Progress Memo – November 14, 2019

To: Technical Advisory Committee, David Stevens – Research Project Manager, Utah Department of Transportation

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Subject: Task 9 – Screening Criteria for Lateral Spread Potential, Pacific Earthquake Engineering Research (PEER) Next Generation Liquefaction (NGL) Database of case histories of liquefaction-induced lateral spread – Pooled fund study TPF-5(350)

This memo summarizes the progress made to date regarding Phase 1 – Task 9 of the PEER NGL database. Following is the approach that the University of Utah has selected in Task 9 to develop screening criteria for lateral spread potential.

Introduction

Engineering practice has a general need to define "screening" criteria for liquefaction-induced lateral spread. These should include the range of sediment, site and seismological characteristics necessary to produce lateral spread. Unfortunately, some engineering practitioners misapply MLR models and attempt to predict lateral spread displacement by extrapolating the input variables (i.e., independent variables) beyond the conditions or data bounds represented in the regression of the original dataset. For example, misuse can occur by inferring critical layer continuity when it may not exist, or by extrapolation of the model to thin layers (i.e., layers less than 1.0 m), or by using the MLR equations to predict displacement in predominately non-plastic silts, etc. (Youd, 2018).

As a possible solution to this problem, we propose to develop a probabilistic-based method to predict lateral spread susceptibility based on the implementation of the following conditional probability statement:

$$P[L_s \mid F, PI, SI, T, D, Z, G. R, M_w, X_n] \quad \text{Eq. 1}$$

where L_s is the probability of occurrence of lateral spread conditioned on the soil and seismological factors such as fines content, F, plasticity index, PI, soil index, SI, layer thickness, T, soil density D, depth of critical layer, Z, relative geologic susceptibility, G, seismic source distance, R, and earthquake magnitude, M_w, and represent other possible variables to be evaluated as part of the research, X_n. These independent variables are further described later in this section.

We propose to use logit analysis to determine the probability of occurrence of lateral spread for a given site using Eq. 1 as a framework. The logistic model (or logit model) is a widely used statistical model that uses a logistic function to model a dichotomous (binary) dependent variable (https://en.wikipedia.org/wiki/Logistic_regression). Logistic regression is used to explain the relationship between one dependent binary variable and one or more nominal, ordinal, interval, or ratio-level independent variables. In our case, we plan to use the logistic model to predict the probability of occurrence (or non-occurrence) of liquefaction-induced lateral spread. We emphasize that the purpose of the logistic model is not to predict the amount of horizontal displacement resulting from lateral spread, D_H; hence it does not replace existing MLR predictive equations such as those developed by Youd et al., 2002 and Gillins and Bartlett, 2013, or by others.

In general, these latter MLR models can be used to predict the probability that lateral spread horizontal displacement, D_H, exceeds some threshold value, y, of engineering interest (e.g., 0.1, 0.3 m, etc.). This is done by evaluating:

$$P[D_H > y] = \Phi\left(-\frac{Log(y) - \overline{Log(D_H)}}{\sigma_{Log(D_H)}}\right) \quad \text{Eq. 2}$$

where Φ is the standard cumulative normal distribution; and, $\sigma_{Log(DH)}$ is the standard deviation of the predicted variable and $\overline{Log(D_H)}$ is the mean value of the logarithm of the lateral spread displacement (D_H is in meters) predicted from the respective MLR model (Youd at al. 2002, Gillins and Bartlett, 2013).

To join the logistic lateral spread screening model with the MLR displacement predictive model, we propose the following conditional probability statement:

$$P[D_H > y] = P[D_H > d \mid L_s] \cdot P[L_s \mid F, PI, SI, T, D, Z, G, R, M_w, X_n] \quad \text{Eq. 3}$$

This conditional probability statement has a distinct advantage over previous approaches by defining factors or conditions that are correlated with the occurrence of lateral spread (i.e., screening criteria) with the prediction of D_H. Because the proposed approach is fundamentally probabilistic, it can more rigorously deal with uncertainty in the various input factors. For example, Bartlett and Youd (1992; 1995) showed that relatively loose saturated sandy deposits are required to generate lateral spread. They proposed that such sediments generally have SPT $N1_{60}$ values less than 10 and almost always have SPT $N1_{60}$ less than 15. However, if the SPT $N1_{60}$ values slightly exceed 15, is it still possible to generate lateral spread under certain conditions (e.g., close-by, large magnitude earthquakes)? Although the probability may be small, it is not zero. Conversely, if a borehole at a site has a saturated sandy layer with SPT $N1_{60}$ values less than 15, the likelihood of lateral spread has increased, but its occurrence is not certain. Therefore, the logistic model allows for the quantification of this probability by including the combined influence of other important independent variables.

