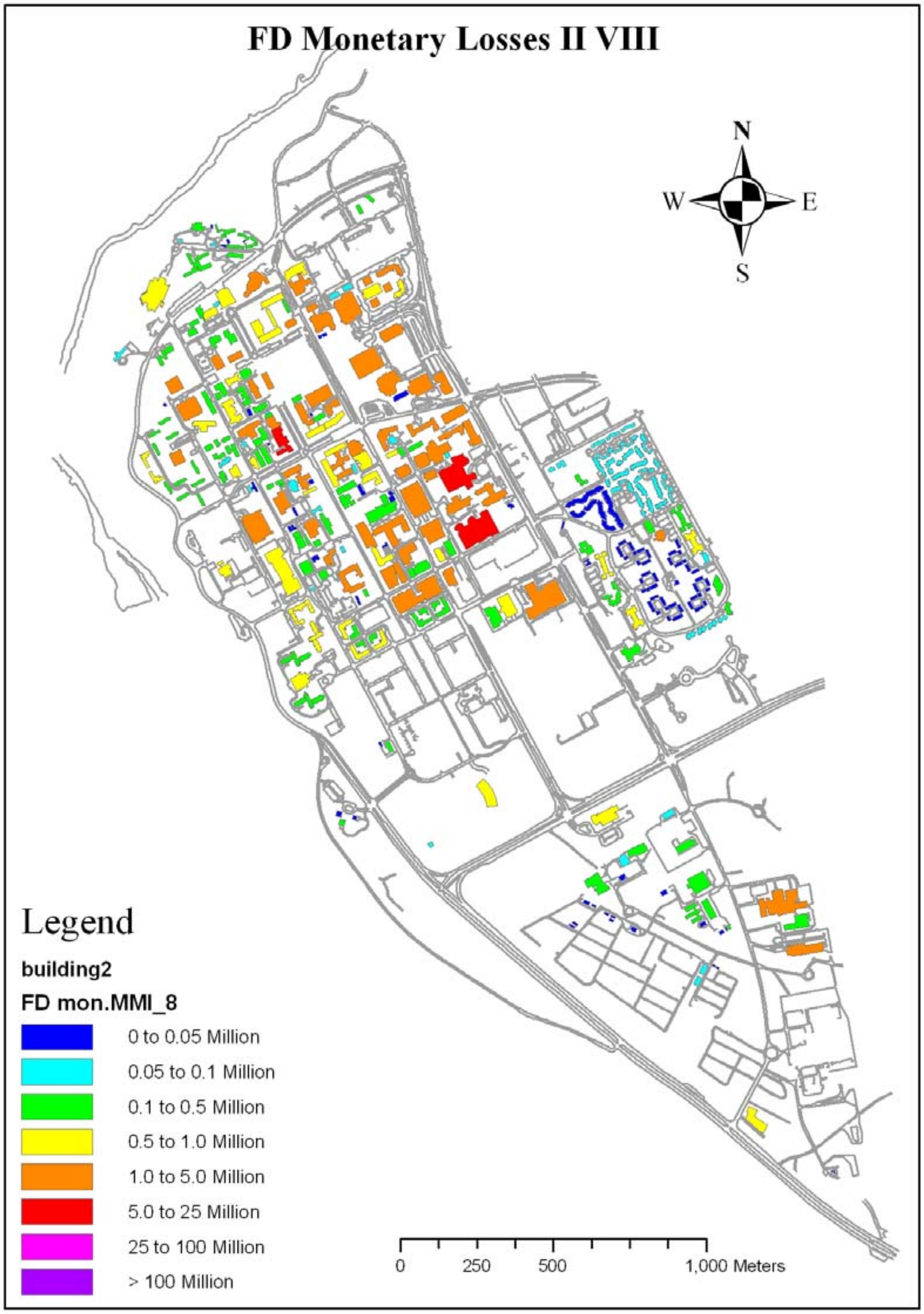
I - 7 UBC FI Monetary Losses – II XII



I - 8 UBC FI Monetary Losses – II VI



I - 9 UBC FI Monetary Losses – II VII



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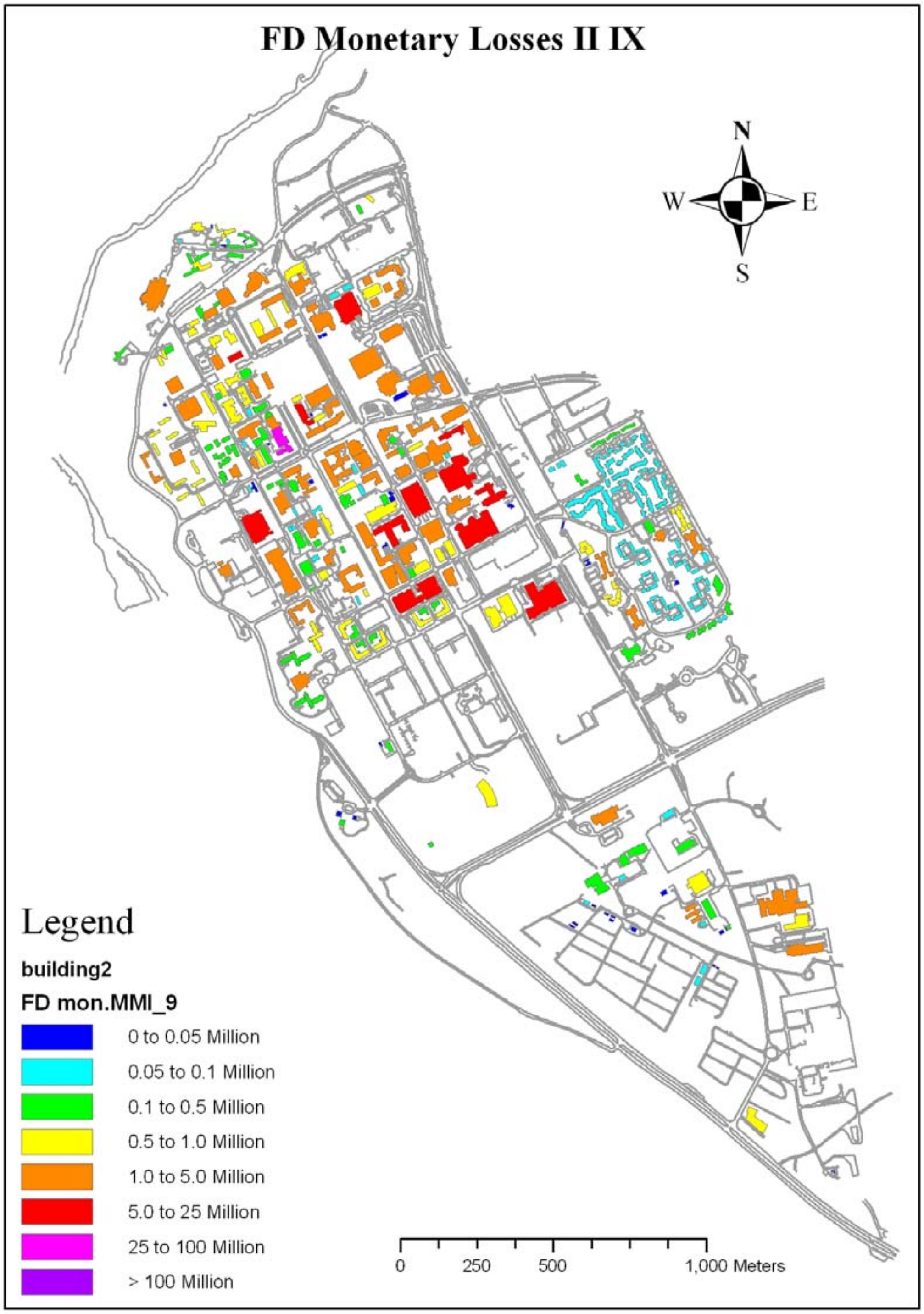
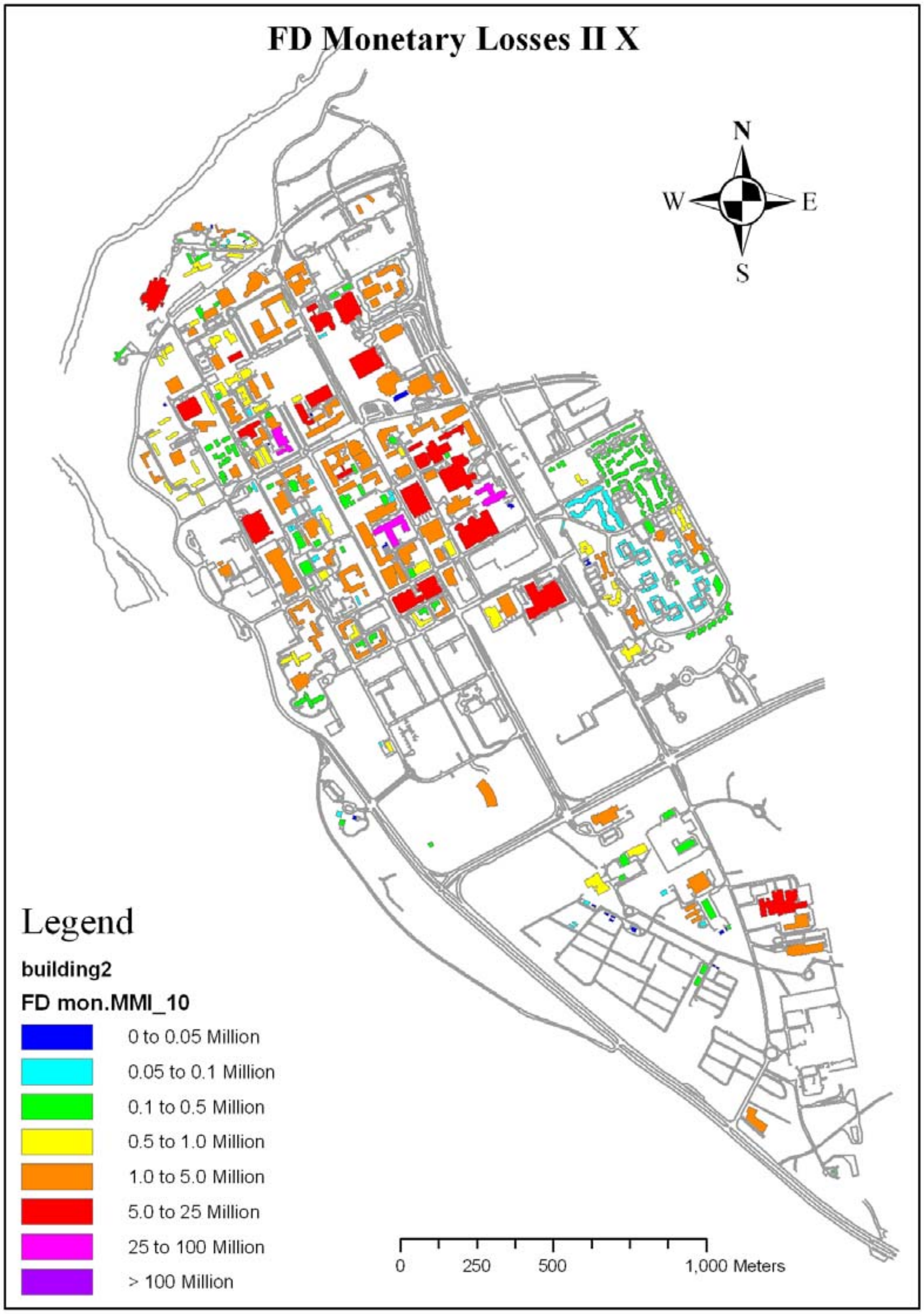


I - 11 UBC FI Monetary Losses – II IX



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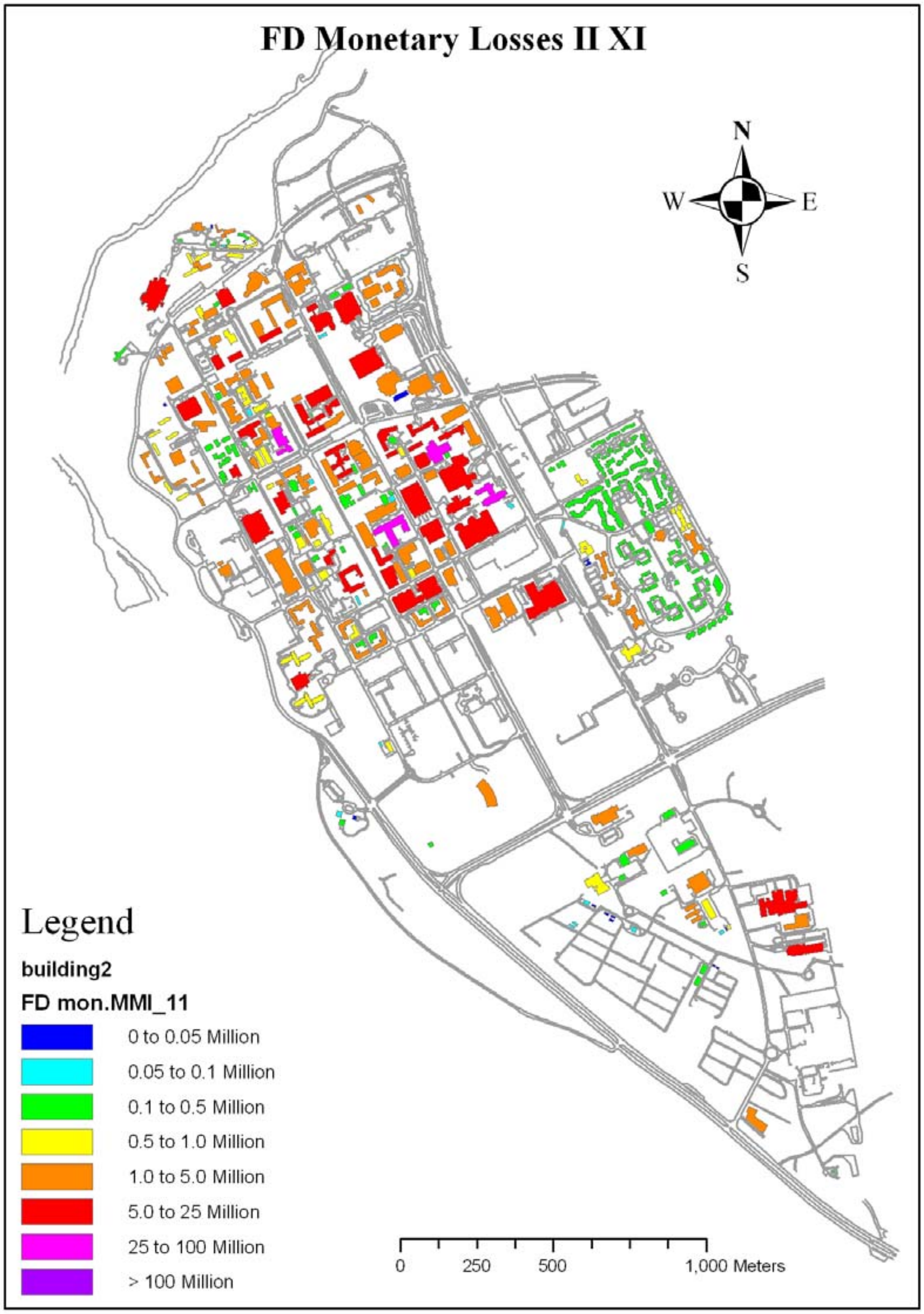
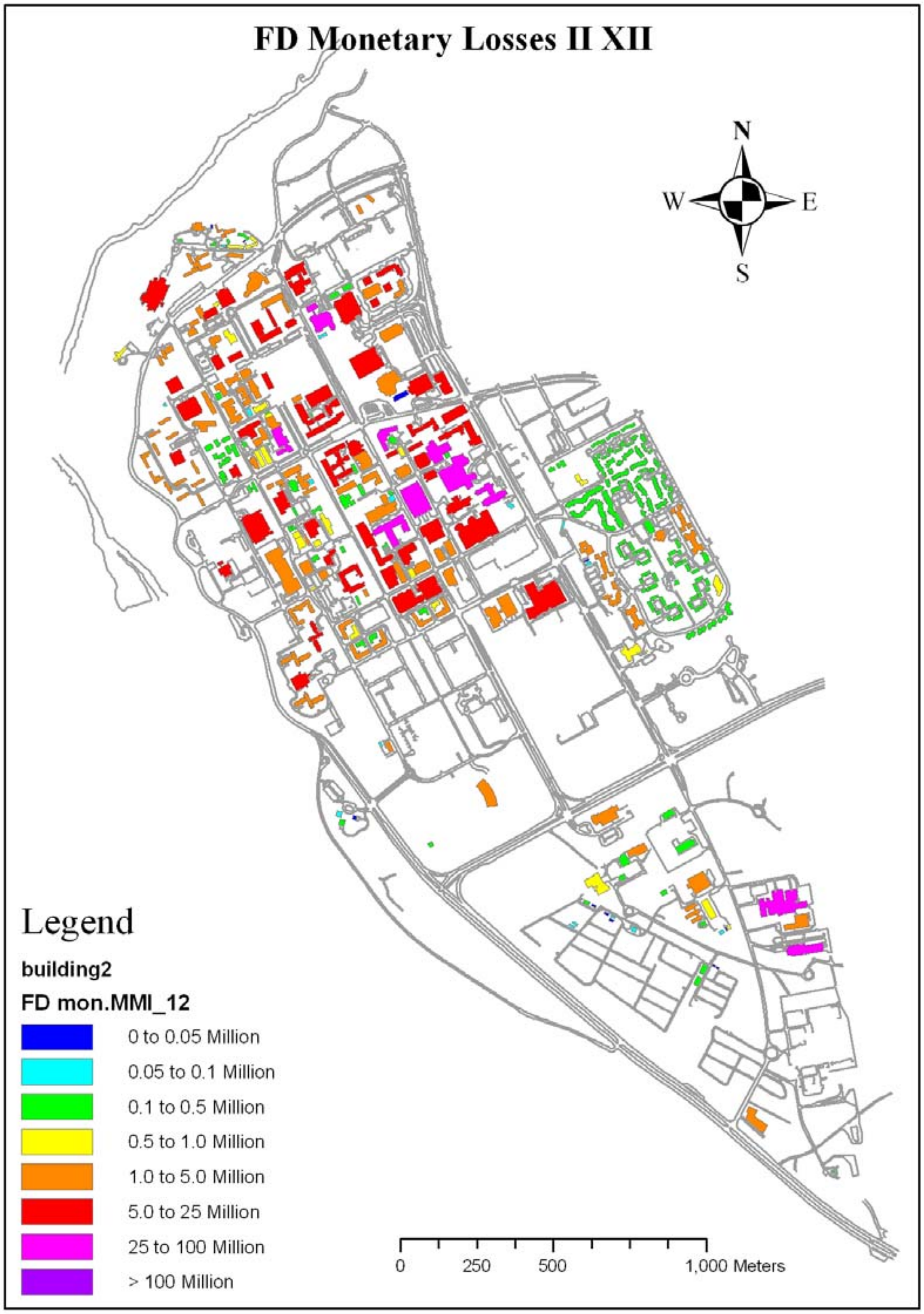


