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PERFORMANCE OF HBF METHOD FOR SOIL LIQUEFACTION ASSESSMENT

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ABSTRACT

Soil liquefaction is one of the complex topics in geotechnical engineering, and a variety of liquefaction studies have been reported, including the hyperbolic function (HBF) method for calculating the liquefaction factor of safety. This research aims to assess its performance, quantitatively, in terms of accuracy, recall, precision, *etc.* To achieve the objective, a new soil liquefaction database with the data from published papers was also compiled. Based on a total of 796 soil liquefaction case histories, the study shows that the accuracy of the HBF method is about 92%. In addition, the findings from this research also include: (i) the accuracy of the HBF method is comparable with other well-known methods (also SPT-based) for computing the liquefaction factor of safety; and (ii) the HBF method mainly developed with the data from Taiwan is applicable to other regions, given its accuracy still above 90% based on the data outside Taiwan.

Key words: HBF method, soil liquefaction, model performance.

1. INTRODUCTION

Soil liquefaction is one of the complex research topics in geotechnical engineering, and it caught our "accelerated" attention after the 1964 Niigata earthquake (Japan) that induced many soil liquefactions in the field, subsequently leading to the failures of structural foundations and the floatation of buried structures (Kramer 1996). Afterwards, many soil liquefaction studies have been conducted and reported (Seed *et al.* 1983; Liao *et al.* 1988; Lai *et al.* 2006; Kramer and Mayfield 2007; Cetin *et al.* 2018), including the simplified procedure for soil liquefaction assessment proposed by Seed and Idriss (1971). The method becomes the foundation for several soil liquefaction assessments nowadays, such as the HBF procedure proposed by Hwang *et al.* (2021). Note that the HBF method was developed by the researchers of Taiwan mainly based on the local (Taiwan) liquefaction case histories. More details regarding the simplified procedure and the HBF method are given in following sections.

Among many different soil liquefaction studies, some developed new methods (in relative to the well-known simplified procedure) and used them for soil liquefaction potential assessment. For example, Hanna *et al.* (2007) developed a new GRNN (general regression neural network) model for soil liquefaction assessment, and examined its performance with the case histories associated with two major earthquakes in Turkey and Taiwan; Hu *et al.* (2016) investigated the effect of sampling bias and class imbalance on the prediction capability of the 4 methods (*i.e.,* Bayesian network, artificial neural network, logistic regression and support vector machine) for soil liquefaction assessment; similarly, Zhou *et al.* (2019) developed a so-called stochastic gradient boosting (SGB) approach for liquefaction potential assessment. Nonetheless, it is noted that those studies had different scopes than this present study, mainly focusing on the quantitative performance assessment on the HBF method along with the compilation of a new soil liquefaction database.

Taiwan is located in a region of high seismicity. Averagely speaking, more than 2,000 earthquakes with moment magnitude (M_w) above 3.0 will occur around the region every year, and a major earthquake, such as the 1999 M_w 7.6 Chi-Chi earthquake, would recur in decades (Wang *et al.* 2013). As a result, the sites in Taiwan are more susceptible to soil liquefaction due to the geological background than those situated in low-seismicity regions. In fact, many incidents of soil liquefaction were observed in the field in Taiwan, induced by the 1999 Chi-Chi earthquake and the 2016 Meinong earthquake (Tsai *et al.* 2018, 2020).

As a result, local projects were funded for investigating the liquefaction potential in Taiwan, including those funded by the Central Geological Survey (CGS) of Taiwan. After the investigations were completed, CGS published the liquefaction potential map for Taiwan on their website, on which a "unit" or an area in 100-by-100 m^2 on the map was characterized as *high*, *moderate*, or *low* liquefaction potential (CGS 2023). Besides, a local technical reference was also developed for governing soil liquefaction investigation. In *Seismic Design Specifications and Commentary of Buildings* implemented by Construction and Planning Agency, Ministry of the Interior (MOI), it regulates that the soil liquefaction assessment has to be conducted with one of the following methods commonly used in Taiwan, Japan, and the United States: namely the HBF method, NCEER method, AIJ and JRA methods (MOI 2022). Note that NCEER, AIJ, and JRA are the acronyms of National Center for Earthquake Engineering Research (USA), Architectural Institute of Japan, and Japan Road Association.

