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A case study on the soil classification of the Yellow River Delta based on piezocone penetration test

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Abstract

Piezocone penetration test (CPTu), the preferred *in-situ* tool for submarine investigation, is significant for soil classification and soil depth profile prediction, which can be used to predict soil types and states. However, the accuracy of these methods needs to be validated for local conditions. To distinguish and evaluate the properties of the shallow surface sediments in Chengdao area of the Yellow River Delta, seabed CPTu tests were carried out at ten stations in this area. Nine soil classification methods based on CPTu data are applied for soil classification. The results of classification are compared with the *in-situ* sampling to determine whether the method can provide sufficient resolution. The methods presented by Robertson (based on soil behavior type index I_c), Olsen and Mitchell are the more consistent and compatible ones compared with other methods. Considering that silt soils have potential to liquefy under storm tide or other adverse conditions, this paper is able to screen soil classification methods suitable for the Chengdao area and help identify the areas where liquefaction or submarine landslide may occur through CPTu investigation.

Key words: soil behavior classification, Chengdao area, seabed piezocone penetration test

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1 Introduction

Cone penetration test (CPT) and piezocone penetration test (CPTu) have been verified to be effective in site characterization and accurate in soil classification. Extensive research has correlated CPT and CPTu, preferred *in-situ* tools for underground surveys, soil exploration, and soil property evaluation, with soil types. Soil classification based on CPT data can guide geotechnical engineers effectively. Despite the ability to define a continuous depth profile and repeatability, CPT does not always evaluate data points of the same soil type in the actual situation.

Extensive research on soil classification based on CPT and CPTu measured parameters has been conducted, which was applied to engineering examples in different countries and regions (Abbaszadeh Shahri et al., 2015; Santoso et al., 2018; Du et al., 2019a).

The methods of classification generally adopts penetration resistance or pore pressure as parameters (Jefferies and Davies, 1991; Olsen and Mitchell, 1995; Eslami and Fellenius, 1997; Jefferies and Been, 2006; Schneider et al., 2008). Robertson et al. (1986) and Robertson (1990) have successively proposed non-normalized and normalized soil type classification charts, which have then been updated and compared (Robertson, 2010, 2016). In contrast, traditional laboratory tests are mainly based on the physical properties of soil (Cai et al., 2011). A large number of field data analysis shows that the soil classification results obtained by CPTu are basically consistent with the laboratory test results, with only a slight difference in the discrimination between silty sand and sandy silt (Osman and Ahmed, 2003; Shen et al., 2010; Eslami et al., 2017). When laying submarine pipelines and building offshore platforms, soil mechanical properties should be taken into account. Therefore, soil classification based on CPTu technology meets the requirements of engineering design better. Based on CPTu data, various classification methods can be used to predict soil types and states. Since the original soils used in the soil classification chart development will generally be different, the effectiveness still needs to be validated for local conditions (Abbaszadeh Shahri et al., 2015).

Chengdao area is the underwater area of the north of the Yellow River Delta with complex terrain, subsidence depression, and many submarine pipelines, submarine cables, natural gas pipelines, and oil platforms nearby. The surface sediments in Chengdao sea area are mainly silty soil, and silty clay (Du et al., 2019b), and the physical and mechanical properties are between sandy soil and clay. In the soft soil seabed foundation, the sink

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tube at the joint is likely to be broken as being settled unevenly along the longitudinal direction. Moreover, under the influence of waves and other factors, the soil is prone to liquefaction, resulting in a series of marine engineering geological disasters such as the dumping of oil recovery platforms and the fracture of submarine pipelines (Xu et al., 2009). Due to the need of engineering construction, the current CPTu test carried out in Chengdao sea area is relatively ordinary. However, it is not clear which currently used soil classification method can provide higher resolution in this area.

This study aims to find an applicable method for the classification of silty soil of the study area. Nine soil classification and prediction methods based on CPTu data, including the traditional and the non-traditional, are tested to find the one with the highest resolution and accuracy for identifying the area with liquefaction or submarine landslide and guiding site selection and foundation design of marine engineering in this area.

2 Soil type classification methods and *in-situ* data acquisition

2.1 *Soil type classification methods*

In recent years, soil classification charts have been widely used to assess the soil type and state based on CPT or CPTu data (Long, 2008; Cai et al., 2011). The methods proposed by Robertson et al. (1986), Robertson (1990), Olsen and Mitchell (1995), Eslami and Fellenius (1997), Jefferies and Been (2015), Brouwer (2007), Robertson (2009) and Robertson (2010) were tested to demonstrate the applicability.

Before Robertson et al. (1986) and Campanella and Robertson (1988) provided a chart based on the piezocone with the cone resistance corrected for pore pressure at shoulder, most classification charts (Douglas and Olsen, 1981; Jones and Rust, 1982) used the cone penetration resistance (q_c), sleeve friction (f_s) and friction ratio (R_f), whose relation can be demonstrated by Eq. (1) :

$$R_f = \frac{f_s}{q_c}. \tag{1}$$

Baligh et al. (1980) have studied the effect of pore pressures on the measured penetration resistance and sleeve friction and proposed that the cone resistance (q_c) could be corrected to a total cone resistance (q_t), using Eq. (2), which includes the pore pressure (u_2) measured at shoulder and the net area ratio (a, a=0.665 in this study) between load cell support and cone:

$$q_t = q_c + (1 - a)\,u_2. \tag{2}$$

Since q_t, f_s and u_2 all tend to increase with increasing overburden, the accuracy of the soil classification charts with q_t and R_f will be affected, and corresponding errors will be generated when the classification charts is used for deep soil. By considering the corrected cone resistance (q_t), the total and effective overburden stress (σ_v and σ'_v), Wroth (1984, 1988) has suggested that CPTu data should be normalized by Eqs (3) and (4), respectively:

$$Q_t = \frac{q_t - \sigma_v}{\sigma'_v}, \tag{3}$$

$$F_r = \frac{f_s}{q_t - \sigma_v}. \tag{4}$$

Although they initially objected to this way of calculating the pore pressure ratio (B_q) (Senneset and Janbu, 1985; Wroth, 1988), the chart of Robertson et al. (1986) introduced B_q, defined by Eq. (5):

$$B_q = \frac{u_2 - u_0}{q_t - \sigma_v}, \tag{5}$$

where u_0 is *in-situ* equilibrium pore pressure.

The Robertson et al. (1986) soil classification chart, which plots q_t against R_f based on CPTu data, is divided into twelve zones to represent different grain size distribution and different soil state or behavior coded by number. For example, zone 1 indicates sensitive fine-grained soil and stiff fine-grained soil belongs to zone 11.

Robertson (1990) has developed a refined soil classification chart using the normalized cone resistance (Q_t) and the normalized friction ratio (F_r). The normalized chart is divided into nine zones coded by number, according to the soil state related to geotechnical properties. Robertson (1990) chart differs from that proposed by Robertson et al. (1986) in that zones 3–10 were redistributed and transformed to zones 3–7.

