A Procedure for Estimation of Lateral Spreading Displacement Using Results of Probabilistic Seismic Hazard Assessment

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ABSTRACT
Empirical and semi-empirical regression models are widely used to estimate liquefaction-induced lateral spreading displacements. These models were developed from case histories with the seismic hazard defined in a deterministic fashion. A difficulty arises when using these models with results from a probabilistic seismic hazard assessment (PSHA) which are made up of contributions from a range of magnitude and distance combinations. There is little guidance on the selection of appropriate values of magnitude and distance from a PSHA for use in these models, and the commonly used mean or modal values may result in misrepresentation of lateral spreading displacements and do not provide information regarding the probability of exceedance of the estimated values. This paper introduces an approach to estimate the annual probability of exceedance of significant lateral spreading displacements (i.e. $\geq$ 0.3 m) using conventional PSHA output. The ground displacement threshold of 0.3 m was selected based on the review of a published database and is considered as a potential threshold to separate inconsequential and consequential ground displacements to some important structures including buried steel pipes and highways. Suggestions are also provided for application of this approach for displacement values other than 0.3 m.

RÉSUMÉ
Des modèles de régression empiriques et semi-empiriques sont largement utilisés pour estimer les déplacements latéraux induits par liquéfaction. Ces modèles ont été développés à partir d'histoires de cas pour lesquels l'aléa sismique est défini de façon déterministe. Lors de l'utilisation de ces modèles, un problème se présente lorsque les résultats d'une évaluation probabiliste de l'aléa sismique (PSHA) sont constitués d'un ensemble de combinaisons de magnitudes et de distances. Peu de recommandations sont disponibles pour aider à sélectionner des valeurs appropriées de magnitude et de distance à partir d'un PSHA et les valeurs moyennes ou médianes couramment utilisées peuvent entraîner une mauvaise évaluation des déplacements latéraux ou de la probabilité de dépassement des valeurs estimées. Cet article présente une approche pour estimer la probabilité annuelle de déplacements latéraux significatifs (supérieurs à 0,3 m) basée sur les résultats d'une PSHA conventionnelle. Le seuil de déplacement latéral de 0,3 m a été choisi en fonction de l'étude d'une base de données publique et est considéré comme une valeur seuil de déplacement latéral pour séparer les déplacements significatifs des non-significatifs pour des ouvrages importants tels que les tuyaux d'acier souterrains et les autoroutes. Des recommandations sont formulées sur la façon de mettre cette approche en pratique pour des valeurs de déplacements latéraux autres que 0,3 m.

1 INTRODUCTION

Parameters required to assess seismic loading on structures may be determined through a deterministic seismic hazard assessment (DSHA) or a probabilistic seismic hazard assessment (PSHA). When a DSHA is used for seismic response assessment, the required seismic parameters of the design earthquake (e.g. earthquake magnitude, M, and source to site distance, R) are known and unique values.

Alternatively PSHA accounts for the variability and uncertainty in seismic parameters for each source zone and provides an intensity-probability curve of the intensity measures at the site for each source. The probabilities of exceedance of the intensity measure from all source zones are then combined and the results are presented in terms of the annual probability of exceedance (APE) of an intensity measure. As such, all source zones with various M and R contribute to the required intensity measure at the target APE. In Canada, due to high uncertainty in source zones, the common practice is to use a PSHA to obtain seismic parameters at the site rather than a DSHA.

The majority of the commonly used liquefaction triggering assessment methods (e.g. Youd et al. 2001, Idriss and Boulanger 2008) and lateral spreading assessment methods (e.g. Youd et al. 2002, Bardet et al. 2002, and Zhang et al. 2004) are empirical or semi-empirical methods that are developed based on the site responses to previous seismic events. These methods can directly be used in a forward analysis using DSHA results for which single values of M and R of the design event and intensity measures at the site are known. However, direct application of PSHA results, such as those available in NRCC (2010), in liquefaction triggering and lateral spreading assessment methods is complicated because of the range of M and R that contribute to the seismic hazard. Such direct application may result in under-prediction or over-prediction of the extent of liquefaction and magnitude of lateral spreading displacement (LD). The following summarizes some of the complexities that arise when using PSHA results with these methods:

- As several source zones, each with a range of M and R, contribute to the hazard at the site, it is not clear what M and R should be used in the lateral spreading assessment models.

- Assessment of liquefaction triggering and lateral spreading at a certain APE of PGA at the site does not provide information regarding the annual probability or return period of liquefaction or calculated lateral spreading.
- Using the same seismic parameters, the results of lateral spreading assessment from different models can be significantly different. This issue is especially apparent in low seismicity areas, where empirical models such as Youd et al. (2002) and Bardet et al. (2002) have been found by the authors to yield LD values one to two orders of magnitude less than those predicted by semi-empirical models such as Zhang et al. (2004).

