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Damage of Houses and Residential Areas by Niigata Prefecture Earthquakes (Part2)

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ABSTRACT

The earthquakes of Chuetsu (2004) and Chuetsu offshore (2007) in Niigata Prefecture, caused liquefaction at many locations, and also caused damages on the residences and the residential areas due to the failure of ground. In the future, the judgment of liquefaction on housing site will become important and it will be thought that the upgrade of soil investigation and liquefaction countermeasure is necessary. In Japan, Swedish weight sounding (SWS) has been widely used in soil investigation on residential areas. Based on the result of SWS, the bearing capacity of ground can be obtained. However, the judgment of liquefaction is not obtained.

This paper reports results of SWS, boring investigation, standard penetration test (SPT), and three component cone penetration test (CPT) on the housing site which caught the liquefaction damage by the earthquake of Chuetsu offshore (2007) in Niigata Prefecture. In addition, it reports the applicability of the CPT on the housing site of Japan.

KEY WORDS: Soil investigation; cone penetration test; Swedish weight sounding; liquefaction; residential areas.

INTRODUCTION

The Building Standard Law of Japan says that "It is necessary for the ground with the fear of the liquefaction by an earthquake to confirm that the harmful damage, transformation, subsidence to the part of a building do not produce". It can be said that the examination of the liquefaction is essential because this law is applied to the private housing without exceptions. The problem of the liquefaction on the housing sites in Japan is viewed easily from a documentary search such as "maps for liquefaction sites", because the SWS are common. In addition, it is difficult to take a liquefaction countermeasure by a private housing financially, and this is a factor to take a liquefaction judgment easy.

The simple judgment method of liquefaction based on soil investigation has a judgment method based on the SPT (N-value) and the CPT (q_c). In Japan, a judgment method based on the SPT is common. It is a big factor that a Japanese design system based on *N*-value is established. However, it is rare that the SPT is performed for the soil investigation on housing areas because the SPT is expensive. On the other hand, the CPT is not common in Japan. This cause is in the Japanese ground where there is gravel carried by the fast flowing stream river from the hilly district to the estuary. Therefore, soil investigation using the CPT is difficult in Japan. However, the CPT is economical in comparison with the SPT and laboratory soil test. In addition, the CPT gives us soil classification, bearing capacity, consolidation of the ground, and the position of groundwater level without the sampling of soil. In this respect, the CPT is effective in the soil investigation on housing sites. Most of this investigation is used by the SWS first. Therefore, it is thought that the trouble that a cone cannot be penetrated get fewer because it can estimate the penetrated power of cone based on the result of the SWS.

This paper reports a result of the SWS, boring investigation, grain size analysis, the SPT, the CPT on the housing site that had been caught the liquefaction damage by the earthquake of Chuetsu offshore (2007) in Niigata Prefecture. In addition, it reports the current status of the seismic performance evaluation and the applicability of the CPT to the residential areas of Japan.

PLAN FOR GROUND INVESTIGATION

The investigation place is two housing sites (Kashiwazaki- Matsunami and Kashiwazaki-Hashiba) that caught the liquefaction damage by the earthquake of Chuetsu offshore (2007) in Niigata Prefecture (Fig. 1). The magnitude (*M*) of this earthquake was 6.8; the peak horizontal acceleration at the ground surface (a_{max}) generated by this earthquake was about 400 gal. The sand boil due to liquefaction was remarkably generated on the both housing sites, and differential settlement was caused in the houses. We investigated the three soundings of the SWS, the CPT, and the SPT in this both sites. Moreover, the grain size distribution was analyzed and the soil classification was examined using the soil samples obtained from boring holes.