Youd *et al.* (2001) summarized the updates and consensuses in two soil liquefaction workshops. The (invited) participants were

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the leading experts in soil liquefaction at that time, including Professor T. L. Youd (Brigham Young University), Professor I. M. Idriss (the University of California at Davis), and Professor R. D. Andrus (Clemson University), among others. One of the consensuses in the workshops was that soil liquefaction assessment procedures developed with the results of in-situ tests (*e.g.,* standard penetration test) were empirical, and for an empirical method, prediction error is inevitable. That is, the model prediction considers the site should not be liquefied on certain earthquake conditions, but in reality, it is liquefied under such conditions.

Therefore, to evaluate the performance or reliability of an empirical method/model, we can compare the model prediction to the observation. When the two are matched, the inference is that the model should be reliable. As a result, the prior task of using such a method to evaluate an empirical model is to collect observation data. Note that such a method has been used for evaluating the accuracy of earthquake early warning and debris-flow early warning systems (Xu *et al.* 2017; Wu *et al.* 2019). For example, based on more than 15,000 observed ground motions and their causative earthquakes, Xu *et al.* (2017) estimated the *accuracy* of an on-site earthquake early warning system is about 83%. The definition of accuracy was given in one following section.

Since the local HBF procedure has been increasingly used for soil liquefaction assessments in Taiwan, this paper evaluates its performance and reported the model's accuracy, precision, recall, *etc.* Specifically, like other studies (*e.g.,* Oommen *et al.* 2010; Chen and Zhang 2014; Yazdi and Moss 2017; Gondia *et al.* 2019; Kardani *et al.* 2021; Zhan and Chen 2021; Kourehpaz and Hutt 2022), we also used the confusion matrix as a tool to evaluate the performance of the HBF method quantitatively, investigating its applicability in a more objective manner. On the other hand, we collected a total of 796 soil liquefaction case studies for this investigation, and the newly compiled database was also presented in this paper. Based on the same database, the accuracy of the HBF method was compared to three other similar methods for calculating the liquefaction factor of safety using the SPT data.

2. METHODOLOGY

2.1 Confusion Matrix and Performance Indices

Table 1 shows the illustrative diagram of the confusion matrix (Sammut and Webb 2010). The confusion matrix was originally proposed by the researchers of computer sciences for characterizing the performance of a prediction model. As shown in Table 1, a confusion matrix is constituted by four elements, namely true positive (TP), false positive (FP), true negative (TN), and false negative (FN). When TP and TN are registered, the inference is that the model is correct or reliable. On the contrary, when FP and FN occurs, the model is considered not correct. Note that TP is registered when both model prediction and observation are a "Yes" or "Positive." For the remaining three, see Table 1.

Table 1 The confusion matrix and its four elements

Prediction / Observation	Yes	No
Yes	True Positive (TP)	False Negative (FN)
No	False Positive (FP)	True Negative (TN)

According to the numbers of TP, TN, FP, and FN in the confusion matrix, the following "performance indices" were proposed:

$$\text{Accuracy} = \frac{\text{TP} + \text{TN}}{\text{TP} + \text{TN} + \text{FP} + \text{FN}} \tag{1}$$

$$\text{Precision} = \frac{\text{TP}}{\text{TP} + \text{FP}} \tag{2}$$

$$\text{Recall} = \frac{\text{TP}}{\text{TP} + \text{FN}} \tag{3}$$

$$\text{F1-score} = \frac{2 \times \text{Precision} \times \text{Recall}}{\text{Precision} + \text{Recall}} \tag{4}$$

Among them, accuracy is most comprehensible and indicative; say, the accuracy of a prediction model is 90%, and the inference is that the prediction will match the observation 90 out of 100 times.

By contrast, precision is the ratio of TP to the sum of TP and FP, so its inference is the relative frequency of TP to FP, which is also known as false alarm. As a result, when the occurrence frequency of false alarm or FP is low, the model precision will be high. On the other hand, recall is the relative frequency of TP to FN, which is also known as missed alarm. Therefore, when the frequency of missed alarm is low, the model recall will be high. Finally, F1-score is defined as the harmonic mean of precision and recall. Its exact formulation was given in Eq. (4).

Since precision, recall, and F1-score is not as "intuitively comprehensible" as accuracy, Xu *et al.* (2017) proposed two basic indices that are as "intuitively comprehensible" as accuracy, namely (i) the rate (R_{FP}) of false positive or false alarm, (ii) the rate (R_{FN}) of false negative or missed alarm:

$$R_{FP} = \frac{\text{FP}}{\text{TP} + \text{TN} + \text{FP} + \text{FN}} \tag{5}$$

$$R_{FN} = \frac{\text{FN}}{\text{TP} + \text{TN} + \text{FP} + \text{FN}} \tag{6}$$

For instance, in the study evaluating the performance of an earthquake early warning system, Xu *et al.* (2017) reported the model's accuracy = 83.4%, R_{FP} = 14.1%, and R_{FN} = 2.5%, and based on the three, the model performance could be clearly portrayed and understood.

