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A review of cone penetration test in marine layered silt
海洋层状淤泥静力触探试验综述

Md. Ashikuzzaman[1], WANG Li-zhong[1,2], HONG Yi[1,2*]

(1. College of Civil Engineering and Architecture, Zhejiang University, Hangzhou 310058, Zhejiang, China;
2. Key Laboratory of Offshore Geotechnics and Material of Zhejiang Province, Zhejiang University, Hangzhou 310058, Zhejiang, China)

Abstract: The cone penetration test (CPT) and its variant with pore water pressure measurement (CPTU) are essential tools for site characterization, providing continuous, repeatable, and reliable data. Marine deposits, influenced by varying water velocities and suspended sediments, often form layered strata of silts, sands, or a mix of both. Even thin layers can significantly affect the overall permeability and degree of consolidation of marine deposits under loading. While many studies have investigated the behavior of uniformly mixed silts using laboratory and numerical methods, the behavior of heterogeneously mixed silts remains less understood. This review highlights research on CPT and CPTU applications, emphasizing the challenges of interpreting data from layered marine soils. It covers key findings on the drainage conditions of intermediate soils, normalized cone penetration parameters, and the impact of soil layering on pore water pressure responses. The review also identifies significant research gaps, such as the need for a better understanding of water flow mechanisms around the cone in thinly layered soils and the lack of a comprehensive framework for analyzing heterogeneously mixed marine silts. By addressing these gaps, future research can improve the accuracy and reliability of CPT and CPTU in characterizing complex marine soil deposits.

Key words: CPT; CPTU; review; layered silt; heterogeneously mixed silt

摘　要：静力触探试验（CPT）及孔压静力触探试验（CPTU）是场地土层参数测定的重要方法，能够获得连续且可靠的数据。海洋沉积物受不同水流速度和悬浮沉积物的影响，通常形成由粉砂、淤泥或两者混合而成的层状地层。即使是较薄的土层也会显著影响海洋沉积物在荷载作用下的整体渗透性和固结程度。尽管许多学者通过室内试验和数值方法研究了均匀混合粉砂的特性，但对异质混合粉砂的特性了解仍然不足。本文综述了 CPT 和 CPTU 的应用研究，指出了目前研究层状海洋土壤存在的问题与挑战。内容包括中层土壤的排水条件、标准化圆锥贯入参数以及土壤层状结构对孔隙压力响应的影响。综述还指出了目前存在的研究空白，例如对薄层土壤中圆锥周围水流机制的理解需进一步加强，以及缺乏分析异质混合海洋粉砂的综合框架。通过完善这些不足，未来的研究可以提高 CPT 和 CPTU 在测试复杂海洋土壤沉积物特性时的准确性和可靠性。

关键词：CPT；CPTU；综述；分层淤泥质土；异质混合淤泥质土

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0 Introduction

The cone penetration test (CPT) or with pore water pressure measurement (CPTU) is a widely used site characterization technique which can get continuous, repeatable and reliable data[1-3]. Marine deposits experience different types of water velocity and rapid variation of suspended residue and therefore, form layered strata of silts or sands or even a mix of both soils. Even if the soil layer is very small, continuous

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作者简介：Md. Ashikuzzaman (1995—), male, born in Meherpur, Bangladesh, PhD Candidate, he is working on the mineralogy and microstructure of glauconite sand with NGI and the University of Massachusetts Amherst. E-mail: ashik@zju.edu.cn.

*通信作者：HONG Yi (1985—), male, born in Jinhua, Zhejiang province, doctor, professor, he is mainly engaged in research in marine geotechnical engineering. E-mail: yi_hong@zju.edu.cn.

and few millimeters thick that could change the overall permeability of the total marine deposit and hence could alter the degree of consolidation under enforced loading effects[4-6]. When a cone approaches a permeable layer ahead of it, which may experience a dramatic behavior of soil due to having mix thin layering. Many researchers have tried to investigate the behavior using homogenously mixed silt in laboratory, and using numerical modeling. Yet the actual mechanism has not been investigated clearly.

This paper will review a quite range published articles and point out the research gaps for future perspective. This paper also creates a short database on CPT penetrating into thinly layered soil in laboratory and numerically.

