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Shaking table test on liquefaction of artificially cemented sands

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ABSTRACT: This paper introduces the premixing method recently developed by the authors. The liquefaction characterristics of the cement-treated model ground constructed by this method are investigated by using shaking table test.Comparative tests on liquefaction in the treated and non treated grounds confirmed that the mixing of small amount of cement is notably effective to prevent the liquefaction in created ground. In regard to the earth pressure during filling works, the strength characteristics of treated sand at young age are examined. It is presented that the cohesion appears fairly early time after the cement mixing. The earth pressure reduction may be expected even at the early stage of filling works.

1 INTRODUCTION

It has been learned from damage suffered in great earthquakes in the past, such as Niigata (1964), Nihonnkai-chubu(1983), and Roma Prieta (1989), that ground consisting of sand fills or deposits is extremely susceptible to liquefaction. On the other hand, it is a well known fact that clays and naturally cemented sands are not easily liquefied due to the cohesion they possess. The premixing method reported here is a new counter-liquefaction measure developed taking full advantage of this fact.

The key point of this method is that a small amount of the cement is mixed with fill materials prior to the filling, to expect the artificial cementation among the contacts of soil particles. As a consequence, when reclaimed land is developed by this method, subsequent liquefaction countermeasures will become unnecessary.

The authors have previously published a number of reports concerning a cement mixing system, reclamation techniques, and the design concept(Umehara etal 1991, Zen et al 1991). The present paper gives the results of liquefaction tests by shaking table and static triaxial tests of treated sand at young age which have subsequently been performed.

2 OUTLINE OF PREMIXING METHOD

2.1 Construction Method

The construction may be divided into the three stages of mixing, conveying, and reclamation. Of these three, conveying is done by conventional methods, using such dump trucks on land and barges in water. The features of the developed method lie in the stages of mixing and reclamation. The construction system is shown in Fig.1.

2.1.1 Mixing Method

Mechanical mixers are often used to mix soils and stabilizers. However, this method has limits in the dearling capacity when mixing a large amount of soil. Therefore, a new mixing system was developed combining belt conveyors and special dumper chutes installed at transfer points of belts. Sand is supplied from two hoppers located above the belt conveyor, while a hopper for cement is installed between the two. As a consequence, the cement is sandwiched by sand so that mixing is easily achieved. According to this method, a large amount of sand can be efficently mixed using less energy than convetional mechanical mixers.

2.1.2 Reclamation with Treated Sand

The reclamation method is assorted into 3 types: (1) spreading by bulldozers on the ground, (2) dumping directly from open-bottom barges, and (3) dropping directly into water through chutes. Method(1) is suited for operation on land, whereas method(2) is on the sea, and these are the same as conventional methods. Method(3) uses the reclamation chute shown in Fig.1, and which is particularly effective in preventing water pollution. This chute consists of a telescoping inner pipe and an outer accordion type pipe of fabric that can be freely extended. The bottom end is maintained closely to the surface of the underwater filled ground at all times in the filling.

2.2 Advantages of Premixing Method

The premixing method has the following advantages:

