Dynamic Strength of Saturated Cohesive Soil

Résistance Dynamique du Sol Cohérent et Saturé

S.OGAWA Associate Professor, Department of Civil Engineering, Niigata University,
T.SHIBAYAMA Civil Engineer, Ohbayashi Gumi Ltd., Tokyo,
H.YAMAGUCHI Graduate Student, Graduate School of Engineering, Hokkaido University, Japan

SYNOPSIS The cyclic loading tests using the triaxial apparatus were conducted in order to obtain the knowledges on the dynamic strength of the saturated cohesive soil, especially, the effects of the confining stresses and over-consolidations. The dynamic behaviors of the cohesive soil under cyclic loading were similar to those of dense sand. But, the effective confining stress did not zero. The relationships between stress ratio ($\sigma_d/2\sigma_c$) and the number of stress cycles (Ny) were uniquely related in spite of the difference of the magnitude of the confining stress. And the effects of over-consolidation on dynamic strength were disappearing with increase of yield number. Moreover, the pore water pressures continued to increase even after ceasing of application of cyclic stress. And Cu/P obtained from the yield condition were much less than that of the static compression tests.

INTRODUCTION

Many experimental investigations have been conducted on the dynamic properties of cohesionless and cohesive soils, especially, liquefaction, dynamic modulus and damping factor of sands.

One of the first experimental works was carried by A.Casagrande and W.L.Shannon (1948) in which the transient loading were applied on clay and sand. H.B.Seed et al. (1955), F.Kawakami and S.Ogawa (1965) performed the repeated loading tests in order to obtain the knowledges on the behaviors of the subgrade under traffic loading on the unsaturated compacted cohesive soils. Moreover, H.B.Seed and C.K.Chan (1966) carrid the pulsated loading tests on the compacted silty clay having a degree of saturation of approximate of 96% in which they investigated on the strength of soils under the sustained and pulsating stress conditions involving symmetrical and non-symmetrical stress pulses and also the influences of anisotropic consolidation and magnitude of the confining stresses on failure condition of soils.

During the earthquake, the soil elements of the underground and the embankment are subjecting to a series of the shearing stresses varing in magnitude. Therefore, the effects of alternating shearing stresses varing in magnitude on the behaviors of soil should be investigated for the purposes of estimating the responses of those soil structure during the earthquake.

K.Ishihara and S.Yasuda (1972,1975) conducted the irregular loading tests in order to make clearer the effects of the time histories of stress changes on sand liquefaction. S.Ogawa (1973) made sure that the effects of the complicated alternating shearing stresses on sand liquefaction could be evaluated on the basis of results of cyclic loading tests of constant magnitude.

Although it is necessary to clarify the effects of the alternating shearing stresses varing in magnitude on dynamic behaviors of the cohesive soils, in this test program, the cyclic loading tests have been conducted with uniform deviator stresses.

The investigation described herein was intended to make clearer the influences of the confining stress and over-consolidation on the dynamic strength of the cohesive soil.

TEST PROCEDURES

The sample used in these tests was silty clay and remoulded fully at the liquid state. After that, it was consolidated in the special consolidation apparatus for 10-14 days under the constant confining pressure of 1.0 Kg/cm^2. Thus, 30 specimens having same conditions were obtained at the same time. They had a degree of saturation of 98-100%, water content of 36-39% and dry density of 1.33 Gr/cm^3.

Those specimens were re-consolidated isotropically in the triaxial cell under various confining pressure (σ_c) brfore subjecting to cyclic deviator stresses (σ_d). Therefore, water content and dry density were changed with increase of the confining pressure. For example, those of the specimens consolidated under the confining stress of 5.0 Kg/cm^2 were changed to 31% and 1.33 gr/cm^3 in average.

The over-consolidation ratio was changed by increasing back-pressure under the constant confining pressure. All tests were conducted under the undrained condition and back-pressure of 1.0-4.0 Kg/cm^2 were applied before dynamic tests.

TEST RESULTS

The behaviors of the saturated cohesive soil were similar to those of the saturated dense sand. The typical patterns of the changes in stress, strain and pore water pressure with time were shown in Fig. 1. The pore water pressures were increasing with increase of the number of stress cycles. After some stress cycles(in this case, about 10 cycles), the strain amplitudes began to increase relatively slowly. Subsequently, the strain amplitudes continued to increase still more and finally the deviator stresses began to decrease. But, the effective confining stress did not zero.

From those test results, the relationships between axial strain amplitude (ϵ_a) and the number of stress cycles (N) were obtained as shown in Fig. 2. The yield cyclic number was defined as the number of stress cycles corresponding to that of minimum radius of curvature of those curves because there were no sudden increase of axial strain as in the case of loose sand. The dotted line in Fig. 2 shows the yield criterion determined by these method.

