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A Framework for the Evaluation of Liquefaction Consequences for Shallow-Founded Structures

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ABSTRACT: Performance-based earthquake engineering is increasingly being used to inform decision-making regarding seismic design. Recent research has provided a number of procedures that yield information needed for the development of a performance-based framework for liquefaction engineering. This study proposes a structure for such a framework for application to shallow-founded structures and identifies procedures that are key to its use. Procedures used in such performance-based engineering frameworks must offer a probabilistic estimate of hazard, demand, and/or damage, rather than a simple deterministic estimate. The framework includes analysis of both foundation and structural performance. The foundation may be subject to settlement and residual tilt if subsurface layers of soil liquefy. Although liquefaction generally reduces the acceleration demand on the superstructure, it may still cause significant damage to nonstructural components or lead to casualties. Further, the framework is organized with mitigation decision-making in mind. Mitigation may reduce the impact of foundation damage, but is expected to simultaneously increase the demand on the superstructure. Decisions about whether to mitigate, and how, must consider this tradeoff.

1. INTRODUCTION

Performance-based earthquake engineering (PBEE) frameworks have been expanded and refined since their first definition about 15 years ago (e.g., Porter 2003, Moehle and Deierlein 2004). In particular, performance-based methods are being developed to analyze more and more types of hazards and structures, including assessing, designing for and mitigating earthquake-induced liquefaction. However, many existing liquefaction methods and procedures are not compatible with performance-based analysis because they do not produce probabilistic estimates of the occurrence or consequences of liquefaction (e.g., Tokimatsu and Seed 1987, Ishihara and Yoshimine 1992, Liu and Dobry 1997). Although recent research has produced probabilistic methods (e.g., Cetin et al. 2009, Bray and Macedo 2017, Bullock et al. 2018a,b), no unified framework for performance-based evaluation of liquefaction engineering has been produced. This paper lays out the pieces of such a framework. Figure 1 shows the steps of the framework.

The key decisions in liquefaction engineering are whether or not to mitigate, and, if so, how and to what extent. Therefore, the critical information needed from a performance-based liquefaction engineering framework includes both the consequences in the mitigated case, and in the counterfactual unmitigated case.

Figure 1. Steps in the performance-based framework for evaluating building performance.

Depending on the conditions of the soil-foundation-structure system and constraints on the implementation of a mitigation strategy, mitigation may or may not bring foundation performance within acceptable limits, meaning that in some cases the framework may be used to recommend an alternative foundation system or location for the structure in question. This study details the procedures needed for the broad framework (Figure 1), and shows how it can be applied to inform mitigation decision-making.

2. HAZARD ANALYSIS

The goal of hazard analysis is to define the hazard at a site in terms of an intensity measure or set of intensity measures of interest, and selection of ground motions for use in analysis that are consistent with these intensity measures. When considering the possibility of liquefaction, hazard analysis becomes more complex than in typical PBEE for a few reasons. In particular, different intensity measures may be needed to evaluate each of the following: (1) the probability that liquefaction influences the performance of the structure (e.g., PGA or CAV_5), (2) ground motions appropriate for use in structural analysis (e.g., S_a at the building period), and (3) the performance of the foundation in terms of liquefaction consequences (e.g., CAV). Properly accounting for these complexities may require estimating the intensity at multiple locations (i.e., in the free field, at the foundation, and/or at a rock outcrop) Furthermore, liquefaction may itself alter the amplitude and frequency content of the acceleration demand on the foundation.

The probability that liquefaction will influence building performance, denoted *P(Liq)* here, has traditionally been tied to the probability of liquefaction triggering (e.g., Cetin et al. 2004, Boulanger and Idriss 2015). However, the probabilistic methods for assessing the likelihood of liquefaction triggering are based on (or validated by) observations of surficial manifestations of liquefaction. Whether or not liquefaction affects the performance of structures is more directly tied to the behavior of the liquefiable soil beneath the foundation than to the behavior of the liquefiable soil in the free field (e.g., Dashti and Karimi 2017, Karimi et al. 2018). As a result, significant softening of liquefiable material, and therefore foundation damage, can occur even if triggering does not. Despite this limitation, probabilities calculated using triggering methods are likely to be correlated to the probability that liquefaction will influence building performance because soil profiles that are more likely to generate surficial manifestations are expected to be more likely to cause foundation damage.

