Simplified procedure for LPI assessment using shear wave velocity

Procédure simplifiée pour l'évaluation LPI à l'aide de la vitesse d'onde de cisaillement

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ABSTRACT: To estimate the liquefaction potential for a wide area, a simplified procedure for liquefaction potential index (LPI) assessment using the shear wave velocity was proposed based on the preconstructed geotechnical database. The shear wave velocity, a key factor in evaluating the seismic sensitivity of the ground, was obtained through the empirical correlations using the SPT-N values, which are easily extracted from the geotechnical database. Considering the fact that the LPI is affected by the liquefiable layer thickness when the non-liquefiable layer effect is negligible and the average SPT-N value is the same, the correlation between the average V_s value of the liquefiable layer and the normalized LPI with thickness was analyzed. The relationship between the average V_s value of the liquefiable layer and the normalized LPI with thickness was analyzed for various earthquake accelerations to derive a single correlation equation. The developed correlation was applied to the average V_s calculation for the entire dataset so that a liquefaction hazard map with the LPI for Seoul, South Korea could be obtained.

RÉSUMÉ: Pour estimer le potentiel de liquéfaction pour une zone étendue, une procédure simplifiée pour l'évaluation de l'indice de potentiel de liquéfaction (LPI) à l'aide de la vitesse d'onde de cisaillement a été proposée sur la base des bases de données géotechniques préconstruites. La vitesse d'onde de cisaillement, un facteur clé dans l'évaluation de la sensibilité sismique du sol, a été obtenue par les corrélations empiriques utilisant les valeurs de SPT-N, qui sont facilement extraites des bases de données géotechniques. Compte tenu du fait que le LPI soit affecté par l'épaisseur de couche liquéfiable lorsque l'effet de couche non liquéfiable est négligeable et que la valeur moyenne de SPT-N est la même, la corrélation entre la valeur Vs moyenne de la couche liquéfiable et l'indice LPI normalisé avec épaisseur a été analysée. La relation entre la valeur Vs moyenne de la couche liquéfiable et l'indice LPI normalisé avec l'épaisseur a été analysée pour diverses accélérations sismiques pour obtenir une seule équation de corrélation. La corrélation développée a été appliquée au calcul des Vs moyennes pour l'ensemble des données afin de pouvoir obtenir une carte des risques de liquéfaction avec le LPI de Séoul, en Corée du Sud.

KEYWORDS: LPI, shear wave velocity, SPT-N value

1. INTRODUCTION

Since recently, damages due to earthquakes have been frequently reported (Japan [M9.0, 2011], Chile [M8.3, 2015], and Nepal [M7.9, 2015]). Earthquake researches have been increasing in South Korea since the record-breaking Gyeongju earthquake (M5.8, 2016). Based on the history of earthquakes, the Korean Peninsula belongs to a region of moderate seismicity. Although South Korea is considered a relatively earthquake-free country, it is necessary to assess the liquefaction sensitivity of urban areas in advance considering the unpredictability of earthquakes and the fact that majority of the human and social-infra resources are concentrated in the downtown areas.

The liquefaction potential index (LPI) was developed by Iwasaki et al. (1978) to assess the potential of liquefaction. Thereafter, it has been widely used by several researchers to predict the potential for liquefaction damage (Sommez, 2003; Chung & Rogers, 2011; Dixit et al., 2012). The application of LPI to a wide target area, however, can be limited due to the shortages in geotechnical borehole information, which is indispensably required for site response analysis and for estimating the seismic sensitivity of the ground for liquefaction potential evaluation.

A database containing spatial information for more than 20,000 site investigations has been constructed in the integrated DB center of national geotechnical information for Seoul, South Korea. Kim and Chung (2016) developed a system for assessing LPI in real time based on the results of pre-performed ground response analyses with the borehole database and online-transmitted seismic-monitored data. It takes a great deal of time and effort, however, to apply it to large sites with very large borehole data because it is necessary to perform ground response analysis for all the boreholes. In this study, a simple method for evaluating the LPI using the shear wave velocity, a key factor in evaluating the seismic sensitivity of the ground, was developed without performing ground response analysis. By analyzing and setting the correlation between LPI and the shear wave velocity, which can be easily determined based on the borehole data, it was determined that the developed method can be effectively applied to a wide area.

