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Classification of Strata Using Screwdriver Sounding Test

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ABSTRACT

Severe liquefaction damage was caused to reclaimed land in coastal areas during the 2011 Great East Japan Earthquake. The ground level has sunk and many houses have tilted so badly on reclaimed land in bay areas around Tokyo such as Urayasu, Funabashi, Yokohama, etc. The phenomenon is often occurred in saturated loose sandy soils which are more vulnerable to liquefaction damage. If it is possible to classify soils by means of ground investigation, risks of liquefaction could be predictable. This paper proposes the Screw Driver Sounding test as an accurate soil classification method.
The effectiveness of the assessment method was confirmed through some case studies on site investigation.

KEY WORDS: Swedish weight sounding test; plasticity model; rod friction; soil classification

INTRODUCTION

It is considered that accurate soil estimation is extremely important in order to prevent land from liquefaction damage caused by massive earthquake. Since SPT(Standard Penetration Test) and CPT(Corn Penetration Test), which are generally used for ground investigation at present, need large equipment and open space, it is difficult to conduct SPT and CPT tests under the ground where roads and buildings have been already constructed on. Therefore, the Swedish Weight Sounding test, hereinafter written as the SWS, which has been widely used to examine performance levels of housing lots, is suggested because of its advantages such as simpler system, faster procedure, lighter reaction weight and better cost efficiency than other sounding tests. The SWS has, however, some disadvantages of having low accuracy of soil classification and including rod friction in the test result. A new operation system for the SWS, the Screw Driver Sounding test, hereinafter called as SDS, is proposed to diminish the disadvantages of the SWS. And the procedure for measuring rod friction during the test is added to the system to omit the rod friction effect from the result. In this paper, based on the results of some field tests conducted, comparison of accuracy of soil classification between the SPT and the SDS, and the effectiveness of measuring rod friction are discussed.

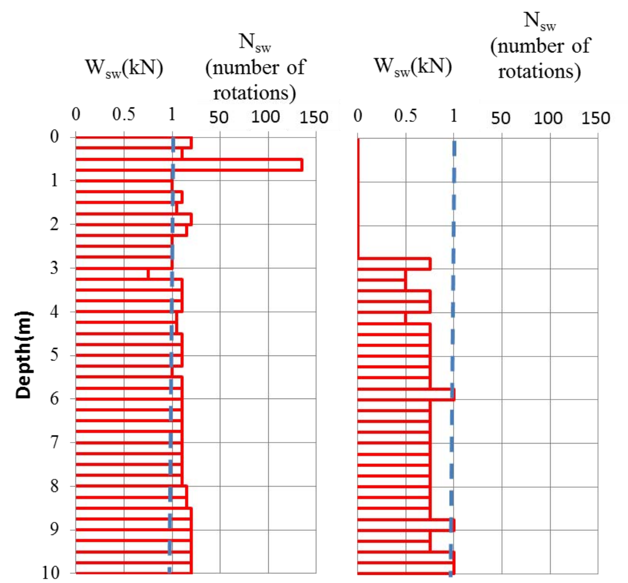

Fig.1 SWS test result at Kawaguchi

As a conclusion, a soil classification chart using the results of the SDS is proposed.

PROBLEMS OF THE SWS TEST

The SWS test has some advantages that the test system is simpler and the cost of the test is lower than other sounding tests like SPT or CPT. On the other hand, the SWS has some problems, one of which is that it has low accuracy of soil classification. In the SWS test, which is usually used without soil sampling, soil classification of a layer investigated is estimated from the test result, local circumstances at the site and a sort of sense of the test examiner. In the SWS test, organic soil as well as clay, silt and loam is classified into a category of cohesive soil. The organic soil is, however, one of warned soils because it has high compression characteristic causing unequal settlement of a house and it contains humid acid preventing cement from being solidified.

