Some Characteristics of the Elastic and Plastic Deformation of Clay on Initial Loading

Caractéristiques des déformations élastiques et plastiques de l'argile au chargement initial

J. K. MITCHELL, *Associate Professor of Civil Engineering and Associate Research Engineer, Institute of Transportation and Traffic Engineering, University of California, Berkeley, California, U.S.A.*

J. R. McCONNELL, *Staff Engineer, Woodward-Clyde-Sherard and Associates, Oakland, California, U.S.A.*

SUMMARY

The nature of elastic deformation in clays is discussed and it is postulated that the elastic response should be non-linear, delayed, and greatly influenced by soil structure. An experimental programme is described wherein measurements of recoverable deformation as a function of load duration were used to estimate the magnitude of elastic strain accompanying the initial loading of specimens of compacted kaolinite. In one series kneading compaction was used to produce a dispersed structure and in another static compaction was used to yield a flocculent structure.

The results showed that the instantaneous deformation was non-linear with respect to stress, that a considerably greater part of the total deformation is elastic in the case of flocculent soil structures than in the case of dispersed structures, that some irrecoverable deformation accompanies load application, even at low stress levels, and creep of the soil structure under sustained stress causes a part of the elastic deformation to relax and become plastic deformation.

SOMMAIRE

On discute, dans cette communication, de la nature des déformations élastiques et on pose, au départ, que le comportement est non-linéaire, retardé et influencé fortement par la structure du sol. Un programme expérimental est décrit où des mesures du recouvrement des déformations en fonction de la durée de chargement sont utilisées pour déterminer la grandeur des déformations élastiques conséquentes au chargement initial d'une kaolinite compactée. On a utilisé dans une première série d'essais un compactage par pétrissage pour produire une structure dispersée et pour d'autres séries d'essais, un compactage statique pour donner une structure flocculée.

Des résultats obtenus, on conclut que les déformations instantanées sont non linéaires en fonction des contraintes, que pour un sol à structure flocculée, une plus grande partie des déformations sont élastiques comparativement à une sol à structure dispersée, qu'une déformation permanente accompagne l'application d'une contrainte, même petite et qu'enfin, le fluage de la structure d'un sol sous charge constante permet à une partie des déformations élastiques de se transformer en déformations plastiques.

IN THE CASE OF STRUCTURES and foundations subjected to transient or repeated loads, such as highway pavements, missile launching pads, vibrating machinery foundations, radar towers, etc., it may be desirable to keep deformations within certain limits, thus taking advantage of essentially elastic behaviour and minimizing irrecoverable deformation. The use of visco-elastic or other techniques which incorporate time effects into analyses requires a knowledge of the extent of elastic and plastic behaviour of soil. In this paper the nature and mechanism of elastic response of clays to application of stress are discussed, a method for separation of elastic and plastic deformations accompanying initial loading is described, and test results are presented illustrating the application of the method and the importance of soil structure in influencing the magnitudes of elastic and plastic deformations.

THE NATURE OF ELASTIC DEFORMATION IN CLAY

Because of the wide range of bond strengths and bond orientations that may exist within any clay structure, purely elastic deformation may develop only under stresses that are very small relative to the strength, since a portion of the bonds may rupture at low stress causing inelastic deformation. However, a portion of the total deformation even under high stresses remains elastic in nature and may be of considerable importance to the deformation process as a whole.

It is likely that the elastic response of a clay should be non-linear with respect to applied stress, since the stress dependence of particle deformation may differ from that of interparticle contact deformation and both types of deformation may be operative. Clays should exhibit delayed elasticity, since effects such as atomic diffusion within particles and at contacts and viscous flow of water within pore spaces may take place subsequent to load application. Since clays exhibit creep behaviour under the action of sustained stresses, it would be expected that the elastic recovery of a specimen would be influenced by load duration. A transfer of elastic to plastic deformation may take place leading to a decrease in recoverable deformation with increased load duration. The relative importance of all of these effects should depend greatly on the soil structure.

