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Some recent applications of Swedish weight sounding tests to earthquake reconnaissance investigations

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ABSTRACT

The empirical procedure to estimate the liquefaction resistance of soils from Swedish weight sounding (SWS) tests is examined based on the empirical relation between the relative density and penetration resistance of SWS gained from laboratory calibration chamber tests and also on the data of the liquefaction resistance plotted against the relative density collected from many sources of past studies. In addition, some recent applications of SWS tests for earthquake reconnaissance investigations are described. A series of SWS tests were conducted at a couple of sites in Itako City, where soil liquefaction was observed during the 2011 Great East Japan Earthquake and trench survey was carried out by Itako City Authority as post-earthquake geotechnical investigations.

Introduction

Swedish weight sounding (SWS) tests have been one of the commonly used tools for earthquake reconnaissance geotechnical investigations (Tsukamoto 2015). Figure 1 illustrates its procedure proposed by Tsukamoto (2015), in which the stability of natural and reclaimed deposits during earthquakes, ranging from flow and slip failures to post-liquefaction settlement and laterally spreading displacements would be analysed, though there are still some technical portions in its procedure which are yet to be examined in detail. One of such missing technical portions is the estimation of liquefaction resistance of soil deposits from the penetration resistance of SWS tests. In the present study, the procedure for empirically estimating the liquefaction resistance of soils from the penetration resistance of SWS tests represented by values of W_{sw} and N_{sw} is examined. In addition, some recent applications of SWS tests to earthquake reconnaissance geotechnical investigations are illustrated, where a series of SWS tests were conducted at a couple of sites in Itako City, Ibaraki, where soil liquefaction was observed during 2011 Great East Japan Earthquake. At those sites, trench survey was carried out by Itako City Authority to find which layer of soil deposits would be responsible for subsurface soil liquefaction which affected infrastructures and residential houses and reached up to ground surfaces as sand boils.

Estimating Liquefaction Resistance from SWS Tests

Figure 2(a) demonstrates a set of data of liquefaction resistance, $R_l = \sigma_{d,l}/(2\sigma'_o)$, plotted against

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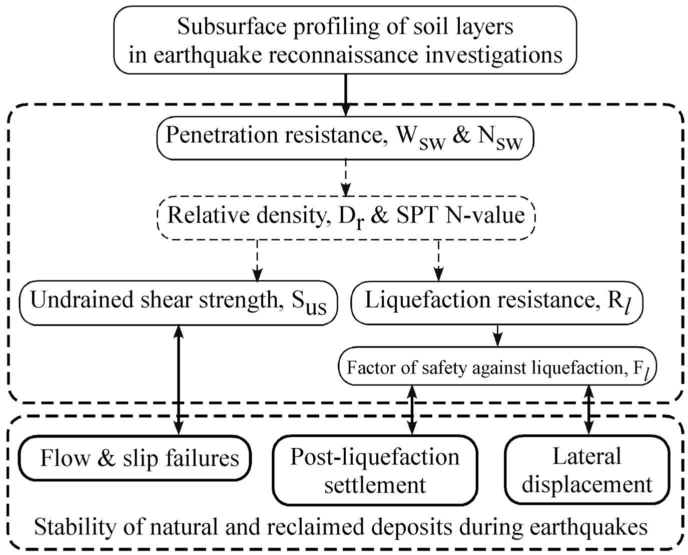

Figure 1. Procedure of earthquake reconnaissance investigations using SWS tests (after Tsukamoto 2015)