2.2 Simplified Procedure and HBF

The simplified procedure (Seed and Idriss 1971) is for computing the liquefaction factor of safety for liquefaction potential assessment. It defined the liquefaction factor of safety as follows:

$$FS_{7.5} = \frac{CRR_{7.5}}{CSR} \tag{7}$$

where CRR denotes the cyclic resistance ratio, and $CRR_{7.5}$ is the CRR on the basis of M_w 7.5. CRR and $CRR_{7.5}$ can be considered the "strength" of the soil against liquefaction. Furthermore, $FS_{7.5}$ denotes the liquefaction factor of safety on the basis of M_w 7.5, and when the causative earthquake magnitude is not equal to 7.5, the resultant FS needs to be adjusted by a so-called magnitude scaling factor (MSF):

$$FS = FS_{7.5} \times MSF \tag{8}$$

In the HBF method, the formulation of MSF is:

$$MSF = \left(\frac{M_w}{7.5}\right)^{-1.8} \tag{9}$$

By contrast, CSR in Eq. (7) denotes the cyclic stress ratio, which is considered the "driving force" to soil liquefaction that is mainly depending on the peak ground acceleration (PGA) of earthquake ground motions. Specifically, it is expressed as follows:

$$CSR = 0.65 \times \frac{PGA}{g} \times \frac{\sigma_v}{\sigma'_v} \times r_d \tag{10}$$

where σ_v and σ'_v denote the total and effective (vertical) earth pressures at the center of the target soil layer. r_d is the stress reduction factor depending on the depth of the target layer. Figure 1 shows the relationship between r_d and depth (Seed and Idriss 1971).

In addition to using different magnitude scaling factors compared to the "equivalent" SPT-based procedures, the HBF method also proposed and used a unique CRR curve for determining $CRR_{7.5}$ based on $(N_1)_{60,cs}$ (the corrected SPT-N value; cs: clean sand). Figure 2 shows such the CRR curve of the HBF method. Nonetheless, like others that were developed empirically based on observed data, the curve in Fig. 2 was also empirical.

Specifically, the CRR curve (Fig. 2) of the HBF method was developed with the following procedures: (i) based on the pool of the observed data, the logistic regression between liquefaction probability (P_L), $(N_1)_{60,cs}$ and $CSR_{7.5}$ (or $CRR_{7.5}$) was developed; (ii) on the basis of liquefaction probability = 50%, a series of (paired) $(N_1)_{60,cs}$ and $CSR_{7.5}$ were back calculated using the logistic regression model; (iii) the series of $(N_1)_{60,cs}$ and $CSR_{7.5}$ were best fit with a HBF using simple regression, and the best-fit hyperbolic function becomes the CRR curve of the HBF method. Because the hyperbolic function was used in the model development, the developers referred to the method as HBF, the acronym of hyperbolic function. More specifically, the proposed CRR curve (Fig. 2) is portrayed by the following equation:

$$CRR_{7.5} = 0.07 + \frac{0.0042(N_1)_{60,cs}}{1-(N_1)_{60,cs}/42} \tag{11}$$

where 0.07, 0.0042, and 42 are the best-fit model parameters of HBF. Again, like other SPT-based methods (*e.g.,* Youd *et al.* 2001), this CRR curve was also empirically developed.

Nonetheless, other technical details of the HBF method, such as the formulations of the stress reduction factor, are not too much different from other SPT-based procedures, so they were not elaborated here. Readers can refer to the paper for more technical details about the HBF method (Hwang *et al.* 2021). Figure 3 shows a simplified flowchart for using the HBF method or equivalents to calculate the liquefaction factor of safety based on the SPT-N value, PGA, soil unit weight, *etc.*

