Statistically determining liquefaction potential index (LPI)-based liquefaction potential classification for the practice in Taiwan

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ABSTRACT: In geotechnical earthquake engineering, the liquefaction potential index (LPI) proposed by Iwasaki et al. (1982) is commonly adopted to quantify the severity of ground manifestation or the damage to low-rise buildings due to soil liquefaction. Iwasaki et al. (1982) also recommended an LPI-based classification for assessing liquefaction risks, which is prevalent in seismic design and liquefaction hazard map generation in Taiwan; however, this classification was derived from the Japan case histories along with the Japanese Road Bridge Design Code calculation procedure, such that its consistency to Taiwan sites and assessing methods in Taiwan seismic design codes remains unknown. To examine its consistency to Taiwan sites and determine the classification for the practice in Taiwan, this paper exploits the liquefied and non-liquefied case histories of the 1999 Chi-Chi earthquake and those of the 2016 Meinong earthquake in Taiwan to evaluate their LPI values by 4 SPT-based simplified methods which are suggested in Taiwan seismic design codes for the ordinary buildings and statistically characterizes the distributions of those LPI values. The characterization results are compared with the classification suggested by Iwasaki et al. (1982), and utilized to determine a new LPI-based liquefaction potential classification, which is believed as a reference for seismic design and liquefaction potential map generation in Taiwan.

1. INTRODUCTION

Assessing the soil liquefaction potential and evaluating the impact on ground manifestation due to soil liquefaction are indispensable for modern seismic engineering design in seismically active countries. For the former, an abundance of approaches have been developed over the past few decades (National Research Council 2016). Among them, it is evident that standard penetration test (SPT)-based methods, which are approaches based on the number of blows of an SPT (SPT-N) and the index properties of split-samples, are popular in engineering practice and have been widely accepted in various seismic design codes for civil structures (e.g., Architectural Institute of Japan (AIJ) 2001; Ministry of Interior (MOI) of Taiwan 2022;

American Association of State Highway and Transportation Officials (AASHTO) 2014; Japan Road Association (JRA) 2017). On the other hand, for quantifying the impacts of liquefaction, the liquefaction potential index (LPI) proposed by Iwasaki et al. (1982, 1984) is commonly adopted and can be calculated as follows:

$$\mathrm{LPI} = \int_0^{20} F(\mathrm{FS}) \cdot (10 - 0.5z)\,dz \tag{1}$$

where z is the depth of soils. F is the function of the anti-liquefaction factor of safety (FS):

$$F(\mathrm{FS}) = \begin{cases} 1 - \mathrm{FS} & \mathrm{FS} < 1 \\ 0 & \mathrm{FS} \geq 1 \end{cases} \tag{2}$$

where FS values can be estimated with SPT data and SPT-based simplified procedure as suggested (Iwasaki et al., 1982, 1984).

In addition to LPI, Iwasaki et al. (1982, 1984) also recommended an LPI-based classification system for liquefaction risk evaluation as follows: $\mathrm{LPI} \leq 5$, liquefaction risk is low; $5 < \mathrm{LPI} \leq 15$, liquefaction risk is high; $\mathrm{LPI} > 15$, liquefaction risk is very high. This classification is derived from cases histories in Japan along with the following observations (Iwasaki et al., 1984):

1. For liquefied sites, the percentage that the LPI value is higher than 15 is about 50%, and for about 20% of those sites the LPI value is less than 5.
2. For non-liquefied sites, most of the LPI values are lower than 15, and the percentage that the LPI value is less than 5 is about 70%.

In other words, Iwasaki et al. (1984) determined the upper bound of low risk of liquefaction with the 20%-quantile of the liquefied cases (Q_{20}^{Liq}) and 70%-quantile of the non-liquefied cases ($Q_{70}^{\mathrm{Non\text{-}liq}}$); the lower bound of very high risk of liquefaction was specified with the 50%-quantile of the liquefied cases in Japan (Q_{50}^{Liq}).

LPI and LPI-based classification system for liquefaction risk evaluation is not only accepted for modern seismic design in Japan but also appearing in the foundation design codes in Taiwan (MOI of Taiwan, 2011) for evaluating the severity of the ground failure and liquefaction hazard map generation. However, the above classification is derived from the Japan case histories along with the Japanese Road Bridge Design Code calculation procedure, such that its consistency with Taiwan sites and assessing methods in Taiwan seismic design codes remains unknown. To determine the classification for the practice in Taiwan, this paper exploits the liquefied and non-liquefied case histories of the 1999 Chi-Chi earthquake and those of the 2016 Meinong earthquake in Taiwan to evaluate their LPI values by 4 SPT-based simplified methods which are suggested in Taiwan seismic design codes for the ordinary buildings and characterizes the distributions of those LPI values. The characterization results are compared with the classification suggested by Iwasaki et al. (1984), and utilized to determine a new LPI-based liquefaction potential classification, which is believed as a reference for seismic design and liquefaction potential map generation in Taiwan.