2. SIMPLIFIED METHOD FOR LIQUEFACTION POTENTIAL EVALUATION

2.1 Shear Wave Velocity and LPI

The shear wave velocity, a basic mechanical property of soil materials, can be obtained through laboratory tests, field tests, and empirical correlations using SPT-N values. To evaluate the shear wave velocity, SPT-N values that can be easily extracted from the pre-established database were used. The correlation of

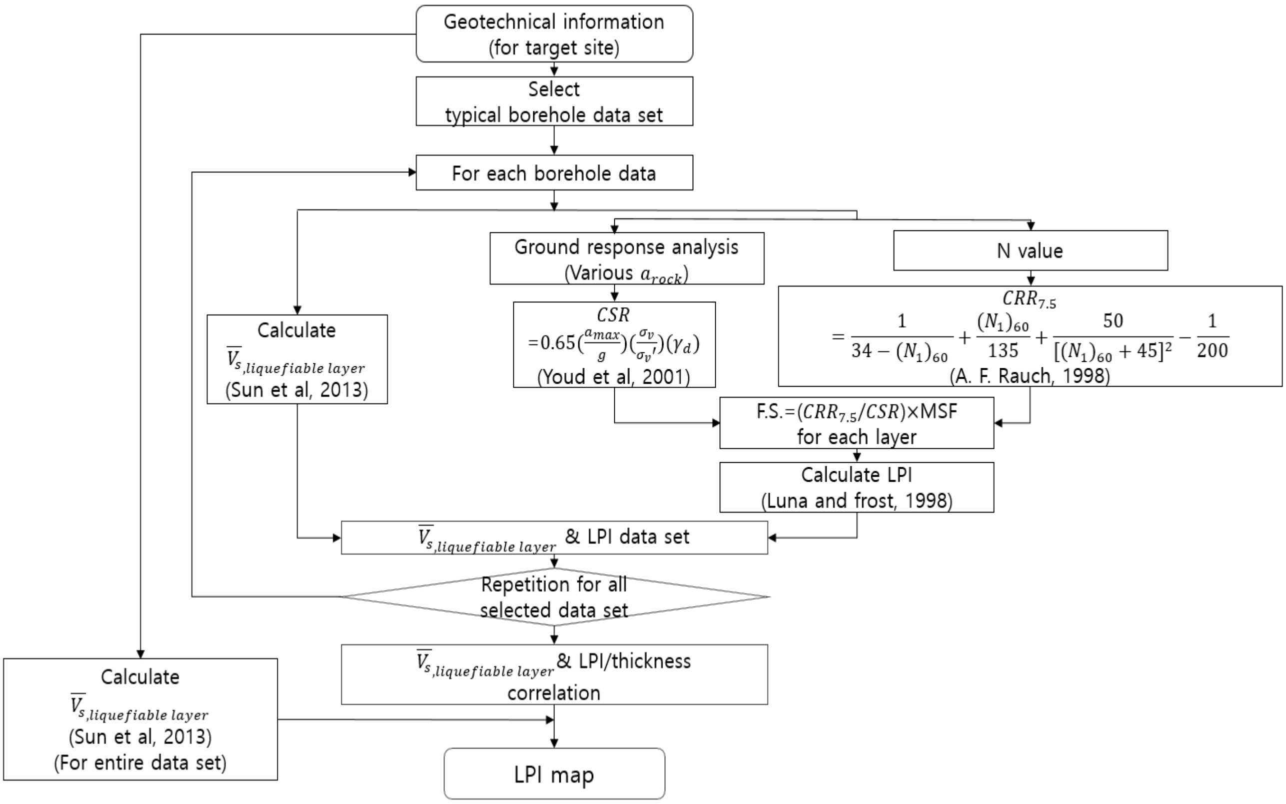

Figure 1. Suggested flowchart for the simplified LPI assessment procedure.

the shear wave velocity and the measured SPT-N values for all the soils in South Korea (Sun et al., 2013) was employed, as presented in Table 1.