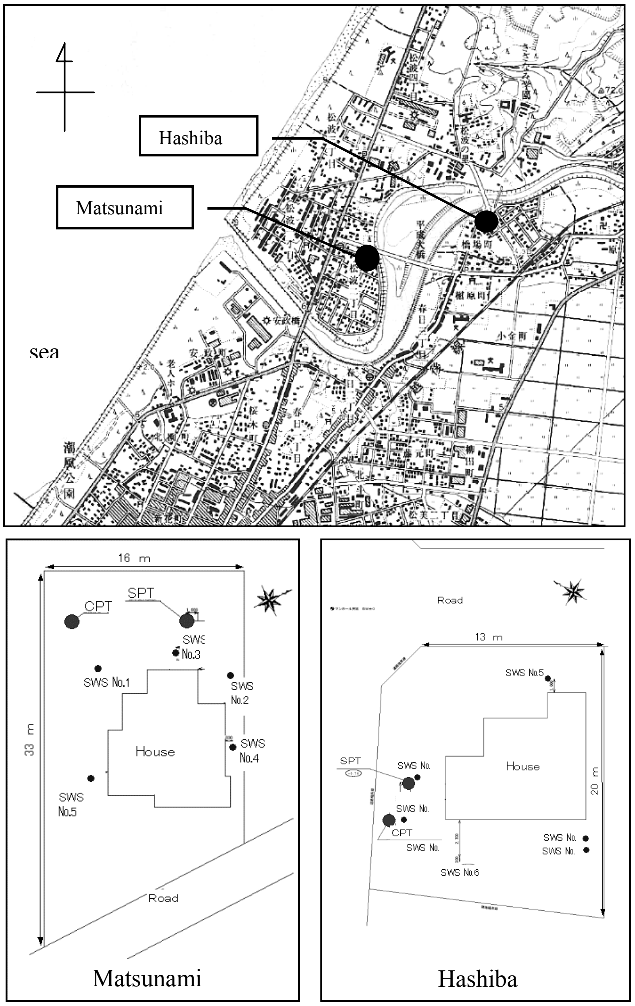

Fig. 1. Location of investigation site

Table 1. This ground investigation and the investigation standard

Examination item	Standard No.	Examination Value
Swedish weight sounding (SWS)	JIS A1221	Static penetration resistance (W_{sw}, N_{sw})
Cone penetration test (CPT)	JGS 1435-2003	Cone resistance (q_c) Pore water pressure (u)
Standard penetration test (SPT)	JIS A1219-2001	N-value
Grain size analysis	JIS A1204:2000	Maximum grain size Grain size distribution curve Fine fraction content

Note: JIS; Japanese Industrial Standard
JGS; Japanese Geotechnical Society

These investigation methods were based on the each standard shown in Table 1. We used the CPT-cone that can measure skin friction (f_s) in addition to general corn that measured cone resistance (q_c) and pore water pressure (u). Moreover, we measured the position of groundwater level by the excess pore water pressure dissipation test of the CPT.

These ground investigation has performed after one month or more passes this earthquake though it is necessary to examine ideally based on the result of ground investigation before the earthquake. The SWS has been done in both residential areas before this earthquake. Therefore, the SWS have gone again to understand the ground characteristic of the earthquake before and after.

RESULTS OF THE GROUND INVESTIGATION

Figure 2(a) shows each investigation results (boring log, the SPT, the CPT, the SWS) of Matsunami area, and Fig. 2(b) shows one of Hashiba area. Matsunami area had fine sand of N-value about 10-20 in GL-4.75-10.5m. Hashiba had filling sand of N- value about 5 in GL-1.95-4.7m on the old river. The position of groundwater level was GL-3.3m at Matsunami area, and GL-3.1m at Hashiba area. The value of each penetration resistance distribution of the SPT (N-value), the CPT (q_c), the SWS (W_{sw}, N_{sw}) shows similar tendency. We obtain measurements at 1.0m intervals from the SPT, and measurements at 0.25m intervals from the SWS. On the other hand, the CPT has an advantage that a thin stratum can be detected because we obtain continuous measurements at 0.01m intervals from the CPT. Equation 1 which evaluates N-value from the SWS results is proposed by Inada (1960).

$$N = \begin{cases} 3.0W_{sw} + 0.050N_{sw} & (cohesive \quad soil) \\ 2.0W_{sw} + 0.067N_{sw} & (sandy \quad soil) \end{cases} \tag{1}$$

Equation 2 which evaluates N-value from the CPT results is proposed by Saematsu and Suzuki (2005).

$$N = \begin{cases} 0.340 I_c^{1.94} (q_t - 0.2)^{(1.34 - 0.0927 I_c)} & (q_t > 0.2MPa) \\ 0 & (q_t \le 0.2MPa) \end{cases} \tag{2}$$

In addition, the conversion method of soil classification using the value of q_c, f_s, and u is proposed. Robertson et al. (1990) proposes soil behavior type index (I_c) calculated from the following equation:

$$I_C = \sqrt{(3.47 - \log_{10} Q_t)^2 + (\log_{10} F_r + 1.22)^2} \tag{3}$$

where Q_t is normalized cone resistance ((q_t - σ_{vo})/σ'_{vo}), and F_r is normalized friction ratio (f_s/(q_t - σ_{vo})). The value of I_c gives us soil classification shown in Table 2. Moreover, Equation 4 which evaluates fine fraction content (F_c) from the value of I_c is proposed by Saematsu and Suzuki (2005).

$$F_C = I_C^{4.2} \tag{4}$$

Table 2. Soil classification using I_c

Division No.	I_c	Soil classification
1	＜1.31	gravelly sand
2	1.31～2.05	sand to silty sand
3	2.05～2.60	silty sand to sandy silt
4	2.60～2.95	silt to silty clay
5	2.95～3.60	silty clay to clay
6	3.60＜	organic material

