CPT-Based Assessment of Wave Induced Non-uniformity Liquefaction inYellow River Delta

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***Abstract*—Liquefaction has caused significant failures and represents a significant problem for the community and geotechnical engineering designers. The survey in the Chengdao sea of Yellow River Delta showed the presence of a large number of pits, geological disasters gullies, landslides, residual body and buried ancient river. In this paper, we utilize in-situ test data in Chengdao sea of Yellow River delta to analyse the non-uniformity liquefaction of the space. The results is exhibited to the vertical non-uniformity, which is located in correlation distance between 0.32~0.93m. The depth of liquefaction varies with the larger storm level, and weak interlayer is susceptible to liquefaction.**

Keywords-liquefaction; non-uniformity; CPT; CRR; CSR

I. INTRODUCTION

Liquefaction has caused significant failures and represents a significant problem for the community and geotechnical engineering designers (Pyrah et al., 1998). However, in practice, a single reliable method for assessing the liquefaction of soils is not well defined. This is due mainly to the fact that most research has been based on 'clean sand' as the calibration to define the boundary between liquefaction and non-liquefaction behaviour. Therefore, a well defined procedure for liquefaction assessment which is applicable to soils is a crucial first step in reducing the risk of substructure failures and mitigating casualties resulting from cycle loading.

Liquefaction is the transformation of coarse-grained soil from a solid state into a liquid state as a consequence of hydrostatic pressure build-up owing to the application of either a sudden shock or cyclic loading (Chaney & Pamukcu, 1990; Youd et al., 2001), such as that caused by earth tremors, wave or sudden loading. The soil layer softens as liquefaction occurs, allowing large cyclic deformations to arise. Generally, the softening of the soil stratum is also accompanied by loss of shear strength that possibly will lead to large shear deformations, ground oscillation or even flow failure (Youd et al., 2001). This phenomenon has devastating effects on structures in many parts of the world (Greene et al., 1994; Power & Holzer, 1996), especially in ocean engineering area.

Liquefiable soils are loose particulate materials, such as silt, sand and gravel which are very difficult to sample in order to provide representative undisturbed specimens for laboratory testing (Glaser & Chung, 1995). Since loose soils are often densified on sampling and handling, laboratory measurement of cyclic strengths are higher than in-situ testing values (Ishihara, 1985). Therefore, in-situ testing is preferred for liquefaction susceptibility prediction (Kulasingam et al., 1999; Martin & Lew, 1999) rather than laboratory testing. Moreover, in-situ testing offers a better opportunity to investigate soil structure, dealing with the arrangement of particle groups, including particle sizes, inclusions and discontinuities (Johnston, 1983). The cyclic resistance ratio CPT-based correlations adopted for the current study contain a significant advance over previously available correlations using CPT data.

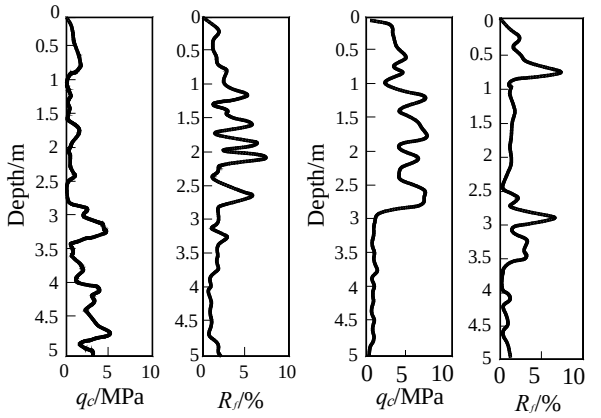
In estuarine and coastal areas, seabed is susceptible to erosion, liquefaction and submarine landslides due to the presence of rapid accumulation of sediment, low intensity, and excess pore water pressure in the case of a storm, which poses a threat to the safety of ocean structures. The survey in the Chengdao sea of Yellow River Delta showed the presence of a large number of pits, geological disasters gullies, landslides, residual body and buried ancient river (Li, 2006). It is usually thought to be directly produced by wave-induced seabed liquefaction. Actually, seabed is non-uniformity so that liquefaction may not start from the surface. In this paper, we utilize in-situ test data in Chengdao sea of Yellow River delta to analyse the non-uniformity liquefaction of the space. One of the major challenges associated with the use of CPT data for liquefaction studies is the relationship of waves and measured resistance for the influence of effective overburden stress. We readdress this issue by applying modified tip resistance methods to a prior empirically based technique. Another challenge was related to build liquefied computational model to study the features of vertical and horizontal non-uniformity liquefaction.

