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Change in the Stability of Slopes with Degree of Saturation

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SUMMARY A series of triaxial tests was conducted on the soil procured from the site of the actual slope failure which took place after heavy rain in Omigawa-cho about 8Ø km east of Tokyo in 1971, and its strength characters were studied under various degree of saturation. Strength parameter, cohesion and internal friction angle, thus obtaind were plotted versus the degree of saturation. It is seen that the values of both cohesion and internal friction angle decrease with increasing the degree of saturation. It seems to be affected not only by the suction but also by the amount of excess pore pressure for each degree of saturation. Stability analyses were carried out with Janbu's method using the strength parameters obtained by the laboratory tests. The result of the analysis obtained for each degree of saturation indicates that the safety factors are more than 1.5 for lower degree of saturation at ordinary times. However, it eventually becomes less than one if the degree of saturation is more than 8Ø%. Therefore, the failure of this slope can be illustrated with the increase of the degree of saturation.

1 INTRODUCTION

There have been so many slope failures due to heavy rain. They seem to be caused not only by the increase of pore water pressure in the slope with the change of the ground water level but also by the degradation of shear strength of the soil with the increase in the degree of saturation, because such reductions in shear strength have been observed for several soils by some investigators (Uno and Miyashita, 1981 ; Kutara and Ishizuka, 1982).

Some of the studies have tried to find effective stresses for partially saturated soils (Bishop and Blight, 1963 ; Karube et al., 1986). However such studies give well theoretical backgrounds to us, it seems difficult to apply the concept to practical slope stability analyses, because it is not simple to estimate the in-situ excess pore air and water pressures at failure. The study to interpret the actual slope failure is, therefore, required.

This text reports the results of the study which investigated the relationship between the strength characteristics of the soil and the degree of saturation, and analyzed the slope stability of the actual failure.

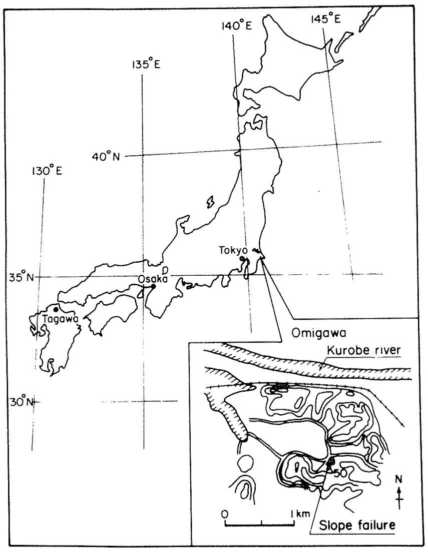

Fig.1 Location of the slope failure

2 SITE DESCRIPTION AND TESTING PROCEDURES

Several slope failures took place in Omigawa-cho about 8Ø km east of Tokyo in September, 1971 because of heavy rain (Fig.1). In the event, the total amount of rainfall during three days was 324 mm. The slope studied was on the flank of the hill about 5Ø m high and the slope failure had a cross section as shown in Fig.2, where the failure was about 32 m in height and about 9Ø m in width.

Disturbed soil sample was procured from the surface of the slope failure. The soil was shown to have a specific gravity of 2.714 and a gradation curve shown in Fig.3, and the material was identified to be a diluvial siluty sand.

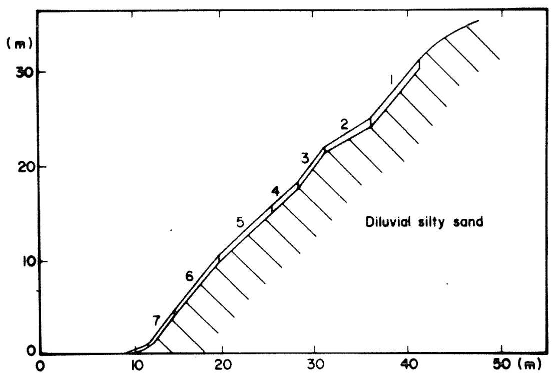

Fig.2 Cross section of the slope

The water content of the soil was first adjusted to obtain the desired degree of saturation, however there were some scatters in the degree of saturation actually obtained. The soil was then tamped in the mold to be the specimen having in-situ dry density of 1.38 g/cm^3.

