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# Evaluation of Soil Liquefaction Potential by Screw Driving Sounding Test in Residential Areas

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## ABSTRACT

The 2011 off the Pacific coast of Tohoku Earthquake caused tremendous liquefaction damage to coastal areas. Most parts of damaged areas were reclaimed land and the phenomenon of liquefaction was thought to occur in saturated sand layers which have been loosely reclaimed. If it is possible to classify types of soil by a soil investigation, a risk of liquefaction can be predictable to some extent. At present, soil investigation methods such as the Standard Penetration Test (SPT) and the Cone Penetration Test (CPT) are used to determine the properties and the liquefaction probability of soils worldwide. These methods, however, are not suitable for housing lots, since they need large test apparatuses and a high cost. In this paper, the Screw Driving Sounding Test, hereinafter referred to as the SDS, is suggested as an adequate method for housing lots. This is a simple soil investigating method using a small machine with a low cost. In order to evaluate the effectiveness of the SDS, a series of field tests of the SDS were conducted. There are various methods to inspect the types of soil where liquefaction is expected to occur. Above all, the method which estimates the safety factor of liquefaction ($F_L$) using N value and fine content of a soil (Fc) is regarded to be effective and widely used in Japan. In this study, therefore, the results of the SDS field tests were investigated to estimate not only N value and Fc, but also a liquefaction resistance of soil ($R_L$) obtained from cyclic undrained triaxial loading tests. Moreover, the $F_L$ obtained from the SDS was compared with that of the SPT. As a result, it was confirmed that the SDS is one of effective methods to predict a risk of soil liquefaction.

## Introduction

Seismic Great Nation of Japan has suffered liquefaction damage every time great earthquakes occurred. Especially after The 2011 off the Pacific coast of Tohoku Earthquake caused extremely severe liquefaction damage to houses in reclaimed land, the demand for predicting a liquefaction risk in residential areas has been increasing. In Japan, a liquefaction risk of ground for large buildings is evaluated by estimating factor of liquefaction ($F_L$) using the N value of the SPT and the fine content of the soil (Fc) taken with the SPT sampler. In case of more important structures, it may be directly evaluated from the resistance of liquefaction ($R_L$) of a soil obtained by the results of cyclic undrained triaxial test performed with the soil. These methods, however, need too much time and too high cost to investigate residential areas. At present, the following process is made to investigate the ground strength for the construction of small-sized buildings. First, a soil layer is investigated on the strength with the Swedish Weight Sounding test (SWS), and classified on soil type and fine content with a sample taken from the borehole made by the SWS.

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Then, when the layer of the soil is determined to be a soft sand layer and also deeper than water level, it is regarded as a liquefaction layer. When the soil layer is determined to be clayey or shallower than water level, it is regarded as a non-liquefaction layer. In some cases, a liquefaction risk of ground is estimated through the thickness ratio of each layer. As the damage caused to houses by the 2011 earthquake was conspicuously large although these investigations have been done, much more accurate evaluation methods of ground are essential for not only important structures but also residential districts. The SDS has the potential to predict a liquefaction risk by estimating the N value and the Fc in a simple way at a low cost. In this study, it was verified that the N value and the Fc obtained by the SPT could be done by the SDS as well. Moreover, $R_L$ assessed by the SDS results was compared with the values from the cyclic undrained triaxial tests and the SPT.

## Estimation of Liquefaction Resistance

As an index for the assessment of a liquefaction risk, the liquefaction resistance factor ($F_L$) is adopted in this paper. Based on "Specifications for Highway Bridge" published by Japan Road Association in March 2012, $F_L$ is defined by $R_L$ which can be calculated from the N value and the Fc. It means a risk of liquefaction can be verified without a series of high-cost cyclic undrained triaxial loading tests. When $F_L$ is under 1.0, the soil is regarded to be vulnerable to liquefaction. The procedure of calculation is as follows:

$$\boldsymbol{F_L} = \frac{\boldsymbol{R}}{\boldsymbol{L}} \tag{1}$$

where $F_L$ is a liquefaction resistance factor, R is a dynamic shear stress ratio and L is a seismic shear stress ratio.