Alternatively, probabilistic procedures for estimating the consequences of liquefaction (e.g., Bray and Macedo 2017, Bullock et al. 2018a,b) can be used to estimate the probability that liquefaction will have consequential impacts on building performance. For example, this probability can be estimated by equating it to the probability that some threshold of settlement or tilt is exceeded.

Considering the abovementioned complexities, Figure 2 shows a flow chart for selecting a suite of n ground motions (GMs) for use in the next step of the framework (fixed-base analysis of a structural model). This study proposes using the same number of GMs as in other performance-based earthquake engineering frameworks (e.g., 11 GMs per ASCE 2016), but altering some of the GMs to reflect the frequency content of the case where

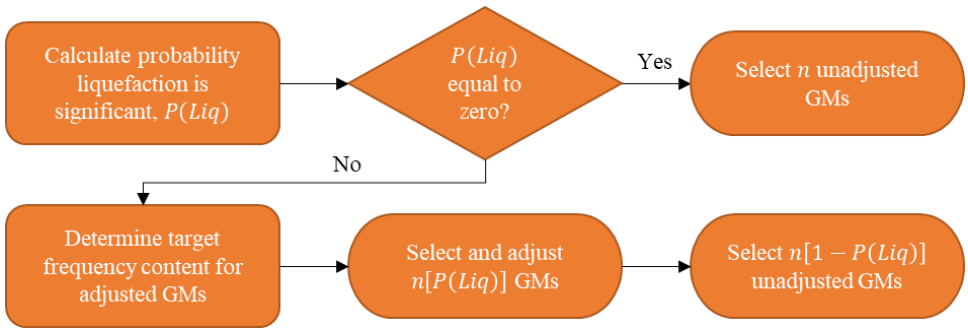

Figure 2. Flow chart for selecting ground motions representative of the surficial hazard at the site.

liquefaction occurs. The number of GMs to be altered in this fashion is proportional to the probability that liquefaction has a significant influence on the overall analysis. Selection of the unadjusted GMs can follow existing PBEE procedures (e.g., Baker 2010). The selection process reverts to the typical procedure if $P(Liq)$ is sufficiently small compared to n that $n[P(liq)]$ rounds to zero. This condition implies that the influence of liquefaction on the character of the hazard at the site is negligible.

However, at present, no methods have been specifically developed for adjusting ground motions to represent the liquefied case. Liquefaction will tend to result in increased low-frequency content, implying that existing spectral matching techniques (e.g., Al Atik and Abrahamson 2010) may be useful for this purpose. However, the time at which liquefaction occurs is also significant and the frequency content before and after the triggering of liquefaction may differ substantially (e.g., Kramer et al. 2015; Karimi et al. 2018). Therefore, new methods based on manipulating frequency content as a function of time (rather than simply frequency content) are needed.

Alternatively, nonlinear time history analyses of the liquefiable soil column can be performed with outcropping rock acceleration histories as inputs. The motion recorded at the ground surface in these analyses provides input motion for the structural model in subsequent sections. This method requires characterization of the dynamic properties of the soils present at the site, and is subject to the limitations of the selected soil constitutive models (e.g., Elgamal et al. 2002, Dafalias and Manzari 2004) as demonstrated by Ramirez et al. (2018). It also fails to account for soil-structure interaction, which may have significant effects on the characteristics of the motion at the foundation (e.g., Karamitros et al. 2012, Karimi et al. 2018).

3. STRUCTURAL ANALYSIS

Structural analysis here includes analysis of a structure, as in conventional PBEE, as well as analysis of foundation performance. Here, we envision generally continuing with analysis of the structure separate from the soil system using typical fixed-based structural analysis methods. However, the structural analysis portion is altered such that a proportional number of the ground motions used include the effects of liquefaction. The results of these analyses are quantified in terms of distributions of engineering demand parameters (EDPs), such as story drifts, floor accelerations and residual drift.

Foundation performance can be evaluated based on average settlement, residual tilt (i.e., differential settlement), and sliding (e.g., Bray et al. 2014).

3.1. *Foundation settlement*

Two primary methodologies exist for estimating average settlement: (1) summing estimates of settlement due to different mechanisms (i.e., volumetric, deviatoric, and ejecta-related settlements); or (2) estimating total settlements directly.