Scholars have proposed the classification charts of normalized SBTn soil type based on that of Robertson (Jefferies and Davies 1991; Olsen and Mitchell, 1995; Ramsey, 2002). Olsen and Mitchell (1995) have laid the foundation of cone normalization by incorporating over twenty years of *in-situ* data and the large database of chamber tests established by other engineers or researchers, which have proposed a soil classification chart plotting Q_t against R_f.

Eslami and Fellenius (1997) have introduced a soil profiling chart according to the non-normalized parameters plotting the effective cone resistance (q_e) against f_s established based on CPT data obtained from 20 sites in 5 countries.

Jefferies and Been (2006) have developed a refined version of the Jefferies and Davies (1993) chart based on the parameter $Q_t\,(1 - B_q) + 1$ to solve the problem that $B_q > 1$ in soft sensitive soils. The parameter $Q_t\,(1-B_q)+1$ can be defined by Eq. (6):

$$Q_t\,(1 - B_q) + 1 = \frac{q_t - u_2}{\sigma'_v}. \tag{6}$$

Brouwer (2007) has presented a soil type classification chart, plotting the cone resistance (q_c) against the friction ratio (R_f) based on a large number of *in-situ* tests. Jefferies and Davies (1993) have found the curve clusters in soil classification chart can be approximated by concentric circles, and defined the radius of the concentric circles as soil behavior type index, I_c, which could represent the SBTn zones in the normalized chart.

By considering the parameter $Q_t\,(1 - B_q)$, which incorporates the normalized B_q into the modified normalized cone resistance, Robertson and Wride (1998) have applied the modified I_c to the Robertson (1990) chart. Ku et al. (2010) have made the applicability of I_c as an index for soil behavior classification in the investigation. Jefferies and Davies (1993) have suggested that Eq. (7) can be applied to the calculation of the SBT index (I_c):

$$I_c = \sqrt{\left[3 - \log_{10} Q_t\,(1 - B_q)\right]^2 + \left(1.5 + 1.3\log_{10} F_r\right)^2}. \tag{7}$$

Robertson (2010) has updated Robertson et al. (1986) chart in terms of dimensionless cone resistance (q_c/p_a), where p_a is the standard atmospheric pressure ($p_a = 100$ kPa) and reduced the number of SBT to nine to match the Robertson (1990) chart.

Moreover, Robertson (2010) has proposed a new non-normalized soil behavior type index ($I_{\rm SBT}$) using the basic non-normalized CPT results, which can be defined by

$$I_{\rm SBT}=\sqrt{\left[3.47-\log_{10}\left(\frac{q_{\rm c}}{p_{\rm a}}\right)\right]^2+(\log_{10}R_{\rm f}+1.22)^2}. \tag{8}$$

Theoretically, the normalized SBT index ($I_{\rm c}$) is more accurate for soil classification than $I_{\rm SBT}$ but the difference is small when the *in-situ* vertical effective stress is between 50 kPa and 150 kPa (Robertson, 2010). Furthermore, the soil classification methods based on the non-normalized soil behavior type index only use the basic CPT measurements. Thus, Robertson (2010) recommended that the normalized SBT chart should be applied to the later post-processing of CPT results, but the non-normalized SBT chart will be suitable for use in real-time data processing and interpretation.

2.2 *In-situ data acquisition*

The cone penetration test equipment used in this paper is the marine engineering geological environment *in-situ* survey system developed by the research team. The equipment adopts the electronic CPTu probes, all of which meet EN ISO 22476-1 standard, and model GC10CFIIP developed by Geomil in the Netherlands. The equipment takes the seabed penetration and sampling platform as the main body and performs seabed static touchingand seabed photography. After the equipment sat on the seabed, the system attitude was checked and adjusted to meet the requirements for the operation. Four anchor rods are inserted, then CPTu probe rods are penetrated, and data collection and storage are completed during the penetration process, and then the sampling tube is penetrated. The system is recovered by pulling out the probing rod, sampling tubes and anchor rods in turn. The structure and technical index of marine engineering geological environment *in-situ* investigation system are shown in Fig. 1 and Table 1.

As the average slope is 7°–8°, and the local slope is about 45°, the study area may be prone to landslides. A thick layer of silty soil dominates the surface of the soil profile. Partially sandwiched silty clay is mainly in a medium-dense state with the standard penetration test-number (SPT-N) values of 12 to 31. The density of the silty soil is 19.4–20.1 kN/m^3 with the mean diameter of 0.03 mm, and moisture content of 27.4%–32.3%.

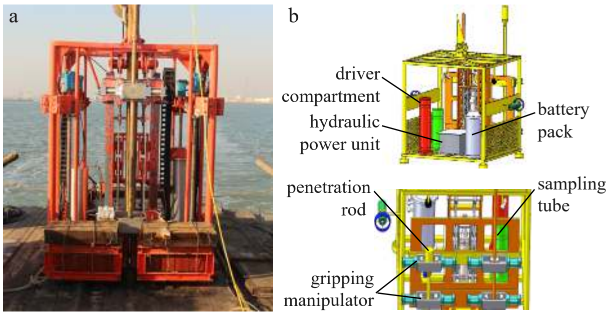

Fig. 1. Photograph (a) and structure (b) of marine engineering geological environment *in-situ* investigation system.

Ten piezocone penetration tests were carried out in the Yellow River Delta region, with average footage of 4.2 m and an average water depth of 16 m. The locations and parameters of the test points are shown in Fig. 2 and Table 2. CPTu data of 1-4, 1-5, 2-4, and 2-5 measurement points were used in this study. Nine soil classification and prediction methods based on CPTu data were tested, including the traditional and the non-traditional. By comparing the advantages and disadvantages of the above methods, the suitable method of processing the silt soil layer data is determined.

3 Interpretation of CPTu data and soil classifications

As indicated in Figs 3a and b, corrected resistance is in the range of 100–1 500 kPa and the sleeve friction is in the range of 0–23 kPa. The cone resistance of 2-4 below 4.5 m and that of 2-5 below 3.4 m varies significantly. Meanwhile, as presented in Fig. 3c, the excess pore pressure is mainly positive and tends to increase, but below 3.4 m depth, the excess pore pressure of 2-5 shows a decreasing trend, which can be interpreted as that the soils are either dense or over-consolidated and will have a decreasing trend in drilling test, even produce negative pore water pressure. Cai et al. (2011) have indicated that high negative pore pressure is also possible for high-density fine sands and dilative silts.