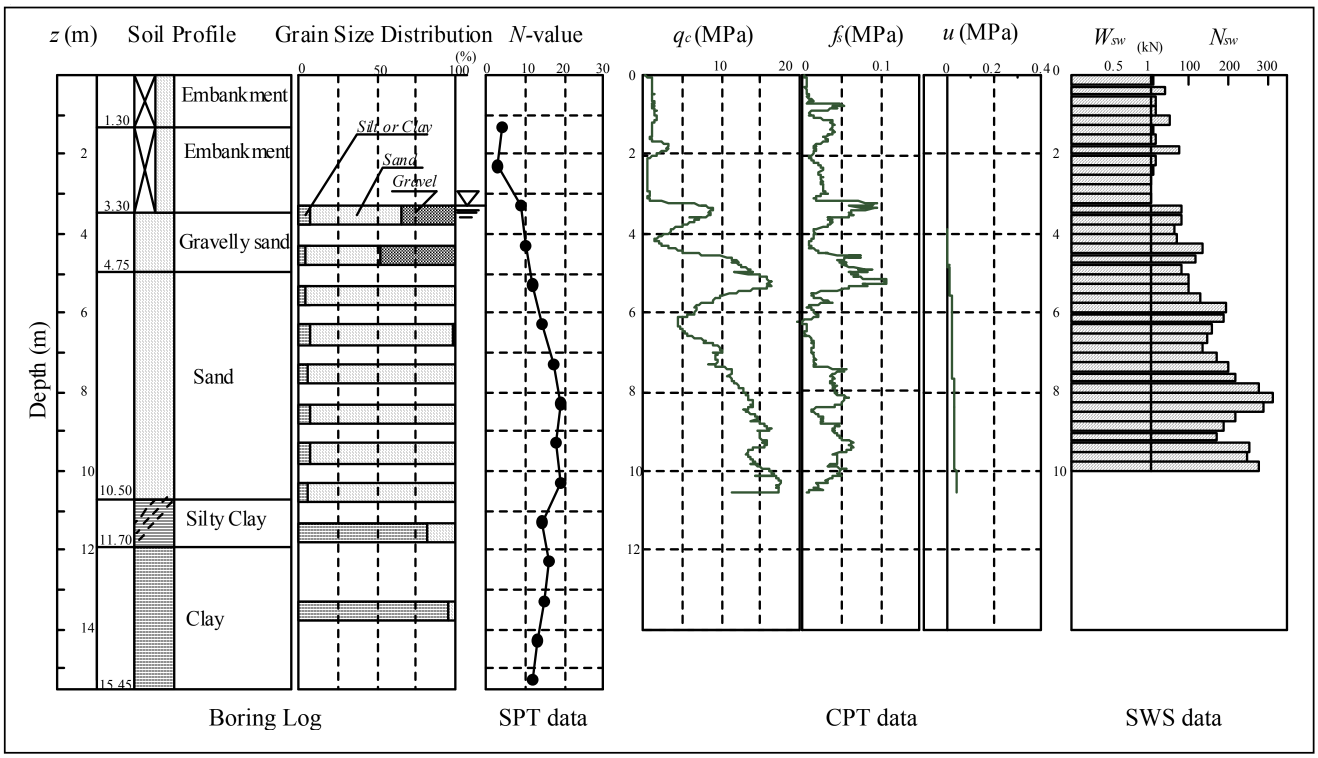

Fig. 2(a). The result of the ground investigation (Site: Matsunami area)

