Strength and Deformation of Compacted Soil Subjected to Repeated Stress Applications

Résistance et déformation du sol compacté soumis à des chargements répétés

F. KAWAKAMI, D.ENG., *Professor of Civil Engineering, Tohoku University, Sendai, Japan*
S. OGAWA, M.S., *Assistant, Tohoku University, Sendai, Japan*

SUMMARY

This paper presents a discussion of some of the mechanical properties of soil, when subjected to repeated stress applications. Repeated axial stresses are applied to compacted specimens of silty loam, clay, and three clay-sand mixtures under given confining pressures. The progressive increase in axial strain and the variation in the modulus of resilient deformation with increase in the number of stress applications during the tests are recorded.

From the results of unconfined compression tests conducted on specimens subjected to repeated stress applications, the curves of stress *versus* rate of strain increase are drawn. These are analysed by comparison with the mechanical properties of the rheological model whose behaviour is similar to that of specimens during a repeated loading test. From these relationships the yield stress and the modulus of elasticity are obtained. Finally, the relationships between the confining stress and the axial strain, modulus of resilient deformation, yield stress, and the modulus of elasticity are discussed.

SOMMAIRE

Ce mémoire a pour but de traiter de quelques propriétés du sol à des chargements répétés. On a appliqué des contraintes axiales sur un spécimen compacté et composé d'argile limoneuse, d'argile et de trois sortes de mélange argile-sable sous une certaine pression latérale. On a enregistré l'augmentation progressive de la déformation axiale et la variation du module de déformation résiliente avec la fréquence croissante des pressions appliquées au cours de l'épreuve.

En se basant sur les résultats des essais de compression simple à contraintes contrôlées, on a tracé les courbes de contrainte contre taux de déformation croissante. On a analysé ces courbes en les comparant aux propriétés mécaniques du modèle rhéologique dont le comportement est semblable à celui des spécimens au cours de chargements répétés. De ces relations, on a obtenu la limite d'élasticité et le module d'élasticité. Enfin, on a traité des relations entre l'effort de contrainte et la déformation axiale, le module de déformation résiliente, la limite d'élasticité et le module d'élasticité.

MANY STUDIES of such mechanical properties of soil, when subjected to the repeated applications of stress, as strength and deformation, have been conducted up to this time (Kawakami and Ogawa, 1963; Seed and Chan, 1957, 1958). However, more investigations are necessary to clarify the complicated properties, which are affected by the external stress, the internal structure of the soil, and other conditions.

The authors have carried out repeated loading tests on compacted specimens of soil under various confining pressures and have investigated the variations of axial strain and modulus of resilient deformation due to the repeated applications of stress. Further, they have conducted unconfined compression tests by means of stress control on specimens which were subjected to repeated stress application. From these they have obtained the yield stress and the modulus of elasticity of compacted soil by comparing the relation between the stress and the rate of strain increase obtained in the unconfined compression tests with the theoretical mechanical behaviour of a simple rheological model (Fig. 1).

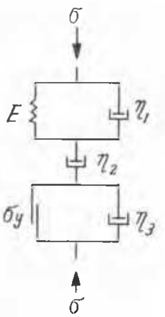

FIG. 1. Rheological model.

RHEOLOGICAL MODEL

A rheological model, whose behaviour is similar to that of soil under repeated applications of stress, is chosen, in which E designates the modulus of elasticity, η_1, η_2, and η_3 are the coefficients of viscosity, and σ_y is the yield stress. When the model is subjected to an axial compressive stress at a constant rate of increase with time ($\dot{\sigma} = \sigma/t$) the strain is given by

$$\epsilon = \frac{\dot{\sigma}}{E}\left(\frac{\sigma}{\dot{\sigma}} - \frac{\eta_1}{E}\right) + \frac{\eta_1 \cdot \dot{\sigma}}{E^2} \cdot \exp\left(-\frac{E \cdot \sigma}{\eta_1 \cdot \dot{\sigma}}\right) + \frac{\sigma^2}{2\eta_2 \cdot \dot{\sigma}} + \left[\frac{1}{\eta_3 \cdot \dot{\sigma} \cdot (n+1)} \cdot (\sigma - \sigma_y)^{n+1}\right]. \quad (1)$$

By differentiating Eq (1) with respect to time and substituting $t = \sigma/\dot{\sigma}$, the rate of strain increase is given by

$$\frac{d\epsilon}{dt} = \frac{\dot{\sigma}}{E}\left(1 - \exp\left[-\frac{E \cdot \sigma}{\eta_1 \cdot \dot{\sigma}}\right]\right) + \frac{\sigma}{\eta_2} + \left[\frac{1}{\eta_3} \cdot (\sigma - \sigma_y)^n\right]. \quad (2)$$