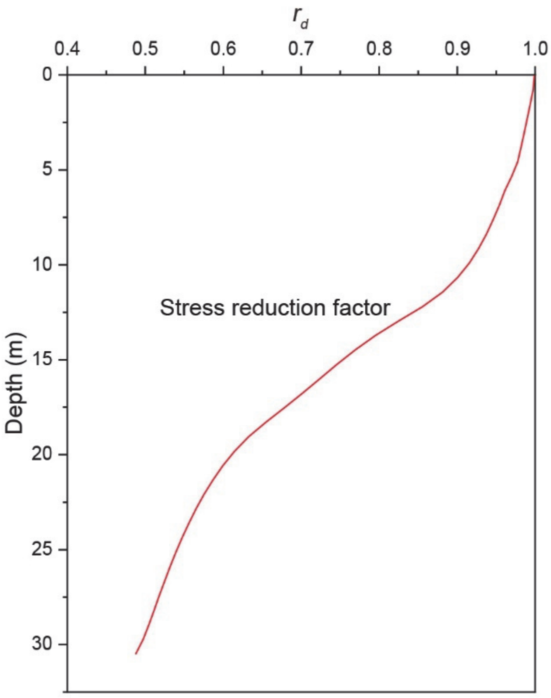

Fig. 1 Relationship between stress reduction factor and depth (Seed and Idriss 1971)

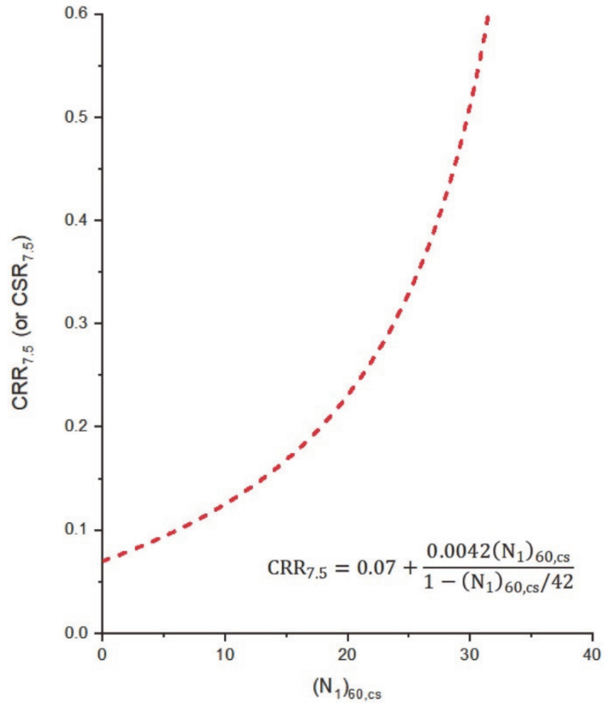

Fig. 2 The CRR curve of the HBF method for calculating the liquefaction factor of safety (Hwang *et al.* 2021)

2.3 Database

As shown in Fig. 3, for using the (SPT-based) HBF procedure and equivalents to calculate the liquefaction factor of safety, the following "raw" data are needed, including SPT-N value, PGA, earthquake magnitude, soil unit weight, fines content (FC), depth, layer thickness, ground water table, *etc.* From the literature, we found three liquefaction databases containing those raw data associated with a liquefaction case history: which are: (i) the database compiled by Idriss and Boulanger (2010, 2014); (ii) the database compiled by Cetin *et al.* (2004); (iii) the database compiled by

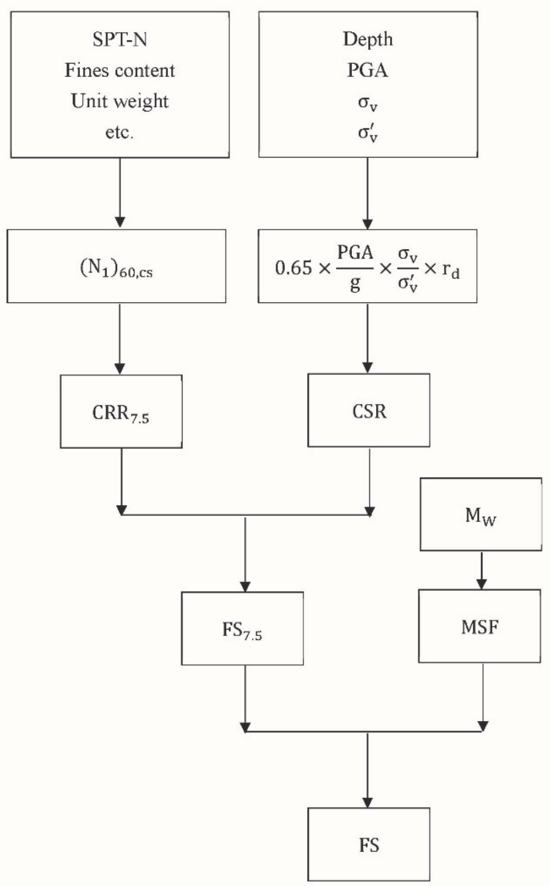

Fig. 3 The flow chart using the SPT-based HBF method or equivalents to calculate the liquefaction factor of safety