1 Application of cone penetration test

1.1 Cone penetration test in uniformly mixed silt

Over the last few decades, researchers tried to investigate the drainage conditions for intermediate soils[7-8] and identified that variable penetration rate could be a suitable method to distinguish drained response from undrained response[7,9]. However, a non-dimensional parameter V is usually practiced to interpret CPT data[10-11], given by Eq. (1):

$$V = \frac{vd}{c_{\mathrm{v}}} \tag{1}$$

Where, v is the penetration velocity (traditionally 20 mm/s); d is the cone diameter (generally standard 35.7 mm); c_{v} is the vertical coefficient of consolidation[12]. The critical value of normalized velocity V are 0.01 and 30 for fully drained and fully undrained penetration[13].

In laboratory, most of the researchers[7,9,14] use uniformly mixed reconstituted silts which are commercially available and artificially produced. Even though different test results have been replotted in Fig. 1, it can be noticeable that a unified trend which form a narrow band. The abscissa represents the normalized cone velocity V and the ordinate presents the normalized pore water pressure which has been achieved by the excess pore water pressure Δu_2 divided by the initial excess pore water pressure $\Delta u_{2\mathrm{ini}}$ [15].

Cone resistance and sleeve friction response of cone penetration test are also important parameters for interpretation. To focus on the main conclusions of this paper, we emphasize on the pore water pressure response versus normalized cone velocity. A soil response taken in the vicinity of undrained region shows the behavior like a clayey soil in soil classification charts whereas a point near the drained region exhibits a sandy behavior. This behavior is well investigated and could involve partial drainage which subsequently affect the soil parameters followed by classification charts[2,7,16-19].

