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ANALYSIS OF LIQUEFACTION-PROOF EFFECTS OF COMPACTION PILE METHODS

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ABSTRACT

The object of this work is to analyze the liquefaction-proof effects of typical compaction pile methods for saturated sandy grounds, subjected to recorded earthquakes, and to show the efficiency of these methods comparing with other ground-improving methods. Analysis also aimes to recommend optimal design parameters for sand-compaction pile (SCP) method and gravel-compaction pile (GCP) method to prevent liquefaction. High performance of compacted sand piles is shown by refering to damages from past earthquakes.

INTRODUCTION

Since 1964 Niigata Earthquake in Japan, numerous methods for predicting and resisting liquefaction have been developed and put into practice. In field, depending on the empirical rules, the sand compaction pile (SCP) method has been conducted as a most popular and reliable countermeasure against soil liquefaction in Japan, e,g. method by Tanaka *et al.*(1991). However, prominent performance of SCP for prevention of liquefaction during past earthquakes have been verified in only several cases; e.g. by Ishihara(1980) and Matsunaga(1993). There are still unknown problems about the effects of SCP method as the countermeasure.

So first to clarify the mechanism of dynamic compaction pile methods and establish an evaluating system of improved-soil stiffness, the improving-process by stiffness-accumulation at each compaction step has been modelled by Akiyoshi *et al.* (1992, 1994a), and a computer code "WAP3" which considers parameters of pile spacing, number of repetition, amplitude and frequency of compaction, and fine contents of soils has been developed. Availability of WAP3 is confirmed by the laboratory tests which have been conducted according to the in-situ ground improvement process by SCP and the field test results. Secondly to investigate the efficientcy of liquefaction-proof methods by SCP or GCP methods, a computer code "NUW2" has been developed by Akiyoshi *et al.* (1993, 1994b) which analyzes liquefaction based on the effective stress method, and availability of NUW2 is confirmed by the shaking table tests for saturated-sand box in the laboratory. Finally ground improvement methods by dynamic compaction are applied to the reclaimed soils in Port Island, Kobe and efficiency of the compaction method is shown by refering to the performance of improved grounds during the 1995 Hyogoken Nanbu Earthquake.

KEYWORDS

Liquefaction; sand compaction pile; gravel compaction pile; ground improvement; saturated sand; void ratio; pore water pressure; Biot's equation; dilatancy.

ANALYTICAL PROCEDURES

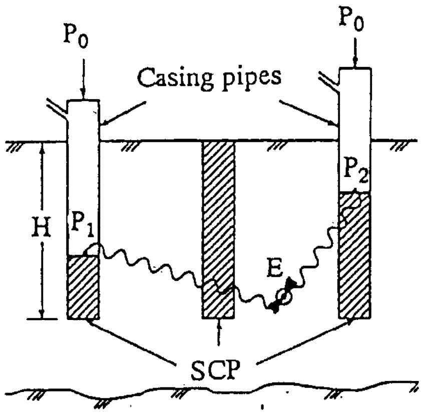
Simulation of sand compaction pile method

The process of sand compaction pile (SCP) method is assumed to consist of two processes; (1) static compaction by the compulsory insertion of steel casing pipes into the original sandy soft ground and (2) dynamic compaction by the vertical vibration of the casing pipes. The decrement Δe_1 and Δe_2 of the void ratio and the increment ΔG_1 and ΔG_2 of the shear moduli of the soil occur in above static and dynamic processes, respectively;

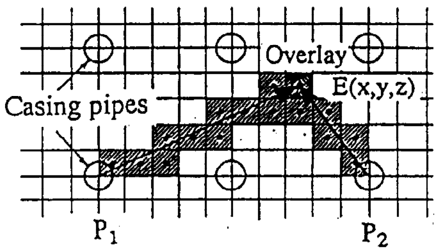
$$e_1 = e_0 - \Delta e_1, \quad G_1 = G_0 + \Delta G_1 \tag{1}$$

$$e = e_1 - \Delta e_2, \quad G = G_1 + \Delta G_2 \tag{2}$$

where e_0, e_1, e are the void ratios of the initial soil,the statically improved soil and the dynamically improved soil, respectively,. G_0, G_1, G the shear moduli of the initial soil, the statically improved soil and the dynamically improved soil, respectively.