Hwang *et al.* (2021). Table 2 summarizes the three databases, including sample sizes, causative earthquakes, *etc.*

It is noted that some datasets were included in more than one database above, so the "overlap" data were not double counted after processing. For example, the database compiled by Hwang *et al.* (2021) contained 509 local (Taiwan) case histories and 31 non-local ones "borrowed" from the database of Idriss and Boulanger (2010). As a result, the 31 cases were only allocated to the original database compiled by Idriss and Boulanger (2010).

After addressing the issue, our new database includes 796 datasets, with each containing PGA, M_w, depth, total stress, effective stress, FC, *etc.* Because the amount of the data is enormous, they were not given in this paper. However, the data were stored in an Excel spreadsheet, and it was accessible from the personal website of the corresponding author (https://jpwang000.wixsite.com/my-site).

Table 2 Summary of three liquefaction databases that contain associated raw data

DB*	Sample size	Data source	Qk**	Period	References
(1)	241	Japan, California, China, Philippines, Guatemala, Argentina, Turkey	27	1944-1999	Idriss and Boulanger (2010, 2014)
(2)	46	Japan	2	1989, 1995	Cetin *et al.* (2004)
(3)	509	Taiwan	2	1999, 2016	Hwang *et al.* (2021)

* Database
** The number of causative earthquakes

3. RESULTS

For explaining the calculation and analysis more clearly, five demonstrations are summarized in Table 3. According to the raw data of the second dataset and the flowchart shown in Fig. 3, we conducted the following calculations for the second dataset, step-by-step:

1. $(N_1)_{60,cs}$ = 29.04;
2. $CRR_{7.5}$ = 0.47 (based on $(N_1)_{60,cs}$);
3. CSR = 0.4 (based on PGA, M_w, *etc.*);
4. $FS_{7.5}$ = 1.16 (based on $CRR_{7.5}$ and CSR);
5. MSF = 1 (based on M_w 7.6);
6. FS = 1.16 (based on $FS_{7.5}$ and MSF).

As a result, the model prediction is that the soil layer would not be liquefied because of FS > 1, which matched the observation. Therefore, the HBF method is correct or reliable as far as this case is concerned. More specifically, it is a TN (true negative) for this case. By contrast, as explained previously, TP, FP, and FN are the acronyms denoting true positive, false positive, and false negative, respectively.

The same calculations were conducted for 4 other cases. Accordingly, there are one TP, two TNs, one FP, and one FN among the 5 cases. Therefore, based on the small sample size, the accuracy is 60%, the rate of false negative is 20%, and the rate of false positive is also 20%.

As the five demonstrations in Table 3, the same calculations were conducted for the remaining of the 796 datasets. Accordingly, the numbers of TP, TN, FP, and FN are 397, 337, 40, and 22, respectively. Accordingly, Fig. 4 shows the performance indices of the HBF procedure for soil liquefaction assessment. It shows that the accuracy of the method is 92.2%, R_{FN} is 2.8%, and R_{FP} is 5%. This illustrates that the empirical HBF procedure is satisfactory for soil liquefaction assessment, with the model's accuracy as high as 92.2% based on 796 observed datasets.

Table 3 Five demonstrations for the performance analysis and calculation for the HBF method

Data No.	r_d	σ_v (t/m²)#	σ'_v (t/m²)#	M_w	PGA (g)	FC (%)	$(N_1)_{60,cs}$	$CRR_{7.5}$	CSR	$FS_{7.5}$	MSF	FS	Observation	Result
2	0.95	5.71	9.28	7.5	0.40	67	29	0.47	0.40	1.16	1.00	1.16	Non-L*	TN**
20	0.97	4.18	6.42	7.6	0.09	5	4.7	0.09	0.09	1.06	0.98	1.04	L	FN**
21	0.93	7.34	13.46	7.6	0.16	2	9.9	0.12	0.18	0.70	0.98	0.69	L	TP**
40	0.92	9.38	16.11	7.0	0.20	50	12.8	0.15	0.20	0.72	1.13	0.82	Non-L	FP**
44	0.88	7.24	13.97	7.5	0.14	3	14.3	0.16	0.15	1.08	1	1.08	Non-L	TN**

