# Prediction methods of earthquake-induced liquefaction surface manifestations

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ABSTRACT: The Liquefaction Potential Index (LPI) is an index which summarizes the liquefaction potential of a geotechnical profile. This index is proportional to the thickness, the depth of the liquefiable layer and the factor of safety while its value at a specific site can be incorporated into a geographic information system, providing liquefaction hazard maps. The main purpose of this work is to estimate the probability of liquefaction surface manifestations based on the LPI values using the logistic regression procedure. Furthermore, the discriminant function analysis is used in order to classify geotechnical profiles in one of the two groups (occurrence or no occurrence of liquefaction) based on LPI values and the thickness H (m) of the upper non-liquefied (cap) soil layer. The high percentage of the correctly classified cases both for the original grouped and cross-validated ones indicate how well the model predicts the liquefaction surface manifestations.

*KEYWORDS : Liquefaction surface manifestation, Logistic regression, Discriminant analysis*

## 1. Introduction

Liquefaction is one of the most important topics in seismic hazard analysis and risk mapping. Soil liquefaction can lead to ground deformation, such as sand boils and lateral movement, and/or to structural damages, like settlement and bearing capacity failure of buildings, waterfront structures and bridge failures. In order to evaluate the liquefaction potential of a soil layer, scientists use mainly in situ tests and procedures as the deterministic "simplified" one, proposed by Seed and Idriss (1971). With this widely used SPT-based method, which has been updated by Seed et al. (1985) and by Youd and Idriss (2001), researchers can estimate the factor of safety against liquefaction, fs, per each soil layer. If fs>1 then the soil is classified as non-potentially to liquefaction, while for fs<1 the soil is classified as liquefiable. Although this SPT-based method can estimate the behaviour of a soil layer, can not evaluate adequately the appearance of liquefaction surface effects. Therefore, Iwasaki et al. (1982), in order to predict the occurrence of liquefaction, proposed the use of Liquefaction Potential Index and its severity scale. Recently, Sonmez (2003) modified the Liquefaction Potential Index by adopting a threshold value of fs equal to 1.2 instead of 1 as the lowest value for non-liquefiable soil and by introducing two new categories of "non-liquefiable" and "moderate". The advantage of the LPI is that can be used in combination with geographic information systems (GIS), compiling liquefaction hazard maps (Toprak and Holzer, 2003).
However, until now the correlation between LPI and the probability of liquefaction – induced ground deformation was not being examined systematically. Toprak and Holzer (2003) attempted to relate these two parameters, using CPT soundings. In their work, they adopted the criteria proposed by Wang (1979), in order to define the susceptibility to liquefaction of the soil layers. However, recent data (Seed at al., 2003), provided by post-earthquake in situ tests at liquefied sites triggered by the last two devastating earthquakes of Kocaeli and Taiwan in 1999, indicate that the "modified Chinese criteria" and the liquefaction

susceptibility criteria proposed by Andrews and Martin (2000) are considered at least as conservative. Seed et al. (2003) concluded that the plasticity behaviour of fine size particles of soils is more important than the percent clay size and proposed new potentially susceptible to liquefaction zones within the Casagrande diagram.

Based on these recommendations, we reassessed the LPI values of collected SPT in situ tests in historical liquefaction sites in Japan and computed the liquefaction potential index of new in-situ tests conducted in liquefied and non – liquefied sites in Taiwan and Turkey. These values were correlated with the description of the surface effects in order to estimate the regression between the probability of liquefaction surface disruption and the LPI.

## 2. Database

In this study, SPT profiles have been collected by published databases referred to different earthquakes and their secondary effects such as soil liquefaction. Analytically, our database contains 30 SPT profiles from liquefied sites and 15 profiles from non-liquefied sites that were triggered by 5 past earthquakes in Japan, published by Iwasaki (1986). 6 SPT borings concerning sites where liquefaction occurred and 5 SPT borings without any liquefaction evidence, respectively, were obtained by the report of Boulanger et al. (1995) for the liquefaction–induced surface deformations at the Moss Landing during the 1989 Loma Prieta earthquake and 14 SPT logs by the field case history database published by Moss (2003). In what concerns the last two devastating earthquakes at Turkey and Taiwan in 1999, the majority of the SPT data were downloaded from the internet.

