

Performance-based assessment of liquefaction-induced free-field ground settlement

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ABSTRACT

The accumulation of liquefaction-induced volumetric strains leads to ground settlement. Volumetric strain is estimated using empirical models based on laboratory data, and settlement is computed as the integration of volumetric strain with depth in the liquefied materials and calibrated using field data. Currently, the assessment of liquefaction-induced free-field ground settlement (S_v) generally follows a deterministic or a pseudo-probabilistic approach. In both cases, the assessment of the ground motion intensity measure (IM) is decoupled from the computation of S_v . For example, a hazard curve for the IM is developed through a probabilistic seismic hazard assessment that accounts for all relevant earthquake scenarios in a pseudo-probabilistic approach. A design hazard level for the IM is defined, and S_v is computed based on this design IM . A key assumption in this approach is that the hazard level of the IM is consistent with the hazard level for S_v . However, this assumption is not always valid. A performance-based approach for the assessment of S_v is developed in which the hazard evaluation for the IM is explicitly incorporated in the assessment of S_v by combining the hazard curve for the IM with the probability of exceeding different S_v levels. Hence, the sources of variability contributing to the IM are incorporated in the assessment of S_v . The variability in the inputs to the empirical model for S_v can also be included through a logic-tree approach. As a result, the hazard curve for S_v is developed, which directly links different hazard levels with their corresponding values of ground settlement. Conventional approaches used currently do not always produce values of settlement that are compatible with design hazard levels.

Keywords: earthquakes, hazard, liquefaction, performance-based engineering, settlement, uncertainty

1 INTRODUCTION

At free-field level ground sites, the accumulation of liquefaction-induced volumetric strains resulting from sedimentation and reconsolidation processes can lead to post-liquefaction ground settlement, S_v (e.g., Ishihara and Yoshimine 1992, Bray and Olaya 2023). The estimation of ground settlement due to liquefaction is important because differential ground settlement can lead to failure of structures, buried utilities, and roadways. The 1995 Kobe earthquake produced extensive liquefaction in the loose sandy hydraulic fill at Port Island. An overall liquefaction-induced settlement of 0.5 m was recorded away from the island edges. The monorail structure to the right in Fig. 1 did not show signs of vertical movement because it was supported by deep foundations that reached competent material below the liquefiable hydraulic fill. The ground settlement at this location was mostly due to liquefaction-induced volumetric sedimentation and reconsolidation.

Currently employed liquefaction-induced ground settlement procedures are based on a limited number of case histories (e.g., Zhang et al. 2002). Olaya and Bray (2023) develop a database of 205 well-documented field case histories of liquefaction-induced ground settlement

characterized by the cone penetration test (CPT). This database differentiates natural soil deposit sites from hydraulic fill sites to account for their different formation processes and their different seismic performance. The enlarged field case history database documents a wide range of liquefaction-induced ground settlement observations at a wide range of soil conditions, ground motion intensity measures, and liquefaction severity indexes. Multiple CPTs are available at several of the sites. Hence, the database provides a robust basis to evaluate the mechanisms of post-liquefaction ground settlement and to assess the variability in its estimation.

In current practice, the procedures to assess S_v are either deterministic or pseudo-probabilistic (Rathje and Saygili 2008) where the ground motion intensity measure (IM) and S_v are computed separately. In the deterministic approach, the IM is obtained from an earthquake scenario consisting of M_w , source-to-site distance (R), and the number of standard deviations above the median ground motion (ϵ). Subsequently, S_v is estimated from empirical models that are usually a function of the soil's relative density (D_r) and the factor of safety against liquefaction (FS_L) computed using the

M_w and IM defined by the selected earthquake scenario. In a pseudo-probabilistic approach, a hazard curve for the IM (λ_{IM}) is developed through a probabilistic seismic hazard assessment (PSHA) that accounts for all relevant earthquake scenarios (M_w , R , and ε). A design hazard level (or return period) is specified, and the corresponding IM value is selected. S_v is then estimated using the D_r of the soil deposit with the FS_L computed using the selected IM and its hazard-consistent M_w . In the pseudo-probabilistic approach, it is implicitly assumed the selected design hazard level of the IM (λ_{IM}) is consistent with the hazard level for S_v ; however, this assumption is not always valid.

