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Developing joint distribution of a_{max} and M_w of seismic loading for performance-based assessment of liquefaction induced structural damage

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ABSTRACT

Earthquake-induced soil liquefaction can cause enormous life and economic losses. The joint distribution of the peak ground surface acceleration (a_{max}) and the moment magnitude of an earthquake (M_w) is crucial to the estimation of soil liquefaction-related hazards. In this paper, a new method is suggested to estimate the joint distribution of a_{max} and M_w. Compared with the existing method, the suggested method is easier to implement, and depends on fewer assumptions. The derived joint distribution is then used to assess the damage state of a building caused by soil liquefaction during a given exposure time. The method is illustrated with an example in which a reinforced concrete frame building is assumed to be at different locations and is subjected to different exposure time. It is found that, as the exposure time increases, the chance of higher degree of damage also increases. When the exposure time is the same, the damage state of the building may also be different when it is at different locations. The method suggested in this paper can be used to quantify the effect of ground condition as well as the seismic effects at a site on the damage state of a building, thus providing a more transparent understanding of the risk associated with the soil liquefaction hazard on structural damage.

1. Introduction

Earthquake-induced soil liquefaction can cause enormous life and economic losses. For instance, approximately 27,000 houses were damaged in the Tohoku and Kanto districts due to soil liquefaction in the 2011 East Japan earthquake (Yasuda et al., 2012), and approximately half of the $30-billion losses associated with the 2010–2011 Christchurch, New Zealand earthquakes were caused by soil liquefaction (Cubrinovski et al., 2010). Severe liquefaction damage was also observed in the 2010 Haiti earthquake (Olson et al., 2011). In the past decades, many studies have been conducted to assess the liquefaction potential of soils. Both deterministic methods (e.g., Seed et al., 1985; Robertson and Wride, 1998; Youd et al., 2001) and probabilistic methods (e.g., Cetin et al., 2004; Moss et al., 2006; Boulanger and Idriss, 2015; Zhang et al., 2016) have been developed and are widely used. The availability of such methods greatly enhances the capability of the profession to predict and mitigate the soil liquefaction induced hazards.

In recent years, the performance-based design has attracted substantial attention in assessing soil liquefaction induced hazards. For instance, Kramer and Mayfield (2007) described a procedure to evaluate the annual probability of soil liquefaction following the Pacific Earthquake Engineering Research (PEER) framework (e.g., Cornell and Krawinkler, 2000). The same procedure can also be used to estimate the hazard curve of lateral displacement caused by soil liquefaction (e.g., Franke and Kramer, 2013). Alternatively, Juang et al. (2008) suggested a method to derive the joint distribution of the peak ground surface acceleration (a_{max}) and the moment magnitude of an earthquake (M_w) during a given exposure time, based on which the probability of liquefaction can be computed based on the total probability theorem. In this study, the exposure time refers to the time period of interest for seismic-risk calculations (e.g., Budnitz et al., 1985). The procedure suggested in Juang et al. (2008) was later extended to estimate the probability of surface manifestation (Juang et al., 2009), the hazard curve of the vertical settlement (Lu et al., 2009), and the exceedance probability of lateral spreading (Liu et al., 2016). The joint distribution of a_{max} and M_w is a key component in the framework suggested by Juang et al. (2008) for performance-based assessment of liquefaction-induced hazards. In Juang et al. (2008), the joint distribution of a_{max} and M_w was developed based on the assumption that the peak ground acceleration at the bedrock (PGA) at a site follow the lognormal distribution. Such an assumption is also followed in many subsequent

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studies. When the PGA cannot be approximated by a lognormal distribution, the method suggested in Juang et al. (2008) may not be applicable.

For geotechnical performance based design, it is preferred if the structural damage caused by soil liquefaction during a given exposure time can be explicitly estimated. Previously, Ishihara and Yoshimine (1992) provided a relationship to estimate the damage state of a building based on the total settlement of the building. Crowley et al. (2004) suggested a displacement-based method to assess the vulnerability of buildings. Bird et al. (2005) presented analytical solutions to assess the vulnerability of reinforced concrete frame buildings to differential ground movements induced by soil liquefaction. A relationship was provided in Bird et al. (2006) to estimate the damage of reinforced concrete frame buildings based on the settlement caused by soil liquefaction. These investigations mainly focus on the vulnerability of buildings subjected to liquefaction-induced ground movement. How to assess the damage state of a building for a given exposure time is still a largely unsolved problem.

The objective of this paper is thus to suggest an improved method to estimate the joint distribution of $a_{\max}$ and M_w, and illustrate how it can be used to assess the damage state of a building caused by soil liquefaction during a given exposure time. This paper is organized as follows. First, a new method is suggested to compute the joint distribution of $a_{\max}$ and M_w during a given exposure time. Then, how to assess the damage state of a building during a given exposure time is described. Finally, the suggested method is illustrated with an example to study the effect of different factors on the damage state of the building. The suggested method provides an enhanced basis for performance-based assessment of liquefaction-induced hazards.

