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Settlement characteristics of sandy ground improved by gravel drain system during earthquakes

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ABSTRACT: The determination of improved area is one of the most crucial problems when countermeasure against liquefaction is designed. The present paper deals with gravel drain system as a countermeasure against liquefaction. The purposes of the paper are to investigate the effects of gravel drain system in the adjacent unimproved ground and to study the settlement characteristics in the site. Small scale vibration tests lead to the following conclusions; the effects of gravel drain system reach the adjacent unimproved area and the settlement there correlates to the maximum excess pore water pressure ratio.

1 INTRODUCTION

Liquefaction of sandy ground during earthquakes often causes extensive damage to civil engineering structures. Examples of the recent damage by soil liquefaction are given in the 1989 Loma Prieta Earthquake and in the 1990 Philippine Earthquake.

If the sandy ground are potentially liquefiable and the liquefaction will be likely to cause damage to the structures, a countermeasure is usually taken to mitigate the potential damage. As one of the countermeasures against liquefaction, gravel drain system is installed in order to increase average permeability of the ground and, thus, reduce the liquefaction potential. It has advantages of low noise and less vibration during construction in comparison with sand compaction method, which has been actually used in many projects. Therefore it can be applicable to sites in urban areas and near structures.

However, several problems still exist for its construction. One of them is residual settlement of the ground after earthquakes (Yoshimi 1991). It is reported experimentally that the settlement of the ground with the gravel drain system is larger than that of the ground without the gravel drain system in case of the same value of maximum excess pore water pressures generated in both ground (Tanaka et al. 1984). The studies for the settlement in sandy ground due to liquefaction have been mainly conducted by laboratory cyclic loading tests. Tokimatsu et al. (1987) have proposed simplified methods of analysis for estimating probable settlement in either saturated or unsaturated sand layers, based on a review of previous studies. They have indicated that the settlement could be related to excess pore water pressure ratio before complete liquefaction, that is, the excess pore water pressure ratio is under 1.0. In complete liquefaction, the settlement could be controlled by the maximum shear strain.

The present paper aims to clarify the settlement characteristics of sandy ground at which the gravel drain system has been installed through small scale vibration tests using a shaking table.

2 TEST PROCEDURE

This study focused on the relation between the maximum excess pore water pressure ratio and settlement. The tests were carried out to clarify the settlement characteristics of sandy ground in which the gravel drain system was installed comparing with the sand compaction method. The reason of comparing with the sand compaction method is to estimate the effects of gravel drain system on settlement.

General view of test apparatus is shown in Figure 1. The model ground was made up to the level of about 250mm in a sand box of steel. The size of the sand box is 500mm in width, 1500mm in length and 350mm in height. The tests were conducted by using a composite ground made of two parts; i.e., one is loose saturated sand layer as unimproved ground, the other improved ground. The former was formed by pouring wet sand into the sand box filled up with water. The latter consisted of gravels for the gravel drain system or densified sand layer for the sand compaction method. The ground for gravel drain system was constructed by stuffing No.5 crushed stones. The ground for sand compaction method was constructed by shaking the loose saturated sand layer using 900 sinusoidal waves with a frequency of 5Hz, whose amplitude was 300gal(3.0m/s^2). The mesh made of nylon was installed at the boundary between the improved and unimproved ground in order to prevent sand transferring. The physical properties of the model ground are listed in Table 1.

An accelerometer was stuck on the sand box to measure the input acceleration, and pore pressure transducers were installed in the unimproved ground to measure the excess pore water pressure during excitation. After excitation, settlements of the ground were measured with a point gauge.

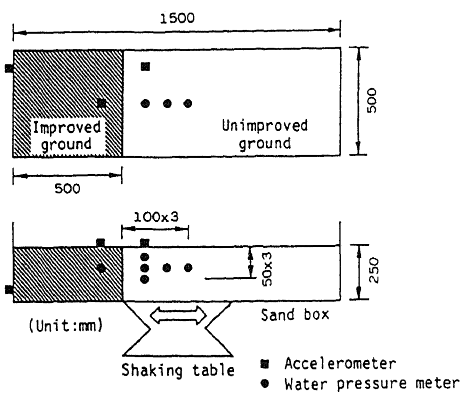

Figure 1. General view of test apparatus.

