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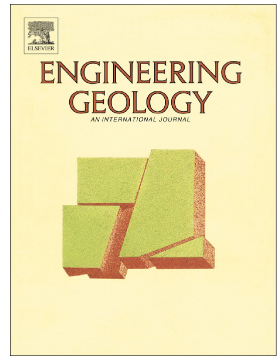

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Assessment on liquefaction potential of seabed soil in Chang-Bin Offshore Wind Farm considering parametric uncertainty of standard penetration tests

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Abstract

Liquefaction potential analysis is a required task in the foundation design process of offshore wind turbine in Taiwan. The standard penetration test (SPT) is mostly used in the preliminary soil investigation of the pilot offshore wind farm in Chang-Bin, Taiwan. Due to the different experimental conditions and operating conditions, the N value (SPT-N) of SPT varies greatly. This study applies statistical methods in conjunction with the New Japan Road Association simplified-empirical method (NJRA method) to incorporate the uncertainty of SPT-N values into the offshore liquefaction potential assessment to quantify the risk of seabed liquefaction. The study statistics the field experimental geotechnical parameters SPT-N and determines the probability density function of the SPT-N distribution of each layer of soil in the offshore wind farm. In order to quantify the risk of seabed soil liquefaction potential, the Monte Carlo random sampling method is used, and by the NJRA method to carry out the seabed liquefaction potential in Changhua, Taiwan. After comparing, the

results obtained by the current SPT-based soil liquefaction potential assessment by deterministic approach are conservative. In the ground investigation of offshore wind farm development, the method proposed in this paper can access the thickness of liquefiable soil layers under any given probability for optimizing offshore wind turbine foundation design.

Keyword: Offshore wind; liquefaction; Monte Carlo method; Risk analysis

1. Introduction

The Chang-Bin offshore wind farm of Taiwan Power Company is located in the offshore area of Changhua. The preliminary geotechnical investigation results show that the seabed of Chang-Bin offshore wind farm in Taiwan is mainly composed of silty sand (SM) and low plasticity clay (CL), it contains a small number of low plasticity silt (ML) and silty poorly graded sand (SP-SM) [CSC (2017), Hai-Shia Offshore Wind Energy Co., LtD. (2017a, 2017b), Chien at al. (2014), TORI (2012), TPC (2012, 2018)].. The soil within 80 meters below the seabed can be roughly divided into three layers. The uppermost layer is mainly loose to medium dense sand (SPT-N<30) and the depth is about 25 meters. The soil conditions of Taiwan's offshore wind farm are very different from the offshore wind farm in the North Sea [Le at al. (2014)].

For a sandy soil within 20 meters of the surface depth, it is highly likely that soil liquefaction will occur when an earthquake occurs [Seed and Idriss (1971)]. The soil liquefaction potential can assess by deterministic approach in Taiwan, which the SPT-N based soil liquefaction potential semi-empirical analysis method is the common adopted in the engineering design in Taiwan [JRA (1996), CPA (2011)], However, soil liquefaction can be affected by soil layer distribution, soil properties, seismic wave transmission, stress conditions, etc. Therefore, quantifying the risk of soil liquefaction in highly seismic region is essential for the development of offshore wind farms.

Christian & Swiger (1975), Tanimoto & Noda (1976), Tanimoto (1977), Xie (1979), Wang et al. (1980), Davis & Berrill (1981, 1982), Berrill & Davis (1985), Gu & Wang (1984) who used linear discriminant analysis to determine the incidence of soil liquefaction by in-situ soil liquefaction and non-liquefaction cases, while Liao et al. (1988), Youd & Noble (1997), and Toprak et al. (1999) collected soil liquefaction and non-liquefaction cases, using a statistical linear logic model for regression analysis to obtain the soil strength under cyclic load and the probability of occurrence of soil liquefaction. Juang & Jiang (2000), Juang et al. (2002, 2012, 2013) calculated the factor of safety against liquefaction F_L with a deterministic approach, and obtained the in-situ soil liquefaction probability P_f through Bayesian interpretation. The

Bayesian mapping function establishes the relationship between the safety factor of the soil liquefaction and the incidence of the soil liquefaction. Haldar & Tang (1979) calculated the probability of occurrence of soil liquefaction with laboratory test results, and evaluated the potential of soil liquefaction in combination with the simplified-empirical method proposed by Seed & Idriss (1971); Chameau & Clough (1983) combined the probability model of the pore water pressure accumulation with the a random seismic load to analyze the soil liquefaction potential; Yegian & Whitman (1978) used seismic hazard analysis and the simplified-empirical method for soil liquefaction analysis to consider the effect of seismic statistical characteristics on the soil liquefaction assessment; Huang & Chen (2000) calculated the probability of earthquake occurrence in the past, simulated the earthquake event with Monte Carlo, and used the simulated earthquake to analyze the soil liquefaction potential, and then statistically obtained the results of the soil liquefaction; Raghu Kanth & Dash (2008) determined the characteristic distribution of SPT-N value along with depth in the river-alluvial region, and randomly gave the SPT-N value of the soil at different depths by Monte Carlo method, and then carried out the soil liquefaction potential assessment by deterministic approach. They analyzed the factor of safety against soil liquefaction (F_L) to calculate the probability of soil liquefaction. The study of Raghu Kanth & Dash (2008) only considered the SPT-N distribution with depth, and didn’t consider the difference in SPT-N distribution and density of soil between different soil types in each soil layers.

Because the variability of geotechnical design parameters may affect the geoengineering design results, in order to quickly analyze the sensitivity of the geotechnical design parameters to the stability of geotechnical engineering, the Monte Carlo method has been widely used in the geotechnical engineering instability risk assessment. This study collects the SPT-N values of the boreholes of offshore wind farms in Taiwan. Referring to the relationship between the SPT-N values and the soil engineering properties recommended by Peck et al. (1953), the probability density function of SPT-N values for each type of engineering soil is obtained by statistical methods. The current borehole data is given to the reasonable SPT-N value range of each engineering soil layer, and then the SPT-N value is randomly generated by the Monte Carlo method according to the probability density function of SPT-N of each engineering soil. The factor of safety against soil liquefaction is determined by the simplified-empirical method suggested by New Japan Road Association [NJR(1996)]. The risk of soil liquefaction of Chang-Bin offshore wind farm is quantified through the probability analysis.