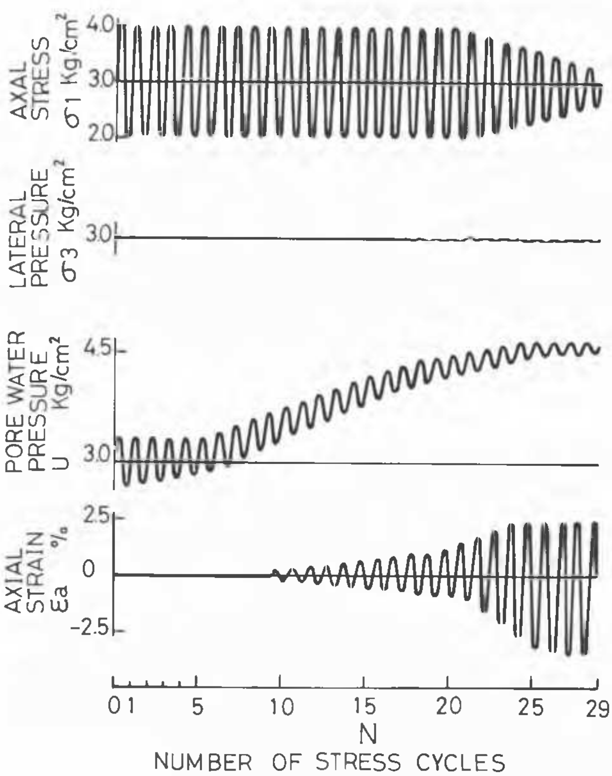

Fig. 1 Typical pattern of cyclic loading tests on cohesive soil

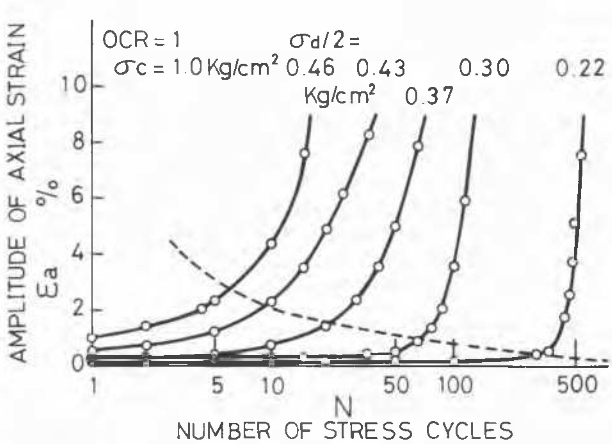

Fig. 2 Changes of axial strain amplitude with increase of the number of stress cycles

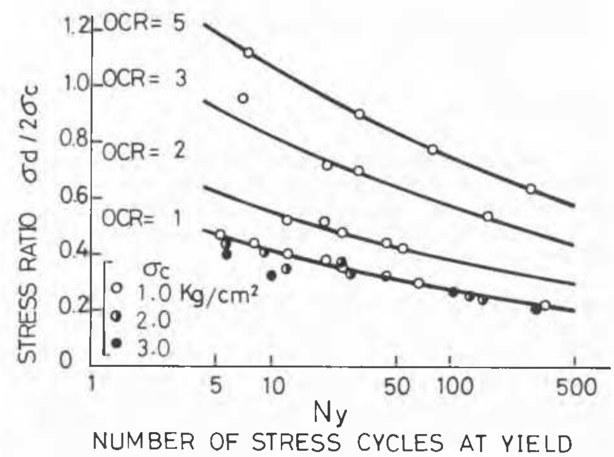

Fig. 3 The relationships between stress ratio and number of stress cycles

Fig. 3 shows the relationships between stress ratio ($\sigma_d/2\sigma_c$) and the yield cyclic number (Ny) obtained from a series of cyclic loading tests with various confining stresses and over-consolidations. Those relationships have same tendencies as those of sand. Dynamic strength (σ_d) at a certain yield number are increasing linearly with increase of the confining stress in the normally consolidated soil. Therefore, $\sigma_d/2\sigma_c$ - Ny relations of those specimens are uniquely related in spite of the difference of the magnitude of the confining stress. However, the values of $\sigma_d/2\sigma_c$ at a certain yield number are increasing with increase of consolidation ratio.

The differences of $\sigma_d/2\sigma_c$ due to the over-consolidation ratio are decreasing gradually with increase of the yield number of stress cycles. Accordingly, it is estimated that all of the $\sigma_d/2\sigma_c$ over some range of yield number of stress cycles probably shall be plotted on the uniquely defined curve.