Reconstituted samples prepared as above were tested in undrained triaxial compression manners with the axial strain rate of 0.45 %/min. after isotropic consolidation at 49, 78.4, and 98 kN/m^2. Some tests were also conducted after anisotropic consolidation for the comparison purpose. In the tests common porous stones and filter papers were used at both ends of the sample.

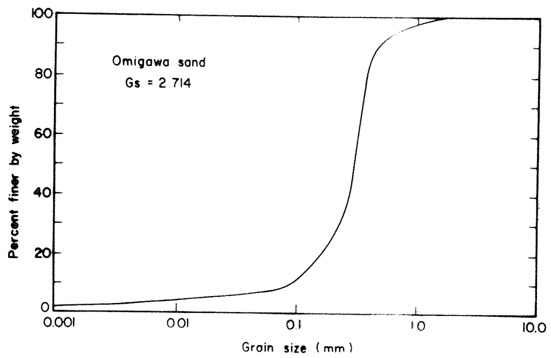

Fig.3 Grain size distribution curve of the soil

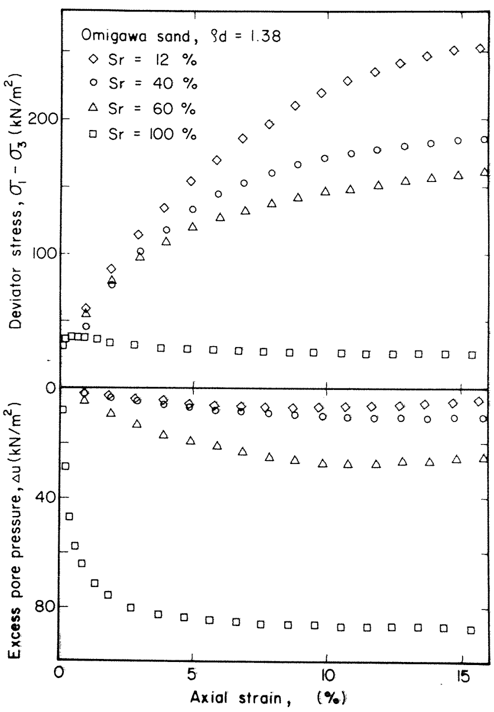

Fig.4 Deformation of isotropically consolidated samples of different degree of saturation

3 TRIAXIAL TESTS ON ISOTROPICALLY CONSOLIDATED SAMPLES

Figure 4 shows some of the test results on the samples which had the degree of saturation of 12, 40, 60, and 100 % respectively and were isotropically consolidated at 98 kN/m^2. The excess pore pressure shown in the figure may be an excess air pressure, since the pore pressure was measured through the rough porous stone (Bishop and Donald, 1961).

It is observed that the deviator stress becomes smaller and the excess pore pressure becomes larger at all strain levels as the degree of saturation increases. In this study the failure was determined by the stress condition at the axial strain of 15 % except for the tests on saturated samples. In case of the saturated sample, the stress condition at maximum deviator stress was chosen as the failure stress.

The stress conditions at failure were plotted in Fig.5 in the form of total stresses. A numeral beside the symbol denotes the degree of saturation of each specimen. It may be seen from this figure that the shear strength of the soil decreases as the degree of saturation increases. It becomes then possible, although there are some scatters among the data, to draw the several lines of failure condition for the each degree of saturation.

