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USE OF FIELD PENETRATION TESTS IN EVALUATING OCCURRENCE OF SOIL LIQUEFACTION AT RECLAIMED DEPOSITS DURING 2000 TOTTORI-KEN SEIBU EARTHQUAKE

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ABSTRACT

The procedure for evaluating the occurrence of soil liquefaction during earthquakes is proposed by using the results of Swedish Weight Sounding Tests. The empirical correlation between the relative density of soils and Swedish penetration resistance proposed by the authors is used. One case history obtained in 2000 Tottori-ken Seibu Earthquake is provided to examine the reliability of this proposed procedure. In the event of Tottori-ken Seibu Earthquake on October 6, 2000, extensive liquefaction and subsequent eruptions of subsurface soils occurred at the reclaimed land of Takenouchi Industrial Complex, which is located along the coast of Sakai-Minato, Tottori, Japan. This industrial estate was built upon the reclaimed fills by dredging seafloor sludge, which is predominantly silt. A series of Swedish Weight Sounding Tests were conducted after the earthquake. Based on the outcome of the field survey and testing, the use of Swedish Weight Sounding Tests is examined as a tool for evaluating the occurrence of soil liquefaction.

Keywords: Soil liquefaction, Field penetration test, Case history

INTRODUCTION

On October 6, 2000, at 13 : 30, the huge earthquake hit the western region of Tottori, Japan. The epicentre of this earthquake was located in the mountain area behind Yonago city, and was about 20 km south of the city centre. The focal depth was as shallow as 9 km and the magnitude was M7.3. At Sakai-Minato fishery port located north of Yonago city as shown in Fig. 1, the quay wall moved outwards for about 1.3 metres at maximum and the ground subsidence of about 0.6 metres at maximum occurred behind the quay wall due to soil liquefaction. The columns supporting the roof of the fish-unloading quay house were subsequently deflected as shown in Fig. 2. At Takenouchi Industrial Complex located along the east coast of Sakai-Minato shown in Fig. 1, the extensive liquefaction and subsequent eruptions of subsurface soils occurred as shown in Fig. 3. This industrial estate has been built upon the reclaimed land by dredging seafloor sludge during the period from 1978 to 1986, which is predominantly silt. The physical properties and grain size distribution of this silt are shown in Table 1 and Fig. 4. The soil liquefaction seems to have continued within relatively impermeable subsurface silt for over 6 hours, and a large mass of the fluidized subsurface silt seems to have been ejected up over the ground surface to a maximum height of 40 cm.

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The field survey and a series of Swedish Weight Sounding Tests have been carried out at Takenouchi Industrial Complex during the period from October 24 to 26, 2000, and are examined in detail in the present study. The locations of field survey and Swedish Weight Sounding Tests are indicated in Fig. 5.