CHANGES OF THE PORE WATER PRESSURE AFTER CEASING OF CYCLIC LOADING

As shown in Fig. 1, the pore water pressure did not rise till values equal to the confining pressure even though the specimens were under yield state. However, they were still increasing after ceasing of cyclic loading. The changes of the pore water pressure with time in the specimens which were subjected to a given number of stress cycles (Ne) are shown in Fig. 4. As a matter of course, the specimens were under yield condition defined previously.

Fig. 4 shows that the pore water pressure in the specimens are increasing towards value nearly equal to the confining stress (σ_c) after ceasing of cyclic loading. From those results, it can be considered that the underground and embankments consisted of the saturated cohesive soils and subjected to

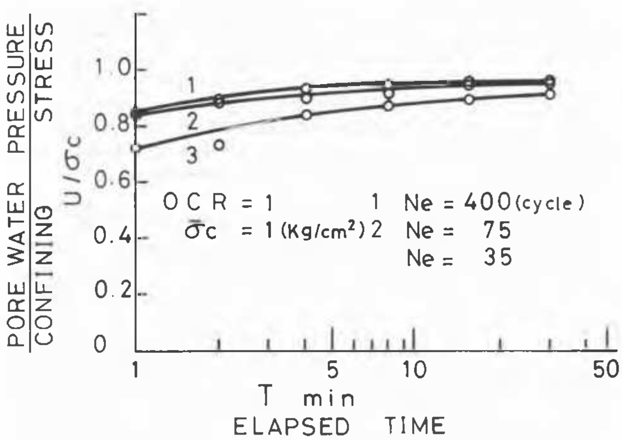

Fig. 4 Changes of the pore water pressure after ceasing of cyclic loading

the shearing stresses during earthquake may be in the range of possibility of failure even after ceasing of excitation by earthquake due to increasing of the pore water pressure and resulted decreasing of the shearing resistance even though they will not failure during the earthquake.

DECREASE OF DYNAMIC STRENGTH DUE TO STRAIN SOFTENING

Fig. 3 shows the decreasing of dynamic resistance with increase of the number of stress cycles at yield. These phenomena were outstandingly in the specimens having high over-consolidation ratio. As a reason of these phenomena. it is considered as follow; the structure of fine particles developed due to consolidation are destroyed gradually by alternating application of strain forced by external stresses.

For making more clear the decreasing of the shearing strength due to strain softening, the hysteresis loops of stress and strain are obtained from the results as shown in Fig. 5. Those loops show that the behaviors of cohesive soil are expressed by bi-linear model until some number of stress cycles which means that of yield condition. After those condition, hystresis loops have different forms from those of bi-linear model as shown in Fig. 5(3),(4). In this tests, the 53th stress cycle is the number of yield condition.

Fig. 5(4) shows that the specimen has lost these shearing resistance in the range of b-c and the relations between stress and strain become more flatter but at the extent beyond these range, the shearing resistances are still remained.

From those experimental facts, it is said as follows; The cyclical application of the shearing stresses will make the specimens softening within some strain amplitudes which are occurred by application of cyclic stresses. Therefore, the shearing resistances are decreasing and the effects of

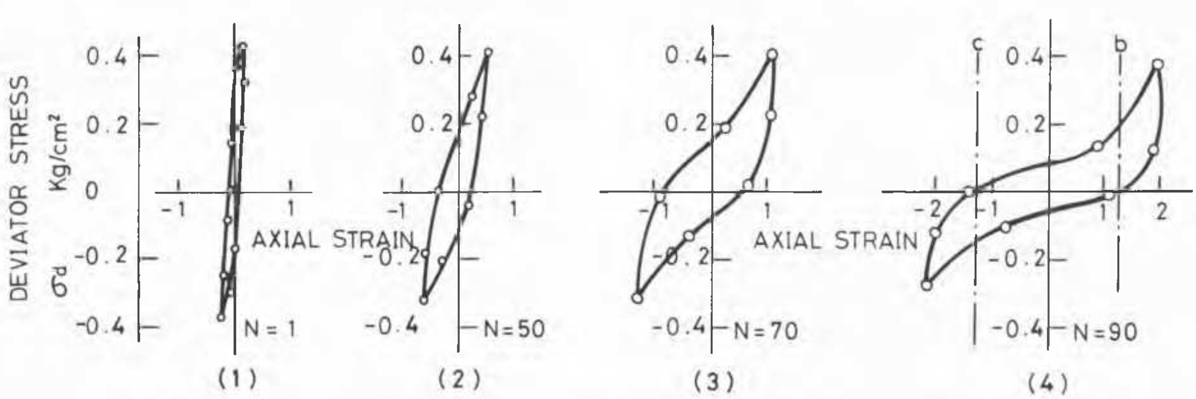

Fig. 5 Hysteresis loops of stress and strain in the cyclic loading test

over-consolidation are disappearing.