(a) Elevation



(b) Plan view

Fig.1. Compacting process in SCP method

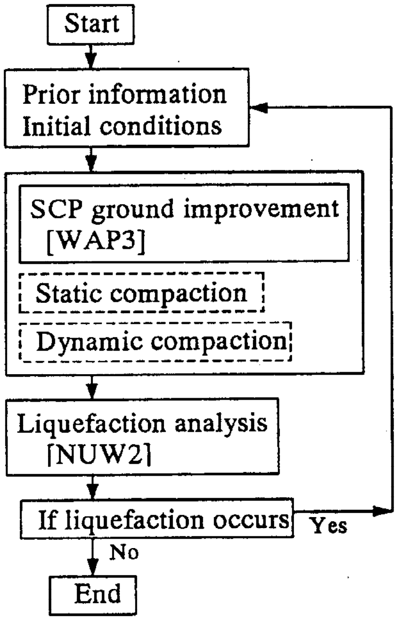


Fig.2. Evaluation system of SCP method and liquefaction

The dynamic compaction process is simulated by overlaying the propagating normal strain due to P-wave induced at the tip of the casing pipe as shown in Fig.1. In (2), the decrement Δe_2 of the void ratio is assumed to be related with the frequency of dynamic compaction N_n and the shear strain ε , exponentially. Next formula is adopted for representing such relation;

$$e = (e_0 - e_{\min}) \mathrm{e}^{-z} + e_{\min} \tag{3}$$

where $z = a\, \varepsilon^b N_n$,; e_0, $e_{\min}$ are initial and minimum void ratios, respectively, ε the volumetric strain-amplitude, and a, b the regression coefficients. In this study, a, b are determined so that the relation of (3) fits to the attenuation of waves in the saturated sands in the laboratory tests (Akiyoshi *et al.*,1992; 1993a). Thus, b = 0.75 and a is expressed in terms of the fine content F_c(%) and the effective vertical pressure σ_v(kPa) ;

$$a = 45.7(F_c/\sigma_v)^{-0.698} \tag{4}$$

If the normal strain ε is renewed due to consolidation of soil structures by the dynamic compaction, the void ratio can be computed by (3). Shear modulus G of the soil may be computed by the formula for the micro strain (Iwasaki *et al.*, 1977);

$$G = A(2.17 - e)^2 \ (\sigma_0')^{0.38} \ / (1 + e) \tag{5}$$

where σ_0' is the effective mean stress of saturated sand and A an empirical coefficient (Iwasaki *et al.*, 1977). According to above static and dynamic compaction processes, the program "WAP3" (wave accumulation process in 3-dimensions) for the total process of gorund-improving by SCP is developed.

ANALYSIS OF GROUND IMPROVEMENT AND LIQUEFACTION

Combination of the SCP-simulation program WAP3 with liquefaction-analysis program NUW2 will enable to design the improvement of soil for preventing liquefaction. Fig.2. shows a flow of the comprehensive evaluation system of the improvement process by SCP and the liquefaction analysis by the programs WAP3 plus NUW2. WAP3 is controlled by the improving rate $r = G/G_{max}$ of the shear modulus of soils, associated with the void ratio e and the fine content F_c,, the compacting force P_0 and frequency of the compaction N_n. NUW2 works for the liquefaction-analysis of the grounds in field or improved by WAP3 and performs the comprehensive evaluation on liquefaction.

Liquefaction-proof effect of SCP method

Liquefaction-proof effects of the SCP method are investigated for the improved model grounds using the simulation program WAP3 and liquefaction-analysis program NUW2.