2. NJRA deterministic approach for soil liquefaction potential assessment

Both Taiwan and Japan are located in highly seismic zone. The SPT-based simplified empirical method is considered as a reliable method for soil liquefaction potential assessment. The factor of safety against liquefaction F_L is calculated when assessing the soil liquefaction potential using the simple empirical method. The factor of safety against liquefaction F_L is defined as the ratio of the cyclic resistance ratio of soil against soil liquefaction $(\tau/\sigma_v')_R$ to the cyclic shear stress ratio $(\tau/\sigma_v')_L$ caused by the earthquake, as in Equation 1. When F_L is greater than 1, the soil will not liquefy when subjected to earthquakes. If F_L is less than 1, soil liquefaction may occur when subjected to earthquakes.

$$F_L = \frac{(\tau / \sigma_v')_R}{(\tau / \sigma_v')_L} \tag{1}$$

The cyclic resistance ratio of soil $(\tau/\sigma_v')_R$ can be obtained by the SPT-N value, as offered by Seed et al. (1975, 1979, 1985), Ishihara & Kosecki (1989), Koester (1994), and the Japan Road Association (1996), Tokimatsu & Yoshimi (1983), and other recommendations. Cyclic resistance ratio of soil $(\tau/\sigma_v')_R$ can also be determined by cone penetration test or in-situ shear wave velocity measurements, such as Robertson & Campanella (1985), Seed & DeAlba (1986), Olsen (1997), Robertson & Wride. (1998), Tokimatsu et al. (1991), Finn (1991), Robertson et al. (1992), and Andrus & Stokoe (2000).

This study evaluated the soil liquefaction potential using the simplified empirical method of New Japan Road Association (NJRA method) recommended by Taiwan's "Seismic Design Specifications and Commentary of Buildings"[CPA (2011)]. The NJRA method suggests to calculate the seismic induced cyclic stress ratio $(\tau/\sigma_v')_L$ by Equation 2, where A_{max} is peak ground acceleration, in gravitational acceleration g; r_d is the reduction coefficient of peak shear stress ratio in the vertical direction, its recommended calculation is as in Equation 3。

$$\left(\tau / \sigma_v '\right)_L = r_d \cdot A_{\max} \cdot \frac{\sigma_v}{\sigma_v '} \tag{2}$$

$$r_d = 1 - 0.015z \tag{3}$$

For the NJRA method shown as Equation 4, the cyclic resistance ratio $(\tau/\sigma_v')_R$ is obtained from the relationship between the cyclic triaxial test results and the local SPT-N. R_L is the cyclic resistance ratio obtained by the cyclic triaxial test, which can be transmitted through the SPT-N. The calculation is as shown in Equation 5; c_w is the correction coefficient as shown in Equation 6.

$$\left(\tau / \sigma_v '\right)_R = c_w \cdot R_L \tag{4}$$

$$R_L = \begin{cases} 0.0882\sqrt{\dfrac{N_a}{1.7}} & , N_a < 14 \\ 0.0882\sqrt{\dfrac{N_a}{1.7}} + 1.6\times10^{-6}\cdot(N_a - 14)^{4.5} & , 14 \le N_a \end{cases} \tag{5}$$

$$c_w = \begin{cases} 1.0 & , R_L \le 0.1 \\ 3.3R_L + 0.67 & , 0.1 < R_L \le 0.4 \\ 2.0 & , 0.4 < R_L \end{cases} \tag{6}$$

Among them, N_a is the SPT-N correction value considering effective vertical stress σ_v' and fine content (FC), and the N_a value of sandy soil in the NJRA method is recommended to be calculated by Equation 7. Among them, N_1 can be calculated with effective vertical stress σ_v' and SPT-N from Equation 8; c_1 and c_2 in Equation 7 are the correction coefficients of fine content (FC), which can be obtained by Equation 9 and 10.

$$N_a = c_1 N_1 + c_2 \tag{7}$$

$$N_1 = \frac{1.7N}{(\sigma_v^{'} / p_a + 0.7)} \tag{8}$$

$$c_1 = \begin{cases} 1 & , 0\ \% \le \mathrm{FC} < 10\% \\ (\mathrm{FC}+40)/50 & , 10\ \% \le \mathrm{FC} < 60\% \\ (\mathrm{FC}/20)-1 & , 60\ \% \le \mathrm{FC} \end{cases} \tag{9}$$

$$c_2 = \begin{cases} 0 & , 0\ \% \le \mathrm{FC} < 10\% \\ (\mathrm{FC}-10)/18 & , 10\ \% \le \mathrm{FC} \end{cases} \tag{10}$$

3. Statistical Characteristics of SPT-N Values of Potential Sites in Chang-Bin Offshore Wind Farm, Taiwan

3.1 Chang-Bin offshore area borehole data

This study collects Chien et al. (2014), TORI (2012), TPC(2009, 2012, 2018) borehole data and public environmental impact assessment report, including a total of 26 holes of standard penetration test data, drilling depth is about 70 to 120 meters. The location of the boreholes is shown in Figure 1. The basic information of each borehole is shown in Table 1. Since part of the borehole data is confidential data, Table 1 only contains 17-boreholes information.

In the early stage of the development of offshore wind farms in Taiwan, Standard Penetration Test (SPT) was used for offshore geotechnical surveys. This study refers to the relationship between SPT-N and soil engineering properties suggested by Peck et al. (1953), and classifies the in-situ soil according to the degree of density. Peck et al. (1953) divided sand and silt into five engineering soils. According to the soil state, the numbers S1, S2, S3, S4 to S5 (sand) and M1, M2, M3, M4 to M5 (silt) were given from very loose, loose, medium dense, dense to very dense, while clay is divided into six different engineering soils, and is given from C1, C2, C3, C4, C5 to C6 from very soft, soft, medium, stiff, very stiff to hard. According to the above description, the soil layers of each borehole can be classified into engineering soil by the soil type and SPT-N value. In this paper, the soil layer of 20 meters of the surface of the Taiwan Power Company's pilot offshore wind farm is used as the research area of the soil liquefaction probability analysis. Figure 2 shows the soil classification results of the surface soil of the 9 borehole (BH01 to BH09) in pilot offshore wind farm.