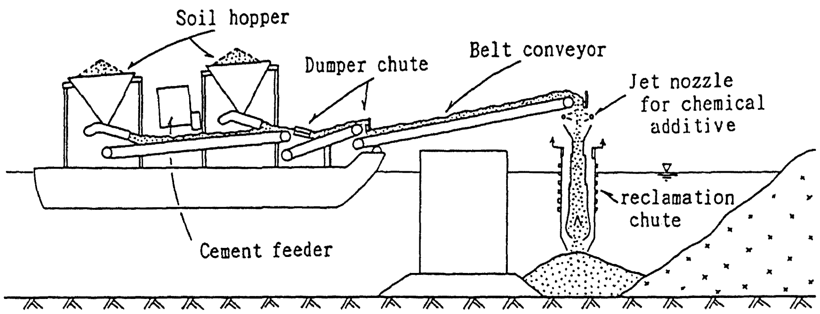

Fig. 1 Construction system for Premixing Method

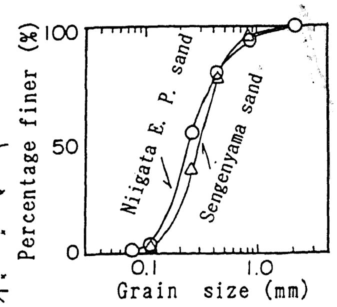

Fig. 2 Grain size distribution curve

1. The construction period and labor works can be reduced because no soil improvements are required after reclamation.
2. A reclamation work in deep sea is possible because the treated sand can be dropped directly from open-bottom barges.
3. The strength of the treated ground can be created arbitrarily within a certain range.
4. The existing facilities and ships can be used, and no special machines or facilities are required.
5. In addition to the usage for countermeasures against liquefaction, the reduction of earth pressure can be expected because of the cementation effect.
6. The earth pressure reduction inevitably yields a great economical effect for such structures as the sheet-pile quay walls, because the structure itself can be made slimmer.
7. Unlike the sand compaction pile method, there is no need for paying attention to large noise and vibration.
8. There is no risk of bulging of sheet piles occurring in backfill of a quay wall because compaction is unnecessary.

3. SHAKING TABLE TEST

3.1 Test Method

Specimen sand was taken from the Niigata East Port. The grain-size distribution curve is shown in Fig.2. The treated sand was made by mixing 1% of the Portrand cement and a chemical additive for preventing the cement dispersion. A foundation layer of crushed stone was provided at the botom part of a shaking container(length 3 m, width 3 m, height 1.2 m) on the shaking table. The container was separated into two chambers in the middle of it, and model caissons were installed independently in each part. Water was then filled in the container, and treated sand and untreated sand were dumped separatly. Neither of the ground models were compacted. The cross sections of the models are shown in Fig.3. The dry densities of the treated and untreated sand were 1.41 t/m^3 and $1.34 t/m^3$, respectively. The accelerat ion, pore water pressure, earth pressure and displacement of caissons and model grounds were measured(show Fig.3). The shaking was done after 7 days of curing. Sine waves of frequency 3 Hz were used for shaking. The applied accelerations were 5 steps, consisting of 50, 100, 150, 200, and 250 gal. The number of wavesfor each step was 20. Cyclic triaxial tests for grasping liquefaction characteritics were also performed using the same samples.

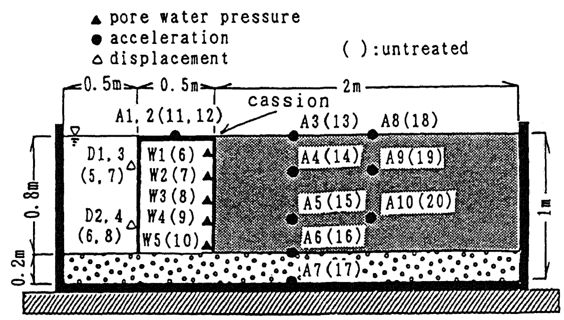

Fig. 3 Profile of the shaking table test

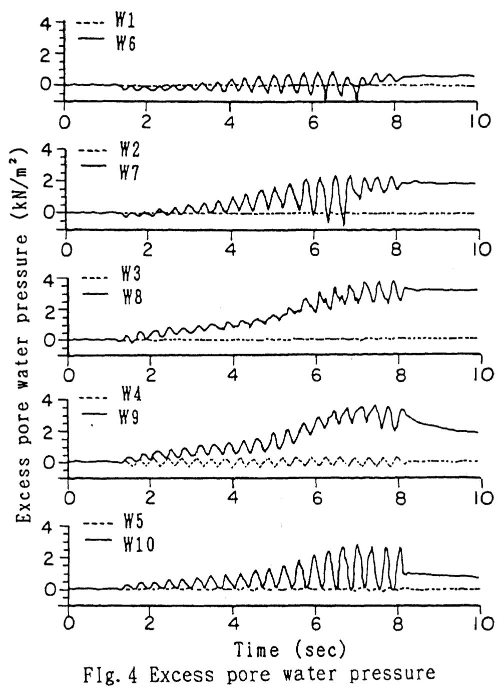

Fig. 4 Excess pore water pressure

3.2 Test Results

The build up of excess pore water pressures to the acceleration of 100 gal, applied to the shaking table, are shown in Fig.4. The solid line in Fig.4 indicates the excess pore water pressure in the untreated sand and the broken line that in the treated sand. According to Fig.4, the excess pore water pressure of the treated sand is one order smaller than that of untreated sand.