Firstly, the three initial model grounds which have the single layers with uniform fine contents in depth and same initial conditions of the standard penetration test (SPT)-N values are used in the numerical computations as shown in Fig.3. SCP with a diameter of 0.4 m and a length of 17 m are built up in the initial model grounds by WAP3, with the compacting force of P_0=600 kN and the frequency of f = 9.3 Hz that have been often used in the field works. El Centro Earthquake (N-S component, 1940) of the maximum acceleration of 0.1g are used as the horizontal input at the bottom surface of the layer. Fig.3. shows that the rate of ground improvement is higher with low fine contents, in which the improvement rate here is defined as the ratio of SPT-N values N/N_{max} or one of shear mokuli G/G_{max}. The improvement ratio r=G/G_{max} versus the excess pore water pressure ratio u^* is plotted in Fig.4. and the liquefaction resistance factor F_L according to JRA specifications (1990) versus u^* is plotted in Fig.5. Here N_{max} or G_{max} is defined as the maximum SPT-N value or shear modulus at at the minimum void (e=e_{min}). Fig.4. and 5. show that there exist the simple relations between r, F_L and u^*. If u^*=0.5 is assumed to be a critical condition for generation of liquefaction, the improvement rate r >30% is required for the safe design as shown in Fig.4. and F_L=0.8 corresponds to u^*=0.5 as in Fig. 5.

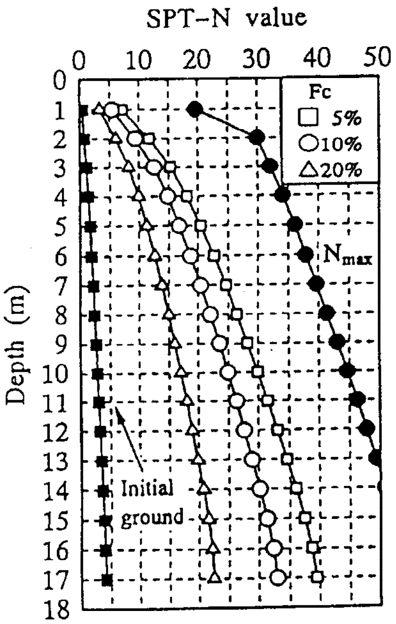


Fig.3. Model ground and improvement (at t_0=200sec)

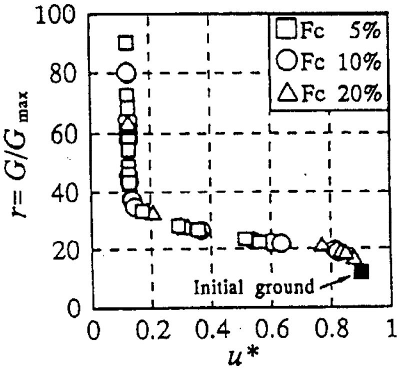


Fig.4. Improvement ratio r=G/G_{max} versus excess pore water pressure ratio u*

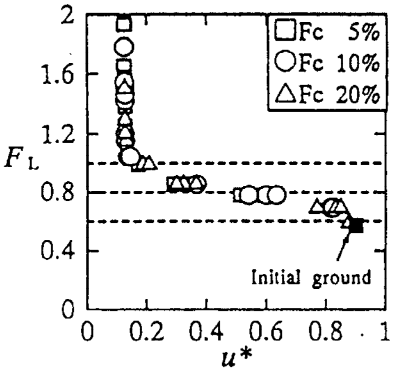


Fig.5. Liquefaction resitance factor F_L versus excess pore water pressure ratio u*

Another example in Fig.6. shows that frequency of compaction N_n (compacting time) at each stage is very low even for higher compaction rate, say for the range of r=G/G_{max}<70%. For the model ground in Fig.6., the excess pore water pressure ratio u* is plotted in Fig.7. for the pile spacing L(m) and the frequency of compaction N_n, subjected to the inputs of the maximum accelerations of 0.13g and 0.25g. Critical values of L and N_n may exist for u*=0.5 and be used for the design of SCP, conveniently.

