Effect of Duration of Stress Application on Soil Deformation Under Repeated Loading

Effet de la durée d'application des contraintes sur la déformation d'un sol soumis à des chargements répétés

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Summary

Test data are presented to show the effect of durations of stress applications ranging from one third second to twenty minutes on the deformation of a silty sand subjected to repeated loading ; similar results for durations of stress application ranging from one third second to twelve hours are presented for a silty clay. It is shown that for the silty sand with intervals between stress applications up to two minutes, increased durations of stress application result in increased deformation. On the other hand, for the silty clay, increased durations of stress application may result in increased or decreased deformations depending on the interval between applications. Deformations occuring in both sands and clays under repeated stress applications are shown to be influenced by phenomena occurring during intervals between stress applications ; for the silty clay these include creep effects, thixotropy, stiffening due to repeated loading and probable loss of resistance due to separation of clay particles during unloaded periods. It is concluded that it is necessary to consider the overall function and traffic pattern for a pavement if data from repeated load tests are to be used to obtain satisfactory estimates of probable pavement deflections.

Sommaire

Les résultats des essais, qui sont présentés ici, montrent l'effet, sur la déformation d'un sable silteux soumis à des chargements répétés, de contraintes appliquées pendant une durée variant de un tiers de seconde à 20 minutes ; des résultats analogues relatifs à des durées d'application variant de 1/3 de seconde à 12 heures sont présentés pour une argile silteuse. Ils montrent que pour un sable silteux et pour des intervalles de temps entre les applications des contraintes au plus égaux à 2 minutes, un accroissement de la durée d'application de ces contraintes produit un accroissement de la déformation. Par contre, pour une argile silteuse, un accroissement de la durée d'application des contraintes peut produire une augmentation ou une diminution des déformations selon la valeur de l'intervalle de temps séparant les applications de ces contraintes. Pour des sables ou des argiles soumis à des applications répétées de contraintes, les déformations sont influencées par les phénomènes prenant naissance pendant les intervalles de temps séparant les applications des contraintes ; pour l'argile silteuse, ces phénomènes comprennent les effets du fluage, la thixotropie, le compactage dû au chargement répété et la perte de résistance probable due à la séparation des particules d'argile pendant les périodes de non-chargement. En conclusion, il est nécessaire de considérer les conditions d'utilisation de la chaussée et le type du trafic toutes les fois que l'on veut obtenir une estimation satisfaisante des déformation verticales probables de cette chaussée, en utilisant les résultats des tests à chargement répété.

In recent years considerable attention has been given to soil behavior under repeated loading conditions. Such studies are particularly important in connection with the design of pavements but they also serve to clarify the nature of phenomena affecting the overall deformation characteristics of soils.

From a pratical standpoint, pavements may be subjected to repeated stress applications of varying magnitudes, durations and frequencies and a satisfactory design procedure requires that the resulting deformations should not exceed a tolerable limit. The influence of such factors as stress intensity, frequency of stress application and stress history and their practical significance have been described in previous publications from the Soil Mechanics Laboratory, University of California [1, 2, 3, 4, 5]. However, little attention has been given previously to the possible influence of the duration of stress application on soil behavior.

For highway pavements, durations of stress application are not likely to vary appreciably (usually some fraction of a second) when traffic is constantly in motion. However, at intersections substantially longer periods of stress application (up to several minutes) are developed while in parking areas the duration of stress application may approach several days. The present paper presents the results of studies conducted to determine the influence of durations of stress application ranging from 1/3 second to 12 hours.

During the past few years apparatus and techniques have been developed at the University of California for testing specimens of soil, representing elements of a highway subgrade, under triaxial stress conditions with repeated axial stress applications [6]. Specimens are placed in triaxial compression cells and subjected to a confining pressure of the desired magnitude, as for a normal type of unconsolidated-undrained test; but instead of slowly increasing the axial stress until the specimen fails, a constant axial stress is repeatedly applied and removed, and the progressive increase in deformation of the specimens with increase in number of stress applications is recorded. Suitable controls are provided to permit variations in intensity, duration and frequency of stress application in different tests.