Data concerning in-situ tests at liquefied sites (24 cases) triggered by the Kocaelli (Turkey) earthquake were downloaded from the website of http://peer.berkeley.edu/turkey/adapazari/phase1/index.html, while data from 58 logs concerning the Chi-Chi (Taiwan) earthquake, 49 liquefaction and 9 non-liquefaction cases, were downloaded from http://peer.berkeley.edu/lifelines/research_projects/3A02/. Finally, 12 SPT profiles are refered to Lefkada island, Greece, earthquake in 2003 published by the KEDE (2004).

Tab. 1. List of selected SPT profiles

| Earthquake | SPT profiles in liquefied sites | SPT profiles in non-liquefied sites | Total number of SPT profiles |
|---|---|---|---|
| Miyagi-ken-oki | 8 | 11 | 19 |
| Tokachi-oko | 2 | - | 2 |
| Niigata | 18 | 4 | 22 |
| Tonankai | 1 | - | 1 |
| Nobi | 1 | - | 1 |
| Loma Prieta | 20 | 5 | 25 |
| Kocaelli | 24 | - | 24 |
| Chi-Chi | 49 | 9 | 58 |
| Lefkada | 9 | 3 | 12 |

These 164 SPT logs were grouped into 3 categories based on the level of information available:

1. In category A, were classified the data that provide complete SPT profile to a depth of 20 meters and complete information about the grain size characteristics of the soil layers.
2. In category B, the data without any information for SPT values below 15 meters.
3. In category C, the data that provide complete SPT profile to a depth of 20 meters and incomplete information about the grading characteristics of the soil layers throughout profile.

In category A, are grouped 49 “liquefaction-occurrence” data concerning the earthquake of Chi-Chi, Taiwan and 9 SPT logs refereeing to the Lefkada, Greece shock. The soil borings with SPT that were performed in Taiwan had a typically 1.0 m spacing and concerning locations where lateral spreading, settled buildings or sand boils were reported and locations without evidence of liquefaction. In addition, the retrieved soil samples were subjected to laboratory index tests per ASTM standards including sieve, hydrometer, liquid limit, plastic limit, density and water content. The 9 SPT profiles, concerning the 2003 Lefkada earthquake, Greece, were drilled mainly in the municipality of the island and provide information about the grading characteristics of the soils and their Atterberg limit values.

Although the data from Kocaelli earthquake, Turkey, provide sufficient information about the grading characteristics of the soils, they are grouped in category B since they do not provide SPT data below 15 m. In the same category, B, are classified the data from Loma Prieta earthquake, USA for the same reason. The SPT profiles of this category B were not taking into account to the final statistical analysis since their LPI values were not computed until the depth of 20 m.

In category C, are classified 30 SPT data from “liquefaction-occurrence” sites in Japan, published by Iwasaki (1986), which provide information only for the water depth, the SPT value and the measured value of $D_{50}$, while the SPT profiles were ended at 20 m. In order to examine the liquefaction susceptibility of the layers in the cases of category C, we adopted the USCS soil type for the fines contents and the unit weight.

The total number of “non-evidence of liquefaction” data is 32. Analytically, 15 of them concern the occurred earthquakes in Japan, 5 data are refereed to Loma Prieta, USA, event, while 9 SPT data were drilled after the chi-chi, Taiwan, earthquake. Finally, 3 of these data are refereed to Lefkada earthquake. We grouped the “non-occurrence of liquefaction” data, including them in every statistical approach as a subgroup of category A or C, respectively, in order to avoid the data imbalance and to achieve a better statistical sample,

## 3. Liquefaction analysis procedure

After this classification, we evaluated the potential of liquefaction based on the deterministic procedure, most known as the “simplified procedure”, proposed by Seed and Idriss (1971). This procedure, which was modified by Seed et al. (1985), proposed the calculation of the factor of safety against liquefaction, fs, as the ratio of CRR (cyclic resistance ratio) to the CSR (cyclic stress ratio). The CRR, according to Youd and Idriss (2001) is approximated with the following equation:

$$CRR_{7.5} = \frac{1}{34 - N_{1(60)}} + \frac{N_{1(60)}}{135} + \frac{50}{\left[10 \times N_{1(60)} + 45\right]^2} - \frac{1}{200} \qquad (1)$$