Gillins (2012) has proposed that Eq. 3 be conditioned on the probability of liquefaction, L, and not the probability of lateral spread, L_s.

$$P[D_H > y] = P[D_H > y|L] \cdot P_L \quad \text{Eq. 4}$$

While this equation is often used for performing probabilistic-based lateral spread evaluations that are coupled with probabilistic liquefaction triggering evaluations and probabilistic seismic hazard analysis (PSHA), Eq. 4 is not necessary as long as Eq. 3 contains independent variables that are correlated with the occurrence of lateral spread and liquefaction. The use of Eq. 3 instead of Eq. 4 in the final probability chain is similar to the approach taken by Franke and Kramer (2014) in developing their predictive equations for lateral spread displacement. These authors introduced a performance-based procedure built upon a probabilistic framework to compute the mean annual rate of exceeding some lateral spread displacement (i.e., $D_H > d$). Their approach modifies the Youd et al. (2002) model by grouping all of the model variables related to seismic loading (i.e., M_W and R) and designating them as an apparent loading parameter, $\mathscr{L}$. Because $\mathscr{L}$ is a function of parameters M_W and R, it is analogous to a ground motion attenuation relationship and can be treated in a similar manner (Sharifi-Mood et al., 2018). Therefore, we propose that Eq. 5 can be used either deterministically for a given earthquake and source distance, or combined with PHSA to perform probabilistic mapping and performance-based assessments:

$$P[D_H > d] = [D_H > d \mid L_s] \cdot P[L_s \mid F, PI, SI, T, D, Z, R, M_w, X_n] \cdot P[M_w, R] \quad \text{Eq. 5}$$

where the $P[M_w, R]$ is obtained from the PHSA for each magnitude-distance pair at the grid point of interest, ultimately, Eq. 5 can be summed across all possible magnitude-distance pairs (M_w, R) using the individual probabilities as weights for each magnitude-distance pair at a given grid point to determine the mean annual rate that D_H exceeds, d.

Influence of Fines Content (F) – The fines content is that percentage of the soil distribution that is finer than 0.075 mm. Field case histories indicate that fine-grained sediment such as those beneath Adapazari, Turkey, although susceptible to liquefaction, were not susceptible to lateral spread. Also, clay-like soils appear to be immune to lateral spread. Empirical models based on SPT sampling suggest that lateral displacement decreases markedly with increasing fines content (Bartlett and Youd 1995, Youd et al., 2002). This finding needs additional definition and confirmation. Predicted lateral spread displacements from CPT methods (e.g., Zhang et al. 2004) do not similarly show the impeding effects of fine-grained soils on lateral spreads.

Influence of Plasticity Index (PI) – The plasticity index is the liquid limit of the soil minus the plastic limit of the soil, as defined by Atterberg (https://en.wikipedia.org/wiki/Atterberg_limits). Monotonic and cyclic undrained loading test data for silts and clays show that they transition, over a fairly narrow range of plasticity indices (PI), from soils that behave more fundamentally like sands (sand-like behavior) to soils that behave more fundamentally like clays (clay-like behavior). Boulanger and Idriss (2006) propose for practical purposes, clay-like behavior is expected for fine-grained soils that have a plastic index (PI) equal to or greater than 7. Bray and Sancio (2006) concluded that loose soils with PI < 12 and *wc* / LL> 0.85 were susceptible to liquefaction, and loose soils with 12 < PI < 18 and *wc* / LL > 0.8 were systematically more resistant to liquefaction. Soils with PI > 18 tested at low effective confining stresses were not susceptible to liquefaction.

Influence of Soil Index (SI) – Gillins and Bartlett (2013) found that the soil classification obtained from borehole logs could supplant the use of fines content and mean grain size in MLR models and develop a soil type factor called the soil index, *SI*. Because often there are descriptions or classifications of the soil recorded on the case history borehole log with the corresponding SPT N values, SI might be useful to replace F_{15} and $D50_{15}$ in the logit analyses (Table 1).