In a performance-based earthquake engineering (PBEE) approach, the hazard evaluation for the IM is incorporated explicitly in the assessment of S_v by combining λ_{IM} with the probability of exceeding different S_v levels. Hence, the variability in the estimate of λ_{IM} is incorporated directly in the evaluation of S_v . In addition, the uncertainty of the inputs to the model for S_v is also included in a performance-based evaluation. The objective of this approach is to develop the mean hazard curve for S_v [i.e., $\lambda(S_v)$]. Different fractiles of $\lambda(S_v)$ can be examined if required by including information on sources of epistemic uncertainty relevant to the calculation of S_v . The hazard curve for S_v enables different hazard levels (or return periods) for S_v to be evaluated directly as opposed to the indirect manner of the pseudo-probabilistic approach. In this paper, a performance-based procedure for the assessment of S_v is presented and its application is illustrated.

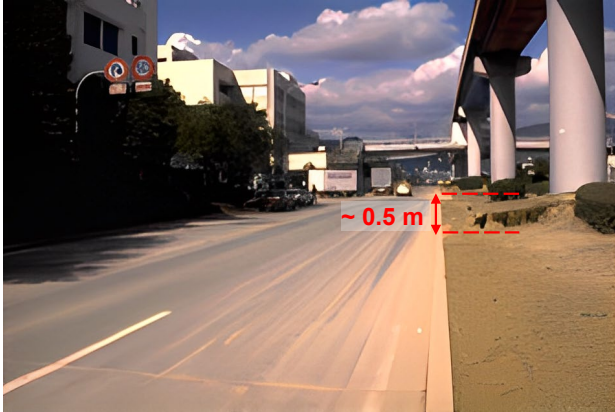


Fig. 1. Ground settlement of liquefied fill at Port Island relative to a pile-supported structure due to the 1995 Kobe earthquake (Akai et al. 1995).

2 PROBABILISTIC LIQUEFACTION-INDUCED GROUND SETTLEMENT PROCEDURE

The probabilistic liquefaction-induced free-field ground settlement procedure of Bray and Olaya (2023) is used in this study. The procedure adopted the Ishihara and Yoshimine (1992) framework but uses the empirical model for ε_v of Olaya and Bray (2022) and is calibrated

using the well-documented database of 205 field case histories of liquefaction-induced ground settlement of Olaya and Bray (2023). The Bray and Olaya (2023) probabilistic procedure is summarized in Eqs. 1 through 3.

$$S_v = C \cdot MF \cdot SB \cdot \sum_i [\varepsilon_{vi} \cdot \Delta z_i] \cdot e^{\delta s_v} \quad (1)$$

$$SB = \exp(-0.675 \cdot \max(I_{c15}, 1.8) + 1.215) \quad (2)$$

$$MF = \exp(0.214 \cdot M_w - 1.498) \quad (3)$$

where $C = 1.50$ for natural soil and $C = 1.05$ for hydraulic fill, ε_{vi} (as a decimal) is the volumetric strain of each soil layer i with thickness Δz_i , and δs_v is the residual term of the model which has zero mean and a standard deviation of 0.54 in natural log units for hydraulic fill and 0.61 in natural log units for natural soil for the volumetric-strain model based on relative density. The procedure can also employ a volumetric-strain model based on the state parameter.