Table 1. Physical properties of sand, gravel and constructed ground(1gf/cm^3=9.8kN/m^3).

Sand		
Specific gravity	2.67	
Uniformity coefficient	2.96	
Maximum void ratio	1.030	
Minimum void ratio	0.721	
50 Percent diameter	0.2	(mm)
Coefficient of permeability	1.92x10^{-2}	(cm/s)
Gravel		
Specific gravity	2.69	
Maximum grain size	25	(mm)
Coefficient of permeability	8.24	(cm/s)
Loose sand layer		
Wet unit weight	1.84	(gf/cm3)
Void ratio	0.95	
Water content	34.2	(%)
Relative density	25.9	(%)
Dense sand layer		
Wet unit weight	1.90	(gf/cm3)
Void ratio	0.87	
Water content	32.9	(%)
Relative density	51.8	(%)

Input waves used in the tests were about 150 sinusoidal waves with a frequency of 5Hz, and target input accelerations were 60gal(0.6m/s^2), 80gal(0.8m/s^2) and 100gal(1.0m/s^2). It reaches the target acceleration after 25 waves.

3 TEST RESULTS AND DISCUSSION

3.1 Effect of countermeasure in improved ground

Figure 2 shows the time histories of excess pore water pressures in the improved and unimproved ground at a depth of 100mm and a distance of 100mm apart from the boundary between the improved and unimproved ground. The input acceleration was 80gal(0.8m/s^2) in this case.

The excess pore water pressure in the improved ground for gravel drain system is close to 0gf/cm^2(0Pa). The liquefaction was completely prevented in this case. However the excess pore water pressure in the improved ground for sand compaction method increases to about 60 percent of that in the unimproved ground.

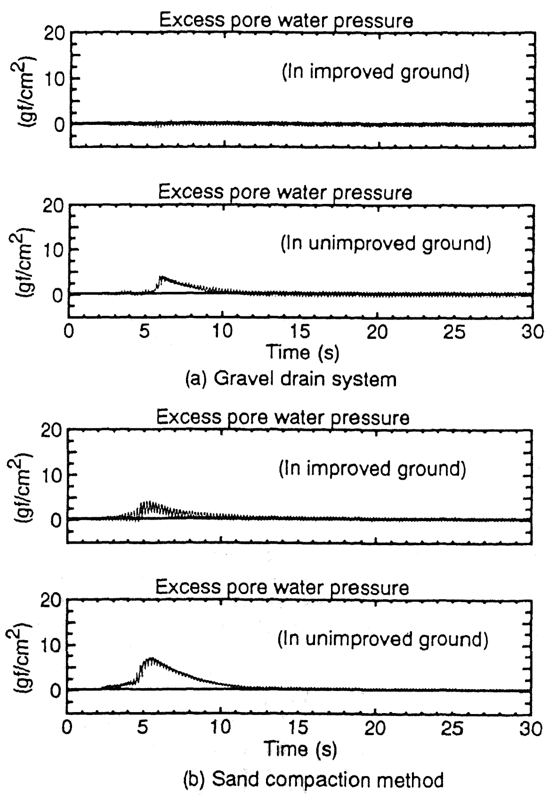

Figure 2. Time histories of excess pore water pressures in improved and unimproved ground(1gf/cm^2=98Pa).

It has reported that the compacted ground against liquefaction gradually liquefies due to the seepage flow from the adjacent liquefied ground (Iai et al. 1987). The results obtained here have good agreement with their results. The settlement of the improved ground little generated in both countermeasures.

3.2 Process of accumulation and dissipation of excess pore water pressure

Figures 3 and 4 illustrate the time histories of the input acceleration and excess pore water pressures in the unimproved ground at a depth of 100mm. B.D.-100 in these figures, for example, indicates that the pore water transducer is installed at a distance of 100mm apart from the improved ground.