Table 1. Descriptions and distributions of T_{15} layers in Youd et al. (2002) database

Soil Descriptions	Count n	$\overline{D50}$ (mm)	σ_{D50} (mm)	$\overline{FC}$ (%)	σ_{FC} (%)	General USCS Symbol	Soil Index SI
Silty gravel with sand, silty gravel, fine gravel	6	5.69	4.26	18.3	6.4	GM	1
Very coarse sand, sand, and gravel, gravelly sand	7	2.15	0.83	7.5	6.4	GM-SP	2
Coarse sand, sand with some gravel	32	0.62	0.18	7.0	4.2	SP	2
Sand, medium to fine sand, sand with some silt	76	0.35	0.02	4.6	2.3	SP-SM	3
Fine sand, sand with silt	50	0.17	0.05	14.3	11.0	SM	4
Very fine sand, silty sand, dirty sand, silty/clayey sand	39	0.11	0.12	36.6	12.4	SM-ML	4
Sandy silt, silt with sand	38	0.07	0.08	57.9	12.2	ML	5
Silty clay, lean clay	--	--	--	--	--	CL	6

Influence of Layer Thickness (T) – Bartlett and Youd (1992, 1995) showed that cumulative thickness of the loose, saturated, sandy deposits influences the occurrence of lateral spread and the resulting amount of horizontal displacement. They defined thickness factors (i.e., independent variables) in their MLR analysis that accounted for the effect of thickness. These were T_{10}, $T_{15,}$ and T_{20}, where T is the cumulative thickness of saturated, granular deposits with $N1_{60}$ values less than 10, 15, and 20, respectively. (Bartlett and Youd (1992, 1995) were careful not to infer that these independent variables represented the thickness of the "liquefied zone." Instead, they were introduced in their evaluation simply as soil factors that were correlated with lateral spread displacement, hence useful without the need of performing liquefaction analysis procedures.) Regarding this, the thinnest T_{15} layer in the Bartlett and Youd (1995) dataset in which measurable lateral spread displacement occurred was about 1.0 m. The thinnest layer observed in CPT data is about 0.6 m (Youd, 2018). Hence, it appears that layers with a thickness less than this are either not continuous across the site or do not have a sufficient thickness to generate sufficient water migration to induce lateral spread displacement (Bartlett and Youd, 1992).

Influence of Soil Density (D) – From their MLR database, Bartlett and Youd (1992) and Youd et al. (2002) concluded that sediments susceptible to lateral spread generally have SPT $N1_{60}$ values less than 10 and almost always have SPT $N1_{60}$ less than 15. Nonetheless, the influence that soil density (i.e., SPT N values) has on the probability of lateral spread occurrence will be more rigorously explored using logistic analyses.

Influence of Depth (Z) – Bartlett and Youd (1992) found that the depth to the critical zone, defined as the lowest $N1_{60}$ value in saturated, granular deposits, was almost always in the upper 15 m of the soil profile. Therefore, the influence of depth will also be explored during this research.

Influence of Relative Geologic Susceptibility (G) – Table 2 will be used to score the relative susceptibility of the deposits according to the depositional environment (i.e., type of deposit) and age. G will be scored as 5 for very high, 4 for high, 3 for moderate, 2 for low and 1 for very low in the logit evaluations.

Table 2. Estimated susceptibility of sedimentary deposits to liquefaction during strong seismic shaking (after Youd and Perkins 1978)

Type of Deposit	General Distribution of Cohesionless sediments in deposits	Likelihood that Cohesionless Sediments, When Saturated, Would be Susceptible to Liquefaction (by Age of Deposit)			
		<500 yr	Holocene	Pleistocene	Pre-Pleistocene
(1)	(2)	(3)	(4)	(5)	(6)
(a) Continental Deposits					
River Channel	Locally Variable	Very High	High	Low	Very Low
Floodplain	Locally Variable	High	Moderate	Low	Very Low
Alluvial Fan and Plain	Widespread	Moderate	Low	Low	Very Low
MarineTerraces/ Plains	Widespread	-----	Low	Very Low	Very Low
Delta and Fan-delta	Widespread	High	Moderate	Low	Very Low
Lacustrine and Playa	Variable	High	Moderate	Low	Very Low
Colluvium	Variable	High	Moderate	Low	Very Low
Talus	Widespread	Low	Low	Very Low	Very Low
Dunes	Widespread	High	Moderate	Low	Very Low
Loess	Variable	High	High	High	Unknown
Glacial Till	Variable	Low	Low	Very Low	Very Low