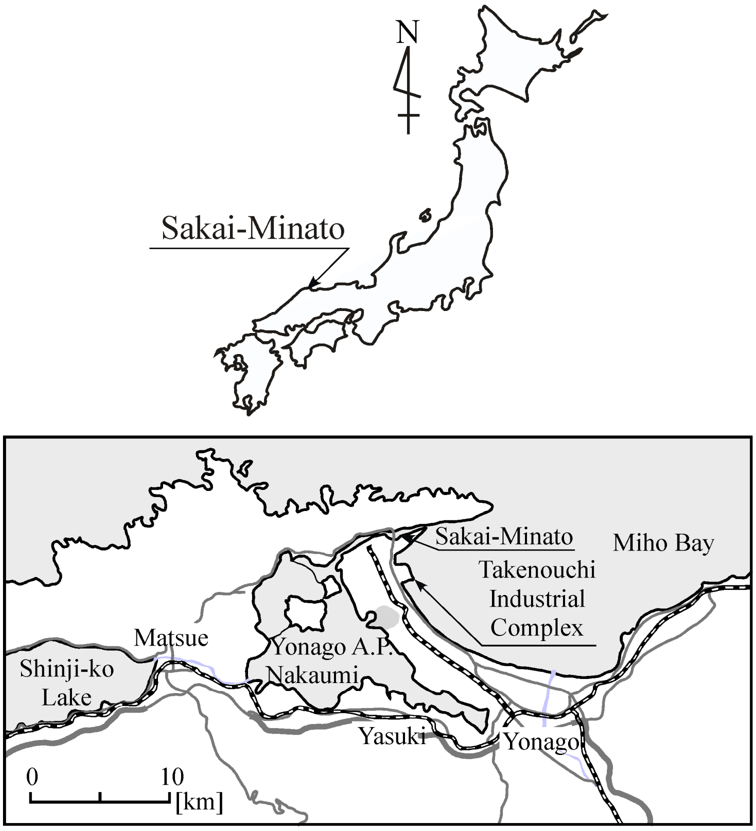

Figure 1. Locations of Sakai-Minato Port and Takenouchi Industrial Complex

Figure 2. Damage to Sakai-Minato Port

Figure 3. Eruption of subsurface silt observed at Takenouchi Industrial Complex

Table 1. Physical properties of silt at Takenouchi Industrial Complex

Fines content finer than 0.075 mm, F_c (%)	98
Gravel content coarser than 4.76 mm (%)	0
Specific gravity, G_s	2.63
Mean grain size, D_{50} (mm)	0.06
Maximum void ratio, e_{max}	1.586
Minimum void ratio, e_{min}	0.858
Void ratio range, e_{max} - e_{min}	0.728
Plasticity index, I_p	NP

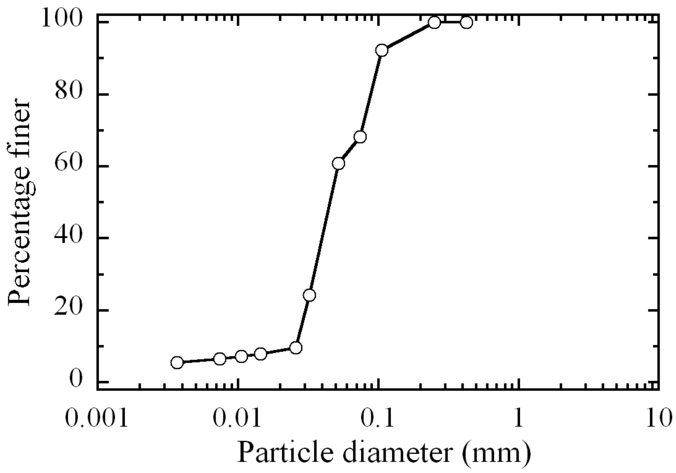

Figure 4. Grain size distribution of erupted subsurface silt at Takenouchi Industrial Complex

FIELD SURVEY AT TAKENOUCHI INDUSTRIAL COMPLEX

The water channel runs through at the west side of Takenouchi Industrial Complex, as shown in Fig. 5. Along the floor of this water channel, the subsurface silt was also observed having boiled up, as shown in Fig. 6. The main portion of the reclaimed land with a dozen of warehouses is located at the east side of this water channel, as shown in Fig. 5. It is interesting to note here that the east face of the water channel was made up of a sheet pile wall, which had not suffered any damage. However, some portions of the asphalt pavements immediately adjacent to the water channel were broken, and several ground cracks were found, as shown in Fig. 7. At some portions of the reclaimed land, the ground surface settled down to about 20 to 30 cm, and was filled with the erupted subsurface silt. Some of the one-storey warehouses suffered differential settlement. The details of damages to warehouses in this reclaimed land are also indicated in Fig. 7.

Some portions of the concrete-block wall comprising the west face of the water channel were collapsed, which can be seen in Fig. 6. Some reinforcement of non-woven geo-textiles has been detected behind this collapsed concrete-block wall. In the wood of pine trees behind this collapsed concrete-block wall at the west side of the water channel, several large ground cracks were found, along which the eruptions of liquefied subsurface silt were also observed, as shown in Fig. 8. The details of the ground cracks and the area covered by erupted subsurface silt are shown in Fig. 9.