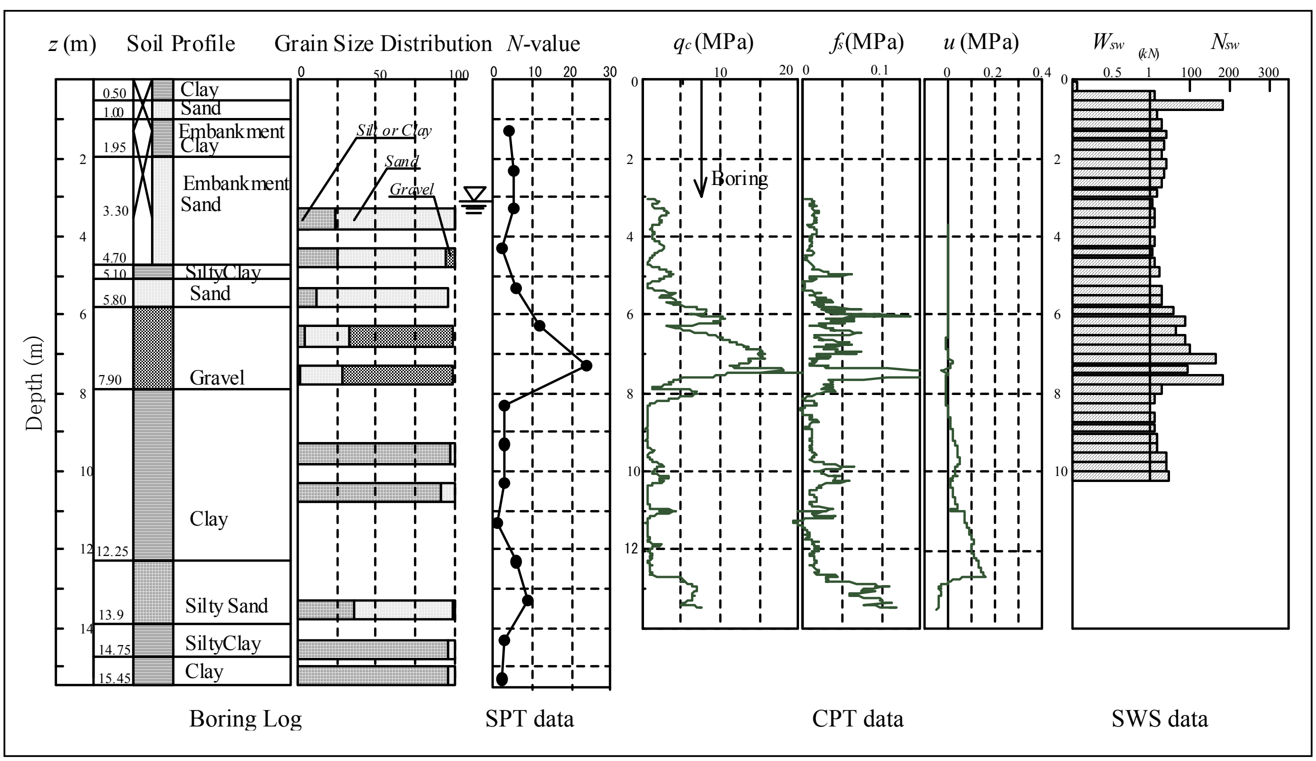

Fig. 2(b). The result of the ground investigation (Site: Hashiba area)

The results of the comparison between I_c and boring log are shown in Fig. 3, and the comparison between fine fraction content based on the CPT results and grain size analysis are shown in Figure 4, and the comparison between *N*-value by the CPT, the SWS and the SPT are shown in Fig. 5. The soil classification and F_c using the CPT results was comparatively similar to the results of boring log and grain size analysis. However, there is a difference in a detailed part of both soil classification, and there is an enough correlation in rough division such as gravel, sandy, silt, and clay. Moreover, the results of *N*-value by the CPT, the SWS agree with it by the SPT.

Figure 6 shows the comparison of the SWS results before the earthquake and after it at Matsunami area. The SWS results at Hashiba area can't be comparable, because the investigation depth (GL-0.25 ~ -0.5m) is too shallow because of the hard embankment. In the result at Matsunami area, *N*-value evaluated using the SWS after the earthquake are smaller than ones before the earthquake. Generally, it is said that the ground, which liquefied in the past, increases the liquefaction resistance, because the wet density increases. This result implies that there is not the effect of compaction due to the earthquake motion. This result is only at one area and it cannot be said enough volume of data.

However, there is a case with little compaction effect of earthquake like this result. We think that the ground that is not equal in density, the time of the earthquake motion and the residual displacement after the earthquake are related to the factor of this result. Therefore, we think that the ground that has been caused liquefaction due to the earthquake is a possibility of liquefaction due to a similar earthquake again.