2. Joint distribution of $a_{\max}$ and M_w

In general, the joint distribution of the ground motion parameters can be computed through ground motion attenuation analysis considering the potential earthquakes from all sources (e.g., Bazzurro and Cornell, 2002; Baker and Cornell, 2005). Alternatively, it may also be determined utilizing the information from the Unified Hazard Tool available on the United States Geological Survey (USGS) website (USGS, 2017), which is a tool to extract information from the National Seismic Hazard Maps compiled by USGS. By using the existing USGS data, the need for detailed attenuation analysis could be largely avoided. In Juang et al. (2008), a method is suggested to estimate the joint distribution of $a_{\max}$ and M_w based on the data from the USGS website, assuming that the PGA at a site follow the lognormal distribution. In this study, a new method will be suggested to estimate the joint distribution of $a_{\max}$ and M_w without the lognormal assumption about PGA. Let h denote a given value of PGA. In the Unified Hazard Tool, the available information relevant to the present analysis for a specific site includes the annual exceedance probability of PGA and the conditional distribution of M_w for a given hazard level of $PGA > h$, both of which are available in a discrete form. Let $p(M_w|PGA > h)$ denote the probability mass function of M_w given $PGA > h$ from the USGS website. As an example, Fig. 1 shows the annual exceedance probability of PGA at a site in Watsonville West, Santa Cruz, California, USA (Longitude = $-121.79°$, latitude = $36.96°$), and Fig. 2(a) shows the conditional distribution of M_w given $PGA > h$ at this site. In the following, we will describe how to estimate the joint distribution of $\{a_{\max}, M_w\}$ based on such information.

Let λ denote the annual rate that the PGA at a site will be larger than h. Assuming the occurrence of earthquakes is a realization of a Poisson process (Cornell and Krawinkler, 2000), the probability that PGA will be larger than h during an exposure time of T can be computed as follows (e.g., Ang and Tang, 2007)

$$P(PGA > h) = 1 - \exp(-\lambda T) \quad (1)$$

In the USGS website, information about $a_{\max}$ is not directly

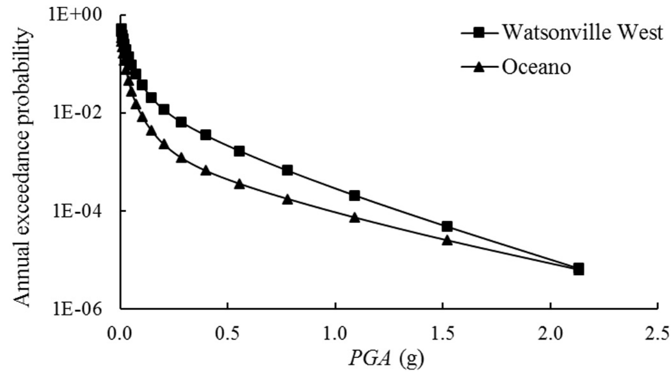

Fig. 1. Annual exceedance probability of PGA at different site.

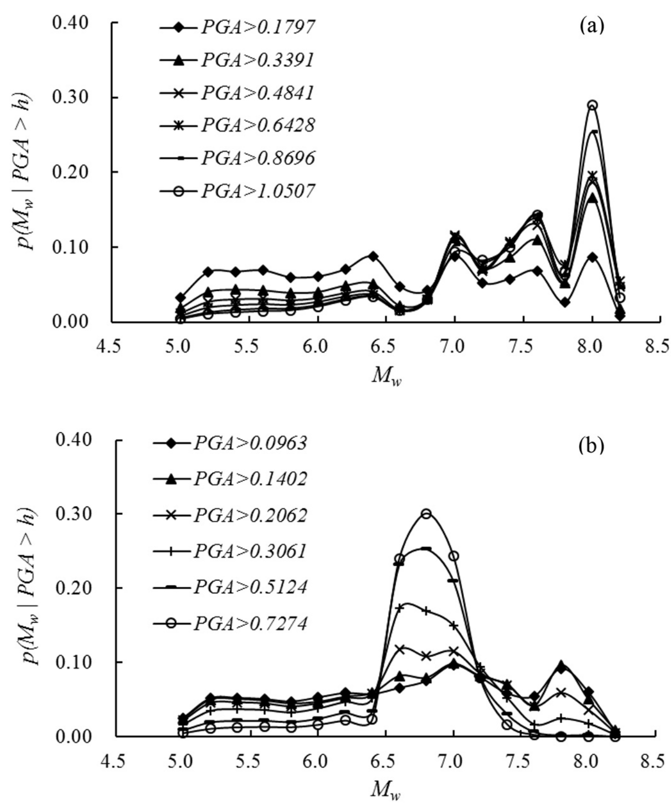

Fig. 2. Distribution of M_w at difference hazard levels: (a) Watsonville West site; (b) Oceano site.

available. However, it can be estimated based on its relationship with PGA through a site amplification factor F as follows (Seyhan and Stewart, 2014; BSSC, 2015)

$$a_{\max} = F \cdot PGA \quad (2)$$

How to determine the distribution of F will be discussion later in this paper. Based on Eq. (2), when the value of PGA is known, the probability of $a_{\max}$ being less than a value a can be computed as follows

$$P(a_{max} < a \mid PGA) = P(F \cdot PGA < a \mid PGA) = P\left(F < \frac{a}{PGA} \mid PGA\right) \quad (3)$$

The above equation is the conditional cumulative distribution function (CDF) of $a_{\max}$. The conditional probability density function (PDF) of $a_{\max}$, which is denoted as $f(a_{\max}|PGA)$ here, can be then obtained by differentiating the conditional CDF of $a_{\max}$ as follows

$$f(a_{max} = a \mid PGA) = \frac{\partial P(a_{max} < a \mid PGA)}{\partial a} = \frac{\partial P\left(F < \frac{a}{PGA} \mid PGA\right)}{\partial a} \quad (4)$$