Changes in Strength of Soils Under Earthquake and Other Repeated Loading

by

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Synopsis

When most natural soils are subjected to earthquake or other dynamic loading the resulting fluctuations in stress produce irreversible changes in pore fluid pressures. These produce long term or short term changes in soil strength. A rational model is developed based on the theory of a critical state (or critical void ratio) at failure. The response of several soil types within this model is predicted and compared with field and laboratory results. A table of recommended design guidelines is presented as a summary.

Introduction

Two approaches to engineering of soils subjected to earthquake or other repeated loading are available, a modification of the common static upper bound or limit equilibrium solution using loading factors, and by lower bound solutions requiring a constitutive equation for the soil. In the first type of analysis the problem may require selection of a soil strength under repeated loading which is different from the strength appropriate to problems involving slower rates and single applications of loading. In the second approach the problem is selection of a stress-strain relationship and also a limiting or yield strength for the soil under dynamic loading.

A great deal of effort has been directed toward studies of strength changes in particular soils under dynamic loading conditions, principally liquifaction of sand and softening of clays. Since most dynamic loading problems, certainly earthquake loadings, are of short duration, the behavior of the soil during the loading sequence is undrained. Under these conditions pore fluid pressure changes accompany the loading. In laboratory testing of soils to measure strengths appropriate to dynamic conditions, rates of loading are also rapid and under such conditions

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measuring of pore fluid pressures is difficult; consequently, most of the original research on the dynamic strength of soils, and some recent work as well, has been reported in terms of total stress. An effective stress interpretation, however, is necessary for rational design.

In this paper two recent studies of soil's response to dynamic and repeated loading are reviewed. Both were done measuring pore pressures and the resulting effective stress changes have been interpreted in very similar ways using the concept of a critical state or critical void ratio at failure. From this concept several theoretical models of behavior for various kinds of soil are developed. In conclusion, examples of field or experimental data are compared to the theoretical models.

Changes in pore pressures due to repeated loading

The effective stress response to dynamic and repeated loading of saturated clays and sands has been described by Sangrey et al (1969) and by Castro (1969) respectively. These references are complete and essentially consistent in their description of the phenomenon, however a brief review of this work is appropriate as an introduction to this paper.

The basic response of an undrained saturated soil when subjected to stress increase is a pore fluid pressure change; positive pressures for normally consolidated fine grained soils and loose sands at low strains, negative pressure changes for overconsolidated clays and dense sands. These pore pressure changes develop as loading progresses. When a soil is subjected to stress fluctuation, for example an increase and decrease as illustrated in Figure 1, the resulting pore pressures take on additional significance, for just as the soil is not elastic in its deformation it is not elastic in pore pressure response. Consequently there is a residual or plastic strain resulting from the stress cycle and also a residual pore pressure (point b). These observations hold regardless of whether the soil is loaded to failure or not.

Subsequent cycles of loading and unloading may continue to accumulate residual strain and pore pressure effects in the soil. This leads either to failure, Figure 1, or to a condition of equilibrium characterised by closed hysterisis loops of strain and pore pressure with variation in stress, Figure 2. This latter state has been termed nonfailure equilibrium, Sangrey et al.

Whether ultimate failure or nonfailure equilibrium results from repeated loading of a particular soil, either in the lab or field, depends on the level of repeated stress, time and the number and nature of loading cycles. These latter variables, time, number and nature of loadings, produce various transient effects; however it is argued by Sangrey et al and Castro that the critical stress level separating failure and nonfailure is uniquely related to the effective stress state of the soil prior to repeated loading and the maximum stress level associated with this loading. The arguments in this paper are based on this conclusion.

In order to appreciate the significance of repeated loading and the resulting cumulative pore pressure effects it is useful to examine some test results as stress paths in an effective stress space. The examples illustrated, Figure 3, are triaxial test specimens in which the effective axial stress, σ'_1, is the major principal stress and the lateral stress is both minor and intermediate principal stress. Because of the axial symmetry in the lateral direction the general three dimensional stress space can be simplified to the plane representing σ'_1 and $\sigma'_3\sqrt{2}$. The illustrations which follow could just as well be made using any other stress space.

In Figure 3a and b are shown the stress paths followed by the two tests illustrated in Figures 1 and 2. A comparison of the stress paths followed in these tests provides an explanation for their behavior during repeated loading. The most obvious difference between the stress paths is their position with respect to the failure envelope. In test T2 the increase in pore pressure is sufficient to bring the stress path on the third cycle to the failure envelope; nonrecoverable deformations increase with each subsequent cycle of loading. In comparison, repeated loading of a similar sample to lower stress levels results in a lesser build-up of pore pressures and, at nonfailure equilibrium the pore pressures are still insufficient to bring the stress path to the failure envelope. The pore pressures will not increase beyond this point unless the level of repeated stress is increased.