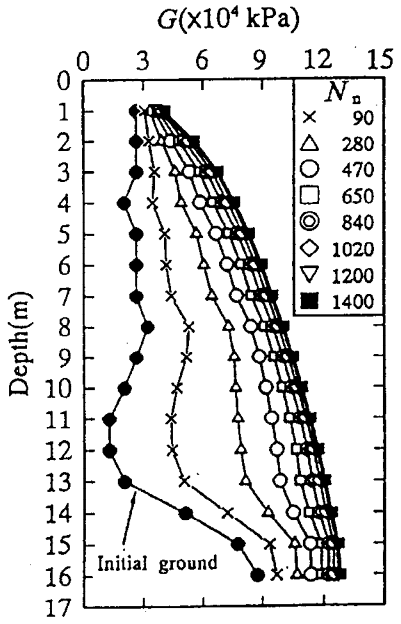
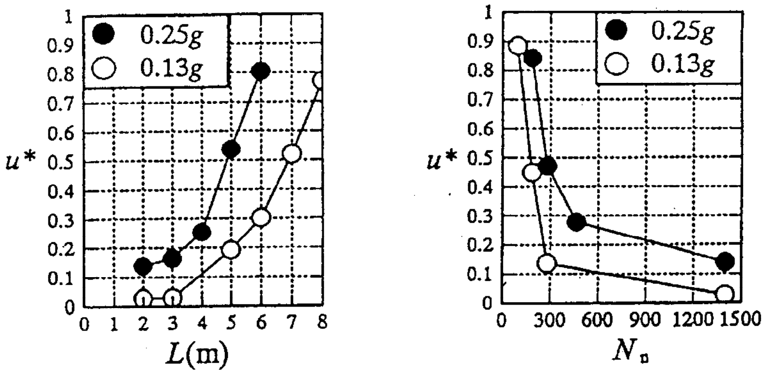


Fig.6. Improvement of shear modulus G with frequency of compaction N_n



(a) Pile spacing

(b) Frequency of compaction

Fig.7. Excess pore water pressure ratio u* versus pile spacing L and frequency of compaction N_n

For practical design purpose of SCP and back-analysis of design parameters, critical liquefaction surfaces can be illustrated in terms of pile spacing L, compaction force P_0 and frequency of compaction N_n as in Fig.8. This comprehensive critical surfaces for (A) $u^*=0.5$ and (B) $u^*=0.2$ are very usuful for the optimal design of anti-liquefaction ground improvement by SCP.

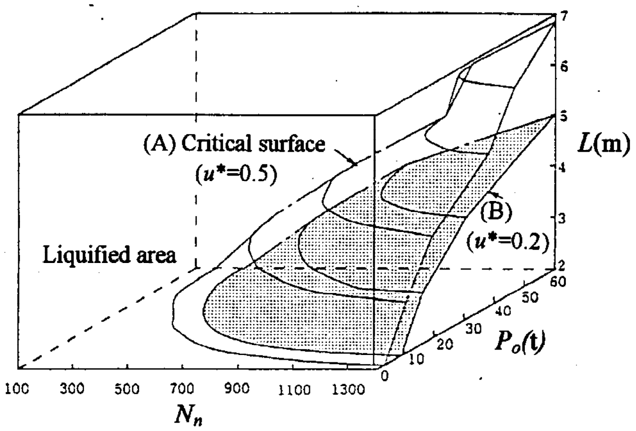


Fig.8. Critical liquefaction surfaces in terms of pile spacing L, compaction force P_0 and frequency of compaction N_n

Comparison of excess pore water pressures

Figs.9. and 10. illustrate the stiffness-increasing effects of SCP, GCP (gravel compaction pile) and GDP (gravel-drained pile) methods for a model ground under the conditions of the pile spacing=2.0 m, compacting force=600 kN, frequency=9.3 Hz and compacting time=60 sec. At this critical case (r=100%) this means that SCP and GCP have almost equivalent potentials and are much more efficient than GDP for preventing liquefaction, except that high fine contents prevent the improvement of soil stiffness.