Variations of corrected tip resistance (from Eq. (4)) versus sleeve friction and friction ratio (from Eq. (5)) for the test points are shown in Fig. 4. Since the CPTu data obtained from the study area show a significant variation in cone resistance 2-4 and 2-5 (can be seen from the ellipse in Figs 4a–d). Therefore, before analyzing soil classification, the relationship between corrected cone resistance and CPTu parameters was established to investigate which soil groups (granular, cohesive, and non-cohesive) the obtained data belongs to. According to Begemann (1965), Sanglerat et al. (1974), and Schmertmann (1975), the friction ratio varies from 2% to 5%, indicating a mixture of clay-sand and silt. The friction ratio mainly changes between 0 and 1.6% (Figs 4e–h), which may indicate sand mixtures to silty mixtures.

4 Evaluation of soil classification method based on CPTu in the study area

4.1 *Evaluation of soil classification charts*

This section presents the classification methods proposed by Robertson et al. (1986), Robertson (1990), Eslami and Fellenius (1997), Jefferies and Been (2006), and Robertson (2010), the charts obtained by traditional site investigation techniques (Olsen and Mitchell, 1995; Brouwer, 2007) were also used for classification and analysis of soil types and behavior. The above soil classification methods had been widely used in engineering examples.

Table 1. Technical index of marine engineering geological environment *in-situ* investigation system

Item	Value	Item	Value
Working depth	1 500 m	Hydraulic	insert 10 MPa/ pull out 12 MPa
Probing rod	Φ36 mm	Control mode	armored coaxial cable deck control
Sampling tube	Φ75 mm/Φ110 mm casing pipe	Penetration way	hydraulic step motor
Penetration depth	7 m (One step penetration 1 m)	Dimensions	2 000 mm×1 600 mm×2 000 mm
Penetration rate	2 cm/s±5%	Weight in air	4.5 t

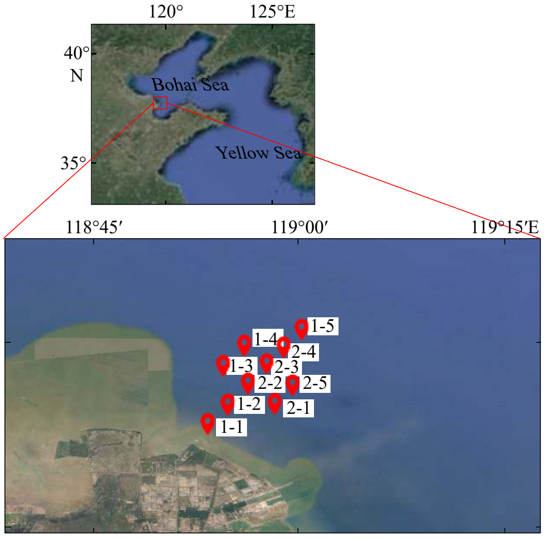

Fig. 2. The map of investigation position in the study area.

The SBT soil classification chart proposed by Robertson et al. (1986) was used to classify the soil and compared with the drilling data. The results are shown in Fig. 5a. It can be seen from Fig. 5a that the SBT chart proposed by Robertson et al. (1986) can accurately distinguish cohesive soil and non-cohesive soil. Test points 1-4 and 1-5 are concentrated in zone 1, the “sensitive fine-grained soil” zone. Most points 2-4 and 2-5 are also concentrated in zone 1, with a few entering zone 3, the “clay to silty clay” zone, zone 5, the “clayey silt & silty clay” zone, and zone 6, the “silty sand to sandy silt” zone.

The uncertainty in determining the type of silty soil in the SBT chart is mainly reflected in the errors at test points 2-4 and 2-5. Some “clayey silt & silty clay” enter into the “clay to silty clay” zone, while others enter into the “clayey silt & silty clay” zone of the SBT chart with great discreteness, affecting the accuracy of soil type classification. It can be seen that the classification accuracy of silt mixtures is poor.

Figures 5b, c and Table 3 show the soil classification results according to the Robertson (1990) soil type classification chart and the Robertson (2010) soil type classification chart, respectively. According to Robertson (1990) SBTn chart, soil state distributes in 1–6 zones but concentrates in 3–4 zones, which is consistent with the properties of silt soils and based on Robertson (2010) SBT chart, soil types of 1-4 and 1-5 change in zone 1, while that of 2-4 and 2-5 change in zone 1, 3, and 4.

All the above three soil-type classification charts can identify the existence of sensitive fine grained soil. According to the sampling data, both 2-4 and 2-5 stations have sensitive fine-grained soil layers. The chart proposed by Robertson (1990) shows good accuracy in the classification of sensitive fine grained soils.

The CPTu data were projected into the traditional field survey techniques proposed by Brouwer (2007), and the classification results were shown in Fig. 6a. As can be seen from the chart,

Table 2. Field parameters of the test points

Position	Latitude	Longitude	Footage/m	Water depth/m
1-1	38°08′07.86″N	118°54′07.86″E	4.2	7.0
1-2	38°09′36.42″N	118°54′44.16″E	4.2	8.5
1-3	38°11′24.60″N	118°53′15.06″E	4.2	10.0
1-4	38°14′03.18″N	118°55′13.32″E	4.2	16.0
1-5	38°17′53.28″N	119°00′57.42″E	4.2	19.0
2-1	38°09′39.00″N	118°57′01.92″E	4.2	10.0
2-2	38°10′25.50″N	118°55′18.72″E	1.3	10.0
2-3	38°13′01.86″N	118°57′15.78″E	4.8	15.5
2-4	38°14′08.10″N	118°58′06.06″E	5.0	16.5
2-5	38°11′24.63″N	118°58′57.84″E	5.0	15.5

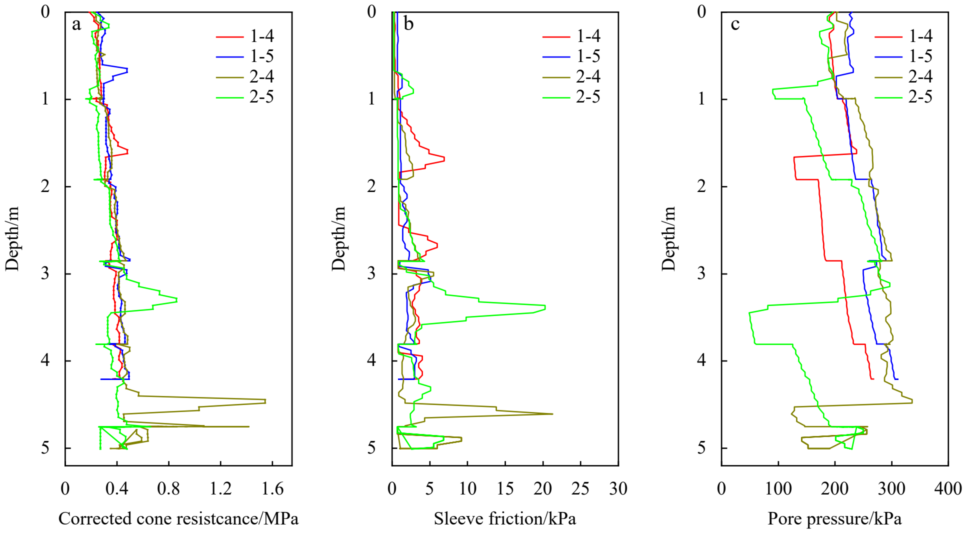

Fig. 3. CPTu plots from four test points in the study area.