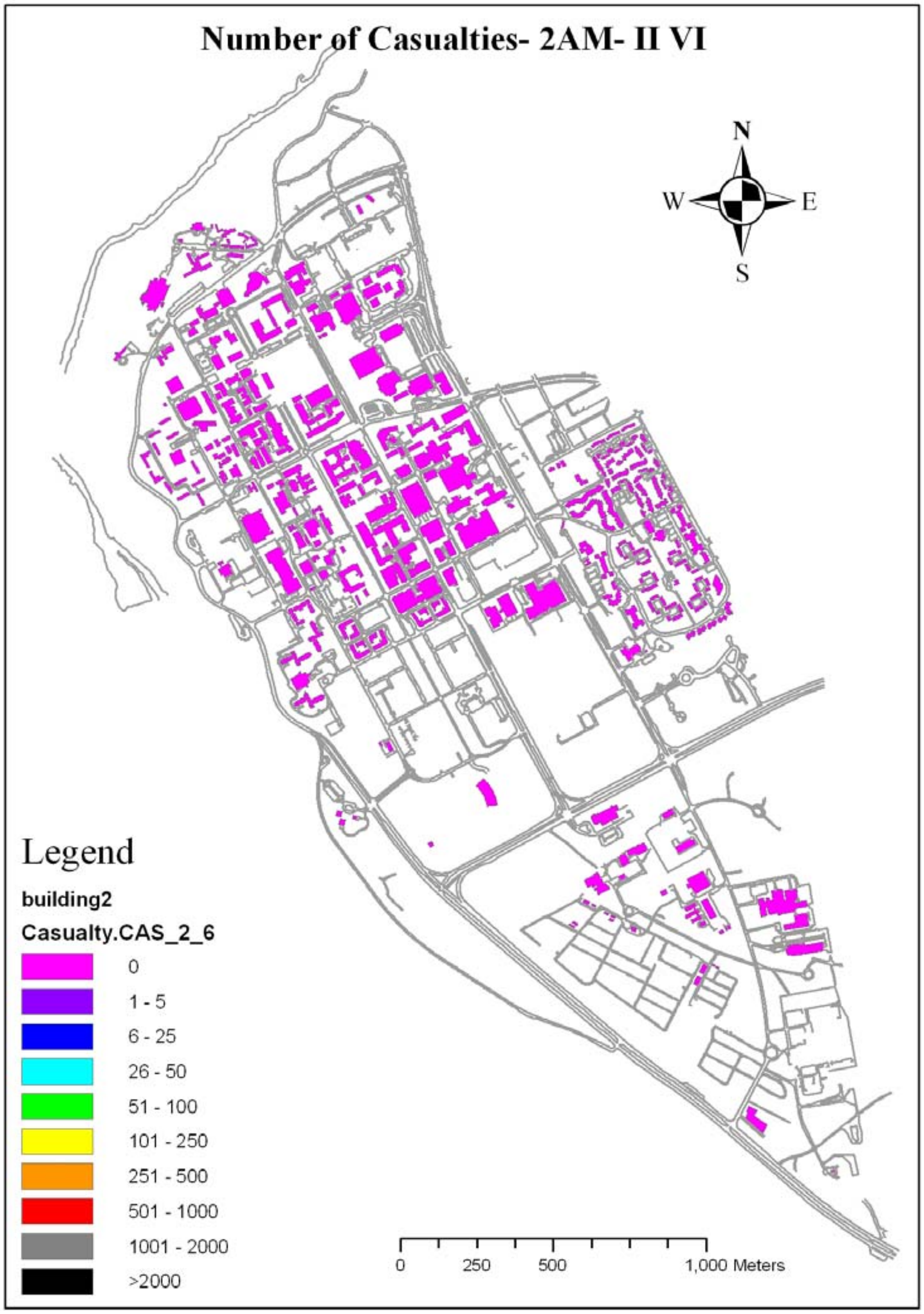
I - 13 UBC FD Monetary Losses – II XI



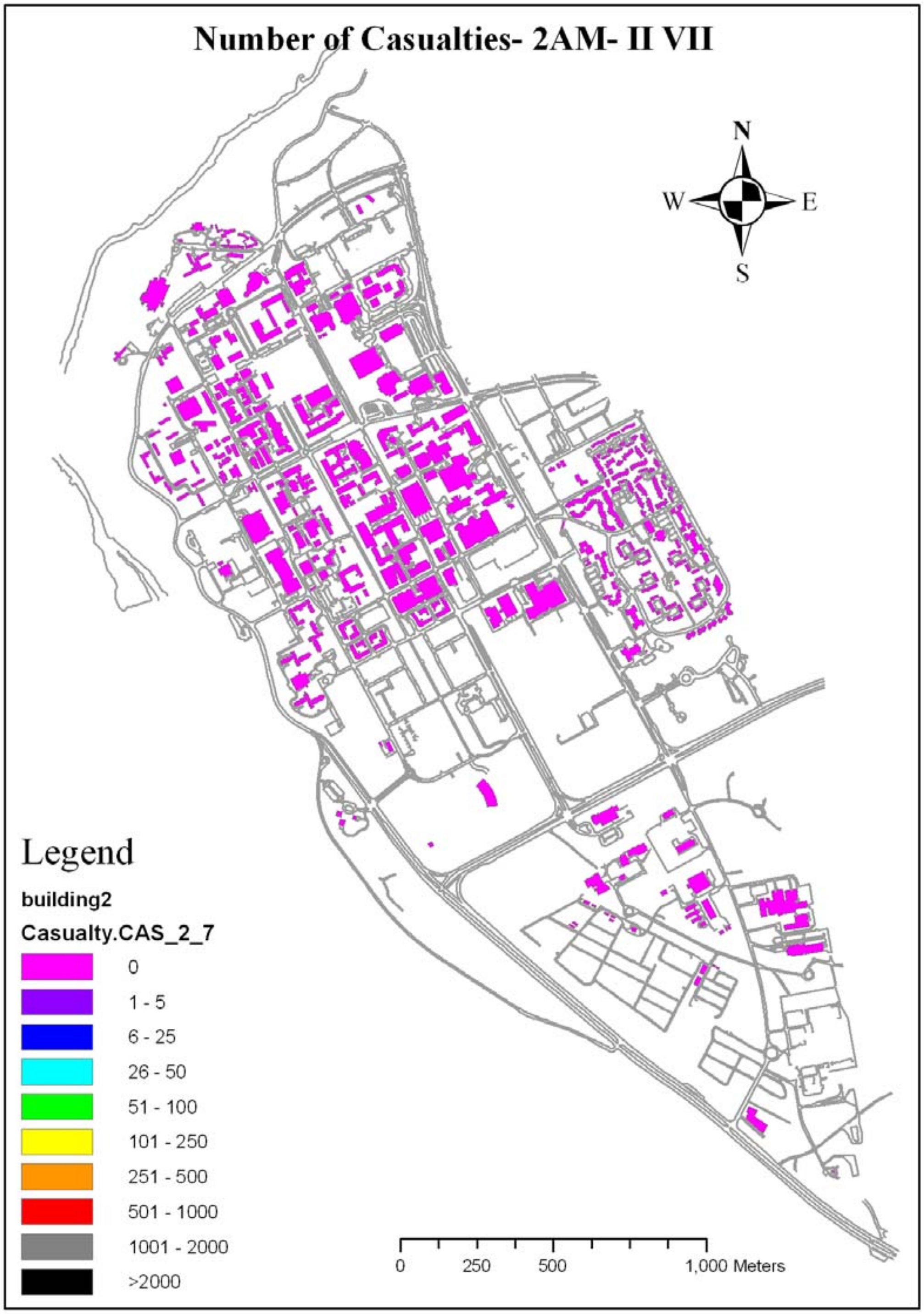
I - 14 UBC FD Monetary Losses – II XII

Appendix J: UBC Casualty Results

This appendix presents the UBC casualty estimation results at three times of day for all seven levels of Instrumental intensity.