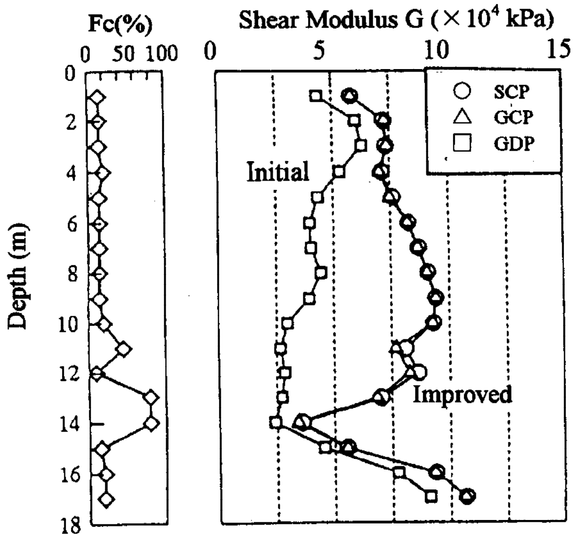
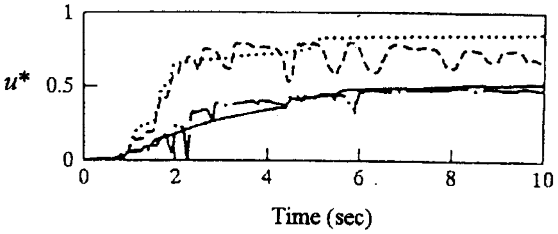
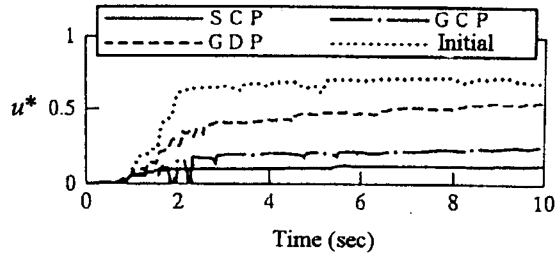


Fig.9. Stiffness-increasing effects of ground-improving methods



(a) Depth=8m (Acc=0.2g)