In the first approach, when estimating settlement (S), volumetric settlements (S_V) can

be estimated probabilistically with Cetin et al. (2009) and deviatoric settlements (S_D) with Bray and Macedo (2017), but some distribution for ejecta-related settlements (S_E) must be assumed. Total settlement is given by Equation 1,

$$S = S_V + S_D + S_E \quad (1)$$

where S_V, S_D, and S_E are lognormal random variables with logarithmic medians μ_V, μ_D, and μ_E and logarithmic standard deviations σ_V, σ_D, and σ_E. This approach has the benefit of providing understanding of the relative importance of the different settlement mechanisms. However, it may require the use of multiple GMPEs for the estimation intensity measures for each component of settlement (e.g., PGA, S_a at a period of 1.0 s, and damage potential CAV for the procedures described here here), as well as a correlation model for the errors of these GMPEs.

In addition, although the sum of multiple lognormal random variables (i.e., Equation 2) is not strictly lognormal, it is desirable to formulate a representative lognormal distribution for total settlement for computational convenience. We suggest summing the means of these variables to determine the mean of the final distribution (Equation 2) and using the weighted sum of their variances and the variance of their means to determine its variance (Equation 3). The mean and variance of S can be used to calculate the logarithmic median and standard deviation of S (μ_S and σ_S) per Equations 4 and 5, which are then familiar to use to calculate exceedance probabilities.

$$\text{mean}(S) = \exp\left(\mu_V + \frac{\sigma_V^2}{2}\right) + \exp\left(\mu_D + \frac{\sigma_D^2}{2}\right) + \exp\left(\mu_E + \frac{\sigma_E^2}{2}\right) \quad (2)$$

$$\text{var}(S) = (\exp(\sigma_V^2) - 1)\exp(2\mu_V + \sigma_V^2) + (\exp(\sigma_D^2) - 1)\exp(2\mu_D + \sigma_D^2) + (\exp(\sigma_E^2) - 1)\exp(2\mu_E + \sigma_E^2) \quad (3)$$

$$\text{mean}(S) = \exp\left(\mu_S + \frac{\sigma_S^2}{2}\right) \quad (4)$$

$$\text{var}(S) = (\exp(\sigma_S^2) - 1)\exp(2\mu_S + \sigma_S^2) \quad (5)$$

In the second approach, total settlement can be estimated directly, as in Bullock et al. (2018a). This methodology also provides a single estimate of the total uncertainty around settlement predictions, alleviating the need to make simplifying assumptions regarding the shape of the distribution and the correlation among the errors around estimates of each component of settlement. However, estimating total settlement obscures any information about the relative importance of deviatoric and volumetric settlement components. In Bullock et al. (2018a), the numerical portion of the settlement may be considered roughly equivalent to the deviatoric-type settlement, although this assumption may not be valid for all soil-foundation-structure system configurations.

3.2. *Foundation tilt*

Likewise, there are two methodologies for estimating foundation's residual tilt (θ_r): (1) producing multiple estimates of settlement at different points under the structure and using geometry to convert them to a value of tilt; or (2) estimating residual tilt directly.

The first method requires describing the soil profile at multiple locations around the site, and will estimate no or small tilt if the site is relatively homogeneous in plan. For example, two estimates of settlement on either side of the foundation (S_1 and S_2) and its width in the direction between them (B) can be combined to estimate θ_r using Equation 6.

$$\theta_r = \sin^{-1}\left(\frac{|S_1 - S_2|}{B}\right) \quad (6)$$

The uncertainty around such estimates depends on the uncertainty in the settlement model used. Both the median prediction of tilt and the uncertainty around it potentially depend on the spatial correlation of the settlement model's errors (i.e., the correlation of the distributions of S_1 and S_2 in Equation 6). None of the existing settlement models explore the possibility of spatial correlation in their errors, and extensive case history observations would be needed to do so rigorously. Sensitivity analysis can be used to determine whether the

spatial correlation has a significant impact on residual tilt predictions in this framework. In addition, the extension of settlement models to predict tilt may not capture the effects of certain parameters on tilt, particularly inertial effects (Bullock et al. 2018b). Additionally, some parameters may increase settlement, but reduce tilt (e.g., increasing bearing pressure may increase the potential for deviatoric-type settlements, but decrease tilt potential through a re-centering mechanism).

These countervailing effects cannot be incorporated into tilt estimates made using settlement models, and a model for predicting tilt directly is needed to do so, i.e. using the second tilt estimation option. At the time of this writing, Bullock et al. (2018b) provides the only probabilistic model that predicts residual foundation tilt independently from predictions of settlement. However, the Bullock et al. (2018b) model for residual tilt is valid only for mat foundations and more detailed analysis is required for buildings on strip or isolated foundation systems.