J - 1 UBC 2AM Casualty Results -II VI



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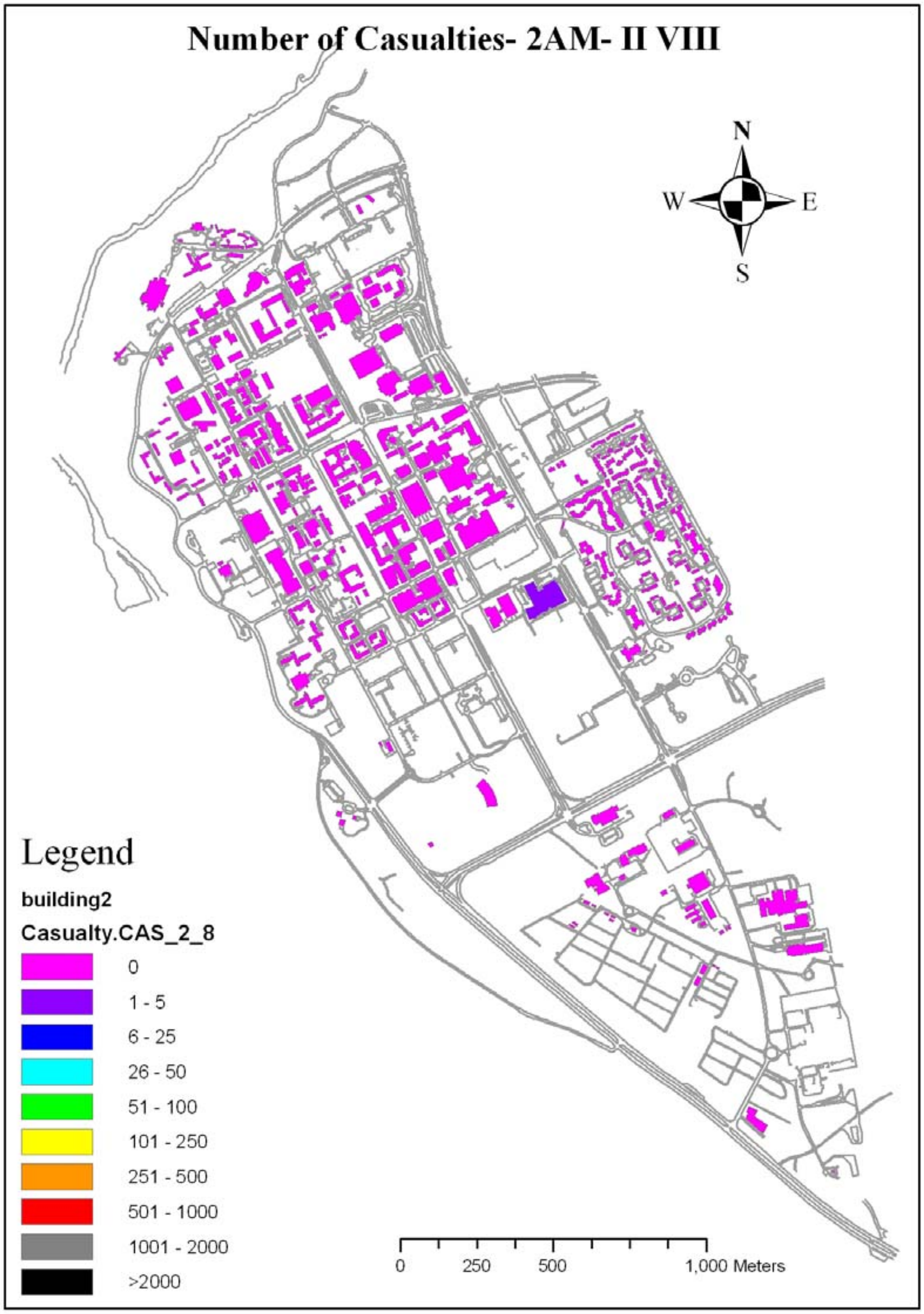
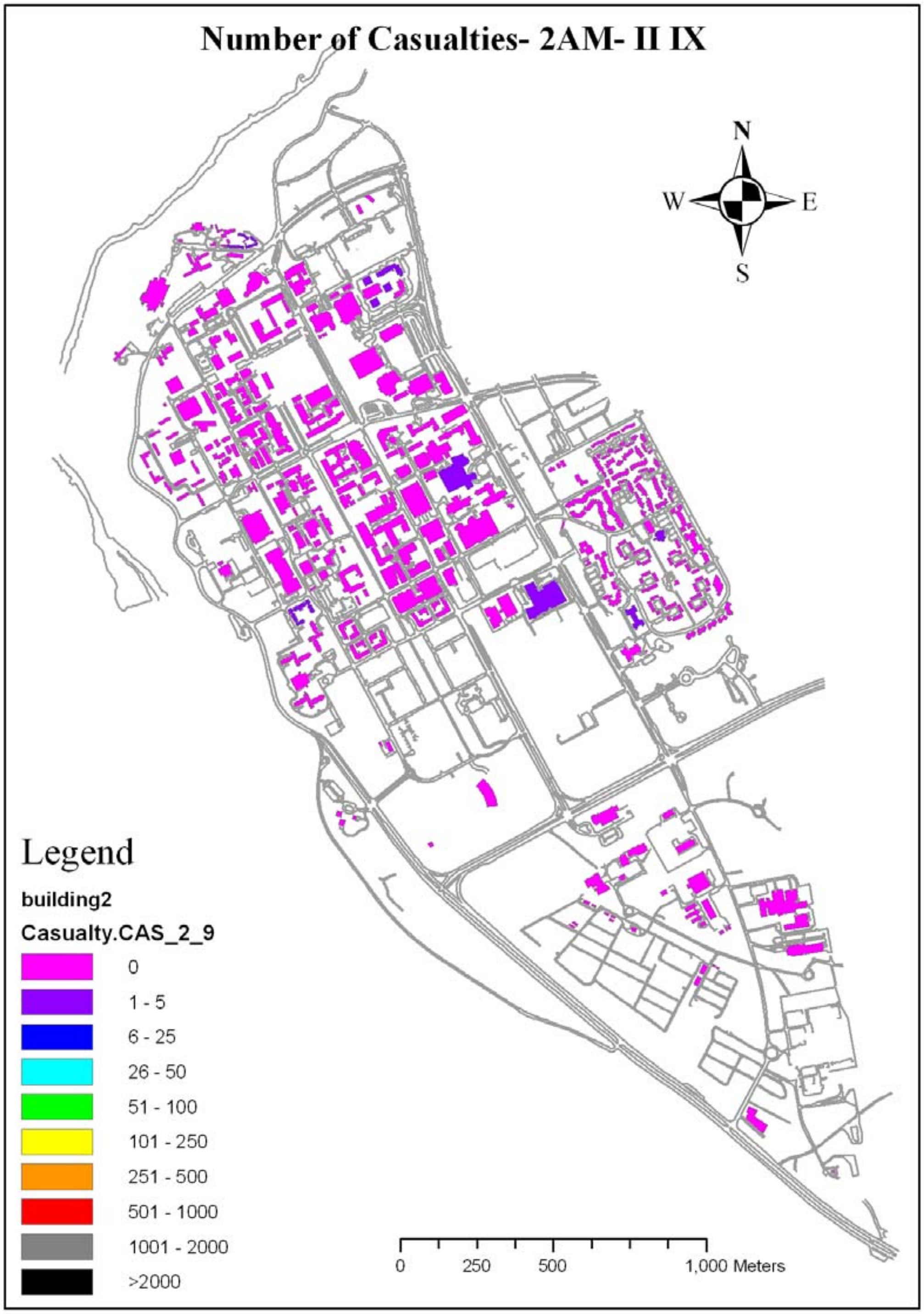
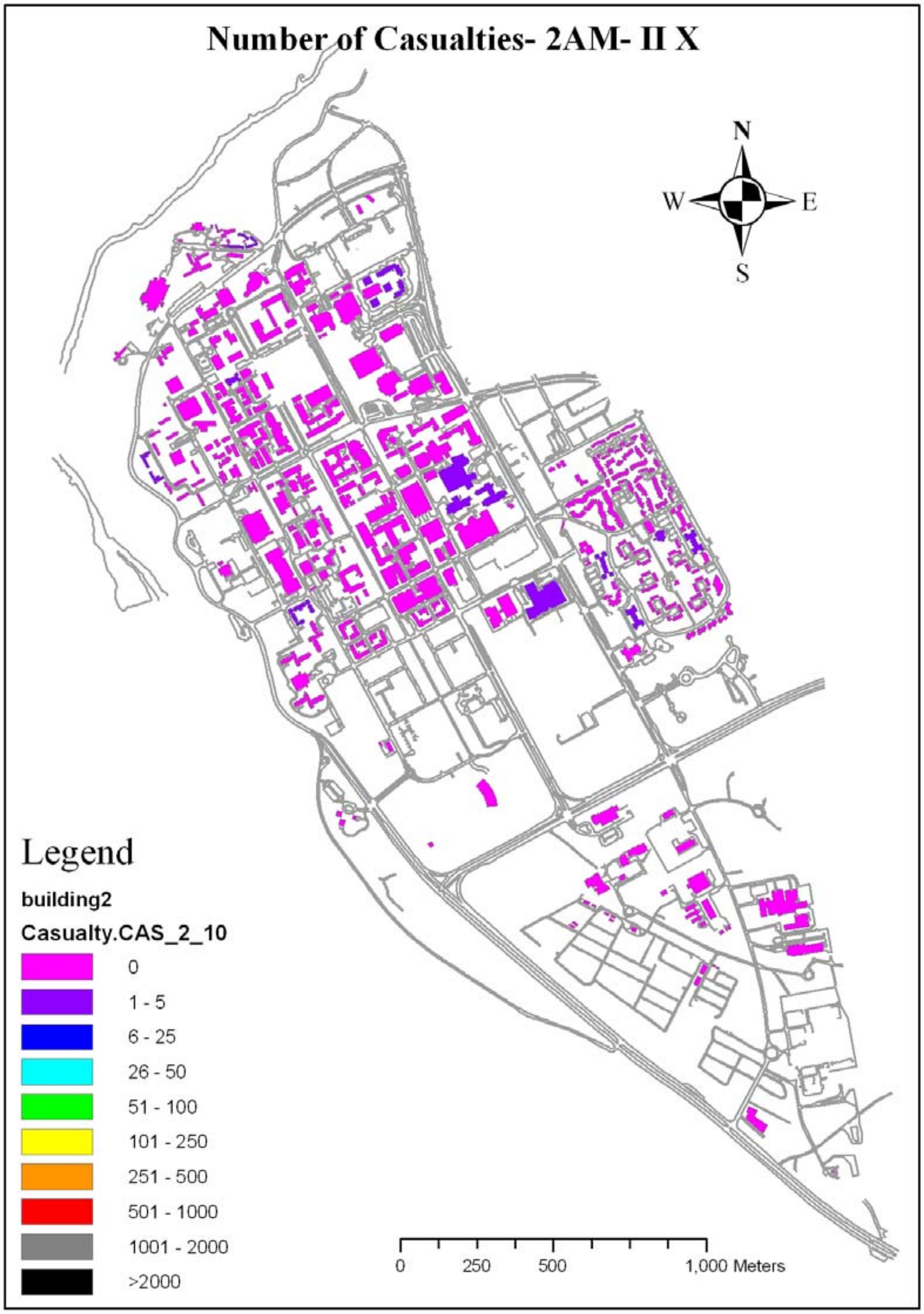