For a particular soil defined by a specific initial state of effective stress and stress history, the changes in pore pressure due to repeated loading increase as the peak stress level increases. Consequently, as the level of repeated stress increases the nonfailure equilibrium stress path comes closer to failure until at a particular stress level, termed the critical level of repeated stress by Sangrey et al and earlier by Larew and Leonards (1962), failure occurs. Any repeated loading above this stress level leads to failure after some number of cycles.

This critical level of repeated stress and the corresponding effective stress failure state have been equated by Sangrey et al (1969) to the critical state of the soil, Schofield and Wroth (1968). Similarly, from the work of Castro, the ultimate failure condition of sand after liquifaction is the critical state or critical void ratio. At the critical state or critical void ratio a soil or other granular material is at failure under a unique combination of effective stress and void ratio. Under these conditions the soil will deform continuously or flow with a constant resistance and constant volume; therefore the strength is essentially the remolded strength.

In summary, the model of behavior for soil subjected to repeated loading is a cumulative build-up in excess pore pressure and strain. This pore pressure change can lead to either a nonfailure equilibrium condition, if repeated stress levels are low, or to failure. The critical level of repeated stress, representing the critical state or critical void ratio of the soil, separates these two limits and represents the highest level of repeated stress which will not cause eventual undrained failure.

Changes in strength resulting from repeated loading

Normally consolidated and lightly overconsolidated soils - undrained

As illustrated by the previous examples, saturated normally consolidated soils accumulate positive pore pressures during repeated loading; this also holds for any other soil which develops positive pore pressures as a result of monotonically increasing loading such as lightly overconsolidated clays. Build-up of positive pore water pressures leads to reduced strength with the critical level of repeated stress being lower than the peak undrained strength.

Much of the published work on response of soils to repeated loading has reported strength results of tests on these kinds of soils, both total stress and effective stress interpretations; (Seed and Chan, 1966; Thiers and Seed, 1968). Typical of the total stress results are the data from undisturbed San Francisco Bay Mud, Figure 4, reported by Seed and Chan. The curves indicate the number of cycles of a particular stress level, expressed as a percent of the normal undrained strength, necessary to cause failure. For all practical purposes these data are indicating an asymptote to a repeated stress of about 50% of the undrained strength. It is reasonable to expect that this is the critical level of repeated stress and that the soil is approaching the critical state.

Although pore pressures were not measured in these tests, they were in a special test on a companion sample of San Francisco Bay Mud reported in the same reference. In this test, pore pressures were measured at intervals during a rather complicated loading program as illustrated in Figure 5. These results clearly show the phenomenon of pore pressure build-up and subsequent failure at levels of stress considerably below the undrained strength.

It is also significant to note from Figure 4 that for a particular initial stress and level of repeated loading the asymptote or critical level of repeated stress is the same even though other characteristics of the loading are different. In this case the differences are the direction of stress cycling, either one or two directional, and the corresponding number of cycles necessary to reach failure. This supports the earlier contention that transient effects are influenced by such variables but that the ultimate condition depends only on repeated stress level as it relates to the critical level.

In summary, the undrained repeated loading of normally consolidated and lightly overconsolidated soils results in decreased strength due to pore pressure build-up. The critical level of repeated loading above which this occurs corresponds to the soil being at the critical state and is therefore the remolded strength. Consequently the ratio of peak undrained strength to the critical level of repeated loading should be the sensitivity of the soil and in the results reported by Sangrey, et al this is precisely the case. Other reported work has not contained sufficient information to permit such a positive conclusion; however, the soil response is sufficiently consistent with the theoretical model to offer at least qualitative support.

Overconsolidated soils - undrained

Limited data are reported for repeated loading of saturated overconsolidated soils (Bishop and Henkel, 1953; Knight and Blight, 1965), however the results which are available, Figure 6, indicate that the behavior of these materials follows logically from the proposed effective stress model. Negative pore pressures due to shear are a characteristic of heavily overconsolidated clays and, as illustrated, repeated loading leads to an accumulation of these negative pressures.

Several complete series of tests were done on heavily overconsolidated samples of Newfield clay in a companion study to that reported by Sangrey et al. The conclusion from this work was that while negative pore pressures do build-up in repeated loading the differences between the accumulated negative pressures and those resulting from normal monotonically increasing loading are small. Consequently the critical level of repeated stress is little different from the normal undrained strength of the overconsolidated soil. As a result, earthquake and other repeated loading does not lead to short term strength changes in these soils.