Figure 3 shows the results in case of 80gal(0.8m/s^2) of the input acceleration. The maximum excess pore water pressures for gravel drain system are less than the effective overburden pressure, therefore all sites do not completely liquefy. Furthermore, this figure suggests that the gravel drain system reduces the rate of accumulation of excess pore water pressure and increases the rate of its dissipation as compared with the sand compaction method. As this tendency is remarkable close to the improved ground, it is evident that the gravel drain system increases the resistance against liquefaction not only in the improved ground but also in its adjacent unimproved ground.

Figure 4 reflects the results in case of 100gal(1.0m/s^2) of the input acceleration. As this acceleration was larger than that of Figure 3, the unimproved ground for the gravel drain system completely liquefied at a distance of 200mm apart from the improved ground. It can be seen from duration of complete liquefaction that the gravel drain system increases the resistance against liquefaction around the improved ground in the same manner as Figure 3.

3.3 Maximum excess pore water pressure ratio

Figure 5 shows the distribution of the maximum excess pore water pressure ratio in the unimproved ground at a distance of 100mm apart from the improved ground in relation to the input acceleration. This figure indicates the maximum excess pore water pressure ratios in the unimproved ground for gravel drain system are less than those for sand compaction method under the same input acceleration level, when the input accelerations exceed about 60gal(0.6m/s^2). This acceleration is supposed to be lower limit of trigger of complete liquefaction in these

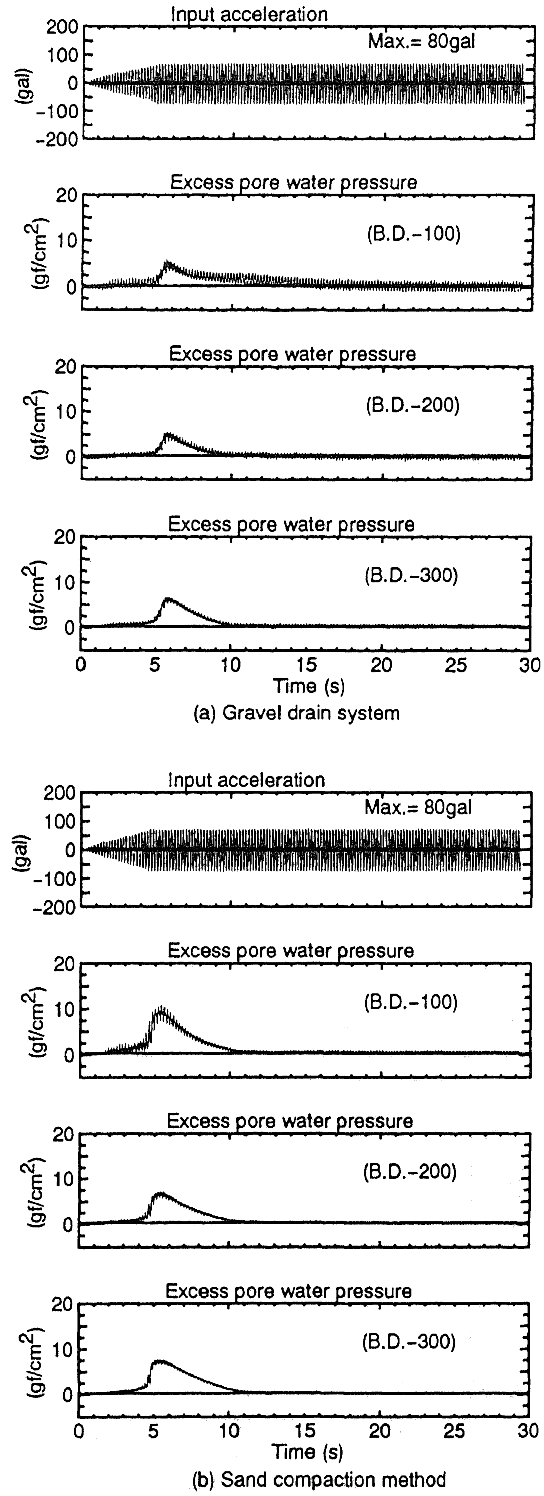

Figure 3. Time histories of input acceleration and excess pore water pressures in unimproved ground(1gal=10^{-2}m/s^2).

tests. This suggests that gravel drain system increases the resistance against liquefaction around the improved ground more than that for sand compaction method under the same input acceleration level.