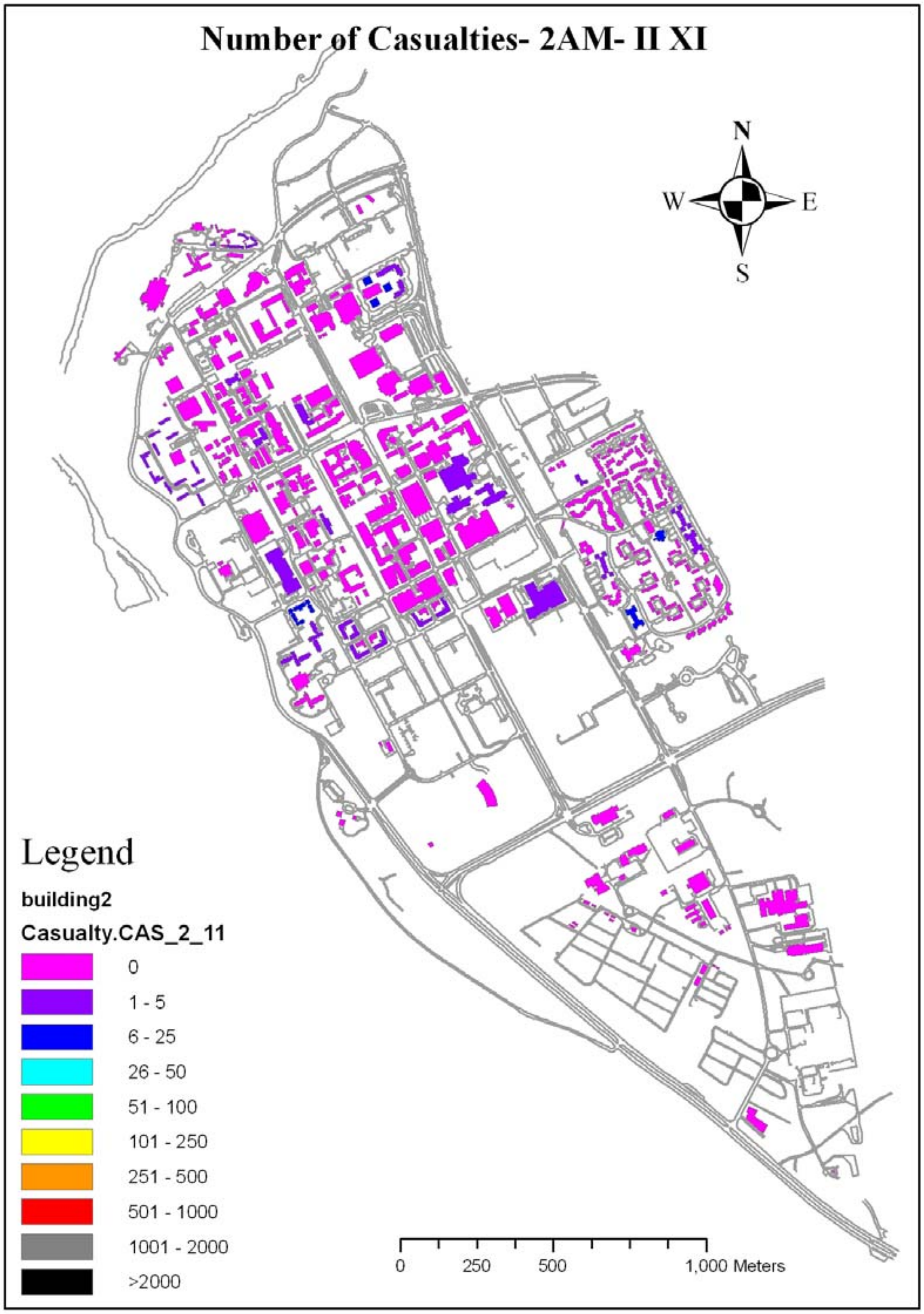
J - 3 UBC 2AM Casualty Results -II VIII



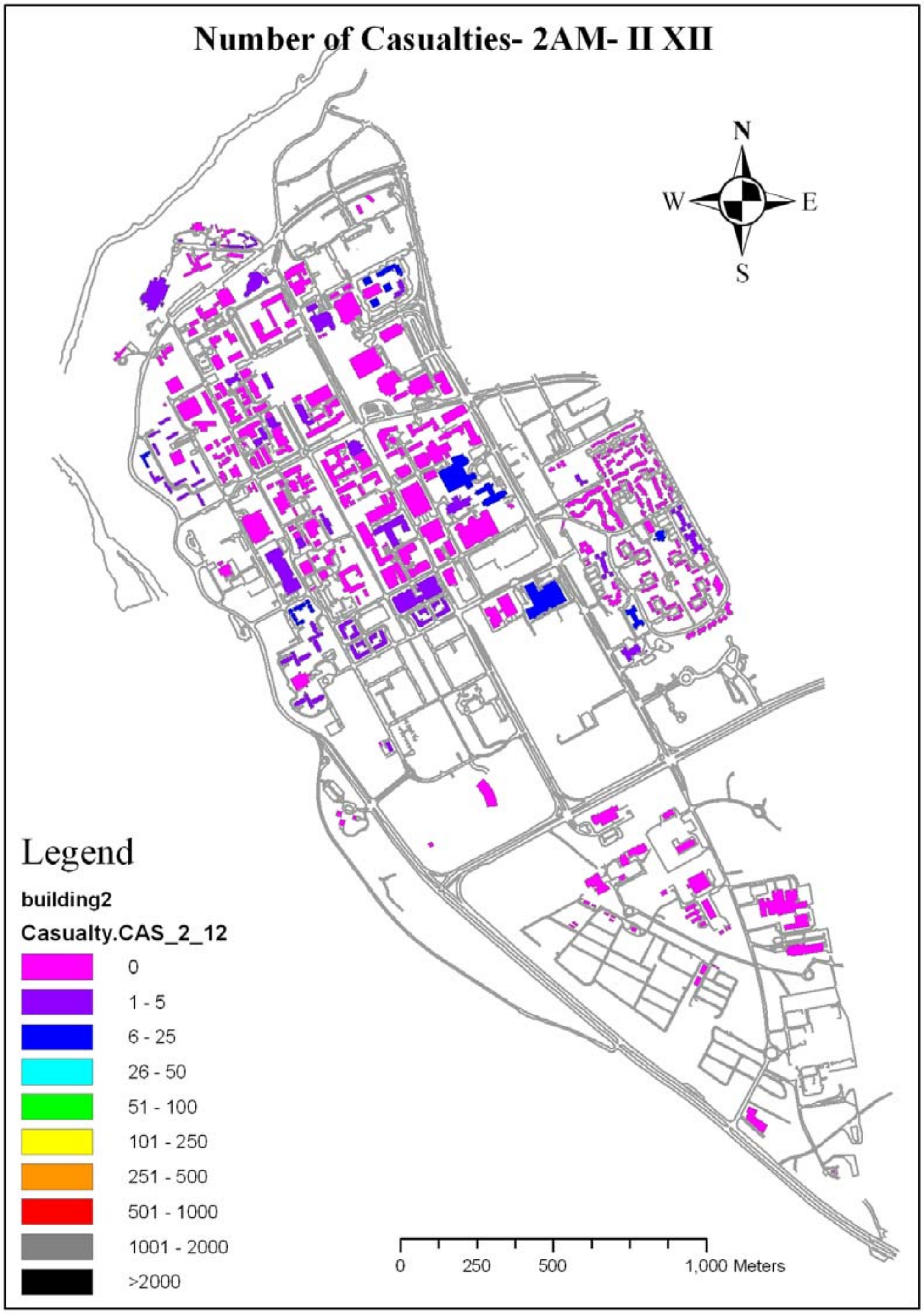
J - 4 UBC 2AM Casualty Results -II IX



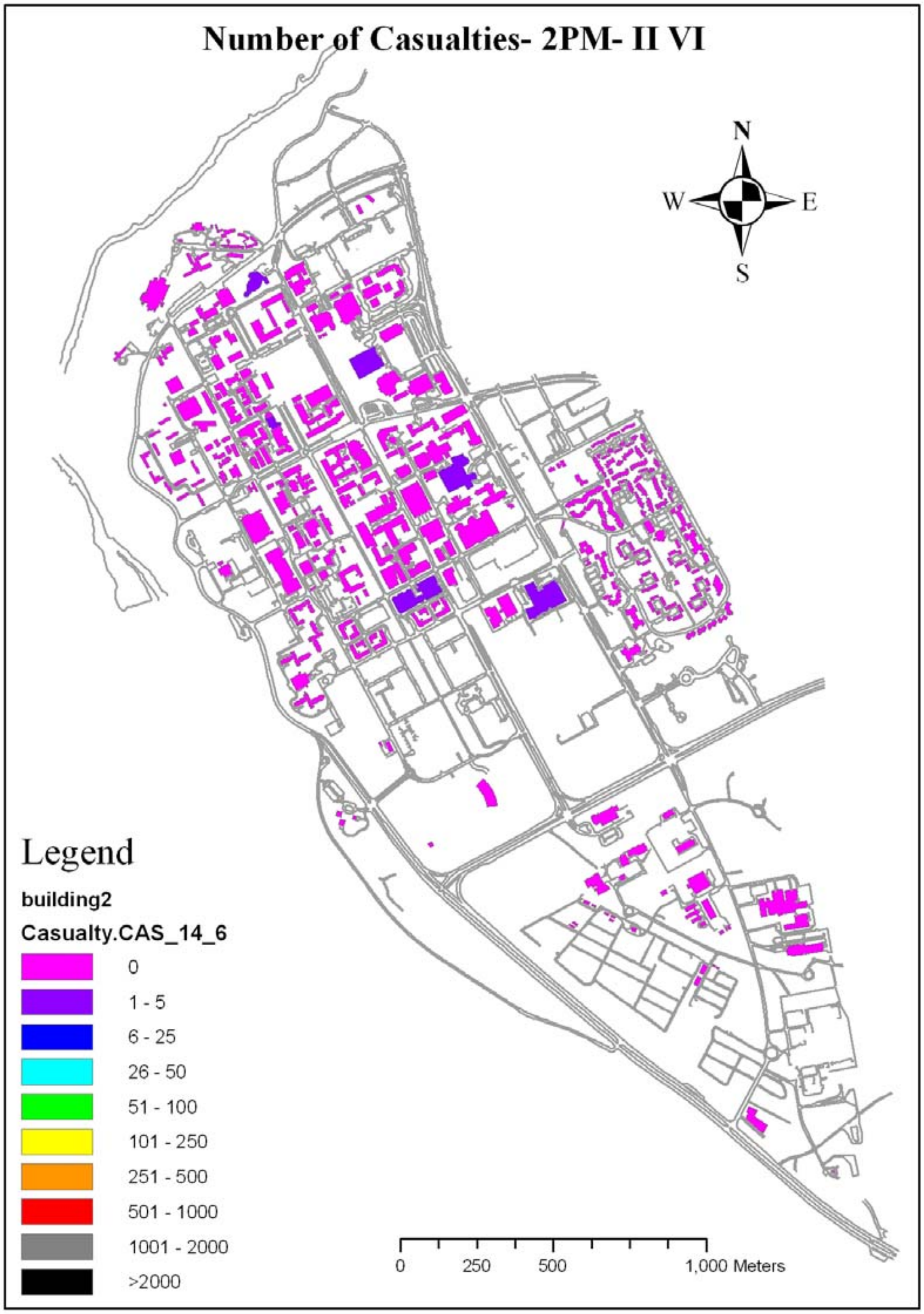
J - 5 UBC 2AM Casualty Results -II X



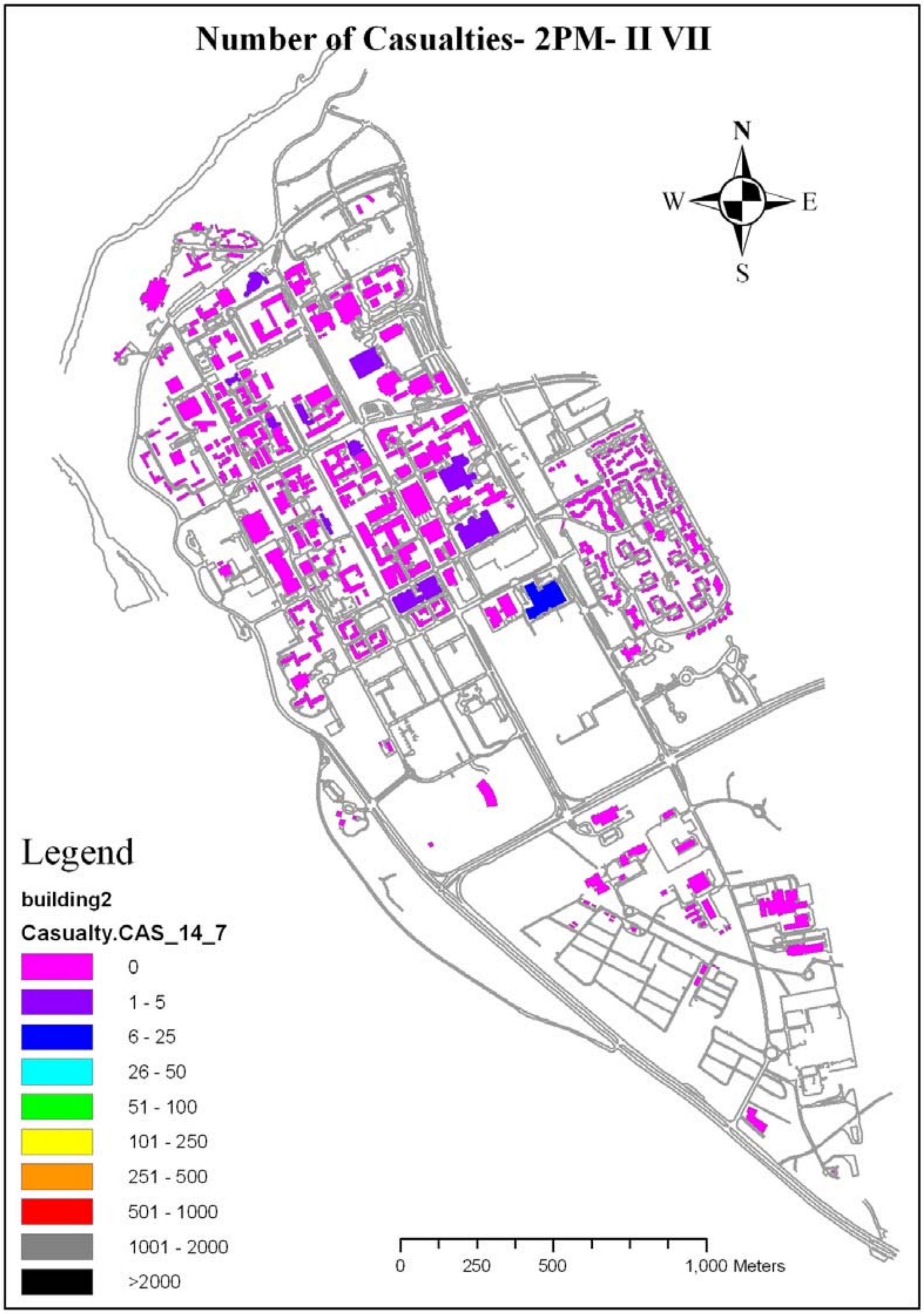
J - 6 UBC 2AM Casualty Results -II XI



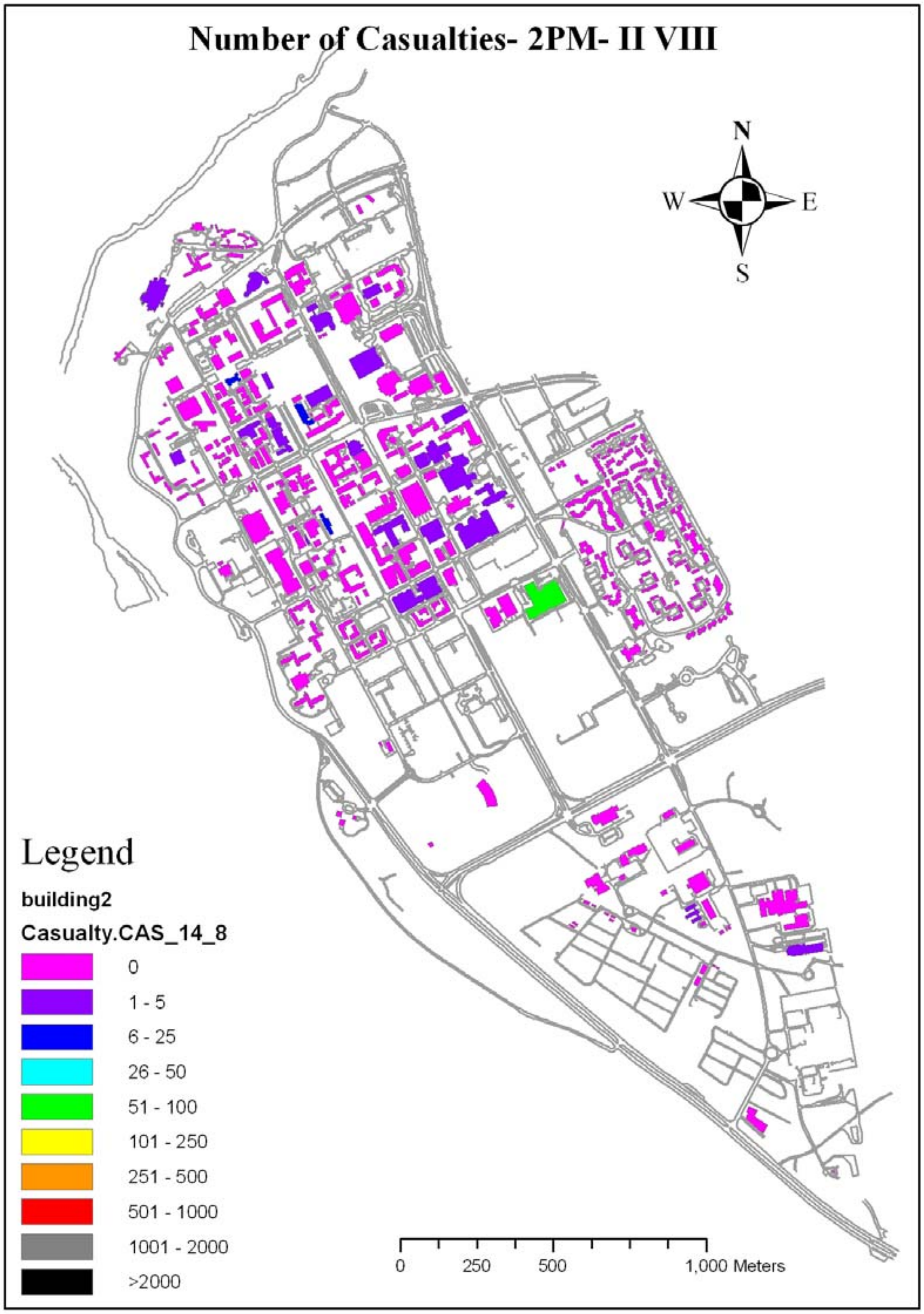