Tests on silty sand—The results of a series of tests on specimens of silty sand subjected to stress repetitions of constant intensity but with different intervals between applications and different durations of stress application are presented in Fig. 1. The applied stress was about 70 per cent of that required to cause failure in a normal strength test. Fig. 1 (a) shows the deformations produced by stress applications having durations of 1/3 sec., 2 mins. and 20 mins. for a constant interval of 1/3 sec., between applications. Figs. 1 (b) and 1 (c) show similar data for tests conducted with intervals between successive stress applications of 2 mins. and 20 mins.

As might be expected, the results show that an increase in duration of stress application leads to greater deformations of the samples. However, it will be seen that the influence of the duration of stress application on the deformations of the samples varies considerably depending on the interval between applications. When the interval between applications is only 0·33 sec. an increase in duration of stress application from 0·33 sec. to 2 mins. has an enormous affect on the resulting deformations. However, the effect of the same variation in duration of stress application is markedly reduced when the interval between applications is increased to 2 mins. and becomes very small when the interval between applications is 20 minutes.

In view of the fact that the strength and deformation characteristics of sands are customarily considered to be essentially physical in nature, it is somewhat surprising that the interval between load applications, when the sand is apparently unstressed, would have any appreciable influence on the results. However, a comparison of the data in these figures shows that some phenomenon occuring durring this unloaded period is apparently largely responsible for the differences in results obtained.

Thus, for example, a comparison of the test data for specimens subjected to stress applications of the same duration but with different intervals between applications is presented in Fig. 2. When the duration of stress application is short, an increase in the interval between applications can lead to

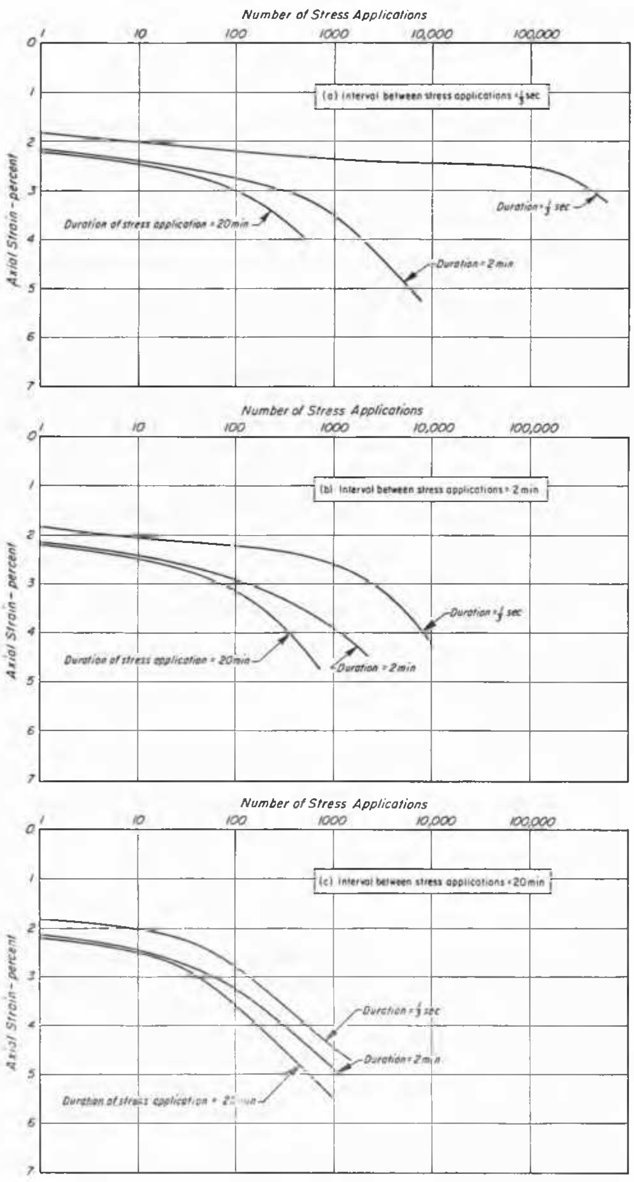

Fig. 1 Effect of Duration of Stress Application on Deformation Deformation of Silty Sand.

