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Evaluation example on effectiveness of countermeasures against liquefaction for residential land – Compaction and drainage methods –

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ABSTRACT

This paper describes the prediction method for the penetrating settlement of the house by use of the static finite element analysis (FEM) including the improved ground by compaction (sand compaction pile: SCP) and drainage (gravel drain: GD) methods. On the evaluation of the improved ground, the compaction improved ground was evaluated additionally based on the past researches that the liquefaction resistance of the SCP-improved ground was higher than that of the natural ground even though both had the same SPT *N*-values. On the other hand, the drainage effect of the GD method was evaluated based on the chart (relation between excess pore water pressure ratio "r_u" and liquefaction resistance factor "F_L") obtained from the element tests. As the results of the reproduction analyses through this earthquake, the predicted values matched well with the observed ones, verifying the validity of each evaluation method.

Introduction

Typical principle for the countermeasures against liquefaction being carried out in our country can be classified roughly into three types i.e. Compaction (densification), Solidification and Drainage (excess pore water dissipation). The vibratory sand compaction pile (SCP) method developed for the purpose of ground reinforcement has been applied to the sandy ground as a suitable method for densifying it since the 1960s and has achieved satisfactory results at many sites. Thereafter, the gravel drain (GD) method became to be applied to the sites which limit vibration and noise after 1970s, and then the lattice type deep mixing method was developed in 1980s. The effectiveness of the compaction method was confirmed firstly on the improved area by the vibro-floatation method at the 1964 Niigata Earthquake (Watanabe, 1966). Subsequently, the earthquakes in Japan provided us the occasion to confirm the improvement effectiveness through investigation on comparison of the damage between the improved area and the unimproved area related to liquefaction countermeasures (Harada, 2011). In spite of a wide range of liquefaction disaster in Urayasu city during the 2011 Off the Pacific Coast of Tohoku Earthquake, the area where countermeasures such as SCP and GD method were implemented was free from the damages as shown in Photo 1.

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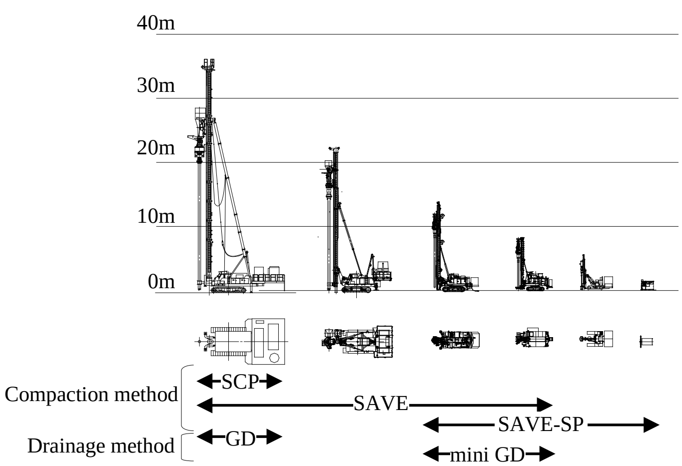
Photo 1. Residential area freed from damage by the Great East Japan Earthquake owing to ground improvement (Towhata et al., 2011)

The problems to be solved when the liquefaction countermeasures are applied to residential land are "Downsizing of equipment" and "Prediction of deformation, particularly by penetration settlement" as an evaluation criteria of countermeasure effectiveness. In regards to the downsizing of equipment, the compaction method and the drainage method began to apply smaller equipment than prior large equipment as shown in figure 1. For solving another problem of deformational prediction by analysis, it is of importance to provide with modeling the effect of improvement works by evaluating them properly.

This paper proposes a method to predict deformation by modeling the ground improved by compaction and drainage methods for further prediction of deformation by liquefaction. The said method is utilized in the reproduction analysis for residential land at Urayasu city, where the treatment by SCP and GD method were done, hit by the 2011 earthquake, and is followed by verification of the prediction method.