The other problem of the SWS is that the test result is fairly influenced by rod friction, which causes lack of accuracy of soil classification. Especially, in case that the ground surface is covered with earth fill containing gravel, the estimation of the lot from the SWS tends to be overvalued as the rod friction at the fill becomes large. Two test results of the SWS conducted in Kawaguchi city are shown in Fig.1 as an example. The location of the test b) conducted was within 1m from that of the test a). By comparing both results, it is clear that the value of the test a) is larger than that of the test b) below 2.5m depth. It is considered that the cause of this difference is due to rod friction.

PLASTICITY MODEL FOR THE SDS TEST

The concept of a proposed model is described in Fig. 2. A plasticity theory analogy model was originally proposed for a shallow foundation problem by Nova and Montrasio (1991). In the model, interactive relationship between combined loads and corresponding displacements can be described in a form of constitutive equation used in the constitutive models for soil element behavior. Fig. 2 illustrates that combination of torque and a vertical load measured in the SDS forms a yield locus, and corresponding incremental components of a rotation rate and a settlement rate obey the plastic potential rule. Suemasa et.al proposed the plasticity model for the SWS by using the results of the SWS miniature test. The outline of the model is described below for better understanding of the SDS result.

An incremental work done by torque and vertical force is given by,

$$\delta E = \pi T \delta n_{ht} + W \delta s_t \qquad (1)$$

where T is rotation torque of a screw point, W is a weighted load, δn_{ht} is the number of incremental half turns and δs_t is incremental settlement caused by the load. When a penetration load W_p is defined as a load by which the screw point is penetrated into ground without rotation, the incremental work is normalized by the penetration load,

$$\frac{\delta E}{W_p D} = \frac{\pi T}{W_p D}\delta n_{ht} + \frac{W}{W_p}\frac{\delta s_t}{D} = T_n \delta n_{ht} + W_n \frac{\delta s_t}{D} \qquad (2)$$

Where D is a diameter of the screw point, T_n and W_n are normalized T and W, respectively. From the observations of the test results, an elliptical yield locus centered on the origin is assumed in this model. That is,

$$c_y T_n^2 + W_n^2 = 1 \qquad (3)$$

where c_y is a coefficient of yield locus. A function of plastic displacement potential is also assumed as the elliptical form as,

$$c_p T_n^2 + W_n^2 = 1 \qquad (4)$$

where c_p is a coefficient of plastic potential. If the associate flow rule is adopted, c_p must be equal to c_y. Differentiating this plastic potential function gives a displacement incremental vector as,

$$N_{sw} D = \frac{\delta n_{ht}}{\delta s_t / D} = c_p \frac{\pi T}{WD} \qquad (5)$$

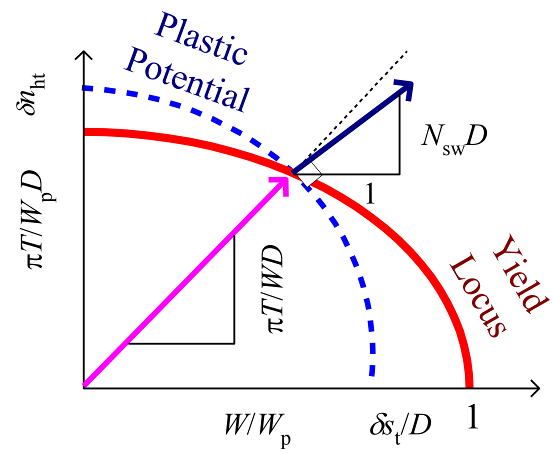

Fig.2 Concept for a plasticity model

Table.1 c_y and c_p for the soil used

Soil type	c_y	c_p
Clay	0.2	0.1
Loam	0.3	0.23
Medium sand	0.4	0.33
Dense sand	0.8	0.4