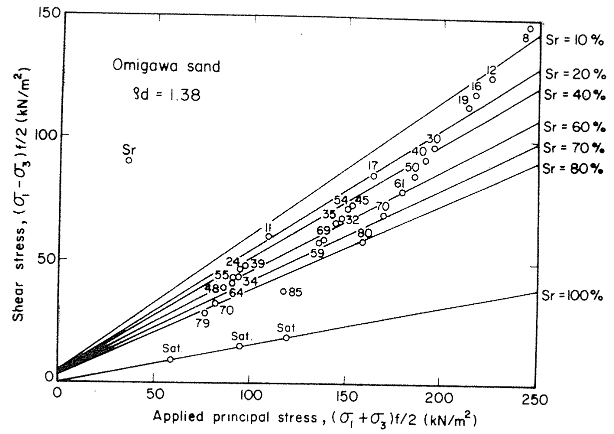

Fig.5 Total stress conditions at failure

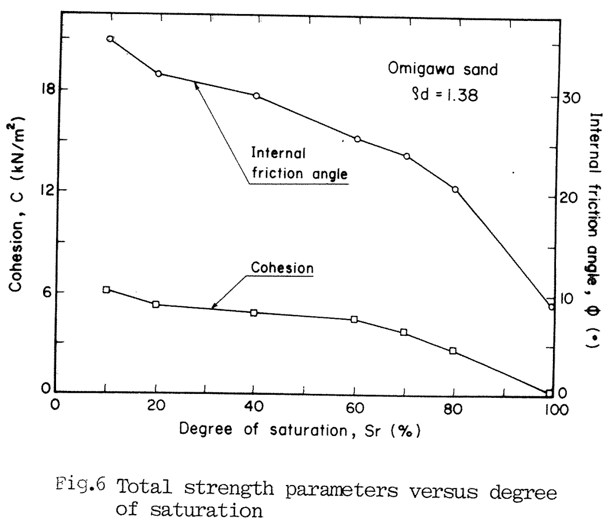

Fig.6 Total strength parameters versus degree of saturation

Strength parameters, c and ϕ , were determined from the above failure lines and plotted versus the degree of saturation as shown in Fig.6. It is noticeable that the strength parameters decrease with the increase in the degree of saturation especially for the higher degree of saturation between 8Ø to 1ØØ %. Uno and Miyashita (1981) reported that, as the degree of saturation increased, the cohesion decreased especially in sandy soils, while both the cohesion and the internal friction angle of the soil with fines decreased. In case of the soil investigated in this study, however it contained little fines, both the cohesion and the internal friction angle determined in the total stresses decreased with the degree of saturation.

4 SLOPE STABILITY ANALYSES

Slope stability analyses were conducted for the cross section shown in Fig.2 using Janbu's method (1955). In the analysis it was assumed that the degree of saturation had changed uniformly in the slope with the seepage, and the unit weight and the strength parameters were changed according to the degree of saturation of the slope. Total stress analysis was carried out assuming there had not been pore pressure prior to the failure.

The factor of safety obtained in the slope stability analysis was plotted in Fig.7 versus each degree of saturation. It is seen that the safety factor shows higher value of more than 1.5 and it decreases gradually with the increase of degree of saturation for the lower degree of saturation up to about 6Ø %. However, the factor of safety decreases rapidly for the higher degree of saturation, and eventually becomes less than 1.Ø if the degree of saturation is more than 8Ø %. Therefore, the slope failure due to heavy rain can be illustrated with the increase in the degree of saturation.