SCP : Vibratory Sand compaction pile
SAVE : Non-vibratory Sand compaction pile
SAVE : Injection type sand compaction pile
GD : Gravel drain
mini-GD: Miniaturized gravel drain

Figure 1. Various kinds of shapes and sizes of equipment

Evaluation of improvement effectiveness

The ground improved by compaction method increases liquefaction resistance because of increase in density and increase in lateral stress right after the treatment (See figure 2(a)), and the ground improved by drainage method effectively exhibits improvement because of quick dissipation of excess pore water which increases during earthquake (See figure 2(b)). Namely, the evaluation of improvement effectiveness of compaction method and drainage method depends on increase in liquefaction strength and restraint of excess pore water pressure, respectively. Therefore, in the case the deformation is predicted by the static analysis of two dimensional finite element analysis named “ALID/win” (Yasuda et al., 1999) influenced by the liquefaction strength R_L and the safety factor for liquefaction F_L, it is necessary to evaluate properly the parameters of such improved ground.

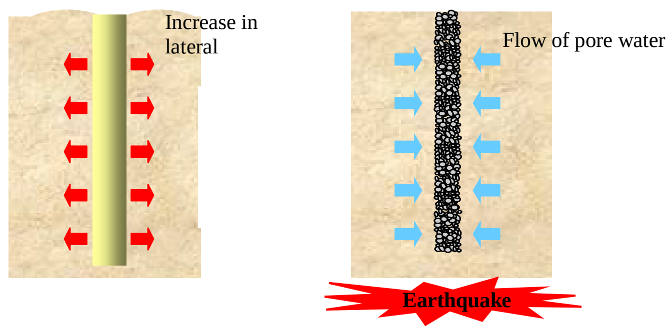


Figure 2. Improvement principle of compaction and drainage methods

Compaction method

Generally, the improvement efficiency of compaction method is confirmed by measuring SPT *N*-value of the ground in-between sand piles. Relationship of an extra coefficient, *C* as expressed by the equation (1) is considered to be completed between liquefaction strength obtained from SPT *N*-value in-between piles and that of overall improved ground (AIG, 2001). This relationship was verified by analysis using F_L obtained from boring data of two artificial islands suffered in the 1995 Hyogo-ken Nambu Earthquake.

$$R_{L\ (\text{composite ground})} = C \cdot R_{L\ (\text{ground in-between sand piles})} \tag{1}$$

Furthermore, the result of reproduction analysis using ALID at structures in the said islands is shown in figure 3, which indicates, assuming 20% increased liquefaction strength, settlement at 5 points a~e (f: unimproved) of the structures built on the improved ground by SCP method coincides exactly with the measured value (Harada et al., 2012). The above description can be interpreted in accordance with the correlation between SPT *N*-value in-between piles, relative density and liquefaction strength as shown in the figure 4. In other words, when the measured SPT *N*-value before improvement $(N)_{pre}$ (assuming coefficient of earth pressure at rest as being K_0=0.5) increased into SPT *N*-value after improvement $(N)_{post}$ (a→c in Fig.4), it corresponds to (a´→b´ in Fig.4) in liquefaction strength without consideration of increase in K_0 (=1.0), so liquefaction strength tends to be underestimated compared to the actual route a´→c´ in Fig.4.

Accordingly, when the compacted ground is estimated based on the measured *N*-value, modelling taking extra coefficient as in equation (1) above into account is required on ALID/win.