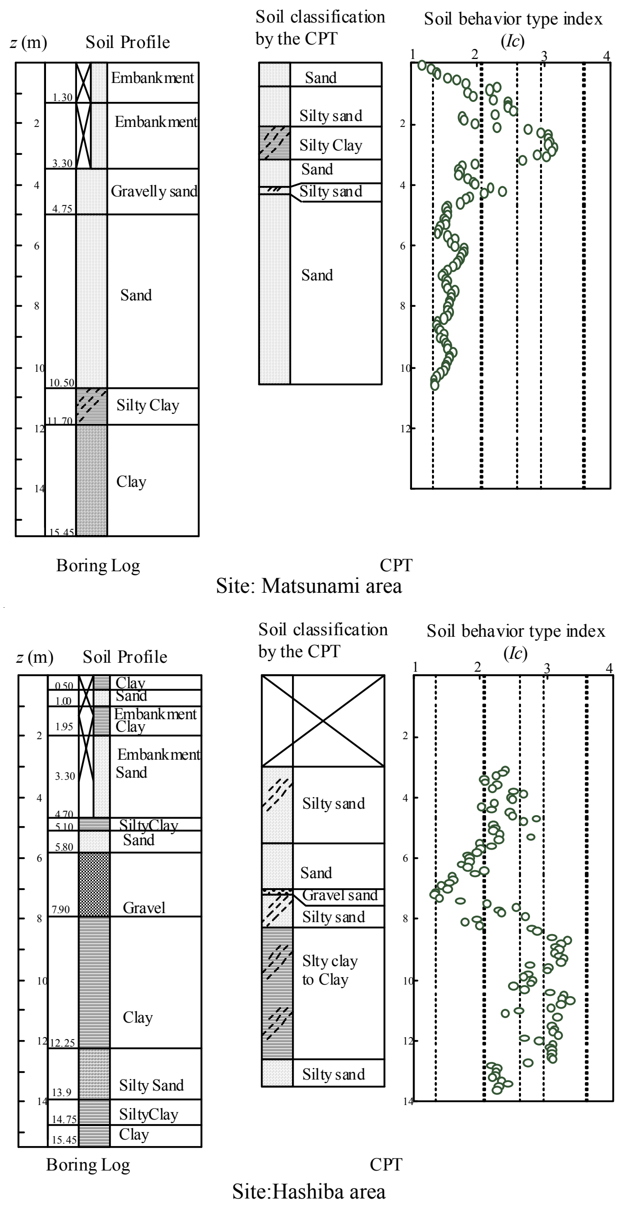

Fig. 3. Comparisons between soil classification based on the CPT results and boring log (reference table.2)

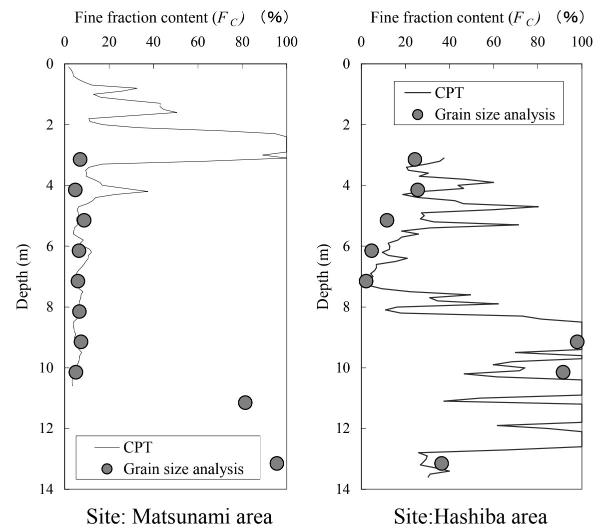

Fig. 4. Comparisons between fine fraction content based on the CPT results and grain size analysis

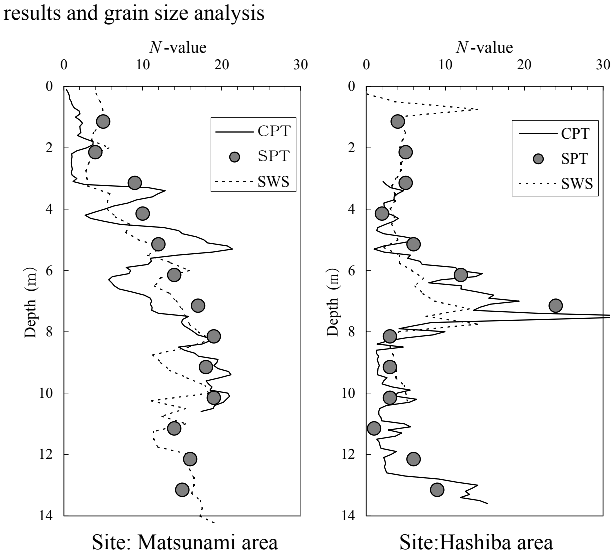

Fig. 5. Comparisons between *N*-value by the CPT, the SWS and the SPT

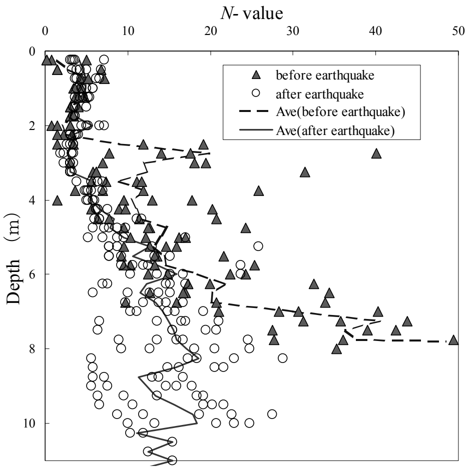

Fig. 6. Comparisons of the SWS results before the earthquake and after one at Matsunami area

COMPARISON BETWEEN THE JUDGEMENT METHOD OF LIQUEFACTION USING CPT AND SPT

The method of judging liquefaction is the detailed one and the simple one, and this research used the simple method. The outline is shown as follows:

(a) Detailed judgment method
The liquefaction resistance ratio (R) is measured from the results of cyclic triaxial test using the undisturbed sample obtained in situ, and the cyclic shear stress ratio (L) is obtained from seismic response analysis etc. Thus, we obtain the liquefaction safety rate (F_L (: R/L)).
(b) Simple judgment method
The liquefaction resistance ratio (R) is converted from the results of ground investigation or laboratory test, and the shear stress ratio (L) is calculated from the design earthquake motion. Thus, we obtain the liquefaction safety rate (F_L (: R/L)).