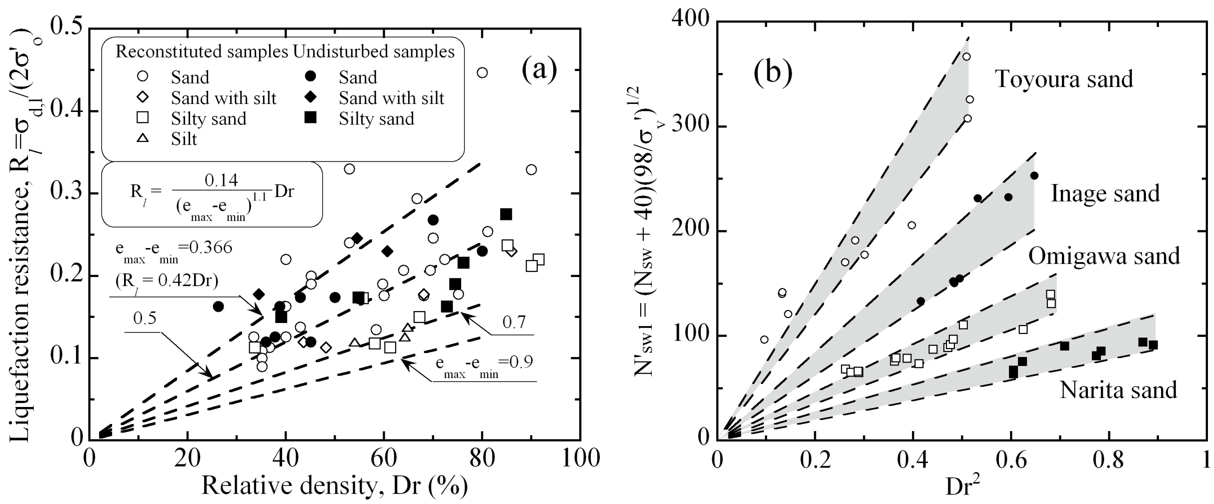

Figure 2. Plots of (a) data of R_l against D_r collected by Nakazawa (2007), and (b) data of N'_{sw1} against D_r^2 after Tsukamoto et al. (2004)

the relative density, D_r, collected from many sources of past studies (Nakazawa 2007). These data include reconstituted samples as well as undisturbed samples, ranging from sands to silt. It would be still controversial to tell the tendency of liquefaction resistance changing with the inclusions of fines, though the data shown in Figure 2(a) would indicate that the ratios of liquefaction resistance to relative density, R_l/D_r, would tend to reduce with the increase of fines content. It is well known that the liquefaction resistance increases linearly with the relative density up to D_r = 80%. However, it tends to increase rapidly when the relative density exceeds D_r = 80% (Ishihara 1973, Tatsuoka et al. 1977, Tatsuoka et al. 1982, Tokimatsu and Yoshimi 1983). With all these findings in mind and focusing on the range of the data up to D_r = 80%, as shown in Figure 2(a), the following empirical relation can be assumed,

$$R_l = \frac{0.14}{(e_{\max} - e_{\min})^{1.1}} D_r \tag{1}$$

where the void ratio range, $e_{max} - e_{min}$, is taken to represent the effects of inclusion of fines, which was proposed by Cubrinovski and Ishihara (2004) and was well illustrated to work sufficiently for analysing the penetration resistance of in-situ tests (Cubrinovski and Ishihara, 1999; Tsukamoto et al. 2004).

The following empirical relation was proposed by Tsukamoto et al. (2004), in which the penetration resistance of SWS, N_{sw}, is correlated by means of effective confining stress, σ'_v, relative density, D_r, and void ratio range, $e_{max} - e_{min}$, as follows,

$$D_r = \sqrt{\frac{(N_{sw} + 40)(e_{\max} - e_{\min})^{2.2}}{90} \sqrt{\frac{98}{\sigma'_v}}} \tag{2}$$

where σ'_v is in kPa. The correlation between the liquefaction resistance, R_l, and the penetration resistance of SWS tests, N_{sw}, can be obtained by combining the above Equations (1) and (2), as follows,

$$R_l = 0.015\sqrt{(N_{sw} + 40)\sqrt{\frac{98}{\sigma'_v}}} = 0.015\sqrt{N'_{sw1}} \tag{3}$$

This empirical equation is assumed for clean and fines-containing sands. It is to note here that the inclusions of fines would not come into effect in Equation (3), and also to note here that it is advantageous to use such a correlation, since there is no soil sampling accompanied in the ordinary SWS testing procedure, and it is therefore difficult to directly obtain physical properties of soils from SWS tests.