3 PERFORMANCE-BASED ASSESSMENT OF LIQUEFACTION-INDUCED GROUND SETTLEMENT

The annual rate at which a given amplitude of liquefaction-induced free-field ground settlement (z) is exceeded ($S_v > z$) for a given level of IM at a site can be evaluated through the Pacific Earthquake Engineering Research Center (PEER) PBEE framework (Deierlein et al. 2003). The information from the seismic hazard evaluation is convolved with an empirical model for S_v to produce the hazard curve for liquefaction-induced ground settlement $\lambda(S_v)$ using Eq. 4.

$$\lambda(S_v > z) = \int_{M_w} \int_{PGA} P(S_v > z | PGA, M_w, I_{c15}, \Sigma_i [\varepsilon_{v,i} \cdot \Delta z_i]) f(M_w | PGA) \left| \frac{d\lambda_{PGA}}{d(PGA)} \right| d(PGA) dM_w \quad (4)$$

where $P(S_v > z | PGA, M_w, I_{c15}, \Sigma_i [\varepsilon_{v,i} \cdot \Delta z_i])$ is the probability that a ground settlement z is exceeded conditioned on PGA , M_w , I_{c15} , and $\Sigma_i [\varepsilon_{v,i} \cdot \Delta z_i]$, $f(M_w | PGA)$ is the probability density function for M_w given the PGA , and $|d\lambda_{PGA}/d(PGA)|$ is the derivative of the hazard curve for PGA . The $f(M_w | PGA)$ term captures the contribution of different M_w scenarios to the seismic hazard for PGA and can be obtained from the seismic hazard deaggregation for PGA . The computation of Eq. 4 for different values of ground settlement produces the mean hazard curve for S_v .

4 MAIN SOURCES OF UNCERTAINTY IN LIQUEFACTION-INDUCED FREE-FIELD GROUND SETTLEMENT

The sources of uncertainty in the Bray and Olaya (2023) PBEE assessment of S_v are categorized as either

aleatory variability or epistemic uncertainty. The aleatory variability is characterized by the standard deviation of the ground motion models considered in the PSHA and by the standard deviation of the empirical model employed to estimate S_v (i.e., Eq. 1). The uncertainty related to the soil characterization parameters that are inputs to the S_v model (i.e., parameters derived from CPT soundings within a site) is treated as epistemic and evaluated using a logic-tree approach that produces alternative hazard curves.

The main CPT measurements are the corrected cone tip resistance (q_t) and the sleeve friction (f_s) which are used as inputs to the correlations to estimate D_r and the liquefaction triggering procedures to calculate FS_L and subsequently ε_v . In the Bray and Olaya (2023) S_v procedure, the ε_v contribution from all layers, $\Sigma_i[\varepsilon_{v,i} \cdot \Delta z_i]$, and the average soil behavior for a site, I_{c15} , are components of the procedure (i.e., Eqs. 1 and 2). Hence, in the Bray and Olaya (2023) S_v procedure, alternative values of q_t and f_s are reflected as alternative values of I_{c15} and $\Sigma_i[\varepsilon_{v,i} \cdot \Delta z_i]$. Therefore, logic trees for I_{c15} and $\Sigma_i[\varepsilon_{v,i} \cdot \Delta z_i]$ can be used to capture the epistemic uncertainty in the soil characteristics measured through the parameters q_t and f_s . Reference values of the epistemic uncertainty in I_{c15} and $\Sigma_i[\varepsilon_{v,i} \cdot \Delta z_i]$ in the form of the coefficient of variation (COV) values are obtained from the Olaya and Bray (2023) database as shown in Table 1.

Table 1. COV for I_{c15} and $\Sigma[\varepsilon_{v,i} \cdot \Delta z_i]$ in terms of I_{c15} .