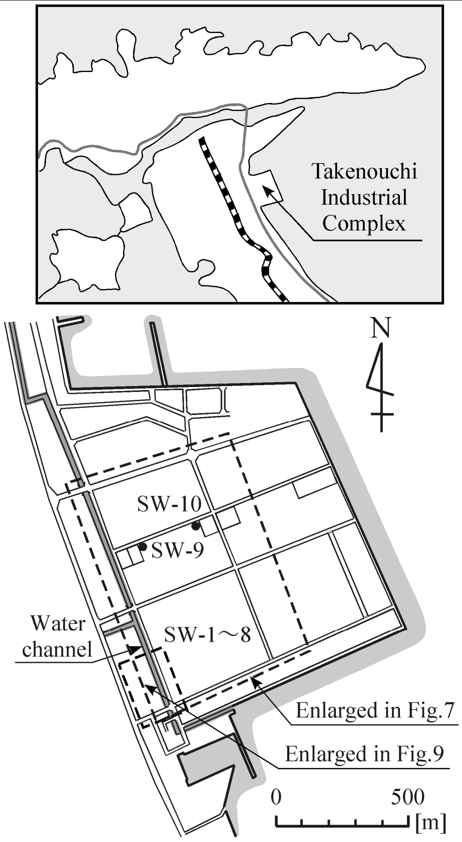

Figure 5. Locations of field survey and Swedish Weight Sounding Tests at Takenouchi Industrial Complex

Figure 6. Erupted subsurface silt in the water channel looking north

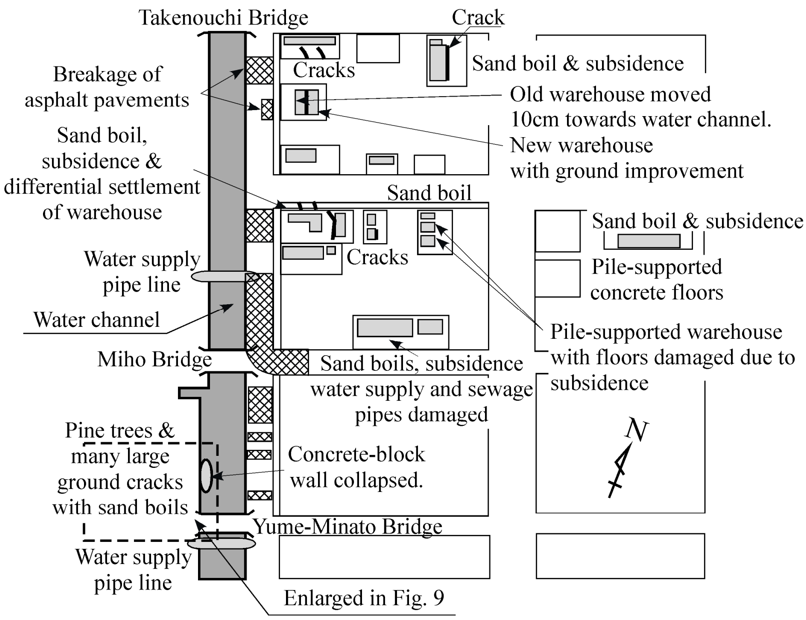

Figure 7. Damages to warehouses

Figure 8. Liquefied subsurface silt erupted from ground cracks at west side of water channel