Effet de la durée d'application de la contrainte sur la déformation d'un sable silteux.

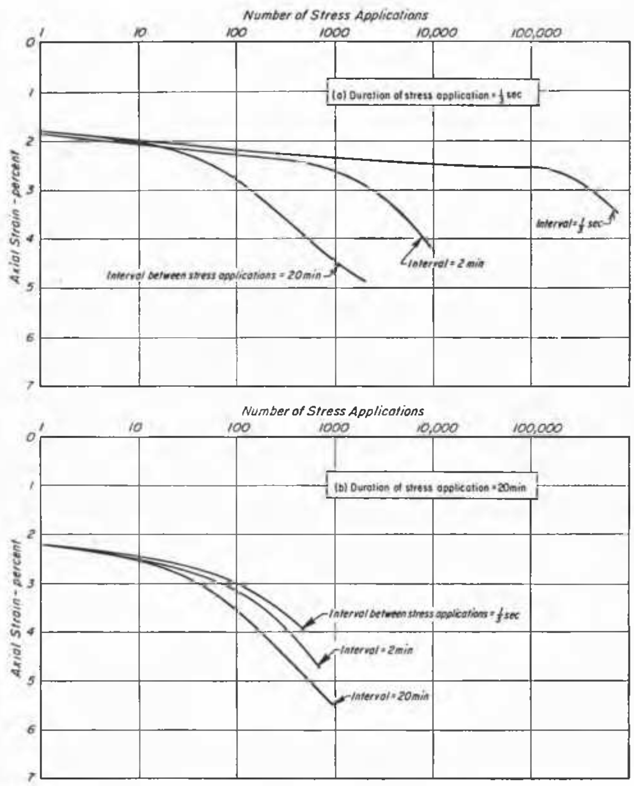

Fig. 2 Effect of Interval Between Stress Applications on Deformation of Silty Sand.

Effet de l'intervalle de temps entre les applications des contraintes, sur la déformation d'un sable silteux.

very large increases in deformation of the samples. For stress applications of longer duration, the same type of effect but of much smaller magnitude is observed. Since the stress intensity and period of application are identical in these cases, the differences must necessarily result from changes occuring in the intervals between stress applications.

Differences in rebound with time would tend to result in smaller deformations with longer intervals between stress applications — the reverse of that observed in the tests. Thus the cause of the effect is not immediately apparent. It appears possible that adsorbed water layers on the surface of sand particles may influence the deformation characteristics of these soils as they do for clays. Thus, for example, application of a deviator stress may result in high stress intensities at points of contact between particles, causing adsorbed water films to be displaced and resulting in essentially true mineral contact between particles. Such contact would produce high frictional resistance to relative displacement. When the stress is removed, the displaced water film may require time to regain its original condition, so that if a second stress application is applied after a very short interval, high frictional resistance will immediately be developed. On the other hand, a long interval between stress applications would permit more complete re-establishment of the water film and a somewhat reduced frictional resistance, leading to relatively larger deformations such as those observed in the tests. Clearly intervals between stress applications exceeding that required for essentially complete re-development of the moisture film would have little influence on the results, suggesting that the effect of interval between applications would decrease with increasing magnitude of the intervals.

In addition to illustrating the complex effect of duration of stress application on the deformation of sands under repeated loading and its dependence on frequency of stress application, it is believed that these results provide evidence of the probability of a stress history effect in sand which must be considered when dealing with short term periods of stress application.