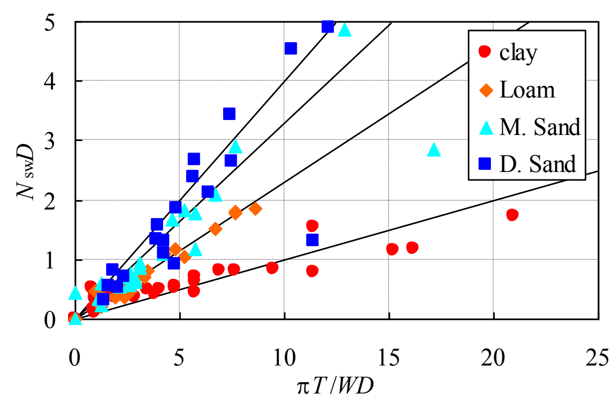

Fig.3 Relationship between $N_{sw}D$ and $\pi T/WD$

Photo.1 SDS test machine

where $N_{sw}D$ is the number of normalized half turns.
The coefficients of yield locus and plastic potential obtained from the test results are summarized in Table 1. And the results of relationship between $N_{sw}D$ and $\pi T/WD$ are also summarized in Fig.3. From these results, it is found that each soil category has a different value of c_p defined as the slope of an approximate liner relationship between $N_{sw}D$ and $\pi T/WD$. If it is possible to measure torque in the SWS, soil classification can be done using the results of the SWS.

THE SDS TEST

Test machine and test method

Photo.1 shows an automatic machine for the SDS test. A machine originally used for the SWS test has been improved to be suitable for the SDS test. In the usual SWS test, there are two loading stages. In the first stage, a vertical load (W_{sw}) is applied to the rod in 4 incremental steps up to a load of 1000N. If the settlement of the rod doesn't reach 25cm depth even in the last load step, the rod is penetrated by rotating the rod to the depth in the second stage. In the SDS test, on the other hand, a monotonic loading system is used, where the number of load step is increased to 6 while the rod is always rotated at a constant rate during the test. The step loads are 0.25, 0.38, 0.5, 0.63, 0.75, 0.88, 1kN in order and the load is increased every revolution of the rod. Measurement items in the test are maximum torque (*Max.T*), average torque (*Av.T*), minimum torque of rod (*Min.T*), a penetration amount (*L*), a settlement rate (*V*) and the number of rotations of rod (*N*). The data is measured every revolution of the rod. In the SDS as well as the SWS, a set of the loading is conducted at every 25cm of settlement of the rod. In the SDS, immediately after the last load, the rod is lifted up by 1cm and then rotated to measure the rod friction.

Estimation of rod friction

The concept of estimating rod friction is shown in Fig.4. The rod friction can be separated into a vertical component (W_f) and a horizontal component (T_f) as the rod is penetrated into the ground while being rotated.
A weighted load (W_a) and measured torque (T_a) are defined as follows,

$$W_a = W_f + W \tag{6}$$

$$T_a = T_f + T \tag{7}$$

where W and T are a load and torque at the screw point respectively. The maximum shear stress acting on rod surface is described as,

$$\tau_{\max} = \frac{T_m}{2\pi r^2 \cdot L} \tag{8}$$

where T_m is torque against rod friction measured at the end of a loading set, r is a radius of the rod and L is a total penetrated length. Supposing combination rate(V) between rotation speed(V_θ) and settlement speed(V_z) is equal to the one between horizontal shear stress(τ_θ) and vertical shear stress(τ_z) on rod surface, the formulas can be given as follows,

$$\tau_\theta = \tau_{\max} \cdot \sin\theta \tag{9}$$

$$\tau_z = \tau_{\max} \cdot \cos\theta \tag{10}$$

By substituting eq. (8) into (9) and (10), the vertical and the horizontal components of the rod friction are obtained as follows,

$$T_f = 2\pi r^2 \cdot L \frac{v_\theta}{\sqrt{{v_v}^2 + {v_\theta}^2}} \cdot \frac{T_m}{2\pi^2 L} \tag{11}$$

$$W_f = 2\pi r \cdot L \frac{v_v}{\sqrt{{v_v}^2 + {v_\theta}^2}} \cdot \frac{T_m}{2\pi^2 L} \tag{12}$$