Drainage following repeated loading of fine grained soils

After a sequence of undrained repeated loading has produced cumulative pore pressure changes, the pore fluid is out of equilibrium with its surroundings and drainage results at rates controlled by soil permeability and boundary conditions. The resulting water content changes produce strength changes which may be more or less severe than any conditions during loading itself. Another consideration is that, unlike the undrained situation in which the constant water content (or void ratio) specifies a single value of critical state, drainage permits change in the critical state. Consequently, the critical level of repeated loading will also change.

Quantitatively these changes can only be defined by measuring the new water content, or void ratio, after drainage has occurred. Qualitatively, however, the changes are obvious.

For normally consolidated and lightly overconsolidated soils the accumulated positive pore pressures dissipate by water draining from the soil; the water content decreases and the shear strength and critical level of repeated stress increase. These soils, therefore, are not a long term problem under earthquake loading just as they are not under sustained loading.

On the other hand, overconsolidated soils clearly are a problem. The accumulated negative pore pressures dissipate by the soils drawing in water, swelling and increasing in water content. The result is a decrease in shear strength and the critical level of repeated stress. An illustration of this softening phenomenon after repeated loadings, Figure 7, is taken from tests by Bishop and Henkel (1953) on heavily overconsolidated Weald clay. In this example the specimen of soil was subjected to an undrained cycle of loading and unloading followed by a drained period during which any excess pore pressures could dissipate. The result was a progressive increase of water content and decrease of undrained strength. A decrease in critical state and critical level of repeated loading can also be inferred.

Clearly, this mechanism explains the common problem of softening of stiff fine grained soils under highway pavements and roadbeds of railways. Whether heavily overconsolidated soils loaded by earthquakes can be softened in a similar way cannot be confirmed by recorded experiences; however, a significant difference between the two problems is the relative accessibility to water. In the case of pavement or roadbed subgrade the softening occurs immediately adjacent to the base course or ballast and the water to satisfy the negative pore pressures is available from this free draining material; drainage distances are short. Also, since the repeated loading is a regular occurance, the soil as it softens continues to be subjected to the peak stresses of the dynamic loading. Earthquake loading, on the other hand, involves generally larger soil masses with correspondingly longer drainage distances. Because the time required to soften such a deposit is long, and the earthquake an irregular event, the softened soil may never be subjected to the levels of stress associated with the transient loading and may be stable under the dead loading stresses alone.

Partially saturated soils, compacted soils

Defining precisely the effective stress state in a partially saturated soil requires knowledge of both the pore air pressure and pore water pressure, Bishop, Alpan, Blight and Donald (1960). This is a formidable problem in a normal loading situation and for more complicated dynamic and repeated loading schemes is practically impossible. However, qualitatively the response of a compacted soil can be developed from the rational effective stress model proposed herein, and examples from testing of compacted soils confirm this behavior.

A typical compacted soil is overconsolidated in the sense that during undrained shear negative pore pressures result; behavior typical of this kind of soil would be expected were it not for air in the voids. Because of the air, however, repeated loading produces densification of the compacted soil by compressing or more likely forcing the air into solution or out of the soil entirely. In general, as the density of the soil increases, the strength also increases. Several investigators have reported, i.e. Seed, McNeill and de Guenin (1958), that "the observed increase in stiffness of soil specimens during repeated loading tests cannot be entirely attributed to an influence of densification"; obviously a negative pore pressure accumulation.

Another observation from repeated loading of compacted soils is that while there is an increase in strength and density there is also an increase in degree of saturation and that when this approaches 100% the soil behavior may change dramatically. Typically, Figure 8, as the soil becomes saturated, not by adding water but by reducing air content, the strength increase due to densification becomes less pronounced and as the sample approaches a high degree of saturation the strength decreases. No pore pressure measurements were made in these test on compacted soils, but clearly changes in pore pressure can explain all of these observations; particularly, an accumulation of positive pore pressures, as saturation is approached, would lead to the strength losses reported.

Extremely sensitive soils

Causes of soil sensitivity vary, Mitchell and Houston (1969), but the highly sensitive ones are apparently either leached or owe their sensitivity and high peak strength to some natural cementation between particles, Sangrey (1971). Most sensitive soils are geologically normally consolidated, undrained normal loading and repeated loading produce positive pore pressures, and their behavior is as illustrated in Figures 1, 2 and 3. Decrease in strength is related directly to sensitivity and the critical level of repeated stress is the remolded strength.

If this were the case for extremely sensitive soils, particularly the leached and naturally cemented ones, the critical level of repeated stress would be very small indeed and repeated loading would be an extremely difficult problem for these materials. This is not the experience of practicing engineers however.