There are several published procedures for estimating the APE of liquefaction triggering and lateral spreading. Kramer and Mayfield (2007) developed a probabilistic framework to calculate the return period of liquefaction at a site using PSHA results with available liquefaction triggering assessment methods. Franke and Kramer (2014) used the Youd et al. (2002) lateral spreading model to calculate the return period of LD. Their procedure involves running a full probabilistic seismic hazard assessment with knowledge of all seismic source zones that contribute to the seismic hazard at the site. For linear structures such as pipelines or highways that pass through various seismic and geologic regions, these procedures would have to be repeated at multiple points along the route. As such these procedures are not yet commonly used in geotechnical practice.

In this paper, common methods for assessment of LD are reviewed and the complexities regarding application of PSHA parameters with each method are discussed. Following the review of lateral spreading assessment methods, a procedure is provided to approximate the annual probability of LD $\geq$ 0.3 m. As will be shown in the following sections, the probability of LD $\geq$ 0.3 m in a potentially liquefiable landform can be simplified to a function of seismic parameters only, and independent of the LD assessment method. Information about the soil profile and topography is only needed for the assessment of liquefaction triggering.

LD of 0.3 m may be considered as a possible threshold separating consequential and inconsequential displacement for many structures including jointed pipes (ALA 2001) and buried steel pipes (Honegger et al. 2014). As such, this procedure can be used as a framework for performance-based design of such structures subjected to seismic liquefaction and associated lateral spreading.

The procedure may be expanded to provide the annual probability of LD greater than other specific values, where sub-surface conditions are known and where topography is generally uniform within the site. However, such expansion of the procedure requires further assessment and validation of the method. Suggestions are provided in Section 4 for generalization of the proceude to values other than 0.3 m.

2 REVIEW OF COMMONLY USED LATERAL SPREADING ASSESSMENT METHODS

Liquefaction triggering is generally assessed using characterizations of the subsurface conditions using the Standard Penetration Test (SPT), Cone Penetration Test (CPT), or shear wave velocity (V_s) data. Commonly used liquefaction triggering assessment approaches (e.g. Youd et al. 2001 and Idriss and Boulanger 2008) require PGA at the site and earthquake magnitude as input parameters. PSHA results provide the PGA for each APE with contribution to the seismic hazard from the full range of source zones' magnitudes and distances to the site.

Selection of appropriate M for liquefaction triggering assessment is not obvious when the hazard is associated with many M-R pairs. Rather than selecting a single value of M to assess liquefaction triggering, Finn and Wightman (2006) provided a weighted averaging method that considers the full range of M that contribute to the seismic hazard.

Following liquefaction, lateral spreading may occur at sites with mildly sloping ground or in the vicinity of a freeface. Several methods are available to estimate LD at a site. The databases used in the development of such methods are not all the same and the calculated results may be quite different. Use of PSHA results in two common methods of LD assessment is discussed in the following sub-sections, with special consideration of the databases used in the development of each method.

2.1 Empirical Method for Lateral Spreading Estimation

In empirical method, LD is estimated using models which were derived from regression of past observations of lateral spreading. These models yield LD as a function of R and M, as well as selected soil and topographical parameters. A widely used regression model was provided by Youd et al. (2002). This model uses M and R as ground motion parameters, liquefiable soil thickness with SPT blowcounts less than 15 (T_{15}), associated fines content (F_{15}) and average grain size (D_{50-15}) as soil parameters, and ground slope (S), height of the nearby freeface (H), and distance from the freeface (L) as topographical parameters. Other regression models use different soil and topographic parameters for the regression analysis. For example using a database similar to that of Youd et al. (2002), Bardet et al. (2002) provided correlations to estimate LD using all above parameters except D_{50-15} and F_{15} to accommodate cases in which soil gradation is unknown, and Rauch and Martin (2000) provided a correlation between LD and four earthquake parameters to accommodate cases in which soil and topographic properties are unknown.

The database used by Youd et al. (2002), which is similar to the ones used by several succeeding researchers (e.g. Bardet et al. 2002) to develop regression coefficients for the selected functional form of their regression models, includes 484 recorded liquefaction-induced lateral spreading cases, with known M and R values. For forward prediction of LD, these models are straightforward to use with DSHA results that provide unique M and R as the ground motion parameters for the design earthquake. A difficulty arises when attempting to use this method with results from a PSHA since the ground motion hazard is comprised of contributions from many combinations of M and R. It is therefore not clear which M and R combination from a PSHA should be used to calculate LD.

To clarify the effect of selected M and R to estimate LD using empirical method, the distribution of M and R of the Youd et al. (2002) database for all 484 case histories is presented in Figure 1. There are generally several cases with the same M and R in this figure, so much less than 484 points are visible. The recorded LD are divided into two groups in the figure: LD $\geq$ 0.3 m and LD < 0.3 m. A clear separation between the two groups is observed. This clear distinction was not observed for other values of LD. The dashed green line and the dashed red line provide a lower limit and an upper limit estimate of M-R pairs that produce LD $\geq$ 0.3 m, respectively. On the basis of these case histories, it can be concluded that earthquakes with M-R pairs to the right of the dashed green line are unlikely to cause LD $\geq$ 0.3 m even in liquefiable ground, and earthquakes with M-R pairs to the left of the dashed green line have the potential to cause LD $\geq$ 0.3 m in liquefiable ground, given soil and topographical parameters that are generally similar to those of the case histories in the database. As this conclusion is based solely on the available database, which is similar for other empirical models, it is not bound to a certain regression model used in LD assessment.