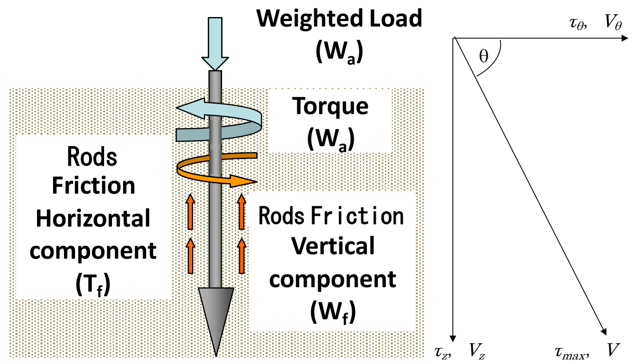

Fig.4 Concept of the rod friction

THE NSWS TEST IN FIELDS

The SDS test

Field tests of the SDS were conducted at 6 sites including 3 diluvial layers and 3 alluvial layers. To be compared with the results of the SDS test, the SPT test was also carried out. Fig.5 shows the comparisons between the SDS and the SPT results. In the figures, corrected torque and the depth derived from the SDS tests results are indicated in red and the N value from the SPT in blue, respectively.
Corrected torque is obtained by deducting a horizontal component of rod friction as shown in eq. (10), from the torque measured at the SDS test.
a) The case of Saitama City Nishi ward
The soil profile at Nishi ward site consists of an earth fill layer from the surface to 1.0m depth, a loam layer to 4.25m depth with the N value of 3 to 4, a tuff clay layer from 4.25m to 5.5m depth with the N value of 2 to 3, and a sand layer from 5.5m to 10.0m depth with the N value of 5 to 17.
b) The case of Saitama City Minuma ward
The soil profile at Minuma ward site is composed of a loam layer from the surface to 0.5m depth with the N value of 5, a tuff clay layer from 0.5m to 4.25m depth with the N value of 5 and a sand layer from 4.25m to 7.5m depth with the N value of 14 to 17.
c) The case of Chiba city
In Chiba site, the soil profile comprises an earth fill layer from the surface to 1.0m, a loam layer from 1.0m to 4.5m depth with the N value of 2 to 3, and a tuff clay layer from 4.5m to 7.5m with the N value of 4 to 5, a sand layer from 7.5m to 8.0m depth with the N value of 6.
d) The case of Ichihara city
The soil profile at Ichihara site includes an earth fill layer from the surface to 1.25m depth, a silt layer from 1.25m to 3.0m depth, a peat