		Natural Soil Hydraulic Fill	
		$I_{c15} < 1.8$	$I_{c15} \geq 1.8$
COV (I_{c15})	$I_{c15} < 1.8$	0.01 - 0.04	-
	$1.8 \leq I_{c15} < 2.2$	0.03 - 0.05	0.02
	$I_{c15} \geq 2.2$	0.03 - 0.05	0.04
COV ($\Sigma[\varepsilon_{v,i} \cdot \Delta z_i]$)	$I_{c15} < 1.8$	0.10 - 0.40	-
	$1.8 \leq I_{c15} < 2.2$	0.10 - 0.30	0.10 - 0.20
	$I_{c15} \geq 2.2$	0.20 - 0.40	0.20 - 0.30

The effect of the epistemic uncertainty in λ_{IM} and S_v is illustrated through a simplified PSHA for two seismic sources in a shallow crustal earthquake setting where three alternative characteristic magnitudes, two annual activity rates, and one rupture location for each fault are considered as shown in Table 2. Two ground motion models (GMMs) were utilized to characterize the PGA at the site with different medians and standard deviations. Given the alternative M_w , rates, and GMMs, a total of 72 alternative hazard curves for PGA were developed.

The epistemic uncertainty in the soil characterization was estimated from Table 1 for a natural soil deposit. For the parameter I_{c15} , a COV of 0.04 is used and for the term $\Sigma_i[\varepsilon_{v,i} \cdot \Delta z_i]$, a COV of 0.20 is used. Five-branch logic trees with branch epsilons of -2, -1, 0, 1, and 2 and weights of 0.065, 0.24, 0.39, 0.24, and 0.065 for I_{c15} and $\Sigma_i[\varepsilon_{v,i} \cdot \Delta z_i]$ were used. A five-branch logic tree

captures the epistemic fractiles of the EDP hazard for a nonlinear system better than the typically used three-branch logic tree. The mean I_{c15} for this example is 1.82 whereas the $\Sigma_i[\varepsilon_{v,i} \cdot \Delta z_i]$ term varies depending on the M_w and PGA scenario being analyzed. The convolution of the 72 alternative hazard curves for PGA with the alternative realizations of the Bray and Olaya (2023) S_v procedure using the five-branch logic tree produces 1800 hazard curves for S_v as shown in Fig. 2.

Table 2. Epistemic uncertainty in the simplified PSHA.

Fault 1		Fault 2	
M_{char}	Rate	M_{char}	Rate
7.5 (0.2)	1/300 (0.5)	6.75 (0.2)	1/1000 (0.7)
7.25 (0.6)	1/150 (0.5)	6.5 (0.6)	1/3000 (0.3)
7 (0.2)		6.25 (0.2)	

Note: The values in parenthesis are the assigned weights to each alternative value.

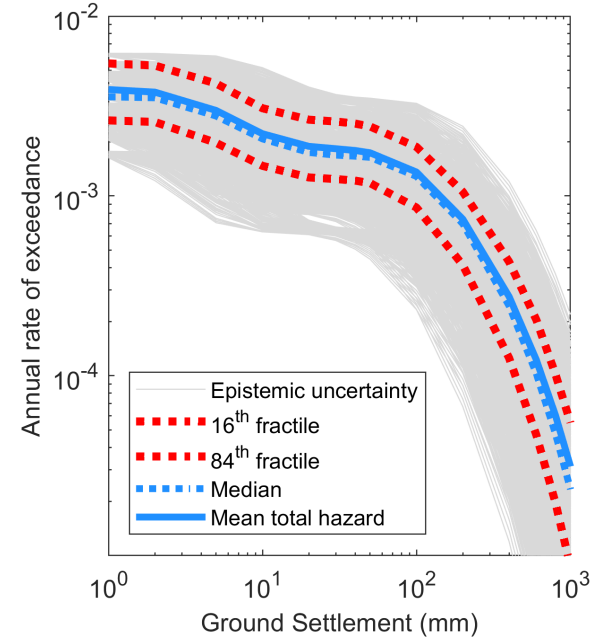


Fig. 2. Alternative liquefaction-induced free-field ground settlement hazard curves for the simplified problem.