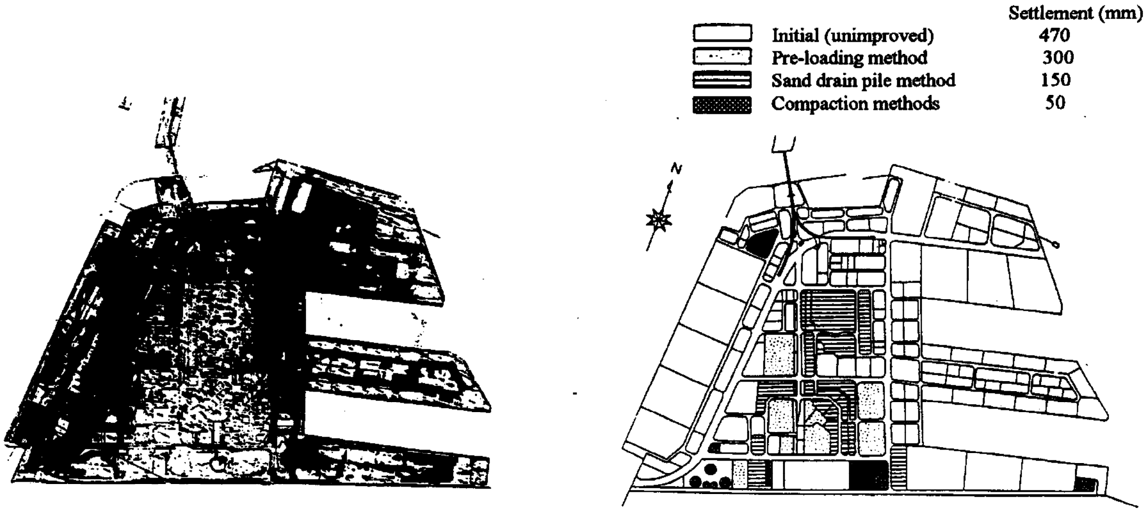


(b) Depth=12m (Acc=0.2g)

Fig.10. Excess pore water pressure ratio u^* (Maximum acceleration=0.2 g)

Ground improvement effect in Port Island, Kobe

As an example of liquefaction-proof performance of improved grounds in the 1995 Hyogoken Nanbu Earthquake, (a)liquefied area (in black in the diagram) and (b) improved area in Port Island (P.I.), Kobe are shown in Fig.11 (Yasuda,1995). The diagram means that the unimproved area after reclaiming caused liquefaction and the improved area after reclaiming prevented liquefaction. Compacting methods such as SCP are very efficient for preventing settlement of ground surface even for such huge quakes.



(a) Liquefied area (in black) (b) Improved area

Fig.11. Liquefaction and ground improvement in Port Island, Kobe

However, Fig.12.shows that liquefaction occured even for the reclaimed soil with such well mixed propotion, compared with other Harbor soils which were suffered from liquefaction for the past earthquakes.

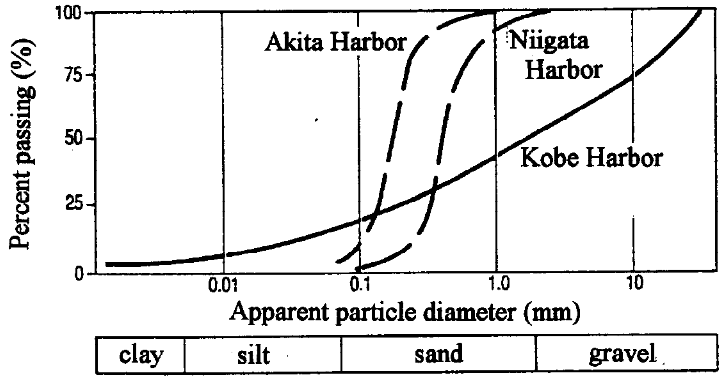


Fig.12. Grain size distribution in Port Island

Fig.13. is to illustrate that in such a profiled ground in P.I. as in Fig.14. the program "SHAKE" (Schnabel, 1972) simulates very similar response waves of the ground at the ground surface level and at -16 m depth level with observed waves (NUW2 also gives almost same results, but ommitted here).