$$\boldsymbol{R} = \boldsymbol{C_W}\,\boldsymbol{R_L} \tag{2}$$

where $C_w$ is a correction coefficient of a seismic ground motion characteristic and $R_L$ is a cyclic triaxial strength ratio.

$$\boldsymbol{L} = \gamma_{\boldsymbol{d}} \times \boldsymbol{k_{hgL}} \times \frac{\sigma_v}{\sigma'_v} \qquad \gamma_{\boldsymbol{d}} = 1.0 - 0.015\boldsymbol{x} \tag{3}$$

$\gamma_d$ : an attenuation coefficient of a seismic shear stress ratio in depth direction
$k_{hgL}$ : a design horizontal seismic scale on the surface of ground
$\sigma_v$ : total overburden pressure ($kN/m^2$)
$\sigma'_v$ : effective overburden pressure ($kN/m^2$)
$\boldsymbol{x}$ : depth from the ground surface (m)

$R_L$ is calculated from N value and Fc as follows,

$$\boldsymbol{R_L} = \begin{cases} 0.0882\sqrt{\boldsymbol{N_a}/1.7} & (N_a < 14) \\ 0.0822\sqrt{\boldsymbol{N_a}/1.7} + 1.6\times10^{-6} \cdot (N_a-14)^{4.5} & (14 \leqq N_a) \end{cases} \tag{4}$$

$$N_a = c_1 N_1 + c_2 \qquad N_1 = 170N/(\sigma'_v+70) \tag{5}$$

$$C_1 = \begin{cases} 1 & (0\% \leqq FC < 10\%) \\ (FC+40)/50 & (10\% \leqq FC < 60\%) \\ FC/20-1 & (60\% \leqq FC) \end{cases} \tag{6}$$

$$C_2 = \begin{cases} 0 & (0\% \leqq FC < 10\%) \\ (FC-10)/18 & (10\% \leqq FC) \end{cases} \tag{7}$$

## The SDS Test

### *Test Machine and Test Method*

Figure 1(a) shows an automatic SDS test machine. It is so small and simple that even one person can control it. A rod equipped with a screw point is the same as that of the SWS. The SDS adopts a monotonic loading system where a rod rotates and penetrates constantly while a load is stepwisely increased at each rotation. The loading started from 0.25kN of load and then kept on increasing by 0.125kN up to 1kN. Measured items were torque (T), total penetration length (L) and settlement velocity (V). These were measured at every rotation of rod. The loading was set back to the initial condition at every 25cm of settlement and this process was made repeatedly. In order to measure rod friction, torque was measured immediately after the rod was lifted up by a few cm and rotated.

### *Estimation of Rod Friction*

In order to estimate torque and a load applied to the tip of rod accurately, rod friction was corrected in the following procedure during the SDS. Figure 1(b) shows the concept of estimating rod friction. $W_a$, $T_a$, $W_f$ and $T_f$ are defined as applied load, applied torque, vertical rod friction force and horizontal rod friction torque, respectively. Moreover, when a load (W) and torque (T) are defined as values directly applied to a screw point, the relationships between these loads and torques are defined with the following formulas.

$$T_a = T_f + T \tag{8}$$

$$W_a = W_f + W \tag{9}$$

Assuming the direction of combined speed and that of maximum shear stress are same when penetrating in one direction, the following formulas (10) are given. θ is defined as the angle made by the direction of maximum shear stress and a horizontal plane.

$$\tau_h = \tau_{max} \cos\theta \qquad \tau_v = \tau_{max} \sin\theta \tag{10}$$

A friction torque of rod rotation $T_f$ and a friction force of penetration $W_f$ are expressed as follows.

$$T_f = 2\pi r^2 \cdot L \cdot \tau_h \qquad W_f = 2\pi r \cdot L \cdot \tau_v \tag{11}$$

where *r* is a radius of the rod and *L* is a penetration amount.