METHOD OF INVESTIGATION

Measurement of the elasticity characteristics of clays is by no means a simple task. Wilson and Dietrich (1960) showed that sonic velocity and vibratory resonant frequency measurements are useful for evaluation of a dynamic modulus of elasticity. These methods do not allow, however, the estimation of the magnitude of elastic strain which a sample may undergo; nor can the linearity of elastic response with stress be evaluated. Static tests of two types were also described by Wilson and Dietrich. In one case a specimen was subjected to incremental loading and the "instantaneous" strain under each load was determined and designated as elastic strain. In the second type of static load tests a sub-failure stress is repeatedly applied until the strain on reloading becomes constant, or the specimen is allowed a long period of creep followed by unloading and then reloading. This approach has a disadvantage in the necessity for pre-stressing the specimen, so that the elastic response upon first loading becomes obscured.

Seed, Chan, and Lee (1962) used repeated loading techniques for the determination of the total and resilient deformation characteristics of compacted clays. This approach provides an excellent means for study of the change in elastic properties that may result from large numbers of stress applications, as would be the case for a pavement subgrade, for example.

In the present investigation the initial elastic response of specimens was of interest and a technique for separation of elastic and plastic effects was desired. Since a load cannot be instantaneously applied, the measured initial deformation may contain an inelastic component. Thus recovery after load removal would appear more representative of true elastic behaviour than would the initial deformation. The use of recoverable strain is complicated, however, by the fact that a transfer of elastic to plastic strain may take place during the time the load is acting. What is really desired is the elastic recovery that would occur if the load did not act for any finite time.

Therefore, specimens of compacted kaolinite were prepared and tested at different magnitudes of deviator stress. Each specimen was subjected to a single load pulse of

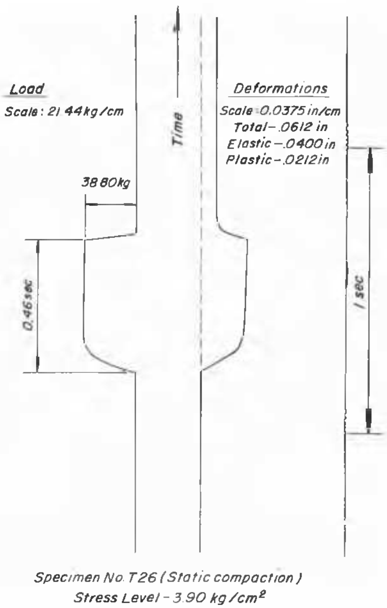

FIG. 1. Typical load *vs.* time and deformation *vs.* time data for compacted kaolinite.

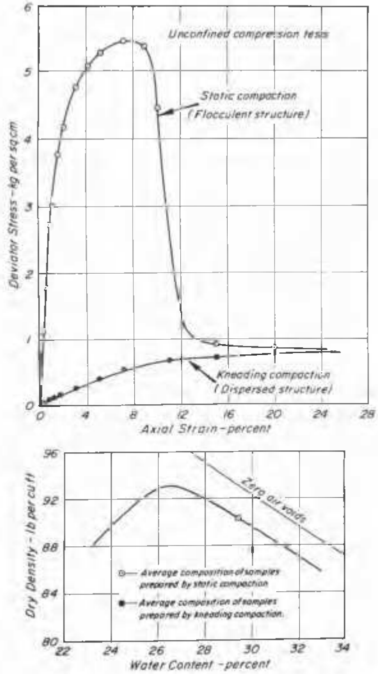

FIG. 2. Compaction conditions and stress-strain characteristics for samples of kaolinite used in study.

different duration in the range 0.06 to 1.50 seconds using the repeated loading apparatus described by Seed and Fead (1960). Loads were measured with a load cell and deformations were measured with a linear variable differential transformer. Ouput of the load cell and transformer was recorded on a Sanborn recorder; a typical set of data is shown in Fig. 1. By plotting the strain recovery as a function of load duration, it was possible to extrapolate to zero time of load duration, thus giving an estimate of the magnitude of elastic strain in the absence of plastic deformation. Separate specimens were used for each load duration to eliminate the possible influence of prestress effects. At the same time, however, the sample subjected to the load of shortest duration was subjected to additional pulses of increasing duration to see if a plot of recovery *versus* cumulative load duration would give essentially the same result as was obtained from the measurements on separate samples.

Specimens of kaolinite having both flocculent and dispersed structures were tested. The structure of this material is very sensitive to method of compaction when specimens are compacted wet of optimum moisture content. Seed and Chan (1959) have shown that a shear-strain–inducing method of compaction such as kneading yields a dispersed particle arrangement; whereas static compaction which does not induce large amounts of shearing strain results in a flocculent structure. Fig. 2 shows the compaction conditions and stress *versus* strain curves for the specimens prepared by the two compaction methods.