II. NON-UNIFORMITY

Several procedures utilising in-situ testing have been developed to assess the liquefaction potential of soils (Andrus et al.,1999; Youd et al., 1998). Each method has its own advantages and limitations in terms of the number of test measurements at the liquefaction site, the capability of the in-situ testing and the measured test parameters (Youd et al., 1998). The US National Center for Earthquake Engineering Research (NCEER) has identified the electrical cone

penetration test (CPT) as an excellent in-situ testing method for geotechnical site characterisation for the evaluation of soil liquefaction.

Ten test boreholes, the average depth of 5 meters, was drilled using the Mini-CPT at Chengdao Sea of Yellow River Delta. The results show that two typical stratums exist with or without the weak interlayer.



(a)not existing weak interlayer (b) existing weak interlayer

FIGURE I. TWO TYPICAL SEABED LAYER S AT CHENGDAO SEA

Taking the 1# and 8# borehole for instance, the characters of stratum varies rapidly along the depth, shown in Fig.1. There is the weak interlayer at the depth of 3 meters in 8# borehole. Combined with the other drilling data, the maximum depth of weak interlayer maybe extend to 13 meters. The non-uniformity can be presented by the correlation distance of soil parameter, calculation of the correlation distance between 0.32~0.93m using the recurrence space method. Meanwhile, the seabed soil strength mainly depend on some physical and mechanics parameters, the differences between the two type soil are listed in Table 1.

The factors, that can change the stratum struction, are a large quantity. It generally includes: (1) To some extent, the non-uniformity phenomenon occurs, because repeatedly diversions of the Yellow River, together with the complicated hydrodynamic conditions, induced some part of soil liquefaction, while the others soil strength may be increased because of drainage variation in the process of soil compress; (2) the non-uniformity phenomenon is aggravated, because recently deposited soil in underconsolidated state, prone to sediment resuspension, transport and redeposited under the wave and current, so as to reduce the soil strength; (3) the seabed soil is highly susceptible to the physical and mechanics parameters, such as partical size, water content, void ratio and so forth; (4) due to biological activity impacting sediment composition, features and transportation, the non-uniformity may be aggravated.

III. COMPUTATIONAL MODEL

A. Wave Induced Shear Stress

Wave travels along the sea, with the constant wave parameters can be considered as a series of an infinite number of unit (wave height, the wavelength and period) of wave. It causes certain pressure to the seabed at the same time of wave propagation, supposing that the wave is simple harmonic wave, the pressure on the seabed changes along with it. Considering seabed sediments as a homogeneous infinite elastic body, the seabed surface pressure for simple harmonic wave can be expressed as equation (1) according to the solution of Boussinesq.

$$p(x) = p_0 \cos\left(\frac{2\pi}{L}x - \frac{2\pi}{T}t\right) \tag{10}$$

Where p_0 is the peak value of wave pressure on seabed surface, kPa; L is wave length, m; T is wave period, s.

Supposing that wave height is much less than wave length, we can calculate according the Airy wave theory just as equation (2).

$$p_0 = \frac{\rho_w g H}{2\cosh\left(2\pi d/L\right)} \tag{2}$$

Where ρ_w is seawater density; g is acceleration of gravity; H is wave height; d is water depth.

Wave propagation can cause the stress in the seabed, the pressure includes: vertical stress σ_v, horizontal stress σ_h and shear stress τ_{vh}, shown as equation (3).

$$\begin{cases} \sigma_v = p_0\left(1+\dfrac{2\pi z}{L}\right)\exp\left(-\dfrac{2\pi z}{L}\right)\cos\left(\dfrac{2\pi x}{L}-\dfrac{2\pi t}{T}\right) \\ \sigma_h = p_0\left(1-\dfrac{2\pi z}{L}\right)\exp\left(-\dfrac{2\pi z}{L}\right)\cos\left(\dfrac{2\pi x}{L}-\dfrac{2\pi t}{T}\right) \\ \tau_{vh} = p_0\dfrac{2\pi z}{L}\exp\left(-\dfrac{2\pi z}{L}\right)\sin\left(\dfrac{2\pi x}{L}-\dfrac{2\pi t}{T}\right) \end{cases} \tag{3}$$

TABLE I. THE PHYSICAL AND MECHANICS PARAMETERS OF DIFFERENT SOIL

Soil Strength	Type	Water Content/%	SPT	Undrained Shear Strength/kPa	Clay Content/%	Ground Bearing Capacity/kPa
Higher	silty sand/silt	20~30	>8	>10	<9	110
Lower	silty clay/mucky soil	30~50	<5	<10	>10	40~100

Where x, z is horizontal and vertical in the seabed surface respectively.