5 PERFORMANCE-BASED LIQUEFACTION-INDUCED GROUND SETTLEMENT APPROACH

The proposed performance-based approach is as follows:

1. Perform a PSHA at the site of interest and obtain the mean hazard curve for PGA and the deaggregation for different magnitude bins at PGA values ranging from 0.01 g to 10 g.
2. Evaluate the epistemic uncertainty of the soil parameters at the site in terms of I_{c15} and $\Sigma_i[\varepsilon_{v,i} \cdot \Delta z_i]$. The epistemic uncertainty may be estimated from four or more representative CPTs performed at the site. The COV ranges provided in Table 1 can be used in the

estimation of the epistemic uncertainty to consider in cases with fewer CPTs available or as a guide in performing site-specific estimates.

3. Eq. 4 is used to compute $\lambda(S_v)$. It is recommended to evaluate settlement values of at least 1000 mm to ensure that low hazard levels (e.g., 10^{-5}) are captured. The epistemic uncertainty in the S_v estimation can be evaluated by including alternative values for I_{c15} and $\Sigma_i[\varepsilon_{v,i} \cdot \Delta z_i]$.
4. Select the return periods of interest (i.e., hazard levels). In engineering practice in the United States, return periods of 475 and 2475 years are often used to assess the seismic performance of the ground affecting new structures. Estimate the mean and 16th and 84th percentile fractiles of S_v at the selected return periods.

6 ILLUSTRATIVE EXAMPLE

The PBEE evaluation of liquefaction-induced free-field ground settlement is illustrated for a test site located in the Sierra Nevada area in California where earthquakes of magnitudes on the order of $M_w = 6.0$ have been observed. Four CPTs are used to show the soil profile characteristics at the site as illustrated in Fig. 3. The soil at the site is composed of a 2-3 m crust material followed by uniform thick layers of clean sands and silty sands with the I_c fluctuating around $I_c = 1.8$ with a representative I_{c15} of 1.86. At a depth of about 12 m, there is a thin layer of clayey material, and a layer of siltier soil is located at depth of 18-19 m. The groundwater table is located at a depth of 2 m. The normalized cone tip resistance increases with depth at the site and the soil units located from a depth of 2 m to a depth of 13 m contribute the most to the potential for liquefaction-induced settlement as illustrated by the distribution of FS_L in Fig. 3, which corresponds to an earthquake event consistent with the 475-year return period PGA at the site.

The PSHA was performed with the open-source software *Haz45.V3* (Abrahamson 2020). Initially, the hazard evaluation for S_v was performed using Eq. 1 for CPT_24630 that is representative of the average soil characteristics at the site, which leads to an estimate of the mean $\lambda(S_v)$. Fig. 4 shows the comparison between the mean hazard curve for PGA (Fig. 4a) and the mean hazard curve for S_v (Fig. 4b). The 475-year and 2475-year return periods are superimposed for reference. The curvatures of the two hazard curves differ, particularly at short return periods where the $\lambda(S_v)$ curve is relatively flat because negligible liquefaction occurs at the site for ground motions with PGA values less than about 0.12 g. A steep $\lambda(S_v)$ curve is observed at long return periods (associated with high $PGAs$) because at high $PGAs$ most of the site liquefies regardless of the PGA with S_v approaching a limiting value. As a result, the aleatory variability of $\lambda(S_v)$ at long return periods results mainly

from the standard deviation of the ground motion (σ_{GM}).

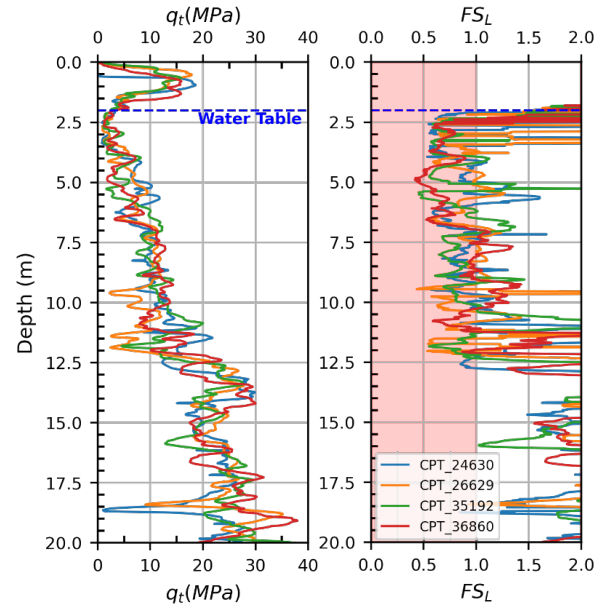


Fig. 3. Four CPTs with their cone tip resistance (q_t) data at the test site with the calculation of the FS_L at the 475-year return period.