3.2 Probability distribution of SPT-N

Observed SPT-N data from 26-boreholes in Chang-Bin offshore wind farm are used to determine the probability distribution of each type of engineering soil (S1, S2, S3, S4, S5, M2, M3, M4, M5, C2, C3, C4, C5, C6), which is a basis of Monte Carlo method. A considerable amount of studies including Wang et al. (2010), Teixeira et al. (2011), Honjo (2011), Yasuda et al. (2012), Baecher & Christian (2005), Magner et al. (2017), Wang & Cao (2013) Muduli & Das (2015) indicated that geotechnical design parameters such as cohesion of soil, friction angle, SPT-N, q_c, and fine content of soil often follow normal or lognormal distributions. Therefore, observed SPT-N data from 26-boreholes in Chang-Bin offshore wind farm, Taiwan are fitted as the normal and lognormal distributions. The probability distribution functions (PDF) of the normal and lognormal distributions are respectively shown as Equations 11 and 12, where f(x) is the probability density function, μ is the sample mean value, σ is the standard deviation, and the subscript *ln* is the statistical value of the lognormal probability distribution.

$$f(x)=\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(x-\mu)^2}{2\sigma^2}},-\infty<x<\infty \tag{11}$$

$$f_{ln}(x)=\frac{1}{x\sigma_{ln}\sqrt{2\pi}}e^{\left[-\frac{1}{2\sigma_{ln}^2}(\ln(x)-\mu_{ln})^2\right]},0<x<\infty \tag{12}$$

In this study, Kolmogorov-Smirnov test (K-S test there after) is used to determine the suitability of the fitted distributions. The results of the K-S test at the significant level of 0.05 are reported in Table 2. The results indicates that SPT-N of most types can be fitted by normal and lognormal distributions, except for SPT-N of C4 and C5 does not pass the of normal distributions, and SPT-N of S3, C4 and C5 does not lognormal distributions. Since the shear strength of the clay layer is mainly due to cohesion, the clay is generally considered to have no soil liquefaction potential. Therefore, the SPT-N of the C4 and C5 engineering soils do not affect the soil liquefaction potential analysis results. The normal distribution is thus selected to represent the probability distribution of SPT-N of various types of engineering soils and is used as a basis from random sampling by Monte Carlo method.

4. Analysis of liquefaction potential of seabed soil in the Chang-Bin offshore wind farm

4.1 Randomly given model of SPT-N value of Chang-Bin seabed soil

Cox & Siebert (2006) suggested that when evaluating the parameter uncertainty by Monte Carlo method, multiple random numbers can be generated according to the probability density function of the target parameter. In this study, 10,000 sets of SPT-N were produced according to the normal probability density function of soil SPT-N. Taking S3 sand as an example, Figure 3(a) randomly generates 10,000 sets of SPT-N values. The probability of occurrence of the 10,000 sets of SPT-N is a normal probability distribution, as shown in Figure 3(b). According to the same stochastic parameter generation process, the SPT-N values of the layered engineering soils contained in each analysis borehole can be separately established (excluding the M1 and C1 engineering soils without samples).

In this paper, the 9 borehole data of the Taiwan Power Company's pilot offshore wind farm is used to analyze the probability of soil liquefaction, and the detailed soil data within a depth of 20 meters (one data per 1.5 m) is obtained, and the engineering soil is classified. The probability density function corresponding to each soil type of the project randomly produces 10,000 SPT-N values, that is, 10,000 SPT-N values are produced every 1.5 m. In the same borehole, the SPT-N values of each detailed soil layer are combined in the order of random numbers, and the simulated soil layer conditions of 10,000 sets of SPT-N values with depth distribution can be obtained. Taking Taiwan Power Company's BH-03 as an example, there are 13 layers of detailed soil stratification in a depth of 20 meters. The soil profile of the project is shown in Figure 4. After randomly generating 10,000 sets of SPT-N values in each detailed soil layer, The 10,000 sets of SPT-N values are sequentially combined with the depth distribution.

4.2 Seabed soil liquefaction potential assessment by deterministic approach

According to Figure 2, the SPT-N value of the original borehole data of the Taiwan Power Company’s pilot offshore wind farm is combined with the New Japan Road Association simplified- empirical method to analyze the seabed liquefaction caused by the earthquake. In order to obtain the peak ground acceleration corresponding to the design earthquake (recurrence period is 475 years) of the offshore wind field, this study refers to Taiwan's 'Seismic Design Specifications and Commentary of Buildings' [CPA (2011)] to obtain the peak ground acceleration of 0.28g in the Changhua area. Figure 5 shows the results of the liquefiable soil layers by deterministic approach. When F_L is less than 1, it is determined that soil liquefaction occurs in this soil layer. The liquefiable soil layer of borehole BH-04 and BH-05 is the thickest, and the total thickness of liquefiable soil layer is more than 15 meters. In order to present the spatial distribution of the soil liquefaction potential by deterministic approach results, the soil layers of the soil liquefaction in each borehole are connected along the north-south direction of the offshore wind field, and the section line is shown in Figure 6. The results of the soil liquefaction area are shown in Figure 7. The boundaries of liquefiable soil layers are determined by the F_L with the distance inverse method and constructed with commercial software GMS for Groundwater Modeling System [AQUAVEO (2018)]. It is obvious that the borehole BH-04, BH-05, BH-06, BH-07 scattered in the middle block of the offshore wind field have the thicker liquefiable soil layer, the borehole BH-04 occurs soil liquefaction within a depth of 16 meters. The south side of the offshore wind farm and the north side are interlaced with non-liquefied soil layers.

4.3 Quantitative risk assessment of seabed soil liquefaction

This study is based on the SPT-N probability density corresponding to each soil layer in the borehole. The SPT-N of each soil layer are determined by Monte Carlo method, and NJRA simplified-empirical method is used to analyze seabed soil liquefaction potential. An accuracy analysis of Monte-Carlo simulation is operated by considering the different order of number of sampling from 100 samples to 100,000 samples. The result shows that there probabilities obtained from the analysis with 10,000 samples and 100,000 samples are identical. Taking Taiwan Power Company's BH-03 as an example, the distribution of SPT-N values of 10,000 random samples is shown in Figure 8. The factor of safety against liquefaction F_L is calculated as the distribution along the direction of depth is shown as Figure 4. In the 10,000 group evaluation results, the number of analysis groups with F_L value less than 1 divided by the total number of analysis groups (10,000 groups) is used to obtain the probability of soil liquefaction (P_f) at each depth, as shown in Figure 9. Chen & Juang (2000) describes the likelihood of soil liquefaction corresponding to the probability of soil liquefaction P_f. As shown in Table 3, the probability of occurrence of soil liquefaction could be turned into a qualitative description. In practical design, it can choose a reasonable probability of soil liquefaction as a threshold of foundation design consideration. Taking borehole BH-03 as an example, under the design earthquake, if the probability of occurrence of soil liquefaction is considered not more than 0.65 in foundation design, the liquefiable soil layers are form 0 meters to 3.5 meters and from 12.5 meters to 17 meters. Soil liquefaction may occur, and the reduction of soil strength should be carried out in the foundation design.