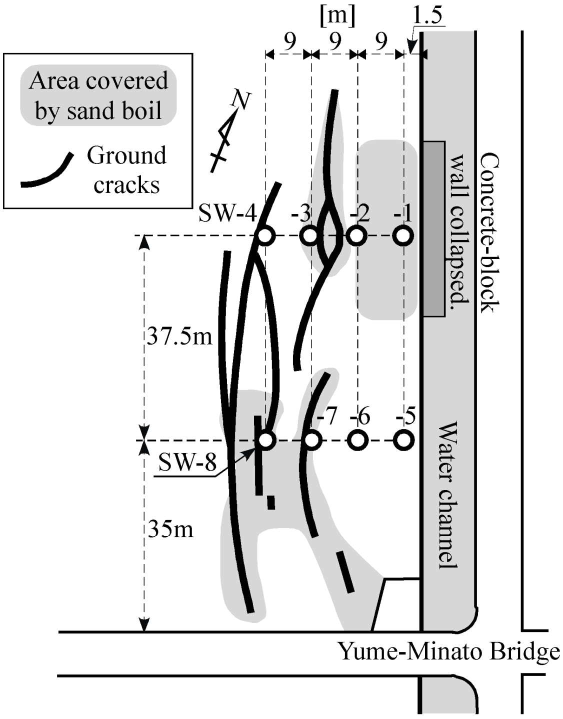

Figure 9. Details of ground cracks and erupted subsurface silt at west side of water channel

SWEDISH WEIGHT SOUNDING TESTS AT TAKENOUCHI INDUSTRIAL COMPLEX

A series of Swedish Weight Sounding Tests were conducted to examine the soil profile of this liquefied reclaimed deposits at Takenouchi Industrial Complex. The testing equipment used for Swedish Weight Sounding Tests is shown in Fig. 10. The details of the testing procedure and the interpretation of test results are described in detail by Tsukamoto et al. (2004). The conduct of this field test is comprised of two phases, static penetration and rotational penetration. In the phase of static penetration, the screw-shaped point, (Fig. 10), attached to the tip of the rod weighing 49 N (5 kg) is statically penetrated by putting several weights stepwise in increments until the total load becomes equal to 980 N (100 kg). At each load increment, the depth of static penetration is measured and the total weight is denoted as W_{sw} (kN). When further static penetration is not possible, the rotational penetration is performed. The horizontal handle attached to the top of the rod is rotated, and the number of half a turn necessary to penetrate the rod through 1 metre is denoted as N_{sw} (ht/m).

The tests of SW-1 to 8 were conducted in the wood of pine trees located at the west side of the water channel, as shown in Fig. 9, where the concrete-block wall was collapsed and several large ground cracks and sand boils were observed. The results of Swedish Weight Sounding Tests along the alignment of SW-1 to SW-4 are shown in Fig. 11, and the results along SW-5 to SW-8 are similarly shown in Fig. 12. It is the normal way of expressing the test results to plot values of W_{sw} (kN) from 0 to 1, and then to plot values of N_{sw} starting from W_{sw} = 1. The reclaimed loose deposits of silt are found in Figs. 11 and 12 down to depths of about 4 to 8 metres from the west to east direction.