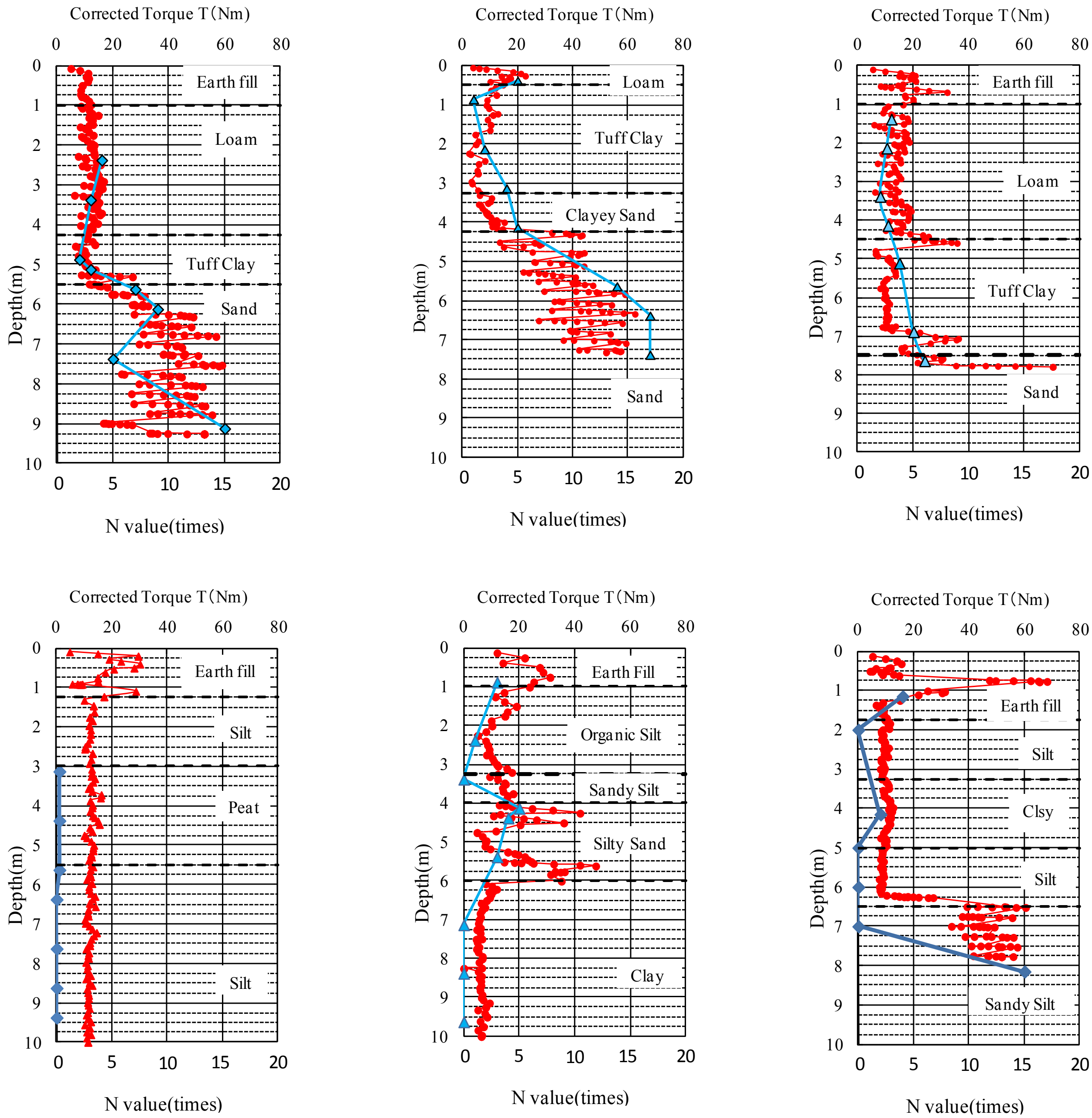

Fig.5 Comparisons between the SDS and the SPT results

layer from 3.0m to 5.5m depth, and a silt layer from 5.5m to10.0m depth. The water level confirmed at the SPT is about 0.85m depth. The N values of the layers at a level deeper than 3m are reduced to almost zero.

e) The case of Saitama pref. Kitakatsushika

In Kitakatsushika site, the soil profile comprises an earth fill layer from the surface to 1.0m depth, an organic silt layer from 1.0m to 3.25m depth with the N value of 1, a sandy silt layer from 3.25m to 4.0m depth with the N value of zero, a silty sand layer from 4.0m to 6.0m depth with the N value of 3 to 5 and a clay layer from 6.0m to 10.0m depth with the N value of zero.

f) The case of Kasukabe city

In Kasukabe site, the soil profile consists of an earth fill layer from the surface to 1.75m depth, a silt layer from 1.75m to 3.25m depth with the N value of zero, and a clay layer from 3.25m to 5.0m depth with the N value of 5, a silt layer from 5.0m to 6.25m depth with the N value of zero, and a sandy silt layer from 6.25m to 8.25m depth with the N value of 15.

