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MAPPING OF INTERDEPENDENCIES THROUGH INTEGRATED HAZARD ANALYSIS: STUDY CASE OF A CANADIAN UNIVERSITY CAMPUS

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ABSTRACT:

This paper presents a general description of a new integrated hazard analysis methodology to study interdependencies among critical infrastructures. This research project results as NSERC and PS Canada initiative to conduct a three year study entitled “Decision Coordination for Critical Linkages in a National Network of Infrastructures”. The overall purpose of our interdisciplinary team of researchers is to develop simulation and human interaction tools to better coordinate joint actions by various organizations before and during situations of large scale emergencies (e.g. earthquake events).

The geographical location, diversity of stakeholders and infrastructure complexity of the University of British Columbia Point Grey Campus (UBC) provide interesting characteristics with which to develop, test and validate the theoretical framework and methodology behind our Infrastructures Interdependencies Simulator (I2Sim). The university is BC’s third largest employer with almost 10,000 full time residents and about 47,000 daily transitory occupants -students, faculty, and staff- interacting in a small area. As such, UBC shares the attributes of a small city.

The 402-hectare campus on the outer western edge of Vancouver is geographically isolated from the urban area by the Pacific Spirit Park. None-the-less, UBC’s strong dependencies to its neighbors, the daily high traffic of people and goods, the presence of well defined and sparse residential, recreational and business areas, and its own utilities’ providers, create a valid scaled-system to test the ontology and analysis methodology.

This work presents the findings of the integrated hazard evaluation of structural, non-structural, lifelines, electric grid, IT network and policy applied to the UBC campus, with earthquake scenarios.

KEYWORDS: Infrastructure, Interdependency, Hazard

1. INTRODUCTION

1.1 Problem

As the rate and severity of natural and man-made disasters’ have increased, so has the possibility that disruption of Critical Infrastructure could result in prolonged loss of essential services. The complex system of interdependencies among critical infrastructure has heightened the risks and vulnerabilities for Canada, and for other countries. And hence, the consequences can lead to cascading effects expanding across sectors and borders, Public Safety Canada, 2008.

The task for Canada and other countries is to establish an action plan to guide the identification of risks, the implementation of protective safety measures, and the proper and effective response to disruptions of critical infrastructure.

1.2 Goals and Objectives

The ultimate goal of this research is to develop a methodology that helps strengthening the resiliency of critical infrastructure. Seismic Risk Assessment methodology will be used as a benchmark, and it will be improved to be able to assess risk for other hazards. This methodology will be used for the identification of interdependencies among critical infrastructure. In this research a "studied space" would be disassembled in a finite number of physical layers (critical infrastructures), that contain both the Building infrastructure and the Lifeline systems, Figure 1. Risks will be estimated separately, and interdependencies will be assessed superimposing the layers one by one.

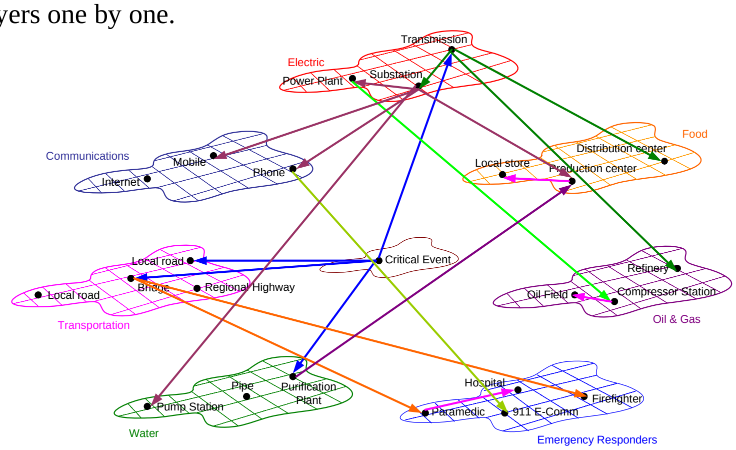

Figure 1. "Studied Space" disassembled in several Physical and Human Layers, (Martí et. al., 2006).