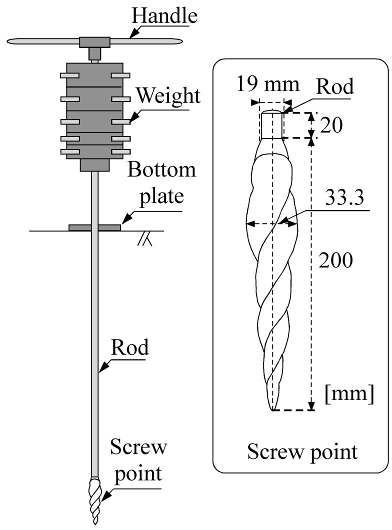

Figure 10. Equipment for Swedish Weight Sounding Tests

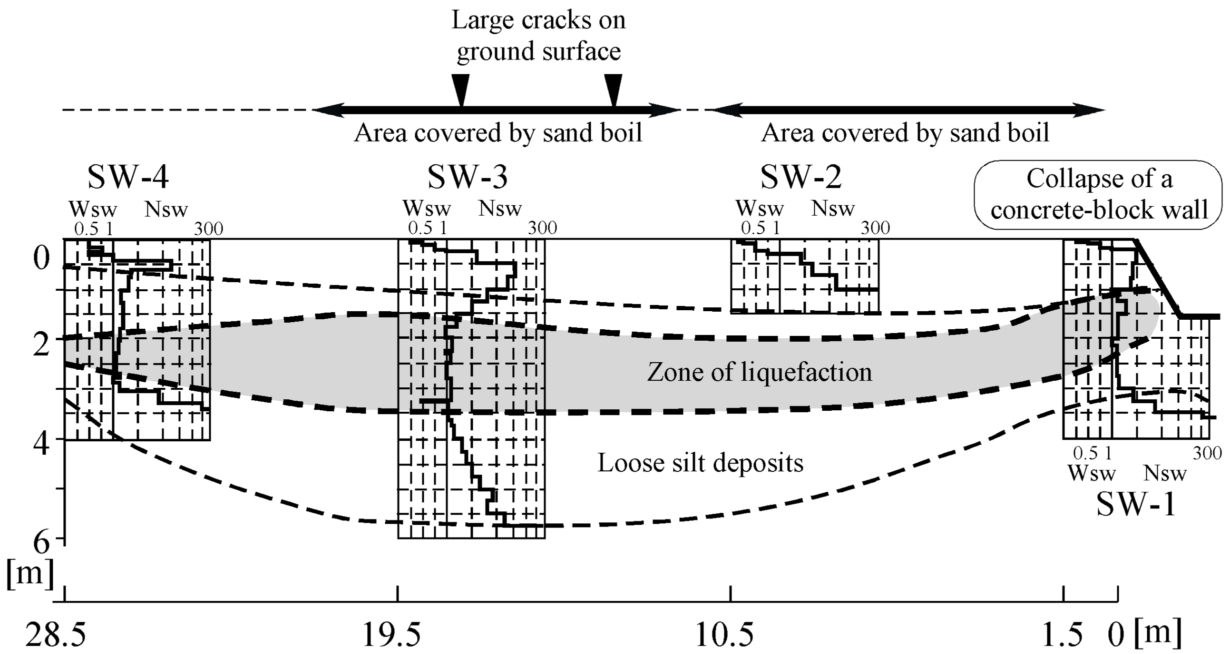

Figure 11. Results of Swedish Weight Sounding Tests at SW-1 to 4 at west side of water channel

ANALYSIS ON LIQUEFACTION

Based on the empirical formulae proposed by Tsukamoto et al. (2004), the values of SPT N, N_1 and the relative density D_r can be estimated from the values of N_{sw} as follows,