When looking closely at the plots of N'_{sw1} against D_r, as shown in Figure 3(a), it was demonstrated by Tsukamoto et al. (2009) that the relations for fines-containing sands would be more suitably represented with the offset in the relative density, i.e. D_r – 0.25, where D_r is in ratio, as follows,

$$N'_{sw1} = \alpha_{sw}(D_r - 0.25)^2 \tag{4}$$

where the value of α_{sw} changes with the inclusion of fines. It is then worthwhile to see if the same assumption can also be applied to the relations between R_l and D_r, as shown in Figures 3(b) and 3(c). It is seen that the direct correlation of $R_l = 0.42D_r$ is valid for clean sand, though the correlations of $R_l = \beta_{tx}(D_r\text{-}0.25)$ can also be assumed for fines-containing sands, where the value of β_{tx} changes with the inclusion of fines.

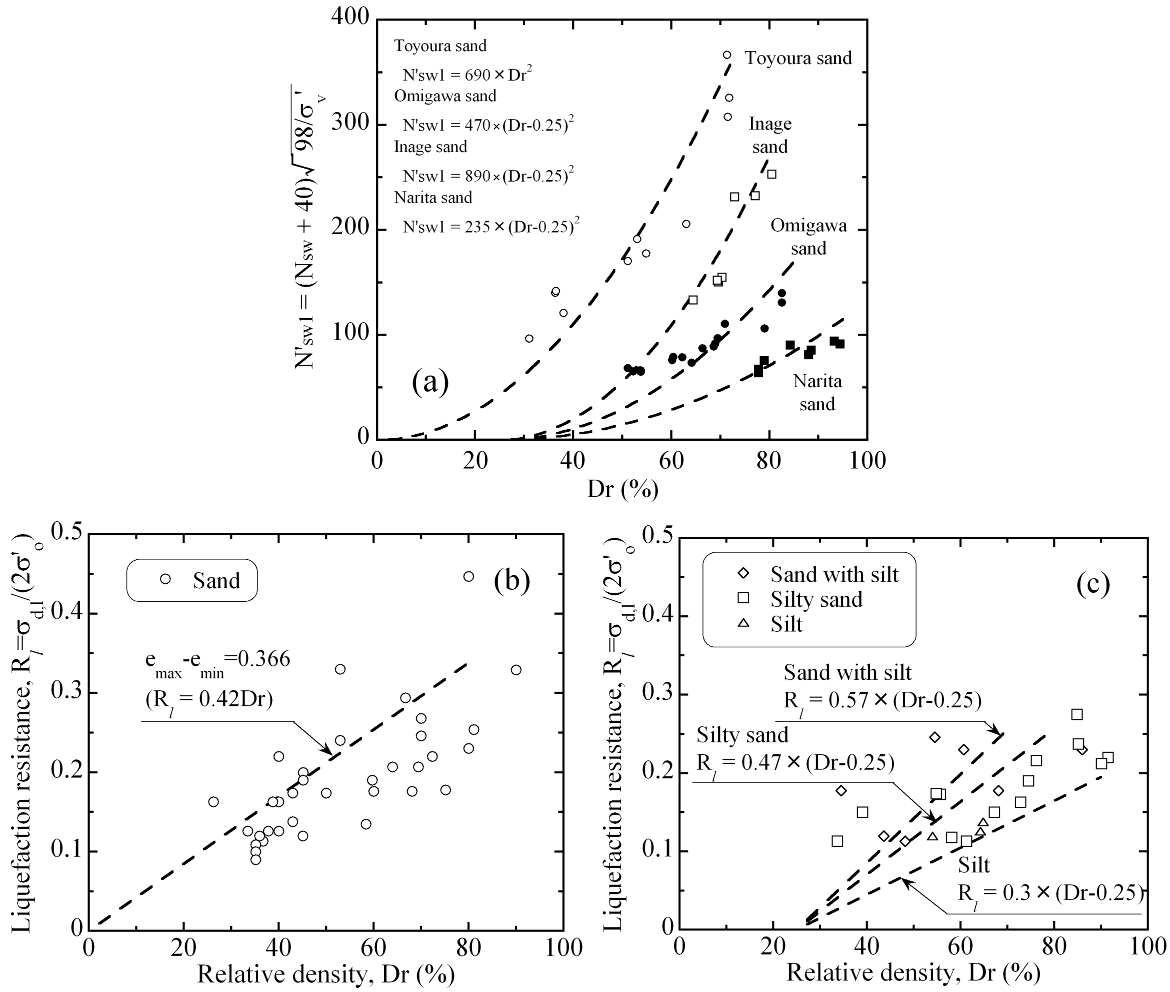

Figure 3. Revised relations on the plots of (a) N'_{sw1} against D_r after Tsukamoto et al. (2009), R_l against D_r for (b) clean sand and (c) sands with fines