In a study of this problem, Gorman (1970), undisturbed specimens of several extremely sensitive Canadian soils, all naturally cemented, were subjected to a program of repeated loading in a triaxial apparatus. Pore pressures were measured. The results confirmed that while there is strength reduction due to the repeated loading, the soils do not revert to remolded behavior but are able to sustain many cycles (up to 100) at levels of stress in the order of 50% of peak strength; Figure 9. The number of tests and types of soil were limited, but the results were consistent in defining a critical level of repeated stress significantly below peak but not at the remolded strength levels. The behavior of these naturally cemented soils suggested a mechanism of fatigue, perhaps of the cementing material, rather than of prefailure pore pressure accumulation. A classical fatigue model such as used for metals or concrete may be more appropriate for this kind of soil than the model used for other soils.

Considerably more experience is necessary to define this problem; however, it is clear that for soils of more moderate sensitivity, attributed to other than cements or leaching, the build-up of pore pressures due to repeated loading does reduce strength to the remolded levels defined by the critical state.

Granular materials

No problem involving dynamic and repeated loading of soils has received more attention than liquifaction of sands. Theories of this phenomenon have developed and been modified as more data were accumulated, most interpreted in total stresses some with pore pressure measurements. A thorough effective stress study has been reported by Castro (1969) and his results can be used to summarize the behavior of sand soils when loaded to produce liquifaction.

Castro did his testing on saturated triaxial specimens of several different sands; sustained, transient and repeated loading schemes were used. In all tests pore pressures were measured. He noted that for looser sands positive pore pressures resulted from all loading conditions while dense sands produced negative pore water pressures.

Liquifaction occurred with some specimens. This liquifaction was associated with accumulated positive pore pressures and the resulting changes in effective stress. The significant observations of Castro were that this behavior was rational and that a. whether a sample liquified or not and the degree of this liquifaction depended on the sample's initial effective stress state, and b. the ultimate effective stress states for samples which liquified defined a unique void ratio - effective stress relationship. These conclusions are illustrated in Figures 10 and 11.

When the void ratio and initial state of stress for samples of a particular sand were plotted, Figure 10, very distinct patterns were observed with respect to subsequent liquifaction. Data of this type enabled Castro to define a line separating the samples which did and did not liquify. At a particular initial state of effective stress the looser soils liquified, denser ones did not.

A rational explanation for the line of separation was possible when it was noted that the conditions defining this line were also the ultimate effective stress failure states for the sand, in other words the critical void ratio or critical state line, Figure 11. Obviously, then, this is completely analagous to the behavior of saturated clays. At a particular void ratio, loose sand exists initially at an effective stress state higher than the critical state at that void ratio, (normally consolidated clays relate in the same way to the critical state, Figure 3). As loading, either sustained, transient or repeated, is applied to the soil, positive pore water pressures develop. If these accumulate the soil will ultimately reach failure at the critical state. In this operation the stress path would move parallel to the axis of stress to the critical void ratio in Figure 11. Since there is a particular strength associated with the soil at a critical state this strength is predictable and it also becomes the critical level of repeated loading and the reasonable design strength under earthquake and other dynamic loading conditions.

Summary

A model has been proposed whereby the pore fluid pressure changes resulting from transient or repeated loading of soils control the ultimate behavior of the material. It has been shown that the changes in pore pressure accumulate until the soil achieves a critical state (or critical void ratio) relationship between effective stress and void ratio. This critical state defines a specific strength for the soil which is also the critical level of repeated loading and consequently the appropriate design parameter.

Within this model various soils respond differently. The response of major soil types has been reviewed and illustrations given. These examples are summarized in Table I in which the soil type, fundamentals of response to dynamic loading and recommended design procedures are noted.