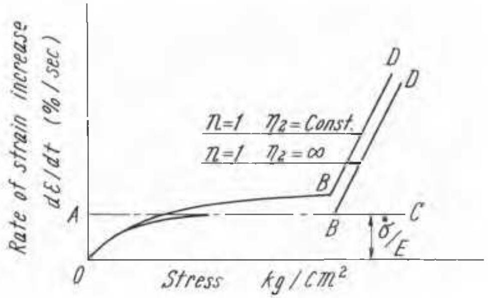

FIG. 2. Theoretical relationship of stress *versus* rate of strain increase in the rheological model.

Substituting (i) n = one, η_2 = constant, and (ii) n = one, η_2 = infinity in Eq (2), curves of σ *versus* $d\epsilon/dt$ can be drawn as shown in Fig. 2, in which the bending points are found. These points correspond to the yield point; the ordinate of the asymptote of the first term in the right side of Eq (2) (A-C line in Fig. 2) is $\dot{\sigma}/E$; and the deviations of the O-B line from the A-C line, and the inclination of the B-D line, are affected by the viscosity of the soil. From these relationships, it is easy to determine the yield stress, the modulus of elasticity, and the coefficients of viscosity of the soil.

APPARATUS AND TEST PROCEDURE

The repeated loading triaxial apparatus, which consists of an ordinary triaxial compression device and a regulating device for axial stress, can apply repeated stresses to a specimen under a confining pressure of a certain magnitude by a controlling oil circuit (Fig. 3). By adjusting the microswitch, repeated stresses of a desired magnitude or at the desired loading and unloading times can be applied. By an

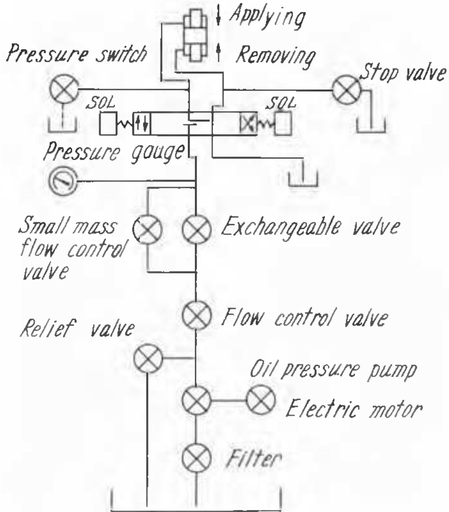

FIG. 3. Controlling oil circuit.

electrical signal from a time unit, a solenoid valve opens to admit compressed oil to the piston through the flow control valve and exchangeable valve, and the axial stress is applied to the specimen. The intensity of stress applied to a specimen is measured by a proving ring and the deformation of the specimen is measured with a dial indicator of 1/100-mm gradations.

Five soil samples were used for this investigation: silty loam, clay, and three kinds of clay-sand mixtures. The physical properties of the samples are shown in Table I.

TABLE I. PHYSICAL PROPERTIES OF SAMPLES

Sample		w_P	w_L	Optimum water content
Soil type	Symbol	(per cent)	(per cent)	(per cent)
Silty loam	A	27	68	29.4
Clay	B	31	71	32.8
Clay-sand mixture (1) (ratio by weight 4:1)	C	27	54	27.8
Clay-sand mixture (2) (ratio by weight 2:1)	D	23	32	25.5
Clay-sand mixture (3) (ratio by weight 1:1)	E	19	25	20.5

The samples were prepared to the desired water contents, stored in a damp box for more than 24 hours, and then compacted in a mould 5 cm in diameter by 12.6 cm in height. The specimens were sealed with paraffin and stored for 24 hours in an air-tight box prior to testing.

To investigate the effects of the confining stress and the axial stress on the mechanical properties of the soil, specimens were subjected to 10,000 repetitions of axial stresses of four magnitudes (0.26 to 0.77; 0.26 to 1.03; 0.26 to 1.28; and 0.26 to 2.05 kg/sq.cm.) under confining stresses of 1, 2, 3, 4, and 5 kg/sq.cm. In addition, some specimens were subjected to a repeated axial stress with an intensity of about 70 to 75 per cent of the unconfined compressive strength in order to investigate the effects of soil types on the mechanical properties. Both the loading and unloading times in these tests were three seconds. The axial strain and the resilient deformation of each specimen were measured with a dial indicator for corresponding numbers of stress applications. The ratio of the repeated stress to the resilient deformation is termed "the modulus of resilient deformation."