The general objectives of the research are to: 1) improve knowledge on multi hazard risk assessment and apply it to the multi hazard setting and construction practices of British Columbia; 2) improve the methodology by evaluating Lifeline Systems; 3) obtain Interdependency Indices for Critical Infrastructure systems; 4) assess the validity of the methodology through a case study; 5) develop multi hazard scenario cases for a case study in BC; 6) provide documentation on how the risk estimates should be implemented by UBC-JIIRP project; and 7) implementation of results, assessments, outcomes for the simulator I2SIM. In this paper a general discussion of the methodology and results will be presented for an earthquake Scenario of Instrumental Intensity IX. The objectives and details of the research are compiled in two companion thesis by Thibert, 2008 and by Juarez, 2008; the latter is still in progress.

2. BACKGROUND

2.1 Previous work on Seismic Risk Assessment in British Columbia

The University of British Columbia and Bell (1998) developed a classification system for buildings in British Columbia. The BC 31 classification system included 31 prototypes based on construction practices in BC, the damage relationships were developed by adapting the ATC-13 (ATC, 1985). 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.

Cook (1999) studied nonstructural component and building content damage. Damage probability matrices were developed from the nonstructural fragility curves that were presented in FEMA/NIBS (1997). These damage probability matrices were applied to the City of New Westminster.

Onur et al (2001) estimated the potential damage and subsequent monetary losses that would result from seismic shaking in the Cities of New Westminster, Victoria and Vancouver.

Comprehensive building databases were assembled from city databases, rapid visual screening and inference schemes. Structural damage was estimated using the damage probability 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.

Thibert (2008) supplied the UBC-JIIRP project with seismic damage estimations of buildings so that realistic disaster simulations could be performed. The research applied and improved an existing methodology to the construction practices of British Columbia; the validity of the methodology was assessed through the use of a case study.

All the previous works were focused on the building infrastructure and non structural components; in this research lifeline systems were also considered for identifying risks in Critical Infrastructure (CI) systems. Seismic Risk Assessment shall be performed on an extended set of Lifeline Systems within the studied case. Furthermore, the consequences of the damages in every CI will be assessed, and how these damages and consequences affect other systems. Interdependencies will be evaluated and ranked for every Lifeline System. Finally the SRA methodology will be modified and extended to include other natural and man-made hazards. This research is believed to contribute in the enhancement of the resiliency of Critical Infrastructures; and that this methodology will help all authority levels to respond collectively to risks and target resources to the most vulnerable areas of critical infrastructure.

2.2 The Joint Infrastructure Interdependencies Research Program (JIIRP)

JIIRP is part of an effort by the Government of Canada, through the Natural Sciences and Engineering Research Council (NSERC) and former Public Safety and Emergency Preparedness Canada (PSEPC) now Public Safety Canada to fund research to develop innovative ways to mitigate large disaster situations. Six universities across Canada were involved. The University of British Columbia (UBC) studied decision making for critical linkage in infrastructure networks. Our standard of life relies on Critical Infrastructure systems.

2.2.1 Infrastructure Interdependencies Simulator

UBC-JIIRP aims to model the real time effects of a disaster and identify the interdependencies among 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. 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.

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. 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 simulator model is made up of three primary components: tokens, channels and cells. The basic function of critical infrastructures is to transfer resources (tokens) from the location where the resources are produced or stored (cell 1) to the location where they are utilized or accumulated (cell 2) through transportation channels. The purpose of the system is to ensure that at any given moment, and under natural or man-made hazard events, the resources (tokens) will be targeted to the most vulnerable areas of critical infrastructure, Marti, et al (2008).

2.3 UBC Test Case

The University of British Columbia Point Grey campus was modeled as a case study, as an implementation of the simulator methodology. The geographical location, infrastructure complexity, and the diversity of its population made it an ideal test case to develop, assess 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.