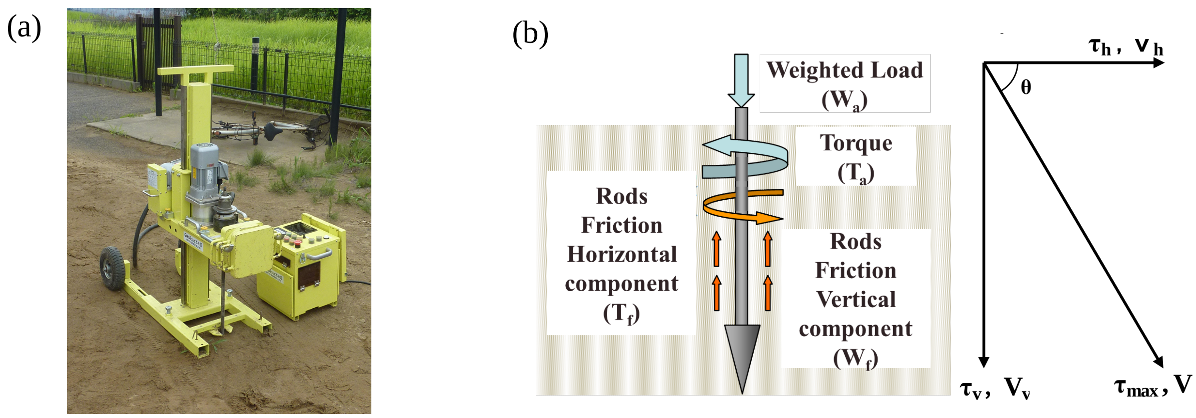


Figure 1. (a) SDS machine and (b) Concept of a rods friction

***Classification of Soil Using the SDS Test***

It was attempted to determine some soil properties using the result of the SDS. Fig. 2 shows the depth distribution of torque obtained at the sites. In addition, the relationship between loads and torque obtained at 25cm penetration is shown in Fig. 3, where data was plotted at two sections of 25cm penetration. According to Fig. 2 and Fig. 3, the relationships were obviously different depending on the types of soil where T increased according as W increased in the sandy soil with a high frictional angle. On the other hand, it was seen that T didn't increase when W increased in the clayey soil without a frictional angle under the undrained condition of loading. Thus, it was concluded that the SDS was capable of categorizing soils by using these responses.