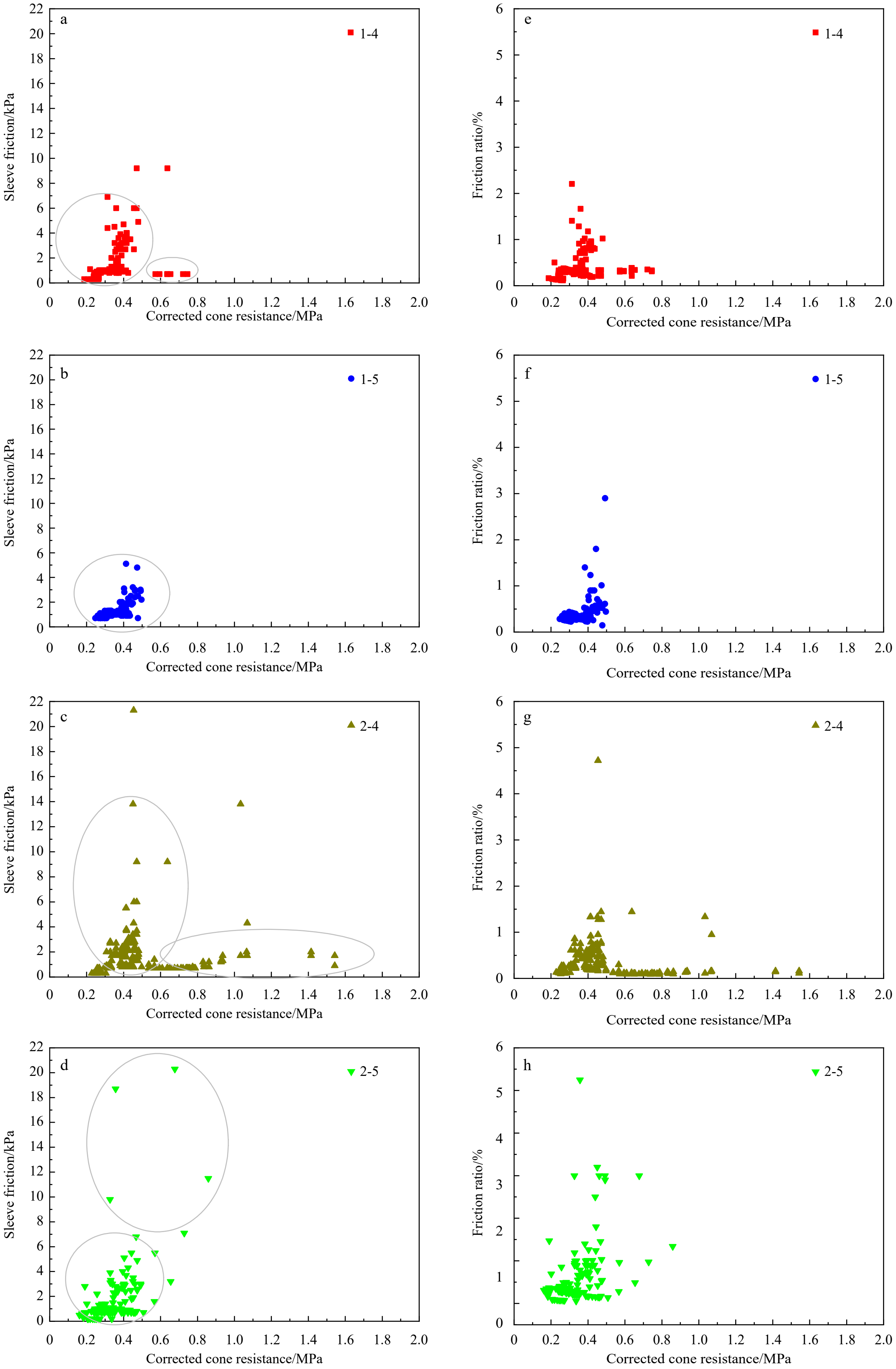

Fig. 4. Variations of corrected cone resistance versus sleeve friction (a–d) and friction ratio (e–h) for the test points.

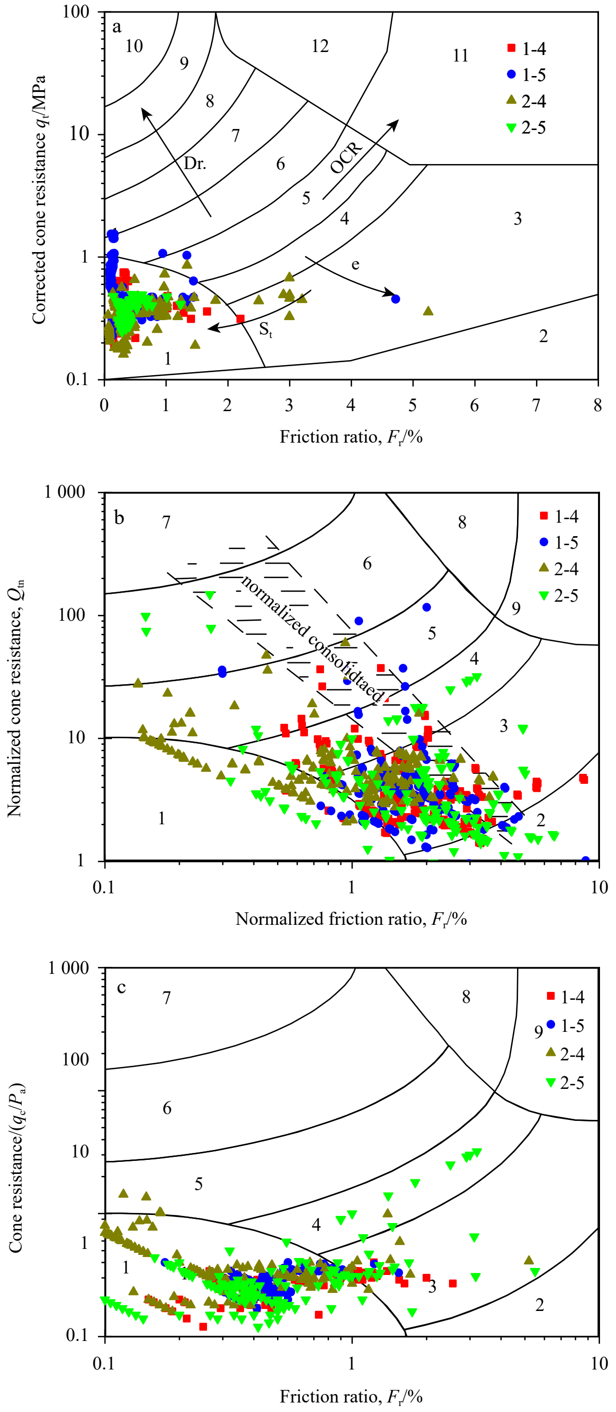

Fig. 5. Soil-type classification based on the chart proposed by Robertson et al. (1986) (a), Robertson (1990) (b) and Robertson (2010) (c). OCR indicates overconsolidation ratio; Dr., density ratio; S_t, sensitivity; e, void ratio.