In order to investigate the distribution of liquefiable soil layer under different probability of soil liquefaction occurrence, the liquefiable soil layers of each borehole are connected along the cross-section of Figure 6 to create a liquefiable soil profile with a probability of soil liquefaction occurrence of 35%, 65% and 85%. When the probability of soil liquefaction occurrence is considered a threshold as 35%, the liquefiable soil layers distribute as in Figure 9(a). Figure 9(b) shows the distribution of liquefiable soil layers when the probability of soil liquefaction occurrence with a threshold as 65% is considered. When a probability of soil liquefaction occurrence of 85% is considered, the liquefiable soil layers presented in Figure 9(c) are almost certain that it will liquefy under given design earthquake in this study. If a high probability of soil liquefaction occurrence is considered as the threshold of foundation design, the thickness of liquefiable soil layers is thinner than the liquefiable soil layers when a low probability of occurrence is considered as the threshold of foundation design. The liquefiable soil layer with high probability of occurrence of soil liquefaction must be taken into account in the foundation stability analysis.

If we compare the results of the soil liquefaction potential by deterministic approach (in Figure 7) with the probabilistic assessment（in Figure 9）, we can see that the liquefied soil layer obtained by the deterministic analysis method is even larger than the liquefiable soil layer with a soil liquefaction probability of 35% (in Figure 9(a)), showing that the results of the simplified-empirical method used in practical engineering design is a conservative estimation.

For a probabilistic assessment, the uncertainty of methods, data and results should be a fundamental for the reliability of analysis results. The simplified empirical method of New Japan Road Association (NJRA method) are verified with the soil liquefaction disasters in Taiwan after Chi-Chi earthquake in 1999 and Meinong earthquake in 2016. However, the application of NJRA method for offshore conditions is still needed verification. In this study, we collect the in-situ standard penetration test data in the offshore wind farm in Taiwan and the fine content FC are also collected from the laboratory test results. These data are introduced in NJRA method to quantify the soil liquefaction potential. The peak ground acceleration of the seabed surface used in this study is subscribed from the onshore building code in Taiwan, and the further PSHA analysis for the offshore wind farm is needed. In Figure 10, the relationship between probability of failure P_f and factor of safety F_L form deterministic and probabilistic methodology is roughly negative correlation. This results may be due to insufficient soil data. This study provide a scheme of soil liquefaction potential quantification in Taiwan's offshore wind farm. The reliability of assessment results is strongly depends on the applied methods (NJRA method) and collection data (SPT-N).

5. Conclusion

The data obtaned from geoloagical survey and geotechnical investigations is the design basis of the foundation design of offshroe wind trubine and is documented as Ground Interpretative Report (GIR). For the offshroe wind farm in Taiwan, soil liquefaction potential and the suggestion of foundation design in liquefiable soil need to be given in GIR. This study collects the boreholes data of Chang-Bin offshore wind farm obtained from geoloagical survey and geotechnical investigations reports, and analyze the soil liquefaction potential by a SPT-based deterministic approach. When a peak ground acceleration (PGA=0.28g) is introduced to the liquefaction potential analysis, which is obtained from a 475-year returned period design earthquake given by the seismic design code for terrestrial buildings in Taiwan [CPA (2011)]. To quantify risk of seabed liquefaction in offshore wind farms, the probability density function of SPT-N values were determined by K-S test. The normal distribution of probability is used to describe the SPT-N values of soil. Numerous analysis data are gernerated by Monte Carlo method, combined with simplifiied-empirical method suggested by NJRA to determine the factor of safty against soil liquefaction F_L. The probability of occurrence of soil liquefaction is accounted by the number of analysis groups with F_L value less than 1 divided by the total number of analysis groups (10,000 groups) at each depth. We found that the thicknesses of liquefiable soil layers determined by the deterministic approach suggested by NJRA are even larger than the liquefiable soil layers with a probability of soil liquefaction occurrence of 35%. The results of the simplified-empirical method used in practical engineering design shows a conservative estimation.

An appropriate peak ground acceleration of design earthquake need to be introduced to evaluate the soil liquefaction analysis. The Bureau of Standards, Metrology and Inspection（MOEA）of Taiwan has completed the Standard of Wind turbines, Part 1: Design requirements (CNS15176-1) [MOEA (2018)]. We recommend to generate the seismic design spectra with PSHA and converting into a design earthquake acceleration series consistent with historical earthquakes through time domain, wherein follow the Appendix H and Appendix I of CNS 15176-1

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Table 1 SPT site test borehole information in Chang-Bin offshore wind farm [CSPC (2017), Hai-Shia Offshore Wind Energy Co., LtD. (2017a, 2017b), Chien, et al. (2014), TORI (2012), TPC (2009, 2018)]

Wind farm	References	Borehole No.	Borehole depth (m)	Water depth (m)	Coordinate (TWD97)	
					E	N
Taiwan power company's pilot offshore wind farm	TPC(2009)	BH-01	80	21.20	185,613	2,672,919
		BH-02	80	18.50	181,753	2,669,129
		BH-03	80	15.60	185,243	2,667,529
		BH-04	80	17.80	179,836	2,664,162
		BH-05	85	19.80	176,338	2,660,864
		BH-06	90	13.90	175,964	2,653,899
		BH-07	80	12.00	174,295	2,648,377
		BH-08	80	20.40	171,753	2,649,409
		BH-09	80	14.70	170,712	2,644,373
	TPC(2018)	B-1	80	27.44	173,367	2656,403
		B-2	80	17.24	174,799	2655,579
		B-3	80	23.31	173,441	2654,289
		B-5	85	20.95	172,567	2651,688
	TORI(2012)	BH-01(TORI)	80	19.45	175,290	2656,258
		BH-02(TORI)	80	22.58	172,724	2652,211
#27 offshore wind farm	Hai-Shia Offshore Wind Energy Co., LtD. (2017a)	SPT-1	70	22.75	156,239	2652,877
#28 offshore wind farm	Hai-Shia Offshore Wind Energy Co., LtD. (2017b)	SPT-2	70	23.01	155,392	2648,803

Table 2

The probability distribution of soil SPT-N and the K-S test, Histogram and Q-Q plot under hypothetical normal distribution and lognormal distribution (α=0.05)