Acknowledgement

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Bibliography

1. Sangrey, D. A.; Henkel, D. J. and Esrig, M. I., "The Effective Stress Response of a Saturated Clay Soil to Repeated Loading" Canadian Geotechnical Journal v6, n3, 1969.
2. Castro, G., "Liquifaction of Sands" Harvard Soil Mechanics Series No. 81. Cambridge, Mass. 1969.
3. Schofield, A. N. and Wroth, C. P., Critical State Soil Mechanics, McGraw-Hill, London, 1968.
4. Larew, H. G. and Leonards, G. A., "A Repeated Load Strength Criterion" Proc. Highway Research Board #41, 1962.
5. Seed, H. B. and Chan, C. K., "Clay Strength under Earthquake Loading Conditions" Proc. ASCE v92, sm2, 1966.
6. Thiers, G. R. and Seed, H. B., "Cyclic Stress-Strain Characterstics of Clay" Proc. ASCE v94, n2, 1968.
7. Bishop, A. W. and Henkel, D. J., "Pore Pressure Changes during Shear in Two Undisturbed Clays" 3rd ICSM and FE v1, 1953.
8. Knight, K. and Blight, G. E. "Studies of Some Effects Resulting from the Unloading of Soils" 6th ICSM and FE v11, 1965.
9. Bishop, A. W.; Alpan, I.; Blight G. E. and Donald, I. B., "Factors Controlling the Strength of Partially Saturated Cohesive Soils" Proc. ASCE Research Conference on Shear Strength of Cohesive Soils, Boulder, 1960.
10. Seed, H. B.; McNeill, R. L.; and de Guenin, J., "Increased Resistance to Deformation of Clay Caused by Repeated Loading" Proc. ASCE v84, sm2, 1958.
11. Mitchell, J. K. and Houston, W. N., "Causes of Clay Sensitivity" Proc. ASCE v95, sm3, 1969.
12. Sangrey, D. A. "Naturally Cemented Sensitive Soils" Geotechnique, v21, n2, 1971.
13. Gorman, A. E. "Repeated Loading of Sensitive Clays" M.Sc. Thesis, Queens University at Kingston, Ontario, 1970.

SOIL TYPE	DESIGN STRENGTH FOR EARTHQUAKE AND REPEATED LOADING	FUNDAMENTALS OF RESPONSE
SATURATED NORMALLY CONSOLIDATED CLAY - UNDRAINED	STRENGTH AT CRITICAL STATE; REMOLDED STRENGTH	ACCUMULATING POSITIVE PORE WATER PRESSURES
SATURATED NORMALLY CONSOLIDATED CLAY - DRAINED	NO REDUCTION - SEE N. C. UNDRAINED	DRAINAGE UNDER POSITIVE PORE PRESSURE GRADIENT
SATURATED OVERCONSOLIDATED CLAY - UNDRAINED	LITTLE STRENGTH CHANGE UNLESS ZONAL	ACCUMULATED NEGATIVE PORE WATER PRESSURE
SATURATED OVERCONSOLIDATED CLAY - DRAINED	SOFTENED STRENGTH DETERMINED BY CHANGING CRITICAL STATE - TEST	NEGATIVE PORE PRESSURES DISSIPATE BY INCREASING WATER CONTENT, DECREASING CRITICAL STATE
PARTIALLY SATURATED SOILS	DENSIFICATION THEN STRENGTH REDUCTION AS SOIL BECOMES SATURATED - TEST	AIR FORCED INTO SOLUTION OR OUT OF SOIL
EXTREMELY SENSITIVE NATURALLY CEMENTED SOILS	REDUCED STRENGTH - TEST AT APPROPRIATE STRESS LEVEL	FATIGUE OF CEMENTATION BONDS BETWEEN PARTICLES
LOOSE GRANULAR MATERIALS	STRENGTH AT CRITICAL STATE OR CRITICAL VOID RATIO	ACCUMULATION OF POSITIVE PORE PRESSURES
DENSE GRANULAR MATERIALS	NO REDUCTION UNLESS ZONAL	DILATION

TABLE I DESIGN RECOMMENDATIONS FOR STRENGTH OF SOILS SUBJECTED TO EARTHQUAKE OR OTHER REPEATED LOADING

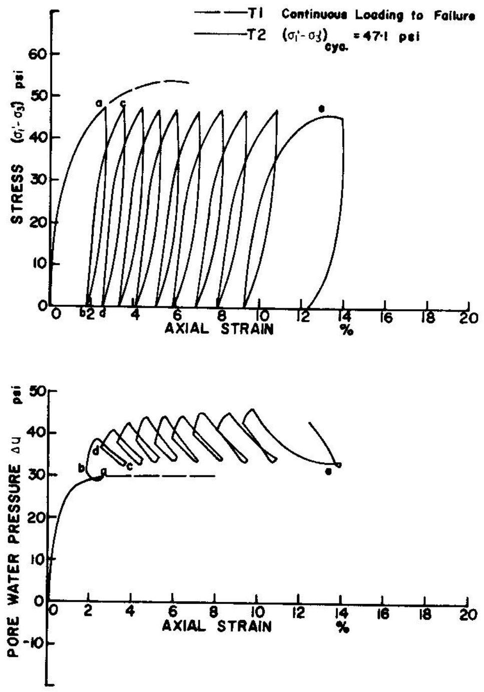

FIGURE 1 ACCUMULATION OF PORE PRESSURES DUE TO REPEATED LOADING RESULTING IN FAILURE (FROM SANGREY ET AL, 1969)