1-4, 2-4, and 2-5 data points are divided into very silty soil, and a very small amount of data points are divided into soft clay and soft organic clay. Most of the data points in 1-5 are divided into a very loose sand zone, and a small number of data points are divided into “coarse sand and gravel” and “sandy clay” zone, and a tiny number of data points are divided into stiff clay area.

According to Fig. 6b, in the charts offered by Jefferies and Been (2006), soil state distributes in all five zones but concentrates in “clayey silt” and “silty sand to sandy silt” zones. Based on the charts proposed by Eslami and Fellenius (1997), soil is classified as sensitive-collapsable clay silt, sometimes clay silt, as shown in Fig. 6c. As shown in the chart, 1-4 and 1-5 points are mostly divided into zone1-collapsive soil and sensitive soil, 2-4 and 2-5 points are also mainly divided into zone 1 and zone 2-soft clay and soft silt. However, a few 2-5 points are divided into zone 5-sand and gravel, indicating that some errors occur in the judgment of silty clay, silty sand, and silt.

According to the soil classification method developed by Olsen and Mitchell (1995), the classification varies significantly from clays to loose sand with a predominance in silt mixtures and sand mixtures, as shown in Fig. 6d. Olsen and Mitchell (1995) soil type classification chart is similar to that of Jefferies and other soil type classification charts. However, parameters *c* of soil compaction degree and consolidation degree are added in the chart proposed by Olsen and Mitchell (1995), improving the resolution and engineering application value.

4.2 *Evaluation of soil behavior type index*

Robertson (2010) has shown how to identify soil type according to the soil behavior type index, namely the normalized index I_c and the non-normalized index I_{SPT} (from Eqs (10) and (13) in Robertson (2010)). The SBT zones are color coded. Figure 7 shows the results of the four test points using normalized and non-normalized index classification charts. Based on the method using I_{SBT}, 1-4 and 2-4 and 2-5 points are covered with very soft, organic clay from the surface to a depth of about 0.6 m. Underlying are basically classified as clay to a depth of about 4 m. 1-5 point is classified as clay. According to the method using I_c, four points are mainly classified as sand mixtures, silty mixtures and clays. Where point 1-4 is at about 1 m depth, point 1-5 is at about 3 m and 3.7 m depth, and point 2-5 is at 2 m, 2.9 m, and 4.7 m all show the existence of clay-organic layers. Figure 7 shows that there is little difference between the soil behavior type interpretation for the profiles. In contrast, the classification method using the normalized index I_c is more responsive to changes of the soil type.

5 Discussion

Success rate, that is, the ratio of the number of correct predictions to the total number of predictions that classify the soil as coarse or fine-grained one is proposed as a standard to evaluate different methods. The success rate of the chart proposed by Robertson et al. (1986) is 65%, 80% using Robertson (1990), 70% using Robertson (2010), 85% using normalized index I_c, 75% using non-normalized index I_{SPT}, 70% using Eslami and Fellenius (1997), 80% using Brouwer (2007), 80% using Jefferies and Been (2006) and 85% using Olsen and Mitchell (1995). The difference in the success rate of Robertson’s series of classification methods is because the normalized cone resistance Q_{tn} calculation method considers the difference between cohesive soil and non-cohesive soil. As the difference is more significant in the non-cohesive soil zone, the boundary between different soil types is more obvious.

Success rate of Olsen and Mitchell and normalized index I_c both reach 85%. The former is based on the experience of a large number of measured data, while the latter is derived by formula. One limitation of normalization based on empirical data is that the soil layer must be “uniform” and must extend to a depth sufficient to be used to calculate the normalization data. It is difficult for

Table 3. Proposed unification between 12 SBT zones and 9 SBTn zones (adopted from Robertson (2010))

SBT zone (Robertson et al., 1986)	SBTn zone (Robertson, 1990), SBT zone (Robertson, 2010)	Proposed common SBT description
1	1	sensitive fine-grained
2	2	clay-organic soil
3	3	clays: clay to silty clay
4&5	4	silt mixtures: clayey silt & silty clay
6&7	5	sand mixtures: silty sand to sandy silt
8	6	sands: clean sands to silty sands
9&10	7	dense sand to gravelly sand
12	8	stiff sand to clayey sand*
11	9	stiff fine-grained*

Note: * Overconsolidated or cemented.