The liquefaction resistance ratio (R) in any depth can be converted from some methods. Recommendations for design n of building foundations issued by Architectural Institute of Japan (2001) shows the following two methods as a method with high reliability.

1) Method of presuming R based on the SPT results (N-value) and the grain size analysis results (F_C).
2) Method of presuming R based on the CPT results (q_c, f_s and u).

The cyclic shear stress ratio (L) is calculated from the following equation:

$$L = \frac{\tau_d}{\sigma'_z} = r_n \frac{a_{\max}}{g} \frac{\sigma_z}{\sigma'_z} r_d \tag{5}$$

where τ_d (stress reduction coefficient); σ_z and σ'_z (total and effective vertical overburden stresses); g (acceleration of gravity); $a_{\max}$ (peak horizontal acceleration at the ground surface generated by the earthquake): r_n(correction coefficient to cyclic count(=0.1(M-1); M = magnitude)): r_d (decrease coefficient (= 1 - 0.015z; z = depth (meter))).
Figure 7 shows the depth distribution of F_L on input earthquake condition (M: 6.8,a_{max}: 250gal) used to design generally. Figure 8 shows the depth distribution of F_L by value on the earthquake of Chuetsu offshore (2007) in Niigata Prefecture (M: 6.8, a_{max}: 400gal). The depth distribution of F_L based on the CPT results and based on the SPT and the grain size analysis results are roughly corresponding though F_L based on the CPT results is a little smaller than it based on the SPT and the grain size analysis results. There is little liquefied layer (F_L <1.0) at the design condition on both areas (Fig. 7). On the other hand, when the earthquake condition measured in this time is given, the liquefied layer on Hashiba area is calculated GL-3~-7m, and it on Matsunami area is calculated GL-3~-10m(Fig. 8). The sand boil is greatly generated due to the liquefaction on this earthquake in both housing areas. It can be said that F_L shown in Figure 7 almost agrees with this phenomenon.

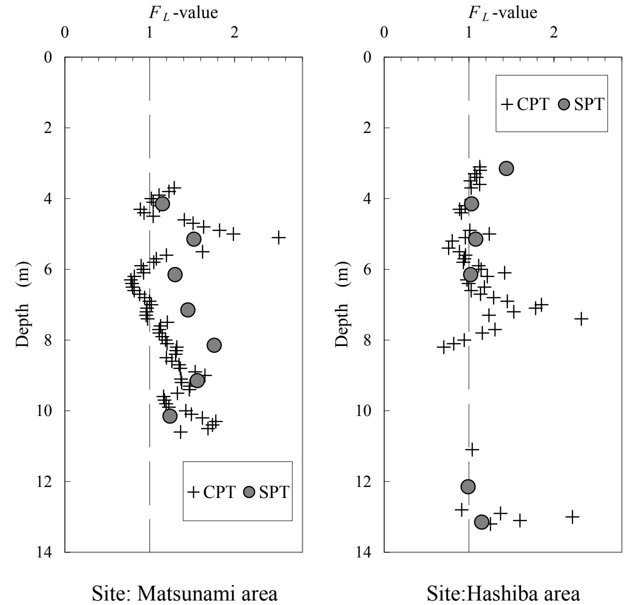

Fig. 7. The depth distribution of F_L on input earthquake condition (M:6.8,a_{max}:250gal) used to design generally

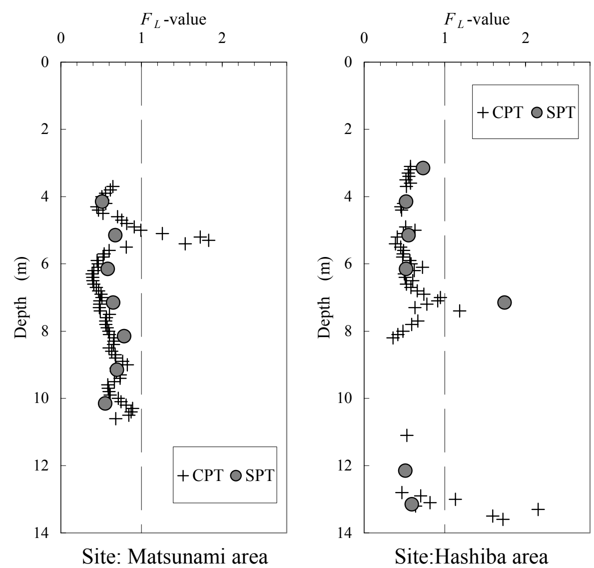

Fig. 8. The depth distribution of F_L by value on the earthquake of Chuetsu offshore (2007) in Niigata Prefecture (M:6.8, a_{max}:400gal)

