IN SITU EVALUATION OF NUCLEAR DENSITY CONE PENETROMETERS IN MARINE SEDIMENTS

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ABSTRACT

The geotechnical properties of the bottom sediments on the inner and outer sides of the Isahaya Bay dyke were investigated using nuclear density cone penetrometer (ND-CP) for predicting bottom sediment transport and assessing environmental impacts about opening the two gates of the dyke. The nuclear density cone penetrometer test (ND-CPT) device was put on the boat and penetrated by the self-weight to investigate the properties of the marine sediments, and a total of 71 ND-CPTs were conducted. Furthermore, 26 undisturbed soil samples were obtained for the laboratory soil density and vane shear tests to evaluate the ND-CPT results. The test results show that the values of soil density and undrained shear strength obtained from the ND-CPTs can compare well with those from the laboratory tests on undisturbed soil samples, and the ND-CPT results show good repeatability. The water depth and fluid mud thickness can be determined according to the density values obtained from the ND-CPTs.

Keywords: nuclear density cone penetrometer, soil density, undrained shear strength, marine sediments, Isahaya Bay

INTRODUCTION

It has been decided that the two gates of the Isahaya Bay dyke in the Ariake Sea, southern Japan, will be opened within 3 years from December 2010 and keep open for 5 years to study the dyke’s impacts on the marine environment and fisheries. However, it is not clear whether the environment of Isahaya Bay and Ariake Sea will be improved after opening the gates, and which method of opening the gates is most suitable for the environment improvement. For predicting bottom sediment transport and assessing environmental impacts about opening the gates, the geotechnical properties of the bottom sediments around the dyke need to be investigated, e.g. soil density, water content and undrained shear strength.

It is preferable to do an in situ test for natural environment investigation rather than laboratory test. The piezocone test is an in situ testing method used to determine the geotechnical engineering properties of soils and represents the most versatile tools for in situ soil exploration. However, it is difficult to obtain the soil density from the piezocone test. Radioisotope has been widely used in geotechnical engineering to measure the soil density (ASTM, 2005). Nieuwenhuis and Smits (1982) and Tjelta et al. (1985) developed the nuclear density probe for in situ soil investigations. Then the nuclear density cone penetrometer (ND-CP) was developed through combining nuclear density probe with piezocone probe (Ledoux et al. 1982; Mimura et al. 1995; Shibata et al. 1994). The ND-CP has been used for soil investigations where continuous data of soil density are required and can obtain reliable values of soil density (Dasari et al. 2006; Karthikeyan, 2005; Karthikeyan et al. 2007; Shibata et al. 1994; Umezaki et al. 2006; Umezaki et al. 2009).

In this study, the geotechnical properties of bottom sediments around the Isahaya Bay dyke were investigated using a newly developed ND-CP. The principle and equipment of the nuclear density cone penetrometer test (ND-CPT) were described. The ND-CPT method in marine sediments and the ND-CPT results were presented. Undisturbed soil samples were obtained for the laboratory soil density and vane shear tests to evaluate the ND-CPT results. The values of soil density and undrained shear strength obtained from the ND-CPTs were compared with those from the laboratory tests on undisturbed soil samples. The two times ND-CPT results at the
same location were compared. The values of water depth obtained from the ND-CPTs were compared with those from the portable echo sounder, and the thicknesses of fluid mud on the inner and outer sides of the dyke were investigated.

**ND-CPT EQUIPMENT AND METHOD**

The principle of the soil density measurement in ND-CPT is using the Compton scattering when gamma rays pass through matter. The gamma rays emitted from the source collide and scatter repeatedly with the electrons in the materials constituting the ground. In this process, some of gamma rays are absorbed while part can reach the detector without being absorbed. The gamma rays reaching the detector are related to the abundance of materials constituting the ground (density), so the soil density can be determined according to the gamma rays intensity detected by the detector.

For getting the accurate gamma rays from the source after the absorption by the soil, the natural gamma rays (background count) need to be measured and subtracted from the total gamma rays reaching the detector (density count). The original design of the ND-CP required two probing for every single measuring point, first to obtain the background count rate and three parameters measured during a piezocone test using a gamma rays detector combining with piezocone penetrometer, and then the density count rate using a gamma rays source as well as a detector. However, in marine environment it is difficult to ensure that both probing are penetrated in the same location.

In this study, a ND-CP which can simultaneously measures the cone resistance, pore pressure, sleeve friction, background count rate and density count rate was newly developed and adopted (Fig. 1). The lower part, which is for piezocone testing and has a length of 651.5 mm, consists of a cone which has an apex angle of 60° and a base diameter of 35.7 mm (10 cm² cross-sectional area), pore pressure filter behind the cone and 150 cm² friction sleeve. The upper part, which is for soil density measuring, consists of inclinometer, gamma rays source, lead shield, density count gamma rays detector and background count gamma rays detector, and has a diameter of 48.6 mm and length of 1124.5 mm. The distances between pore pressure sensor, sleeve friction sensor, inclinometer sensor, density count gamma rays detector, background count gamma rays detector and cone resistance sensor are 0.04 m, 0.11 m, 0.5 m, 0.6m and 1.2m respectively.