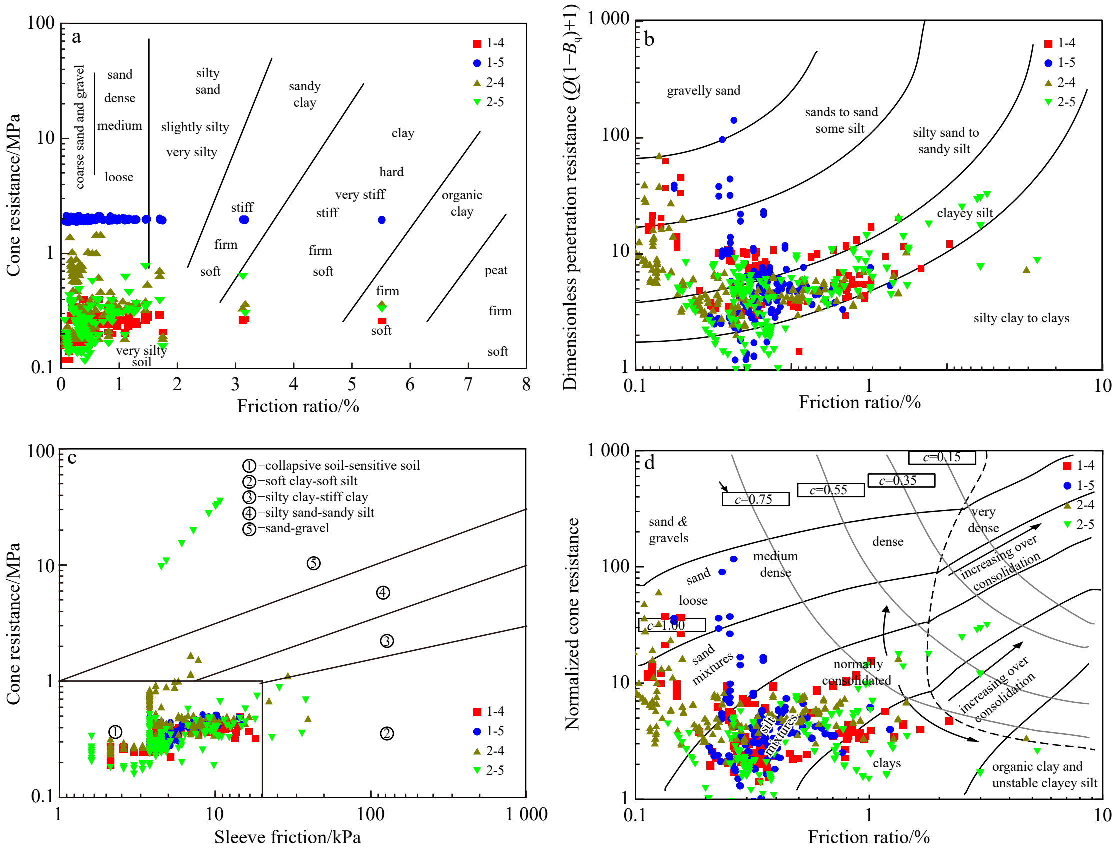

Fig. 6. Soil type classification based on the chart proposed by Brouwer (2007) (a), Jefferies and Been (2006) (b), Eslami and Fellenius (1997) (c), and Olsen and Mitchell (1995) (d).

silts to find uniform layers in the field to generate normalization data. Comparatively speaking, the methods based on normalized index I_c can be used to interpret the CPTu data on site more conveniently, while the chart proposed by Olsen and Mitchell can provide additional reference for compactness of soil.

According to the laboratory measurements of the boring samples, the correct prediction should be silty clay and silty soil. The classification charts proposed by Robertson (2010) (based on normalized index I_c), Robertson (1990), Brouwer (2007), Eslami and Fellenius (1997), Jefferies and Been (2006), and Olsen and Mitchell (1995) show a high success rate to predict soil types. But only the charts proposed by Robertson (2010) (based on normalized index I_c) and Olsen and Mitchell (1995) provide enough resolution. Therefore, the soil classification methods proposed by Robertson (2010) (based on normalized index I_c) and Olsen and Mitchell (1995) are recommended for the investigation of the silty soil area. Two other test points that had both CPT data and corresponding soil layer relationships obtained from the drilling were selected for analysis and comparison (Jia et al., 2011; Chu et al., 2017). The same concept of success rate is used to classify soils as either coarse-grained or fine-grained (Table 4). From two points it can be seen that the methods proposed by I_c and Olsen and Mitchell (1995) still provides a higher success rate.

From the geological map of marine hazards in the Yellow River Delta (Zhou et al., 2004), it can be seen that the four test points are in the transition position from the front edge of the disturbed delta to the front edge of the smooth delta, and according to the geological data this area belongs to the steep slope zone (average slope of 8°) and exists sediment cliff (Jia et al., 2004; Meng et al., 2008; Yang et al., 2020). According to the classifica-

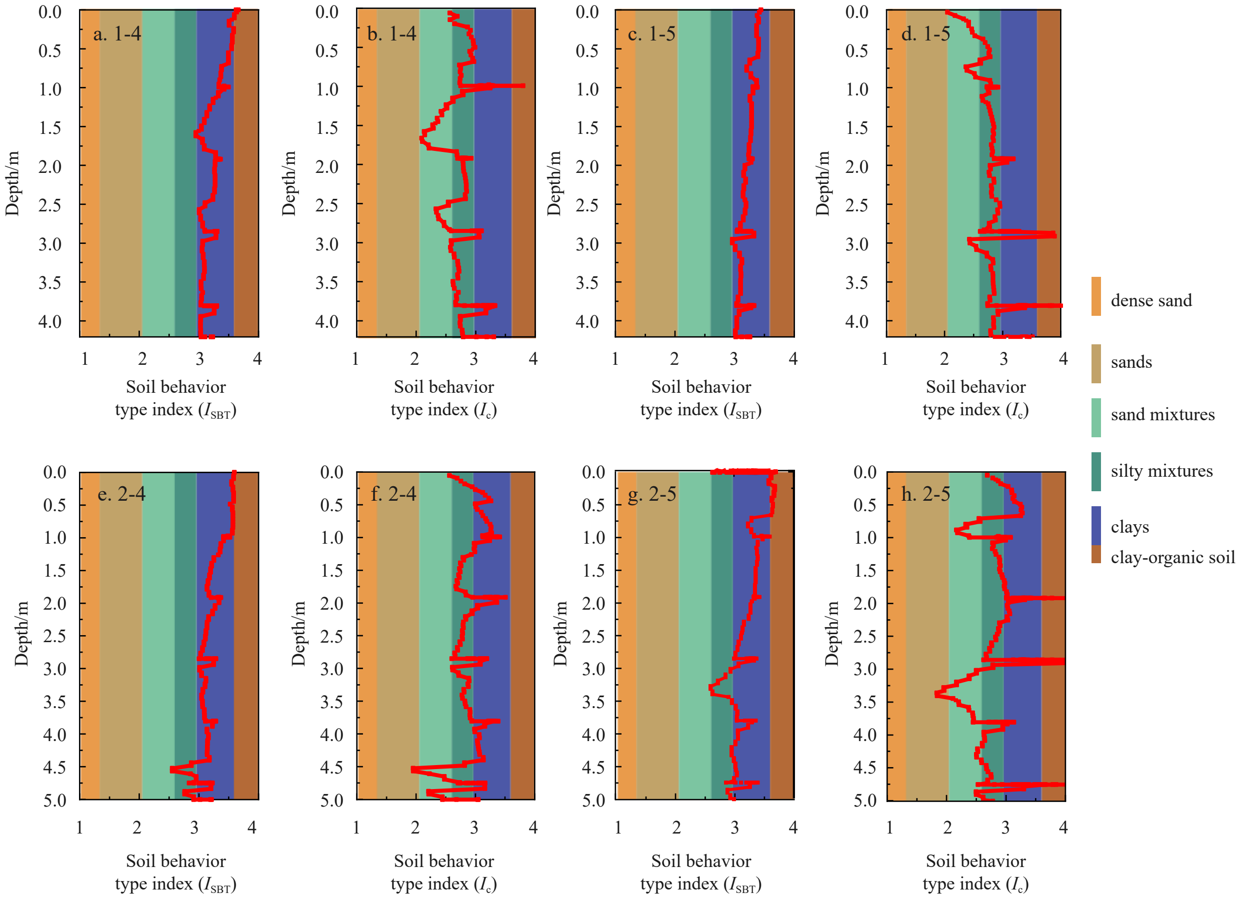

Fig. 7. Soil type classification for test points based on I_{SBT} (a, c, e and g) and I_c (b, d, f and h).