Tests on compacted silty clay—Consideration of the nature of clay soils would indicate that the influence of duration of stress application on the deformations occuring during repeated loading would be more complicated than for sands. This is illustrated by the test data presented in Fig. 3, obtained in a series of tests on a compacted silty clay. Samples were prepared by kneading compaction and stored at constant composition for a period of 2 weeks prior to test. The effects of variations in duration of stress application for constant intervals between applications of 1/3 sec., 2 min. and 12hours are shown in the figure.

It will be seen that for a short interval between stress applications (say 1/3 sec.) the results are quite different from those obtained in tests on sand, but for long intervals between applications the nature of the effect of duration is quite similar. Furthermore it may be noted from Fig. 4 where the same data is replotted to show the influence of interval between stress application for durations of stress application of 0·33 sec. and 12 hours, that the effect of the interval between applications reverses itself completely as the duration of stress application increases. For stress applications of short duration, an increased interval between applications causes a reduction in deformation; for stress applications of long duration, an increased interval between applications causes an increase in deformation.

Consideration of the nature of compacted clays reveals that the variations in effects of different combinations of duration and frequency of stress applications are likely to be influenced by various phenomena including :

(1) an increase in deformation with time under load due to creep effects;

(2) an increase in resistance to deformation with time due to thixotropy. Compacted clays have been shown to possess substantial thixotropic characteristics [7]. Thus as the interval between stress applications (or in some cases the duration of stress application) increases, the clay will regain some of the thixotropic strength lost during deformation under the first stress application, and if it had not acquired its maximum thixotropic strength at the start of the test, continue to increase due to normal thixotropic causes;

(3) an increase in resistance to deformation due to changes in structure induced by sustained or repeated stress applications. There is some reason to believe that stiffening of the clay induced by loading is due to extrusion of adsorbed water from between clay particles resulting in a small decrease in spacing at points of close proximity and a consequent increase in strength [3];

(4) a possible re-separation of clay particles to some extent during periods of unloading resulting in a decreased resistance to deformation. The phenomenon would be similar to that described in connection with sands.

Different combinations of these effects, and possibly others, could well account for the complicated effects of duration and frequency of stress application on the deformation of clays. For example, if the interval between stress