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 probable seismic damage. Seismic Risk Assessment (SRA) was carried out for the buildings and lifeline networks on campus.

3. METHODOLOGY

3.1 Risk Assessment for Critical Infrastructure

Seismic Risk Assessment methodology will be used in this research. It is not the purpose of this paper to exhaust in the methodology of SRA, but to comment some of the key aspects. The key for estimating seismic risk is to estimate damage to structures and to lifelines as a function of ground motion. Ground shaking is the classic intermediate step between earthquake occurrence and damage, because it allows the use of results from one earthquake to estimate damage for future events.

A brief description of SRA, is a methodology that requires a logical and consistent approach to evaluating the effects of future earthquakes on people and structures. First is the Probabilistic Seismic Hazard Assessment which gives a probabilistic description of earthquake characteristics such as ground motion amplitudes and fault displacement. Second is the estimation of earthquake damage to structures (buildings and lifelines). Third is the translation of seismic hazards into seismic risks by using the selected damage or loss of functions. Fourth is the formal or informal analysis of earthquake mitigation decisions. The ultimate goal of SRA is to develop the elements that can be used to make rational decisions, McGuire (2004) and Dowrick (2003).

3.1.1 A methodology for assessing the seismic risk of Critical Infrastructure (CI) systems

In this research, Seismic Risk Assessment was used to evaluate damage in CIs at UBC Campus Case. This involved the development of a database, the assessment of the expected level of damage to Lifeline Systems (Buildings **-** structural and nonstructural building components **-**, Water, Roads, Gas and Electricity systems), and the estimation of monetary, human and functionality losses. In general, damage functionality conditions were defined, loss of service and interdependencies were also evaluated.

The research is focused on 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.

The vulnerability functions are intensity based damage probability matrices. For buildings, they were developed for 31 prototypes for BC Southwestern area, and were based on expert opinion. Direct losses are the result of earthquake damage and include the loss estimation of human (casualties), monetary and functionality conditions. 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 event. Three times of day were selected for the casualty estimation: 2am, 2pm and 5pm.

Lifeline systems, such as Water, Gas, Electricity and Road systems were also assessed in this research. Electricity and Road systems were assessed using the ATC-13 methodology and FEMA-224. Gas and Water systems were assessed using the FEMA/NIBS 2005 methodology. The methodology used for Lifeline systems is a traditional SRA methodology. Permanent ground displacements were taken into consideration for the damage estimation of underground pipelines, and functionality conditions of roads were affected by slope failure in the studied area.

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

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.

4. INTERDEPENDENCIES

Critical Infrastructures in a "studied space" are the main components or systems upon which we depend, the interdependencies amongst them are complex, and sometimes difficult to observe and assess. In this research a "studied space" would be disassembled in a finite number of physical and human layers (critical infrastructures), that contain both the Building infrastructure and the Lifeline systems.

Once the layers are defined, the "Hazard Event" (earthquake, storm or blast loading) will be applied to the studied space; the corresponding damage assessment is then obtained. Each individual damage assessment provides outcomes that only affect the functionality of each layer.

In the following paragraphs two examples of these interdependencies are presented; the examples show the affection between building and water systems, and building and road systems. The different outcomes of these two systems affect other CIs, and the cascading effects are then clearly observed in the overall "studied space".

4.1 Interdependency among critical infrastructure (water system and buildings)

The general information of the earthquake scenario is as follows: a) Location (shown in Figure 3): UBC Point Grey Campus; b) Time: 2 pm and; c) Instrumental Intensity IX. In the building damage assessment, Figure 3, the majority of buildings will be non functional (orange color: moderate to heavy damage), non structural components and building contents' damage will also affect the overall functionality of buildings. The damage assessment to the water supply system shows the damage to the water pipelines by segment. The methodology ignores the directionality of the water flow in the water system, and thus the accumulation of losses through the length of the pipelines, and it also neglects the distribution to other trunk lines within the system. The overlaying of both damage assessments does not show the hidden consequences of the interdependencies of these two Critical Infrastructure systems.