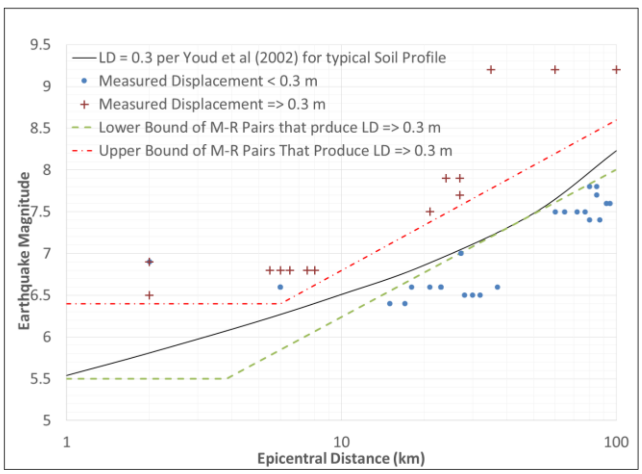

Figure 1. Database of Youd et al. (2002) – Distance versus Magnitude for LD $\geq$ 0.3 m and LD < 0.3 m

Franke and Kramer (2014) provided a hypothetical soil profile, representative of the types of profiles found in lateral spreading case history databases. This typical soil profile is shown in Figure 2. The M-R pairs that yield LD equal to 0.3 m using Youd et al. (2002) regression equation for this soil profile are shown in Figure 1 with a solid black line. This line falls between the dashed red and the dashed green lines.

To choose M and R for calculating LD via empirical models from PSHA results, one of the following approaches is commonly adopted.

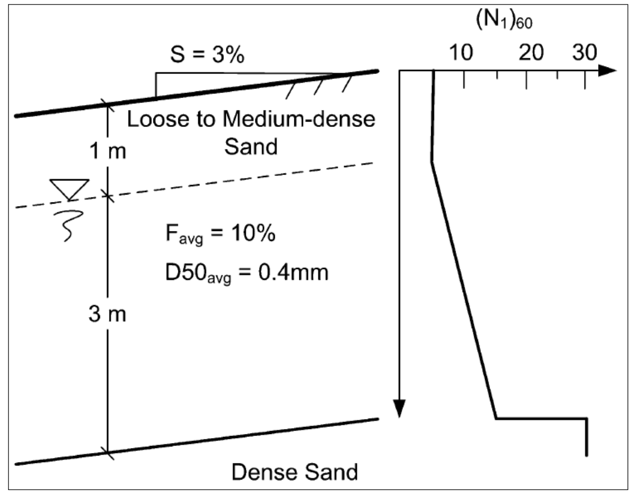

Figure 2. Soil Profile Representative of Soil Profiles in LD Databases, Adopted from Franke and Kramer (2014).

- Using some combination of mean and modal magnitude and distance as calculated from the seismic hazard deaggregation of PGA for a particular APE.
- Using PGA for a particular APE at the site and a ground motion prediction equation to calculate an equivalent distance for mean magnitude, R_{eq}, and then using mean magnitude and R_{eq} to estimate LD at the site.
- Estimating LD for all M-R combinations and calculating the weighted average LD considering the contribution of each M-R pair to the total PGA hazard for a particular APE.

Franke and Kramer (2007) showed that using mean, modal, or a combination of mean and modal values for M and R can yield highly variable results. They also showed that using mean and model values may yield lower LD for longer return periods of PGA. Moreover, in cases that the mean or modal values of M and R plot to the right of the dashed green line of Figure 1, where LD is almost certainly less than 0.3 m, contributions to the total seismic hazard from M-R pairs left of the dashed green line that can result in larger LD are neglected. A similar argument is applicable when M and R_{eq} are used to predict LD.

The weighted average approach may also misrepresent LD as a single value. If M-R pairs right of the dashed green line in Figure 1 make a significant contribution to the seismic hazard, which is the case for most of Canada, the weighted average of LD is dominated by M-R pairs that result in small LD and the contribution of larger LD is excessively down-weighted.

A final limitation of these approaches for using PSHA results is that neither provide information regarding the APE of predicted LD values.

2.2 Semi-empirical Method for Lateral Spreading Estimation

In semi-empirical method, soil and seismic parameters are used to calculate the factor of safety against liquefaction, FS_{liq}, which in turn is used to estimate shear strain in the soil layer based on correlations with the laboratory testing results. Shear strain is then integrated through the entire soil layer to provide a lateral displacement index (LDI). Recorded case histories are employed to calibrate LDI versus site topographical parameters and to provide an estimate of site-specific LD. A commonly used semi-empirical model is from Zhang et al. (2004), which used a database of 291 recorded cases to develop their model. This model does not directly use M and R; however M and PGA of the design ground motion are used to calculate FS_{liq}.