Figure 6 shows the distribution of the maximum excess pore water pressure ratio in relation to the distance from the improved ground. The input acceleration was about 80gal(0.8m/s^2) in this case. The maximum excess pore water pressure ratio for sand compaction method was almost unchangeable irrespective of the distance; while that for gravel drain system decreased with a decrease in the distance.

These results can be summarized as follows; construction of gravel drain system improves the permeability in the surrounding loose saturated sand layer, consequently the resistance against liquefaction increases around the improved ground. And it can be expected that the maximum excess pore water pressure ratio will decrease not only in the improved ground but also in its adjacent unimproved ground.

Iai et al.(1987) have proposed a procedure of the determination of improved area for sand compaction method based on their laboratory tests.

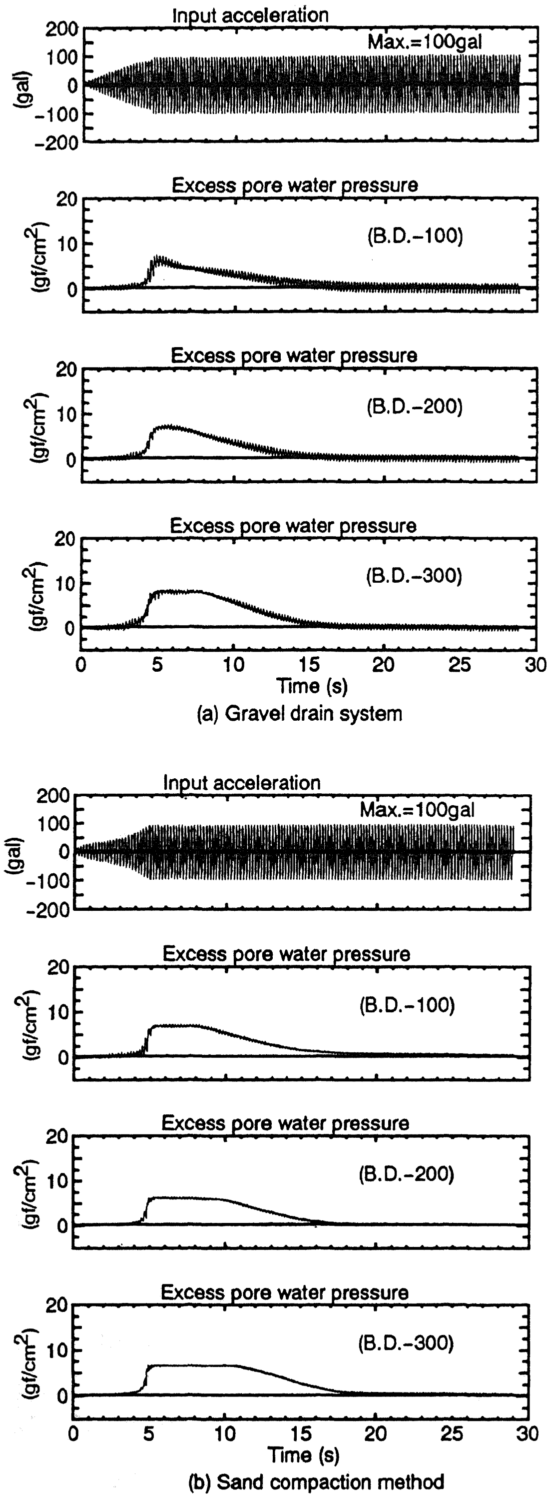

Figure 4. Time histories of input acceleration and excess pore water pressures in unimproved ground(1gal=10^{-2}m/s^2).