J - 7 UBC 2AM Casualty Results -II XII



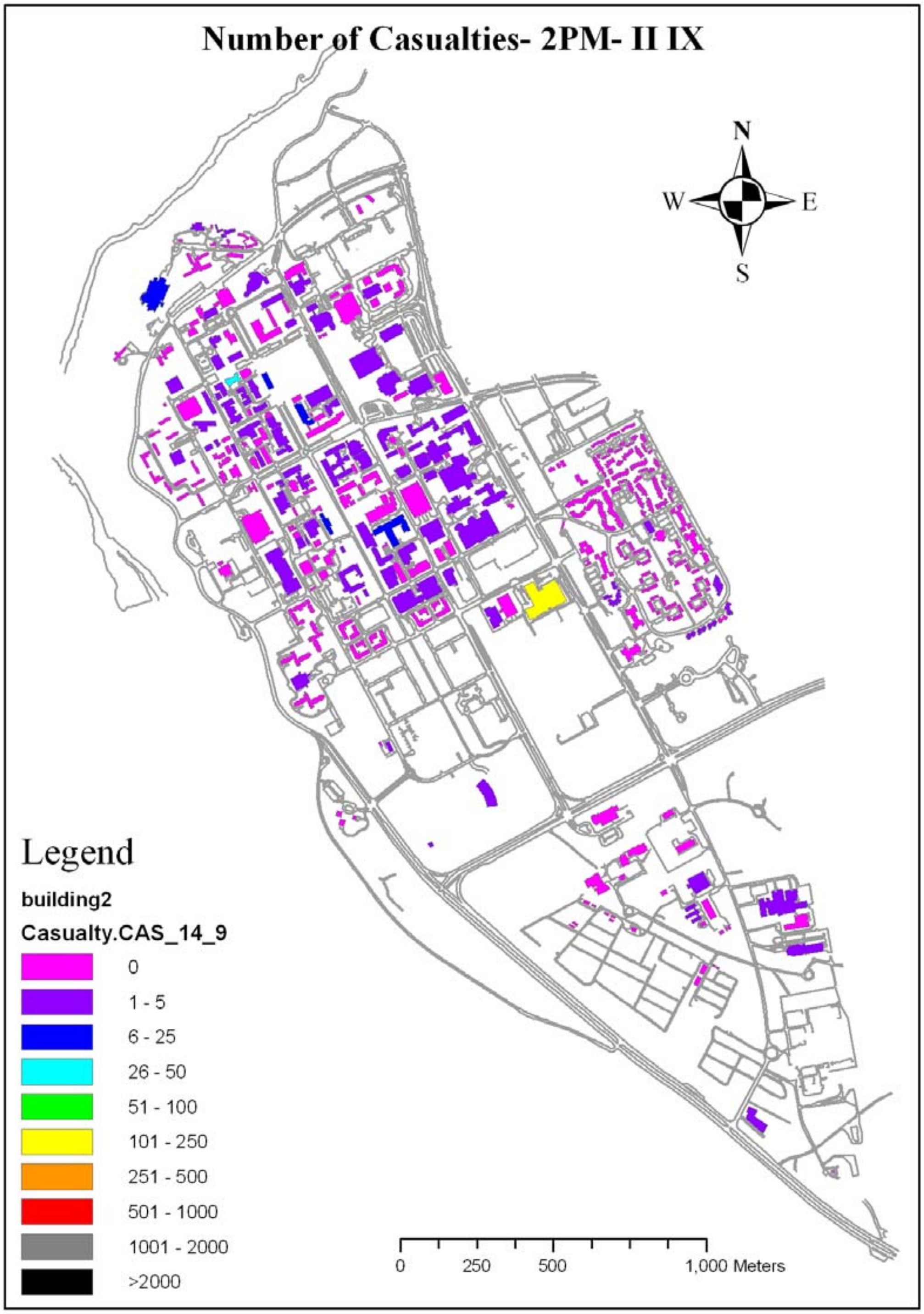
J - 8 UBC 2PM Casualty Results -II VI



J - 9 UBC 2PM Casualty Results -II VII



J - 10 UBC 2PM Casualty Results -II VIII



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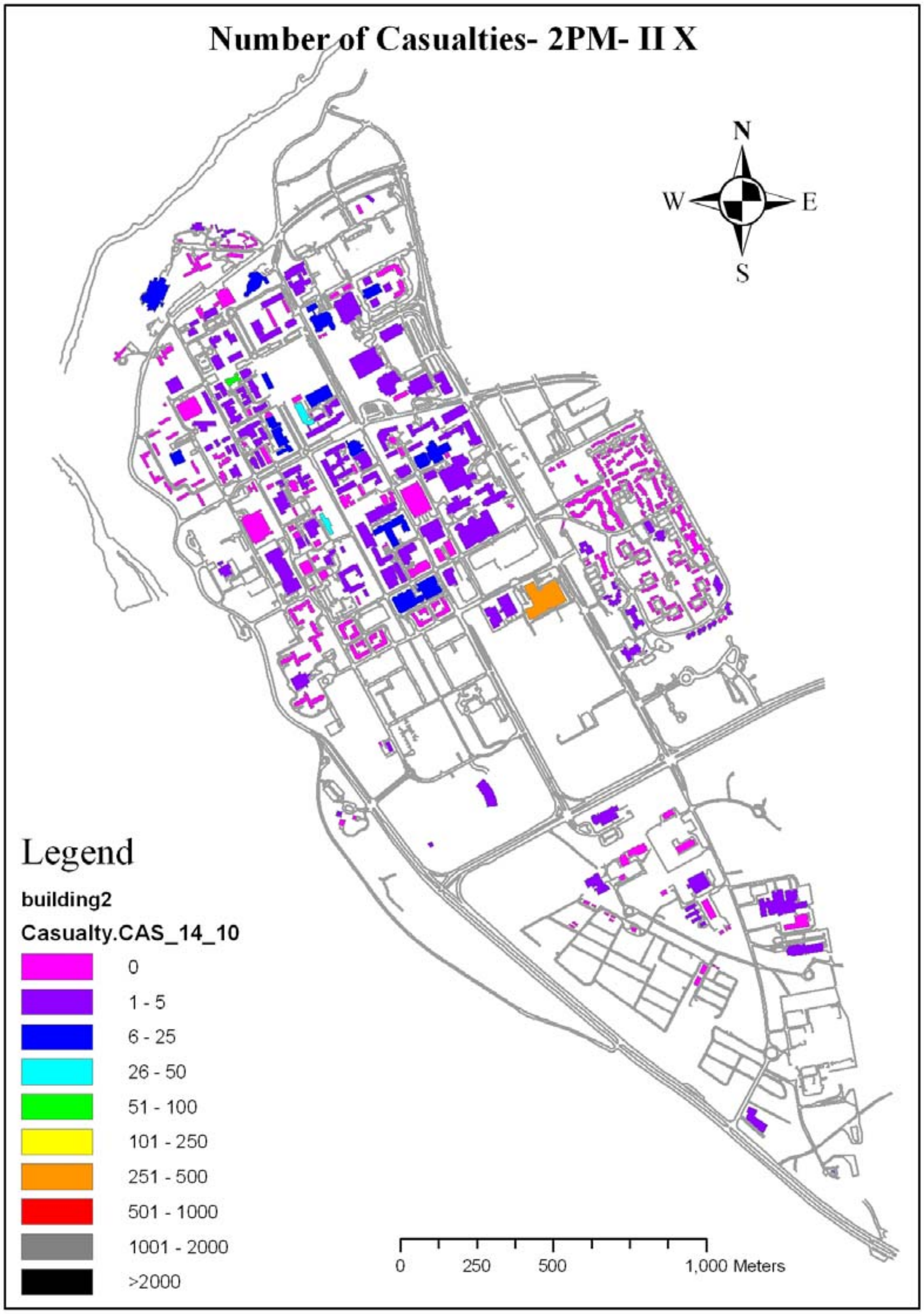
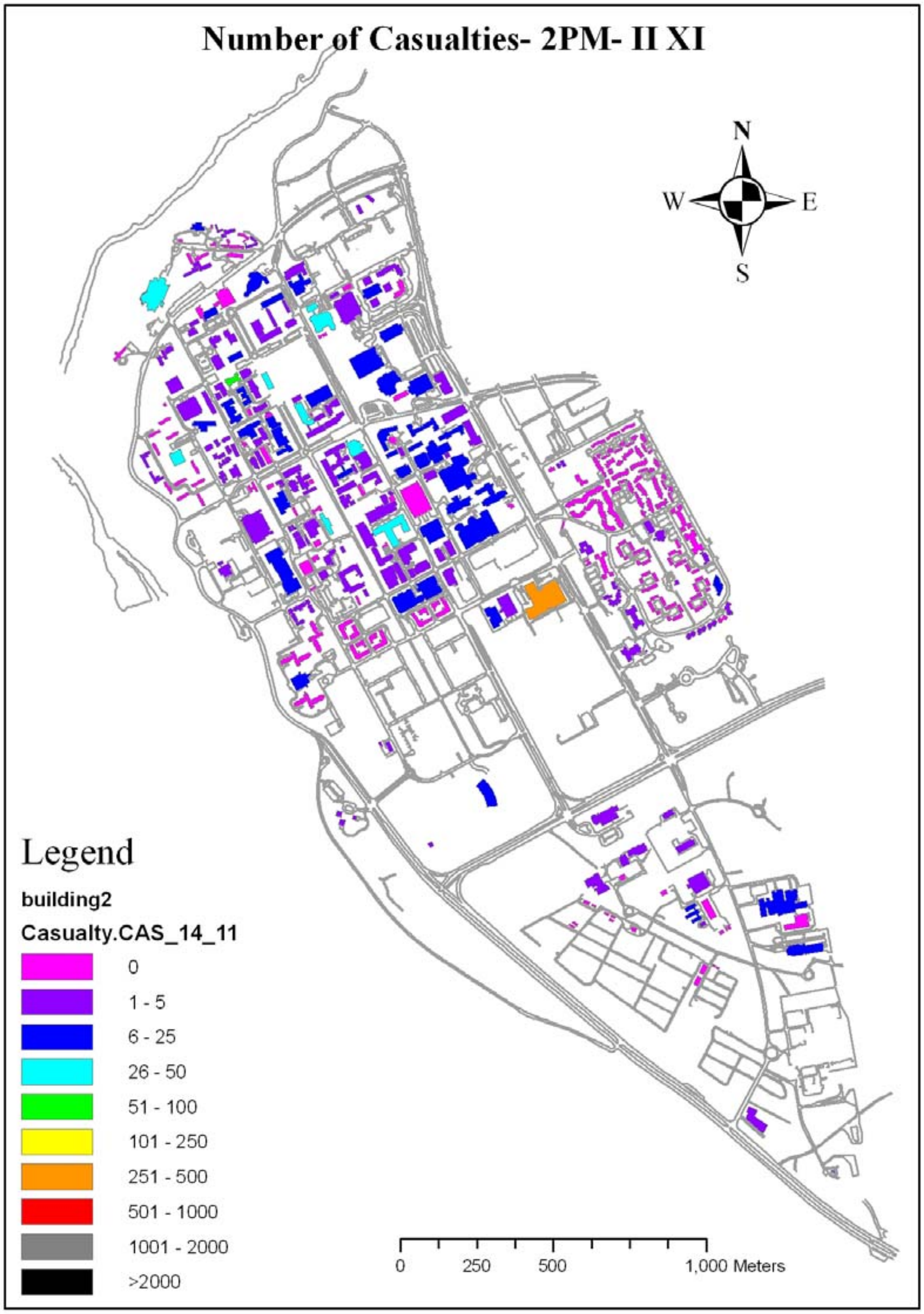
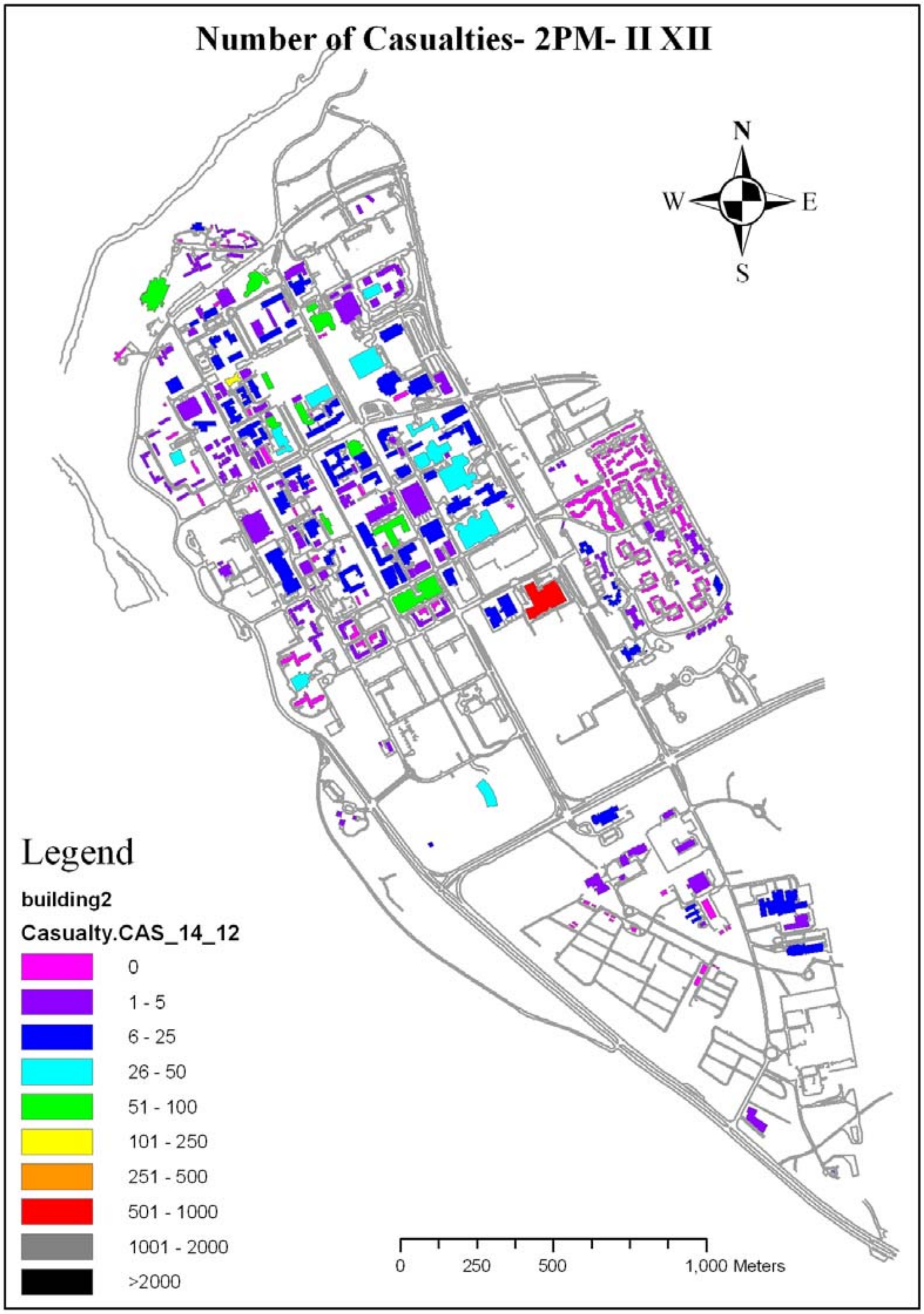