At Kitakatsushika site, it is found that variation of corrected torque to increasing load at each 25cm section becomes large at the earth fill and silty sand, and very small at clay layer. The average corrected torque at each 25cm section corresponds to the N value at the same depth. It is, therefore, concluded that not only corrected torque

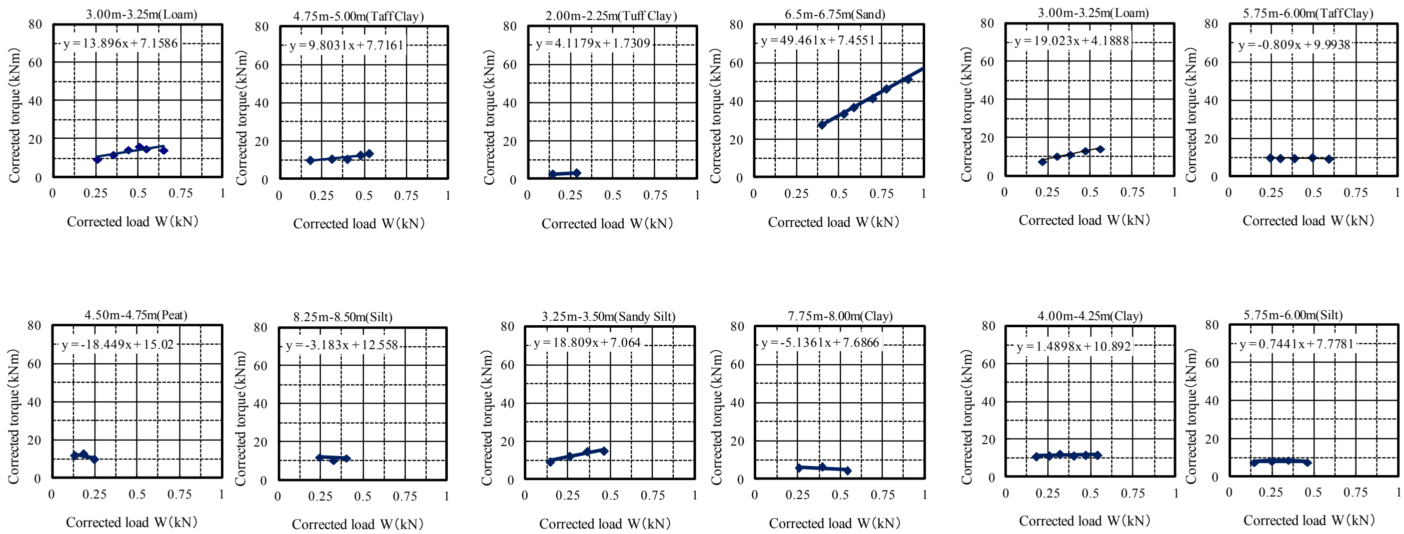

Fig.6 Relationship between a corrected load (*W*) and corrected torque (*T*) at every 25cm

