An Integrative Framework to Measure the Impacts of Earthquake-Induced Landslides on Transportation Network Mobility and Accessibility

Shangjia Dong[1]; Haizhong Wang[2]; Michael J. Olsen[3]; Andre R. Barbosa[4]; and Michael D. Bunn[5]

[1]Dept. of Civil and Environmental Engineering, Univ. of Delaware, Newark, DE.
Email: sjdong@udel.edu
[2]School of Civil and Construction Engineering, Oregon State Univ., Corvallis, OR.
Email: haizhong.wang@oregonstate.edu
[3]School of Civil and Construction Engineering, Oregon State Univ., Corvallis, OR.
Email: olsen@oregonstate.edu
[4]School of Civil and Construction Engineering, Oregon State Univ., Corvallis, OR.
Email: andre.barbosa@oregonstate.edu
[5]School of Civil and Construction Engineering, Oregon State Univ., Corvallis, OR.
Email: bunnmi@oregonstate.edu

ABSTRACT

This paper presents an integrative analysis framework combining natural hazards with network mobility to provide insights on disaster preparedness and relief. In particular, this framework characterizes the impact of seismically induced landslides on network mobility to reveal the mobility changes immediately after the events and throughout the course of restoration and recovery efforts. Landslides not only undermine the structural integrity of roadways, but also deposit a significant amount of material on the road surface, usually resulting in partial or complete road closure to traffic. The highly populated Portland, Oregon, Metro is selected as a case study to demonstrate this framework given that the Pacific Northwest is highly prone to large earthquakes as part of the Cascadia Subduction Zone as well as highly susceptible to landslides given its high topographic relief and wet climate. In this case study, travel time to the west and east sides of Willamette River, which divides the Portland Metro area, shows an abrupt change in mobility. In particular, the Portland Hills region with its steep topography is identified as the most vulnerable region. Based on a temporal analysis of recovery, the majority of the network mobility is expected to be restored after 30 days. The results of this study serve as a preliminary assessment of the impact of landslides on network mobility and can facilitate decision making in emergency planning.

INTRODUCTION

Transportation infrastructure systems serve as the backbone of society to support the mobility of people and goods, connect businesses, and provide the support for supply chains and offer accessibility to vital resources for both daily activities and in emergency situations (Faturechi and Miller-Hooks, 2014). In emergency situations, transportation networks play a vital role in evacuation, rescue operations, and community reconstruction, and recovery. The frequency of disasters (e.g., natural and man-made) has been increasing in the last decade (Gupta, 2001). Due to the increased system complexity and interdependency, the impacts of such events on transportation system have been drastically intensified (Faturechi and Miller-Hooks, 2014). Disastrous events such as Hurricane Sandy (2012), the Sichuan Earthquake China (2008), the

Canterbury earthquake sequence in New Zealand (multiple events from 2010-2015), and the Kaikoura earthquake in New Zealand show how vulnerable transportation systems are in such disruptive circumstances.

Other natural hazards such as landslides can result in significant disruptions on the transportation network, which eventually lead to connectivity and mobility loss. Generally, landslides are widespread in regions that have steep slopes, weak soil, and significant precipitation or storm events (Iverson et al., 2015). In addition to precipitation-induced landslides, earthquakes can generate large amounts of medium to large landslides (Keefer 1999, 2002). As an example, the 2016 M7.8 Kaikoura earthquake caused widespread landslides and rockfalls and resulted in severe disruptions to the state highways and local road network due to the large quantities of soil and rock debris on the road (Mason et al., 2017), isolating Kaikoura for several weeks. Immediately after the earthquake, large sections of the New Zealand State Highway (SH) SH-1 and SH-7 and the major railway line running parallel to SH-1 were closed. Some segments were partially opened 3 days later; however, access was restricted in those segments to local traffic, emergency responders, or construction crews. During this time of closure, traffic was re-routed inland as part of a detour, resulting in hours of increase in travel time partially due to the increased length in travel but also due to the significant congestion from the increased traffic. In addition, shipping containers that were typically transported by rail, were then transported by trucks, which further increased the roadway transportation network congestion. A large section (25 km) of SH-1 remained closed for 9 months until the landslides were cleared and the engineering work and construction was performed to stabilize several slopes. Although the entire highway was opened with restricted hours one year after the earthquake, at the time of writing of this paper (1.5 years after the earthquake), construction efforts are still underway to stabilize precarious slopes. Several sections of the highway are still reduced to one direction of travel at a time.