Type	Sample number	Normal distribution		Lognormal distribution	
		p-value	K-S test	p-value	K-S test
S1	12	0.461	O	0.501	O
S2	41	0.298	O	0.222	O
S3	311	0.055	O	0	X
S4	232	0.357	O	0.149	O
S5	34	0.475	O	0.139	O
M2	16	0.814	O	0.631	O
M3	61	0.481	O	0.893	O
M4	7	0.471	O	0.531	O
M5	9	0.478	O	0.447	O
C2	6	0.393	O	0.459	O
C3	50	0.178	O	0.378	O
C4	115	0	X	0.003	X
C5	164	0.004	X	0.001	X
C6	12	0.688	O	0.956	O

p.s. “O” stands for hypothesis, “X” not stands for hypothesis

Table 3 Soil liquefaction likelihood classification [Chen & Juang (2000)]

Class	Probability of soil liquefaction (P_f)	Description of likelihood
5	$P_f \geq 0.85$	Almost certain that it will liquefy
4	$0.65 \leq P_f < 0.85$	Very likely to liquefy
3	$0.35 \leq P_f < 0.65$	Liquefaction and no liquefaction are equally likely
2	$0.15 \leq P_f < 0.35$	Unlikely to liquefy
1	$P_f < 0.15$	Almost certain that it will not liquefy

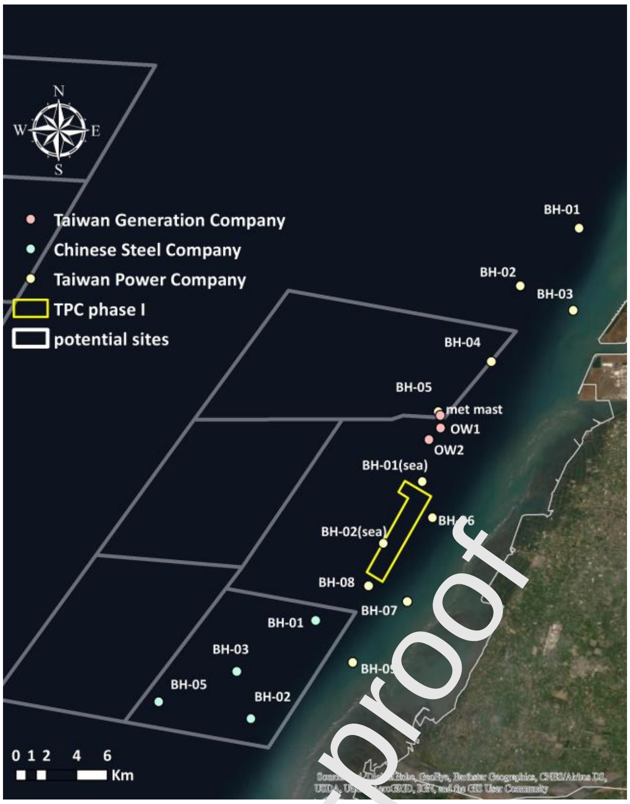


Figure 1 Distribution of boreholes in Chang-Bin offshore wind farm [Kuo (2016)]

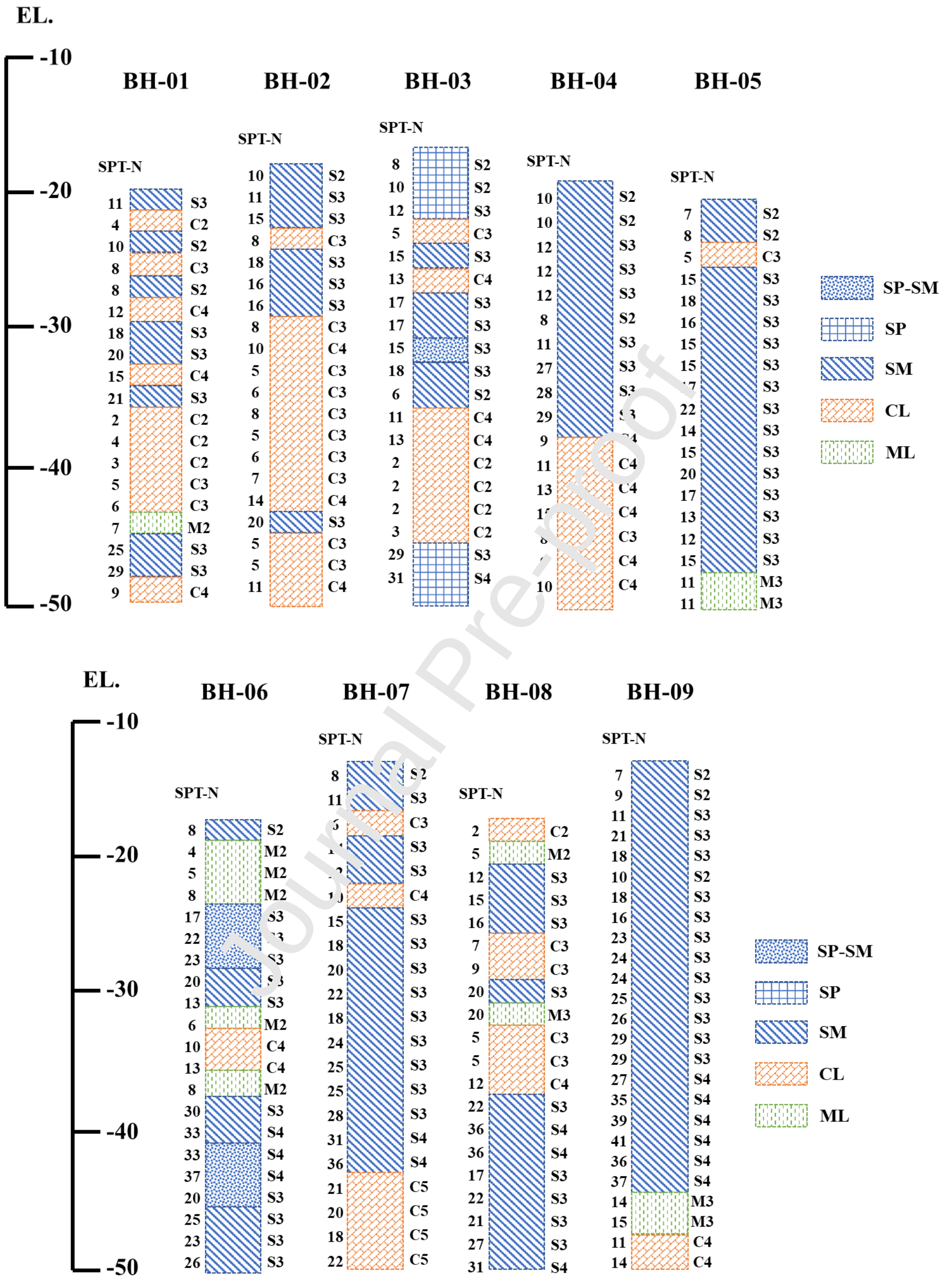


Figure 2 Soil profile and soil types within 30 meters of the shallow surface of the Taiwan Power Company's pilot offshore wind farm