2. CONSISTENCY OF LPI VALUES OF CASE HISTORIES

This section demonstrates the distribution of the LPI values of liquefied/non-liquefied case histories in Taiwan and examines its consistency with the cases in Iwasaki et al. (1984).

There are 124 SPT soundings for liquefied sites, and 66 for non-liquefied sites exploited in this study. Some of these case histories in this study were investigated at Taichung, Changhwa, and Nantou County in Taiwan after the 1999 Chi-Chi earthquake struck, which is composed of 111 SPT sounding at liquefied sites and 66 at non-liquefied sites. The other was investigated at Tainan City in Taiwan after the 2016 Meinong earthquake, which consists of 13 SPT records at liquefied sites. The detailed information of these case histories and SPT records such as SPT-N values and the index properties of split-samples can be referred to Hwang et al. (2021).

The LPI values of the cases mentioned above are evaluated as Eq. (1), and the corresponding anti-liquefaction factor of safety (FS) values are assessed by SPT-based methods. The methods adopted in this study are proposed by Youd et al. (2001) (denoted as NCEER), Architectural Institute of Japan (2001) (denoted as AIJ), Japan Road Association (1996) (denoted as JRA96), and Hwang et al. (2021) (denoted as HBF) respectively, which are suggested in Taiwan seismic design codes for the ordinary buildings as well.

The histograms and cumulative densities of LPI values evaluated as above are shown in Figure 1 for comparison with Japan case histories in Iwasaki et al. (1984). Figure 1 shows that the cumulative distribution of LPI in Taiwan sites is evidently inconsistent with those in Japan sites collected by Iwasaki et al. (1984), which indicates that the experience learned from Japan case histories is not perfectly suitable for Taiwan sites. Thus, it is inevitable to calibrate a new LPI-based liquefaction risk classification for Taiwan sites based on case histories of liquefaction in Taiwan.