EVALUATION OF THE LIQUEFACTION INFLUENCE IN THE HOUSING

The damage of the housing caused by liquefaction becomes at the position of the liquefaction layer that is thick and shallow remarkable. The damage of the foundation and the housing is different in the level, the thickness, the depth of the liquefaction layer etc. Moreover, it is not related to the damage of the housing and the residential area immediately even if the liquefaction layer is in the ground. Therefore, it is necessary to evaluate the influence that liquefaction gives the housing. In this research, the three evaluation methods of the influence (a, b, c) that liquefaction gives the housing in the flat ground are used. The methods are shown as follows.

(a) Evaluation method by the liquefaction index (P_L) (N.L.A., 1998)
The liquefaction index (P_L) is proposed as one index that evaluated the influence that liquefaction gives the housing. It is calculated from the following equation:

$$P_L = \int_0^{20} (1 - F_L) \cdot (10 - 0.5z) dz \qquad (1 - F_L \geqq 0) \tag{6}$$

Table 3 shows the liquefaction judgment division by P_L according to the liquefaction region-zoning manual (1998).

Table 3. The liquefaction judgment division by P_L

Liquefaction extent of the impact	P_L-value	
	Middle ground motion	Large ground motion
Small	$0 \leqq P_L \leqq 5$	$0 \leqq P_L \leqq 5$
Large	$5 < P_L \leqq 15$	$5 < P_L \leqq 20$
Huge	$15 < P_L$	$20 < P_L$

(b) Evaluation method by the dynamic surface displacement (D_{cy}) (A.I.J., 2001).

The dynamic surface displacement (D_{cy}) is proposed as one index that shows the relation between the dynamic horizontal displacement of the ground surface caused by liquefaction and the damage level of the housing. It depends on the following procedures when the CPT result is used.

1) N-value converted by the CPT results (Eq. 2) is treated as N-value by the SPT results.
2) Corrected N-value (N_a) to F_c and σ'_z is calculated from Equation 7.

$$N_a = N_1 + \Delta N_f \tag{7}$$

where N_1 = corrected N-value concerning confining pressure ($N_1 = \sqrt{98/\sigma'_z} \cdot N$):ΔN_f = corrected increment value concerning F_c shown in Figure 9.
3) Cyclic shear stress of the both depth corresponding to N_a and τ_d/σ'_z (γ_{cy}) is presumed from Figure 10.
4) It is assumed that γ_{cy} of the each depth is generated in the same direction. And, γ_{cy} is integrated into a vertical direction. And, the maximum horizontal displacement by integrating γ_{cy} into a vertical direction is obtained.
5) The maximum horizontal displacement is treated as the dynamic surface displacement (D_{cy}). And the influence that liquefaction gives the housing is evaluated to the value of D_{cy} shown in Table 4.

(c) Evaluation method using the relation of two-layer ground (the liquefied layer and the non-liquefied layer(U.D.Co., 2003)

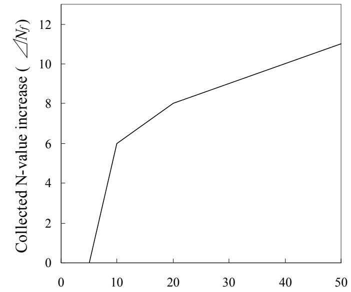

Fig. 9. Relation between F_c and ΔN_f

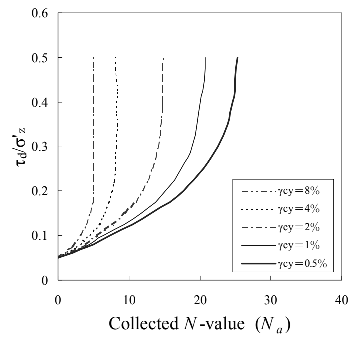

Fig. 10. Relation between N_a, γ_{cy} and τ_d/σ'_z

Table 4. Relation between D_{cy} and the damage level of liquefaction

D_{cy} (cm)	Liquefaction extent of the impact
0	None
5	Minor
5-10	Small
10-20	Medium
20-40	Large
40	Huge