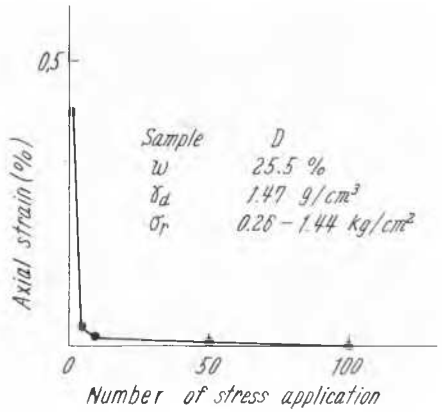

FIG. 4. Rate of strain increase in the repeated loading test.

After the specimens had been subjected to the desired applications of stress, unconfined compression tests were conducted using stress control at a rate of application of 0.018 kg/sq.cm./sec.

TEST RESULTS

Repeated Loading Tests

The axial strain of a specimen under the repeated applications of stress increases with the intensity of the repeated stress and with the number of stress applications. The rate of strain increase becomes so small that it cannot be measured with a dial indicator of 1/100-mm gradations when the number of stress applications is more than about fifty to one hundred (Fig. 4); it is inferred therefore that the coefficients of viscosity η_1 (or η_2, and η_3) in the rheological model then become extremely high. Also, the higher the intensity of repeated stress, the larger is the resilient deformation and it increases when the number of applications is greater than about five hundred to one thousand. Therefore, the modulus of resilient deformation increases when the number of stress applications exceeds about one thousand.

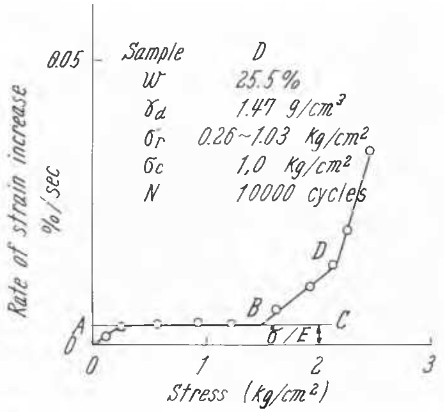

FIG. 5. Curves of σ to $d\epsilon/dt$ in the unconfined compression test.

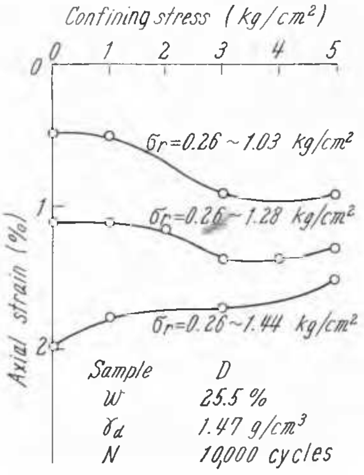

FIG. 6. Relation between the confining stress and the axial strain in repeated loading tests at different intensities of axial stress.

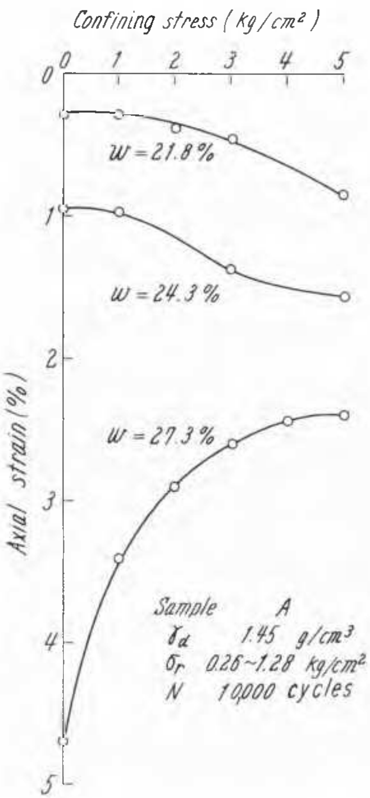

FIG. 7. Relation between the confining stress and the axial strain in repeated loading tests at different water contents.

Unconfined Compression Tests on Specimens Subjected to Repeated Loading

For specimens which have been subjected to repeated stress applications the relationships between the axial stress and the rate of strain increase (σ *versus* $d\epsilon/dt$) measured in unconfined compression tests are similar to the behaviour of the rheological model (Figs. 2 and 5) under the application of a compressive stress (Eq 2). Therefore the yield stress σ_y, the modulus of elasticity E, and the coefficients of viscosity η_1, η_2, and η_3 of a specimen subjected to repeated stress applications can be determined by comparing the results of an unconfined compression test with the theoretical properties of a rheological model. Besides, it is found that the coefficient n in the third term of Eq (2) approaches unity by the repeated applications of stress.

