SIMULATION-BASED PERFORMANCE EVALUATION OF REDUNDANT EVACUATION PATH

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Introduction

Earthquakes are a catastrophic disaster that causes severe consequences including loss of life and property damage. Evacuation modeling is a part of emergency planning aims to safeguarding affected people (e.g. population exposed to fire, injured population, displaced population seeking shelters) to safe locations to minimize the impact of the disaster (potential casualties and physical damage of buildings). This study focuses on risk analysis of earthquakes and evaluates the performance of evacuation path in the aftermath of earthquakes for Montreal Island. Seismic risk analysis is conducted to obtain inputs that are required for performance evaluation of evacuation routes.

It is now widely accepted that eastern Canada is susceptible to seismic risk. Charlevoix region of Quebec have the highest earthquake shaking probabilities, higher than 70% for MMI V within 50 years and in Montreal structurally damaging shaking probabilities are less than 10% and widely felt probabilities are greater than 40% (Onur et al, 2008). Montréal Island is located in the Western Québec Zone, which experienced at least three significant earthquakes since 1732. According to Natural Resource Canada, 1732-earthquake (magnitude 5.8) caused destruction of 300 houses and 185 dwellings in Montréal because of aftershock fire. Furthermore, based on population, structure, infrastructure and regional seismic hazard, Montréal is ranked as second for seismic risk after Vancouver in Canada (Rosset and Chouinard, 2008). Montreal is vulnerable to seismic hazards due to large number of population, aging infrastructure and regional seismic hazards. Seismic risk analysis includes wide range of aspects such as; vulnerability assessment of buildings and socio-economics, transportation system, infrastructure system and critical facilities.

The study area comprised of the following evacuation areas: Ville-Marie, Plateau Mont-Royal and CDG/NDG. The objectives of this study are: (1) seismic risk analysis of Montreal Island (2) estimation of the number of evacuees due to earthquake disaster (3) estimation of the total network evacuation time and (4) identification of the major bottlenecks, congestion, and other operational difficulties in the areas covered by the network.

Methodology

Delineation of Emergency Planning Zones (EPZs)

HAZUS-Canada 2.1 software is used to analyze risk for this study area. HAZUS-Canada is GIS based software developed by Federal Emergency Management Agent (FEMA) for the purpose of regional hazard loss estimation. The database required to analyze seismic risk is: 1) the building inventory 2) hazard maps regarding soil amplification, liquefaction, and landslides 3) population distribution at three different times of the day 4) census demographic information and 5) synthetic ground motion contour maps for the study area. The first step is Peak Ground Acceleration (PGA) calculation for probabilistic and deterministic hazards scenarios. The second step is earthquake induced damage estimation for the study area to delineate EPZs.

Emergency Planning Zones (EPZ) are delineated based on direct and induced damage such as fire following earthquakes. The first step of Fire Following Earthquake (FFE) module on HAZUS is to estimate number of fires (ignitions) that occur after an earthquake. The equation used to estimate frequency of ignition per census tract is proposed by FEMA (2003):

$$Ing / TFA = 0.581895(PGA)^2 - 0.029444(PGA)$$

Where, Ign/TFA is the mean number of ignitions per million sq. ft. of building total floor area of each census tract. The input parameter is Peak Ground Acceleration (PGA) and is calculated based on the Ground Motion Prediction Equation (GPME) by Atkinson and Boore (2006). In earthquake scenario, magnitude 6.3 and distance 30Km North West from Montreal is selected. Soil amplification effects are obtained from the Vs_{30} soil classification map (Rosset and Chouinard, 2011).

Fire spread in urban areas is estimated based on a model developed by Hamada (1975), $N_{tv} = \frac{1.5\delta^2}{a^2} * Ks * (K_d + K_u)$

Where,

Ntv = Number of structures fully burned	n= no of structures
t = time, in minutes after initial ignition	d = average building separation, in meters
V = wind velocity, in meters per second	Ks = half the width of fire from flank to flank (m)
δ= "Built-upness" factor; $\delta = \frac{\sum_{i=1}^{n} a_i^2}{TractArea}$	Kd = length of fire in downwind direction, from the initial ignition location, in meters
a = average structure plan dimension (m)	Ku = length of fire in upwind (rear) direction, from the initial ignition location (m)