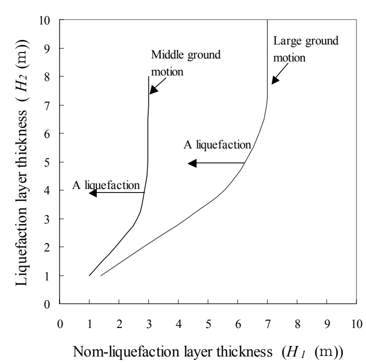

Fig. 11. The borderline of liquefaction in relation between H_1 and H_2

The clay soil or unsaturated soils that is shallower than the position of groundwater level are the soil layers where the possibility of liquefaction is a little. Therefore, even if the saturation sandy soil under groundwater level is caused by liquefaction at the earthquake, it might not influence the housing area and the housing by non-liquefied layer on the surface ground. Figure 11 shows a borderline of liquefaction in the both earthquake motion. This plotted points in Figure 11 gives us the presence of damage by liquefaction. Table 5. shows the evaluation result of the influence that liquefaction gives the housing using method 1-3. It is calculated that P_L= 0.0 ~ 1.2 (Matsunami), P_L= 0.0 ~ 1.1 (Hashiba), D_{cy}= 0.0 ~ 1.0 (Matsunami), and D_{cy}= 0.3 ~ 1.5 (Hashiba), and it can be said that the influence by liquefaction on the housing is a little in the design earthquake condition (a_{max}= 250gal). However, it is calculated that P_L= 9.0 ~ 16.7 (Matsunami), P_L= 12.9 ~ 16.2 (Hashiba), D_{cy}= 10.2 ~ 15.3 (Matsunami), and D_{cy}= 7.6 ~ 11.5 (Hashiba), and it can be said that the influence by liquefaction on the housing is very large in this seismic condition. In addition, the evaluation method using

Table 5. The evaluation result of the influence that liquefaction gives the housing

Site:Matsunami area

Earthquake emotion		Method		Ground Investigation data		Reference
M	***a_{max}***			**CPT**	**SPT,F_c**	
6.8	250 gal	a	P_L-value	1.2	0	Table. 3.
			Judgment	Small	Small	
		b	D_{cy}	1.0	0	Table. 4.
			Judgment	Minor	None	
		c	H_1 (m)	5.8	-	Fig.11
			H_2 (m)	1.5	0	
			Judgment	OK	OK	
	400 gal	a	P_L-value	16.7	9.0	Table.3.
			Judgment	Large	Large	
		b	D_{cy}	10.2	15.3	Table. 4.
			Judgment	Middle	Middle	
		c	H_1 (m)	3.7	4.15	Fig. 11
			H_2 (m)	6.5	6.0	
			Judgment	NG	NG	

Site:Hashiba area

Earthquake emotion		Method		Ground Investigation data		Reference
M	***a_{max}***			**CPT**	**SPT,F_c**	
6.8	250 gal	a	P_L-value	1.1	0.02	Table. 3
			Judgment	Small	Small	
		b	D_{cy}	0.3	1.5	Table. 4
			Judgment	Minor	Minor	
		c	H_1 (m)	5.2	12.2	Fig.11
			H_2 (m)	0.8	1.0	
			Judgment	OK	OK	
	400 gal	a	P_L-value	12.9	16.2	Table.3
			Judgment	Large	Large	
		b	D_{cy}	7.6	11.5	Table. 4
			Judgment	Small	Middle	
		c	H_1 (m)	4.6	4.2	Fig. 11
			H_2 (m)	3.6	5.0	
			Judgment	NG	NG	

Note: NG; A-liquefaction OK; Non-liquefaction

the relation of the non-liquefied layer and the liquefied layer of the ground surface gives us the similar result to method 1and method 2. Thus, we obtained an almost similar result by three methods. Moreover, an obviously different results in case of design condition and this time earthquake condition is obtained. We thought that the liquefied layer became remarkably thick because this earthquake motion is larger than the earthquake motion using the designs. The layer that changes into the liquefied layer by the difference of this earthquake motion is thought to be sand layer of *N*-value 15~20.

CONCLUSIONS

This paper reports a result of SWS, boring investigation, standard penetration test (SPT), and three component cone penetration test (CPT) on the housing areas that had been caught the liquefaction damage by the earthquake of Chuetsu offshore (2007) in Niigata Prefecture. As a result, the following conclusions were obtained.

(a) The judgment method of liquefaction by the CPT results was compared with the judgment method by the SPT and grain size analysis results. It has been obtained a result similar to both though it is a simple method. In addition, these judgment results were able to explain the housing damage and the boil sand caused by an actual liquefaction.

(b) It was observed that the maximum horizontal acceleration was larger than the designed acceleration used in general, and the value of seismic intensity scale is strong with 6^+. Therefore, it has been understood that the non-liquefied layer in the design condition became a liquefied layer because of this earthquake condition.

It is necessary to establish the soil investigation of private housing that used by the judgment of liquefaction in Japan. It may be said that the CPT is the investigation method that is influential at the point where there is easily a liquefaction judgment. We think that it will be necessary to suggest a ground improvement method of housing sites aimed for liquefaction countermeasure as well as investigation method in future.

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