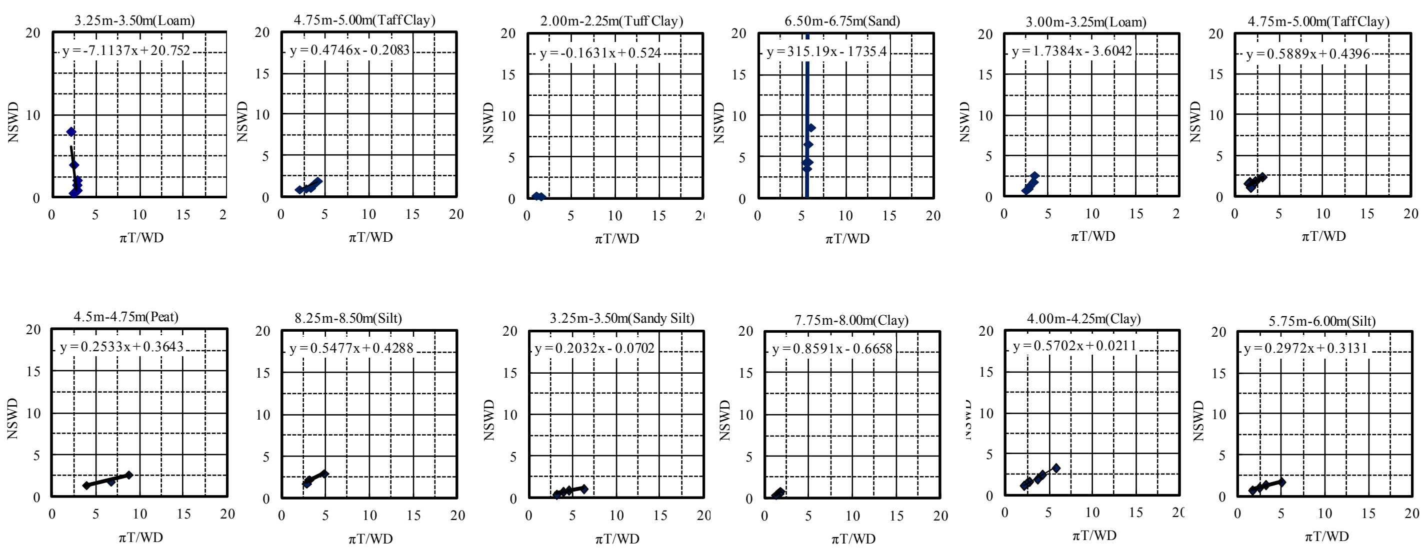

Fig.7 Relationship between a normalized half turns number (*NswD*) and a normalized torque ($\pi T/WD$) at every 25cm

in the N value but also the tendency of the variation of torque can give good estimation of soil layer separation from the SDS results.

Soil classification from the SDS test

Fig. 6 shows relationship between a corrected load (*W*) and corrected torque (*T*) at each 25cm section and Fig. 7 shows relationship between the number of normalized half turns (*NswD*) and normalized torque ($\pi T/WD$), in which data is extracted from two different depths at one site. The slope tends to have a positive value for frictional soil like sand or loam, and a negative value or zero for clay and silt. For peat or organic soil, as well as other frictional soil, a corrected load is very small and corrected torque increases as corrected load increases. As to peat, since it includes undegraded branches and leaves, and easy to be entangled at the screw point, corrected torque has a tendency to increase. For tuff clay, corrected torque tends to be constant or decrease with an increasing corrected load. Although tuff clay is stiff with a grain aggregate structure, it is compressible and shows brittle response in shear due to many large gaps containing in it. In the tuff clay, it is thought that corrected torque is small though the N value is high because the structure of the tuff clay is damaged by rotation of the screw point in the SDS. The slope of an approximate line obtained from relationship between the number of normalized half turns (*NswD*) and normalized torque ($\pi T/WD$) is a coefficient of plastic potential(c_p). Relationship between c_p and dT/dW is shown in Fig.8. The values of *cp* for loam, loamy clay and tuff clay categorized into diluvial layer are over 1(Area.A). On the other hand, silt is from 1 to 0.3(Area.B) and peat and organic soil are less than 0.3. For diluvial layer, c_p is over 1 and dT/dW is positive, c_p is less than 1 for alluvial layer, and c_p is less than 0.3(Area.C) for peat layer. From the results, it is concluded that soil is classified by using c_p values.

The estimation of the N value

Penetration energy($\delta E'$) is defined as follows,

$$\delta E' = 2\pi r T\frac{\delta n_{st}}{2} + W\delta S_t \tag{13}$$

where T is corrected rotation torque, δn_{ht} is incremental half turns, W is a corrected load, and δs_t is incremental settlement caused by the load.

$$\Sigma E = \delta E'_{0.25kV} + \delta E'_{0.38kV} + \ldots + \delta E'_{1.0kV} \tag{14}$$