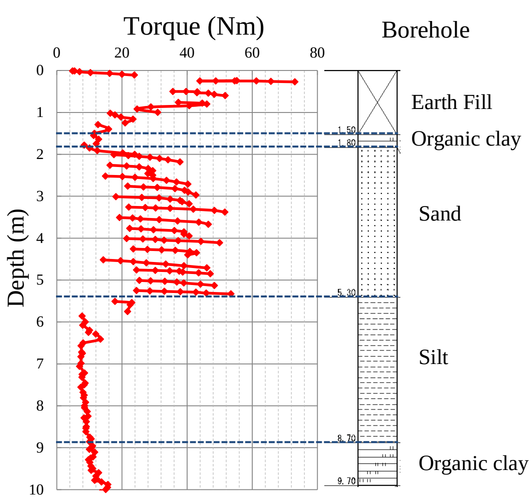


Figure 2. Torque and types of soil

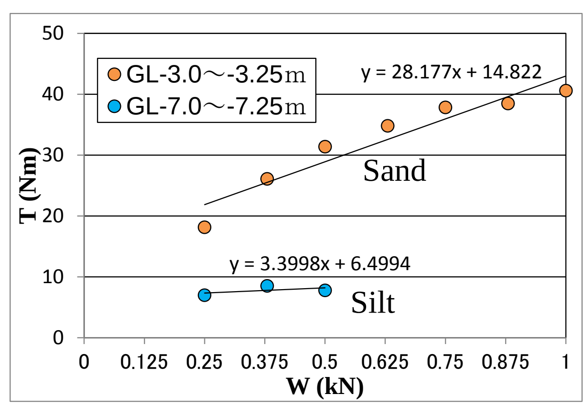


Figure 3. Relationships between T and W compared with types of soil

*Estimation of N Value and Fc Using the SDS Test*

In order to estimate the N value, a series of the SDS were performed at forty sites where the SPT had been already performed nearby. Among these test results, the data including 76 sets for sandy soil and 96 sets for clay soil (silt, clay, organic soil, loam, etc.) were selected to be analyzed. The regression analysis to assess the $N_{SPT}$ was conducted using the parameters derived from the SDS. The N value ($N_{SDS}$ ) derived from the parameters is expressed as

$$\boldsymbol{N}_{\boldsymbol{SDS}} = \alpha_1 \times \boldsymbol{dT} / \boldsymbol{d}\Sigma\boldsymbol{s}_{\boldsymbol{t}} + \alpha_2 \times \boldsymbol{E}_{0.25} + \alpha_3 \times \boldsymbol{C}_{\boldsymbol{nl}} + \alpha_4 \qquad (12)$$

where each $\alpha_{1\text{-}4}$ is a coefficient of parameters from the regression analysis, $dT/ds_t$ is a slope of torque with penetration amount, $E_{0.25}$ is an total penetration energy needed for 25cm penetration of the screw and $C_{nl}$ is a coefficient of non-linearity with an increasing tendency of penetration energy. Fig. 4 and Fig. 5 show the correlation between the $N_{SDS}$ and the N value of the SPT in sandy and clayey soil, respectively.

Similarly, in order to estimate the Fc, the data of the SDS obtained at the 26 sites was compared with that of the SPT, including 63 data for clayey soil whose Fc was less than 50% and 55 data for sandy soil whose Fc was more than 50%. Using the parameters derived from the SDS results by the regression analysis, the equation to estimate Fc, is expressed as

$$\boldsymbol{Fc}_{\boldsymbol{SDS}} = \alpha_1 \times \boldsymbol{W}_{0.25} + \alpha_2 \times \boldsymbol{dT} / \boldsymbol{dWD} + \alpha_3 \qquad (13)$$

where each $\alpha_{1\text{-}4}$ is a coefficient of parameters derived from the regression analysis, $W_{0.25}$ is a vertical load needed for 25cm penetration and dT/dWD is a normalized rate of torque with respect to weighted load. The correlation between the $Fc_{SDS}$ and the Fc from the SPT test is shown in Fig. 6. It indicates that the SDS can classify soils into clay and sand.