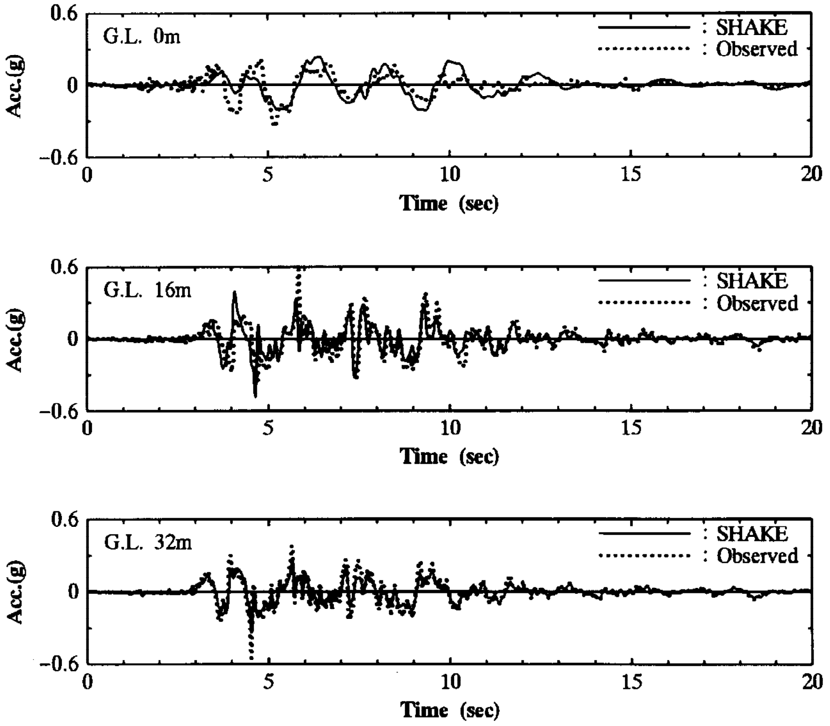
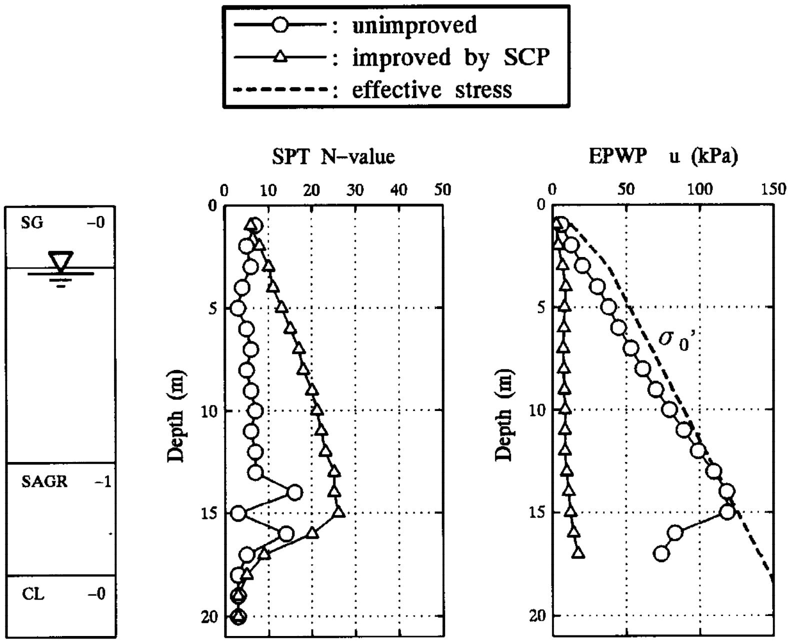


Fig. 13. Comparison of observed and simulated waves in Port Island

In Fig. 14. the initial (reclaimed) ground shown in the diagram (a) in Fig. 14. may be compacted by SCP method using WAP3 program, and NUW2 illustrates drastic depression of excess pore water pressure *u*.



(a) SPT N-value (b) Maximum EPWP u

Fig. 14. Effect of ground-improvement by SCP in Port Island, Kobe

CONCLUSIONS

Liquefaction-proof effects of SCP and GCP methods for saturated sandy grounds are analyzed comparing with gravel drained (GDP) method for the recorded earthquakes. Main results of analysis are sumarized as follows:

(1) Combination of the programs WAP3 and NUW2 fabricates a comprehensive evaluation system of SCP and GCP-construction process and liquefaction-analysis, and enables the optimal design of liquefaction-proof ground improvement by compaction pile methods.
(2) SCP and GCP have euqivalent potentials and are much more efficient than GDP for preventing liquefaction.
(3) Much of existing ground improvements by compaction pile methods based on conventional design standards in Japan are over-designed for preventing liquefaction.
(4) Proposed evaluation system of gound improvement and liquefaction analysis explains well the evidences of liquefaction in Port Island, Kobe for the 1995 Hyogoken Nanbu Earthquake.

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