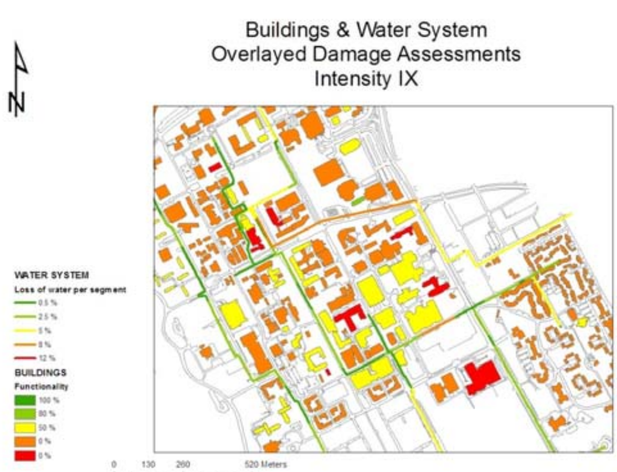

Figure 3. Overlaid Damage Assessments of the water System and Buildings, II IX.

Figure 4 shows the interdependency of both systems, the trunk line providing water to the water station has an accumulated loss of 8 %, but the water station is non-functional due to the extended damage to its structure and non structural components. A more realistic situation would be that the entire UBC campus will be suffering from a shortage of water and will remain non-functional, as shown in Figure 4.

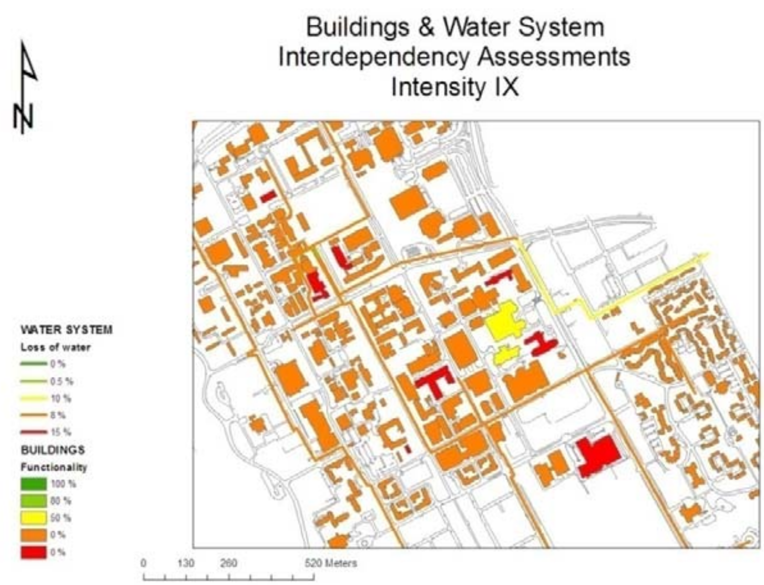

Figure 4. Functionality conditions due to Water System and Buildings Interdependencies.

4.2 Interdependency among critical infrastructure (roads and buildings)

The following damage estimation considers that 39,210 users of UBC Campus were present at the moment of the event; Figure 5 shows the distribution of people per building.