The State of Oregon is severely threatened by potential earthquakes resulting from the Cascadia Subduction Zone (CSZ) (James et al., 2000). The most recent mega-earthquake (estimated M9.0) occurred on January 26, 1700; however, there is a 40% chance of recurrence within next 50 years (Goldfinger et al., 2012). The CSZ earthquake is expected to trigger new landslides as well as reactivate existing landslides (Sharifi-Mood et al., 2017) throughout much of western Oregon. These landslides are expected to cause direct losses and indirect socio-economic losses via travel delays and decreased transportation efficiency (Postance et al., 2017).

Various metrics exist to measure the performance of transportation systems in disasters, e.g., Travel time/distance (Jenelius et al., 2006), throughput/capacity (Sun et al., 2006), accessibility (Chen et al., 2007), topological measures (Sullivan et al., 2010), etc. In this paper, connectivity and travel time is utilized as the measure of the transportation system performance (i.e., mobility and accessibility) in disrupted scenarios. Further, a before and after analysis is conducted to compare the mobility changes through the disruption. The comparison helps identify the most affected regions and provides insights on prioritizing critical infrastructure protection efforts. This work combines natural hazard mapping with transportation mobility analysis to provide a systematic evaluation of network mobility performance in the presence of physical damage (e.g., reduced road capacity) resulting from landslide impacts.

The remainder of the paper is organized as follows. First, the methodology and the study site are described. The next section analyzes the simulation results of the case study and provides a discussion of the main observations. The final section concludes the paper with major findings and future work.

METHODOLOGY

This paper presents an integrated framework combining predictive natural hazard analyses with transportation mobility analysis using a network theory-based approach. Based on transportation network's structure property, the network is considered as a graph, and its topographic feature are transformed into link attributes. The detailed simulation procedures are explained in the following sections.

Simulation Framework. Figure 1 shows the integrated simulation framework of this paper. This research uses a scenario-based analysis approach. By comparing the travel time pre- and post- the occurrence of seismically induced landslides, the mobility change on the network can be measured and visualized, helping identify the impacted regions. The simulation platform is built using a Python module known as NetworkX. The shortest route (in time) is calculated to represent the mobility between a chosen origin-destination pair. Travel time of each link is derived through Equation (1). An afternoon peak-hour traffic volume is used to represent the traffic volume of each link and is provided by Portland Metro (Dong et al., 2016). In the post-landslide scenario, road capacity is modified through Bureau of Public Roads (BPR) function based on the estimated soil debris volume on road, which is described later in this section. Furthermore, to reduce the computation load, the network is divided into 80 × 40 zones, which are each 0.98 × 0.6 miles. The travel time calculation is calculated from centroid-to-centroid distances measured amongst all the zones.

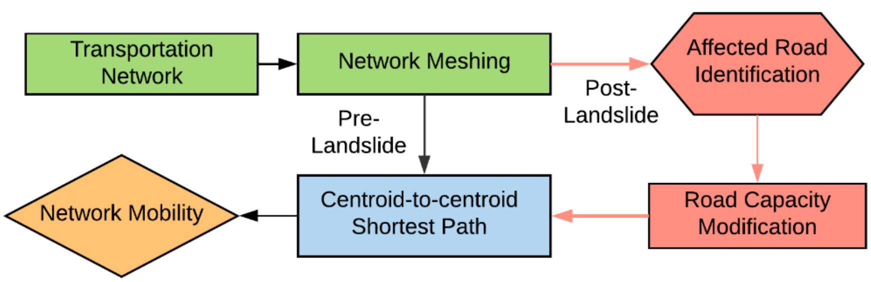

Figure 1. Simulation Framework Combining Landslide Disruption and Mobility Analysis.