Where ΣE is the sum total of penetration energy in every incremental load step. That is, ΣE is the energy to intrude a screw point by 25 cm. Normalized settlement is defined as follows,

$$\Sigma st = \left(\frac{\delta s_t}{0.25m}\right)^{2/3} \tag{15}$$

Normalized settlement ($\Sigma st/0.25$) is the maximum settlement of rod at each 0.25m section. In order to express relationship between ΣE and Σst with approximate slope, Σst is raised to the $^{2/3}$ the power.
Fig. 9 shows relationship between penetration energy (ΣE) and normalized settlement ($\Sigma st/0.25$)$^{2/3}$ at each 0.25m section
Normalized energy ($\Sigma st/0.25$) is calculated by using approximate slope of ΣE and $\Sigma st/0.25$.
Fig. 10shows relationship between $\Sigma E_{0.25}$ and the N value from the SPT As a result, correlation between $\Sigma E_{0.25}$ and the N value from the SPT was confirmed.

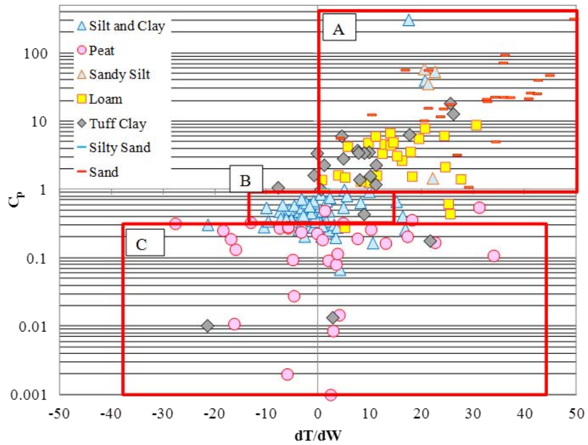

Fig.8 Relationship between *NswD* and *πT/WD*

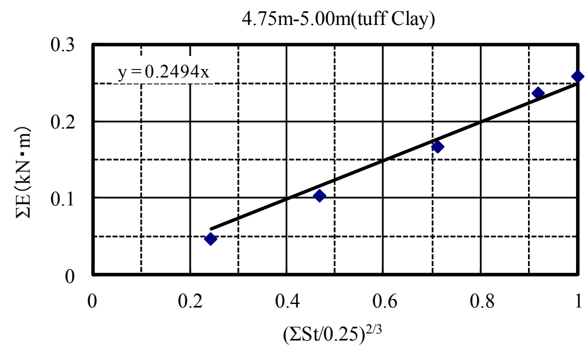

Fig.9 Relationship between a penetration energy(ΣE) at each 25cm section and a normalized settlement ($\Sigma st/0.25$)$^{2/3}$

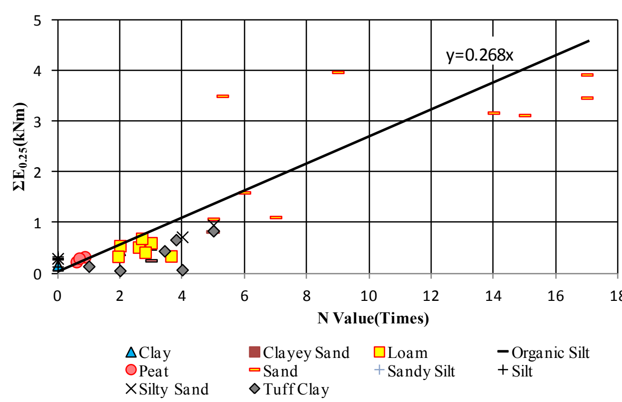

Fig.10 Relationship between$\Sigma E_{0.25}$ and the N value

CONCLUSIONS

The conclusions obtained from the field investigation of the SDS are as follows.
1) It becomes possible to distinguish among diluvial layer, alluvial layer, humous layer and sandy layer by the proposed assessment method using the SDS result and the plasticity theory analogy model.
2) The N value can be estimated from the SDS result.
3) The combination soil classification and the N value estimation using SDS test result enables to assess the risk of liquefaction.

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