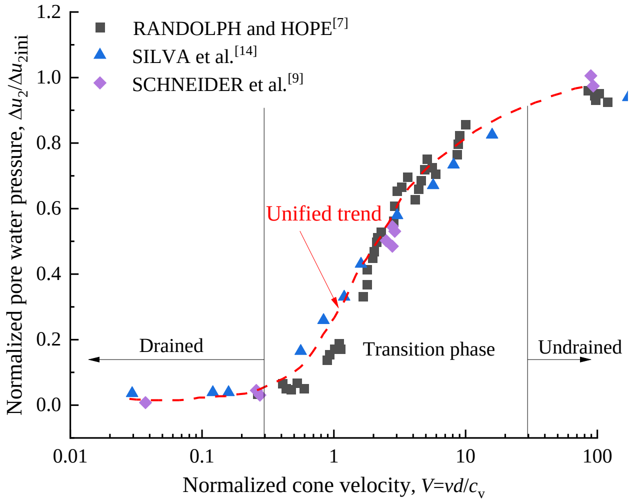


Fig. 1 Normalized cone velocity plotted against normalized pore water pressure

1.2 Cone penetration test with pore water pressure measurement in heterogeneously mixed silt

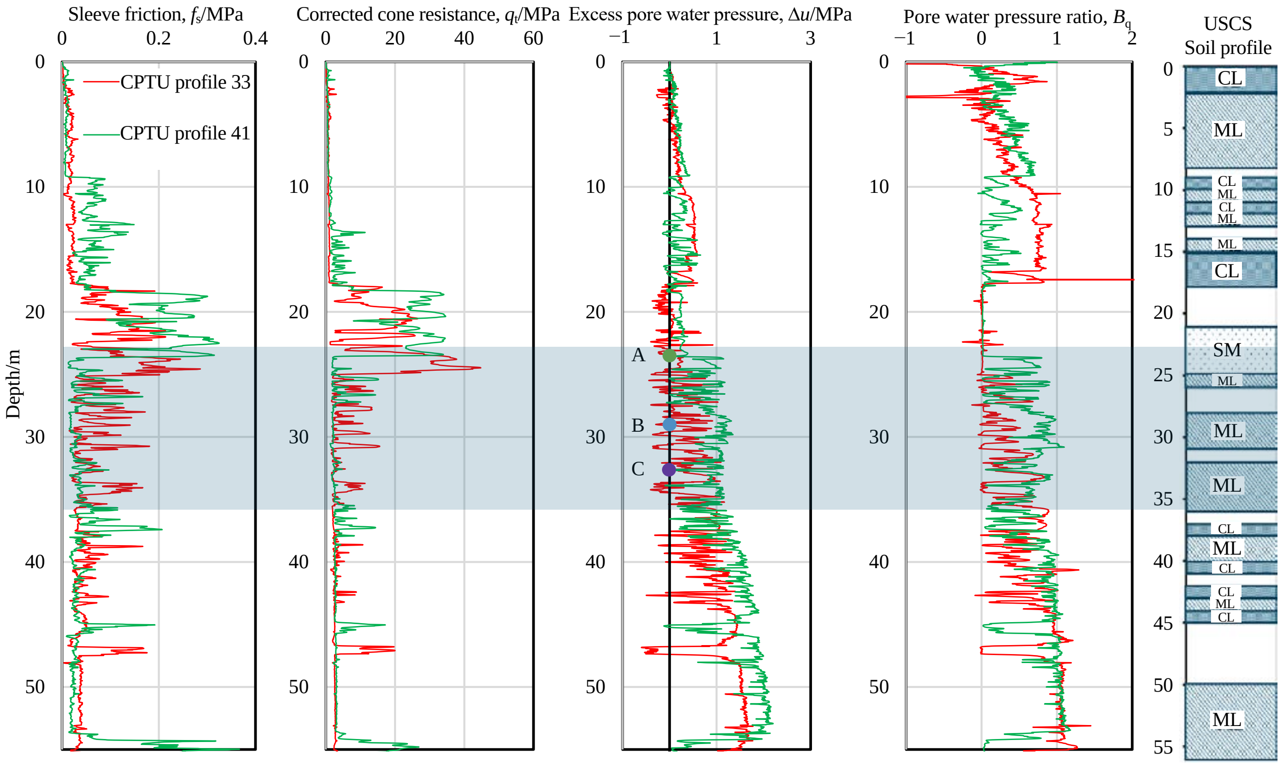
Fig. 2 depicts the typical in-situ CPTU results from the Yellow River along with Unified Soil Classification System (USCS). The undisturbed soil samples were collected carefully using thin-walled borrowers and transferred to the laboratory immediately to ensure high quality sampling. The laboratory testing, USCS classification as well as CPT profiling confirm the statement of presence of heterogeneously mixed thinly layered in the test sites (see Fig. 2). For CPTU profile 33 (Fig. 2), the corrected cone resistance, q_t starts to increase from 18 m below the top surface to a depth of 25 m. Below this layer, a large fluctuation of tip resistance is identified from the piezocone profiles. However, the pore water pressure produced during the cone penetration shows the same oscillations due to soil layering effect. For CPTU profile 41 (Fig. 2), the surface crust of q_t is observed at depth from 19-23 m, 35-37 m, and at 45 m. Pore water pressure at these locations shows corresponding decreasing behavior. Rapid fluctuation of pore water pressure ratio with respect to corrected cone resistance also ensure of having multilayered strata[1,20]. This relation is out of scope of this short review paper, hence are not included in this paper.

The corrected cone resistance, q_t and pore water pressure ratio, B_q are defined by Eqs. (2)–(3).

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

$$B_q = \frac{u_2 - u_0}{q_t - \sigma_v} = \frac{\Delta u}{q_t - \sigma_v} \tag{3}$$

Where, σ_v is the total overburden pressure; q_c is cone tip resistance and Δu is the excess pore water pressure (pore water pressure measured at u_2 position minus the static pore water pressure u_0, u_2 position is the pore water pressure measured by piezocone at cone shoulder position); a is the cone area ratio. Cone area ratio a is measured 0.75 for this investigation.



Note: CL represents low plasticity clay or lean clay; ML represents low plasticity silt or silt; SM represents silty sand.

Fig. 2 Typical CPTU profiles of the Yellow River, China with USCS soil profile

The soil samples were taken from a typical borehole location i.e., CPTU borehole No. 33 and the zone of influence was taken as 25-30 m. The laboratory testing (liquid limit, plastic limit) also confirms the soil as low plasticity silts (low plasticity silt or silt). Details description with methodology have been included in the author's thesis and ongoing research paper. Laboratory investigation mainly focuses homogeneous soil mixture to perform tests while in the field mostly soil prevails non-homogeneous with a combination of different soil strata[21-24]. In the field, ensuring the fully undrained condition is challenging due to the different band of soil strata in the same soil depth and mixing of subsoil.