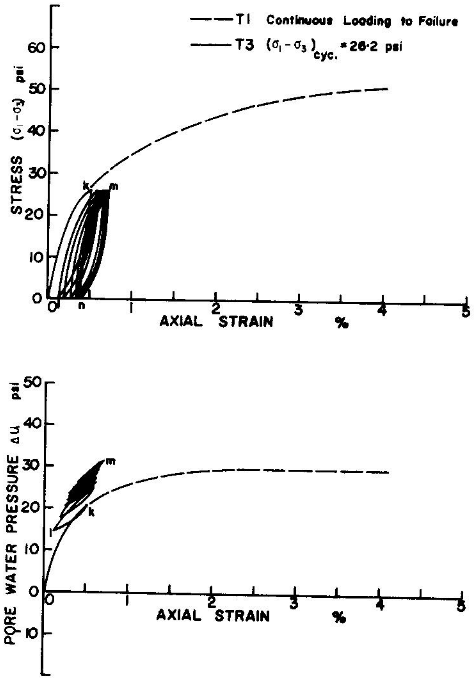

FIGURE 2 PORE PRESSURE AND STRAIN RESPONSE FOR NONFAILURE EQUILIBRIUM (FROM SANGREY ET AL, 1969)

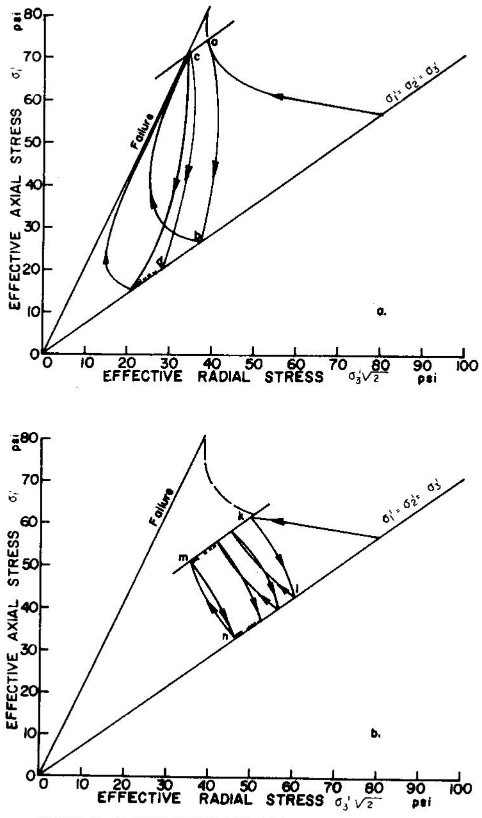

FIGURE 3 STRESS PATHS FOR SOILS ILLUSTRATED IN FIGURES 1 AND 2 ILLUSTRATING FAILURE (A) AND NONFAILURE (B) RESPONSE (FROM SANGREY ET AL, 1969)

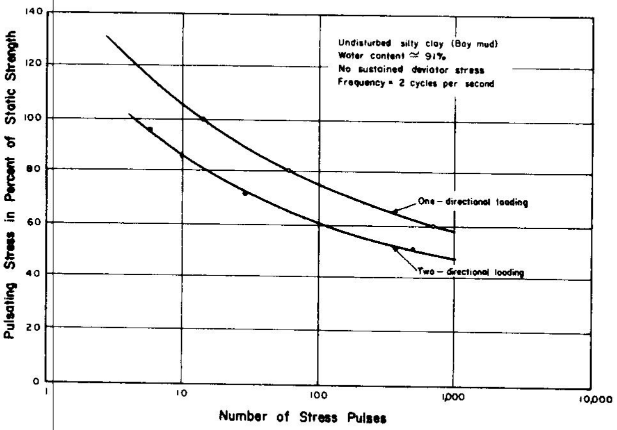

FIGURE 4 NUMBER OF CYCLES OF VARIOUS STRESS LEVELS REQUIRED TO CAUSE FAILURE OF A SATURATED CLAY (FROM SEED AND CHAN, 1966)

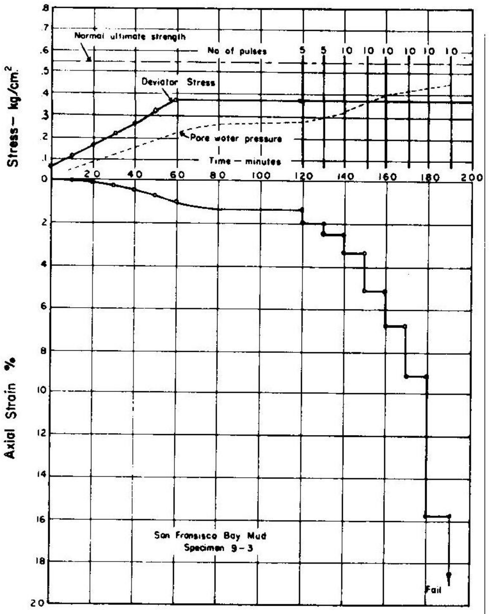

FIGURE 5 PORE PRESSURES MEASURED DURING REPEATED LOADING OF A SATURATED CLAY SOIL
(FROM SEED AND CHAN, 1966)

