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A geographical and multi-criteria vulnerability assessment of transportation networks against extreme earthquakes

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ABSTRACT

The purpose of this study is to provide a geographical and multi-criteria vulnerability assessment method to quantify the impacts of extreme earthquakes on road networks. The method is applied to two US cities, Los Angeles and San Francisco, both of which are susceptible to severe seismic activities. Aided by the recent proliferation of data and the wide adoption of Geography Information Systems (GIS), we use a data-driven approach using USGS ShakeMaps to determine vulnerable locations in road networks. To simulate the extreme earthquake, we remove road sections within "very strong" intensities provided by USGS. Subsequently, we measure vulnerability as a percentage drop in four families of metrics: overall properties (length of remaining system); topological indicators (betweenness centrality); accessibility; and travel demand using Longitudinal Employment Household Dynamics (LEHD) data. The various metrics are then plotted on a Vulnerability Surface (VS), from which the area can be assimilated to an overall vulnerability indicator. This VS approach offers a simple and pertinent method to capture the impacts of extreme earthquake. It can also be useful to planners to assess the robustness of various alternative scenarios in their plans to ensure that cities located in seismic areas are better prepared to face severe earthquakes.

1. Introduction

Thanks to the proliferation of data and the wide adoption of Geographic Information Systems (GIS), researchers have now access to abundant new information that was impossible until recently [1]. The use of this information offers paradigm-shifting opportunities, enabling researchers to increasingly consider data-driven approaches in their analyzes, with notable opportunities in reliability engineering and resilience planning. Indeed, researchers can now relatively easily perform scenario-based analyzes, measure new attributes of systems, and observe the impacts of different changes (i.e., extreme earthquake events) within a system (i.e., transportation networks), potentially contributing to new policies and practices for systems management and the planning and design of more resilient infrastructure systems. Moreover, these data-driven approaches are changing decision-making processes by favoring data-based analyzes [2].

The creation and generation of data is now at its fastest pace [3], and the United States Geological Survey (USGS) is now able to provide data simulating the impact of earthquakes across the United States. Earthquakes have two major attributes: epicenter and magnitude. However, ground-shaking levels are related to many factors such as quality of soil, distance from the earthquake, and complexities in propagation of seismic waves in the Earth's crust [4]. Despite these constraints, USGS ShakeMaps present ground-shaking levels after an earthquake in different sites. The USGS officially states that the goal of producing these rapid-response ground-shaking maps is to "engage a diverse audience including scientists, emergency planning agencies, engineers, and the public media". Thanks to their geographic format, these ShakeMaps offer particular benefits to assess the vulnerability of spatial systems such as road networks.

There is a general consensus on the adverse impacts of "extreme earthquake" events on human activities in urban areas. In 2010, economic losses due to natural catastrophes cost the insurance industry almost USD 40 billion worldwide, and earthquake related losses were nearly one-third of all insured losses. Population growth and urbanization, coupled with the fact that many major urban areas are located in earthquake prone locations, can cause significant losses due to earthquakes; despite the absence of a significant trend in the rise of global seismic activities [5].

Simultaneously, extreme events occurrence (particularly complex ones like earthquake) are nearly impossible to predict, and damages and impacts are usually underestimated [6]. Therefore, a

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comprehensive study of the potential impacts of extreme events must be carried out to be better prepared when these catastrophic events occur.

Nowadays, with the proliferation of freely-available transportation data in cities (e.g., Longitudinal Employer-Household Dynamics (LEHD) work flow data, Census Transportation Planning Products (CTPP) journey-to-work trip data, Census Bureau TIGER products), researchers can investigate the robustness of transportation systems by comparing certain attributes before and after an extreme event. These studies can lead to a better understanding of elements of resiliency and robustness, in turn contribute to better prepare for post-disaster emergency responses. As vital urban infrastructure systems during extreme events, transportation systems are the backbone of emergency management services.

In parallel, the emerging discipline of network science provides immediate benefits for the study of complex transportation systems as topological networks [7–10]. Assimilating transportation systems as networks with nodes/vertices and links/edges can help determine vulnerable critical road segments in the aftermath of extreme events.

In this study, our main goal is to contribute a new pragmatic geographical and multi-criteria vulnerability measure to examine the impacts of extreme earthquakes on urban road networks. This new measure is illustrated with the cases of Los Angeles and San Francisco, the only two major US cities that are prone to seismic hazards. Note that we restricted our study to the municipal boundaries of Los Angeles and San Francisco as opposed to metropolitan areas, since municipal governments have little power beyond their administrative boundaries; in the US, infrastructure planning and design tends to be the responsibility of municipalities.