This phenomenon becomes more complicated in the offshore sides because of continuous thrust from offshore structures, sea waves as well as the presence of interbedded soil layers. This closely spaced sandy layer in silty material accelerate to dissipate the excess pore water pressure during advancing the cone at even higher normalized penetration rate V. To observe the effect of free draining on the normalized parameters and subsequently soil classification charts, we picked three typical points namely A, B and C from the silty (Fig. 2). To observe the movement of data points due to free drainage, the picked data points were plotted on the normalized pore water pressure versus normalized cone velocity (Fig. 3) and on the soil classification chart proposed using normalized parameters (Fig. 4). These data points are plotted in semi-log $Q_\mathrm{t} - \Delta u_2 / \sigma'_\mathrm{v}$ space[25] where normalized cone resistance, Q_t is defined as follows:

$$Q_\mathrm{t} = \frac{q_\mathrm{t} - \sigma_\mathrm{v}}{\sigma'_\mathrm{v}} \tag{4}$$

Where, q_t is the corrected cone resistance; σ_v and σ'_v are the total overburden pressure and effective overburden pressure respectively.

A trimmed sample is attached with Fig. 3. The x-axis and y-axis represents the normalized cone velocity and normalized pore water pressure respectively in Fig. 3. It is interesting to mention that the data points tend to move towards essentially drained region from their actual silty region. This could be because of the thinly layered subsoil residues in the presence of interbedded soil and the ignorance of free drainage effect with closely spaced clean sands in silty marine deposits. The trimmed depicts a typical configuration of soil strata of different bands in this test site. It can be clearly observed the inclusion of clayey soil in between silty sand or vice versa.

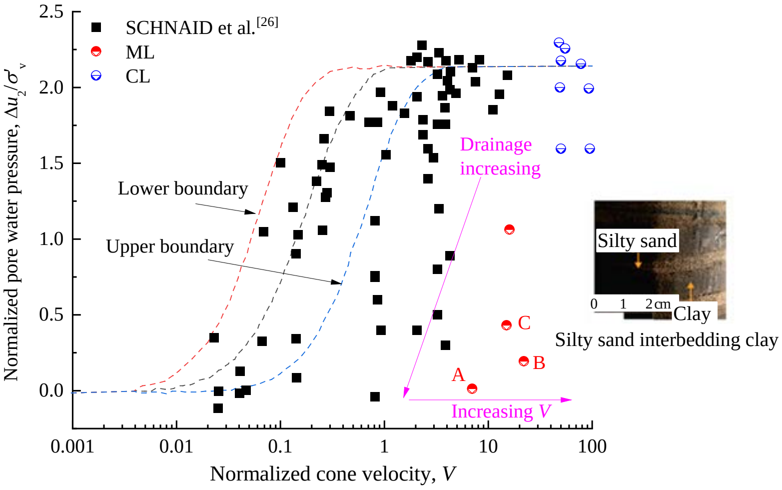


Fig. 3 Normalized piezocone test data

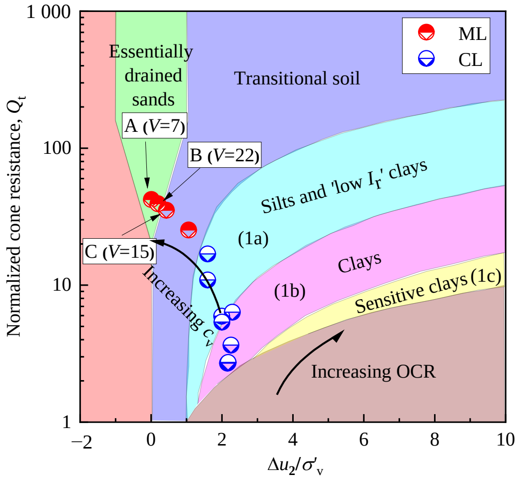


Fig. 4 Typical data points plotted on the SCHNEIDER et al. classification chart[25]

Inclusion of higher permeable layer could change the pore water pressure response around the cone tip. Even layers a few millimeters thick, if present sufficiently frequent and continuous, can strongly affect the overall permeability of the deposit and thus the rate of consolidation under imposed loading. Preliminary investigation was done by considering thin strata of multi-layering sand lenses sandwiched in clay layer[27]. A calibration chamber of having dimensions of 480 mm depth and 400 mm diameter is used to conduct the laboratory investigation. Two miniature piezocones, with cross-sectional areas of 1 cm^2 and 5 cm^2, were used in the research. For simplicity of our conclusions, we presented only the results obtained from 5 cm^2 piezocone. The result clearly states the drastically changes of excess pore water pressure Δu response even when the sandy layer is 2 mm thick (Fig. 5). No numerical analysis into the flow mechanism around the cone underlain with very thin sandy layer was undertaken to propose the mechanism of this sudden reduce of pore water pressure response.