According to equation 3, the maximum shear stress can be calculated by equation 4.

$$(\tau_{vh})_{\max} = \frac{\sigma_1 - \sigma_3}{2} = \sqrt{\left(\frac{\sigma_v - \sigma_h}{2}\right)^2 + \tau_{vh}^2} = p_0 \frac{2\pi z}{L} \exp\left(-\frac{2\pi z}{L}\right) \tag{4}$$

The cyclic stress ratio (CSR), being an dimensionless index, is a measure of the intensity of cyclic loading. In analysing wave-induced liquefaction, vibration at a particular depth in a soil deposit can be expressed with CSR obtained using a formula developed by Ishihara and Yamazakia in 1984:

$$CSR = \frac{(\tau_{vh})_{\max}}{\sigma_v^{'}} = \frac{2\pi}{\rho^{'} g} \frac{p_0}{L} \exp\left(-\frac{2\pi z}{L}\right) \tag{5}$$

Where z is the depth of seabed sediment; $\rho^{'}$ is effective density under water, $\rho^{'} = \rho - \rho_w$.

B. Cyclic Resistance Ratio (CRR)

The capacity of a soil layer to resist liquefaction expressed as the cyclic resistance ratio (CRR), several procedures utilising in-situ testing have been developed to determine CRR (Youd et al., 1998; Andrus et al., 1999). Given the complexity of analysing the liquefaction phenomenon, the evaluation of the CRR in this research utilised the electric cone penetration test (CPT). The CPT is an ideal in-situ test to evaluate the potential for soil liquefaction because of its repeatability, reliability, continuous data acquisition and cost effectiveness (Lunne et al., 1997). Furthermore, the CPT method is widely used and well accepted (Youd et al., 1998). Therefore, we can obtain CSR using a formula developed by Robertson and Wride in 1998 based on CPT test:

$$CRR = \begin{cases} 0.833\left(q_{c1N,cs}/1000\right) + 0.05, & q_{c1N,cs} < 50 \\ 93\left(q_{c1N,cs}/1000\right)^3 + 0.08, & 50 \le q_{c1N,cs} < 160 \end{cases} \tag{6}$$

$$q_{c1N,cs} = K_c q_{c1N}$$

$$K_c = \begin{cases} 1.0, & I_c \le 1.64 \\ -0.403 I_c^4 + 5.581 I_c^3 - 21.63 I_c^2 + 33.75 I_c - 17.88, & I_c > 1.64 \end{cases}$$

$$I_c = \left[(3.47 - \lg Q)^2 + (1.22 + \lg F)^2\right]^{0.5} \tag{7}$$

$$Q = \left[(q_c - \sigma_v)/P_a\right]\left[P_a/\sigma_v^{'}\right]^n \tag{8}$$

$$F = f_s/(q_c - \sigma_v) \times 100\% \tag{9}$$

$$q_{c1N} = C_N q_c \tag{10}$$

Where q_c is the tip resistance, kPa; $\sigma_v^{'}$ is the effective overburden stress, kPa; σ_v is the total overburden stress, kPa; f_s is the sleeve friction resistance, kPa; $q_{c1N,cs}$ is the tip resistance of clean-sand equivalence; P_a is the reference stress, generally equivalent to 100kPa; n is the coefficient considered fine content, $n = 0.5$ for sand, $n = 1.0$ for clay.

Referring to Code for Seismic Design of Highway Engineering (JTJ004-89), we obtain modified curves of the tip resistance in fitting formula as follow:

$$C_N = 1.82 \exp\left(-0.49 \sigma_v^{'}/P_a\right) \tag{11}$$

It is worthwhile to note that Robertson's formula based on earthquake engineering, CRR needs to be corrected. Nataraja and Gill (1983) think liquefaction resistance of soil under wave loads increased by 10% compared to the case of seismic loads, so it can be expressed as follow:

$$CRR_w = 1.1 CRR_e \tag{12}$$

We can calculate cyclic stress ratio and cyclic resistance ratio using the formula (5) and (6), then the safety factor (FS) of liquefied can be expressed as follow:

$$FS = CRR_w / CSR \tag{13}$$

$FS \le 1$, sediments achieve the state of liquefaction, On the contrary, it is non-liquefaction.

IV. LIQUEFACTION

A. Vertical Non-uniformity

Writed liquefied development process program using Matlab computing software, then we calculated FS at different depth in the seabed by substituted the CPT data of Chengdao sea (the tip resistance and sleeve friction) in the program, where the calculation result of 1# and 8# borehole shown in Figure 2. Moreover, $FS = 1$ equal to the liquefaction depth.