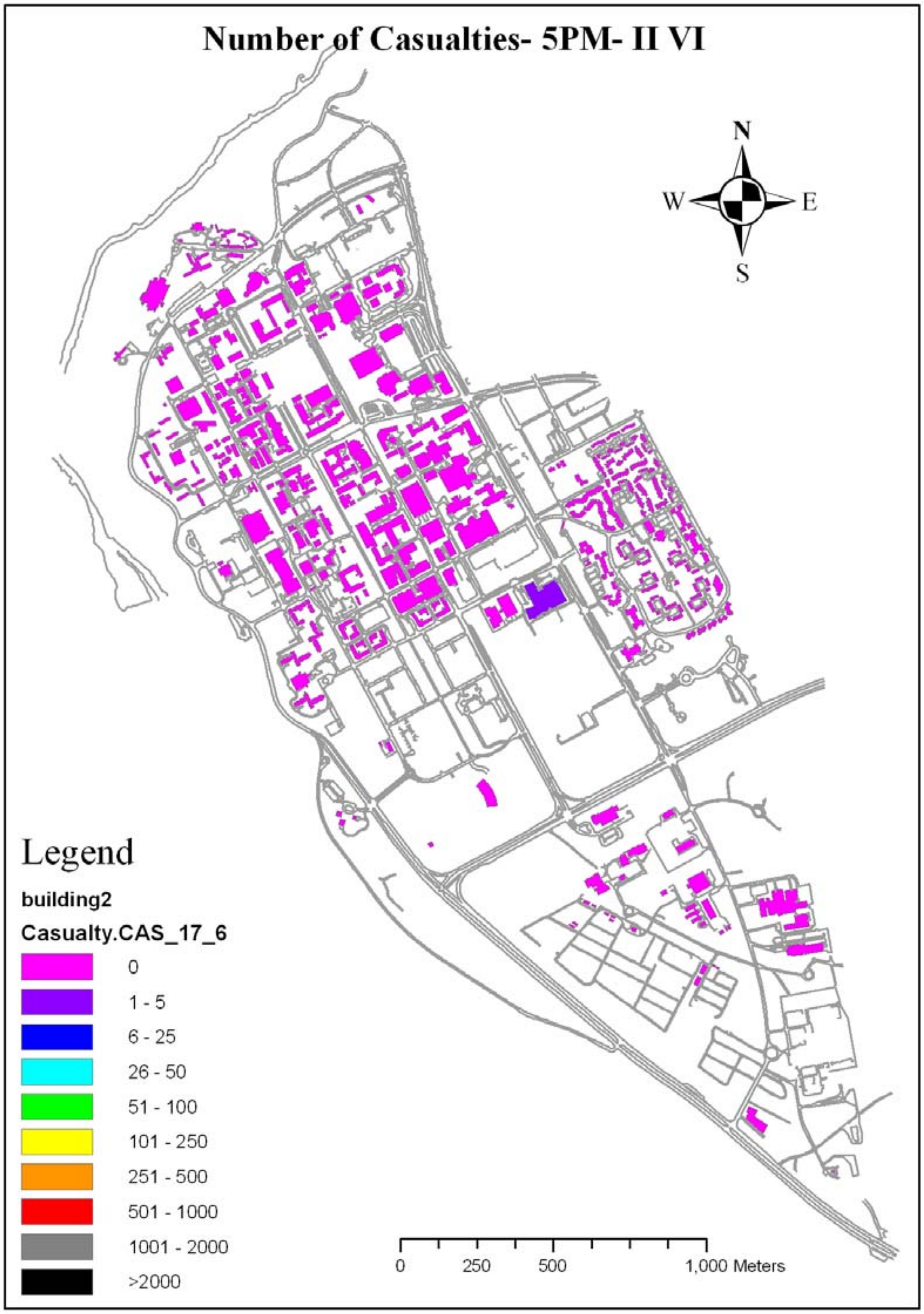
J - 12 UBC 2PM Casualty Results -II X



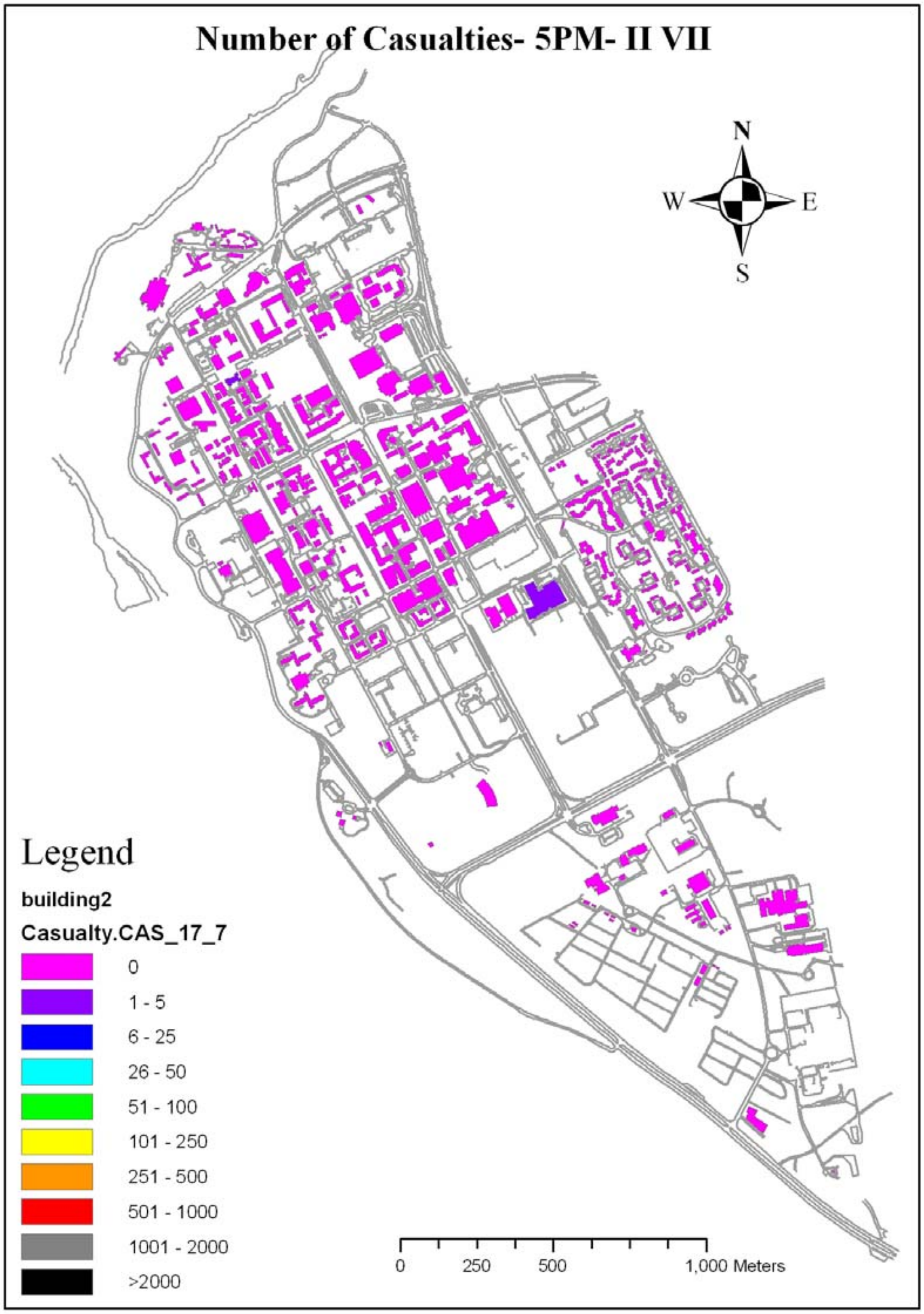
J - 13 UBC 2PM Casualty Results -II XI



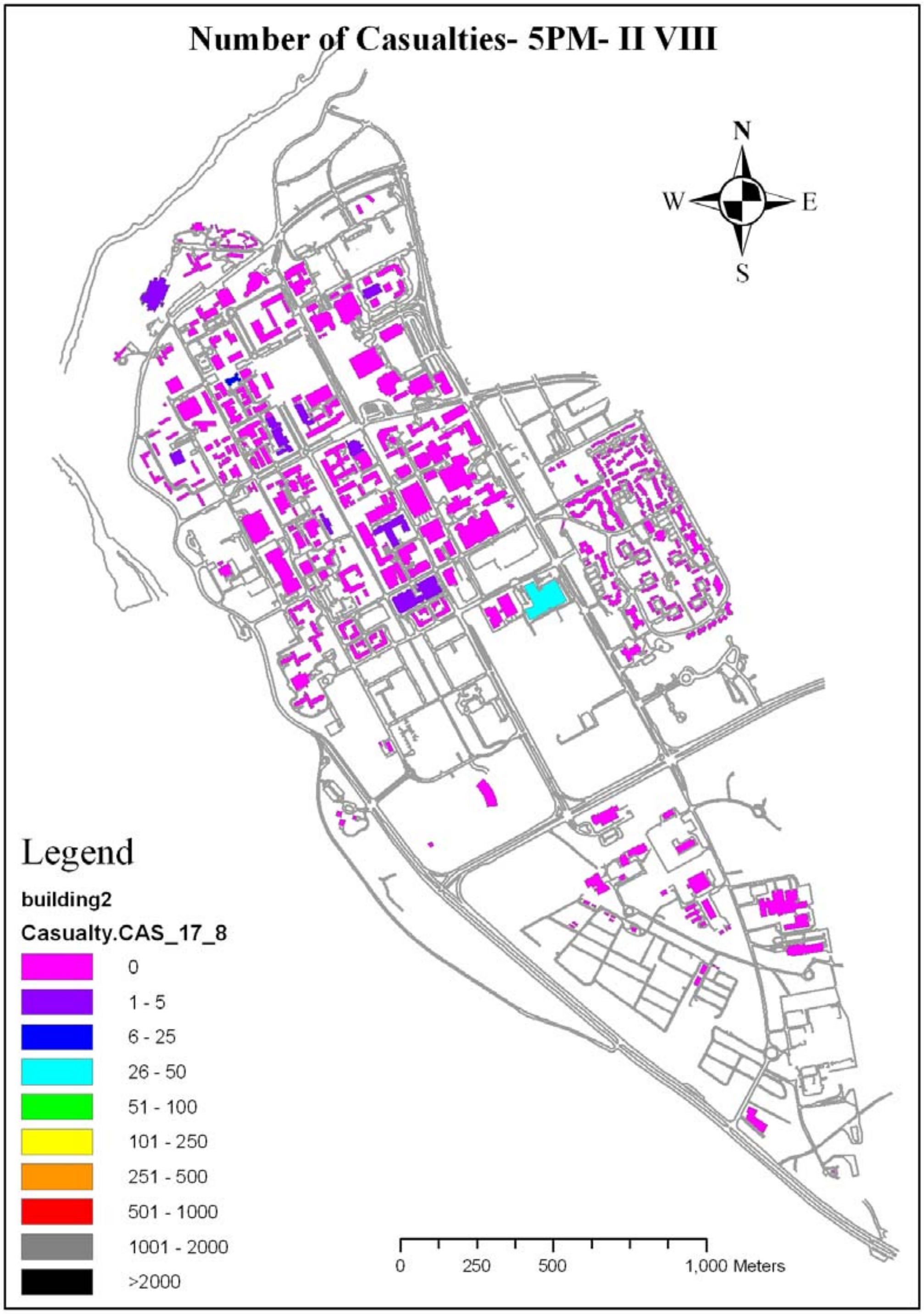
J - 14 UBC 2PM Casualty Results -II XII



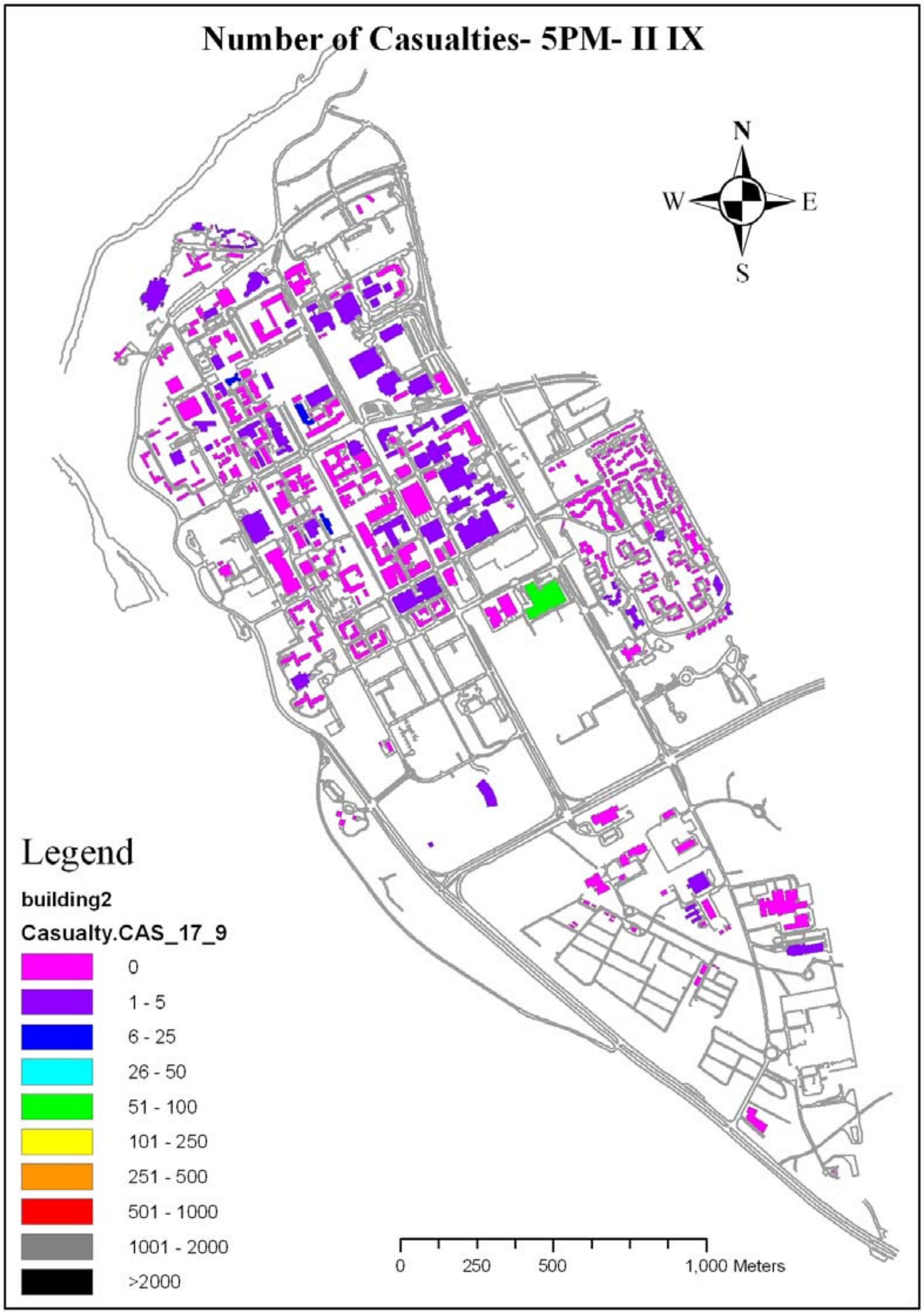
J - 15 UBC 5PM Casualty Results -II VI



J - 16 UBC 5PM Casualty Results -II VII



J - 17 UBC 5PM Casualty Results -II VIII



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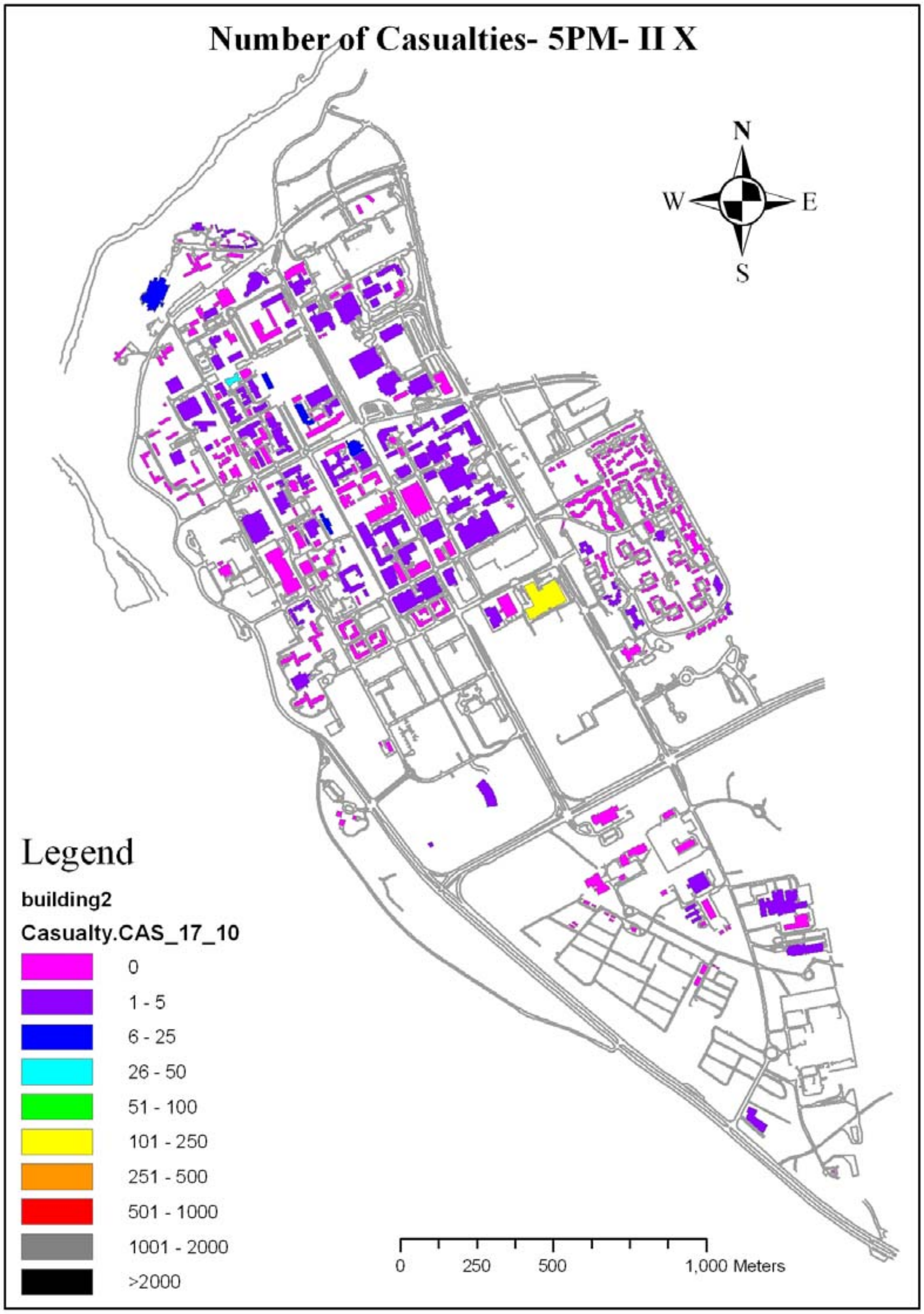

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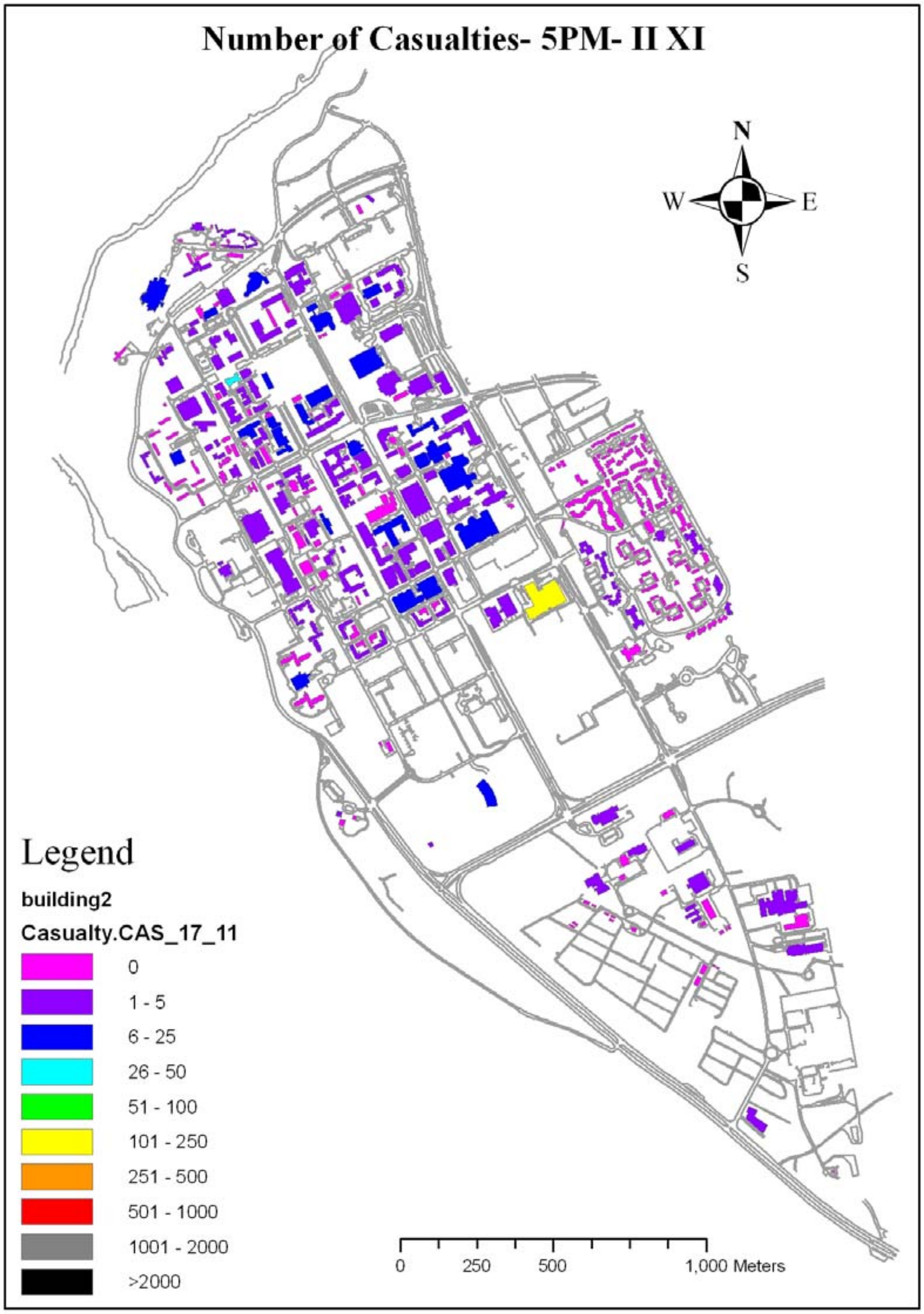