$$N'_{sw} = N_{sw} + 40 \quad (1)$$

$$N'_{sw1} = N'_{sw}\sqrt{98/\sigma'_v} \quad (2)$$

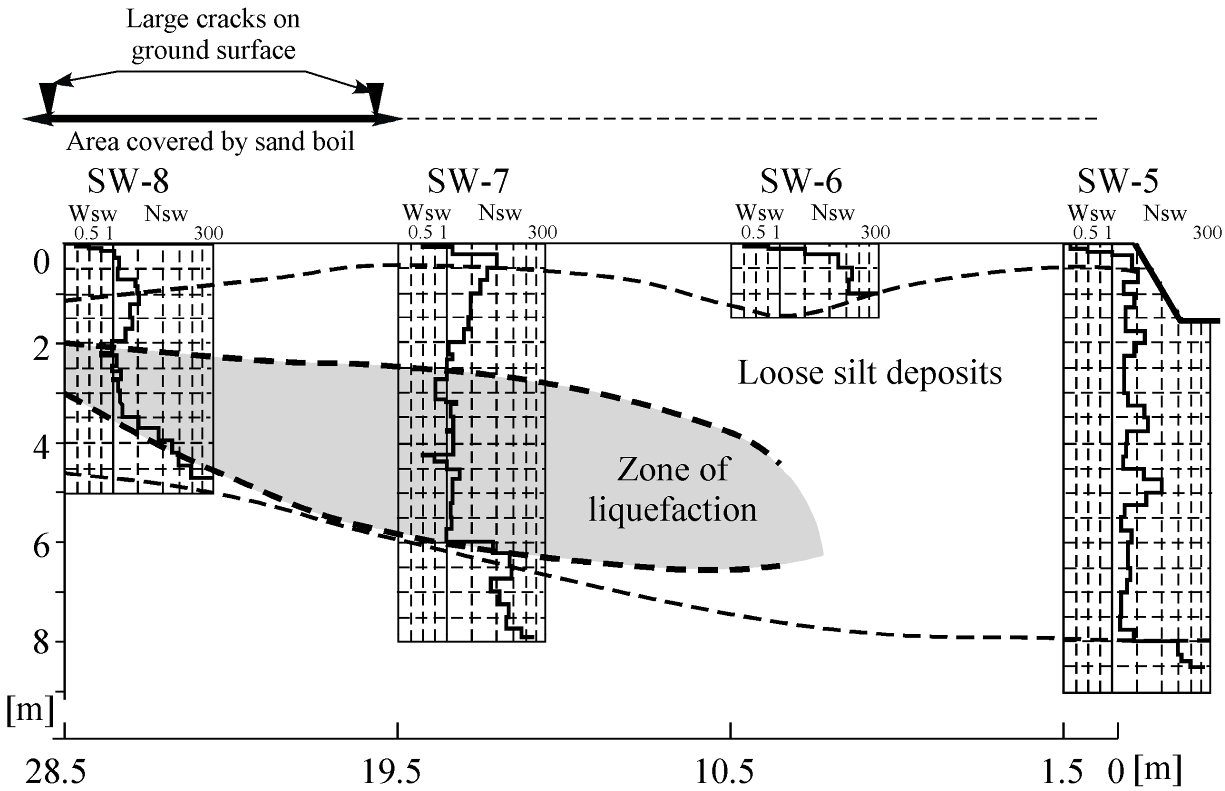

Figure 12. Results of Swedish Weight Sounding Tests at SW-5 to 8 at west side of water channel

$$N = \frac{\sqrt{e_{\max} - e_{\min}}}{10} N'_{sw} \tag{3}$$

$$N_1 = \frac{\sqrt{e_{\max} - e_{\min}}}{10} N'_{sw1} \tag{4}$$

$$D_r = \sqrt{\frac{N'_{sw1}(e_{\max} - e_{\min})^{2.2}}{90}} \tag{5}$$

where σ'_v is in kPa. It is to note here that Eq. (1) is valid only under rotational penetration measuring values of N_{sw}. Under static penetration measuring values of W_{sw}, the values of W_{sw} ranging from 0 to 1 kN are measured. Therefore, under static penetration, N'_{sw} is assumed as $N'_{sw} = 40 \times W_{sw}$ (kN), on behalf of Eq. (1). It then follows that the empirical formulae proposed by Tatsuoka et al. (1980) are adopted to estimate the liquefaction resistance of the soil, $\sigma_{d,l}/(2\sigma'_c)$, in the present study. The maximum shear strength ratio is then assumed to be equal to the liquefaction resistance obtained from laboratory triaxial tests, i.e. $\tau_{\max,l}/\sigma'_v \approx \sigma_{d,l}/(2\sigma'_c)$, as employed in the usual practice, (Ishihara 1996). From the records of ground surface accelerations obtained in Sakai-Minato, the maximum ground surface acceleration is assumed in the present study to be as low as a_{max} = 300 gal at Takenouchi Industrial Complex. The profile of the maximum shear stress ratio with depth can be obtained using the expression of $\tau_{\max}/\sigma'_v = (a_{\max}/g)\, r_d\, (\sigma_v/\sigma'_v)$, where $r_d = 1 - 0.015z$. Since the factor of safety against liquefaction is defined as $F_l = (\tau_{\max,l} / \sigma'_v)/(\tau_{\max} / \sigma'_v)$, the profile of the factor of safety F_l with depth can be obtained as shown in Figs. 13 and 14. It is found that one can detect some layers of soils with the values of F_l less