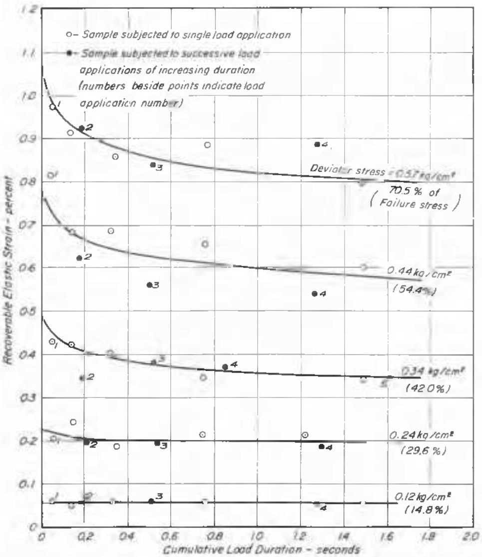

FIG. 3. Recoverable strain as a function of load duration for samples of kaolinite with dispersed structure (kneading compaction).

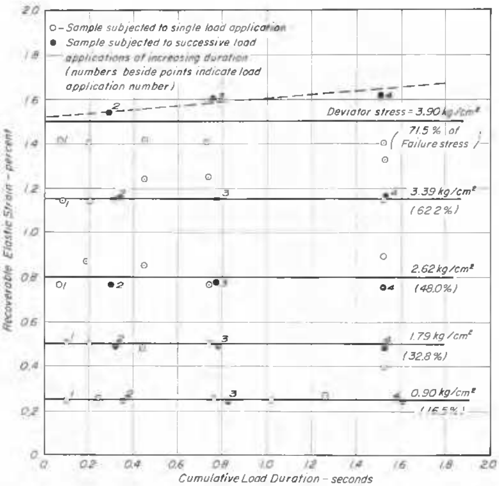

FIG. 4. Recoverable strain as a function of load duration for samples of kaolinite with flocculent structure (static compaction).

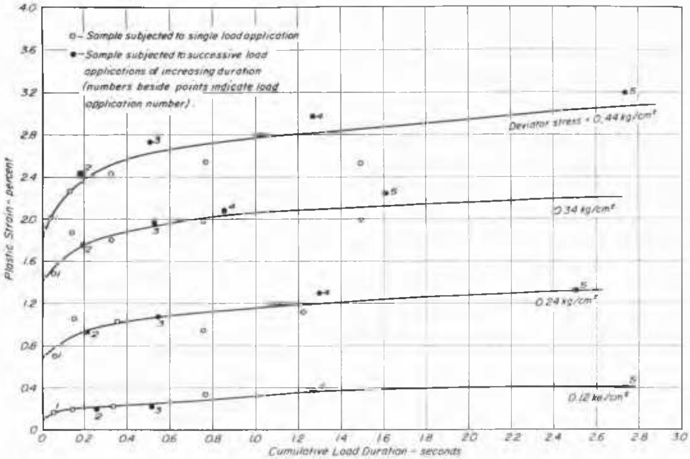

FIG. 5. Plastic strain as a function of load duration for samples of kaolinite with dispersed structure (kneading compaction).

RESULTS AND DISCUSSION

The recoverable elastic strain as a function of load duration at five different stress levels is shown in Fig. 3 for samples having a dispersed structure (kneading compaction). The data clearly show (for stress levels greater than 14.8 per cent of the unconfined compression strength) that the recoverable strain decreases as load duration increases, thus illustrating the transfer of elastic to plastic deformation as a result of stress relaxation within the specimen. The results show that the higher the stress intensity, the more pronounced the effect and also that the rate of transfer from elastic to plastic strain decreases with increasing load duration.