DISCUSSION

Effect of Confining Pressure on Axial Strain

Fig. 6 shows examples of the relation between the confining stress and the axial strain for similar specimens which were subjected to 10,000 repetitions of axial stress at three different intensities. From this figure it is found that the effect on the axial strain appears more pronounced when the confining stress is higher.

The relationship between the confining stress and the axial strain varies with the water content of the specimens, as shown in Fig. 7. The specimen of lower water content is more elastic and its residual strain increases with the intensity of confining stress, owing to the influence of this stress acting on the top of the specimen. Conversely, the specimen of higher water content is more plastic. However when it is subjected to higher lateral confining pressures it becomes more elastic, apparently as a result of increased compactness of the soil and of internal stress, and the residual strain decreases. Therefore, the variation of residual strain due to the difference of water content is smaller under higher confining pressures. As a result of the repeated applications of stresses whose intensities are 70 to 75 per cent of the ultimate compressive strength on specimens compacted at their optimum water contents, it is found that the samples of higher clay content have more absorbed water (which is required to form an electric double-layer, Lambe, 1958), less lubricating water (Proctor, 1933), and higher intergranular attraction. However, the sandy samples have less absorbed water, carrying the external force mostly by friction acting between the soil particles, and the contained water acts as a lubricant when the water contents are higher. If the confining pressure is lower the liquidity of the sandy sample becomes higher and then the residual strain is larger.

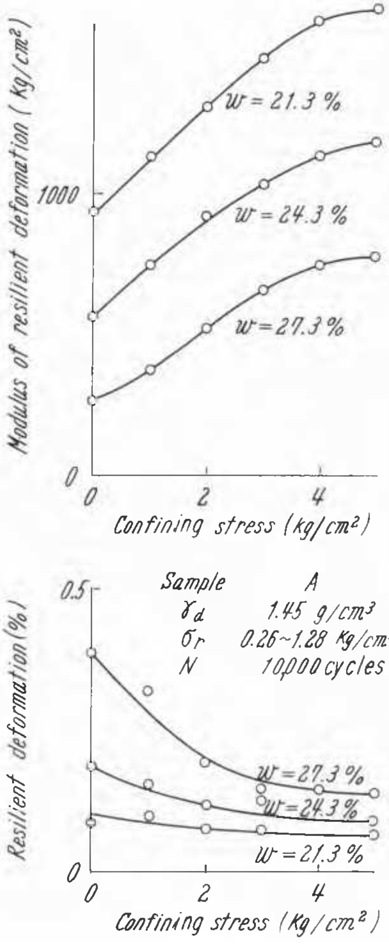

FIG. 8. Relation between the confining stress and the resilient deformation, and the modulus of resilient deformation, in the repeated loading test.

Effect of Confining Stress on Resilient Deformation and on Modulus of Resilient Deformation

When the confining pressure is high the resilient deformation usually decreases and the modulus of resilient deformation increases owing to the apparent hardening effect of the specimens. This tendency is more pronounced when the intensity of repeated stress is low. When specimens of sandy soil or soil of high water content are subjected to high confining pressures the hardening effect is more apparent, and the resilient deformation decreases and the modulus of resilient deformation increases (Fig. 8). The specimens of clayey soil exhibit less hardening effect and their modulus of resilient deformation varies little with variation in the confining stress.

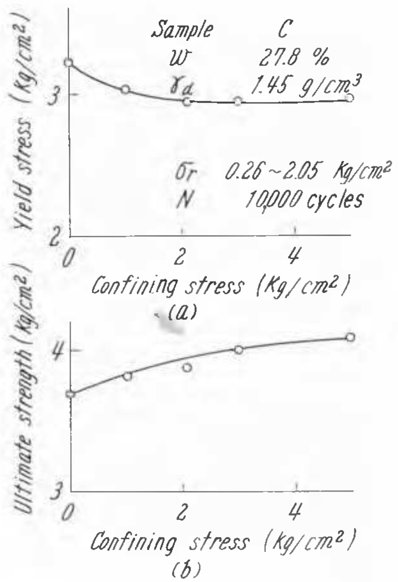

FIG. 9. Yield stress and the ultimate strength of soil after repeated loading.

Yield Stress and Modulus of Elasticity

In general the higher the repeated stress, or the larger the number of applications of stress, the higher is the yield stress. An example of the effect of the confining stress on the yield stress and on the ultimate strength is shown in Fig. 9 (a and b).