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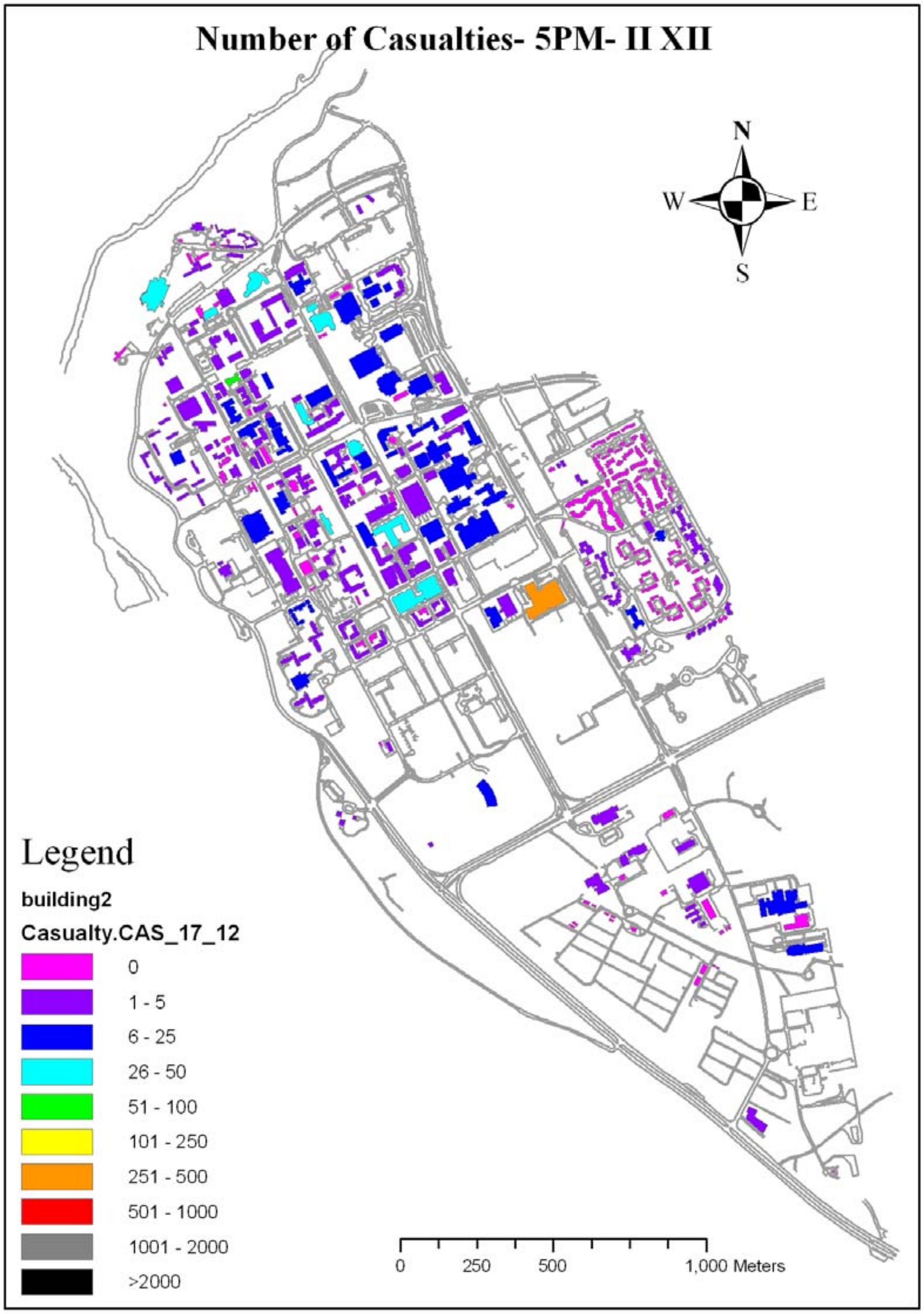
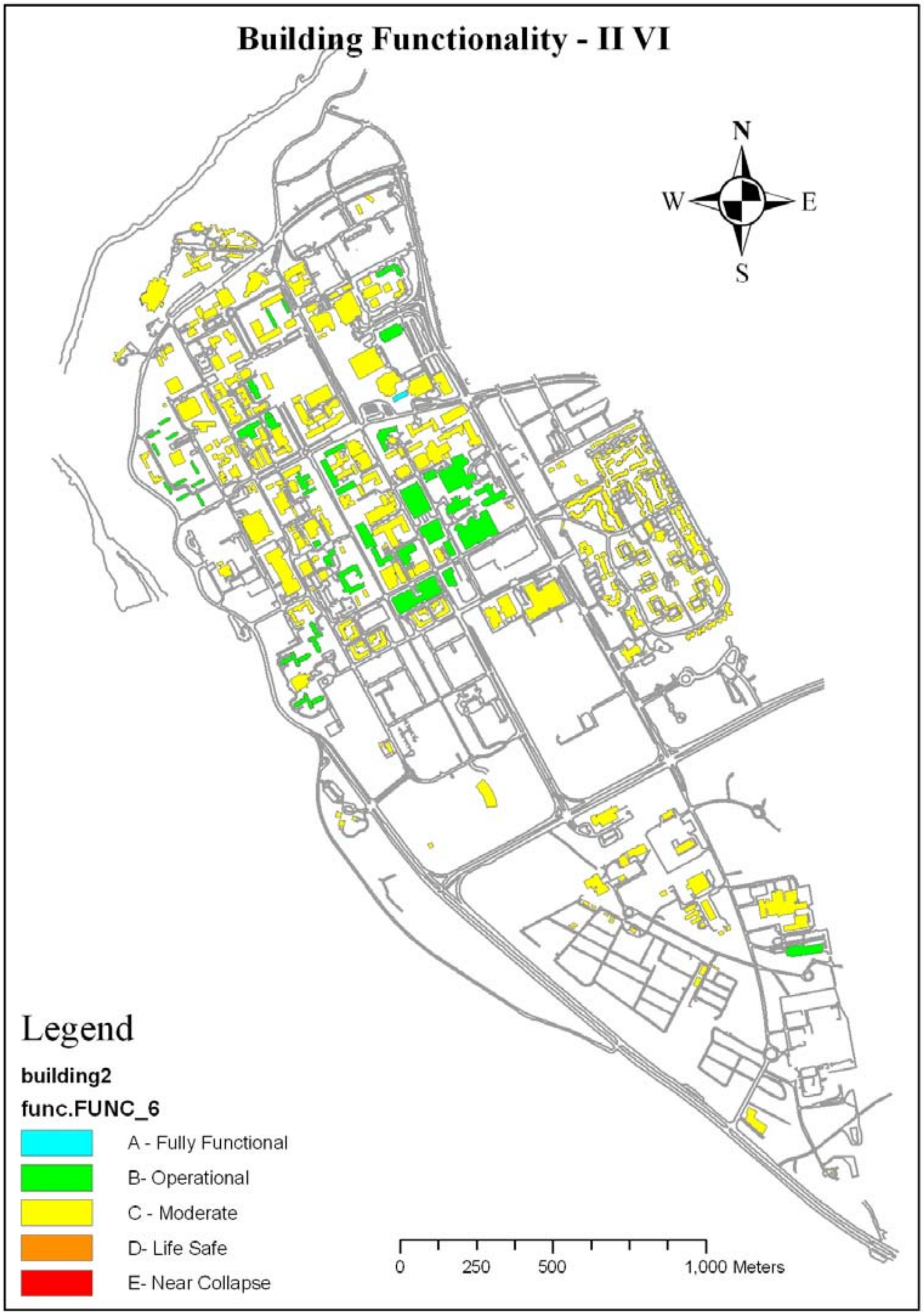


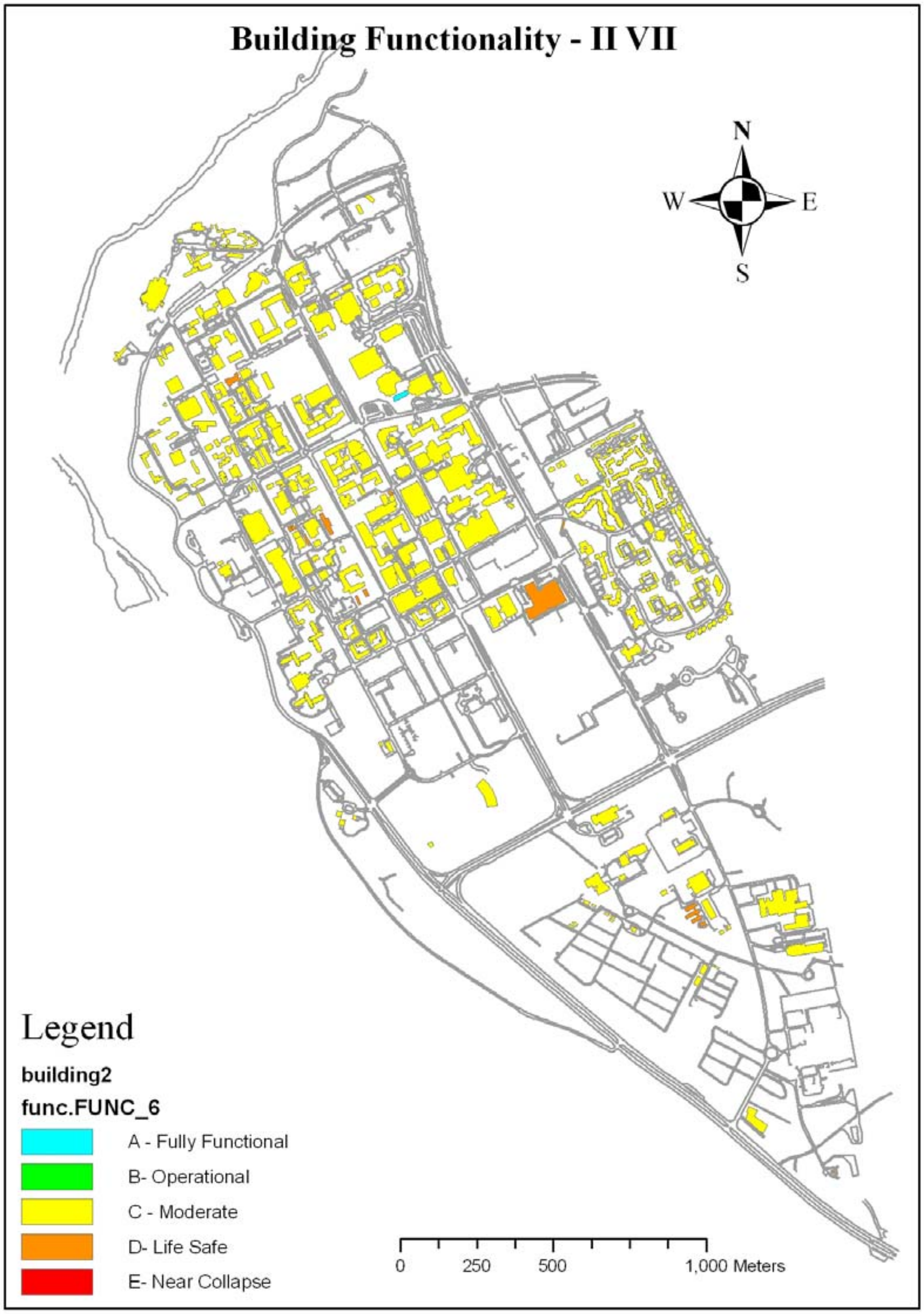
J - 21 UBC 5PM Casualty Results -II XII

Appendix K: UBC Functionality Results

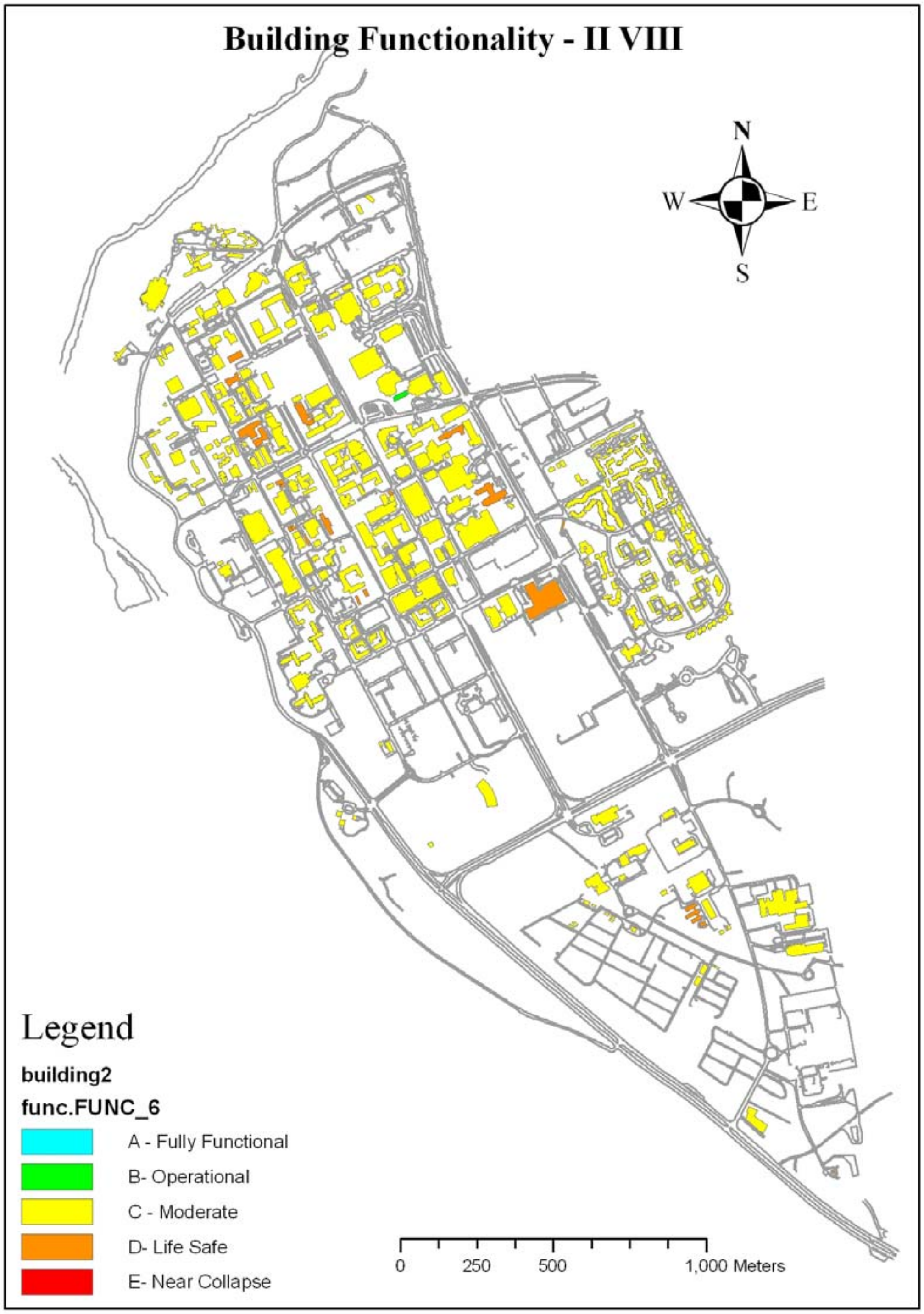
This appendix presents the functionality results of the UBC case study for all seven levels of Instrumental intensity.