Road Capacity Modification. A BPR Function (Tu et al., 2007) was utilized to model the reduction in capacity. Considering a highway network, for each link there is a function characterizing the relationship between resistance and volume of traffic:

$$t_a(q_a) = t_a(1+\alpha\left(\frac{q_a}{c_a}\right)^{\beta}) \tag{1}$$

where t_a is the free flow travel time on link a per unit of time; q_a represents the volume of traffic on link a per unit of time; c_a represents the capacity of link a per unit of time; $t_a(q_a)$ shows the average travel time for a vehicle on link a; α and β are the traffic/delay parameters and dependent on the functional classification of the roadway link. It is suggested that $\alpha \in [0.5, 2]$ and $\beta \in [1.4, 11]$ (Tu et al., 2007). Figure 2 shows the relationship between the capacity drop and travel time under the assumption that we have a one-mile link with free flow speed 96 km/hr, volume 1800 veh/hr/ln, and capacity 2000 veh/hr/ln. It is worth mentioning that in order to present the transition in travel time increase, travel time is convert into log scale.

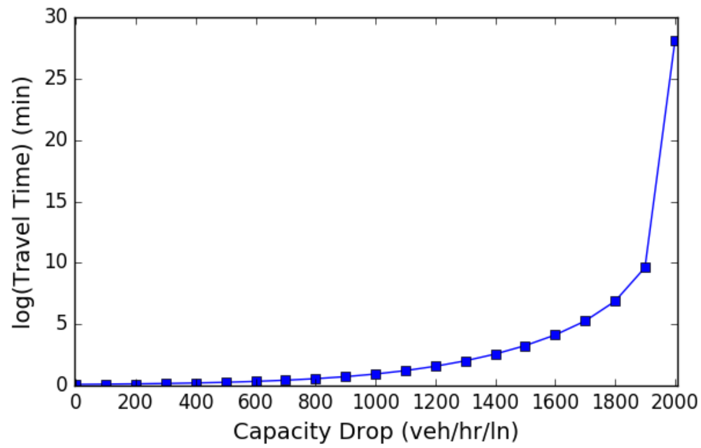

Figure 2. BPR Function Illustration under Capacity Drop.

Landslide Soil Volume Estimation. The determination of future landslide locations and volumes is primarily challenged by uncertainty in the magnitude of seismic hazards, hydrologic conditions, and soil variability. To limit these uncertainties, and to avoid selecting a specific earthquake scenario during this initial assessment, for the sake of this exercise landslides were assumed to originate from all unstable soil or rock masses within the deposits of previously occurred landslides. Landslide deposits contain weak and poorly consolidated soils that are highly susceptible to future landslides (Leshchinsky et al., 2018), and all topographic protuberances within the deposits were considered unstable. Rock outcrops not located within the extents of the landslide deposits were not considered. Using the approach of Leshchinsky et al. (2018), mapped landslides from the Statewide Landslide Information Database for Oregon v3.4 (Burns, 2018), and a 1/3 arc-second digital elevation model, the volume of protuberances was computed for all landslides within 30.48 meters of the highway network. All protuberance volume was assumed to impact the roadway, and protuberances were assigned to their nearest transportation link. Since multiple instabilities could affect a single link, the volume was computed as a cumulative value of all instabilities.

Figure 3 shows the study site selected for this research. The network data provided by Portland Metro contains the freeways, highways, major streets, and arterials. Traffic attributes such as link speeds, capacities, and the afternoon peak-hour traffic volume are included in the link attributes (Dong et al., 2016). There are a total of 12,535 links and 9,486 nodes in the network. In Figure 3, the coloring indicates the volumes of soil debris expected on links that are prone to landslides. The landslide impacted road (O-HELP, 2018) is considered impassible immediately after the landslide, and soil removal is assumed at the rate of 14 m^3 (500 ft^3) per day based on values determined from Leshchinsky et al. (2018).