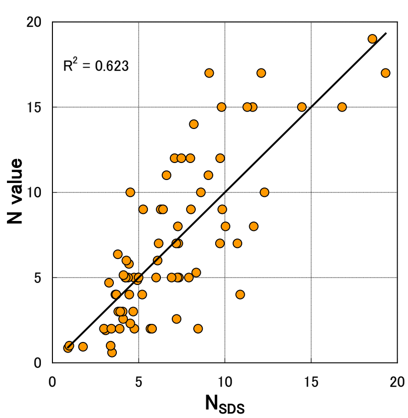


Figure 4. Correlation between N value and $N_{SDS}$ in sandy soil

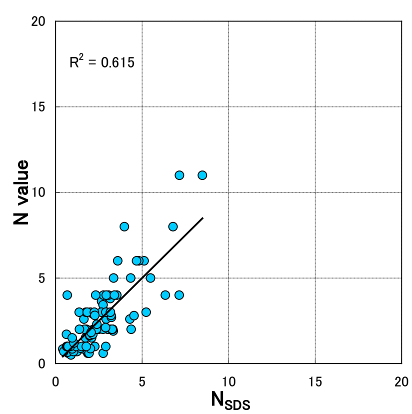


Figure 5. Correlation between N value and $N_{SDS}$ in clayey soil

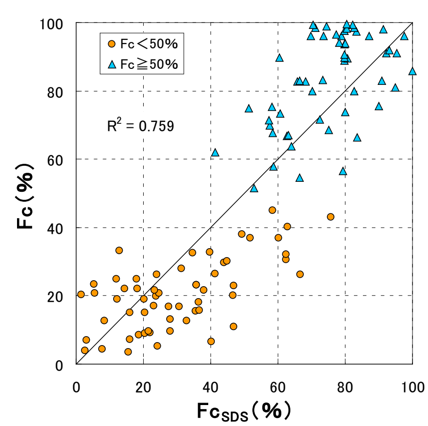


Figure 6. Correlation between Fc and $Fc_{SDS}$

### ***Direct Estimation of $R_L$ Using the SDS Test***

Laboratory tests were conducted to estimate $R_L$ using the soil samples taken from the 38 points at the 8 sites of the SPT, whose results were used as a statistical population to evaluate $R_L$ from the SDS. A regression analysis for this was performed and the following equation was derived using the parameters obtained from the SDS results.

$$\boldsymbol{R}_{LSDS} = \alpha_1 + \alpha_2 \times \boldsymbol{c}_p + \alpha_3 \times \boldsymbol{dT/d}_{st} + \alpha_4 \times \boldsymbol{E}_{0.25} \qquad (14)$$

where each $\alpha_{1\text{-}4}$ is a coefficient of regression parameter, $c_p$ is a screw effect index which is the ratio of rotation number to settlement divided by the ratio of torque to vertical load, $dT/ds_t$ is a slope of torque to settlement and $E_{0.25}$ is a penetration energy needed for 25cm penetration. Fig. 7 shows the relationship between the $R_L$ obtained from laboratory tests and the $R_L$ calculated from the equation (14). Although scatter can be seen in the figure, it suggests that the equation proposed can predict $R_L$ directly without the estimation of the N value. However, as $R_L$ was concentrated around 0.3 as seen in Fig. 7, it was revealed that further work was needed for the test in order to estimate $R_L$ more accurately.

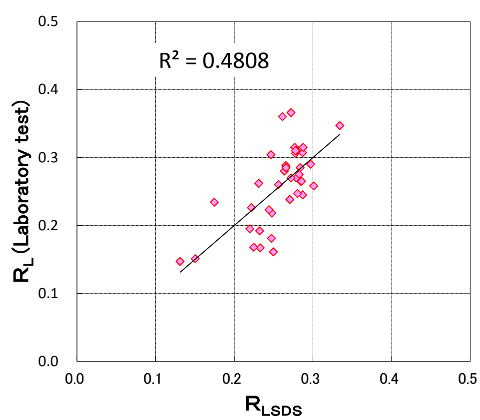


Figure 7. Relationship between $R_L$s from the laboratory and the SDS

## **Test Site**

Fig. 8 shows the comparisons between the results from the SDS, the SPT and the laboratory tests on N value, Fc and $F_L$, conducted in Urayasu city. Fig. 9 also shows the results at some sites in Katsushika Ward, Tokyo.

Both test sites are more than 360km far away from the epicenter of The 2011 off the Pacific coast of Tohoku Earthquake. The soil profile in Urayasu is that the layer is sandy earth fill from surface to 2.5m depth, covered by dredged earth layers consisting of sand, clay and sand in order from 2.5m to 7.1m depth. The layer from 7.1m to 7.5m depth is clayey silt and that deeper than 7.5m depth is mainly sand. Thus, the ground in Urayasu consists of several layers of different soil properties and this makes it more difficult to classify the soils.

On the other hand, the soil profile in Katsushika is much more simple, which is composed of earth fill from surface to 1.8m depth and sandy fill layer from 1.8m to 3.6m depth. The layer deeper than that is natural deposited sand from 3.6m to 8.9m overlying a thick natural clay layer.