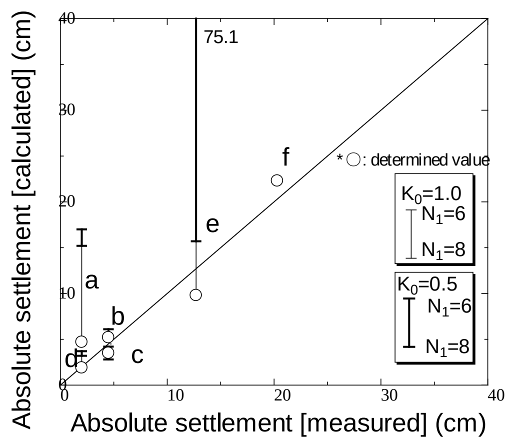


Figure 3. Comparison between measured and calculated settlements

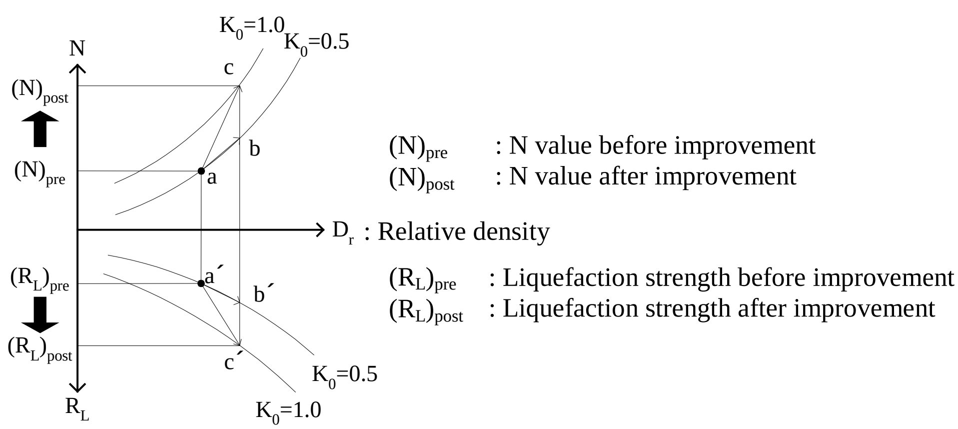


Figure 4. Schematic figure of improvement effect by compaction

Drainage method

Because of the drainage method's principle that depends on restraint of excess pore water pressure generated by earthquakes in-between gravel piles, it is needed to evaluate quantitatively drainage effect. One method for resolving the problem is to evaluate the drainage effect by restraining excess pore water pressure i.e. reducing the excess pore water pressure ratio and increasing safety factor for liquefaction, $F_{L.}$ In order to apply this method, it is needed to establish the relationship between F_L and r_u, regarding which the equation (2) (Yasuda, 1985) is made known. In the figure 5, factor α β are sorted into sandy soil and clayey soil, and liquefaction strength R_L is indicated as parameter. By using this and determining drainage pile's distance *a/b* (*a*: radius of pile, *b*: radius of equivalent circle) as shown in the figure 6, prediction (A→B) of r_u can be made and F_L after treatment can be obtained. At this time, designing chart indicating the relationship between *a/b* and average r_u (ex. PWRI, 1999) are useful to estimate r_u.

$$r_u = \alpha (F_L)^{-\beta} \tag{2}$$

(Sandy soil)

$$\alpha = \exp(1.43 \times R_{L20}{}^2 + 0.05 \times R_{L20} - 0.15)$$

$$\beta = 0.30 \times R_{L20}{}^{-1.95}$$

(Clayey soil)

$$\alpha = \exp(-4.49 \times R_{L20}{}^2 + 0.86 \times R_{L20} - 0.38)$$

$$\beta = 1.96 \times R_{L20}{}^{-0.33}$$

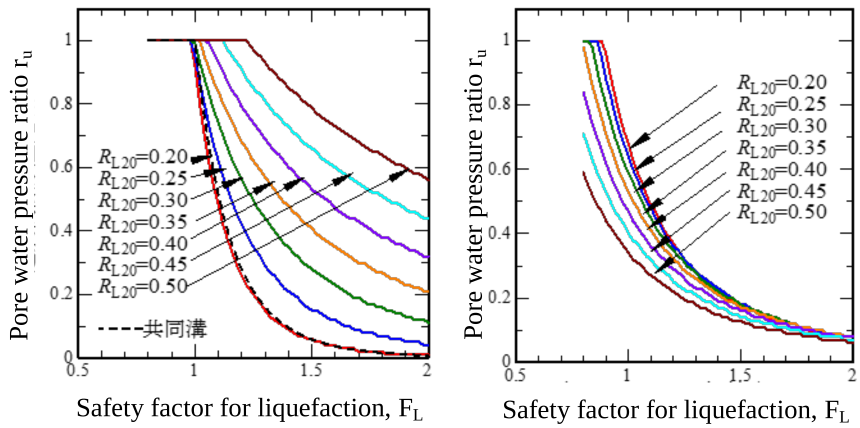


Figure 5. Relationship between safety factor for liquefaction and excess pore water pressure ratio (Ishikawa et al., 2013)