RESULTS AND ANALYSIS

Through the simulation framework, the travel time between a given origin-destination pair can be derived. Access to hospitals is critical, especially during the initial disaster response where many people are likely to be injured. Therefore, we selected Cedar Hills Hospital as the destination point to measure the network mobility and accessibility. Figure 4 shows the travel time pre- (left panel) and post- (right panel) landslide from the rest of the zones to Cedar Hills Hospital (marked as the blue star).

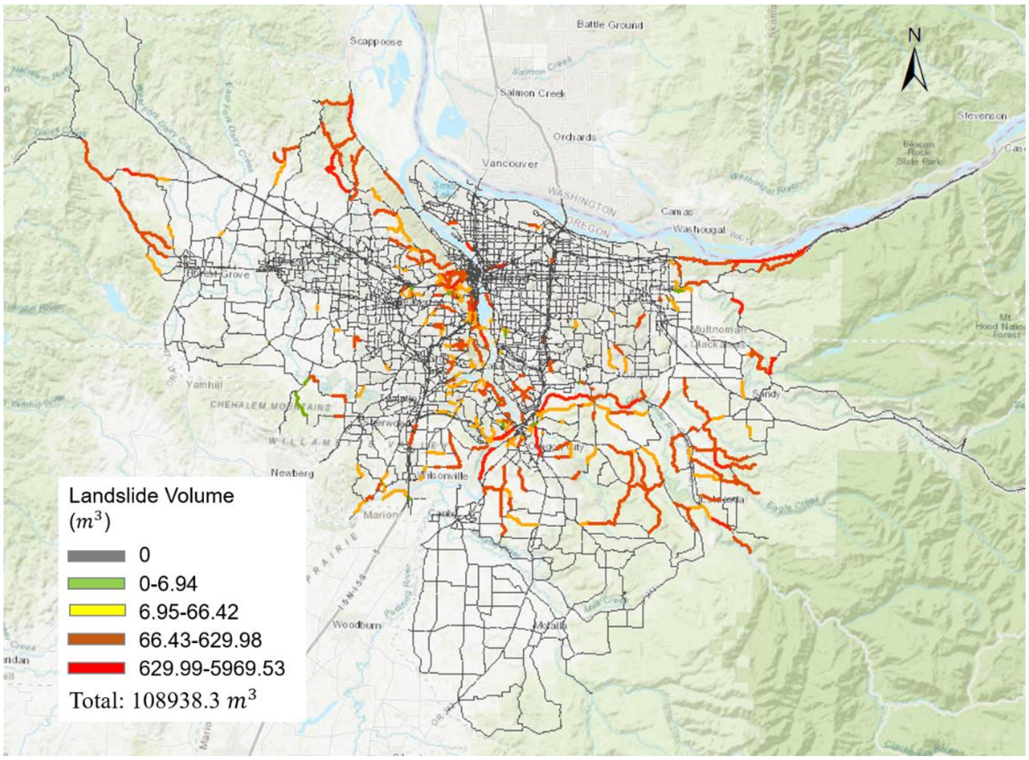

Figure 3. Portland Metro Transportation Network.

Before the landslides, the mobility shows a centralized spreading pattern. This occurs because, without any disruption on the network, farther distance, in general, means longer travel time. With disruptions from landslides, the mobility impact becomes apparent. In general, the landslides create local barriers which block a subset of roadway segments/links out of the entire transportation network, the travel time can be dramatically increased due to localized road closures and the locations of closures are often not known to the evacuating traffic or utility restoration crew members. Not surprisingly, the travel time across the Willamette River shows a dramatic increase, which suggests that east-side of the river will have limited access to facilities located at west-side of the river.

The travel time derived through the proposed simulation framework excluded factors such as signal timing, departure time variations, choice of modes and routes; hence, the travel time may be lower than the actual travel time after the occurrence of a real event. However, we can use the travel time increase ratio to eliminate the impact of these external factors. Figure 5 shows travel time ratios of the mobility pre- and post-landslide occurrence. The pre-landslide condition, which approximates the normal peak hour traffic, is used as the base scenario. The lighter colored area shows the impacted region. We can identify the Portland Hills area as the most vulnerable site because in this steep terrain, landslides will cut off most of the roads which leave no alternative routes for the detour; thus, the accessibility to the site is limited.