The measurements are evaluated in an extended volume around the central point of the gamma rays source and detector, which is called the “measuring volume”. The measuring volume around the source and detector of the ND-CP used in this study is about 30 cm in radius. The radiation exposure of user does not exceed radiation exposure limits in Japan, 1mSv per year, and is no harm to human health.

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**Fig. 1 Investigation equipment**

Due to the investigations in this study were conducted on the sea and bottom sediments in the sea are very soft, the ND-CPT device was put on the boat instead of the truck generally used on the land and penetrated by the self-weight (Fig. 1). The weight of the ND-CP is about 15 kg and the additional weight is 60 kg. The winch was used to control the up and down movement of the ND-CP and the penetration speed, a rate of approximately 1-2 cm/s. The advantages of this investigation method are miniaturization and lightweight of the device due to reaction system does not require. The boat can be moved easily and the investigation can be conducted quickly. The disadvantage of this investigation method is that the inclination of the ND-CP during the investigation is bigger due to the boat without an anchor system to prevent the wave action. The average and maximum inclination of the ND-CP from the vertical during the investigations were about 1° and 3° respectively. But it is still within an acceptable error range.
IN SITU INVESTIGATION

The investigation locations are shown in Fig. 2. A total of 71 ND-CPTs (outside 47 and inside 24) were conducted, and 26 undisturbed soil samples (outside 16 and inside 10) were obtained for the laboratory tests to evaluate the ND-CPT results. Two times investigations were conducted on December 2010 and February 2011 respectively. 24 ND-CPTs were conducted and 8 undisturbed soil samples were obtained in the first time. 47 ND-CPTs were conducted and 18 undisturbed soil samples were obtained in the second time, in which 8 ND-CPTs were conducted and 8 undisturbed soil samples were obtained at the same locations with the first time.

Two sample tubes each about 1.0 m long were obtained at each time in one location. One is for the soil density test and one is for the vane shear test. The soil samples were extruded from the tube and cut into pieces in the height of 5 cm, 10 cm, 20 cm, 30 cm, 40 cm, 50 cm, 60 cm, 70 cm, 80 cm and 90 cm from the top surface of the sample. The weight of each soil sample was measured to determine the density of the soil sample. The newly developed vane shear test device was adopted to obtain the undrained shear strength in the field immediately after obtaining the undisturbed soil samples. The thin-wall tube was fixed vertically and the vane shear test was conducted directly on the sample in the tube. The blade of the vane shear test device has the height of 4cm and the diameter of 2cm. The undrained shear strengths at different depths, 5 cm, 15 cm, 30 cm, 50 cm, 70 cm and 90 cm, were measured.

TEST RESULTS AND DISCUSSIONS

Evaluation of ND-CPT

Typical ND-CPT results

Figures 3 and 4 show the typical ND-CPT results at point e1 and c5 (second time). The cone resistance ($q_c$), pore pressure ($u$), sleeve friction ($f_s$), background count rate (BCR) and density count rate (DCR) can be directly obtained from the ND-CPT. Mean sea level is used as the zero level for depth values. In the figures, $\sigma_v$ is the total effective vertical stress and $u_0$ is the in situ pore pressure. The corrected cone resistance ($q_t$), $q_t$ corrected for pore water pressure effects, can be calculated using the following equation:

$$q_t = q_c + (1 - a)u$$

where $a$ is the area ratio of the cone and 0.75 is adopted in the ND-CP in this study.

Subtracting background count rate from density count rate provides the count rate of gamma rays from the source after the absorption by the soil. The count rate ratio $R_p$, rather than the count rate, is used to calculate the soil density for considering the radioisotope decay and is defined as:

$$R_p = \frac{DCR - BCR}{SCR}$$

where SCR is the standard count rate. For reducing the statistic error of the gamma rays emitted from the source, the average count rate (the average value
of the count rate in the interval of 10 cm) was normalized by the standard count rate to get the count rate ratio.

Then the soil density ($\rho$) can be calculated from the following field calibration equation:

$$\rho = \frac{4.0954 - \sqrt{2.5056 R - 0.3715}}{1.2528}$$

(3)

Assuming the degree of saturation ($S_r$) of the bottom sediment is 100%. The water content ($w$) can be calculated from the following equation:

$$w = \frac{\rho_w - \rho}{G_s \rho - \rho_s}$$

(4)

where $\rho_s$ is the density of solid particles and $G_s$ is the specific gravity.

The undrained shear strength ($c_u$) can be estimated from the following equation (Lunne et al., 1997):

$$c_u = \frac{q_t - \sigma_{c0}}{N_{kl}}$$

(5)

where $N_{kl}$ is the empirical cone factor and 10 was adopted in this study. The undrained shear strength increases with depth due to the consolidation by the self-weight of sediments.