The ratios of R_l/D_r for clean sand and $R_l/(D_r-0.25)$ for fines-containing sands are plotted against the void ratio range, $e_{max} - e_{min}$, as shown in Figure 4(a). The data for fines-containing sands are then fitted with the following equation,

$$\frac{R_l}{D_r - 0.25} = \frac{0.2}{(e_{\max} - e_{\min})^{1.6}} \tag{5}$$

With the same principle in mind, the ratios of N'_{sw1}/D_r^2 for clean sand and $N'_{sw1}/(D_r-0.25)^2$ for fines-containing sands are plotted against the void ratio range, $e_{max} - e_{min}$, as shown in Figure 4(b).The data for fines-containing sands are then fitted with the following equation, as follows,

$$\frac{N'_{sw1}}{(D_r - 0.25)^2} = \frac{96}{(e_{\max} - e_{\min})^{3.2}} \tag{6}$$

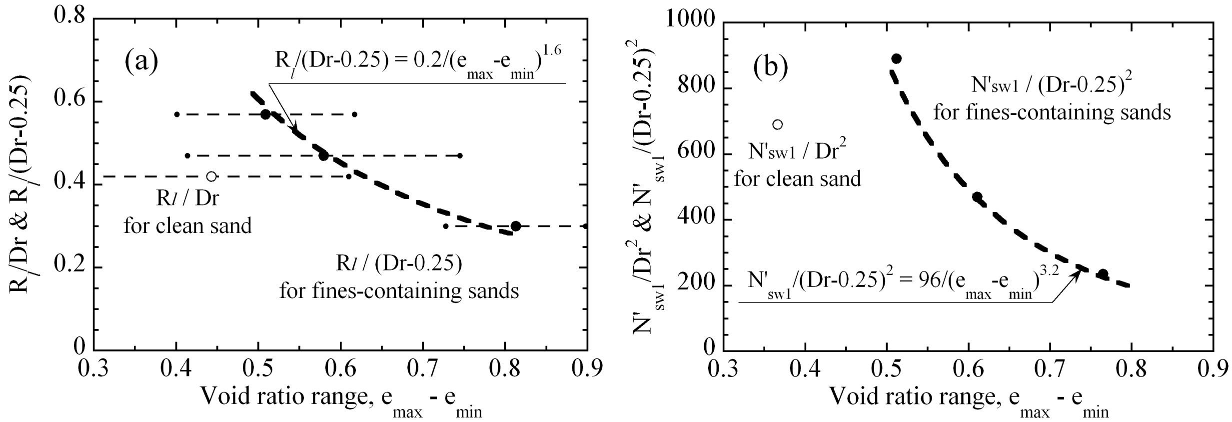

Figure 4. Plots of (a) data of R_l/D_r & $R_l/(D_r$-0.25) against void ratio range, e_{max}–e_{min}, and (b) N'_{sw1}/ D_r^2 & $N'_{sw1}/ (D_r-0.25)^2$

From the data and the empirical equations fitted in Figures 4(a) and 4(b), the correlations between R_l and N'_{sw1} can be derived for clean sand and fines-containing sands, as follows,

$$R_l = 0.0160\sqrt{N'_{sw1}} \text{ (for clean sand)}, \; R_l = 0.0204\sqrt{N'_{sw1}} \text{ (for fines-containing sands)} \tag{7}$$