When used with PSHA results, the effect of various earthquake magnitudes contributing to the seismic hazard can be incorporated through the weighted averaging method provided by Finn and Wightman (2006) to calculate FS_{liq}. However, the lateral spreading displacement of Zhang et al. (2004) model can be insensitive to variations in M; for a very loose material the change in FS_{liq} for different values of M often does not translate into a change in the calculated shear strain and estimated LD. Similar to empirical method, the semi-empirical method does not provide information regarding the APE of predicted LD values.

To compare results of empirical and semi-empirical methods, M and R from the Zhang et al. (2004) database are presented in Figure 3. Again, the measured values of LD are divided into two groups: LD ≥ 0.3 m and LD < 0.3 m. The dashed green line in this figure is the same as that in Figure 1. Comparison of Figures 1 and 3 demonstrates that the majority of data points right of the dashed green line in the Youd et al. (2002) database, with LD < 0.3 m, are not considered by Zhang et al. (2004) in their regression analysis of LD/LDI. As such, the Zhang et al. (2004) model may result in a high estimate of LD for a specific ground motion, as many cases with low lateral spreading values are not included in their database. The authors noted that this was especially apparent for ground motions with a significant contribution to the total seismic hazard from M-R pairs right of the dashed green line.

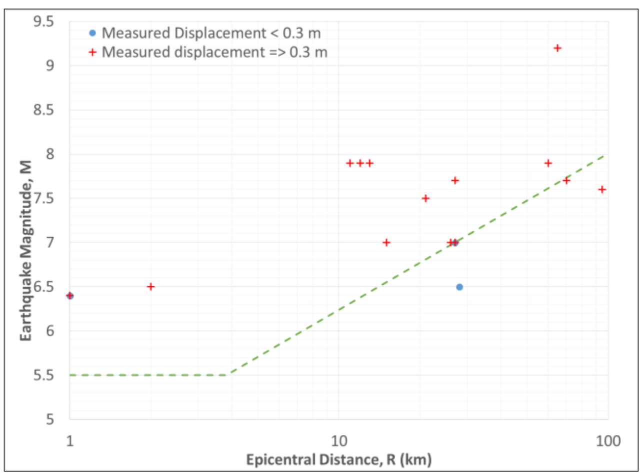

Figure 3. Database of Zhang et al. (2004) – Distance versus Magnitude for LD ≥ 0.3 m and LD < 0.3 m

3 ESTIMATING ANNUAL PROBABILITY OF LD GREATER THAN 0.3 M

Using one of the three methods described in Section 2.1 for selecting a single M-R pair from a PSHA will likely result in misrepresentation of LD. Particularly, in cases that the selected M-R pair plots right of the dashed green line in Figure 1, the estimated LD would most likely be less than 0.3 m; hence the participation from M-R pairs that yield high LD values would likely be neglected in the design. Also, the APE of the predicted LD from regression models will not be the same as the APE of the associated ground motion. As such, providing a single value of LD for a certain ground motion does not provide information regarding probability of exceedance of such LD.

In order to improve the representation of LD, an approach is presented in this paper that approximates the annual probability of LD exceeding 0.3 m, using PSHA results. The value of 0.3 m was selected as a threshold between high and low LD for two reasons:

1. The lateral spreading case history database as shown in Figure 1 indicated a clear distinction between LD less than and greater than 0.3 m. This database then provides a basis for estimating the annual probability of LD ≥ 0.3 m in the absence of site-specific sub-surface investigation. Such clear distinction was not observed for other values of LD.
2. Ground displacements less than 0.3 m may be considered as an inconsequential displacement for many structures such as jointed and welded steel pipes (ALA 2001, Honegger 2014) and highways.

The approach to estimate the annual probability of LD ≥ 0.3 m has two steps. The first step includes estimating the probability of LD ≥ 0.3 m in a liquefied soil profile subjected to a specific ground motion. In the second step, the probability of LD ≥ 0.3 m at a specific ground motion is integrated over the entire range of possible ground motions to provide the annual probability of LD ≥ 0.3 m. These two steps are described in the following sub-sections.

3.1 Probability of LD ≥ 0.3 m at a specific ground motion

Liquefaction triggering at a site subject to a specific PSHA ground motion (e.g. the 1 in 2,475-year PGA) can be assessed using one of the triggering assessment methods (e.g. Youd et. al. 2001, Idriss and Boulanger 2008) and the weighted average procedure described by Finn and Wightman (2004). For sites that liquefy due to a specific APE ground motion, the probability of LD less than and greater than 0.3 m subjected to that ground motion can be determined as follows:

- The relative contributions to the PGA ground motion of all M-R pairs right of the dashed green line in Figure 1 are summed and presented as the probability of LD < 0.3 m, conditional upon liquefaction due to the particular ground motion. This value is referred to as P(LD < 0.3 m | Liq).
- The relative contributions to the ground motion of all M-R pairs left of the dashed green line are summed and presented as the probability of LD ≥ 0.3 m, conditional upon liquefaction due to the particular ground motion. This value is referred to as P(LD ≥ 0.3 m | Liq).