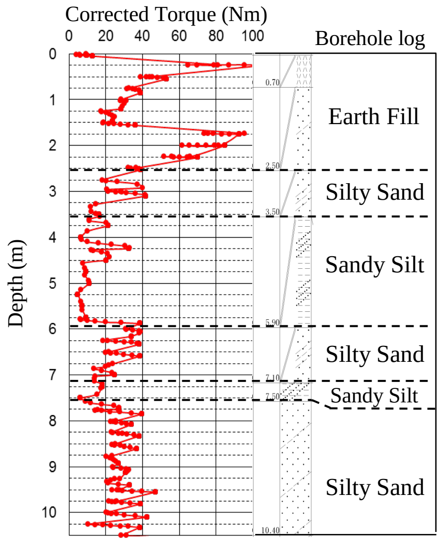


Figure 8. The results in Urayasu city of Chiba

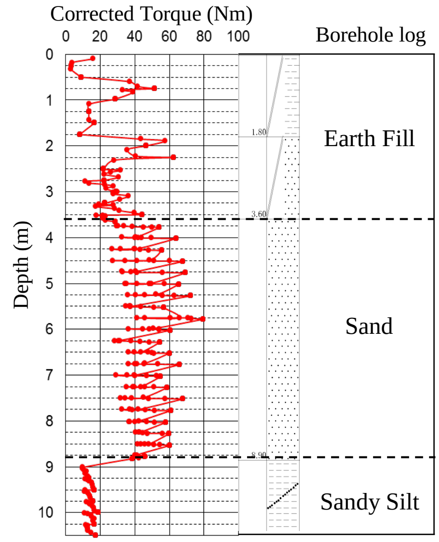


Figure 9. The results in Katsushika Ward, Tokyo

## ***Estimation of $F_L$ Using the SDS Test***

$F_L$ was estimated from the proposed equations by assuming a medium-scale earthquake, called level 1 earthquake. The example of the SDS result in Urayasu is shown in Fig. 10 and that in Katsushika in Fig. 11, respectively. The results of the N value in the layer from surface to 3.6m depth were omitted from the graphs, as it contained impurities such as broken pieces of concrete or cobble stones.

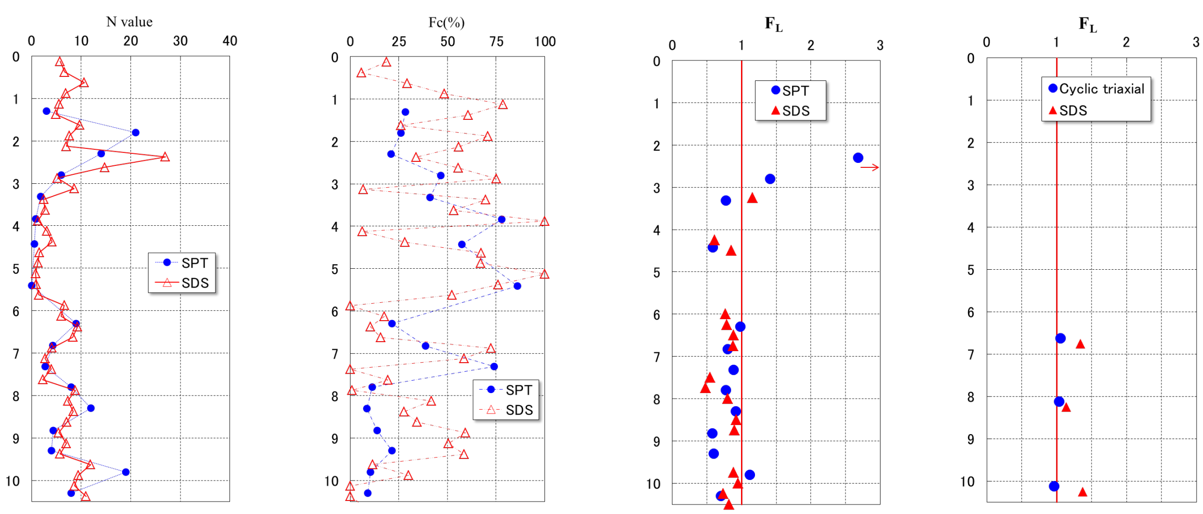


Figure 10. Estimated N, Fc and FL values from the SDS tests in Urayasu compared with SPT tests and laboratory test results.