The probabilistic procedures outlined above all assume level ground and level subsurface layers. If this assumption is violated, the models may not yield accurate estimates, and foundation sliding may also become an important component of demand. Procedures for estimating slope displacements may be useful for estimating foundation sliding (e.g., Franke and Kramer 2013). Complex, project-specific nonlinear time history analyses with soil structure interaction may be used in place of the probabilistic procedures outlined above. Such analyses should be conducted with a suite of outcropping rock GMs as inputs to the base of the soil column. Although these analyses yield more specific estimates of the demand on the foundation, they require substantially more information about the site and computational time to generate. Depending on the scope of the project, they may or may not be feasible to perform. If not, the uncertainty around the estimates produced using models such as Bullock et al. (2018a,b) may be widened to account for their use in an unintended context (i.e., according to FEMA P-58 Appendix H).

4. DAMAGE ANALYSIS

The framework presented in this study distinguishes between structural damage measures (SDMs) and foundation damage measures (FDMs). SDMs are calculated in the same manner as in existing PBEE frameworks: by analyzing a structural model under a suite of ground motions and calculating EDPs from the results per the previous step in the framework, and then relating these EDPs to damage states using fragility curves (e.g., Porter et al. 2007).

Foundation damage measures may be described by corresponding EDPs. Damage states corresponding to settlement and residual tilt may be governed by exceedance of threshold values corresponding to serviceability limits (e.g., 10/1000 as identified by Yasuda and Ariyama 2008). If such tilt occurs, the stiffness or ductility of the foundation system may be irrelevant (i.e., demolition may be necessary regardless of cracking or deformations in the foundation). However, detailed analysis of the strains in the foundation may be required, particularly if effective repair strategies are available. For example, if it is feasible to use jacks to alleviate residual tilt rather than demolishing the structure, repairs to the foundation itself will be salient to total losses.

5. LOSS ANALYSIS

Losses depend on damage to structure and/or the foundation. Depending on their relative severity, SDMs and FDMs may contribute to losses in additive or multiplicative ways. For instance, some degree of foundation settlement may add to losses while also increasing the cost of repairing damage to superstructure. However, one type of damage may be irrelevant if the other type is severe enough to incur total losses. Thresholds of SDMs and FDMs that result in total losses may be highly dependent on local context. If repair strategies for residual tilt are unavailable or prohibitively costly, FDMs are

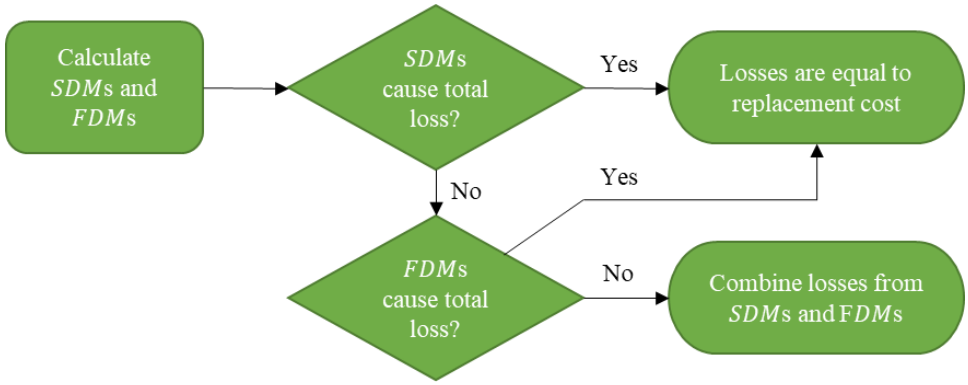

Figure 3. Flow chart for calculating losses due to simultaneous structural and foundation damage.

likely to cause total losses in many cases (e.g., Yasuda and Ariyama 2008). Further, the language of insurance policies written in the region may determine whether repairs are feasible or if demolition and replacement is the preferable course of action (e.g., Van Ballegooy et al. 2014). Figure 3 presents the process for determining losses in the form of a flow chart.

6. SYNTHESIS AND IMPLEMENTATION

Figure 4 assembles the steps in the framework described above. Figure 4 also includes the mathematical outputs of each step.

The framework can be expressed as an altered form of the typical triple integral encountered in PBEE, as shown in Equations 7 through 11. In these equations, the rates of occurrence of structural and foundation damage measures are calculated (Equations 7 through 10) and combined separately to calculate the decision variable (e.g., losses; Equation 11). Separating these calculations is necessary due to the potentially complex nature of combining losses from damage to the structure and from consequences on the foundation (as described in Figure 3).