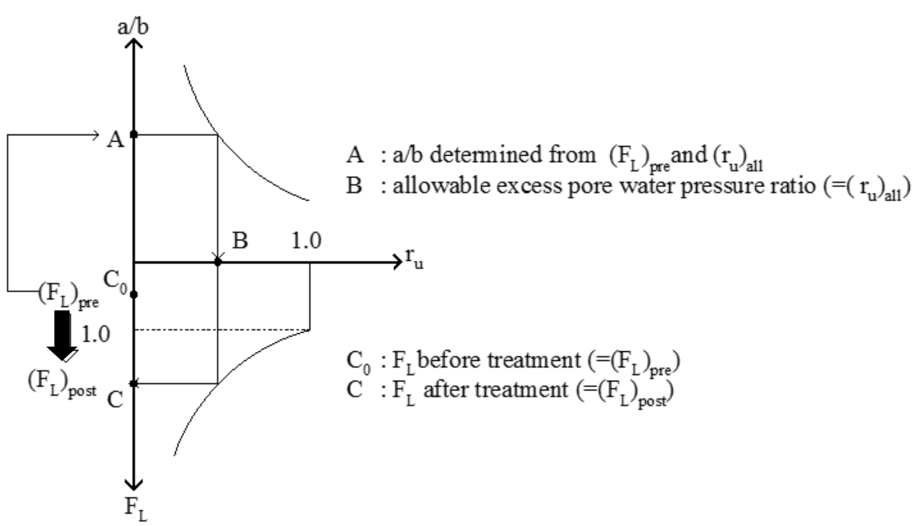


Figure 6. Schematic figure of improvement effectiveness by drainage

Case studies for verification

Conditions for study

For the purpose of verifying the evaluation for each improvement methods, reproduction analysis for residential land in Urayasu city suffered by the 2011 earthquake was applied. The figure 7(a) shows a plan of the object area. The structures at the area have foundations improved by SCP and GD methods. The A-A´ section is as shown in the figure 7(b), where stratum constitution is composed of surface layer, fill layer (B-layer), dredged layer (F-layer), alluvium sandy layer (As-layer), alluvium clay layer (Ac-layer) from top to bottom. At the improved zone, lower end of both SCP and GD piles does not reach alluvium clay layer, namely remaining unimproved zone. Regarding external force, K-net for analysis, composite acceleration 174.3 gal of NS component and EW component was applied (Yasuda et al., 2012). The contact pressure of structures was set as 70kN/m^2 for a three-storied building having SCP foundation and 50kN/m^2 for a two story building having GD foundation.

The ground was modeled on the basis of existent boring data at the time of construction, where water table was set as TP+1.527m, the mean value of the data. The fines content, *Fc* was estimated from data by Urayasu city (CCILMUC, 2011), and R_L obtained from SPT N-value and *Fc* was calculated using the evaluation equation (Kamei et al, 2002) for Tokyo low land, as the result of cyclic triaxial test in the document indicated the approximate value. The corrected coefficient, C_w related to earthquake ground motion characteristics was obtained from the equation (Ishikawa et al., 2014) which takes earthquake ground motion with long duration time into account, and the ground fixed number was appreciated by means of No. 1 in table 1 for the unimproved ground. In regards to the ground improved by SCP method, R_L was calculated using SPT N-value obtained from the boring data (Yasuda et al., 2012) carried out after improvement and fines content, Fc, followed by extra coefficient of C=1.2 in the equation (1). As for the ground improved by GD method, evaluation was done in two ways such as No.2 gravel piles + in-between gravel piles and No.3 composite ground in table 1. Shear modulus of composite, G_{0comp} ground was calculated by equation (3) (Harada et al., 2012). The average SPT N-values and the fines content of each layer are also shown in figure 7(b).

$$G_{0comp} = \frac{(1-a_s)\,G_{0soil} + n a_s G_{0pile}}{1 + a_s(n-1)} \tag{3}$$

Herewith, G_{0soil}: shear modulus of soil in-between gravel piles, G_{0pile}: shear modulus of gravel pile, a_s: improvement ratio (=0.082), n: stress concentration ratio (=1)

Drainage effect was evaluated according to the drainage effect evaluation method, that excess pore water pressure ratio, $\Delta u/\sigma'_c$ (=0.85 : r_u as synonyms) at the area of GD piles' spacing of 1.8m with equilateral triangular arrangement is calculated, and F_L is estimated using the equation (2) and the figure 5. This F_L was determined to be input the value.