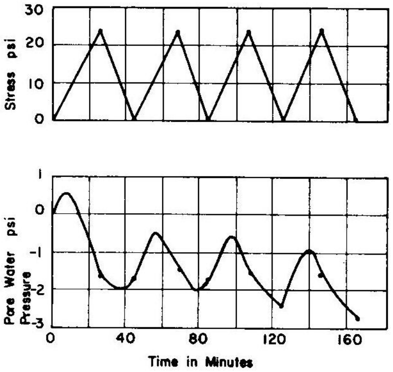

FIGURE 6 ACCUMULATING NEGATIVE PORE PRESSURES RESULTING FROM REPEATED LOADING OF OVERCONSOLIDATED CLAY
(FROM KNIGHT AND BLIGHT, 1965)

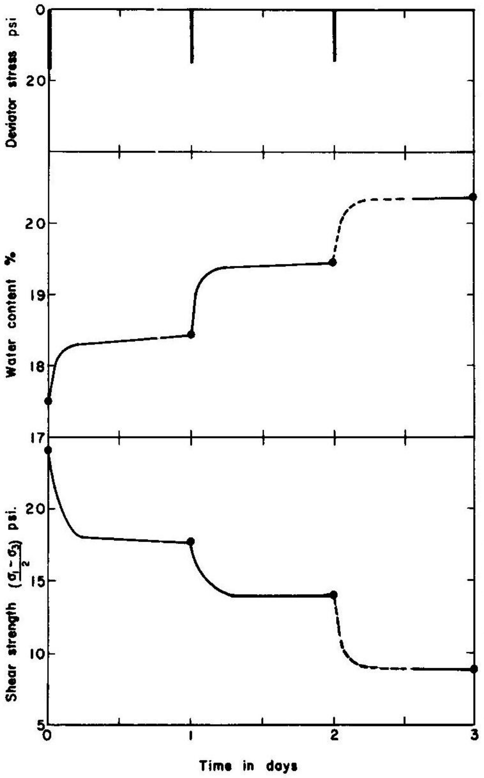

FIGURE 7 WATER CONTENT AND STRENGTH CHANGES RESULTING FROM ALTERNATE CYCLED LOADING AND DRAINAGE OF OVERCONSOLIDATED CLAY
(FROM BISHOP AND HENKEL, 1953)

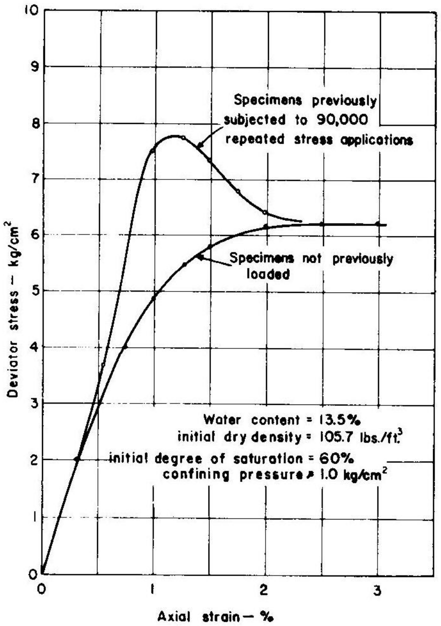

FIGURE 8 DENSIFICATION OF COMPACTED SOIL DUE TO REPEATED LOADING, FOLLOWED BY COLLAPSE AS SATURATION APPROACHES 100%
(FROM SEED ET AL, 1958)