Based on the above Equations (3) and (7), the liquefaction resistance would be conservatively estimated as follows,

$$R_l = 0.015\sqrt{N'_{sw1}} \tag{8}$$

Some Recent Investigations Using SWS Tests at Trenching Sites in Itako City

A series of Swedish weight sounding tests were carried out at a couple of sites in Itako City, Ibaraki, Japan. Itako City is located at downstream areas of Tonegawa river, as shown in Figure 5, and is one of the areas where extensive soil liquefaction was observed during the main shock and aftershocks of 2011 Great East Japan Earthquake. Following the extensive damages on infrastructures as well as residential houses incurred due to soil liquefaction, Itako City initiated field geotechnical investigations at a couple of sites, where the trench survey on No.1 and No.2 was carried out at the same site, and described in detail below.

The trenches No. 1 and No.2 are located close to each other, as shown in Figure 6. The history of land use certainly affects layering of soil deposits. In this area, paddy fields had been prevailing for over longer times, in which networks of small water channels were formed for irrigation and transport of agricultural purposes. This area was then reclaimed, upon which residential houses and infrastructures were built. In fact, one of the major purposes of trench survey was to see if any soil materials reclaimed in such old small water channels were responsible for extensive soil liquefaction observed around this area. In the trench No.1, some remains of old water channels were found as shown in Figure 7(a), and it was found that those old water channels were reclaimed with clayey soils, at least in this area, and less responsible for soil liquefaction. Instead, some traces of soil liquefaction were observed in the underlying stratum of fine sand, which is a grey-coloured natural deposit, as shown in Figure 7(b). In fact, grey-coloured sand boils were observed around the trench No.1, as shown in Figure 6. On the other hand, brown-coloured sand boils were observed around the trench No.2, as shown in Figure 6. The trench survey at the trench No.2 revealed that those brown-coloured sand boils should have come from the reclaimed deposit of silty sand overlain by the most recent fill, as shown in Figure 7(c). The results of SWS tests conducted at the trenches No.1 and No.2 are shown in Figure 8. It is found that the differences in the W_{sw} and N_{sw}-values of static penetration resistance of SWS tests are visible among the different soil layers, and the layers of soil deposits are clearly connected along Sw-1 and Sw-2 as well as Sw-1 and Sw-3.