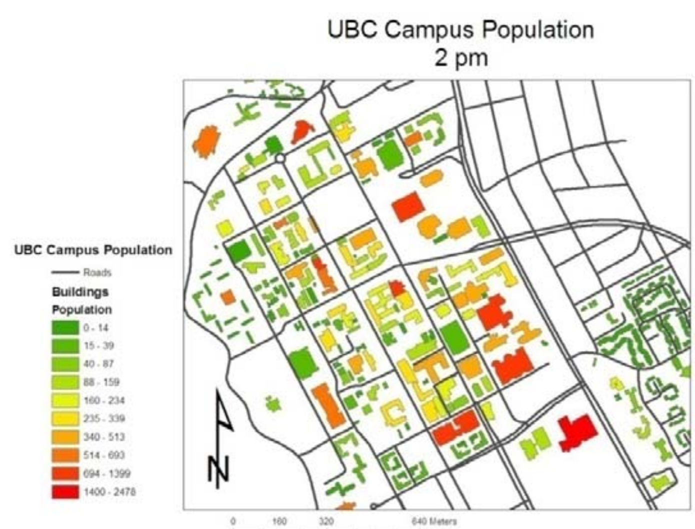

Figure 5. Population at 2 pm in some buildings of UBC Campus

Figure 6, shows the distribution of casualties, severity level injuries 1, 2, 3 and 4 and the percentage of length of the road with damage after the earthquake event. "*Severity 1: Injuries requiring basic medical aid that could be administered by paraprofessionals. Severity 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. Severity 3: Injuries that pose an immediate life threatening condition if not treated adequately and expeditiously. Severity 4: Instantaneously killed or mortally injured.*", FEMA/NIBS (2005).

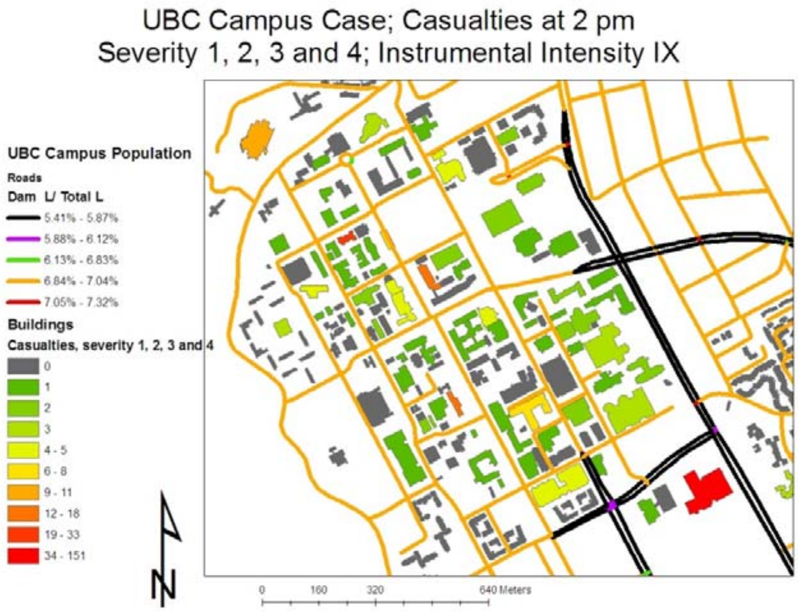

Figure 6. Road damage assessment and buildings with casualties (Severity levels 1, 2, 3 and 4).

Figure 8 shows buildings with casualties, severity level 2, 3 and 4. Injured people are either trapped or in such condition that they will need aid to reach emergency human layers (97 persons).

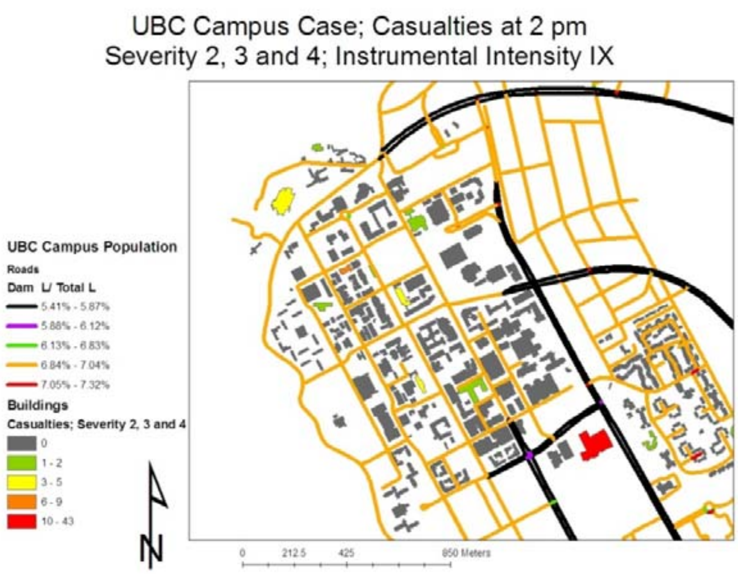

Figure 8. Buildings with casualties 2, 3 and 4 and Road Damage Assessment.

