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Calibration of liquefaction potential index: A re-visit focusing on a new CPTU model

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ABSTRACT

This paper presents a review of the state-of-the-art of Liquefaction Potential Index (LPI), a parameter created by Iwasaki and his co-workers to characterize the potential for surface manifestation of liquefaction, and the results of an extensive calibration of the LPI with a focus on a new model based on piezocone testing (CPTU). The results show that the threshold criteria developed by Iwasaki and his co-workers for interpreting the calculated LPI are not universally applicable. To the contrary, the LPI must be re-calibrated when any component model of the LPI framework is replaced with a new model. The new CPTU model is a significant advance in the cone penetration-based liquefaction evaluation; in fact, it is the first simplified model that explicitly incorporates pore pressure measurement as one of its input parameters. This CPTU model is applicable to a wide range of soil types and thusly enables a more convenient and effective modeling of liquefaction effects within the LPI framework. Probabilistic characterization of the new CPTU model is carried out. Finally, the results of the calibration of the LPI calculated with this CPTU model, along with the concept of the probability of surface manifestations, are presented and discussed.

1. Introduction — an overview of liquefaction potential index

Liquefaction hazard maps have increasingly been incorporated into the seismic safety plans of communities and also used for regulatory purposes (CDMG, 1997). Early maps of liquefaction hazards were mostly based on surficial geologic parameters and qualitative rankings (Youd and Hoose, 1977; Youd and Perkins, 1987). Later, use of field penetration data for mapping liquefaction hazards was proposed (Kavazanjian et al., 1985; Elton and Hadj-Hamou, 1990), where the liquefaction potential for a specific location and depth within the soil was assessed using the simplified procedure developed by Seed and Idriss (1971, 1982). In recent years, use of the Liquefaction Potential Index (LPI), developed by Iwasaki et al. (1978, 1982), as a parameter to characterize the potential for the occurrence of damaging liquefaction in a geologic unit has received greater attention (Frost et al., 1997; Luna and Frost, 1998; Divakarla et al., 1998; Holzer et al., 2002). Toprak and Holzer (2003) suggested that LPI is also useful for describing the geographic variability of liquefaction hazards; together with Geographical Information System (GIS) applications, LPI can greatly facilitate the preparation of liquefaction hazard maps. In fact, this index has been used in several U.S. Geological Survey (USGS) liquefaction hazard mapping projects (e.g., Holzer et al., 2006a).

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Liquefaction Potential Index (LPI), as formulated by Iwasaki et al. (1978, 1982), is computed by integrating the "contribution" of liquefaction potential, in terms of factor of safety (F_S) against the initiation of liquefaction, over the depth at a "borehole" location. Symbolically, this index is expressed as follows:

$$\mathrm{LPI} = \int_0^{20} F \cdot w(z) dz \tag{1}$$

in which the depth weighting factor, $w(z)=10-0.5z$ where z=depth (m). Thus, the weighting factor is 10 at $z=0$ and linearly decreases to 0 at $z=20$ m, which implies that the severity of surface manifestation of liquefaction (such as sand boils, lateral spreads, and settlement) is proportional to the proximity of the liquefied "layer" to the ground surface. The variable F is defined as follows:

$$F = 1 - F_S, \text{ for } F_S < 1; \text{ and } F = 0 \text{ for } F_S \geq 1. \tag{2}$$

in which F_S is the factor of safety against the occurrence of liquefaction of a soil element at a given depth. This definition of variable F implies that only soils with $F_S<1$ "contribute" to the severity of liquefaction at the ground surface. Finally, the integration (or summation) over the depth of 20 m implies that the severity of liquefaction is proportional to the thickness of the liquefied layer, and that no contribution from soils below 20 m. Fig. 1 shows an example of the calculation of LPI based on the cone penetration sounding profiles, which is the focus of this paper and the details will be presented later.

In the formulation by Iwasaki et al. (1982), the factor of safety (F_S) is determined using a standard penetration test (SPT)-based

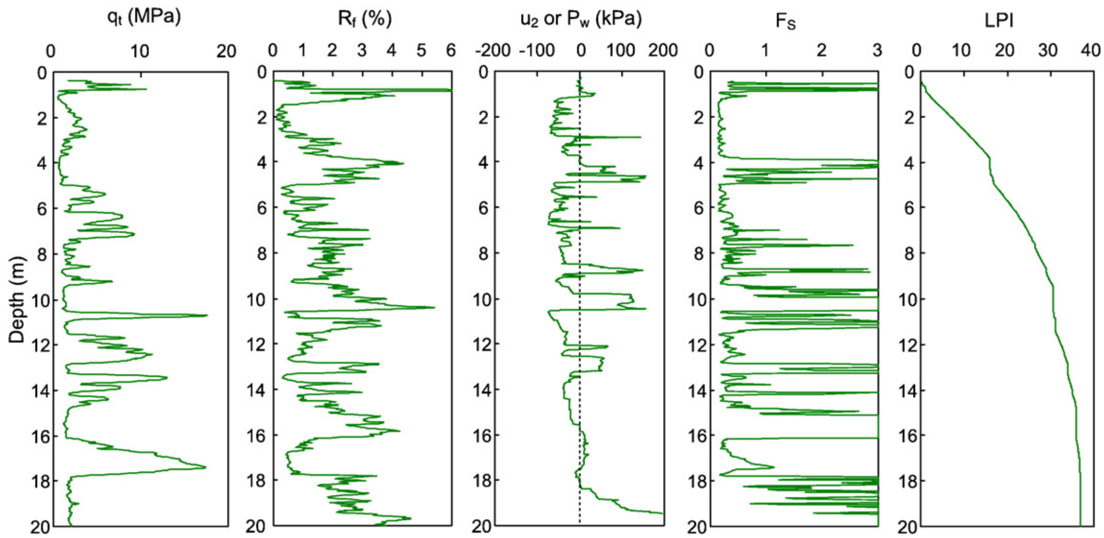

Fig. 1. CPTU soundings and the analysis results at location CPT-G1 in Adpazari (source data from Bray et al., 2004).