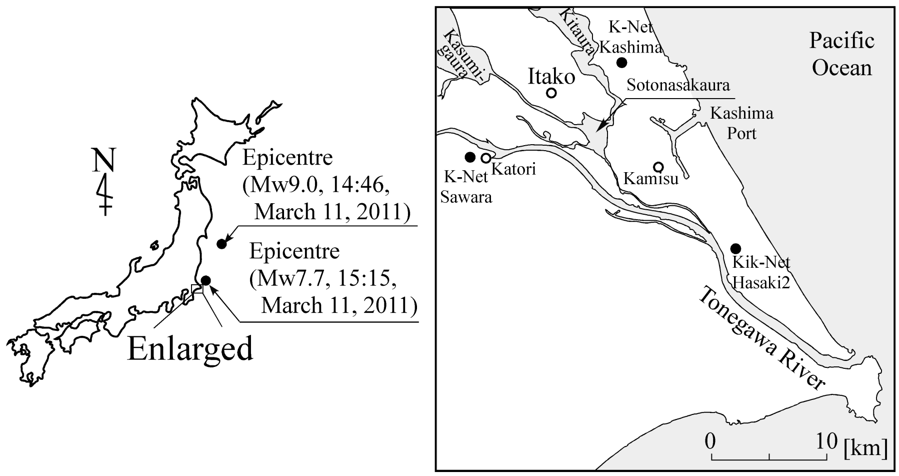

Figure 5. Location of Itako City

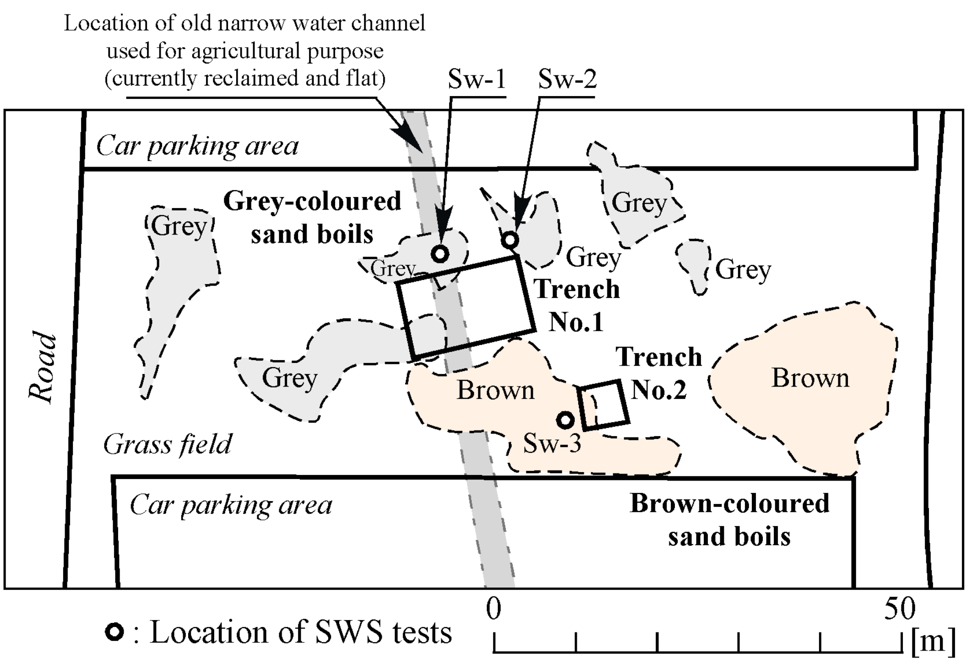

Figure 6. Location of SWS tests at trenches No.1 and No.2 (reproduced after Itako City 2014)

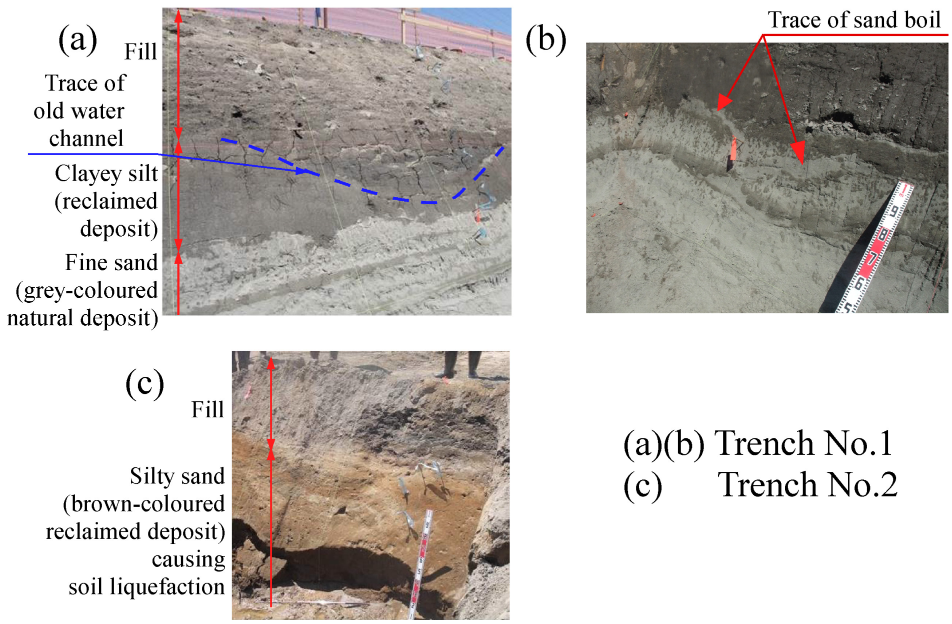

Figure 7. Observation of cross section views of trenches, (a) overall observation at trench No.1, (b) trace of soil liquefaction at trench No.1, (c) observation at trench No.2