Table 4. Correlation level of different soil classification methods to the test points

Methods	Point C3/K3 (Chu et al., 2017)	Point in Dongying Port (Jia et al., 2011)
Robertson et al. (1986)	65	65
Robertson (1990)	70	70
Robertson (2010)	65	65
Olsen and Mitchell (1995)	70	70
Eslami and Fellenius (1997)	50	50
Jefferies and Been (2006)	45	50
Brouwer (2007)	60	65
I_c	75	70
I_{SBT}	65	60

tion method of normalized index I_c, it can be presumed that four test points are mainly silty clay and silty sand, with all overlying soft soil layers (Fig. 8). Soft silt soil layers may liquefy under extreme sea conditions, and exist a higher risk of landslide. A large number of oil pipelines and oil drilling platform are located in the deep flat-bottom areas on the edge of the study area, which will certainly cause economic losses during the occurrence of marine geological hazards. Further submarine geological investigation of the area is desperately needed.

6 Conclusions

In this study, the CPTu test results of the Yellow River Estuary were used to predict soil depth profiles. Nine soil classification methods based on CPT data, including those proposed by Robertson et al. (1986), Robertson (1990), Olsen and Mitchell (1995), Eslami and Fellenius (1997), Jefferies and Been (2006), Brouwer (2007), and Robertson (2010) were applied for soil type and state prediction and interpretation.

(1) The analysis shows that the classification methods can explain the submarine soil types, but the accuracy needs to be tested. The comparison indicates that soil types can be predicted with CPTu data. In this study, the methods proposed by Robertson (based on normalized index I_c) and the charts proposed by Olsen and Mitchell are the most consistent and compatible ones.

(2) The sensitive fine-grained soil layer of the test station can be identified more accurately by normalized index I_c proposed by Robertson. Combined geological data from the surveyed area (average slope of 8° with overlying soft soil), the potential landslide risk in the sea near the test stations can be predicted.This paper helps to recognize and identify zones comprising silty soils in Chengdao area.

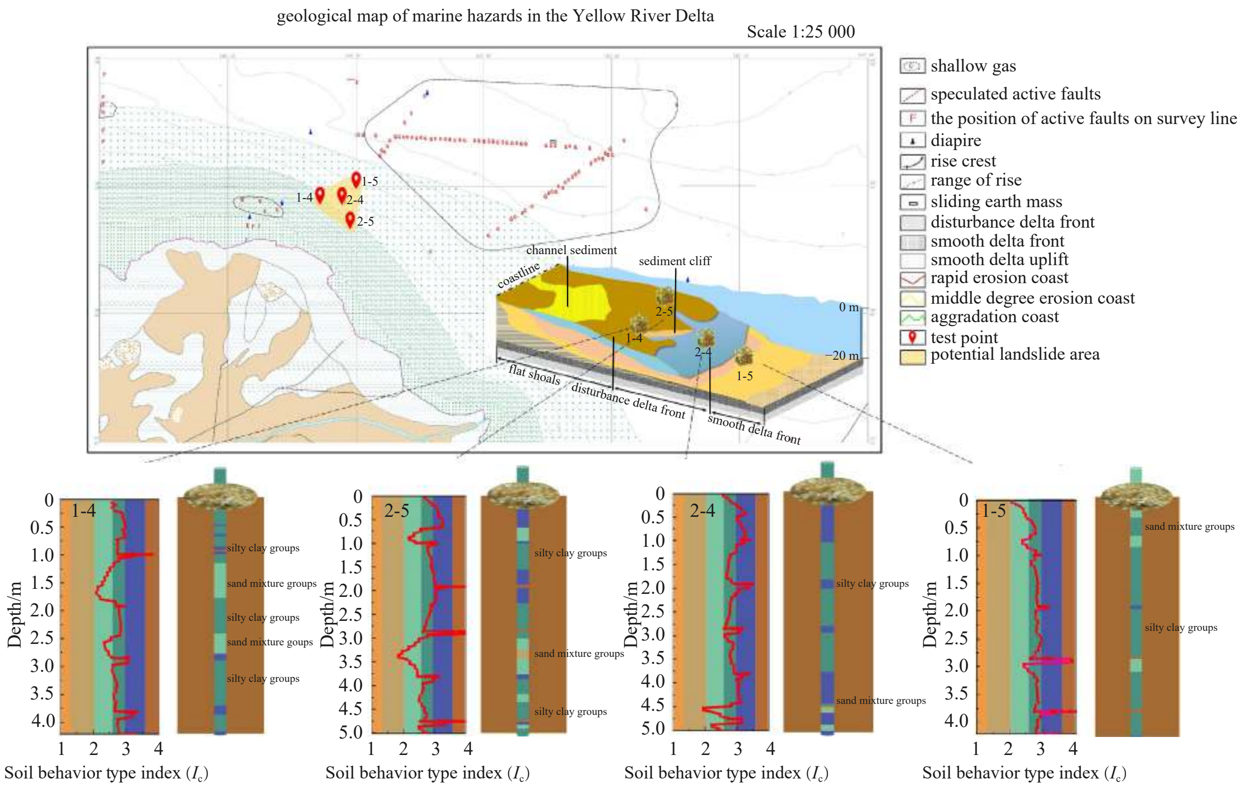

Fig. 8. Prediction of potential landslide risk areas based on soil classification method.

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References

Abbaszadeh Shahri A, Malehmir A, Juhlin C. 2015. Soil classification analysis based on piezocone penetration test data—A case study from a quick-clay landslide site in southwestern Sweden. Engineering Geology, 189: 32–47, doi: 10.1016/j.enggeo.2015.01.022

Baligh M M, Ladd C C, Vivatrat V. 1980. Cone penetration in soil profiling. Journal of the Geotechnical Engineering Division, 106(4): 447–461, doi: 10.1061/AJGEB6.0000948

Begemann H K S. 1965. The friction jacket cone as an aid in determining the soil profile. In: Proceedings of the 6th International Conference on Soil Mechanics and Foundation Engineering. Montreal: Springer, 17–20

Brouwer H. 2007. *In Situ* Soil Testing. East Sussex: Lankelma, 144

Cai Guojun, Liu Songyu, Puppala A J. 2011. Comparison of CPT charts for soil classification using PCPT data: example from clay deposits in Jiangsu Province, China. Engineering Geology, 121(1-2): 89–96, doi: 10.1016/j.enggeo.2011.04.016

Campanella R G, Robertson P K. 1988. Current status of the piezocone test. In: Proceedings of the 1st International Symposium on Penetration Testing. Orlando, FL: Pergamon Press, 93–116

Chu Lipeng, Sun Yongfu, Song Yupeng, et al. 2017. Application of seabed cone penetration test in research on the seafloor geotechnical engineering characteristics in the Yellow River Estuary. Coastal Engineering, 36(1): 22–33

Douglas B J, Olsen R S. 1981. Soil classification using electric cone penetrometer. In: Cone Penetration Testing and Experience. St. Louis, MO: ASCE, 209–227