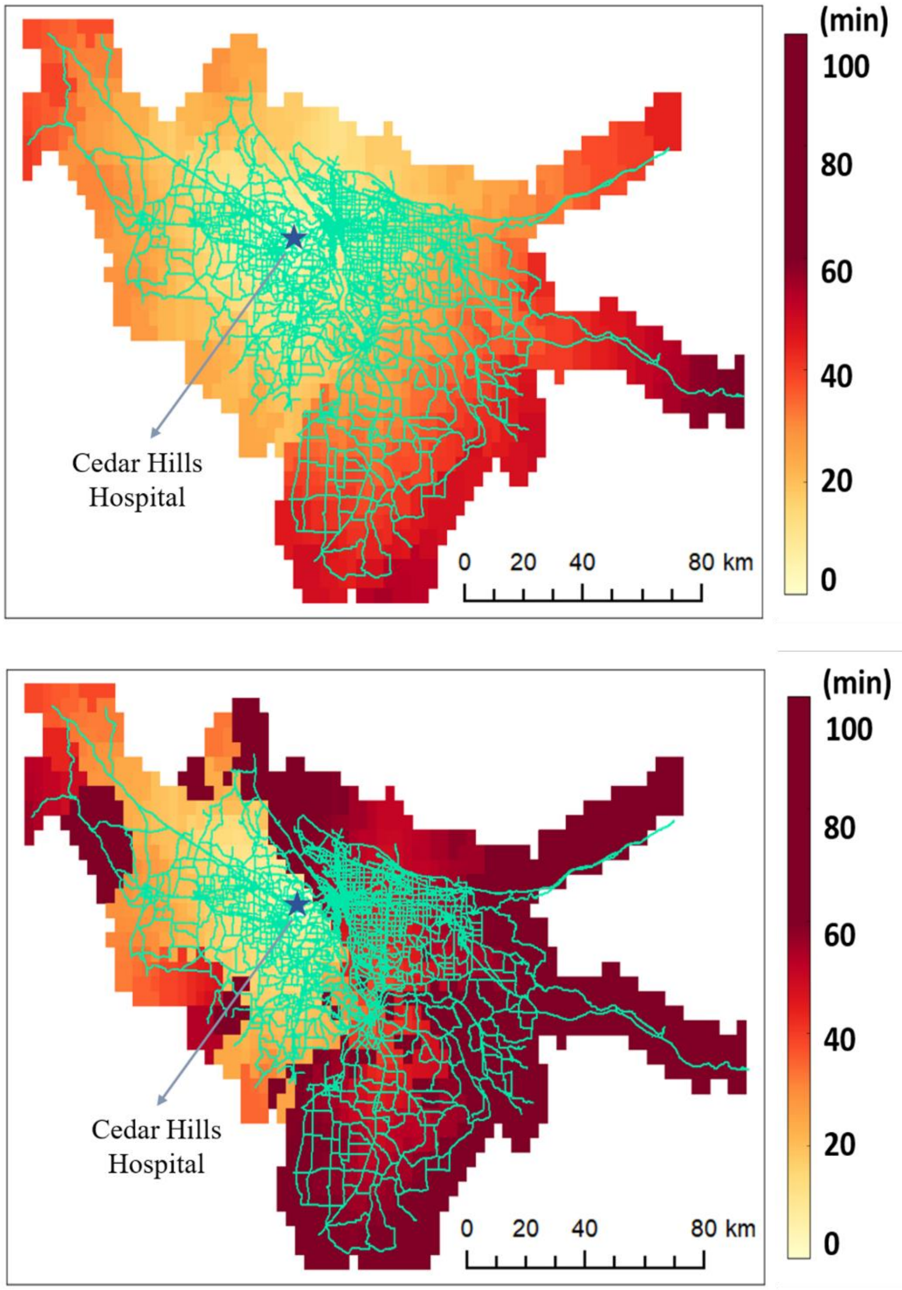

Figure 4. Network Travel Time to Cedar Hills Hospital: Pre- and Post- Landslides.