This procedure is illustrated graphically in Figure 4, for a site located in northern British Columbia, Canada using

PSHA results for the PGA ground motion with an APE of 1 in 2,475. This site consisted of loose fluvial deposits that were considered to be liquefiable under the design ground motion. Relative contributions of M-R pairs to the design PGA hazard are shown in this figure (e.g. earthquakes with M = 7 to 7.5 and R = 20 to 40 km contribute 4.9% of the PGA hazard). The data points and dashed green line are the same as those in Figure 1; however this figure is presented on a linear horizontal scale for easier illustration of the contributions of deaggregated M-R pairs. The deaggregation implies that there is an 80% chance that LD < 0.3 m when subjected to the 1 in 2,475 PGA ground motion, since 80% of the PGA hazard is from M-R pairs that have resulted in LD < 0.3 m in the case history database (summation of contributions in the blue zone). By contrast, there is a 20% chance that LD ≥ 0.3 m when subjected to the 1 in 2,475 PGA ground motion, since 20% of the PGA hazard is from M-R pairs that have resulted in LD ≥ 0.3 m in the database (summation of contributions in the red zone).

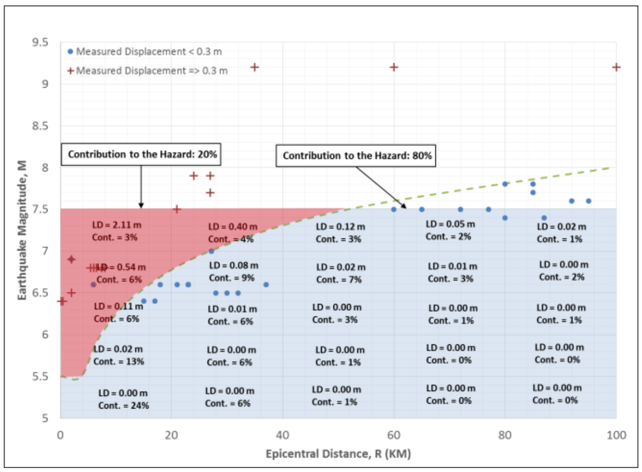

Figure 4. Example of Using Deaggregation Results to Estimate P(LD≥0.3 m | Liq) at a Specific Ground Motion

The dashed green line demarking the boundary between LD less than and greater than 0.3 m is solely based on the available database of recorded LD. This line is only a function of magnitude and distance and is independent of soil profile parameters and site topography. As such, the estimated P(LD ≥ 0.3 m | Liq) is model-independent and would not change with variations of soil profile or topographic condition, provided the site is liquefiable under the design ground motion.

3.2 Annual Probability of LD ≥ 0.3 m, considering the entire range of PGA ground motion

The procedure explained in the previous sub-section can be expanded to take into account all ground motion return periods at the site and provide an approximation of the annual probability of LD ≥ 0.3 m. Equation [1] is used to add the probability of LD ≥ 0.3 m over the entire range of PGA ground motions and provide approximate annual probability of LD ≥ 0.3 m, P(LD ≥ 0.3 m).

$$P(LD \geq 0.3\ m) = \sum \{ P(PGA_R)_i \times P(Liq \mid (PGA_R)_i) \times P(LD \geq 0.3\ m \mid Liq)_i \} \quad [1]$$

To estimate P(LD ≥ 0.3 m), ground motions at all return periods at the site that contribute to the liquefaction and lateral spreading hazard are considered and the summation is conducted over the entire range of PGA values at the reference site class, referred to as PGA_R.

A description of each of these terms is provided in the following example calculation. To provide a comparison with the results of the fully probabilistic LD assessment conducted by Franke and Kramer (2014), three of their example cities in the US have been selected - Butte, Montana; Portland, Oregon; and Seattle, Washington - and the parameters in Eq. [1] are provided for a soil profile similar to that presented in Figure 2 in these cities.

<u>$(PGA_R)_i$, Annual probability of the i-th PGA range at reference site class</u>

PGA values and accompanying deaggregation at a reference site class with APE of 0.01, 0.0021, 0.001, and 0.000404 (i.e. 100, 475, 1,000 or 2,475-year return period) are publicly available for any location in Canada through the Natural Resources of Canada (NRCan) or in US through the US Geological Survey (USGS). USGS also provides the PGA and accompanying deaggregation for an APE of 0.0002 (i.e. 5,000-year return period) and smaller, if required. The reference site class is site class C in Canada and site class B/C boundary in US.

Values of PGA_R for site class B/C boundary are shown in Figure 5 for the three cities. In the summation, the PGA_R values should be divided into bins (e.g. bins with approximately 0.05g intervals). The annual probability of occurrence of each PGA_R bin is the difference between the annual probability of exceedance of the lower limit and the upper limit of the bin. For example, the annual probability of occurrence of PGA_R between 0.05 g and 0.10 g for Butte is equal to 0.0009 (0.0015 minus 0.0006).