The liquefaction-induced ground settlement values estimated using a deterministic procedure, the pseudo-probabilistic, and the performance-based approaches for the 475-year and 2475-year return periods are compared in this paper. The earthquake scenario for the deterministic procedure is a $M_w = 6.2$ event with rupture distance (R) = 7.5 km based on the sources that contribute the most to the seismic hazard for PGA at the site. In practice, the 84th percentile ($\varepsilon = 1.0$) ground motion is often used for critical projects to account partially for the variability in the IM estimation. The deterministic PGA at the site was evaluated using the Abrahamson et al. (2014) GMM with $\varepsilon = 1.0$. The deterministic estimate of $S_v = 190$ mm is shown as a vertical line in Figure 4b because the estimate of S_v is not directly associated with a specific return period in a deterministic procedure. The ground settlement is read directly from the hazard curve for S_v in the performance-based approach (Fig. 4b). In the pseudo-probabilistic approach, the input PGA and M_w values at the return periods of interest are first obtained. For the test site, the $PGAs$ are 0.30 g and 0.60 g for the 475-year and 2475-year return periods, respectively, and the controlling M_w are 6.2 and 6.4 using the results of the PSHA in terms of PGA . The resulting values of the estimated liquefaction-induced ground settlement are presented in Table 3.

Table 3. Estimates of ground settlement at test site.

Return Period (yr)	S_v (mm)		
	Deterministic using 84 th percentile PGA	Pseudo-Probabilistic	Performance-Based
475	190	90	65
2500		310	300