Fig.5 shows the distribution of maximum excess pore water pressure and primary effective overburden pressure. It is apparent from Fig.5 that liquefaction clearly occurs up to the depth of 40cm in the untreated ground, while only slight excess pore water pressure is generated in the treated ground.

Fig.6 is an example of changes in acceleration under the same experimental case. The wave form of the untreated ground has been disturbed considerably by liquefaction, and the acceleration is amplified by about 3 times, whereas that of the treated sand is uniform and is practically equal to the table acceleration. Furthermore, liquefaction phenomena of the treated sand were not observed even when 250 gal was applied. It can be concluded that a prominent cementation effect is attained by the addition of only 1% cement to construct the liquefaction-free ground.

Fig.7 shows the displacements of the ground models and caissons after shaking at each step. The distribution of the front side caisson of the untreated ground shows a remarkably large displacement toward the front side, whereas that of the treated ground shows almost no displacement.

Fig.8 shows the relationship between the stress ratio and number of waves at the double amplitudes of axial strains in cyclic triaxial tests, 5%. Fig.8 describes the test results for the 3 cases of treated sands cured for 14 days and 28 days, and untreated sands. It is clear that the stress ratio is definitely increased by treatement.

Addition of 5% cement or unconfined compressive strength of 50 to 100kN/m² have been tentatively prpposed for making liquefaction-free ground(Umehara et al 1991). However, according to the results of shaking table tests carried out this time, it may be suggested that there is a possibility to reduce the cement content.

4 STATIC STRENGTH CHARACTERISTICS AT YOUNG AGE

4.1 Test Method

When backfilling structures such as a quay wall or a retaining wall by this new method, it is important to clarify strength and deformation characteristics of treated sands not only after construction, but also during construction works, since earth pressure reduction due to cementation will appear with

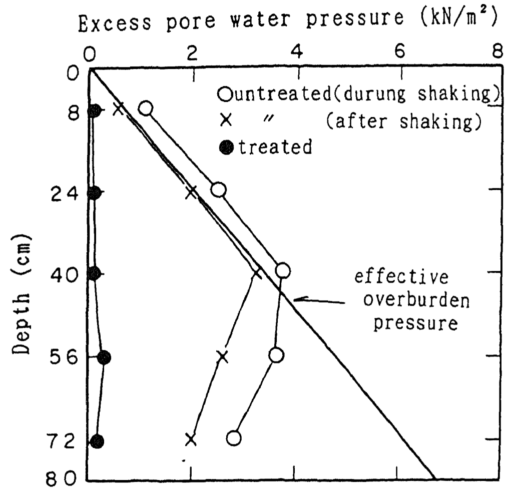

Fig. 5 Maximum excess pore water pressure

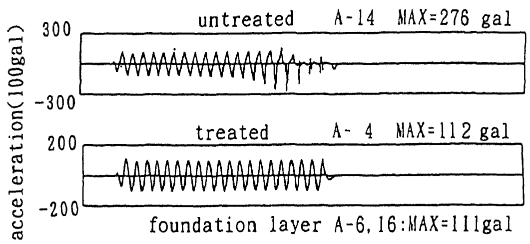

Fig. 6 Acceleration

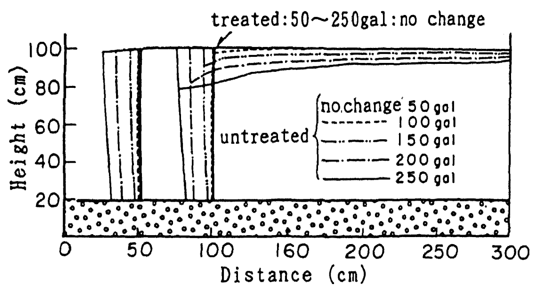

Fig. 7 Displacement of ground and caisson

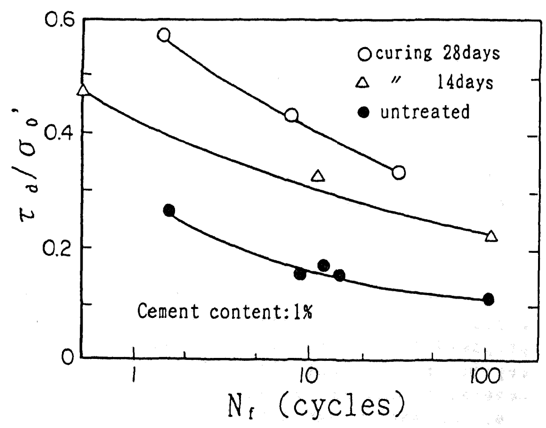

Fig. 8 Cyclic strength of treated sand

time, and the stability condition immediately after construction is the most dangerous against earth pressure.