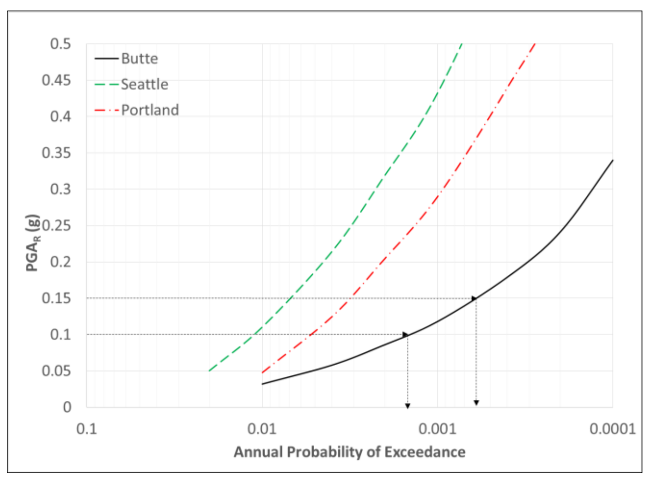

Figure 5. PGA_R versus Annual Probability of Exceedance for the Three Example Cities

Generally smaller bin intervals will increase the resolution and accuracy of the calculations. Sensitivity analysis on the number of bins indicated that at least four bins are generally required.

$P(Liq \mid (PGA_R)_i)$ - Probability of liquefaction triggering for the i-th given ground motion, $(PGA_R)_i$

The results of a liquefaction triggering assessment were used to assign a value of 0 or 1 to the probability of liquefaction triggering for each PGA_R bin. The following steps illustrate this procedure:

1. A PGA value at which minimum FS_{liq} = 1 over the assumed soil profile was calculated. This PGA value is referred to as PGA_{trig}. The Finn and Wightman (2006) weighted average method and the magnitude deaggregation of PGA_{trigg} were used to incorporate the contribution of various M into the Idriss and Boulanger (2008) liquefaction triggering assessment.
2. The calculated PGA_{trig} is the amplified PGA at the ground surface at which liquefaction is triggered. The corresponding PGA value at the reference site class, PGA_R, was calculated considering $(PGA)_{trig}$ and the site class amplification factor for the assumed soil profile, F_a, per ICC (2006). The resulting value is referred to as $(PGA_R)_{trig}$.
3. The magnitude contribution factors used in step 1 were updated to represent the magnitude deaggregation at $(PGA_R)_{trig}$.
4. Bins with $(PGA_R)_i < (PGA_R)_{trig}$, had $FS_{liq} > 1.0$ through the entire soil profile and a value of 0 was assigned to $P(Liq \mid (PGA_R)_i)$. Alternatively, bins with $(PGA_R)_i \geq (PGA_R)_{trig}$, had minimum $FS_{liq} \leq 1.0$ and a value of 1 was assigned to $P(Liq \mid (PGA_R)_i)$.

It is recognized that specifying a value of 0 or 1 to $P(Liq \mid (PGA_R)_i)$ is a simplistic assumption compared to the more rigorous treatment of liquefaction probability and hazard as described by Boulanger and Idriss (2014) and Kramer and Mayfield (2007), and further refinements are being considered.

For the example soil profile of Figure 2, PGA_{trig} was calculated as 0.14g, 0.11g, and 0.12g for Butte, Portland, and Seattle, respectively. Considering site class D for the example soil profile and amplification factor of 1.6 as per ICC (2006), $(PGA_C)_{trig}$ was calculated as 0.09g, 0.07g, and 0.08g for Butte, Portland, and Seattle, respectively. For a more straightforward summation in Eq. [1], the PGA_R bins were selected so that $(PGA_R)_{trig}$ marked the border between the first and the second bins.

$P(LD \geq 0.3\ m \mid Liq)_i$ - Probability of LD $\geq$ 0.3 m for liquefied soil profile, at the i-th ground motion, $(PGA_R)_i$

As explained earlier, the probability of LD $\geq$ 0.3 m in a liquefied soil profile subjected to ground motion with PGA_R is considered as the sum of the contribution of the M-R pairs from the PGA_R deaggregation that are to the left of the dashed green line in Figure 1. This probability changes with PGA_R as the contribution of M-R pairs to the total PGA_R hazard is different for each return period. This probability also is a function of site location due to different seismic sources contributing to the PGA_R hazard at each site.

The deaggregation results for each PGA_R value were used to calculate $P(LD \geq 0.3\ m \mid Liq)_i$ at the site. Figure 6 shows $P(LD \geq 0.3\ m \mid Liq)$ as a function of PGA_R for the three example cities. The curve of $P(LD > 0.3\ m \mid Liq)$ versus PGA_R is unique for each site and depends only on the M-R pairs contributing to the PGA_R hazard at the site. $P(LD \geq 0.3\ m \mid Liq)$ is not dependent upon the soil properties and topography of the site; however it is conditional on liquefaction occurring ($FS_{liq} \leq 1.0$) at the site and uses PGA at the reference site class.