Table 1. Evaluation on analyses of parameter for unimproved and GD improved grounds

No.	Ground model			Evaluation method related to liquefaction	Evaluation method related to shear modulus, *G*
1	unimproved			R_L calculated from N-value and Fc. (*N*-value obtained from boring log, *Fc* obtained from existing data)	*G* (original ground)
2	GD improved	Grave pile + in-between ground	in-between ground	$\Delta u/\sigma'_c$ calculated from the relation between a/b and $\Delta u/\sigma'_c$. F_L of improved ground calculated from the relation between $\Delta u/\sigma'_c$ and F_L.(Figure 5)	*G* (original ground)
			gravel pile	Gravel pile is evaluated as unliquefied soil.	*G* is evaluated as 100,000kPa and estimated as the equivalent to the area with depth of 1m.
3		Composite ground		Composite ground is evaluated same as uniform ground as in-between ground in No.2.	*G* is evaluated as composite ground and calculated from equation (3).

(a) plane figure

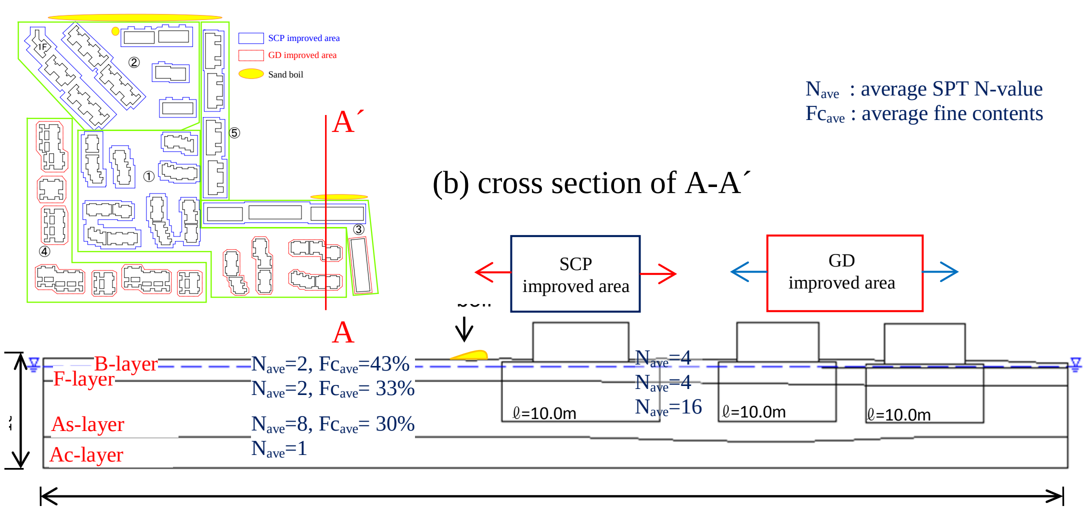


Figure 7. Plane figure and cross section

Results of analysis

The analysis result is shown in figure 8, in which the ground area improved by the SCP method is deemed as having the same strength with the overall ground (composite ground) by adding extra strength and the ground improved by the GD method is estimated as the composite ground (No.3 in the table 1). The effectiveness of countermeasures become evident by the fact that the settlement of the ground improved by the SCP is about 4 cm. and that of by GD is 5 to 8 cm., in contrast with the settlement of about 20 cm at the unimproved ground. The phenomenon that penetrating settlement is not found at the ground improved by the GD method like by the SCP method conforms to the neighboring circumstances after earthquake.

In the figure, the analyzed value is compared with the mean measured value (Suyama et al., to be submitted) by air-borne LODAR. Although the measured value of the unimproved area is a little smaller than the analyzed value, the analysis resulted generally close in the actually damaged value at the improved area. Settlement of the ground having no ground improvement treatment under the buildings which were supported by the conventional rigid piles near the area for analysis was about 18 cm (CERC, 2011). By contrasting the depth wise directional distribution of settlement as shown in the figure 9 for the unimproved area (A-A´ section in Fig. 8), the improved area by SCP (B-B´ section in Fig.8) and the improved area by GD (C-C´ section in Fig.8), it may be understood that the settlement occurred only at the unimproved As-layer regarding SCP's area , and the unimproved As-layer plus F-layer regarding GD's area, while it occurred at shallower zone than As-layer regarding the unimproved area. The bottom end of both improvement methods does not reach the lower part of liquefaction zone, and the similar cases that structures with spread foundation on the SCP improved ground that did not reach enough depth settled several centimeters were also found at the artificial land suffered by the 1955 Hyogo-ken Nambu Earthquake (Kakurai et al., 1996).