Fig. 4 presents similar data for specimens prepared by static compaction and having a flocculent structure. In this case the recoverable strain is essentially independent of load duration. This behaviour reflects the much greater rigidity of flocculent structures compared to dispersed structures and suggests that creep of the soil skeleton either does not occur after the load is initially applied (load rise time

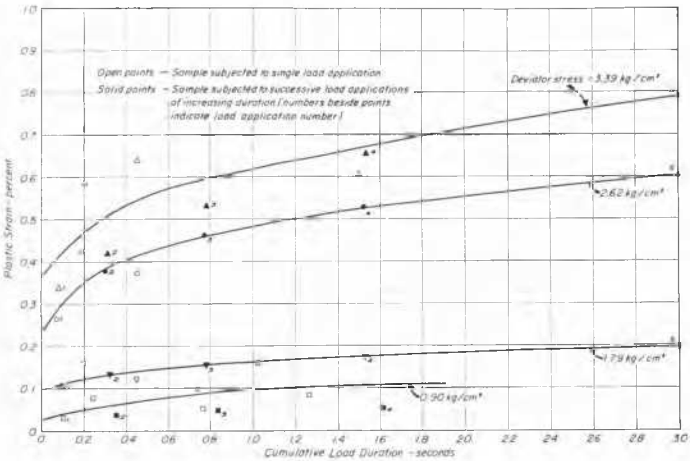

FIG. 6. Plastic strain as a function of load duration for samples of kaolinite with flocculent structure (static compaction).

of 0.07 sec. for these specimens) or that any elastic strain lost to plastic deformation after the load has been applied is balanced by a further increase in elastic strain of the intact portion of the soil skeleton. Such an increase in elastic strain might arise, for example, through the formation of new bonds after plastic flow or as a result of delayed elasticity effects. Since Fig. 6 shows that the plastic deformation does increase with increased load duration, the latter explanation would appear the more tenable.

Values of plastic strain as a function of load duration are shown in Figs. 5 and 6. Finite values for plastic deformation are shown for zero time of load duration because not all deformation was recoverable at the instant the load was fully applied. These deformations probably reflect the fact that the load could not be instantaneously applied and plastic deformation developed during the rise time rather than the possibility that plastic flow developed instantaneously.

The recoverable elastic strain values in Figs. 3 and 4 and the plastic deformation values in Figs. 5 and 6 show that essentially the same results are obtained for the case where separate specimens are used for each point as for the case where a single sample is subjected to a succession of load pulses of increasing duration. Thus, for the material studied, prestress effects do not appear of great significance.

Fig. 7 shows that the recoverable deformation of specimens with flocculent structures ranges between 60 and 90 per cent of the total deformation, whereas the recovery of specimens with dispersed structures is only of the order of 15 to 30 per cent of the total deformation. Similar behaviour has been reported by Seed, Chan, and Lee (1962) and illustrates the much greater ability of the braced-box type of particle arrangement possessed by the flocculent structures to resist stress without permanent deformations than is possible in the dispersed structure where particles are arranged in parallel arrays and have, on the average, fewer contacts with their neighbours.

Values of recoverable elastic strain assuming zero time of load duration have been plotted in Fig. 8 as a function of stress intensity. This figure shows the elastic response to be non-linear with stress as postulated earlier.

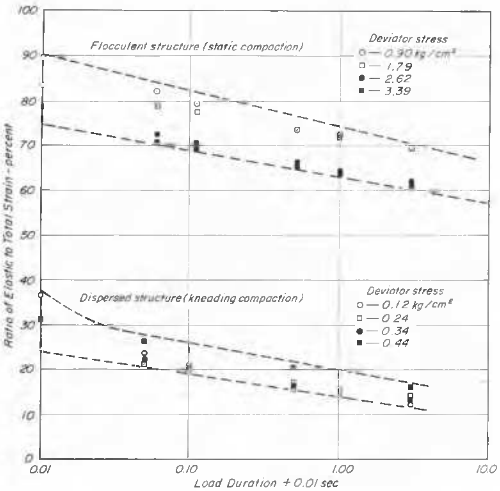

FIG. 7. Ratio of recoverable to total strain for samples of kaolinite with flocculent and dispersed structures.

In Fig. 9 the relationship between elastic strain and stress as determined by the method described herein is compared with the relationship obtained by assuming that the deformation at the instant the load is fully applied ("instantaneous" strain) represents a fully elastic response. It is clear that the "instantaneous" strain involves irrecoverable as well as recoverable deformation and results from the fact that a finite time is required for load application during which plastic flow may occur.