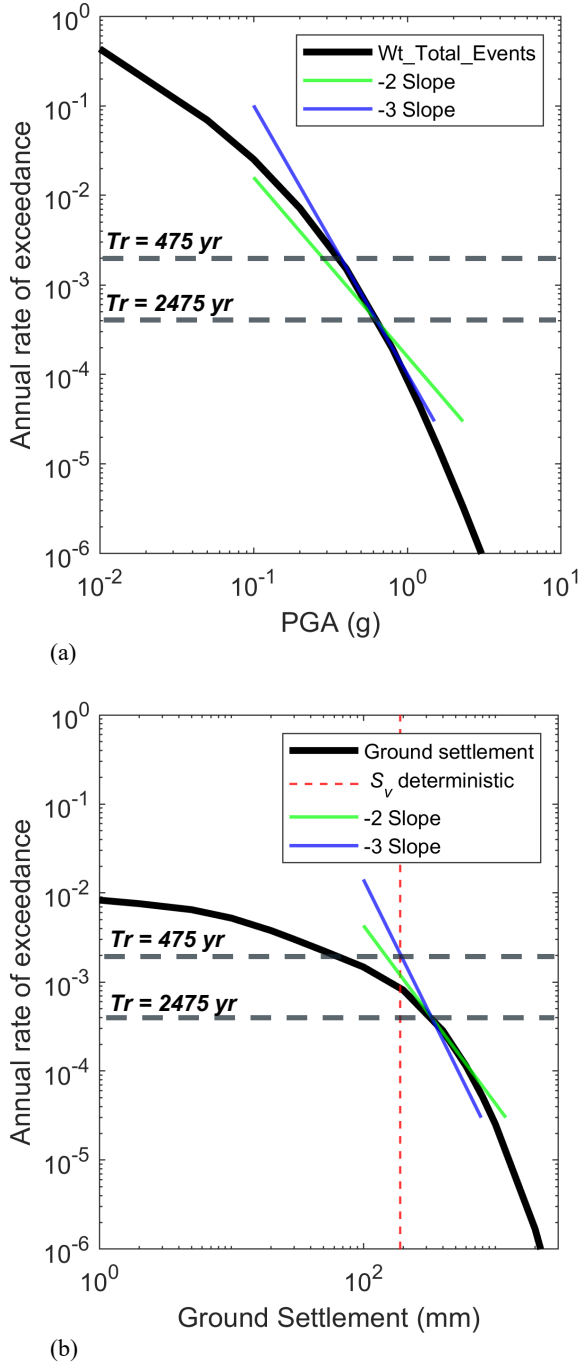


Fig. 4. (a) Mean total hazard curve for PGA , and (b) mean hazard curve for S_v at the test site.

The pseudo-probabilistic approach overestimates S_v compared to the more robust performance-based approach at the 475-year return period. The pseudo-probabilistic approach produces a mean S_v that is 40% greater than the mean estimate of S_v using the performance-based approach because the slopes of the hazard curves differ significantly at this return period. The pseudo-probabilistic and performance-based approaches coincidentally provide similar estimates of S_v at the 2,475-year return period. The performance-based assessment of S_v can also be used to evaluate the

deterministic estimate of S_v . A return period of about 1170 years is associated to the deterministic S_v using the hazard curve in Fig. 4b. Hence, the deterministically computed settlement based on the 84th percentile ($\varepsilon = 1.0$) ground motion from a controlling earthquake scenario does not produce a conservative estimate of liquefaction-induced ground settlement relative to the 2500-year return period estimate. An 84th percentile deterministic ground motion is not necessarily conservative as it is sometimes assumed in engineering practice.

The test site evaluated in this example is also used to illustrate the effects of considering epistemic uncertainty in the soil parameters. In this paper the effect of alternative values for $\Sigma_i[\varepsilon_{v,i} \cdot \Delta z_i]$ is illustrated. The four CPTs used to characterize the soil at the site yield a $COV(\Sigma_i[\varepsilon_{v,i} \cdot \Delta z_i]) = 0.15$. However, to further illustrate the effect of including epistemic uncertainty in the soil characterization, the upper limit of $COV(\Sigma_i[\varepsilon_{v,i} \cdot \Delta z_i]) = 0.30$ in Table 1 is also evaluated. The resulting range in $\lambda(S_v)$ is shown in Fig. 5. The epistemic uncertainty in $\Sigma_i[\varepsilon_{v,i} \cdot \Delta z_i]$ has a significant effect on $\lambda(S_v)$ at long return periods as shown in Fig. 5. Increasing the $COV(\Sigma_i[\varepsilon_{v,i} \cdot \Delta z_i])$ from 0.15 to 0.30 approximately doubles the range of the estimated S_v at longer return periods (i.e., between 2,475 years and 10,000 years).

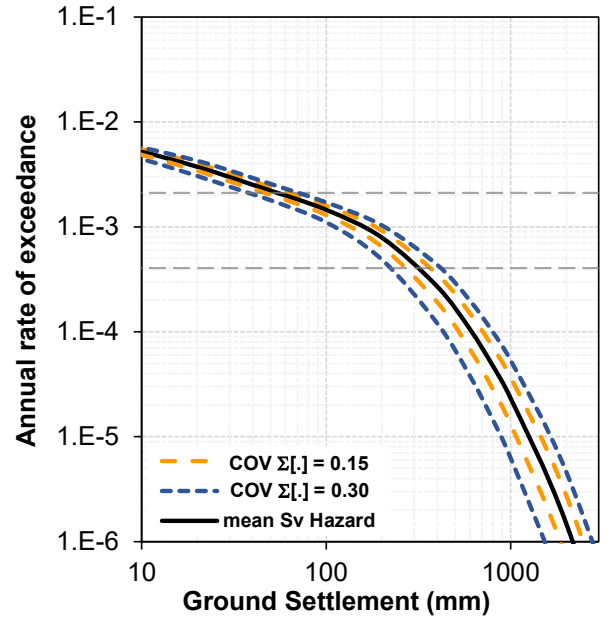


Fig. 5. Effect of epistemic uncertainty in $\Sigma_i[\varepsilon_{v,i} \cdot \Delta z_i]$ on $\lambda(S_v)$.