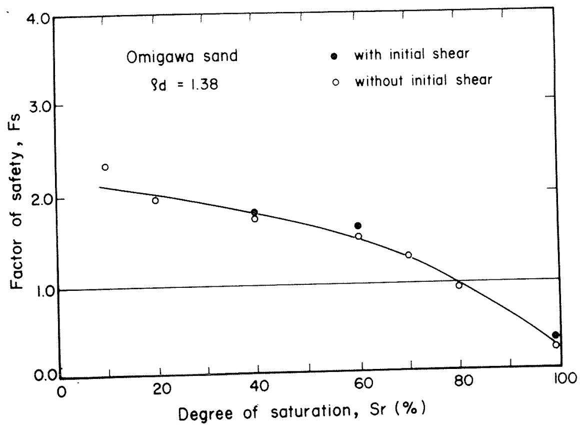

Fig.7 Relationship between the factor of safety and the degree of saturation

5 TRIAXIAL TESTS ON ANISOTROPICALLY CONSOLIDATED SAMPLES

It has been discussed before about the undrained triaxial test results on isotropically consolidated samples. However, such isotropic stress condition is not necessarily appropriate for the slope stability problem, since a soil element in the slope is bjected to the shear stress even at ordinary times. Terefore, some undrained triaxial tests were also conducted on the samples which were sheared in drained condition initially up to 7Ø % of the shear strength after the isotropic consolidation, where 7Ø % of the initial shear corresponds to the factor of safety of about 1.5.

The stress conditions at failure were plotted by black circles in Fig.8 in terms of total stresses and the failure lines were drawn for the degree of saturation of 4Ø, 6Ø and 1ØØ %, respectively. The test results on the isotropically consolidated samples denoted by white circles were also plotted for the comparison purpose.

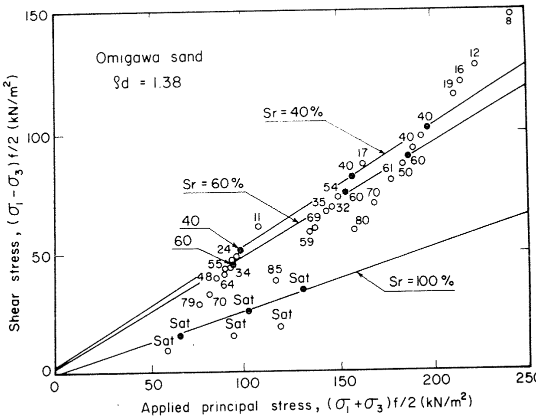

Fig.8 Total stress conditions at failure

It may be seen that the initially sheared sample shows higher shear strength than that of the isotropically consolidated sample and the extent of the increase in the shear strength is higher for the sample which has the higher degree of saturation. As the results, the cohesion, c, of the sample consolidated anisotropically was almost the same as that of the sample consolidated isotropically. However, the angle of internal friction, ϕ, was larger by about 1.Ø to 6.Ø degrees for the initially sheared sample than that of the isotropically consolidated sample.

Black circles in Fig.7 denote the factors of safety calculated by using the shear strength parameters obtained as above. It is seen that such a factor of safety gives the slightly higher value than the corresponding value of the factor of safety calculated by using the shear strength of isotropically consolidated sample of the same degree of saturation. Since the slope failure studied was a shallow one, the difference in the factors of safety is not sizable between the values calculated for respective conditions with the same degree of saturation. If the slide surface has a more depth, however, the factor of safety may be affected more by the increase in the angle of internal friction.

6 EXCESS PORE PRESSURE IN PARTIALLY SATURATED SOILS

The stress paths were plotted from the test results of undrained triaxial tests on isotropically and anisotropically consolidated samples which had the degree of saturation of 4Ø, 6Ø and 1ØØ %, respectively, as shown in Fig.9 to compare the behavior of the soils during shear. The abscissa of Fig.9 represents the toatal mean principal stress minus the excess pore pressure. However the measured excess pore pressure might be the excess air pressure

(Bishop and Donald, 1961), it has the similar meanings as the effective mean principal stress. The white circles denote the stress conditions at failure of the isotropically consolidated samples. The black squares indicate the stress conditions at failure of the samples which were sheared in undrained condition after the application of the initial shear stress under drained condition up to 70 % of failure stress.