In Urayasu results, the values of $F_L$ estimated using the SDS results ($F_{LSDS}$) were approximately the same as not only those calculated from the N value but also the values obtained from the laboratory test results. It is revealed, therefore, that the SDS is useful enough to predict the liquefaction risk.

Although a disorder was seen in the result of Fc in Urayasu because of a dredged earth fill, Fc didn't seem to have as much influence as the N value did on the estimation of $F_L$.

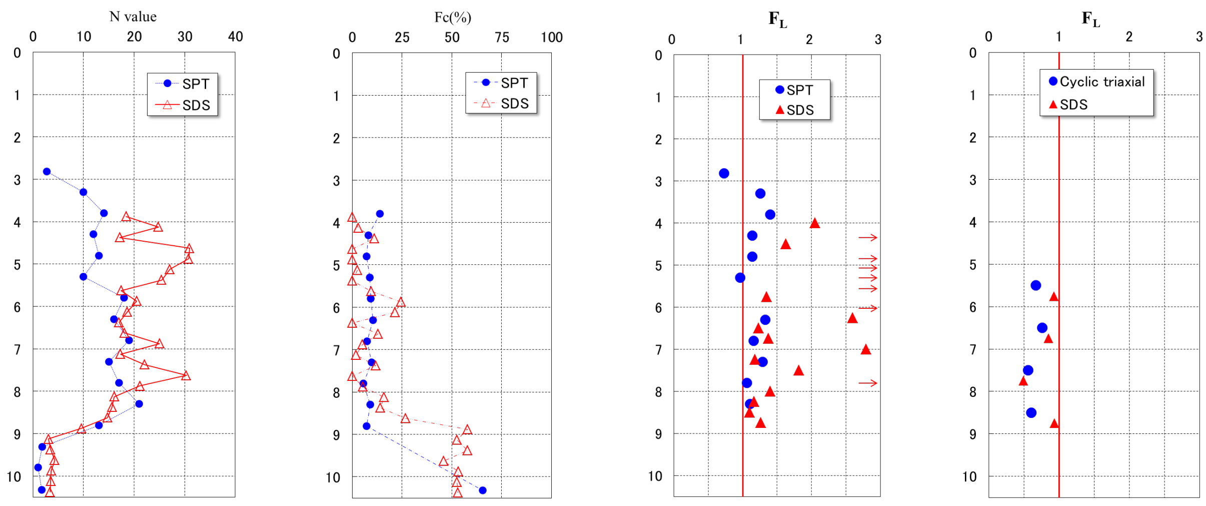


Figure 11. Estimated N, Fc and $F_L$ values from the SDS test in Katsushika compared with SPT tests and laboratory test results.

In Katsushika, the values of $F_{LSDS}$ were almost the same as those obtained from the laboratory test, while these were relatively different from the values calculated from the N value. From the results, it was cleared that improvement of the estimation accuracy was necessary in the harder ground where the N value was more than 10. On the other hand, for the results of the $F_L$ around 1, the $F_{LSDS}$ values were the same as both those calculated from the N value and those obtained from the laboratory tests. As a result, it indicated that the SDS could estimate a risk of liquefaction as accurately as the SPT could.

## Conclusions

1) The estimation of $R_L$ obtained by the regression analysis using the laboratory test data was more accurate than the one calculated from the N value and the Fc, even though there was not many enough number of data for the estimation.

2) There is a possibility that $F_L$ is able to be estimated by the SDS as accurately as the SPT, by estimating $R_L$ in two ways calculating from the N value and the Fc and using the laboratory test results.

3) It was shown that the SDS is one of the simplest methods to investigate a risk of liquefaction efficiently.

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