* L: liquefaction
** TN: true negative; FN: false negative; TP: true positive; FP: false positive
\# 1 t/m² = 9.8 kPa

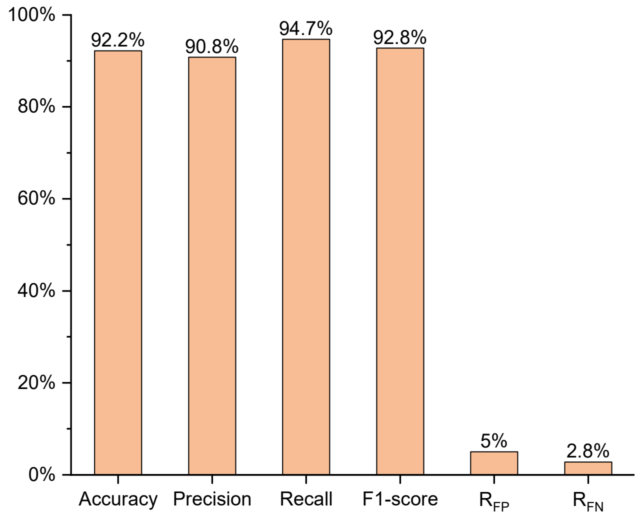

Fig. 4 The performance indices of the HBF method based on 796 observed data

4. DISCUSSIONS

4.1 Excluding Model-Development Data

Several studies (*e.g.,* Anbazhagan *et al.* 2021) have commented that certain geotechnical empirical models could be subject to the "local data effect" and their performance could vary significantly when applied to "non-local" areas. In other words, such models (*e.g.,* the relationship between SPT-N value and shear wave velocity) need to be used with caution when applied to non-local sites.

The HBF model performance (*e.g.,* accuracy) shown above was based on 796 observed datasets from three databases, including the local (Taiwan) one compiled by Hwang *et al.* (2021) who also used the data for developing the HBF procedure. In other words, those local (Taiwan) datasets were used for both the model development and the performance evaluation, which might be the reason that the accuracy of the model can be as high as 92%.

To clear the doubt, we repeated the analysis and calculated the confusion matrix based on 287 non-local data only, which were not used for developing the HBF procedure. Figure 5 shows the performance indices of the HBF method under the situation. Accordingly, the accuracy of the model was 89.5%, the rate of FP (or false alarm) was 7.3%, and the rate of FN (or missed alarm) was 3.2%. It shows that based on the pool of the non-local observed data, the model's accuracy only decreased 2%, inferring that the "local data effect" on the HBF method is insignificant for soil liquefaction assessment.

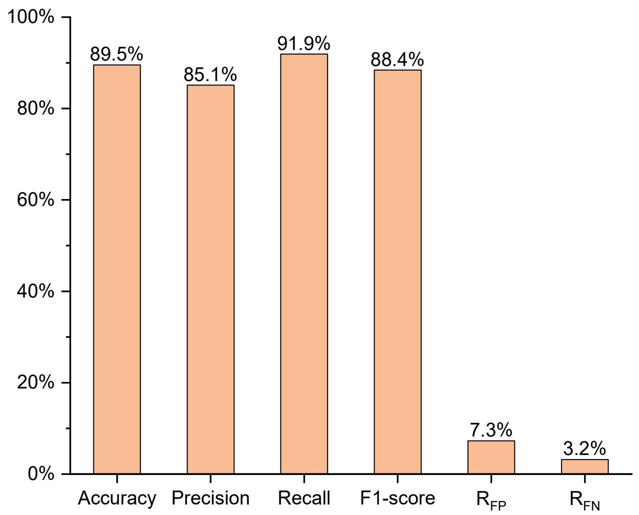

Fig. 5 The performance indices of the HBF method based on 287 datasets that were not used for the model development

4.2 Performance of the NCEER Method

As mentioned previously, Youd *et al.* (2001) summarized the consensuses and updates from the liquefaction workshops organized by NCEER, and in that paper, a SPT-based procedure for soil liquefaction assessment was elaborated, which is usually referred to as the NCEER procedure. The NCEER procedure was commonly used in soil liquefaction case studies, especially in the United States (Juang *et al.* 2003, 2008).