Tuft	Rare	Low	Low	Very Low	Very Low
Tephra	Widespread	High	High	?	?
Residual Soils	Rare	Low	Low	Very Low	Very Low
Sebkha	Locally Variable	High	Moderate	Low	Very Low
(b) Coastal Zone					
Delta	Widespread	Very High	High	Low	Very Low
Esturine	Locally Variable	High	Moderate	Low	Very Low
Beach					
High Wave Energy	Widespread	Moderate	Low	Very Low	Very Low
Low Wave Energy	Widespread	High	Moderate	Low	Very Low
Lagoonal	Locally Variable	High	Moderate	Low	Very Low
Fore Shore	Locally Variable	High	Moderate	Low	Very Low
(c) Artificial					
Uncompacted Fill	Variable	Very High	-----	-----	-----
Compacted Fill	Variable	Low	-----	-----	-----

Influence of Seismic Source Distance (R) – For similar magnitude earthquakes, liquefaction effects are known to attenuate with decreasing seismic energy associated with further distances from the seismic source (Youd and Perkins, 1987; Ambraseys, 1988; Bartlett and Youd, 1992, 1995; Youd et al., 2002). The effects of source distance on the occurrence of lateral spread will also be explored and evaluated.

Influence of Earthquake Magnitude (M_w) – At susceptible sites and all other factors being equal, the occurrence of lateral spread and the magnitude of the associated displacement increases with earthquake magnitude (Bartlett and Youd, 1992; 1995).

Influence of Other Variables (X_n) – Other variables, not mentioned above, may be defined and evaluated during the research.

References

Ambraseys, N. N. (1988). "Engineering Seismology," Earthquake Engineering and Structural Dynamics, Vol. 17, pp. 1-105.

Bartlett, S.F. and Youd, T.L. (1992). Case Histories of Lateral Spreads Caused by the 1964 Alaska Earthquake: in Case Studies of Liquefaction and Lifeline Performance During Past Earthquakes: National Center for Earthquake Engineering Research Technical Report NCEER-92-0002, v. 2, 127 p.

Bartlett, S. and Youd, T. (1995). "Empirical Prediction of Liquefaction-Induced Lateral Spread." J. Geotech. Engrg., 10.1061/(ASCE)0733-9410(1995)121:4(316), 316-329.

Bray, J. D., and Sancio, R. B. (2006). "Assessment of the Liquefaction Susceptibility of Fine-Grained Soils," J. Geotech. Engrg. 10.1061/(ASCE)1090-0241(2006)132:9(1165), 1165-1177.

Boulanger, R. W., and Idriss, I. M. (2006). "Liquefaction Susceptibility Criteria for Silts and Clays," J. Geotech. Geoenviron. Eng., 10.1061/(ASCE)1090-0241(2006)132:11(1413), 1413-1426.

Franke, K.W., Kramer, S.L., (2014). "Procedure for the empirical evaluation of lateral spread displacement hazard curves." J. Geotech. Geoenviron. Eng. 140 (1), 110–120.

Gillins, D.T., Bartlett, S.F., (2013). "Multilinear regression equations for predicting lateral spread displacement from soil type and cone penetration test data." J. Geotech. Geoenviron. Eng. 140 (4), 04013047.

Gillins, D.T. (2012). "Mapping the Probability and Uncertainty of Liquefaction-Induced Ground Failure, Ph.D. Dissertation, University of Utah, Salt Lake City.

Sharifi-Mood, M., Gillins, D. T., Franke, K. W., Harpert, J. N., Bartlett, S.F. and Olsen, M. J. (2018). "Probabilistic Liquefaction-Induced Lateral Spread Hazard Mapping and its Applications to Utah County, Utah," Engineering Geology, 237(2018)76-91.

Xia, Jingfeng (2012). "Metrics to Measure Geospatial Data Quality," Issues in Science and Technology Librarianship, DOI: 10.5062/F4B85627, http://www.istl.org/12-winter/article1.html

Youd, T. L., (2018). Application of MLR Procedure for Prediction of Liquefaction-Induced Lateral Spread Displacement," J. Geotech. Geoenviron. Eng., 2018, 144(6): 04018033.

Youd, T. L., and Perkins D. M. (1987). "Mapping of Liquefaction Severity Index," Journal of Geotechnical Engineering, ASCE, Vol. 113, No. 11 pp. 1374-1392.

Zhang, G., Robertson, P.K., Brachman, R.W.I. (2004). "Estimating Liquefaction-Induced Lateral Spread Displacements Using the Standard Penetration Test or Cone Penetration Test," Journal of Geotechnical and Geoenvironmental Engineering, Vol. 130, No. 8, August 2004.