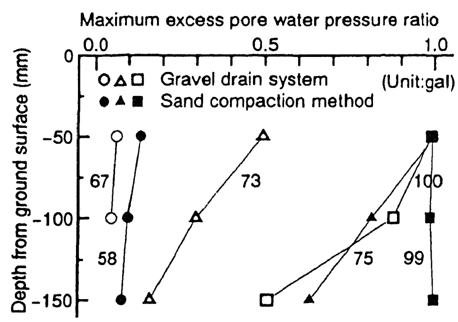

Figure 5. Maximum excess pore water pressure ratio in relation to input acceleration (1gal=10^{-2}m/s^2).

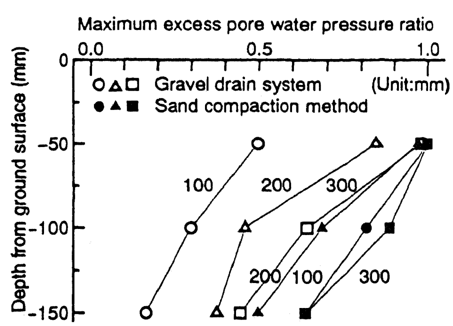

Figure 6. Maximum excess pore water pressure ratio in relation to distance from improved ground.

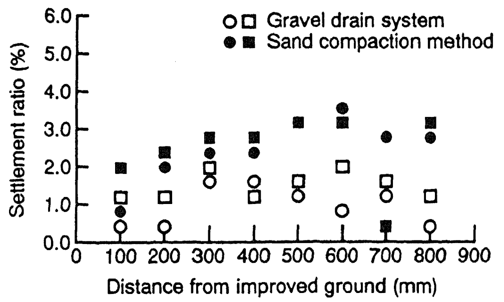

Figure 7. Settlement ratio in relation to distance from improved ground(Input acceleration is 80gal($0.8m/s^2$)).

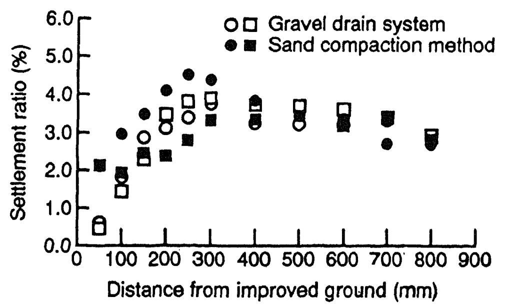

Figure 8. Settlement ratio in relation to distance from improved ground(Input acceleration is 100gal($1.0m/s^2$)).

Their procedure indicates that the improved area should be decided in considering the seepage flow from the liquefied ground, as mentioned in Chapter 3.1. As gravel drain system does not need to consider the influence of the seepage flow, the improved area becomes smaller than that for sand compaction method in order to obtain the same effect against liquefaction.

3.4 Horizontal distribution of settlement

Figures 7 and 8 show the distribution of settlement ratio at the unimproved ground in relation to the distance from the improved ground. The figures are corresponding to the cases of the Figure 3 and 4 respectively. Settlement ratio means a vertical strain of ground that is defined as vertical displacement of ground surface divided by initial thickness of the ground.

Figure 7 indicates that the settlement ratios for gravel drain system are smaller than those for sand compaction method. In this case, the unimproved ground for gravel drain system did not reach complete liquefaction and the maximum excess pore water pressure ratios are smaller than those for sand compaction method(See Figure 3).