CHANGES OF Cu/P BY CYCLIC LOADING

In the static loading tests of normally consolidated soils, it is well known that Cu/P is nearly constant. In the same manner, Cu/P corresponding to a given yield number in the cyclic loading tests can be obtained as shown in Fig. 6 in which Cu is the shearing stress equal to $\sigma_d/2$ and P is the initial effective confining stress (σ_c). In this case, Cu/P in the static tests was o.46 which was larger than those obtained by other investigators.

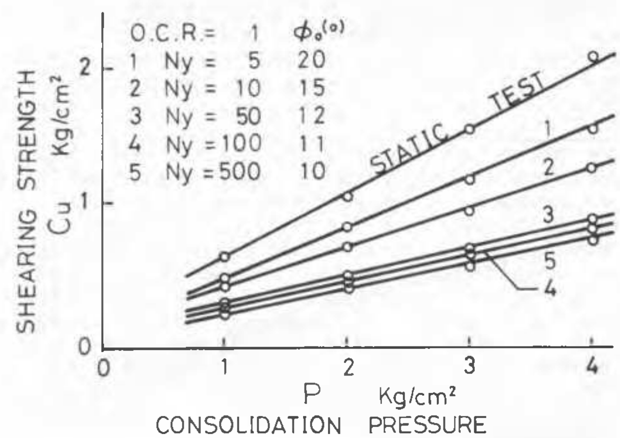

Fig. 6 Cu/P at a given yield number in the cyclic loading tests

Cu/P in the cyclic loading tests decrease as Ny increase. Therefore, it is too dangerous to evaluate the stability of the underground during earthquake on the basis of Cu/P obtained from the static compression tests.

CONCLUSIONS

The behaviors of the saturated cohesive soil under cyclic loading were similar to those of dense sand. The pore water pressures were increasing gradually with increase of the number of stress cycles. And the axial strain amplitude began to increase after some stress cycles. But, the pore water pressure did not rise till the values equal to the confining stresses and there were no sudden failure.

The relationships between $\sigma_d/2\sigma_c$ and Ny in the normally consolidated soil were uniquely related as those in the saturated sand. And the values of $\sigma_d/2\sigma_c$ at a certain yield number were increasing with increase of over-consolidation ratio. But, the effects of over-consolidation on dynamic strength of soil were disappearing with increase of the yield number of stress cycles.

As the pore water pressures in the specimens yielded during the cyclic loading tests were still increasing after ceasing of stress cycles, the underground and the embankment consisted of the saturated soil and subjected to exitation by the earthquake may break down after ceasing exitation during the earthquake.

The hysteresis loops of stress and strain under cyclic loading were expressed by bilinear model until the specimens were under the yield condition, but after yield condition, those forms were distorted.

The shearing resistances of soil were decreasing due to strain softening. Therefore, Cu/P under the dynamic condition were decreasing with increase of the yield number. From those test results, it is said as follows; it is too dangerous to evaluate the stability of the undreground and the embankment consisted of the saturated cohesive soils on the basis of Cu/P obtained from the static compression tests.

REFERENCES

Casagrande,A. and W.L.Shannon (1948), "Strength of Soil under Dynamic Load," Trans. ASCE, Vol. 74, No. 4, pp. 591-608

Ishihara,K. and S.Yasuda (1972), "Sand Liquefaction due to Irregular Exitation," Soils and Found., Vol. 12, No. 4, pp. 65-77

Ishihara,K. and S.Yasuda (1975), "Sand Liquefaction in Hollow Cylinder Torsion under Irregular Exitation," Soils and Found., Vol. 15, No. 1, pp. 45-60

Kawakami,F. and S.Ogawa (1965), "Strength and Deformation of Compacted Soil Subjected to Repeated Stress Application," Proc. 6th Int. Conf. S.M.F.E., Vol. 1, pp. 264-268

Ogawa,S. (1973), "Liquefaction of Saturated Sand Subjected to Complicated Alternating Shear Stress," Proc. 8th Int. Conf. S.M.F.E., Specialty Session, Vol. 4.3, pp. 452-453

Seed,H.B., C.K.Chan and C.L.Monismith, (1955), "Effects of Repeated Loading on The Strength and Deformation of Compacted Clay," Proc. Highway Research Board, Vol. 34, pp. 541-558

Seed,H.B. and C.K.Chan (1966), "Clay Strength under Earthquake Loading Condition," Jour. of ASCE, Vol. 92, No. SN2, pp. 53-78