Du Guangyin, Gao Changhui, Liu Songyu, et al. 2019a. Evaluation method for the liquefaction potential using the standard penetration test value based on the CPTU soil behavior type index. Advances in Civil Engineering, 2019: 5612857

Du Xing, Sun Yongfu, Song Yupeng, et al. 2019b. In site monitoring of wave-induced pore pressure of silt in Chengdao sea area of Yellow River Estuary. Haiyang Xuebao (in Chinese), 41(7): 116–122

Eslami A, Alimirzaei M, Aflaki E, et al. 2017. Deltaic soil behavior classification using CPTU records—Proposed approach and applied to fifty-four case histories. Marine Georesources & Geotechnology, 35(1): 62–79

Eslami A, Fellenius B H. 1997. Pile capacity by direct CPT and CPTu methods applied to 102 case histories. Canadian Geotechnical Journal, 34(6): 886–904, doi: 10.1139/t97-056

Jefferies M G, Been K. 2006. Soil Liquefaction—A Critical State Approach. New York: Taylor & Francis, 206-217

Jefferies M G, Been K. 2015. Soil Liquefaction: A Critical State Approach. Boca Raton, FL: CRC Press

Jefferies M G, Davies M P. 1991. Soil classification by the cone penetration test: Discussion. Canadian Geotechnical Journal, 28(1): 173–176, doi: 10.1139/t91-023

Jefferies M G, Davies M P. 1993. Use of CPTU to estimate equivalent SPT *N*60. Geotechnical Testing Journal, 16(4): 458–468, doi: 10.1520/GTJ10286J

Jia Yonggang, Huo Suxia, Xu Guohui, et al. 2004. Intensity variation of sediments due to wave loading on subaqueous delta of Yellow River. Rock and Soil Mechanics, 25(6): 876–881

Jia Yonggang, Shan Hongxian, Yang Xiujuan, et al. 2011. Sediment Dynamics and Geologic Hazards in the Estuary of Yellow River, China. Beijing: Science Press, 103–116

Jones G A, Rust E. 1982. Piezometer penetration testing CUPT. In: 2nd European Symposium on Penetration Testing. Amsterdam: CRC Press, 607–613

Ku C S, Ou C Y, Juang C H. 2010. Reliability of CPT I_C as an index for mechanical behaviour classification of soils. Géotechnique, 60(11): 861–875

Long M. 2008. Design parameters from *in situ* tests in soft ground—recent developments. In: Geotechnical and Geophysical Site Characterization. Taipei: CRC Press, 97–124

Meng Xiangmei, Jia Yonggang, Liu Xiaoli. 2008. Study on zoning and liquefaction induced by wave of Chengdao in Yellow River Delta. Journal of Engineering Geology, 16(S1): 44–53

Olsen R S, Mitchell J K. 1995. CPT stress normalization and prediction of soil classification. In: International Symposium on Cone Penetration Testing. Linköping: SGI report, 257–262

Osman M A, Ahmed E F O. 2003. Evaluation of cone penetration test (CPT) classification methods for some local soils. Journal of Building and Road Research, 5(1): 37–46

Ramsey N. 2002. A calibrated model for the interpretation of cone penetration tests (CPTs) in North Sea Quaternary Soils. In: Offshore Site Investigation and Geotechnics: Diversity and Sustainability. London, OnePetro, 341–356

Robertson P K. 1990. Soil classification using the cone penetration test. Canadian Geotechnical Journal, 27(1): 151–158, doi: 10.1139/t90-014

Robertson P K. 2009. Interpretation of cone penetration tests—a unified approach. Canadian Geotechnical Journal, 46(11): 1337–1355, doi: 10.1139/T09-065

Robertson P K. 2010. Soil behaviour type from the CPT: an update. In: 2nd International Symposium on Cone Penetration Testing. Huntington Beach: Cone Penetration Testing Organizing Committee, 575–583

Robertson P K. 2016. Cone penetration test (CPT)-based soil behaviour type (SBT) classification system—An update. Canadian Geotechnical Journal, 53(12): 1910–1927, doi: 10.1139/cgj-2016-0044

Robertson P K, Campanella R G, Gillespie D, et al. 1986. Use of piezometer cone data. In: Use of in Situ Tests in Geotechnical Engineering. Blacksburg, VA: ASCE, 1263–1280

Robertson P K, Wride C E. 1998. Evaluating cyclic liquefaction potential using the cone penetration test. Canadian Geotechnical Journal, 35(3): 442–459, doi: 10.1139/t98-017

Sanglerat G, Nhim T V, Sejourne M, et al. 1974. Direct soil classification by static penetrometer with special friction sleeve. In: 1st European Symposium on Penetration Testing. Stockholm: National Swedish Building Research, 337–344

Santoso P B, Yanto, Apriyono A, et al. 2018. Inverse distance weighting interpolated soil properties and their related landslide occurrences. MATEC Web of Conferences, 195: 03013, doi: 10.1051/matecconf/201819503013

Schmertmann J H. 1975. Measurement of *in situ* shear strength. In: *In Situ* Measurement of Soil Properties. Raleigh, NC: ASCE,57–138

Schneider J A, Randolph M F, Mayne P W, et al. 2008. Analysis of factors influencing soil classification using normalized piezocone tip resistance and pore pressure parameters. Journal of Geotechnical and Geoenvironmental Engineering, 134(11): 1569–1586, doi: 10.1061/(ASCE)1090-0241(2008)134:11(1569)

Senneset K, Janbu N. 1985. Shear strength parameters obtained from static cone penetration tests. In: Strength Testing of Marine sediments: Laboratory and *In-Situ* Measurement. West Conshohocken, PA: ASTM International, 41–54

Shen Shuilong, Wang Junpeng, Ma Lei. 2010. Identification of soil stratigraphy of soft deposit in Shanghai from CPTU test. In: Deep Foundations and Geotechnical *In Situ* Testing. Shanghai: ASCE, 384–392

Wroth C P. 1984. The interpretation of *in situ* soil tests. Géotechnique, 34(4): 449–489

Wroth C P. 1988. Penetration testing: a more rigorous approach to interpretation. In: 1st International Symposium on Penetration Testing. Orlando, FL: Pergamon Press, 303–311

Xu Guohui, Sun Yongfu, Wang Xin, et al. 2009. Wave-induced shallow slides and their features on the subaqueous Yellow River delta. Canadian Geotechnical Journal, 46(12): 1406–1417, doi: 10.1139/T09-068

Yang Zhongnian, Liu Xuesen, Guo Lei, et al. 2020. Evaluation of the soil characteristic parameters of the Yellow River Subaqueous Delta using CPT. Marine Georesources & Geotechnology, doi: 10.1080/1064119X.2020.1853287

Zhou Liangyong, Liu Jian, Liu Xiqing et al. 2004. Coastal and marine geo-hazards in the modern Yellow River Delta. Marine Geology & Quaternary Geology, 24(3): 19–27