Although immediate post-landslide mobility is critical for the initial disaster response, the mobility during recovery phase is also important for the business restoration and risk control in planning. Comparing the base version, Figure 6 shows the mobility restoration at different phases. Based on Leshchinsky et al. (2018), the soil removing rate is considered as 14 m^3/day (500 ft^3/day). Throughout the 30-day restoration course, the mobility on the road network increases as the ratio of the pre- and post-landslide travel time decreases. However, we can still observe the impact at Portland Hills area. This area calls for special attention in disaster relief and emergency planning.

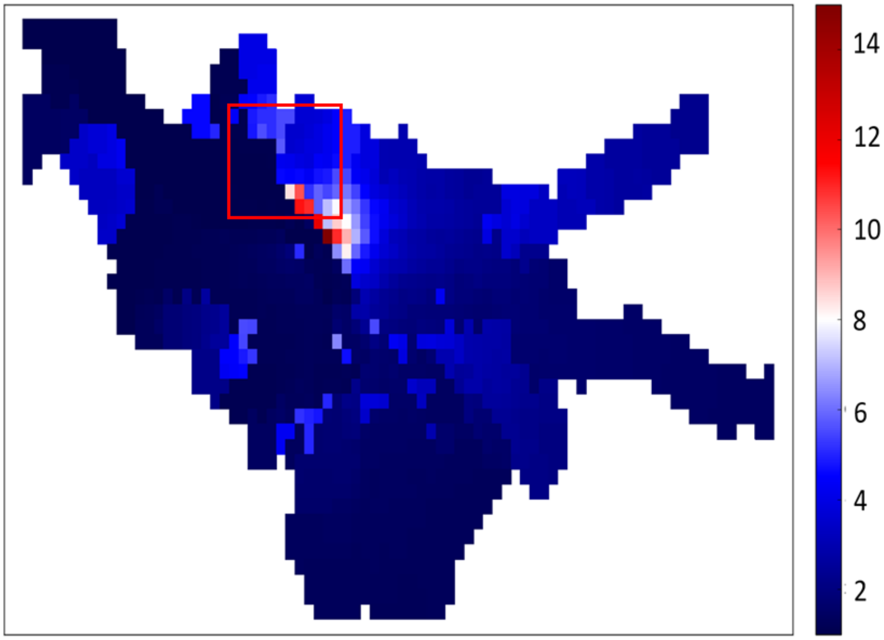

Figure 5. Impact to mobility expressed as the ratio of Post- to Pre- landslide conditions travel time.