Estimation of the total number of evacuees

HAZUS is widely used to estimate the number of displaced persons seeking public shelter for earthquake scenarios. The HAZUS methodology assumes that the number of people who require short-term housing is a function of income, ethnicity, ownership and age. The following equation is developed in the HAZUS methodology (FEMA, 2003):

$$\#STP = \sum_{i=1}^{5}\sum_{j=1}^{5}\sum_{k=1}^{2}\sum_{l=1}^{3}\left[\alpha_{ijkl} \cdot \left(\frac{\#DH \cdot POP}{\#HH}\right) \cdot HI_i \cdot HE_j \cdot HO_k \cdot HA_l\right]$$

Where,

#STP - Number of people requiring short term housing

α_{ijkl} - is a constant

HI_i - Percentage of population in the i^{th} income class

HE_j - Percentage of population in the j^{th} ethnic class

HO_k - Percentage of population in the k^{th} ownership class

HA_l - Percentage of population in the l^{th} age class

POP - Population in census tract

The constant α_{ijkl} is calculated using a combination of shelter category "weights" (which sum to 1.00) and assigning a relative modification factor for each subdivision of each category.

$$\alpha_{ijkl} = (IW \cdot IM_i) + (EW \cdot EM_j) + (OW \cdot OM_k) + (AW \cdot AM_l)$$

Where,

IW is the income weighting factor (0.73)

EW is the ethnic weighting factor (0.27)

OW is the ownership weighting factor (0.00)

AW is the age weighting factor (0.00)

Estimation of evacuation time for Montreal

Extreme events such as earthquakes may generate extra traffic demands as well as obstacles that may have adverse impacts on the transportation network. Population density, maximum capacity of road and speed of the vehicles are important parameters of road congestion. In addition, the probability of population movement during evacuation and traffic capacity of a particular link would affect other links and eventually reduce the speed of evacuating demand.

The traditional methods rely on simulation techniques to analyze evacuation for scenarios. The variables involved in emergency evacuation planning are the destinations of evacuees (shelters, hospitals) and evacuation routes. For this study, a macro-simulation evacuation model (OREMS) is used to simulate traffic conditions over a transportation network as evacuation progresses. Evacuation simulation is performed based on the User Equilibrium (UE) principle. The objective model can be mathematically described as follows:

$$\text{Min } Z(x) = \sum_{a} \int_{0}^{x_a} t_a(\omega)\, d\omega$$

Subject to:	$f_k^{rs} \geq 0$
$X_a = \sum_r \sum_s \sum_k f_k^{rs} \delta_{a,k}^{rs}$	$X_a \geq 0$
$\sum_k f_k^{rs} = q_{rs}$	$t_a(X_a) = t_a^0 \left[1 + \alpha \left(\frac{x_a}{C_a} \right)^{\beta} \right]$

Where,

Z (x) = the objective function, the sum of the integrals of the link performance functions	q_{rs} = flow rate between origin r and destination s, veh/hr
X_a , ta = flow and travel time on link *a*	$\delta_a^{rs} = Indicator\ \mathrm{var}\, iables$
$t_a(x_a)$ = impedance function, minute	$\delta_{a,k}^{rs}$ = 1 if link *a* is part of path k connecting O-D pair r-s = 0 otherwise
t_a^0 = travel time on link a in free speed, minute	c_a = Capacity of link a veh/hr; and
f_k^{rs} = flow on path k connecting O-D pair r-s	α,β = pending coefficient

The macro-simulation model of an earthquake evacuation traffic assignment is a non-linear programming model with linear constraints. For large networks, this nonlinear programming problem can be solved using a numerical procedure called Frank-Wolfe (F-W). The traffic and road geometric data is collected from Ville de Montreal (2010). The outputs of the macro-simulation model are evacuation times for multi-priority groups such as; evacuation time from EPZs to public shelters and hospitals; travel time estimation for fire trucks, ambulances to reach EPZs and so on.

Performance evaluation of transportation network of Montreal Island is conducted by TRANSCAD software. Individual congested portion of the road network can be identified by using localized service Level-of-Service (LOS) measure that is volume/capacity (V/C) ratio. A V/C ratio greater than one is indicative of congestion.

Expected Outcomes

The expected outcomes of this research are:

- Identification of the vulnerable boroughs based on building damages
- Estimation of the total number of evacuees
- Estimation of evacuation time for the highly vulnerable areas and
- Performance evaluation of evacuation routes

References

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