7 CONCLUSIONS

The Bray and Olaya (2023) probabilistic procedure to estimate liquefaction-induced ground settlement is incorporated in a performance-based earthquake engineering procedure to enable engineers to estimate ground settlement with consideration of key sources of aleatory variability and epistemic uncertainty.

Performance-based procedures are preferred to state-of-practice procedures that decouple the assessment of seismic demand and engineering response parameters. The primary inputs to the proposed performance-based procedure are the mean seismic hazard curve for PGA , the deaggregation information by magnitude at different PGA values, and the Bray and Olaya (2023) empirical procedure for estimating free-field liquefaction-induced ground settlement.

Epistemic uncertainty is captured in the evaluation of $\lambda(S_v)$ using logic-trees. Five-branch logic trees are used instead of the conventional three-branch logic trees to better capture the range of epistemic uncertainty in problems involving nonlinear soil response. The effects of the epistemic uncertainty of the geotechnical parameters can then be viewed by examining how they modify the liquefaction-induced ground settlement hazard curve.

The performance-based procedure is recommended for use in engineering practice because it delivers estimates of liquefaction-induced ground settlement consistent with the target hazard levels and enables the evaluation of different sources of epistemic uncertainty and their effects on liquefaction-induced ground settlement.

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REFERENCES

- 1) Abrahamson, N. A. (2020). Haz45 computer program. <https://github.com/abrahamson/HAZ>. (Last accessed June 2020).
- 2) Abrahamson N.A., Silva W.J., Kamai R. (2014). Summary of the ASK14 ground motion relation for active crustal regions. *Earthq Spectra* 30(3):1025-1055.
- 3) Akai et al. (1995). Geotechnical Reconnaissance of the Effects of the January 17, 1995, Hyogoken-Nanbu Earthquake, Japan,” Sitar, N., ed., Earthquake Engineering Research Center, Report No. UCB/EERC-95/01, Univ. of California, Berkeley, July.
- 4) Bray J.D., Olaya F.R. (2023). 2022 H. Bolton Seed Medal Lecture - Evaluating the Effects of Liquefaction. *J Geotech Geoenviron Eng.*, ASCE, 149(8), doi: 10.1061/JGGEFK.GTENG-11242
- 5) Deierlein, G., Krawinkler, H., and Cornell, C., (2003). A framework for performance-based earthquake engineering, *Pacific Conf. EQ Eng*, 13–15 Feb, Christchurch, New Zealand.
- 6) Ishihara K, and Yoshimine M. (1992). Evaluation of settlements in sand deposits following liquefaction during earthquakes. *Soils Found.*, 32(1),173–188.
- 7) Olaya F.R., and Bray J.D. (2022). Strain potential of liquefied soil. *J Geotech Geoenviron Eng.*, ASCE, 148 (11): 04022099.
- 8) Olaya F.R., and Bray J.D. (2023). Post-liquefaction free-field ground settlement case histories. *Int. J of Geoeng. Case histories.*, ISSMGE, V. 7(3), 18-33.
- 9) Rathje, E. M., and Saygili, G., (2008). Probabilistic seismic hazard analysis for the sliding displacement of slopes: scalar and vector approaches, *J. Geotech. Geoenviron. Eng.*, ASCE 134(6), 804–814.
- 10) Zhang G., Robertson P.K., and Brachman R.W.I. (2002). Estimating liquefaction-induced ground settlements from CPT for level ground. *Can Geotech J*, 39, 1168–1180.