7. CONCLUDING REMARKS

The framework described here allows engineers to compare the performance of shallow-founded structures on liquefiable ground for multiple hypothetical cases and to select the optimum design for mitigation. These decisions are informed by the performance of both the structure and the foundation for each case, allowing the quantification of the tradeoffs between structural damage and liquefaction consequences, such as foundation settlement.

However, several components needed for the implementation of the framework in practice have not yet been developed. Firstly, no procedure exists for quantifying the influence of liquefaction on the acceleration demand at the base of the structure. Secondly, while existing methods for estimating liquefaction consequences can be extended to the mitigated case for densification by using a correspondingly increased relative density as an input, this approach may not be accurate because

$$\nu(SDM) = \nu(SDM|Liq) + \nu(SDM|\overline{Liq}) \quad 7$$

$$\nu(SDM|Liq) = \int P[Liq|IM_{OR}] \iint G(SDM|EDP)dG(EDP|IM_S, Liq)d\lambda(IM_s|Liq)\, d\lambda(IM_{OR}) \quad 8$$

$$\nu(SDM|\overline{Liq}) = \int P[\overline{Liq}|IM_{OR}] \iint G(SDM|EDP)dG(EDP|IM_S, \overline{Liq})d\lambda(IM_s|\overline{Liq})\, d\lambda(IM_{OR}) \quad 9$$

$$\nu(FDM) = \iint G(FDM|EDP)dG(EDP|IM_{OR})d\lambda(IM_{OR}) \quad 10$$

$$\nu(DV) = f\big(\nu(SDM), \nu(FDM)\big) \quad 11$$

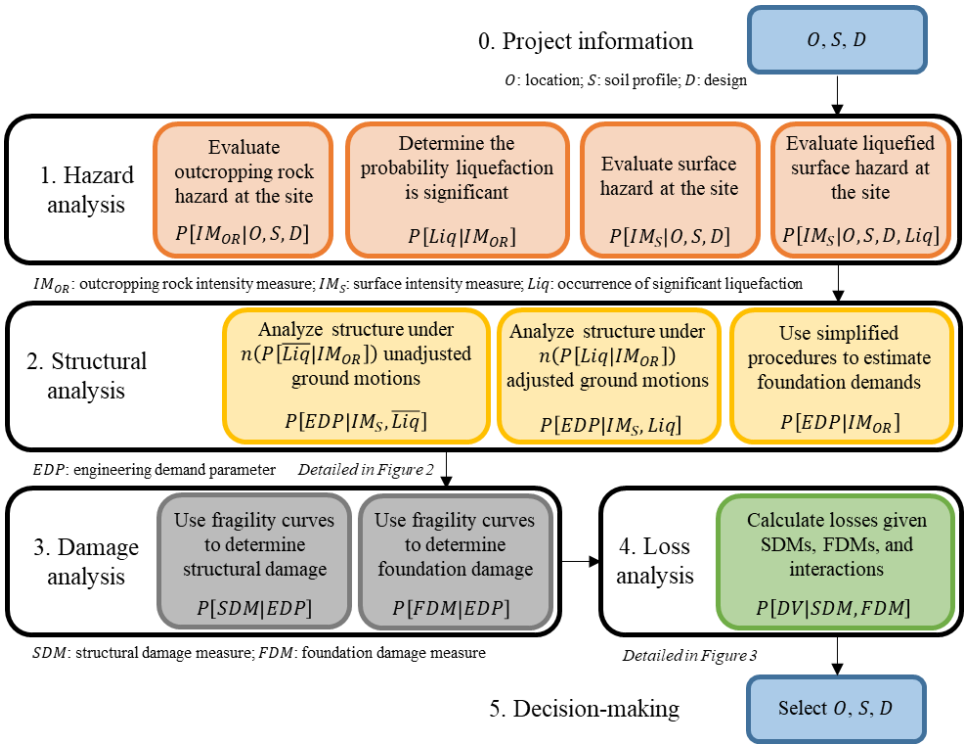

Figure 4. The assembled framework for evaluating mitigation of liquefaction consequences.

densification is not equivalent to instantaneously replacing a soil profile with a denser one. This approach can also not be employed for other mitigation strategies, including stone columns or prefabricated drains. More work is needed to define loss thresholds and damage states for foundation damage states.

8. ACKNOWLEDGMENTS

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