Table 1. Correlation between the shear wave velocity and the measured SPT-N values in South Korea (Sun et al., 2013)

Geology	Soil type	Correlation
Alluvial soil	Gravel	$V_s=78.63N^{0.361}$
	Sand and silt	$V_s=82.01N^{0.319}$
Weathered residual soil	Sand	$V_s=75.76N^{0.371}$
Weathered rock	Sand	$V_s=107.94N^{0.418}$
All soils		$V_s=65.64N^{0.407}$

LPI is determined by the factors of safety of the liquefiable layer within the depth of 20 m. To increase the correlation with LPI, the average V_s ($\overline{V_s}$) value of the liquefiable layer was obtained. The liquefiable layer depends on several factors, such as the SPT-N values, fine content, plasticity index, depth from the surface, and groundwater level. The details of the conditions of liquefiable soils are in the earthquake resistance design regulations for subway structures (Ministry of Land, Infrastructure, and Transport in Korea, 2009). In the preliminary study, it was confirmed that the existence of a non-liquefiable layer beneath the liquefiable layer did not noticeably affect the LPI estimation. The average V_s value can be determined using the following equation:

$$\overline{V_s} = \sum_{i=1}^{n} V_{si} H_i / H_i \quad (1)$$

where n denotes the number of discretized layers, V_{si} the shear wave velocity for layer i, and H_i the thickness of the discretized layers.

Meanwhile LPI can be evaluated by:

$$LPI = \sum_{i=1}^{n} F_i(z) W_i(z) H_i \quad (2)$$

where F_i denotes the liquefaction severity, which is a function of the factors of safety for liquefaction (F_i=1-FS for FS<1.0; F_i=0 for FS>1.0); W_i is the weighting function; and W(z)=10-0.5z, for layer i.

A series of site response analyses was performed for various rock outcrop accelerations (0.11, 0.15, 0.22, and 0.28 g: National Emergency Management Agency, 2013) using Proshake, and the CSR and CRR values were calculated according to the domestic seismic design criteria, using the analytical results and SPT-N values, respectively. After that, the factors of safety for liquefaction by depth were obtained from the ratio of CSR and CRR. In this study, the method developed by Luna and Frost (1998), a suitable LPI calculation method for applying discontinuous data like SPT, was used to evaluate LPI.

2.2 Correlation between $\overline{V_s}$ and LPI

The flowchart for the simplified LPI assessment procedure suggested in this study is shown in Figure 1. A typical borehole dataset is selected from the geotechnical database for the target site. For each borehole data, the $\overline{V_s}$ of the liquefiable layer is calculated with SPT-N value and the thickness of each soil layer based on the correlation between the SPT-N value and V_s (Sun et al., 2013). Meanwhile, the cyclic stress ratio (CSR) of each layer is computed based on maximum acceleration value obtained from ground response analysis, and the cyclic resistance ratio (CRR) is computed with SPT-N value. The ground information, such as the SPT-N value and the soil layer thickness by the depth of the target ground, obtained from the database of Seoul, South Korea was utilized. For a conservative design, the analysis was performed assuming that the groundwater level is rising up to the ground surface. Resultantly, the LPI is computed from the factors of safety (CRR/CSR) for each layer. Also, to assess the effect of earthquake intensity, a series of site response analyses is performed, changing the rock outcrop accelerations and the correlation between $\overline{V_S}$ and LPI can be obtained according to the various rock outcrop accelerations. The LPI value was expressed as a form normalized by the thickness of the liquefiable layer to take into account the effect of increasing the liquefaction potential as the liquefiable layer becomes thicker, even for a similar $\overline{V_S}$ value. The preliminary study confirmed that even with the same average SPT-N value, the LPI increases with the thickness of the layer, and when the LPI is normalized to the layer thickness, the difference can be negligible. Finally, the $\overline{V_S}$ for the liquefiable layer and the normalized LPI with thickness correlation can be obtained. Applying the correlation to the entire dataset, a liquefaction hazard map with LPI for the target site can be obtained.

3. RESULTS AND DISCUSSION

The distribution of the $\overline{V_S}$ values of the liquefiable layer, which was evaluated based on 20,803 geotechnical investigation data in Seoul, is shown in Figure 2. A total of 104 boreholes were extracted randomly according to the distribution ratio of $\overline{V_S}$. The distribution of the average Vs ($\overline{V_S}$) for the selected boreholes is also shown in Figure 2.