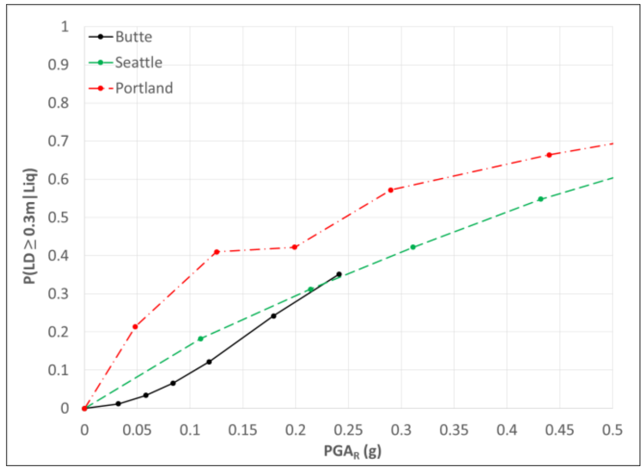

Figure 6. $P(LD \geq 0.3\ m \mid Liq)$, versus PGA_R for the Example Cities

$P(LD \geq 0.3\ m)$ – Annual probability of LD $\geq$ 0.3 m

With all components of the summation in Eq. [1] determined, the annual probability of LD $\geq$ 0.3 m for the example cities and the assumed ground profile of Figure 2 can be calculated. Table 1 summarizes the components of the summation in Eq. [1]. The calculated $P(LD \geq 0.3\ m)$ for these three cities is presented in Table 2.

Table 1. Parameters for estimation of $P(LD \geq 0.3\ m)$ in Eq. [1]

		i = 1	i = 2	i = 3	i = 4
Butte	$(PGA_R)_i$ - (g)	< 0.09	0.09-0.15	0.15-0.20	> 0.20
	$P((PGA_R)_i)$	0.998	0.0014	0.0003	0.0003
	$P(Liq \mid (PGA_R)_i)$	0	1	1	1
	$P(LD \geq 0.3m \mid Liq)_i$	0.03	0.13	0.24	0.35
Seattle	$(PGA_R)_i$ - (g)	< 0.08	0.08-0.15	0.15-0.30	> 0.30
	$P((PGA_R)_i)$	0.985	0.008	0.0048	0.0022
	$P(Liq \mid (PGA_R)_i)$	0	1	1	1
	$P(LD \geq 0.3m \mid Liq)_i$	0.07	0.19	0.33	0.50
Portland	$(PGA_R)_i$ - (g)	< 0.07	0.07-0.15	0.15-0.25	> 0.25
	$P((PGA_R)_i)$	0.992	0.005	0.0017	0.0013
	$P(Liq \mid (PGA_R)_i)$	0	1	1	1
	$P(LD \geq 0.3m \mid Liq)_i$	0.15	0.35	0.42	0.60

Franke and Kramer (2014) calculated the APE of LD through full probabilistic hazard assessment and presented seismic hazard curves of LD for 10 different cities in US, including the example cities assessed in this paper. Mean annual rates of LD exceeding 0.3 m, which are equivalent to $P(LD \geq 0.3\ m)$ estimated in this paper, have been extracted from the LD hazard curves of Franke and Kramer (2014) and presented in Table 2 for comparison. Despite significant differences in the approach, the results of the two methods are in good agreement.

Table 2. P(LD ≥ 0.3 m) for the example cities and comparison with full PSHA results

	Butte	Seattle	Portland
P(LD ≥ 0.3 m) (This Study)	3.6×10^{-4}	4.2×10^{-3}	3.2×10^{-3}
APE of 0.3 m LD (Franke and Kramer)	4×10^{-4}	1×10^{-2}	4×10^{-3}

4 DISCUSSION

A clear distinction in the Youd et al. (2002) database between LD less than and greater than 0.3 m provides a basis to assess the probability of significant lateral spreading displacements (i.e. LD ≥ 0.3 m) in a liquefiable ground on a regional scale, knowing contribution of various earthquake M and R to the ground motion and in the absence of detailed soil profile parameters. Other researchers have studied the effect of liquefaction and lateral spreading on a regional scale and provided correlations based on M and R to assess liquefaction triggering and the consequences of seismically induced liquefaction. Youd and Perkins (1978) presented a correlation between M and R for significant liquefaction-induced ground failure. In their assessment, differential vertical or horizontal displacement of 100 mm or greater was considered as significant ground failure. Youd and Perkins (1987) revised their earlier correlation and provided a family of curves for M versus R with uniform liquefaction severity index (LSI), where LSI represents expected LD in inches. The family of LSI curves are shown in Figure 7 along with the proposed threshold for LD ≥ 0.3 m (the dashed green line from Figure 1).