In the column labeled “Profile”, the fluid mud on the inner side of the dyke (e1) is assumed as the sediments whose densities range from 1 to 1.2 g/cm$^3$ and the fluid mud on the outer side of the dyke (c5) is assumed as the sediments whose densities range from 1.025 to 1.2 g/cm$^3$ (Morris and Fan, 1997). The sediments under the fluid mud is classified by the Robertson’s method according to the normalized cone resistance and pore pressure ratio from the ND-CPT results (Robertson, 1990).

The values of soil density and undrained shear strength obtained from the laboratory tests are also shown in Figs. 3 and 4. It can be seen that the values of soil density and undrained shear strength obtained from the ND-CPTs can compare well with those from the laboratory tests.
Comparison of soil density values

A total of 237 laboratory data points of soil density from 26 boreholes at various depths obtained from the laboratory tests are compared with those from the NN-CPTs at the corresponding depths in Fig. 5. The comparisons show good agreement. The scattered data may be caused by the limits of accuracy of the calibration equation (±5%) for calculating the density from the count rate ratio. The compression of the soil when the soil samples were extruded from the thin-wall tube and the height measurement when the soil samples were cut during the laboratory test may also cause errors.

Comparison of two times ND-CPT results

The values of soil density and undrained shear strength at the location c5 obtained from the two times ND-CPTs are compared in the Fig. 6. It can be seen that the two times ND-CPT results can compare well. The repeatability of the ND-CPT results also shows that the ND-CPT result is reliable and the ND-CPT can be used for in situ soil investigation.

Background count rate in different soil types

The values of background count rate obtained from the ND-CPTs in the locations e1, c5 (first time), a10 (first time) and g11 (first time) are shown in Fig. 7. The values of background count rate in the locations a10 and g11 are much less than that in the locations e1 and c5. A large number of sand particles were found on the ND-CP after the ND-CPTs were finished in the locations a10 and g11. It can be seen that the background count rate profile is depend on the soil type and is weak in sand as compared with clay. So the background count rate can be used for the tentative classification of the soil and roughly identify the boundary of clay and sand layers.

Water Depth and Fluid Mud Thickness from ND-CPT Results

Comparison of water depth values

Figure 8 shows the comparison of values of water depth obtained from ND-CPT and portable echo sounder.

The acoustic frequency of portable echo sounder used in this study is 200 kHz and is corresponding to the sediment density of 1.14 g/cm³. So the water depth can be determined from the water surface to the sediment density of 1.14 g/cm³ according to the ND-CPT results. A total of 21 water depth values obtained from the ND-CPT and portable echo sounder in the first time investigation are compared in Fig. 8, it can be seen that the values of water depth obtained from the ND-CPT can compare well with those from the portable echo sounder.
Distribution of the thickness of fluid mud

The thickness of the fluid mud, which is difficult to sample, can be determined according to the density values (1 or 1.025 g/cm² to 1.2 g/cm³) obtained from the ND-CPTs. The distribution of the thickness of fluid mud in the whole investigation region is shown in Fig. 9. The average values were used in the locations where two times investigations were conducted. It can be seen that the values of thickness of fluid mud in the coastal area are thicker than that in the depth water area on the outer side of the dyke due to the wave motion. However, the values of thickness of fluid mud around the locations a10 and g11 are not thicker because the sand depositions were found in these areas. The values of thickness of fluid mud in the locations a2 and e3 are thicker may due to the water motion from Honmyo River and Ariake River on the inner side of the dyke.

The ND-CPT results, e.g. soil density and undrained shear strength, can be used to calculate the critical shear stress and erosion rate (Winterwerp and Van Kesteren, 2004) for simulating the bottom sediment transport and assessing environmental impacts when the two gates of Isahaya Bay dyke are opened.

![Fig. 8 Comparison of water depth values determined from portable echo sounder and ND-CPTs](image)

![Fig. 9 Distribution of the thickness of fluid mud (cm)](image)

CONCLUSIONS

A total of 71 nuclear density cone penetrometer tests (ND-CPTs) were conducted for investigating the geotechnical properties of the bottom sediments around the Isahaya Bay dyke, and 26 undisturbed soil samples were obtained for the laboratory soil density and vane shear tests to evaluate the ND-CPT results. Based on the test results, the following conclusions can be drawn.

1. The ND-CPT is applicable to investigate the properties of marine sediments by self-weight penetration on a boat, and the continuous data of soil density can be obtained.
2. The obtained soil density and undrained shear strength values from the ND-CPTs can compare well with those from the laboratory tests on undisturbed soil samples, and the ND-CPT results show good repeatability. So the ND-CPT can be used for in situ investigation of marine sediments.
3. The water depth and fluid mud thickness can be
determined according to the density values obtained from the NC-CPTs. The values of water depth obtained from the ND-CPTs can compare with those from the portable echo sounder. The ND-CPT results can be used to calculate the critical shear stress for bottom sediment transport simulation.

REFERENCES