CPTU interpretation is affected by huge uncertainties, particularly for deposits containing multiple thin strata due to occasional flow-related sediment deposits, which frequently change the layers of sand and clay in sediment settings, especially in channel and levy faces. To increase CPTU competences, probable solutions can be found by using smaller sized cones (minicone). Many researchers have tried to model cone penetration into stratified soils using diverse methods (see Table 1). The goal of cone modeling in those studies were to penetrate into the stratified soil, to propose the validated available test methods (which were not many) and to suggest a modification method.

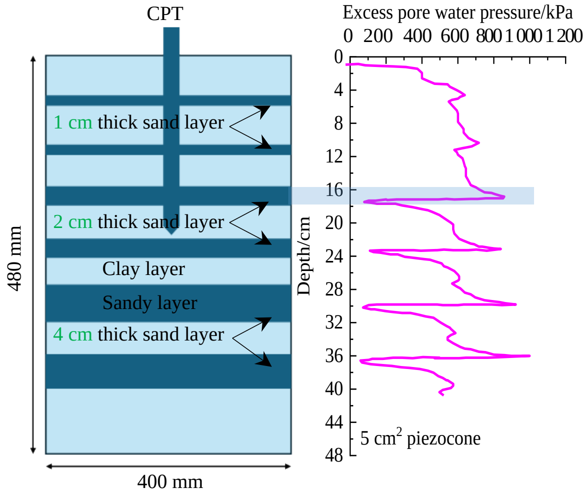


Fig. 5 Excess pore water pressure investigation using layered sand in laboratory[27]

Table 1 Literature related to existing CPTU works on thinly stratified soil

References	Layering style	Model Test
VREUGDENHIL et al.[28]	Thin stiff layer in between thick stick layers	Numerical
MEYERHOF et al.[29]	Layered sand and clay	Model test
ROBERTSON and WRIDE[30]	Thin stiff layer in between thick stick layers	Numerical
VAN DEN BERG et al.[31]	Sand on clay; clay on sand	Calibration chamber
YUE and YIN[32]	Layered elastic solids	Analytical
YOUD et al.[33]	Granular soil sandwiched between softer soils	Numerical
HIRD et al.[27]	Thin sand layer embedded in clay	Calibration chamber
SILVA and BOLTON[34]	Layered sand	Centrifuge
AHMADI and ROBERTSON[35]	Thin sand layer embedded in soft clay	Numerical
XU and LEHANE[36]	Layered sand and clay	Numerical
WALKER and YU[37]	Undrained clays comprising three layers	Numerical
MŁYNAREK et al.[38]	A layer of sand and silty clay	Numerical
MO[39]	Strong soil within weak soil; weak soil within strong soil	Centrifuge
MO et al.[40]	Strong soil within weak soil; weak soil within strong soil	Centrifuge
MO et al.[41]	Strong soil within weak soil; weak soil within strong soil	Numerical
MA et al.[42]	Soft-stiff-soft clay	Numerical
MA et al.[43]	Soft-stiff-soft clay	Numerical
MO et al.[44]	Strong soil within weak soil; weak soil within strong soil	Centrifuge
VAN DER LINDEN et al.[45]	Inter layer soil	Calibration chamber
KHOSRAVI et al.[46]	A layer of sand between overlying and underlying layers of low plasticity clayey silt	Centrifuge
DE LANGE et al.[47]	Inter layer soil	Calibration chamber
BOULANGER and DEJONG[48]	Sand embedded in clay	Numerical
YI[49]	Thinly layered	Field study

References	Layering style	Model Test
TEHRANI et al.[50]	Layered sand	Calibration chamber
XIE et al.[51]	Stiff over soft clay	Centrifuge
YOST et al.[52]	Inter layering soil	Numerical
FARD and CHANG[53]	Soft soil embedded in dense soil	Numerical
YOST et al.[54]	Inter layering soil	Numerical
KHOSRAVI et al.[55]	Inter layering with weak and dense soil	Centrifuge

2 Research gaps

After evaluating the published articles of cone penetration test of layered soil, authors find out two main research gaps from future research works on which the authors are working.

When the cone penetrates into the thinly layered, flow mechanism of the water around the cone surroundings has not been well investigated.

No numerical or experimental framework has been developed to capture the behavior of the heterogeneously mixed marine silts.

3 Conclusion

This paper reviews the existing published works on cone penetration test of homogeneously mixed silt and heterogeneously mixed marine silts. Then the authors identify the limitations of the existing research which researchers may perform further experiment on.

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