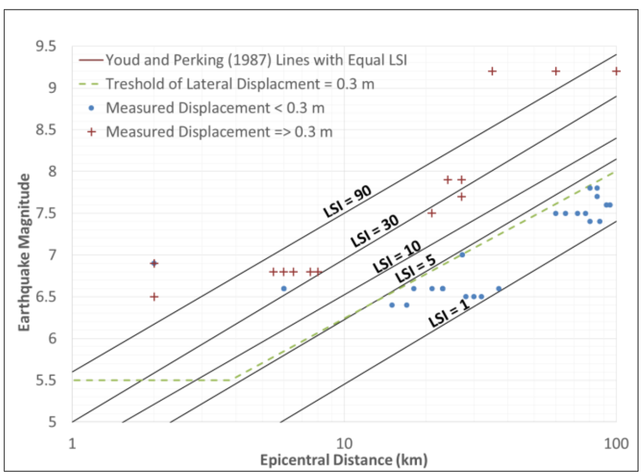

Figure 7. Comparison of Proposed Threshold for LD ≥ 0.3 m and LSI Curves as per Youd and Perkins (1987)

The proposed 0.3 m LD curve is nearly parallel to the uniform LSI lines of Youd and Perkins (1987) and approximately coincides with the line for LSI = 5. As per Youd and Perkins (1987), LSI = 5 indicates “very sparsely distributed minor ground effects including sand boils with sand aprons up to 0.5 m in diameter and minor ground fissures with openings up to 0.1 m wide and ground settlements of up to 25 mm”. As per the definition of LSI, the expected LD for LSI = 5 is 5 inches or approximately 0.1 m. As such, the presented dashed green line of LD = 0.3 m in this paper is slightly more conservative than the uniform LSI curves presented by Youd and Perkins (1987).

The proposed curve for the boundary between LD less than and greater than 0.3 m is based only on the case histories in the Youd et al. (2002) database, with no interpretations or assumptions regarding the geology and topography, but with the implicit assumption that liquefaction occurs. All 27 cases plotting right of this curve had LD < 0.3 m. From 457 cases that plot left of the green line, 452 cases had lateral spreading displacements ≥ 0.3 m and 5 cases (approximately 1%) had LD < 0.3 m. It should be noted that there is a gap between data points with lateral spreading displacements greater than and less than 0.3 m; the proposed boundary curve (i.e. the dashed green line) is placed conservatively at the edge of that gap and hence the probability of LD ≥ 0.3 m may be overestimated by this method to some degree.

A similar approach is conceptually possible to estimate the probability of LD in a liquefied soil profile greater than a value other than 0.3 m ,X , when subjected to a specific ground motion. For the probability of LD ≥ X, the dashed green line should be replaced by a limit state line of LD = X based on a regression model (e.g. Youd et al. 2002). As such, the expansion of this method to LD values other than 0.3 m would require information about the soil and topographic conditions of the site as required by the selected regression model.

The probability of LD ≥ X at a given PGA ground motion can then be integrated over the entire range of PGA ground motions (as explained in Section 3.2. for LD = 0.3 m) to approximate annual probability of LD ≥ X. Further analysis and comparison of the results with a full probabilistic hazard assessment (e.g. Franke and Kramer, 2014) should be done to validate the approach for estimation of annual probability of LD ≥ X.

5 CONCLUSIONS

Commonly used methods for LD assessment have been developed based on observations of LD during historical earthquakes and are thus most applicable in forward estimates with DSHA results. Application of these methods with the results of PSHA is complicated and may result in misrepresentation of lateral spreading displacement. Moreover, the annual probability of the calculated LD value that is conditional upon a specific ground motion is not defined through direct application of LD prediction methods with PSHA results.

Probabilistic approaches have been proposed by various researchers that use empirical LD assessment methods and provide the annual probability of LD exceeding certain values (e.g. Franke and Kramer 2014, Honegger et al. 2014). However, these approaches include a complete probabilistic seismic hazard assessment and require detailed sub-surface information and topographical conditions at the site as well as all characteristics of the seismic source zones in the area. Such analysis may not always be practical due to the budget and time restraints especially for linear structures such as pipelines and highways that cover a wide range of geology, topography, and seismicity along their route.

The probabilistic framework presented in this paper uses publically available PSHA results to approximate the annual probability of LD $\geq$ 0.3 m. Review of lateral spreading case histories indicates that LD of 0.3 m in a liquefiable ground is strongly correlated with earthquake magnitude and distance. The results of this approach are compared with the results of a full probabilistic assessment for three cities in US and indicated good agreement.

Considering that ground movement of 0.3 m can be tolerated by many structures, such as buried steel pipes and highways, without major concern to their integrity, the probability of LD $\geq$ 0.3 m provides a useful screening tool to identify problematic areas that require further assessment.

The proposed framework can be generalized to estimate annual probability of LD exceeding an arbitrary value, if subsurface conditions are known and topographic data are available. Additional assessment is required to validate the application of the procedure for LD values other than 0.3 m.

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