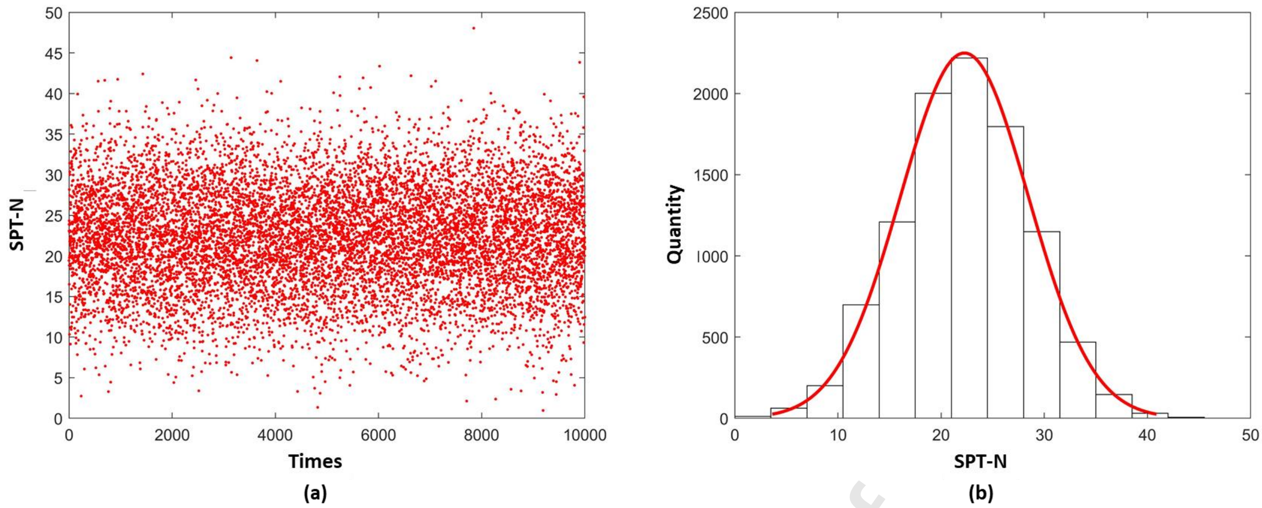


Figure 3 10,000 sets of SPT-N values simulated by Monte Carlo method (Engineering soil S3) (a) SPT-N analog value output order (b) SPT-N probability distribution histogram

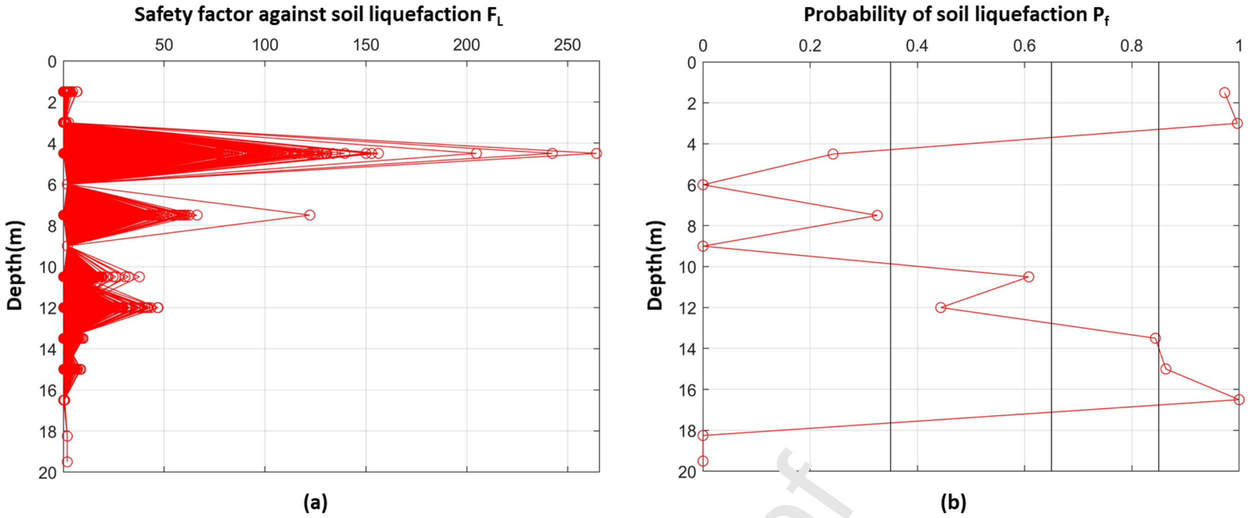


Figure 4 Random sampling 10,000 sets of soil liquefaction analysis results for Taiwan Power Company's BH-03

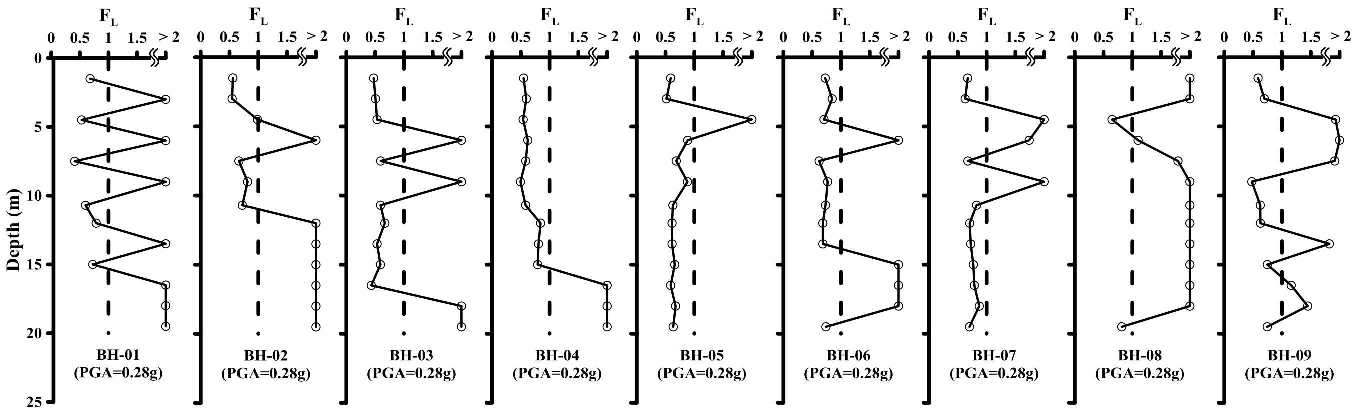


Figure 5 Factor of safety against liquefaction F_L of each borehole of Taiwan Power Company's offshore wind farm