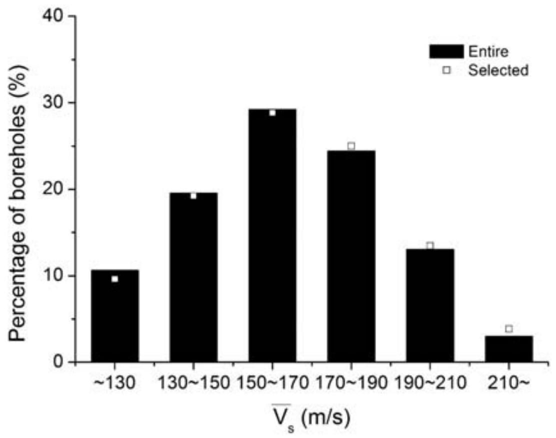

Figure 2. Distribution of the average V_s for the liquefiable layers in Seoul, South Korea.

Following the suggested flowchart in Figure 1, the correlations between $\overline{V_S}$ and the normalized LPI with thickness can be obtained. The correlations are best considered a form of linear equation and are grouped according to the rock outcrop accelerations, as presented in Figure 3 and equation (3).

$$LPI/thickness=A^* (\overline{V_S}) +B, \quad (3)$$

where *A* and *B* are the coefficients of the equation.

Figure 4 and 5 show the relationships between the coefficients, A and B, and the rock outcrop accelerations, respectively. Coefficient A is assumed to be the constant because the deviation according to the rock outcrop acceleration is small, as shown in Figure 4. On the other hand, coefficient B and the rock outcrop acceleration correlation is the best-fitted form of quadratic function, as shown in Figure 5. Based on the results of the regressions for the coefficients, as in Figure 4 and 5, a single correlation between the normalized LPI with thickness and $\overline{V_S}$ according to the various rock outcrop accelerations (a_{rock}) for the ground condition of Seoul can be drawn, as follows:

$$LPI/thickness=-0.046^* (\overline{V_S}) + (-167.4^*a_{rock}^2+85.9^* a_{rock}+0.4) \quad (4)$$

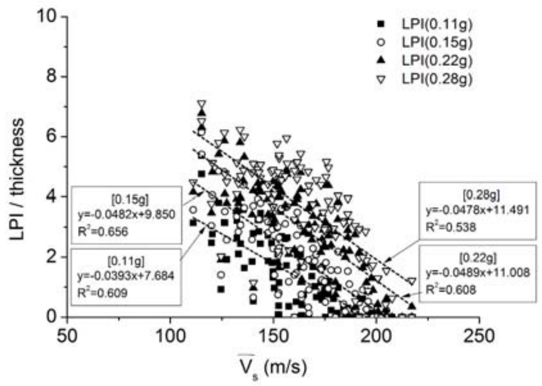

Figure 3. Correlation between the average V_s and the LPI/thickness.

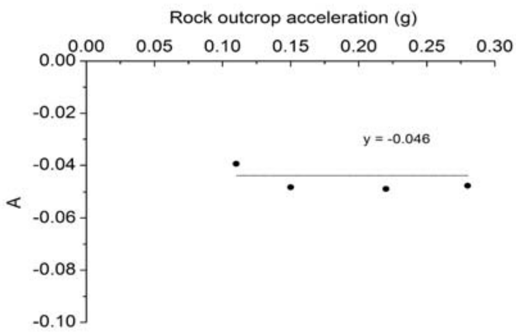

Figure 4. Correlation between a_{rock} and coefficient A.

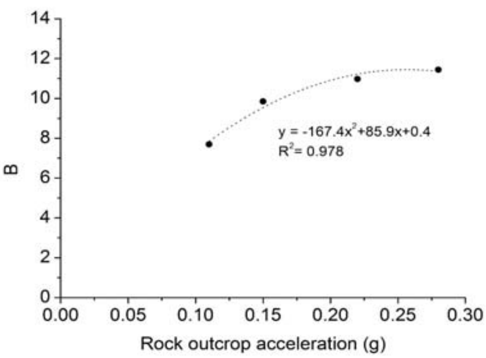

Figure 5. Correlation between a_{rock} and coefficient B.