The calculation of $N_{1(60)}$ is influenced also by the measured standard penetration resistance N, the overburden pressure factor Cn, the correction for hammer energy ratio (ER) Ce, the correction for borehole diameter, Cb the correction factor for rod length Cr and the correction for samplers with or without liners. The Cn was calculated according to the equation proposed by Liao and Whitman (1986), $Cn=(Pa/\sigma_{vo})^{0.5}$, while the others factors were estimated using the parameters suggested by Youd and Idriss (2001). Afterwards, a “fine content” correction was applied to the calculated $N_{1(60)}$ value in order to obtain an equivalent clean sand value $N_{160cs}$ given by the equations proposed by Youd and Idriss (2001).

The CSR defines the seismic demand and is expressed as:

$$CSR = 0.65 \times \left(\frac{a_{\max}}{g}\right) \times \left(\frac{\sigma_{vo}}{\sigma'_{vo}}\right) \times r_d \qquad (2)$$

Where $\sigma_{vo}$=total vertical stress at depth z, $\sigma'_{vo}$=effective vertical stress at the same depth, $a_{max}$=peak horizontal ground acceleration, g=acceleration due to gravity and $r_d$=stress reduction factor. In this study the term rd was estimated using the Liao and Whitman (1986) equation:

$$r_d = 1 - 0.00765 \times z \quad \text{for } z \leq 9.15 \text{ m} \tag{3}$$

$$r_d = 1.174 - 0.0267 \times z \quad \text{for } 9.15 \text{ m} < z \leq 23 \text{ m} \tag{4}$$

Finally, the CSR value have been divided by the magnitude scaling factor, MSF, which can be calculated by the following equation, Youd and Idriss (2001):

$$MSF = \left( \frac{Mw}{7.5} \right)^{2.56} \tag{5}$$

In our liquefaction analysis, we adopted the value of 1.2 as the lowest value of factor of safety characterized a non-liquefiable soil layer (Sonmez, 2003). Afterwards, we applied to the soil elements with fs <1.2 the liquefaction susceptibility criteria suggested by Seed et al. (2003).

### 3.1. Liquefaction potential index

The LPI was defined by Iwasaki (1982) as:

$$LPI = \int_0^z F(z) W(z) dz \tag{6}$$

Where z is the depth below the ground surface in meters and is calculated as w(z)=10-0.5z; F(z) is a function of the factor of safety against liquefaction, Fs, where F(z) =1-Fs when Fs<1 and if Fs>1 than F(z)=0. Sonmez (2003) modified the LPI by adding a threshold value of 1.2 instead of 1, of the factor of safety. Hence, when Fs<0.95, $F(z)=2 \cdot 10^6 e^{-18.427Fs}$ if 0.95<Fs<1.2 and if Fs>1.2, F(z)=0. Equation (6) gives the values of LPI ranging from 0 to 100. In our assessment of the LPI per each borehole, we took into consideration all the soil layers with factor of safety less than 1.2, which satisfied also the liquefaction susceptibility criteria suggested by Seed et al. (2003).

## 4. Using the LPI to predict a liquefaction surface disruption

In order to predict and estimate the probability of the earthquake-induced liquefaction surface disruption, the classified data in category A and C were both analysed using the discriminant analysis and the logistic regression model respectively. Due to the fact that, the SPT profiles of category a are more reliable and accurate from the data that were classified in category c, as it was mentioned above, only the results that were estimated based on the proceeding of these data are going to be presented.

### 4.1. Logistic regression

The logistic regression procedure was adopted as the probabilistic method for calculating the predicted probability of liquefaction occurrence. This method, which is a variation of ordinary regression, is useful when the observed outcome is restricted to two values that usually represent the occurrence or non-occurrence of some outcome event, usually coded as 1 or 0, respectively (Norusis, 2003). It produces a formula that predicts the probability of the occurrence as a function of the independent variables. Logistic regression fits a special s-shaped curve by taking the linear regression, which could produce any *y*-value between minus infinity and plus infinity, and transforming it with the function:

$$p = \left( \frac{1}{1 + e^{-(y)}} \right) \tag{7}$$

which produces *p*-values between 0 (as *y* approaches minus infinity) and 1 (as *y* approaches plus infinity). The data that were used in this work for the estimation of the predicted probability were classified into two categories: i) “non-occurrence of liquefaction”, labeled as 0, and ii) “occurrence” coded as 1, while the categories based on the level of information available are still valid.