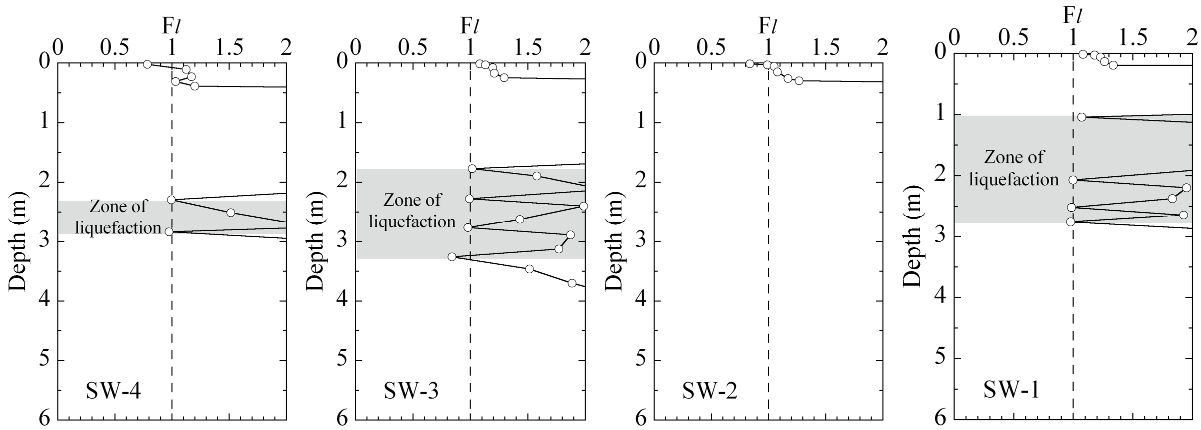

Figure 13. Distributions of factor of safety against liquefaction F_l with depth at SW-1 to 4

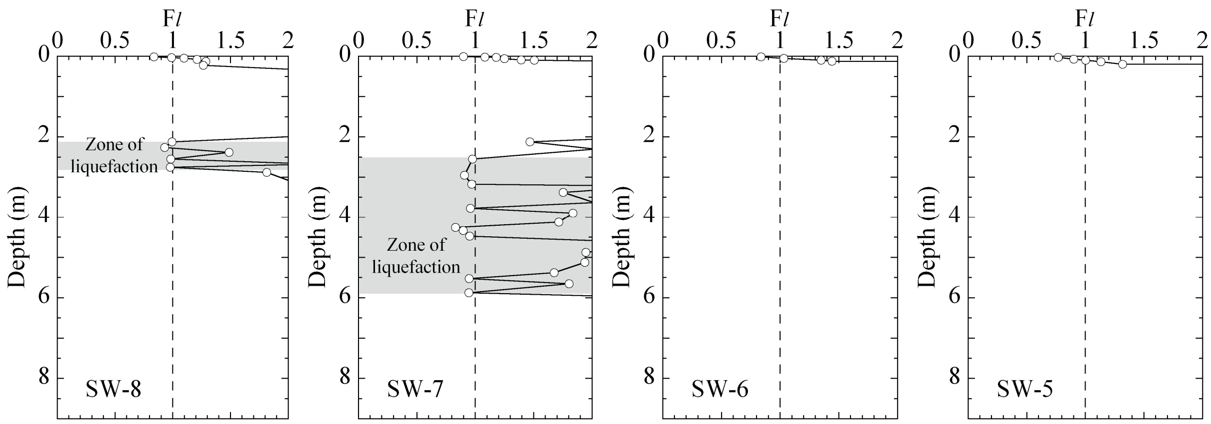

Figure 14. Distributions of factor of safety against liquefaction F_l with depth at SW-5 to 8

than 1, indicating the occurrence of soil liquefaction. The depths at which the values of F_l are less than 1 are then drawn in the soil profiles shown in Figs. 11 and 12, and the subsurface zone indicative of occurrence of soil liquefaction is indicated. On top of each diagram, the positions of large ground cracks and area covered by erupted subsurface silt are also shown. It is found that behind the collapsed portion of the concrete-block wall, a large zone of soil liquefaction is detected. It is also found that the large ground cracks are developed above the zones of soil liquefaction which are covered by erupted subsurface silt.