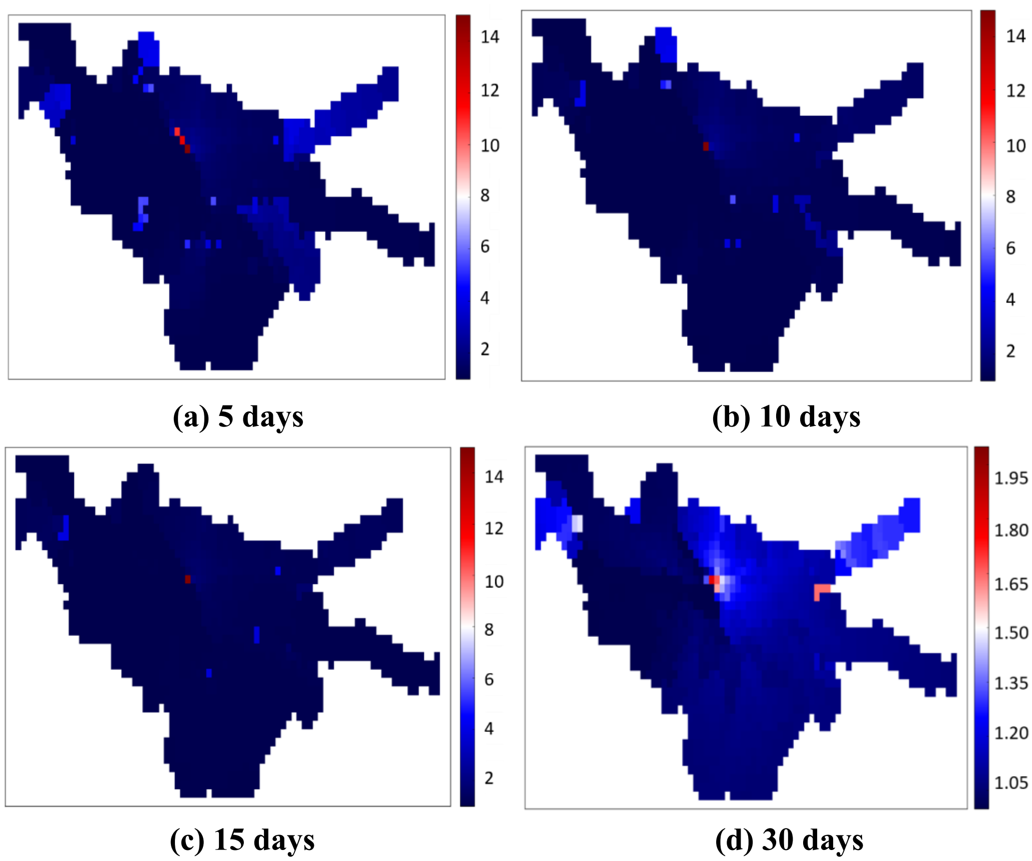

Figure 6. Increased Travel Time Ratio during Different Restoration Phase.

SUMMARY AND FUTURE REMARKS

In this paper, we measured the mobility impacts of landslides to a post-disaster transportation network. Portland, OR is selected as the study site, and freeway, highway, major arterials, and streets are included in the study scope. The travel time of each road segment is calculated through the use of the BPR function, which also has the capability to approximate the landslide impact by reducing the link capacity. Given an origin-destination pair, the travel time can be derived. By iterating across the network, we can evaluate the system-wide transportation network mobility and accessibility to critical facilities. Comparing the travel time pre- and post-landslides, the disruption caused by the landslide to the road network demonstrates the impacts of the earthquake-induced landslides on network mobility reduction and the duration of the disruption following an event. Within the Portland Metro, we identified the Portland Hills region is one of the most vulnerable sites. Notably, the Willamette River also creates a natural barrier for travel across the river immediately after the landslides. The landslides-disrupted road segments or links are expected to be restored after 30 days.

The results of this research can serve as a preliminary assessment of network impact under landslide disruptions. However, there are other types of hazards can be induced by the earthquake. In future research, we plan to integrate multiple hazards to enable the creation of an integrative and probabilistic analysis framework for post-earthquake transportation infrastructure network mobility and accessibility studies. Moreover, the occurrence of a hazard is probabilistic and varies at a temporal and spatial scale across the entire infrastructure network. To encapsulate this stochastic nature of hazards, we can further incorporate the probability of hazards occurrence in the network disruption modeling. In addition, the current soil removal is subjected to various resource limitations (e.g., materials, machineries, construction/maintenance crews) that would likely occur with widespread repairs required across the state. Therefore, we will also investigate the restoration scheduling problem to optimize the recovery with constrained resources.

ACKNOWLEDGEMENT

The authors would like to acknowledge the funding support from the Cascadia Lifeline Program (CLiP) and its consortium members including Oregon Department of Transportation, Portland Water Bureau, Portland General Electric, Bonneville Power Administration, Port of Portland, NW Natural, Eugene Water & Electric Board, and Tualatin Valley Water District. The authors are also grateful to Portland Metro's collaboration by sharing the Portland Metropolitan Transportation Network which is an important component of this analysis. The authors are appreciative of Dr. Ben Leshchinsky's insightful comments on the estimation of landslides volumes and closure times.

REFERENCES

Burns, W. J. 2018. *Statewide Landslide Information Database for Oregon*, Release 3.4: Oregon Department of Geology and Mineral Industries.

Chen, A., C. Yang, S. Kongsomsaksakul, and M. Lee. 2007. Network-based accessibility measures for vulnerability analysis of degradable transportation networks. *Networks and Spatial Economics*, 7(3), pp.241-256.