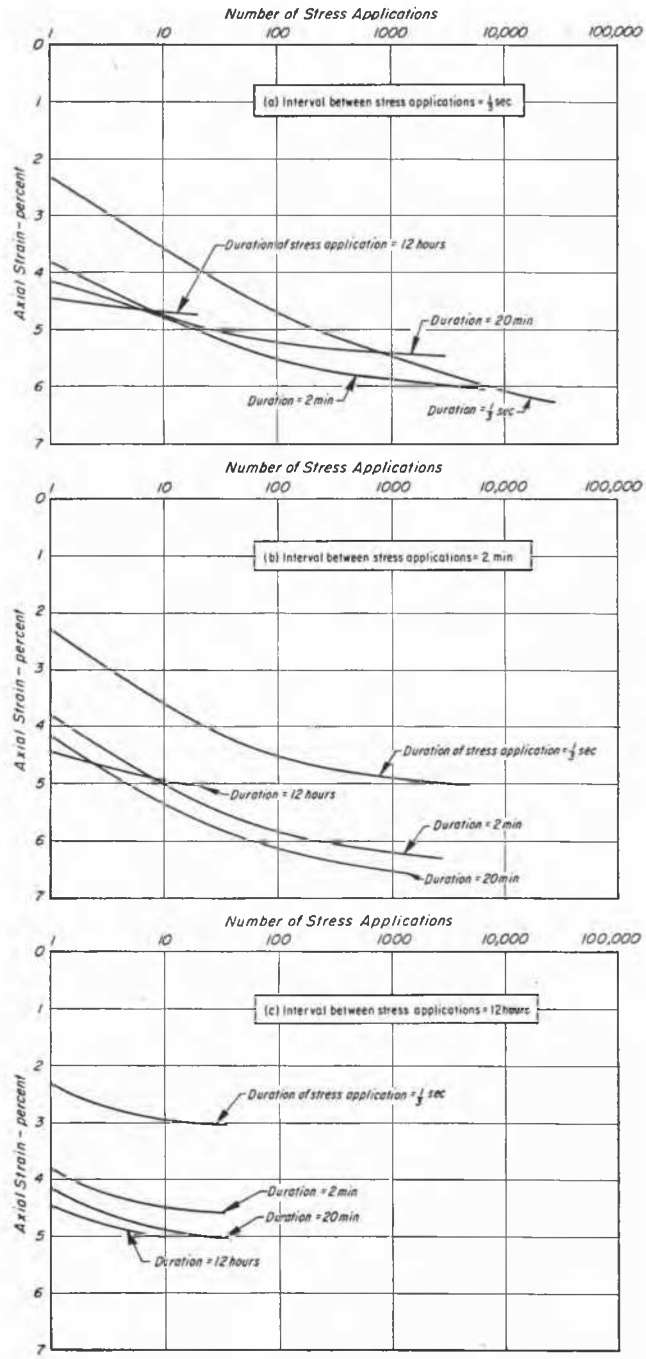

Fig. 3 Effect of Duration of Stress Application on Deformation of Silty Clay.

Effet de la durée d'application de la contrainte sur la déformation d'une argile silteuse.

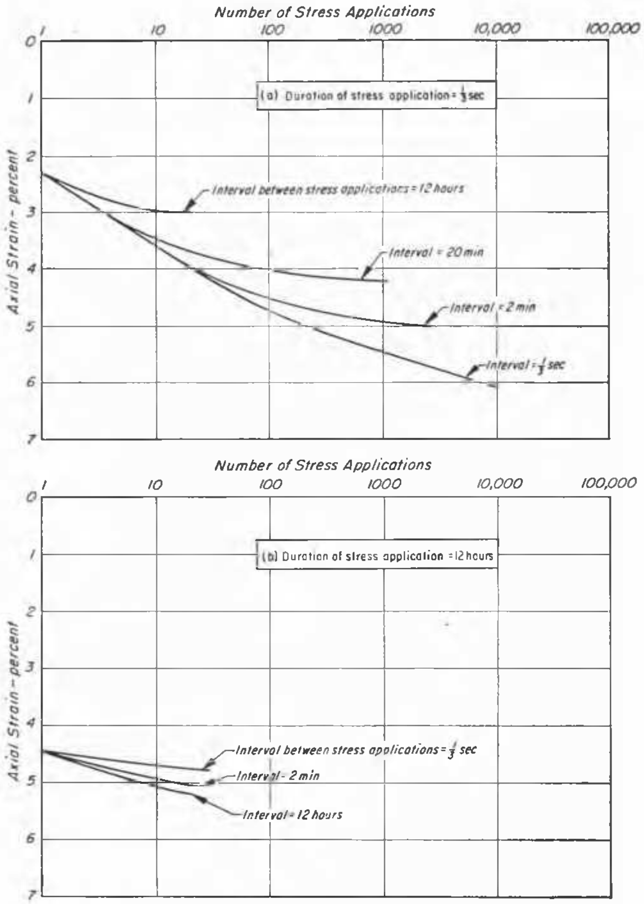

Fig. 4 Effect of Interval Between Stress Applications on Deformation of Silty Clay.

Effet de l'intervalle de temps entre les applications des contraintes, sur la déformation d'une argile silteuse.

applications is short, item (4) above would have little influence on the results and deformations would depend mainly on the combined effects of creep, thixotropy and stiffening due to stress applications. Thus for stress applications of short duration, creep would be small, resulting in a low initial deformation, but the rate of thixotropic strength regain with number of stress applications would also be small, resulting in a considerable increase in deformation as the number of applications increased. On the other hand, for stress applications of long duration, creep deformations under the first stress application would be large, but there would be time for substantial thixotropic strength regain so that the increase in deformation with number of applications might be quite small. Such effects would explain the pattern of test data shown in Fig. 3 (a).