simplified method established by the Japan Road Association (1980). On the basis of field observations at liquefaction sites in Japan, Iwasaki et al. (1982) concluded that severe liquefaction is very likely at sites with LPI > 15 and that severe liquefaction is very unlikely at sites with LPI < 5. In other words, the liquefaction risk is low if the LPI < 5, and high if the LPI > 15. This criterion with the two threshold values of 5 and 15 is referred to herein as the *Iwasaki criterion*.

Toprak and Holzer (2003) computed LPI values from cone penetration test (CPT) at sites with surface manifestations of liquefaction during the 1989 Loma Prieta, California, earthquake. In their calculations, they used the same formulation of LPI as defined by Iwasaki et al. (1982) except that factor of safety (F_S) was calculated using the CPT-based method by Robertson and Wride (1998), which employs the simplified procedure pioneered by Seed and Idriss (1971, 1982). Toprak and Holzer (2003) reported that sand boils typically occurred at soundings where the LPI ≥ 5, and that lateral spreads typically occurred where the LPI ≥ 12. They emphasized that these threshold values are *median* LPI values, and the lower and upper *quartiles* were 3 and 10 for sand boils, and 5 and 17 for lateral spreads, respectively (Fig. 2). They suggested that LPI ≥ 5 can be used as a threshold for the surface manifestation of liquefaction, which is consistent with the original suggestion by Iwasaki et al. (1982) and supported by findings of subsequent studies of Holzer et al. (2005, 2006a,b). These studies by Holzer and his co-workers, made possible by the enormous efforts by the U.S. Geological Survey in collecting *in situ* data at liquefaction and no-liquefaction sites in recent earthquakes, represent an important milestone of LPI calibration. These studies showcase the advantages of using LPI in the regional mapping of liquefaction hazards.

In a recent comprehensive study, Lenz and Baise (2007) computed LPI values for geologic units across the East Bay of the San Francisco California Bay Area using both CPT and SPT data sets. They found that CPT-based LPI characterization results in higher hazard in the same study area than those derived from the SPT. They suggested that the bias could be caused by either misclassification of soil type in the CPT or a bias in the CPT-based simplified procedure for liquefaction potential. They attributed the latter to the finding by Juang et al. (2002) that soils with an equal F_S value, determined with different simplified methods, may not have the same liquefaction potential due to the different degrees of model bias associated with these methods. Another important finding of the Lenz and Baise study (2007) is that the CPT-based LPI values have a much higher degree of *spatial correlation* and a lower variance over a greater distance than those estimated from SPTs (Fig. 3). Thus, they determined that only CPT-based LPI values allowed for direct interpolation between data through ordinary kriging; the SPI-based LPI values showed no spatial correlation and kriging was not possible. They concluded that CPT is a more reliable and consistent measure of liquefaction potential. This is perhaps the first time direct evidence is presented that showcases the advantage of using the CPT over the SPT in the LPI framework.

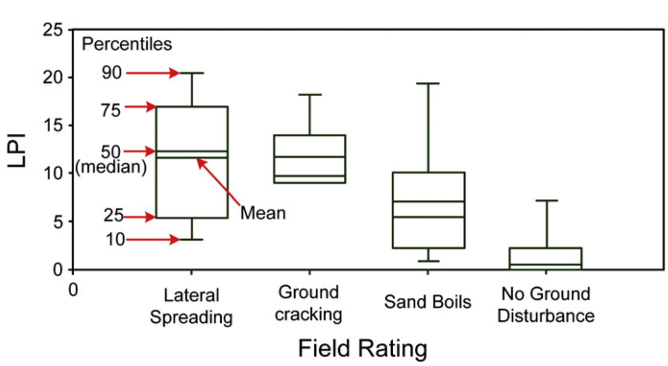

Fig. 2. Correlation of LPI values with surface effects for the 1989 Loma Prieta Earthquake (reproduced from Toprak and Holzer, 2003 with permission from American Society of Civil Engineers).

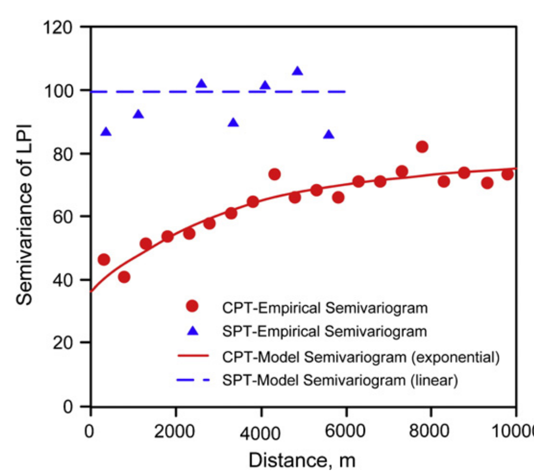

Fig. 3. Empirical semivariograms of LPI for CPT and SPT (Reproduced from Lenz and Baise, 2007 with permission from Elsevier Ltd.).