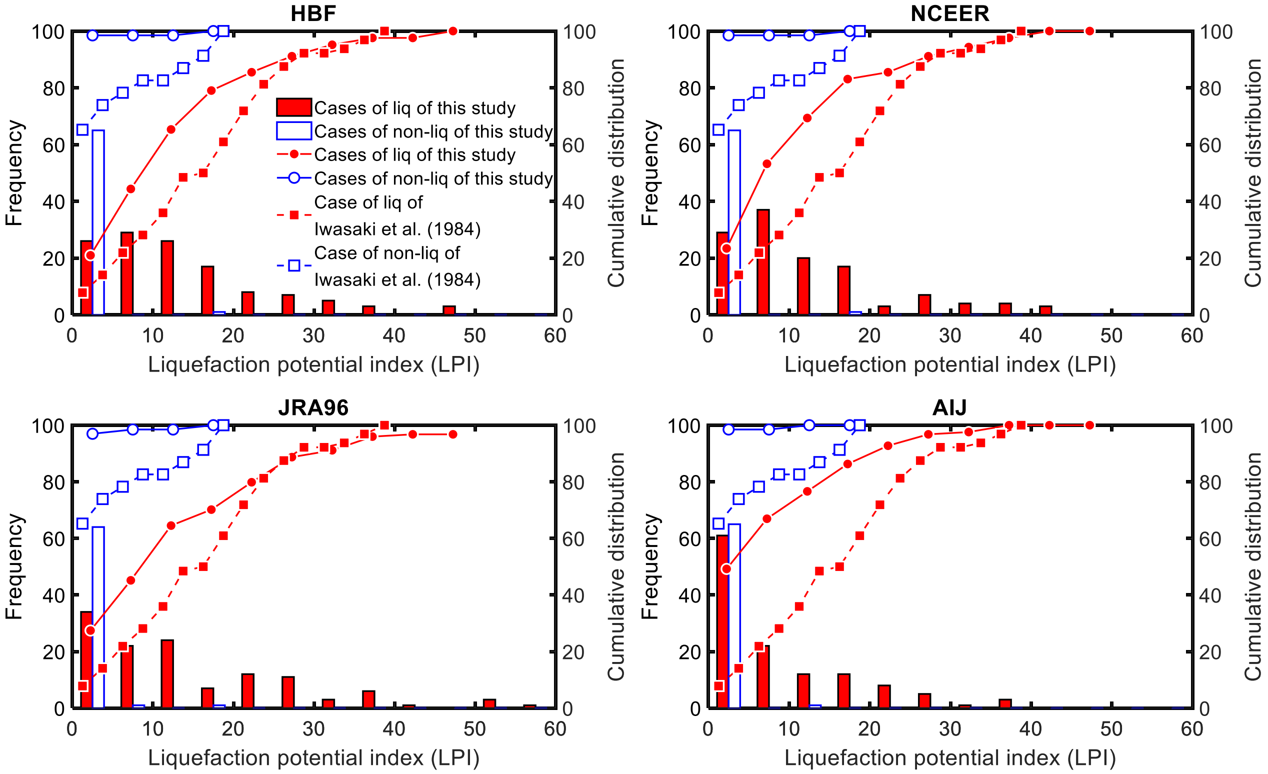

Figure 1 Distribution of LPI values of the liquefied and non-liquefied case histories in Taiwan

3. DETERMINING THE CLASSIFICATION FOR THE PRACTICE IN TAIWAN

The uniqueness of liquefied and non-liquefied sites in Taiwan is found in the above section. To determine the liquefaction risk classification for Taiwan sites, this section characterizes the quantiles of the LPI data of Taiwan case histories of liquefaction based on the concept of Iwasaki et al. (1984). Recall their concept to determine the liquefaction risk classification is equivalent to characterizing three quantiles of LPI values of cases histories of liquefaction: Q_{50}^{Liq}, Q_{20}^{Liq}, and $Q_{70}^{Non\text{-}liq}$. Based on this concept and cases of liquefaction from Taiwan, these three quantiles can be characterized and the results are shown in Table 1. Table 1 shows that all the quantiles from Taiwan case histories of liquefaction are lower than those in Iwasaki et al. (1984). In particular, the Q_{50}^{Liq} values by those 4 simplified procedures of interest are significantly lower than 15, the lower bound of very high risk liquefaction recommended by Iwasaki et al. (1984), which suggests that the application of classification by Iwasaki et al. (1984) to sites with very high risks in Taiwan may lead them to be classified as high liquefaction risk sites, and bring to underestimations of liquefaction potential assessments.

For the practice of seismic design in Taiwan, the liquefaction risk classification should depend on the quantile values in Table 1 along with the SPT-based procedure adopted. For instance, when the HBF method (Hwang et al., 2021) is adopted to assess soil liquefaction potential along with evaluating the LPI value, the liquefaction risk should be evaluated as follows: LPI $\leq Q_{20}^{\mathrm{Liq}} = 4.81$, liquefaction risk is low; $4.81 < \mathrm{LPI} \leq Q_{50}^{\mathrm{Liq}} = 11.07$, liquefaction risk is high; LPI > 11.07, liquefaction risk is very high. On the other hand, when the NCEER method (Youd et al., 2001) is performed to assess soil liquefaction potential, the Q_{50}^{Liq} and Q_{20}^{Liq} should be 9.56 and 3.90 to evaluate the liquefaction risks.

Table 1 Quantiles of LPI values of case histories of liquefaction in Taiwan and in Iwasaki et al. (1984)

Method	Q_{50}^{Liq}	Q_{20}^{Liq}	$Q_{70}^{Non\text{-}liq}$
—	15^{a}	5^{a}	5^{a}
HBF	*11.07*	*4.81*	*0*
NCEER	*9.56*	*3.90*	*0*
AIJ	*5.14*	*0.06*	*0*
JRA96	*10.86*	*2.92*	*0*

[a] *Iwasaki et al. (1984)*

4. CONCLUDING REMARKS

This study proposes LPI-based liquefaction risk classifications for the practice in Taiwan by characterizing the quantiles of LPI values of the case histories of liquefaction of the 1999 Chi-Chi earthquake and 2016 Meinong earthquake. The characterization results show the inconsistency of the cumulative distribution of LPI from Taiwan case histories and those from Japan cases. The results also suggest that the application of classification by Iwasaki et al. (1984) to sites in Taiwan may bring the liquefaction risk evaluation to being underestimated; however, it still needs more case histories in Taiwan for further validations.

5. REFERENCES

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