Figure 9 shows the structural damage of buildings. Buildings with orange colors are supposed to have sustained structural damage between 30 to 60 %; hence partial localized collapses might be observed, cracked windows and building debris might be blocking the surrounding sidewalks and roads. Red color buildings have sustained structural damage of 60 to 100 %, these buildings might be in a "life safety" to "total collapse" condition.

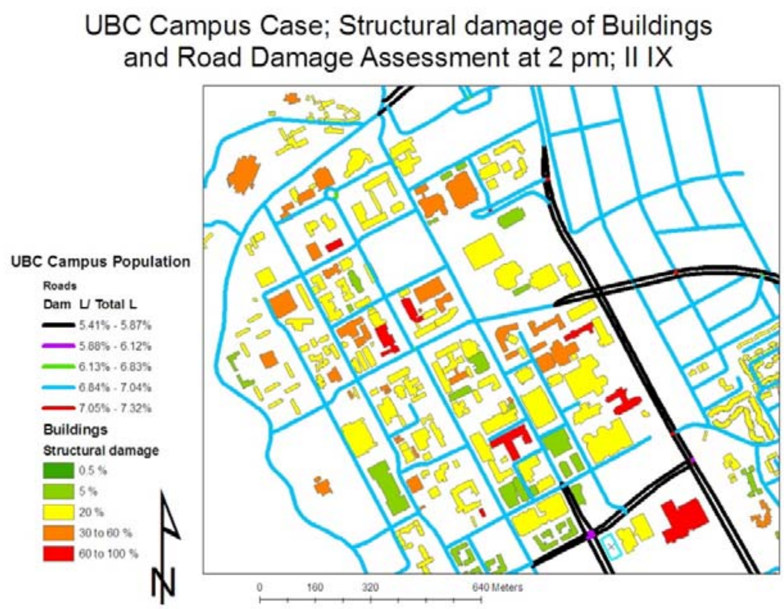

Figure 9. Structural damage of buildings, and road damage assessment.

The road conditions will depend on the damage sustained by the buildings, the functionality of non structural components and building contents, and the number of injured people. Road blocks will be needed, at least, in those 9 locations were injured people are located.

5. SITUATION ANALYSIS AND INTERDEPENDENCIES

- 39, 210 is the population at the time of the Earthquake event, (Figure 5)
- Highways have sustained 5.5 % and Local roads 7 % of their length with slight to moderate damage; hence they will remain 95 % and 90 % functional. Possible time delays will be expected and crews might be needed to survey the conditions of the local roads for major cracks impeding traffic flow
- 416 people are injured: 264 (severity 1), 65 (severity 2), 10 (severity 3), 22 (severity 4), (Figure 6)
- 101 buildings have injured people: 87 buildings (Severity 1), 13 buildings (severity 2), 4 buildings (severity 3), 6 buildings (severity 4)
- 28,334 people need to be evacuated, if the criteria for evacuation is the overall functionality condition of the buildings (0 % functional), (Figure 7)
- 11,022 people will be evacuated, if the criteria for evacuation is the structural damage condition of the buildings (30 to 100 % damage), (Figure 9)
- 314 buildings will be declared non functional, if the criteria is due to the overall functionality conditions, (Figure 7)
- 48 buildings will be declared non functional, if the criteria is due to the severity of the structural damage; 39 buildings will be 30 to 60 % damaged; 9 buildings will be 60 to 100 % damaged (Figure 9)
- 266 buildings will be declared non functional, if the criteria is due to the damage sustained to the Drift Sensitive Non Structural Components (Figure 7)
- Road blocks associated to damage of buildings: 9 because of major structural damage to buildings, (Figure 9); or 24 because of people with injuries with severity 2, 3 and 4, (Figure 8); or 48 because of structural damage D and E, (Figure 9).