CONCLUSIONS

The following conclusions appear warranted:

1. The technique used for the study described herein

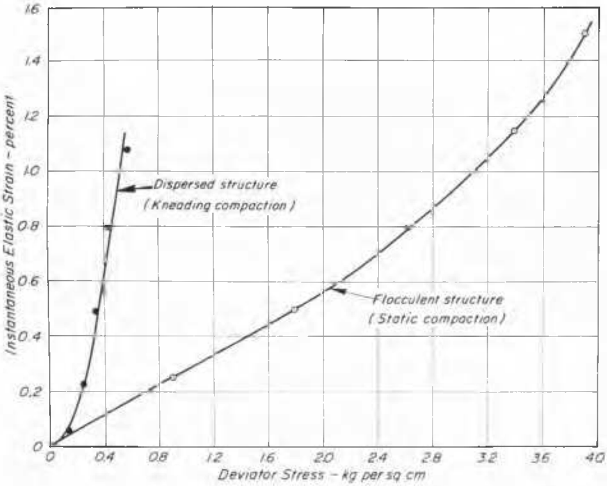

FIG. 8. The variation of instantaneous elastic strain with deviator stress for two different structures.

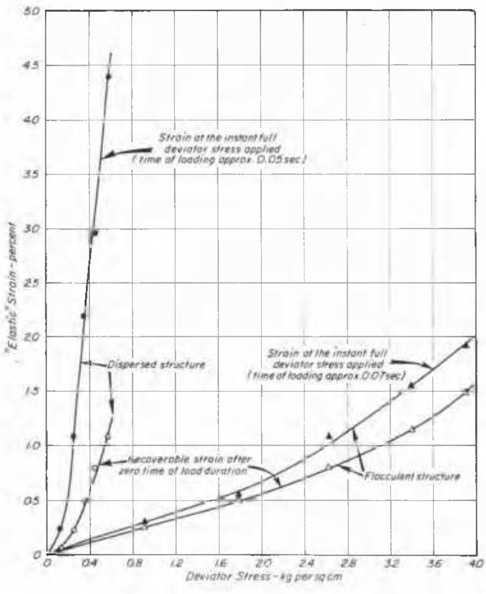

FIG. 9. Comparison between "elastic" strain determined as initial deformation and as recoverable strain at instant load fully applied.

provides a possible approach for separation of elastic and plastic deformations.

2. Some amount of irrecoverable deformation may be expected to accompany load application to most clay soils, even at stresses as low as 15 per cent of the stress required to cause failure because the wide range of bond strengths in clay means that some bonds will always rupture under very low stresses.

3. A proportionately greater part of the total deformation is recoverable in the case of flocculent soil structures than in the case of dispersed structures.

4. Under sustained stress creep of the soil structure tends to cause a transfer of deformation from a recoverable elastic type to an irrecoverable plastic type. This effect is more predominant for dispersed structures than for flocculated structures.

5. The instantaneous elastic deformation of the material studied was non-linear with respect to stress.

6. Since both elastic and plastic deformations are involved in the initial deformation of clays (as usually determined), since the relative proportions of elastic and plastic deformation vary with stress intensity, and because elastic deformation itself varies with stress intensity, computed values for modulus of elasticity may be very sensitive to method of measurement. That this is indeed the case has been shown by Seed and Monismith (1962).

REFERENCES

SEED, H. B., and C. K. Chan (1959). Structure and strength characteristics of compacted clays. *Jour. Soil Mechanics and Foundations Division*, American Society of Civil Engineers, vol. 85 (SM5), pp. 87–128.

SEED, H. B., C. K. CHAN, and C. E. LEE (1962). Resilience characteristics of subgrade soils and their relation to fatigue failures in asphalt pavements. *Proc., International Conference on Structural Design of Asphalt Pavements* (Ann Arbor, Michigan), Aug. 20–24, 1962.

SEED, H. B., and J. W. N. FEAD (1960). Apparatus for repeated load tests on soils. American Society for Testing and Materials, *Special Technical Publication*, no. 254, pp. 78–87.

SEED, H. B., and C. L. MONISMITH (1962). Strength evaluation of structural elements. Moderator's report, Session V, *Proc. International Conference on Structural Design of Asphalt Pavements* (Ann Arbor, Michigan), Aug. 1962.

WILSON, S. D., and R. J. DIETRICH (1960). Effect of consolidation pressure on elastic and strength properties of clay, *Proc. American Society of Civil Engineers*, Research Conference on Shear Strength of Cohesive Soils, pp. 419–35.