By use of *Sengenyama sand shown in Fig.2*, triaxial compression tests(C.D.conditions) were performed. Cement contents were 7.5 and 11%. Dry density was $1.43t/m^3$, and the curing times were 0, 4, 8, and 24 hours. Taking into account that cementation proceeds under a condition that certain over burden pressures are exerted during actual sand-fill work, the curing was done inside a cell with the specified confining pressure. The applied confining pressures were 49, 98 and $196kN/m^2$.

4.2 Test Results

The stress-strain curves for the cement content of 7.5% are shown in Fig.9. Up to curing time of 4 to 8 hours, specimens being tested do not show distinct failure planes, and no distinct peaks are seen in stress-strain relationships. When the curing time is 24 hours, it becomes possible to differentiate distinctly between the peak strength and the residual strength. As a whole, when the curing time is longer, the strain at the peak becomes smaller, and the modulus of deformation, E_{50}, becomes larger. This indicates that the peculiar properties of sand gradually fade while those of treated material override the former.

From these results, the relationships of cohesion, c_d, and internal friction angle, ϕ_d, with the curing time are drawn in Fig.10. In all cases, c_d and ϕ_d are increased with the curing time, and the increase in c_d is especially prominent. This clearly indicates that the effect of "additing cohesion to sandy soil", which is the feature of the premixing method, appears quickly even at young age. It may be concluded that the earth pressure reduction is expected at the early stage of filling works.

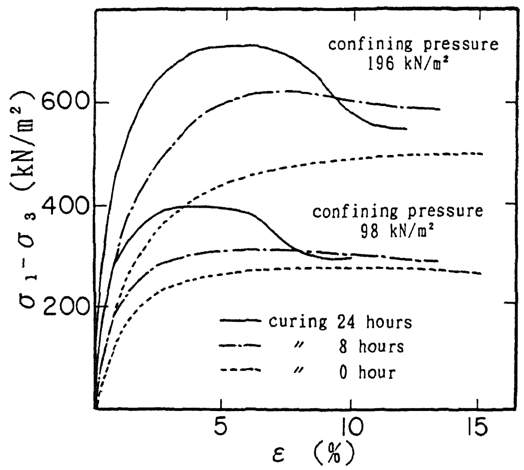

Fig.9 Stress-strain curves

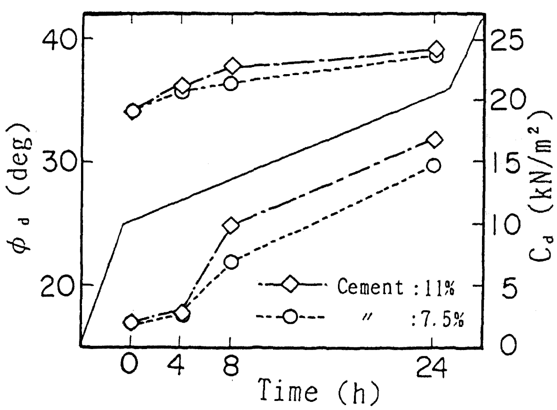

Fig.10 Comparisons of strength constant

5 CONCLUSION

The principal conclusions drawn from the present study are as follows:

1. The liquefaction-free ground can be successfully constructed by using cement-treated sand fill. In the shaking table test, only 1% of cement-mixing was sufficient to prevent the liquefaction from the applied acceleration up to 250 gal.
2. The acceleration in the treated ground was about 3 times smaller than that in the untreated ground where the liquefaction occurs.
3. The results of shaking table tests suggest that the cement content tentatively proposed to use to prevent the liquefaction, say about 5%, may be reduced by another several percentage points.
4. It was found from triaxial compression tests at young age that the cementation effect of treated sand appears from a fairly early time(within 24 hours).

ACKNOWLEDGMENT

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