The other series of Swedish Weight Sounding Tests were conducted at the sites of SW-9 and 10, as shown in Fig. 5, which were located at the east side of the water channel, and the test results are shown in Fig. 15. It is found that the reclaimed loose deposits of silt prevail to a depth of more than 10 metres. By adopting the same procedure as described above, the profile of the factor of safety F_l with depth can then be obtained as shown in Fig. 16. It is found that almost all the layers of the reclaimed deposits exhibited the values of F_l less than 1, indicating extensive soil liquefaction to have occurred during this earthquake.

CONCLUSIONS

The field survey and Swedish Weight Sounding Tests were conducted at the reclaimed land of Takenouchi Industrial Complex, which had liquefied during 2000 Tottori-ken Seibu Earthquake. The procedure for

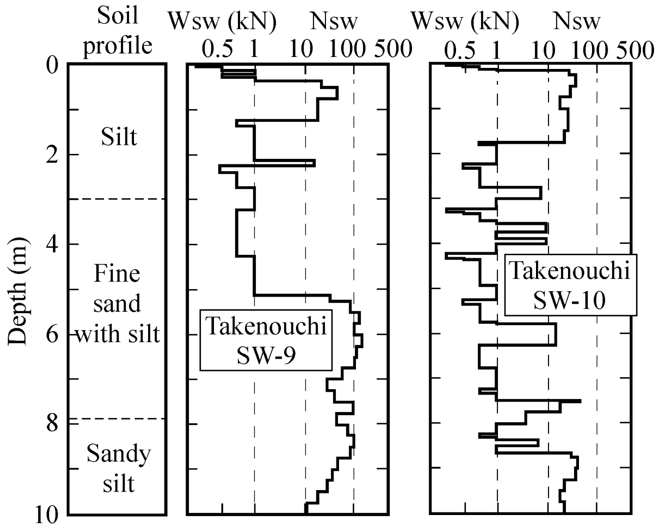

Figure 15. Results of Swedish Weight Sounding Tests at SW-9 and 10

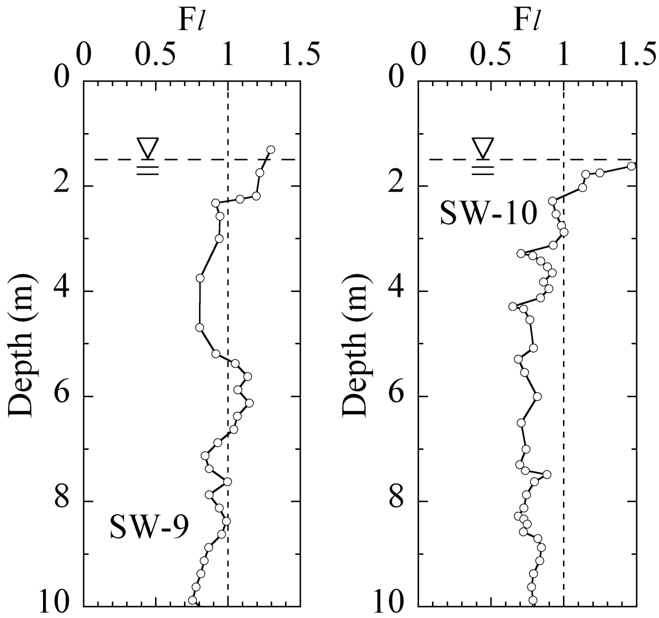

Figure 16. Distributions of factor of safety against liquefaction F_l with depth at SW-9 and 10

detecting soil layers which might liquefy in future earthquakes by means of Swedish Weight Sounding Tests was proposed and examined in detail. The outcome of the field survey and Swedish Weight Sounding Tests conducted at this reclaimed land indicated that by adopting the procedure proposed in the present study, liquefiable soil layers can be effectively detected.

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