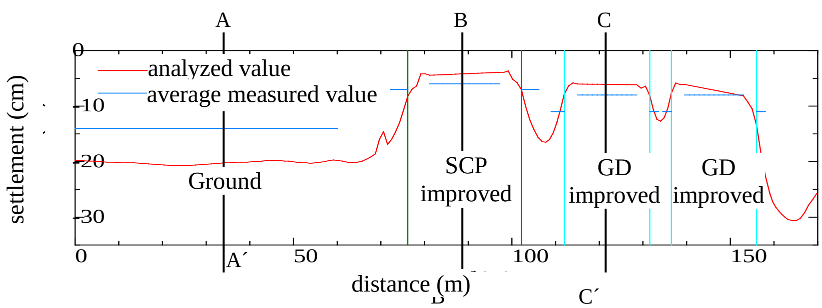


Figure 8. Ground settlement

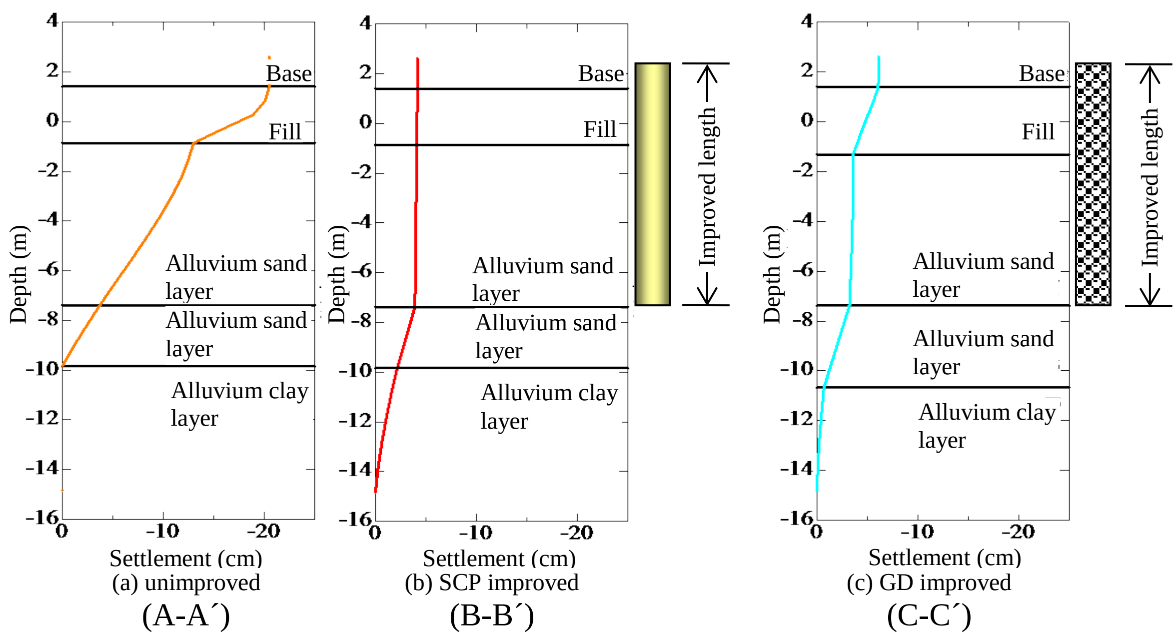


Figure 9. Depth distribution of settlement

According to the above results, it may be said that the validity of evaluation by the ALID on the liquefaction strength for overall ground (composite ground) improved by the SCP and the drainage effect for the ground improved by GD, depending on the method proposed in this paper, was verified.

Conclusions

As for the corresponding method to the problems on the application of liquefaction countermeasures to residential land, “the prediction of deformation” such as penetrating settlement was raised, and prediction method for penetrating settlement by static finite element analysis including the improved ground by the compaction method and the drainage method was disclosed as a process for the proposed prediction. By providing the reproduction analysis of the earthquake, the validity of evaluation method for the ground improved by the respective methods was verified. It is conceivable that such knowledge can be applied to estimate the settlement volume even in case of exceeding seismic motion beyond assumption (i.e. excess external force), thus it is expected that the method will be used as a way to explain quantitatively the effectiveness of countermeasures together with increasing its accuracy.

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