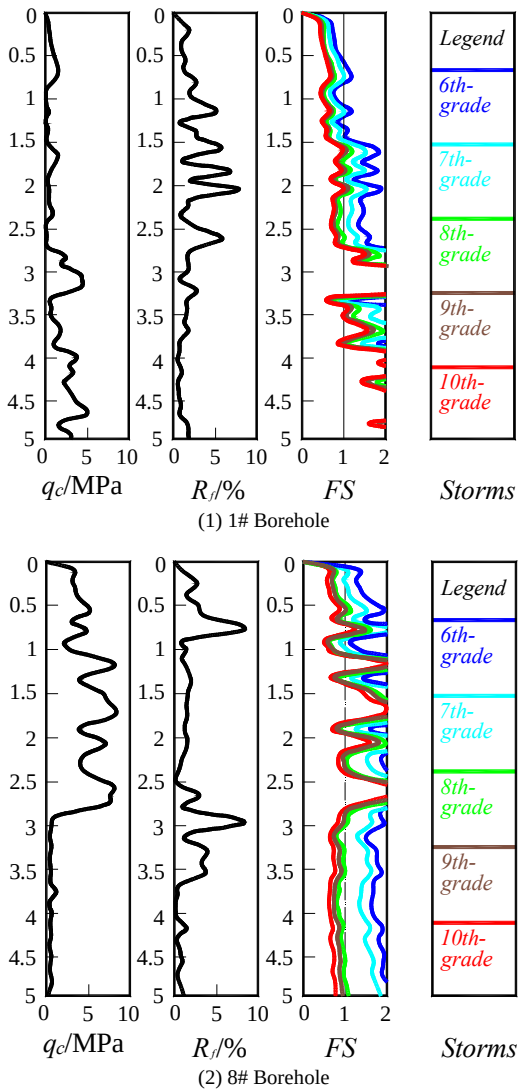


FIGURE II. THE FS OF ANT-ILIQUEFACTION UNDER 6-10TH STORMS

As can be seen, the liquefaction depth becomes larger with the increase of storm level. Liquefaction depth is about 1.5m under 6th-grade storm, while liquefaction depth reaches to 3.4m under 8th-grade storm and reaches to 3.8m under 10th-grade storm. Due to the vertical non-unfomity of soil strength, there are several points that FS equals to 1. It causes the vertical distribution of liquescent sandwich.

B. Horizontal Non-uniformity

The maximum liquefaction depth at level 6-10th grade waves collected in Table 1, it can be seen that maximum liquefaction depth exists differences due to the horizontal heterogeneity. The maximum liquefaction depth is only 0.9m under 10th-grade storm in the 3 # borehole because of soil strength is greater than others. By comparison, the maximum liquefaction depth exceeds 5m under 10th-grade storm in 8# and 9# borehole.

Different regions vary the depth of soil liquefaction, because of existing a certain slope in the area (generally less than 1.0 degrees), soil after liquefaction can slide along the slope under the complex hydrodynamic conditions. Slide depth has relationship with the depth of liquefaction, after slide it will form a non-uniform landforms. Addition, horizontal non-uniform liquefaction also have an important impact on the subsea pipeline. It should be valued that uneven settlement of the pipeline caused by horizontal non-uniform liquefaction could rupture pipelines.

V. CONCLUSION

In this paper we present a new correlation for CPT-based assessments of wave-induced soil liquefaction hazard. The new correlation employs several high quality in-situ experiments. In processing the CPT data, we have utilized new liquefaction computational model to study the vertical and horizontal non-uniformity in Chengdao sea, drawed the following conclusions:

First, there are two typical formation in Chengdao sea that exists or do not exist the presence of weak interlayer weak interlayer. Both formation were exhibited to the vertical non-uniformity, which is located in correlation distance between 0.32 ~ 0.93m.

Second, the depth of liquefaction varies with the larger storm level, and weak interlayer is susceptible to liquefaction. Meanwhile, seabed liquefaction has an important impact on the pile and landslides.

Third, soil liquefaction depth varies in different regions, the paper carries on the statistics of 10 boreholes. In the 10th-grade storms, the minimum liquefaction depth less than 1m, while the maximum is more than 5m. Moreover, seabed liquefaction will form the uneven non-uniform topography.

TABLE II. THE LIQUEFACTION DEPTH UNDER DIFFERENT STORMS

No.	Coordinate (E/N)	Water Depth/m	Liquefaction depth under different storms/m				
			6th-grade	7th-grade	8th-grade	9th-grade	10th-grade
1	20658703 4230007	6.5	1.5	3.4	3.4	3.8	3.8
2	20659836 4230008	6.5	0.5	2	2.3	3.5	3.7
3	20659877 4230746	9.1	0.1	0.1	0.3	0.6	0.9
4	20662152 4231180	6.5	0.7	2.2	2.6	3.6	4.4
5	20662126 4230039	8.5	0.8	1.5	2.6	2.7	3.5
6	20658818 4231214	10.1	0.8	1.6	4	4.1	4.5
7	20660438 4227441	4.5	1.2	1.2	2.4	2.4	4
8	20659578 4233335	11.8	0.1	1	4.6	>5.0	>5.0
9	20659669 4232593	11.8	0.4	0.5	3.6	4.7	>5.0
10	20662139 4233187	11.7	0.1	0.2	4.8	4.8	4.8

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