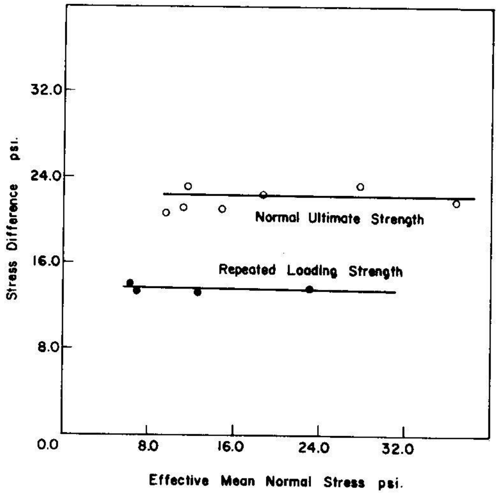

FIGURE 9 LOWER CRITICAL LEVEL OF REPEATED LOADING DEMONSTRATED BY EXTREMELY SENSITIVE LEDA CLAY

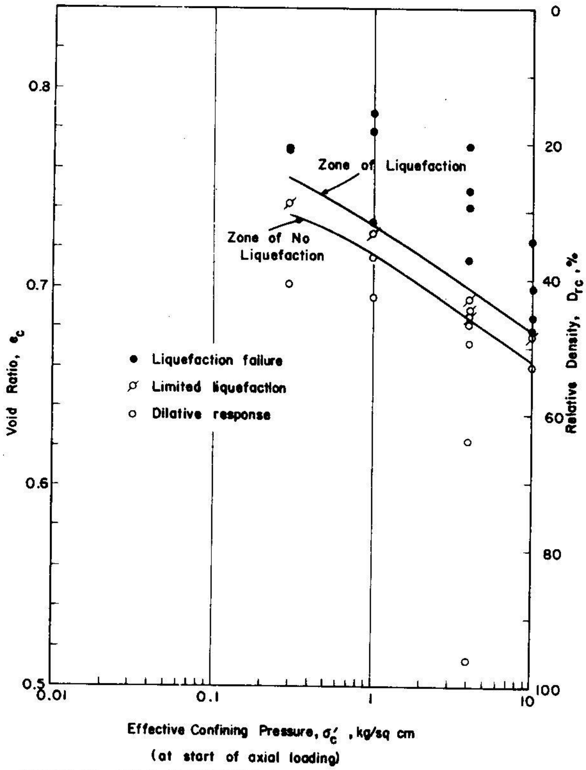

FIGURE 10 TYPES OF BEHAVIOR RESULTING FROM TESTS ON A SAND FROM DIFFERENT INITIAL CONDITIONS
(FROM CASTRO, 1969)

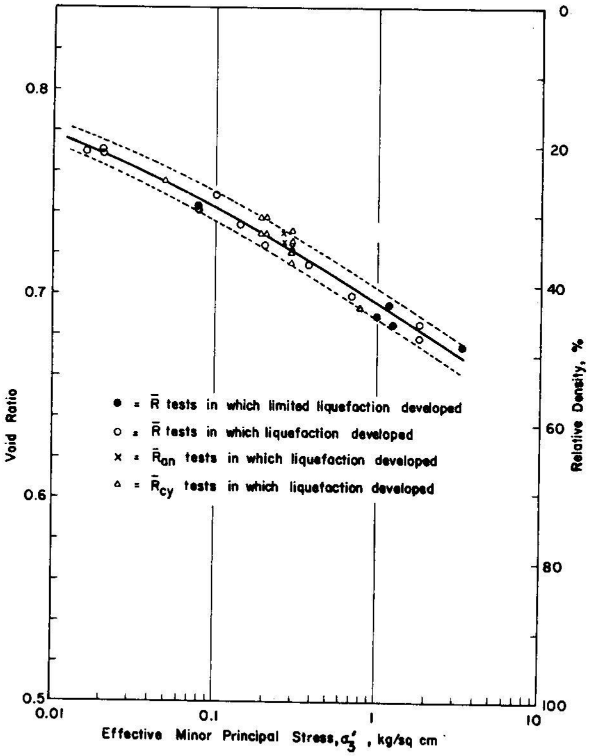

FIGURE 11 THE ULTIMATE CONDITION OF LIQUIFIED SAND SAMPLES, OR THE CRITICAL VOID RATIO
(FROM CASTRO, 1969)

DISCUSSION OF PAPER NO. 5

CHANGES IN STRENGTH OF SOILS UNDER EARTHQUAKE AND OTHER REPEATED LOADING

by

D. A. Sangrey

Discussion by: M. A. Sherif

The accumulative negative pore pressure build-up in overconsolidated soils referred to by the speaker suggests that such soils do not lose strength during earthquakes. This is not the case, however, for all overconsolidated soils, but depends to a great extent on the overconsolidation ratio of the soils. Our results at the University of Washington show that overconsolidated soils gain strength when the overconsolidation ratio is up to 8. When the overconsolidation ratio is considerably over 8, these soils lose strength. This may imply that the pore pressure effects and the dilation tendency of overconsolidated soils must be considered simultaneously in assessing the shear behavior of overconsolidated soils during dynamic excitations.

Reply by: D. A. Sangrey

One might speculate that the strength loss for heavily overconsolidated soils subjected to dynamic and repeated loading, as observed by Dr. Sherif, is a consequence of breakdown or loss of effective stress cohesion. To expect this loss to be related to pore pressure increases is, I think, unreasonable.

The observed strength decrease, for whatever reason, is, however, an important qualification of the conclusions drawn in the paper.