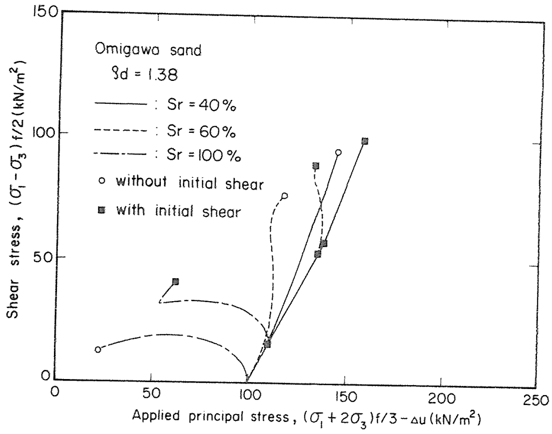

Fig.9 Stress path during undrained triaxial compression

It is observed in Fig.9 that the excess pore pressure generated in the anisotropically consolidated sample during undrained shear was smaller than that of isotropically consolidated sample. Difference between two generated excess pore pressures was greater for the sample which had higher degree of saturatation. As the result of such difference in the characteristics of pore pressure generation, the strength of soil showed higner value for the initially sheared sample with the lower degree of saturation. Therefore, the factor of safety of the slope calculated using the strength parameters obtained for the anisotropically consolidated samples is slightly larger than that using the parameters derived for the isotropically consolidated samples as shown in Fig.7.

The increase in the shear strength of soil with the decrease in the degree of saturation as discussed above may also be seen in Fig.4. The amount of generated excess pore pressure increases as the degree of saturation increases, however the excess pore pressure is almost same between the samples which have the degree of saturation of 12 % and 40 %, respectively. The difference in the shear strength between these two samples may come from the difference in the suction.

The stress conditions at failure were plotted in Fig.10, where stresses were expressed in terms of total stress minus excess pore pressure. Karube et al. (1978) also plotted the stress conditions at failure in the same manner with the suction taken as a parameter. They pointed out that the failure points drew parallel straight lines for each values of suction with the exception of the results on saturated samples. It is observed in Fig.10 that the stress conditions at failure in this study is almost uniquely determined irrespective of the degree of saturation except for the test results on saturated samples, however there are some scatters among the data. Therefore, it may suggest that the strength characteristics of unsaturated soils are

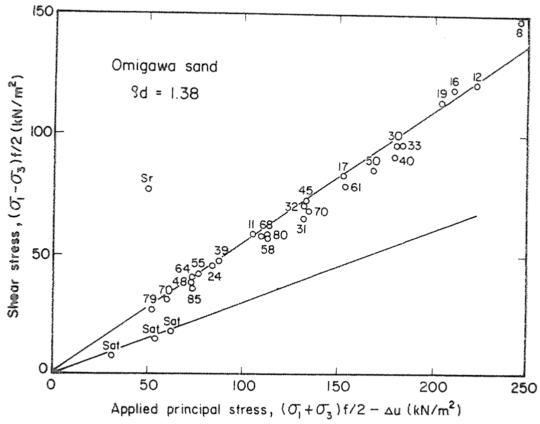

Fig.10 Stress conditions at failure in terms of total stress minus excess pore pressure

described in terms of total stress minus excess pore pressure as indicated above.

7 CONCLUSIONS

A series of undrained triaxial tests was conducted on the soils procured from the failure surface and the stability analyses were carried out using the strength parameters obtained from the laboratory tests. From the results of this study, following conclusions were obtained.

1) The strength parameters, both cohesion and angle of internal friction, decreases as the degree of saturation increases. The reduction of those values is particularly remarkable within the range of degree of saturation between 80 % and 100 %.

2) The factor of safety shows higher value of more than 1.5 for the lower degree of saturation. However, it decreases with the degree of saturation and eventually becomes less than 1.0, if the degree of saturation is more than 80 %. Therefore, the slope failure due to heavy rain can be illustrated with the increase in the degree of saturation.

3) The amount of excess pore pressure generated during undrained shear was also discussed in this paper. The stress condition at failure has a unique relationship irrespective of the degree of saturation except for the results on the saturated samples, if the stress is expressed in terms of total stress minus measured excess pore pressure.

8 ACKNOWLEDGMENT

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