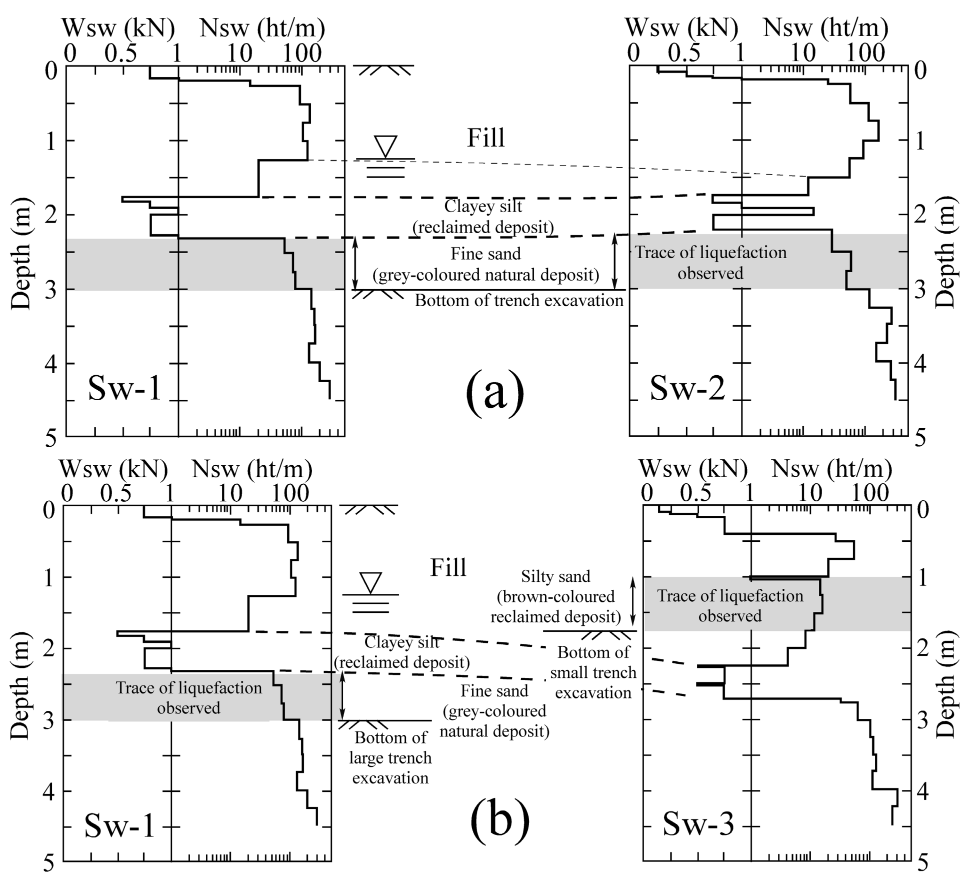

Figure 8. Distributions of W_{sw} and N_{sw} for (a) Sw-1 & Sw-2 and (b) Sw-1 & Sw-3, with depth

Conclusions

The simple empirical procedure was proposed to estimate the liquefaction resistance of soils from robust SWS tests, which allows estimation of liquefaction resistance of soils directly from the penetration resistance of SWS tests and is free from any effects of fines content and relative density of soils concerned. The advantage of using such a simple empirical equation is emphasized since there is no soil sampling currently accompanied in the ordinary SWS testing procedure. A series of SWS tests were conducted at a couple of sites in Itako City, where soil liquefaction was observed during the 2011 Great East Japan Earthquake and trench survey was carried out by Itako City Authority as post-earthquake geotechnical investigations. The soil layers observed on the cross section views of the trenches were compared with the depth-wise distributions of penetration resistance of SWS tests, and the use of SWS tests was found useful in detecting soil layers prevailing over some areas.

Acknowledgments

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