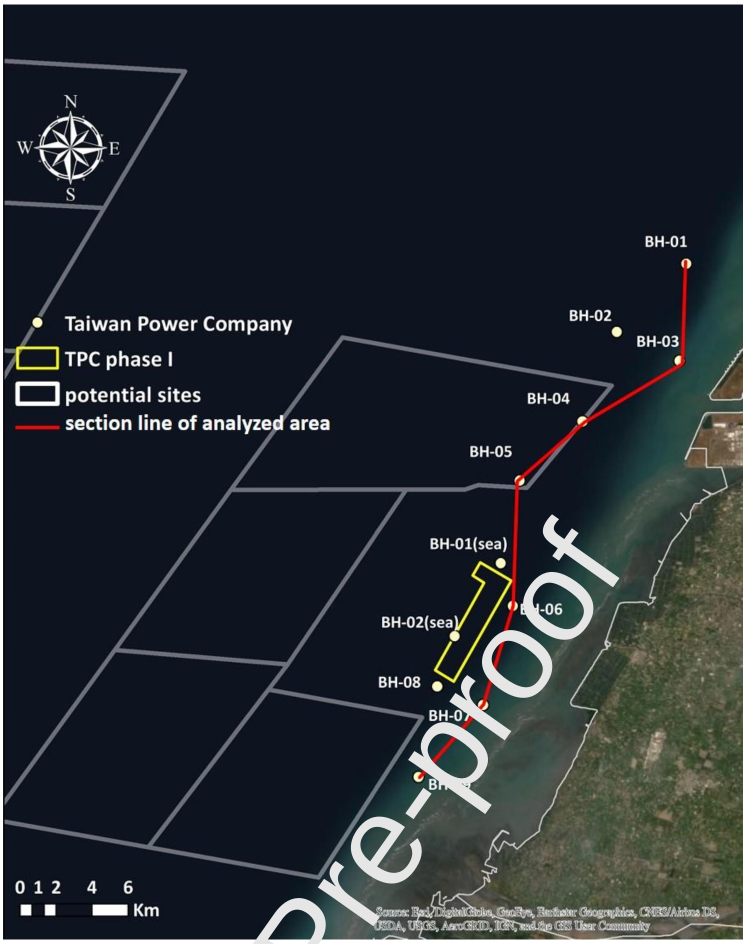


Figure 6 Section lines of soil liquefaction analysis

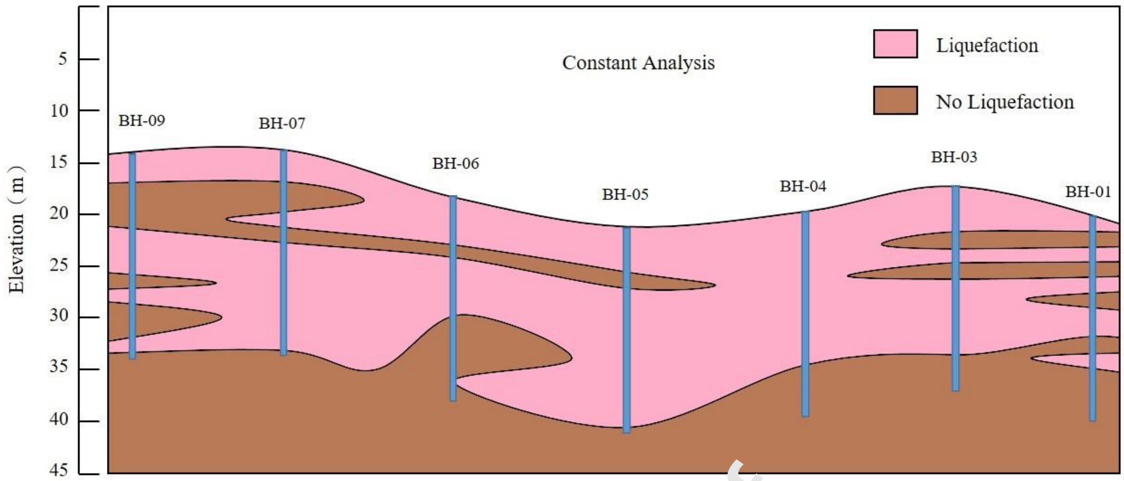


Figure 7 Liquefiable soil layer distribution determined from deterministic analysis method