Figure 6 compares the LPI obtained from the proposed correlation ($LPI_{(corr)}$) and that obtained from the site response analyses ($LPI_{(sra)}$) for a total of 170 data. The highest peak ground acceleration of 0.15 g, which was the seismic record of the Gyeongju earthquake (M6.5, 2016) event, was applied. In the case of the evaluation of the LPI using the proposed correlation, the results are slightly less (4%) than those of the LPI evaluation with site response analysis.

The higher the LPI is, the greater the potential for liquefaction. Iwasaki et al. (1978, 1982) found that severe liquefaction is likely to occur whenever the LPI is greater than

15, and that minor liquefaction is likely to occur whenever the LPI is less than 5. After Iwasaki et al. (1978, 1982), several researchers proposed and modified the categories of liquefaction severity. Typically, Chung et al. (2011) proposed that the liquefaction severity is none for LPI=0, little to none for 0<LPI<5, moderate for 5≤LPI<15, and severe for LPI≥15. Following Chung et al. (2011), the LPI ranges were denoted in Figure 6. The accuracy of the LPI range evaluation is 83%. Minor deviations (indicated by an ellipse) were observed, where the deeper the layer is, the softer it also is. To improve the prediction accuracy, this should be considered in the further study.

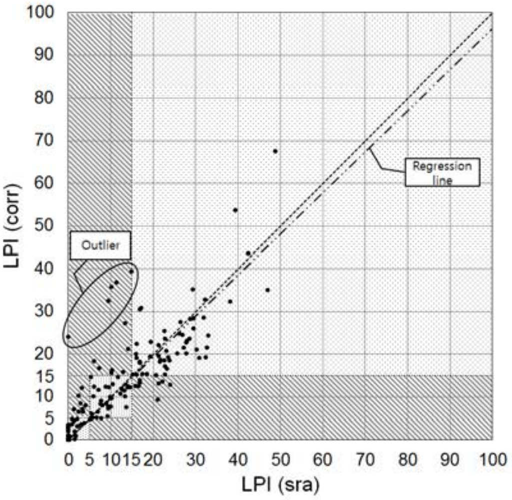

Figure 6. Comparison of LPI(sra) and LPI(corr).

The correlations were applied to each borehole in Seoul to visualize the results of the assessment of the liquefaction potential, so that a liquefaction hazard map with LPI was obtained (Figure 7). As the groundwater level is assumed to rise up to the ground surface, the result tends to be risky. Most of the areas in Seoul are not sensitive to earthquakes because they are composed of rock, weathered rock, and very stiff soil, but partial areas made up of deep and soft soils are sensitive to earthquakes. When the groundwater level is lowered by 1 m, the LPI value is lowered by 10, and when the groundwater level is lowered by 2 m, the LPI value is lowered by 15. Using the method presented in this study can enable seismic hazard (liquefaction) prediction with only the borehole data with SPT-N values. These results also can be used to predict local effects of earthquake damage.

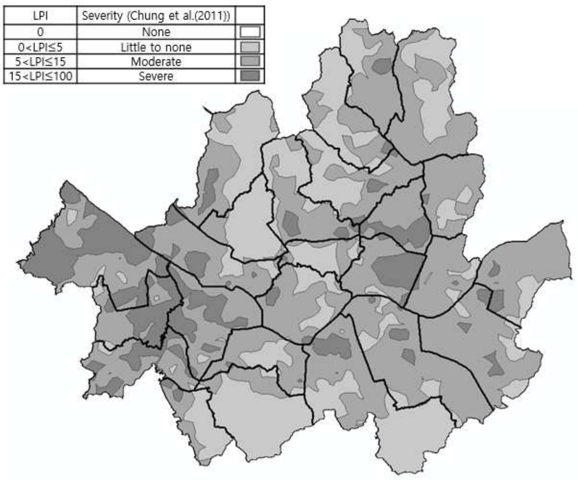

Figure 7. LPI map of Seoul, South Korea for 0.15 g.

4. SUMMARY AND CONCLUSIONS

This paper presents a simple method for evaluating the liquefaction potential index (LPI) with simple borehole data. Considering the fact that the LPI is affected by the liquefiable layer, the methodology to establish the correlation between the average V_s value of the liquefiable layer and the normalized LPI with thickness was proposed. The developed correlation was applied to Seoul, South Korea for 0.15 g (a_{rock}) and it proved that the proposed method can enable seismic hazard (liquefaction) prediction with only the borehole data with SPT-N values.

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