Dong, S., A. Mostafizi, H. Wang, and P. Bosa. 2016. Post-Disaster Mobility in Disrupted Transportation Network: Case Study of Portland, Oregon. *ASCE International Collaboration in Lifeline Earthquake Engineering IRP* 1, pp.501-507.

Faturechi, R., and E. Miller-Hooks. 2014. Measuring the performance of transportation infrastructure systems in disasters: A comprehensive review. *Journal of infrastructure systems*, 21(1), p.04014025.

Goldfinger, C., C. H. Nelson, A. E. Morey, J. E. Johnson, J. R. Patton, E. Karabanov, J. Gutierrez-Pastor, A. T. Eriksson, E. Gracia, G. Dunhill, and R. J. Enkin. 2012. Turbidite event history: Methods and implications for Holocene paleoseismicity of the Cascadia subduction zone. US Geological Survey Professional Paper, 1661, p.170.

Gupta, U. 2001. *Earthquake loss estimation including transportation network damage* (Doctoral dissertation, Massachusetts Institute of Technology).

Iverson, R. M., D. L. George, K. Allstadt, M. E. Reid, B. D. Collins, J. W. Vallance, S. P. Schilling, J. W. Godt, C. M. Cannon, C. S. Magirl, and R. L. Baum. 2015. Landslide mobility and hazards: implications of the 2014 Oso disaster. *Earth and Planetary Science Letters*, 412, pp.197-208.

James, T. S., J. J. Clague, K. Wang, and I. Hutchinson. 2000. Postglacial rebound at the northern Cascadia subduction zone. *Quaternary Science Reviews*, 19(14-15), pp.1527-1541.

Jenelius, E., T. Petersen, and L.-G. Mattsson. 2006. Importance and exposure in road network vulnerability analysis. *Transportation Research Part A: Policy and Practice*, 40(7), pp.537-560.

Keefer, D. K. 1999. Earthquake-induced landslides and their effects on alluvial fans. *Journal of Sedimentary Research*, 69(1).

Keefer, D. K., 2002. Investigating landslides caused by earthquakes–a historical review. *Surveys in geophysics*, 23(6), pp.473-510.

Leshchinsky, B. A., M. D. Bunn, and M. J. Olsen. 2018. Enhancing Landslide Inventorying, Lidar Hazard Assessment and Asset Management, Final Report, Project SPR-786: Oregon Department of Transportation, Under Review.

Mason, D., P. Brabhaharan, and G. Saul. 2017. Performance of road networks in the 2016 Kaikōura earthquake: observations on ground damage and outage effects. *Proc. 20th NZGS Geotechnical Symposium*.

O-HELP. 2018. Oregon Hazard Explore for Lifeline Program, Cascadia Lifeline Programs (CLiP), http://ohelp.oregonstate.edu/.

Postance, B., J. Hillier, T. Dijkstra, and N. Dixon. 2017. Extending natural hazard impacts: an assessment of landslide disruptions on a national road transportation network. *Environmental Research Letters*, 12(1) p.014010.

Sharifi-Mood, M., M. J. Olsen, D. T. Gillins, and R. Mahalingam. 2017. Performance-based, seismically-induced landslide hazard mapping of Western Oregon. *Soil Dynamics and Earthquake Engineering*, 103, pp.38-54.

Sullivan, J. L., D. C. Novak, L. Aultman-Hall, and D. M. Scott. 2010. Identifying critical road segments and measuring system-wide robustness in transportation networks with isolating links: A link-based capacity-reduction approach. *Transportation Research Part A: Policy and Practice*, 44(5), pp.323-336.

Sun, Y., M. Turnquist, and L. Nozick. 2006. Estimating freight transportation system capacity, flexibility, and degraded condition performance. *Transportati-on Research Record: Journal of the Transportation Research Board*, No. 1966, pp.80-87.

Tu, H., J. Van Lint, and H. Van Zuylen. 2007. Impact of traffic flow on travel time variability of freeway corridors. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1993, pp.59-66.