As a result, it is worth comparing the performance of the HBF method to the "benchmark" NCEER method, on the basis of the same pool of observation. Based on the same 796 datasets compiled by this study, we repeated the calculation and analysis following the "numbers and equations" (*e.g.,* CRR curve, MSF) of the NCEER method. For example, Fig. 6 shows the NCEER's CRR curve along with the CRR curve of the HBF method. As Youd *et al.* (2001) indicated in that paper, the NCEER's CRR curve was empirically developed, and the whole method was developed on the basis of the simplified procedure proposed by Seed and Idriss (1971).

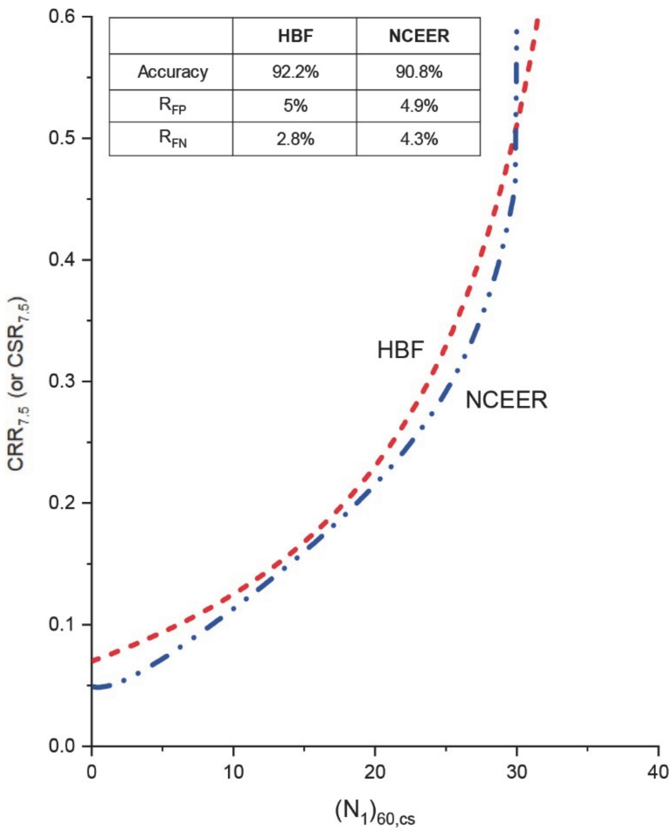

Fig. 6 The CRR curves in association with the HBF and NCEER procedures for calculating the liquefaction factor of safety

Based on the same pool of 796 datasets, the calculations show that the numbers of TP, TN, FP, and FN are 385, 338, 39, and 34, respectively. According to the numbers in the confusion matrix, Fig. 7 shows the performance indices for the NCEER procedures: its accuracy was 90.8%, and the rate of missed alarm (or FN) was 4.3%, and the rate of false alarm (or FP) was 4.9%.

With the accuracy of the NCEER procedure at 87.5%-90.8%, the procedure for soil liquefaction assessment is also satisfactory and acceptable. Moreover, its accuracy is comparable to the HBF method at 92.2%, although the two methods are slightly different in the aspects of the CRR curve, MSF, *etc.*

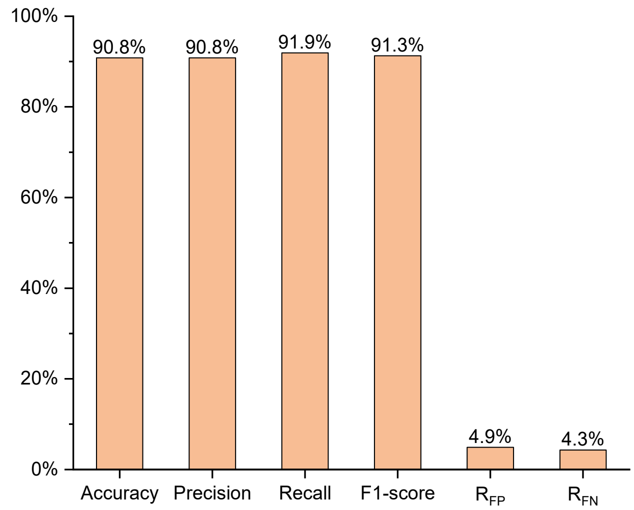

Fig. 7 The performance indices of the (SPT-based) NCEER procedure for calculating the liquefaction factor of safety based on the 796 observed datasets

4.3 Comparison with Similar Methods

According to Hwang *et al.* (2021), there were 6 similar SPT-based methods for soil liquefaction assessment, all developed within the framework of the simplified procedure (Seed and Idriss 1971), namely the HBF method, the NCEER method (Youd *et al.* 2001), the I-B method (Idriss and Boulanger 2010), the AIJ method (AIJ 2001), the JRA method (JRA 1996), and the Cetin method (Cetin *et al.* 2004). However, because the Cetin method also requires Vs_{12} (the average shear wave velocity of the upper 12 meters) for the analysis but such data are not available in our database, we cannot evaluate its accuracy using our database. Similarly, because the JRA method also requires D_{50} (the median size of soil) for the analysis, we cannot evaluate its accuracy using our database, either.