From these results it is inferred that before the specimen yields it bears the external stress by intergranular friction, and by elasticity of double layer and clay structure; after it yields, the external stress is borne by intergranular friction and viscosity, the latter influenced by the hardening effect due to the repeated stress and the confining pressure.

Fig. 10 shows the relationship between the confining stress during the repeated loading and the coefficient of viscosity of the soil after yielding (η_3 in the rheological model). The specimen of clayey soil is hardened less and the modulus of elasticity is little affected by the application of confining pressure. On the other hand, the specimen of sandy soil loses the apparent hardening effect and the modulus of elasticity decreases owing to the dispersion of internal stress, which resists the repeated stress, when it is released from the confining stress (Fig. 11).

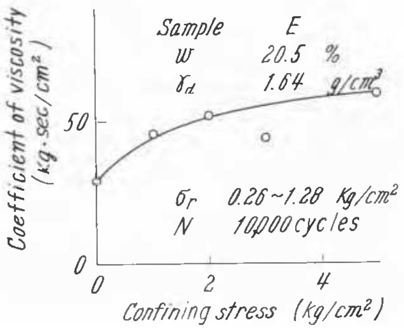

FIG. 10. Relation between the confining stress during repeated loading and the coefficient of viscosity (η_3) of soil after yielding.

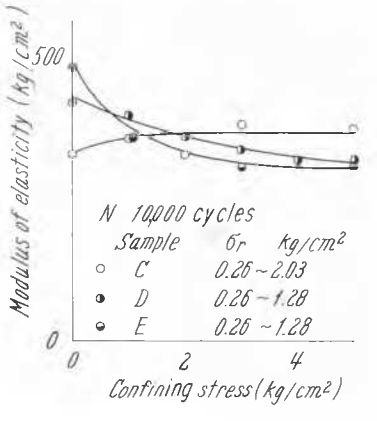

FIG. 11. Modulus of elasticity of soil after repeated loading.

CONCLUSIONS

From the test results the following conclusions can be drawn.

1. The axial strain of specimens of compacted soil subjected to repeated stresses becomes larger with the number of applications of stress and is influenced by the intensity of repeated stress, water content, density, and the confining stress during the repeated loading.
2. The higher the intensity of repeated stress and the higher the water content, the larger is the resilient deformation of the specimen under the application of the repeated loading. When the confining stress is high, the resilient deformation decreases rapidly and therefore the modulus of resilient deformation increases. The modulus of resilient deformation of sandy soil is larger than that of clayey soil.
3. By comparison with the properties of a rheological model the yield stress and the modulus of elasticity of a soil can be determined readily from the results of unconfined compression tests carried out on specimens which have been subjected to repeated stress applications.
4. In general the yield stress decreases and the ultimate compressive strength increases with the intensity of confining stress during the repeated loading test.
5. Clayey soils are not affected by confining stress but by the repeated stress, and sandy soils are little influenced when the confining stress is high.

REFERENCES

KAWAKAMI, F., and S. OGAWA (1963). Mechanical properties of soil subjected to repeated stress application. *Proc. Second Asian Regional Conference on Soil Mechanics and Foundation Engineering*, Vol. 1, Paper 1/25.

——— (1964). Yield stress and modulus of elasticity of soil. *Rheologie et Mécanique de Sols, Symposium International de Grenoble.*

LAMBE, T. W. (1958). The structure of compacted clay. *Proc. American Society of Civil Engineers*, Vol. 84 (SM2), Paper 1654.

PROCTOR, R. R. (1933). Fundamental principle of soil compaction. *Engineering News-Record*, Vol. 3, p. 245.

SEED, H. B., and C. K. CHAN (1958). Effect of stress history and frequency of stress application on deformation of clay subgrade under repeated loading. *Proc. Highway Res. Board*, Vol. 37, p. 555.

——— (1957). Thixotropic characteristics of compacted clays. *Proc. American Society of Civil Engineers*, Vol. 83 (SM4), Paper 1427.

SEED, H. B., C. K. CHAN, and C. L. MONISMITH (1955). Effect of repeated loading on the strength and deformation of compacted clay. *Proc. Highway Res. Board*, Vol. 34, p. 541.

SEED, H. B., and R. L. MCNEIL (1957). Soil deformation under repeated stress application. Conference on Soils for Engineering Purposes (Mexico City), American Society for Testing Materials, *Special Technical Publication*, No. 232, p. 177.

SEED, H. B., R. L. MCNEIL, and J. DE GUENIN (1958). Increased resistance to deformation of clay caused by repeated loading. *Proc. American Society of Civil Engineers*, Vol. 84 (SM2), Paper 1645.