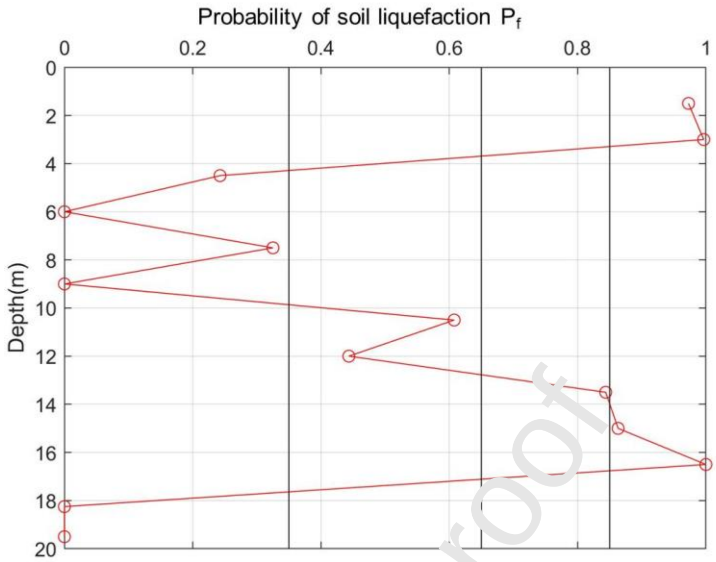
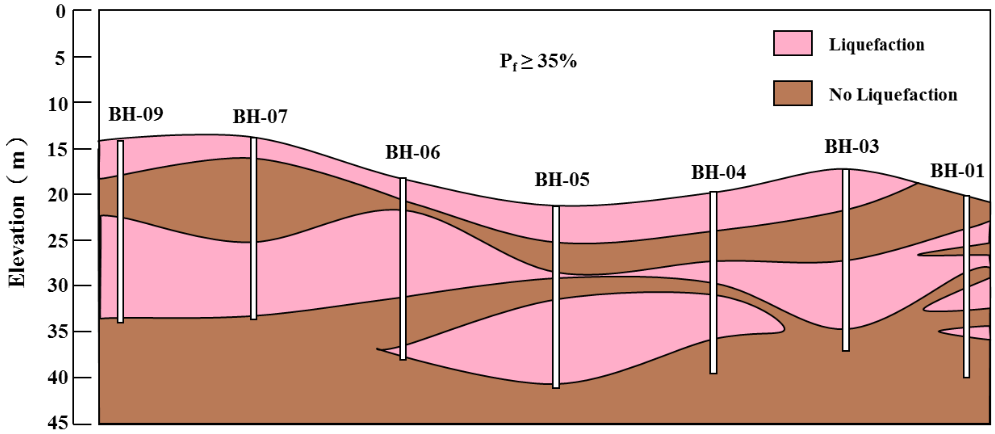
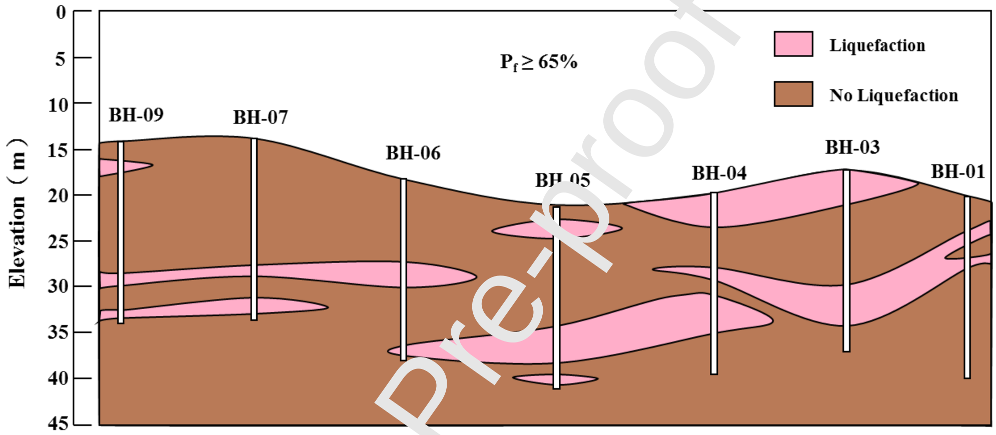


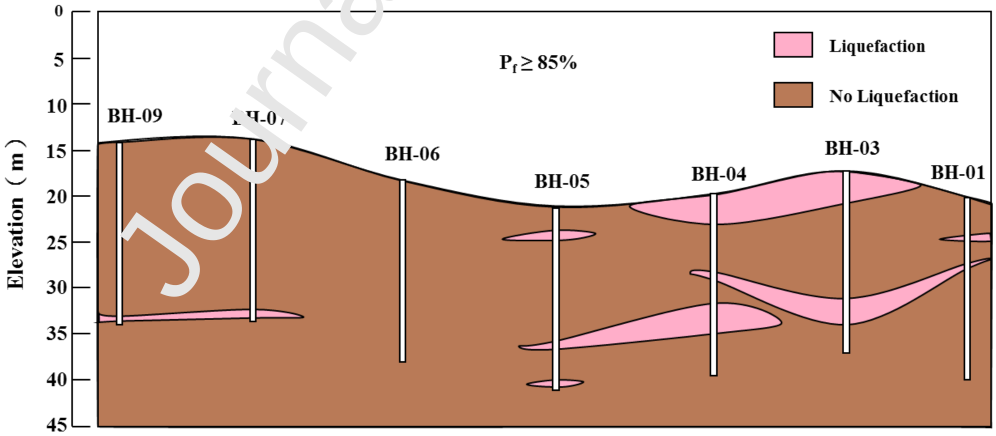
Figure 8 Soil liquefaction incidence varies with depth for Taiwan Power Company's BH-03



(a) P_f =35%



(b) P_f =65%



(c) P_f =85%

Figure 9 Distribution of the soil layers with probability of soil liquefaction

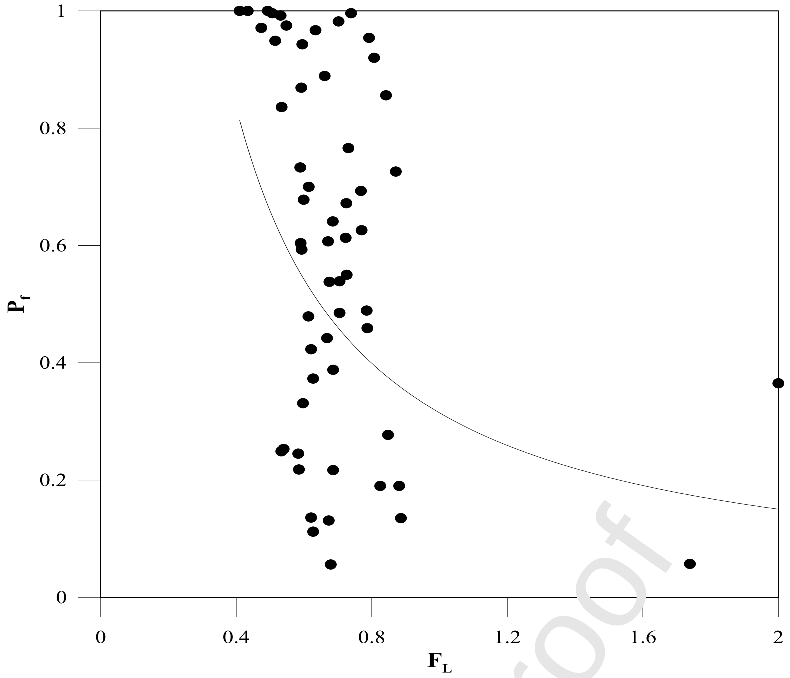


Figure 10 The relationship between probability of failure Pf and factor of safety F_L form deterministic and probabilistic methodology

Research Highlight

Title: Assessment on the liquefaction potential of seabed soil in Chang-Bin Offshore Wind Farm considering the parametric uncertainty of standard penetration tests

1. We propose a new method to quantify the risk of the seabed soil liquefaction potential.

2. This method can assess the thickness of liquefiable soil layers under any given probability.

3. We present probability distribution of soil SPT-N obtained from offshore wind farms in Taiwan.

4. The effect of uncertainty of SPT-N on the soil liquefaction potential assessment is presented.