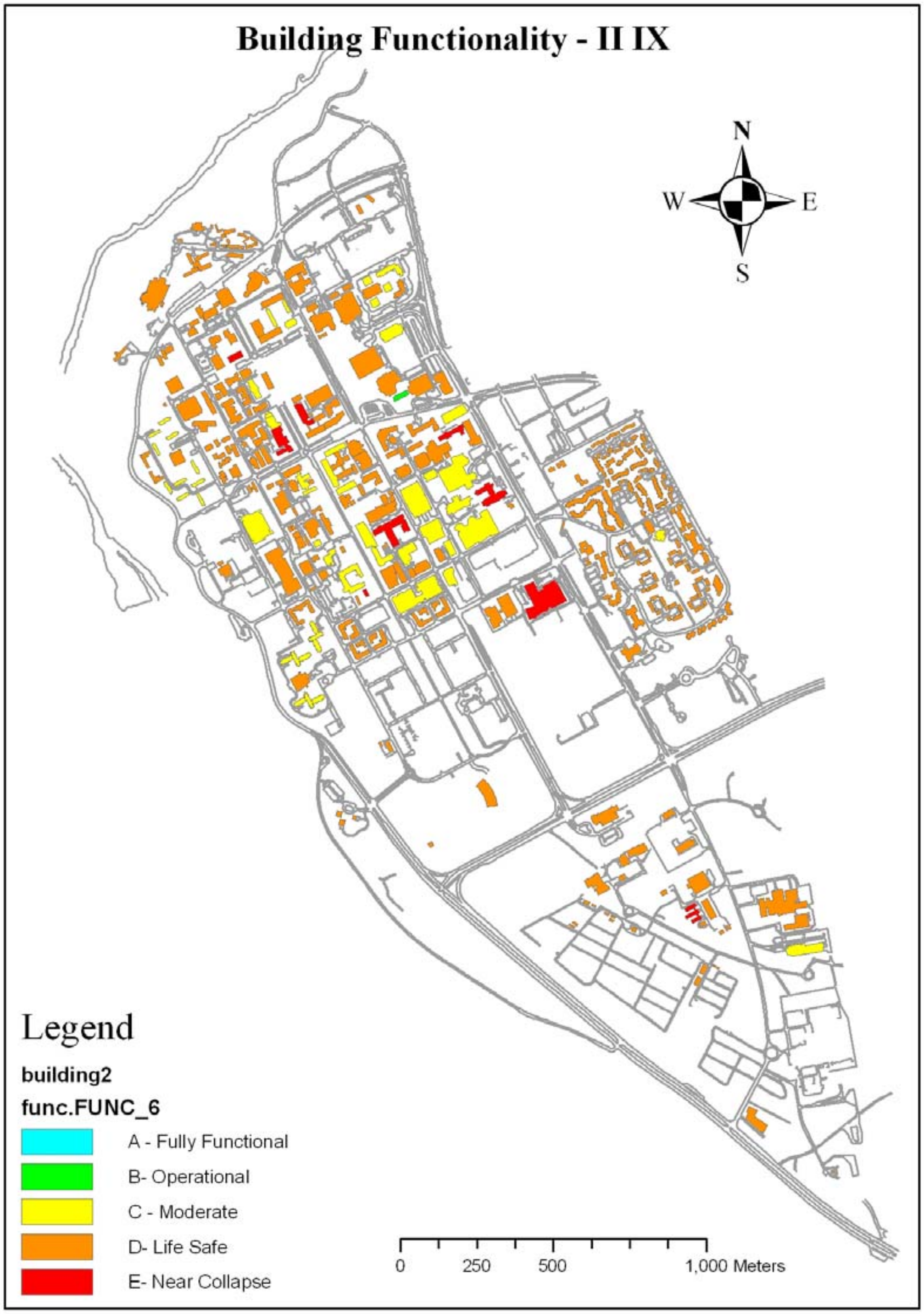
K - 1 UBC Building Functionality - II VI



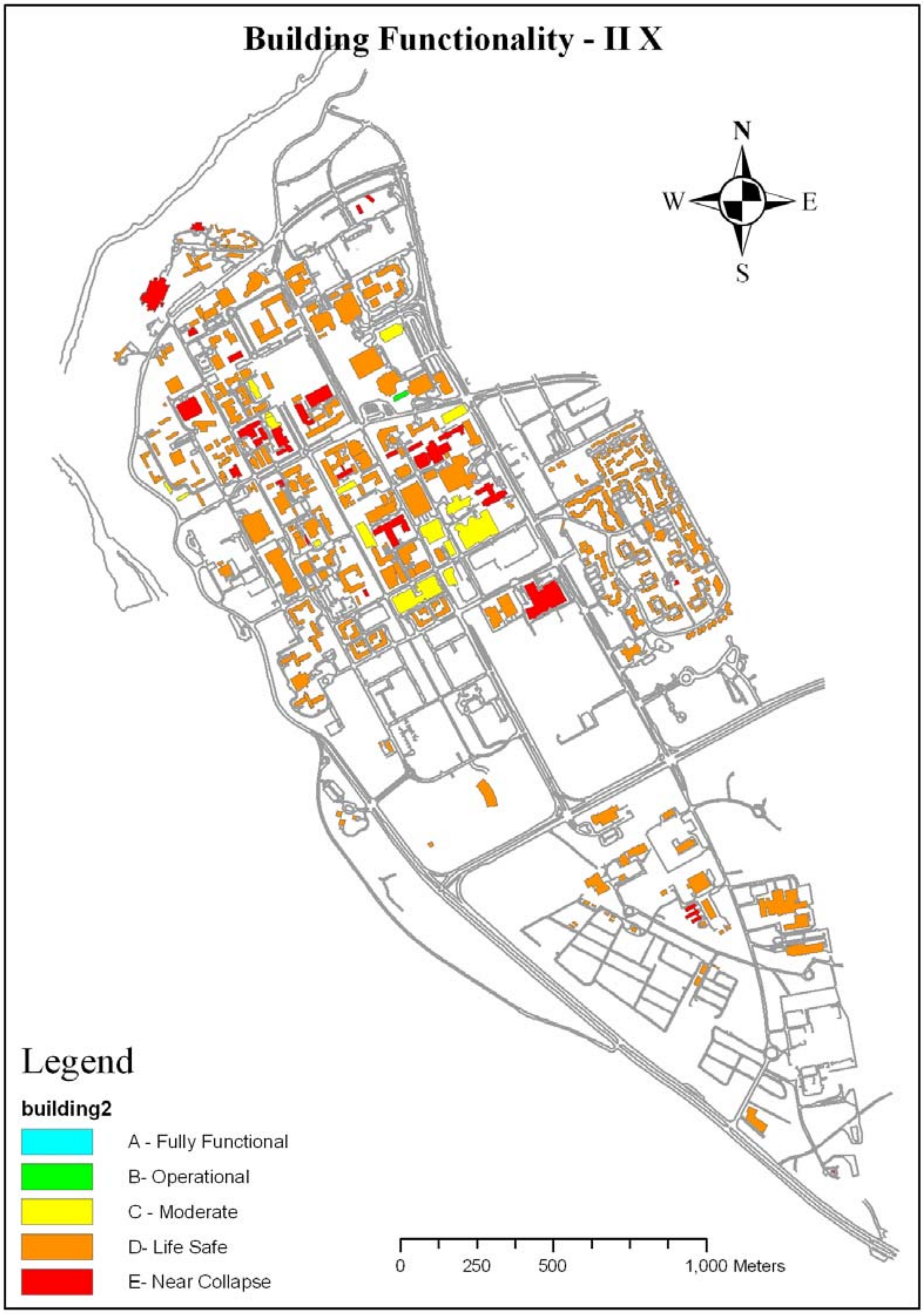
K - 2 UBC Building Functionality - II VII



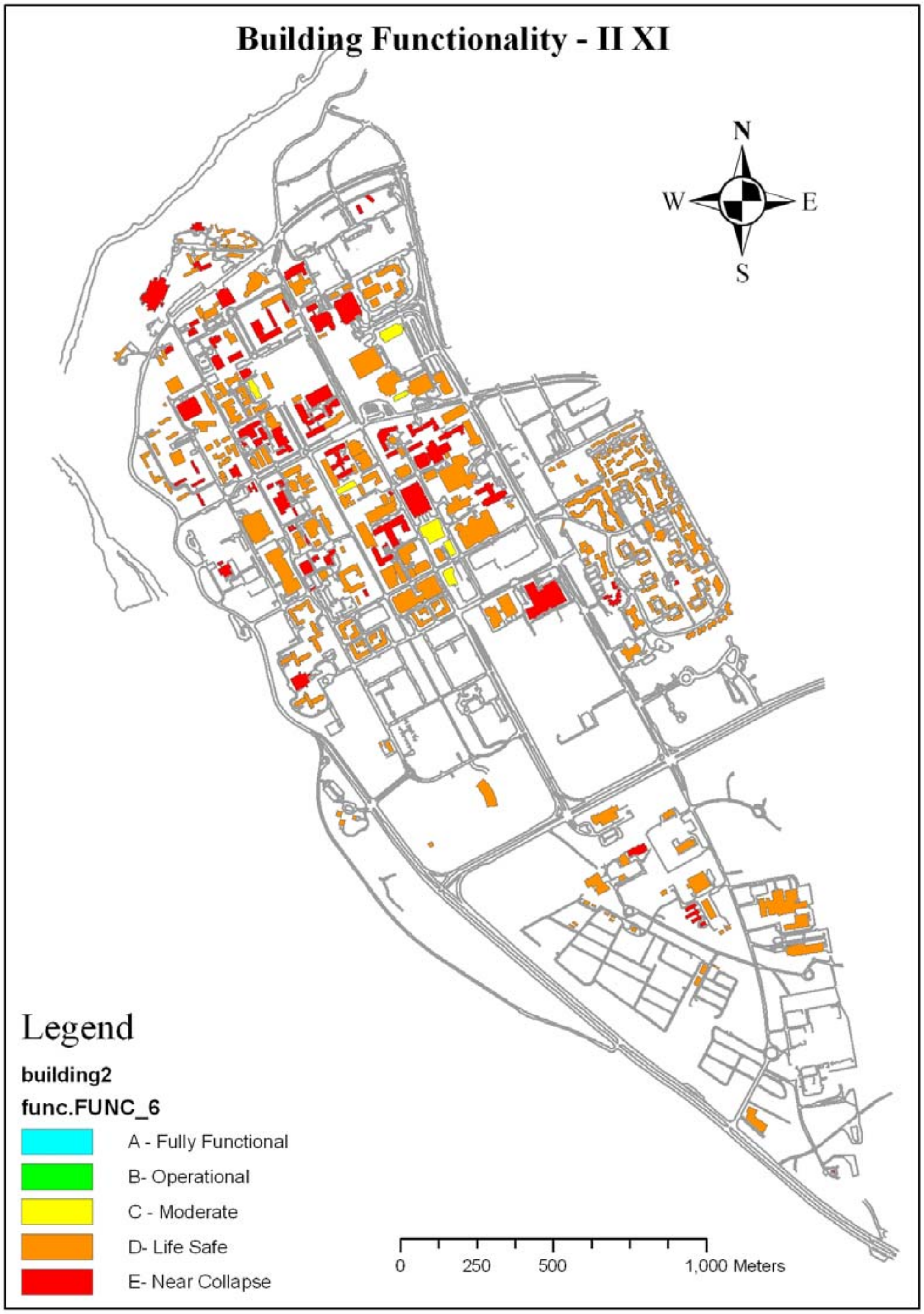
K - 3UBC Building Functionality - II VIII



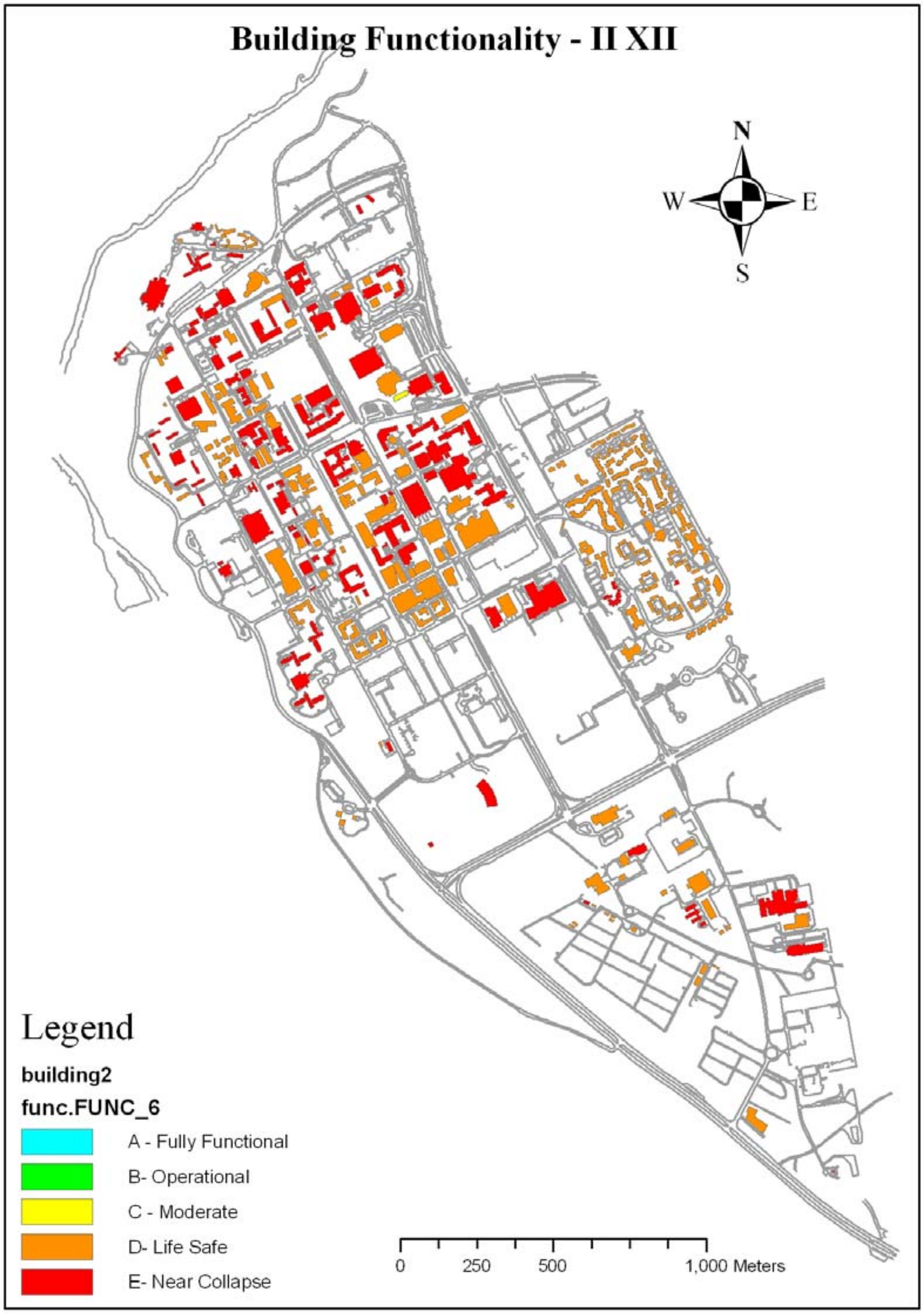
K - 4 UBC Building Functionality - II IX



K - 5 UBC Building Functionality - II X



K - 6 UBC Building Functionality - II XI



K - 7 UBC Building Functionality - II XII

Appendix L: Supervisor Recognition

Chapter 5 was developed based on discussions with Dr. Carlos Ventura (Supervisor). The author of this thesis is responsible for the literature review, collection of data, development of the methodology, performing the case study and interpreting the results.

The manuscript preparation for publications is done in collaboration with the co-author. The author of this thesis is responsible for the major portion of the writing, performing the assessments, and preparation of the tables and figures, and entirely accountable for any inaccuracies and errors.