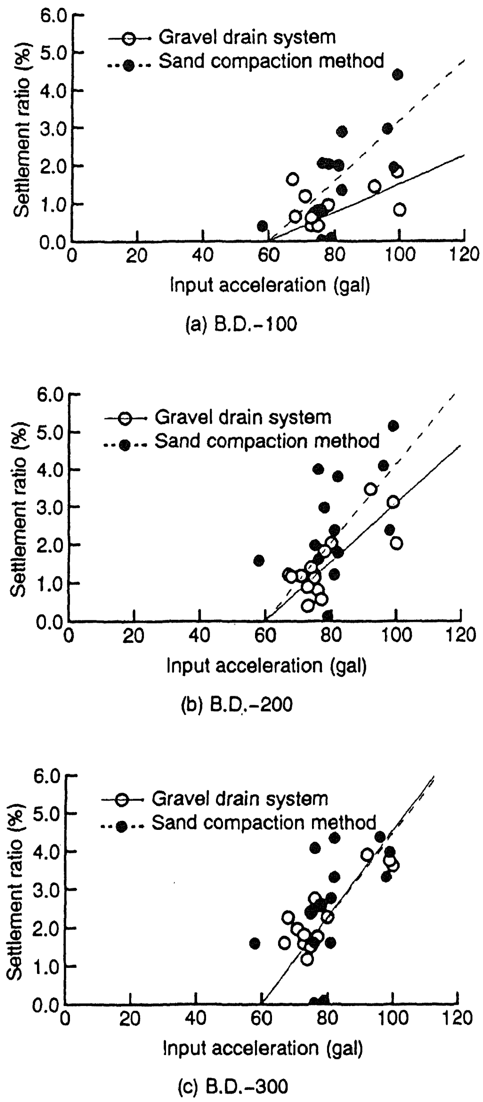

Figure 9. Relationship between input acceleration and settlement ratio(1gal=10^{-2} m/s^2).

However Figure 8 indicates the similar settlement ratios for both countermeasures and the value of settlement ratio is greater than that in Figure 7. The complete liquefaction occurred for both countermeasures in this case. These results suggest that the settlement correlates the degree of liquefaction, especially whether the ground completely liquefies or not.

3.5 Relationship between input acceleration and settlement

Figure 9 shows the relationship between the input acceleration and settlement ratio.

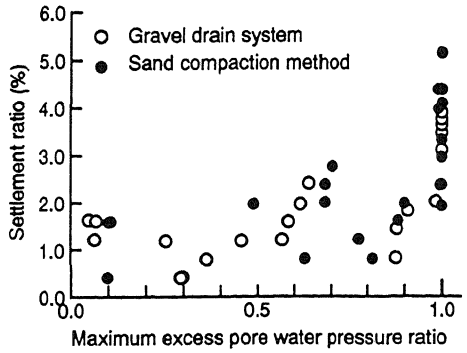

Figure 10. Relationship between maximum excess pore water pressure ratio and settlement ratio.

Two lines shown in these figures are linear regression lines for both countermeasures. The figures indicate that the settlement ratios for both countermeasures increase with a increase in the input acceleration. The slopes of line for sand compaction method are almost unchangeable irrespective of the distance from the improved ground; while those for gravel drain system become gentle with a decrease in the distance. The difference between the two, therefore, increases with a decrease in the distance.

It can be explained by the relation shown in Figures 5 and 6, that is, the relationship among the excess pore water pressure ratio, input acceleration and distance from improved ground. These results confirm that the settlement at the unimproved ground greatly depends on the maximum excess pore water pressure ratio.

3.6 Relationship between maximum excess pore water pressure ratio and settlement

Figure 10 shows the relationship between the maximum excess pore water pressure ratio and settlement ratio. This figure indicates that many dots of large settlement ratio are plotted at the maximum excess pore water pressure ratio of 1.0. Therefore, the individual characteristics of both countermeasures can not be found in this figure. This suggests that the settlement characteristics of the unimproved ground around the improved ground correlate to the maximum excess pore water pressure independently of a kind of countermeasures.

Consequently, the settlement around the improved ground much depends on the maximum excess pore water pressure ratio as mentioned above.
Therefore, it can be expected that the settlement around the improved ground would decrease when the maximum excess pore water pressure ratio reduced under 1.0 by the countermeasure.

4 CONCLUSIONS

The present paper experimentally investigated the settlement characteristics around the ground improved by gravel drain system against liquefaction. Findings in the paper can be summarized as follows;

1. The gravel drain system shows the effect not only in improved ground but also in its adjacent unimproved ground as a countermeasure against liquefaction due to its permeability.
2. The settlement characteristics of the unimproved ground around the gravel drain system correlate to the maximum excess pore water pressure ratio, that is, the settlement decreases with a decrease in the maximum excess pore water pressure ratio.

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