Figure 8 shows the comparison of the four methods in terms of model accuracy. The result shows that the accuracy of the HBF, NCEER and I-B methods is comparable with their accuracy all above 90%, while the accuracy of the AIJ method is about 85% based on the same database.

4.4 Stress Reduction Factor, r_d

It is noted that although the methods shown in Fig. 8 were all developed within the framework of the simplified procedure, the stress reduction factors are not the same. Note that this study used the corresponding r_d equation for estimating each method's accuracy. Table 4 summarizes the equations of r_d used by the 4 methods.

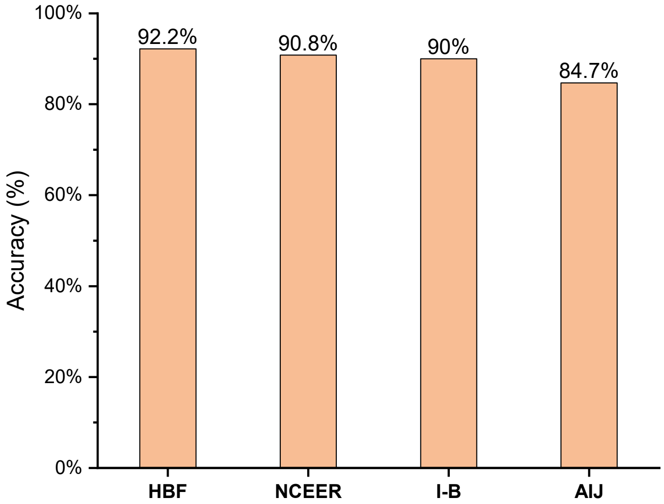

Fig. 8 The performance of the four similar methods in terms of model accuracy based on the same pool of 796 data

Table 4 The respective r_d equations used by the 4 similar SPT-based methods

Method	Equation
HBF	$r_d = \begin{cases} 1.0 - 0.01z & z \le 10\text{m} \\ 1.2 - 0.03z & 10\text{m} < z < 20\text{m} \end{cases}$
NCEER	$r_d = \dfrac{1 - 0.4113z^{0.5} + 0.04052z + 0.001753z^{1.5}}{1 - 0.4177z^{0.5} + 0.05729z - 0.006205z^{1.5} + 0.001210z^2}$
I-B	$r_d = \exp[\alpha(z) + \beta(z) M_w]$ $\alpha(z) = -1.012 - 1.126 \times \sin\left(\dfrac{z}{11.73} + 5.133\right)$ $\beta(z) = 0.106 - 0.1186 \times \sin\left(\dfrac{z}{11.28} + 5.142\right)$
AIJ	$r_d = 1 - 0.015z$

z: depth in m; M_w: earthquake moment magnitude

CONCLUSIONS

The merits and findings from this research are as follows:

1. A new soil liquefaction database was compiled, including 796 liquefaction case histories with each dataset containing PGA, M_w, total stress, effective stress, depth, *etc.*
2. Using the raw data of the database, we calculated the liquefaction factor of safety and compared it to the observed outcome (liquefaction or non-liquefaction) for each case. Accordingly, the accuracy of the HBF method for soil liquefaction assessment was 92.2%, the rate of false positive or false alarm was 5%, and the rate of false negative or missed alarm was 2.8%.
3. Excluding the data used for the HBF model development, the accuracy of the method was 87.5%, the rate of false positive or false alarm was 8.4%, and the rate of false negative or missed alarm was 4.2%.
4. Based on the same pool of the 796 observed data, the accuracy of the NCEER method was 90.8%, the rate of false positive or false alarm was 4.9%, and the rate of false negative or missed alarm was 4.3%. It shows that the performances of

the two SPT-based procedures for soil liquefaction assessment are comparable. More importantly, with both methods having the model's accuracy about 90%, they are satisfactory and acceptable.

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DATA AVAILABILITY

All of the raw data used in this study are accessible on the personal website of the corresponding author.

CONFLICTS OF INTEREST

The authors have no conflicts of interest to disclose.

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