For long intervals between stress applications the effects of thixotropic strength regain would be minimized since all specimens would have opportunity to develop resistance to deformation by this phenomenon. For the same reason all specimens would have opportunity for re-separation of particles between stress applications. Thus the deformation pattern might well be dominated by the effects of creep, resulting in greater deformations for longer durations of stress application (see Fig. 3 (c)).

Following the same reasoning, in cases where the duration of stress applications was maintained constant, creep effects and stiffening effects due to stress applications would tend to be similar for all cases and the influence of different intervals between applications might well be governed largely by thixotropy and re-separation of particles in intervals between stress applications. For short durations of stress application the effect of thixotropy would appear to govern the deformation characteristics so that short intervals between stress applications (high frequencies) permit little chance for strength regain and produce the larger deformations (Fig. 4 (a)). For long durations of stress application all samples have opportunity for thixotropic strength regain so that the re-separation of particles during intervals between stress application would tend to control the deformation pattern. Thus long intervals between stress applications would lead to greater separation of particles and larger deformations (Fig. 4 (b)).

It is hoped that this brief presentation and discussion of test data concerning the effects of duration and frequency of stress application on soil deformations will serve to illustrate the complex nature of the problem and the phenomena involved. Even for sands time effects can have a substantial influence on deformations. In Fig. 5 is shown a compilation of data which might be applicable to a lightly travelled highway, an intersection and a parking area, together with data that might be obtained in a test using relatively high frequency stress applications. It is apparent that data for any particular situation are not readily transferable to other situations and that data obtained in vibratory type studies would give an unduly safe picture of the deformations that might ultimately occur. The test data for clays presented earlier confirms the need for great care in translating deformations measured for any particular frequency and duration of loading to those occuring under different conditions.

Conclusions

On the basis of the data presented in the paper, the following conclusions may be drawn :

(1) The effect of duration of stress application on the deformation of soils subjected to repeated loading varies widely, both for sands and clays, depending on the interval between stress applications.

(2) Deformations occurring in both sands and clays under repeated stress applications are influenced by phenomena occurring during intervals between stress applications.

(3) For the silty sand investigated with intervals between stress applications up to 2 minutes, increased durations of stress application resulted in increased deformation; for

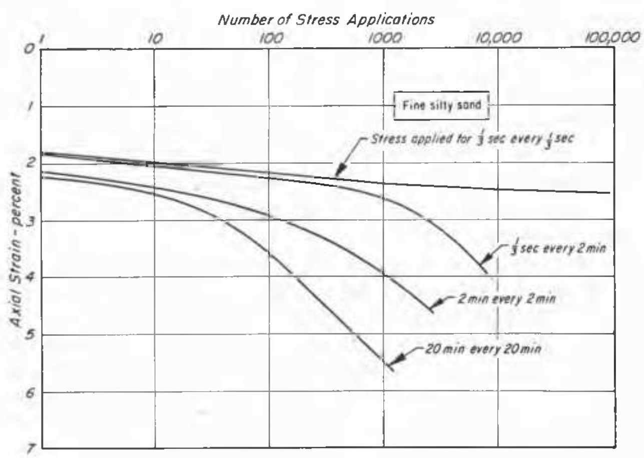

Fig. 5 Deformations of Silty Sand for Various Durations and Frequencies of Repeated Stress Applications.

Déformations d'un sable silteux pour des applications répétées de contraintes, de durées et de fréquences variées.

the compacted silty clay with intervals between stress applications up to 2 minutes, increased duration of stress application resulted in increased or decreased deformations depending on the interval.

(4) The deformations of clays under repeated loading are influenced by a variety of phenomena including creep effects, thixotropy, stiffening due to repeated stress applications and probably, loss of resistance due to separation of clay particles during unloaded periods.

(5) From a practical standpoint in the use of data obtained under conditions of repeated stress for the design of pavements, it is necessary to consider the overall function and traffic pattern for the pavement in order to arrive at satisfactory estimates of probable deflections.

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