- No water will be available in some areas of UBC Campus due to the structural damage sustained by the Water Station in UBC Point Grey Campus
- The Substation of UBC Campus has sustained 40.7 % damage. This condition will affect the electrical grid in UBC

The following is a set of possible consequences due to the interdependency of the systems:

1) **First responders (police or transit personnel, paramedics, rescue teams and qualified Structural Engineers):** for this situation qualified Structural Engineers might be needed to assess the structural conditions of buildings. Other problems that the first responders will have to observe are the road blocks due to structural damage, debris, and stranded people trying to reach shelters or aid
2) **Medical care (hospital services, emergency care units):** emergency layers will attend people with injuries: (264) Severity 1; (65) Severity 2; (10) Severity 3; (22) instantaneously killed or mortally injured. These injuries will translate into: 264 emergency patients; 65 short-term patients; and 10 long-term patients. The overall condition of the Hospital was assessed as 50 % functional. The functionality of the Hospital will also be affected by the damage to other physical layers (water, electricity, gas and road conditions)
3) **Human layer (users of UBC Point Grey Campus):** 28,334 or 11,022 people will be evacuated due to functionality conditions. Shelters, food, water and services will be needed. Structural engineers will be needed to provide the structural conditions of the residences and also the possible locations of shelters
4) **Transportation (Planning, Transportation, Police):** 28,334 or 11,022 people will be evacuated due to functionality conditions or structural damage
5) **Roads (Planning, transit personnel, police, first responders):** the number of road blocks 9, 24 or 48, will determine the accessibility for UBC Campus. Those road blocks will be successful if they are coordinated properly with UBC Planning services, police, transit personnel and first responders. UBC Point Grey Campus will probably have to be closed for a few days.

6. CONCLUSIONS

The outcomes of each individual damage assessment do not show the complexity of interdependencies of the systems within a "studied space". But when they are arranged and the interdependencies are observed and taken into account for the risk management and mitigation plans, all of a sudden they are very important; and will help develop better action plans, in order to reduce vulnerabilities, or to decide where to put more resources in the critical infrastructures that need more attention. This example of interdependencies can be observed dynamically through the I2SIM Simulator that will produce static and dynamic visualization tools; so that operators of the CIs could see the outcomes in real time.

Three hazards are considered in this research: earthquake, storm and blast loading. These hazards often impose a serious threat to cities and populations by the consequences of their impacts. The earthquake methodology will be implemented in order to consider other hazards, hazard-damage relationships, if necessary will be developed to extend the applicability of the methodology into a multi-hazard risk assessment, with emphasis in the interdependency among critical infrastructure.

All security agencies must take into account all elements of the "studied space" (a venue, urban sector, a facility, a city, etc.), to find out which critical infrastructure is important to take into consideration for the multi-hazard approach. In some cases it will be important to consider airspace, or cyberspace, in other cases these or other elements might not be relevant. All the planning for the interdependency of Critical Infrastructures cannot take place in isolation, it requires multi agency planning so that objectives, assessments and outcomes will be properly matched.

A key objective of the authorities of the "studied space" is the protection of the identified Critical Infrastructure from human and natural hazards, and to minimize the consequences on an emergency event. In order to accomplish all that, it is important to understand the vulnerabilities, the Interdependency of Critical Infrastructure, and the hazards.

One of the contributions of this research is to implement the methodology in the I2SIM Simulator, so that this tool can be used to assess interdependencies of Critical Infrastructures, during an emergency event (multi-hazard event). Part of the implementation of the methodology includes: provide a set of scenario cases for the simulator, situation analysis, and the final outcomes for every case.

The simulator I2SIM is a powerful tool that will allow the owner of the "studied space" to investigate possible outcomes, vulnerabilities, interdependencies among Critical Infrastructure, so that consequences can be minimized.

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