To achieve our goal, we adopt a data-driven Geographic Information System (GIS) approach, coupled with a network science approach. The vulnerable characteristics of road networks are captured with four families of metrics namely: (1) overall properties; (2) network science robustness topological indicators, i.e., betweenness centralities; (3) GIS accessibility network analyst metrics; and (4) real trip changes using LEHD data. These families are metrics have a proven track record of being pertinent to assess robustness [11,12]. For instance to evaluate vulnerability of road networks to extreme earthquakes, Basöz and Kiremidjian [13] considered network connectivity, Wakabayashi and Kameda [14] looked at traffic patterns and flows, Chang [15] and Koenig [16] studied accessibility. In previous work, we have also used some of these metrics to measure and visualize the robustness of road networks to random zonal disturbance, central targeted disturbance and extreme flooding events in metropolitan cities [17,18].

In this work, to compare the robustness of road networks of the two cities, we have developed a new pragmatic Vulnerability Surface (VS) approach, which essentially combines multiple vulnerability metrics into one spider diagram (also called radar diagrams or star diagram). Here, we use USGS ShakeMaps to identify area-wide vulnerable locations in road networks. ShakeMaps reveal the relations between recorded ground motions and damage intensities. To simulate the impact of an extreme earthquake using USGS intensity ShakeMaps, we adopt a deterministic approach and remove entire road sections located within higher than "very strong" intensity areas. This deterministic binary system, i.e., road closed or opened whether it is on the "very strong" intensity locations of ShakeMaps or not, offers a pragmatic solution to dealing with the uncertainty linked with earthquakes. A deterministic approach is also preferred to a stochastic approach here for several reasons, including ease of computation and calibration issues [19]. In the same fashion, to measure the robustness of road network, as a substitution for all possible traffic flows in a network, we calculate the betweenness centrality of road segments and analyze how the distribution of betweenness changes after the extreme earthquake. In addition, we examine the impacts of extreme earthquake on real trips inside the road networks using LEHD data. Moreover, we note that we focus purely on road segments as opposed to considering the various urban transportation modes (i.e., private, public, and active transportation). In the following sections, we describe the implementation of our methodology. Then, we analyze and discuss the results of the different metrics in details. This study was performed in python, all network properties were calculated using the igraph library [20], and all maps and trip properties were compiled using ESRI's GIS software (ArcGIS).

2. Background

From the transportation network point of view, a vulnerable system is a system prone to extreme strains. Berdica describes "vulnerability" in transportation engineering as "a susceptibility to incidents that can result in considerable reductions in road network serviceability" [21]. These extreme strains can be a result of a hard-to-predict rare event, with high level of catastrophic consequences known as *black swans* [22]. The vulnerability of transportation networks to these catastrophic events (e.g., 1995 Kobe earthquake in Japan) have been addressed by many previous studies [15,21,23].

Most of these previous studies were conceptual methods on resilience without focusing on holistic approach to quantify and evaluate the vulnerability of transportation networks. Rosenkrantz et al. [24] suggest the idea of a "Structure-Based Resilience Matrix" to measure the resilience of networks components (i.e., edges and nodes). Scott et al. [25] used network flows, link capacity and network topology to develop a network robust index measure in the transportation network. Leu et al. [26] used a network analysis to measure the robustness of ground transportation system, with a focus on physical aspects of the network, for Melbourne, employing real data. These studies as well as many others offer pertinent references on quantifying resilience, robustness, and vulnerability in networks, in the area of network science, to form a relationship between the network topology and vulnerability in transportation networks [18,27]. We can note that in this work, because we are not considering resilience as a time dependent function [28], we prefer to use the term "robustness" as opposed to "resilience", although the two terms are often used as synonyms [29]. For us, vulnerability (i.e., defined as the opposite of robustness [30]) of a transportation system is seen as a quantitative decrease that can capture physical attributes of a transportation network.

Damages and destructions to road networks due to an extreme earthquake can be categorized by the original source of its cause. These causes fall into four major groups [31]. First, ground failure; showing itself as landslides, lateral spreads, differential settlements, and ground cracks. This tectonic-generated ground failures are the major road networks damages due to earthquakes (e.g., Earthquake of Hebgen Lake Montana 1959; Fig. 1a). Road network after severe shakings can be ripped apart, settled, tilted, or blocked with rockfalls for hours after the extreme earthquake. Second, faulting; constituting the movement of roadbed in horizontal and/or vertical planes a cross the roads and highways. This will cause buckling, distortion and ruptures in transportation networks. These ruptures and fault displacements may vary in length and differential offset up to 400 km and 10 m respectively (e.g., Earthquake of San Fernando 1971; Fig. 1b). Third, earthquake vibration: representing the most common problem in road