The proposed, by this study, equation that can be used in order to estimate the predicted probability of liquefaction surface manifestation, using the logistic regression procedure, is:

$$p = \left( \frac{1}{1 + e^{-(-1.367 + 0.196 \times LPI)}} \right) \tag{8}$$

where LPI is the Liquefaction Potential Index of the borehole. According to this approach, for a given LPI value of 14 the predicted probability of liquefaction occurrence is 79%. The S-shaped logistic curve for different values of y is plotted in figure 1.

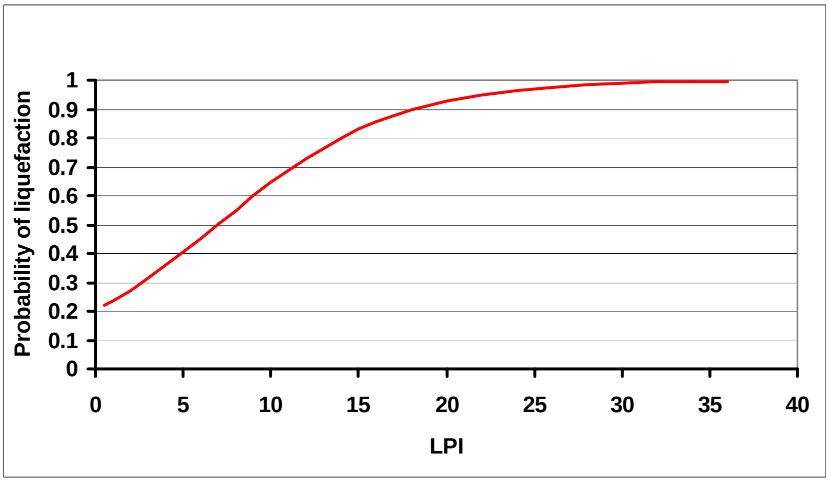

Fig. 1. Plot of logistic regression curve

### 4.2. Discriminant analysis

One of the purposes of this study was to provide a discriminant prediction equation in order to classify a soil column in one of the two categories of occurrence or no occurrence of liquefaction. In order to accomplish this equation, the LPI and the thickness (H) of the cap layer per each SPT profile, listed in table 1, were computed according to the suggestions of Sonmez (2003) and Ishihara (1985) respectively. Ishihara (1985) introduced for the first time the parameter of the thickness of the overlying nonliquefiable layer in the assessment of the potential of the liquefaction surface manifestations.

Tab. 2. Classification results

| | | Group | Predicted group | | Total |
|---|---|---|---|---|---|
| | | | no | Yes | |
| Original | Count | No | 24 | 3.0 | 27.0 |
| | | yes | 16 | 45.0 | 61.0 |
| | % | no | 88.9 | 11.1 | 100.0 |
| | | yes | 26.2 | 73.78 | 100.0 |

The table above is used to assess the performance of discriminant analysis. In our case it correctly classifies about 81.4% of the cases, thus can be considered that the classification works well. The proposed classification equation based on the unstandarized discriminant function coefficients, which can be used to classify new cases is:

$$Z = -0.464 + 0.098 \times LPI - 0.350 \times H \qquad (9)$$

where Z is the discriminant score. For Z>0 and Z<0, the case (SPT profile) is classified in the group of occurrence and no occurrence of liquefaction respectively.

## 5. Conclusions

Empirical relationships that can predict the surface occurrence of liquefaction and estimate the predicted probability of these manifestations are proposed by this study. These two suggested methods are based on the discriminant function analysis and the logistic regression method, using the Liquefaction Potential Index and the thickness of the overlying nonliquefiable layer (cap layer) of SPT profiles. Based on these values of probability, liquefaction hazard maps can be compiled.

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