SOIL STRENGTH DURING EARTHQUAKES

by

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Synopsis

Apparatus for testing soils under simulated earthquake loading conditions is described and test data are presented to show the combinations of sustained stress and simulated earthquake stress intensities which will cause failure in a compacted silty clay and a medium sensitive undisturbed clay. Conclusions are drawn concerning the factor of safety required to prevent failure of these soils during earthquakes and the applicability of transient and vibratory test methods for determining soil strength under earthquake loading conditions.

Introduction

During earthquakes the soils underlying building foundations and in earth structures themselves are subjected to a series of vibratory stress applications of limited duration. Seismograph records indicate that during the main shock the ground is subjected to a horizontal acceleration which may approach its peak intensity as many as 15 to 20 times in a period of about half a minute; including after shocks the total number of the larger vibratory pulses may thus be as great as 50 or 60. Each pulsation will cause an increase in shear stress in the soil and thus increase the tendency for shear deformations to occur.

However, the effect of an earthquake on the stability of a soil is not so readily apparent. Whether or not the increased shear stresses will decrease the stability of the soil will depend on the shear strength mobilized by the soil during the earthquake; if this exceeds the shear stresses no failure will result. If it is assumed that the shear stresses induced in soils by earthquakes can be calculated approximately by analytical procedures, then the problem of determining the stability of soils during earthquakes is reduced simply to that of ascertaining the shear strength of the soil during the increased stress application.

Unfortunately normal strength tests on soils are not satisfactory for this purpose. In a conventional strength test of a soil specimen the load is increased gradually over a period of 10 to 15 minutes until failure occurs. This loading condition is very different from that which develops during an earthquake; the rate of stress application is much slower and

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there is no repetition of stress. Consequently special laboratory studies of soil strength during earthquakes have been conducted with the object of determining soil behavior under stress conditions more nearly analogous to actual conditions.

Most laboratory studies conducted in Japan have attempted to do this by measuring the shear strengths of soils while they are subjected to continuous vertical vibrations.[1,2,3] However, the duration of vibratory stress applications has often been excessively long compared with that of an earthquake and furthermore during an earthquake the shear stresses are also vibratory in character.

In the United States earthquake loading conditions have often been considered to be analogous to those of transient load tests on soils.[4,5,6,7,8] The results of these tests show that when a soil is loaded to failure in a period of time corresponding to that of an earthquake pulse the strength is greater than that developed under static loading conditions. However, it must be borne in mind that the application of a transient load is simply analogous to the first pulse of an earthquake; under this pulse a soil can apparently mobilize additional strength which may well be sufficient to prevent failure or even to prevent any appreciable permanent deformation of the soil. However, with subsequent reversals and reapplications of the stress the soil may deform sufficiently either to (1) remold the soil enough to cause a reduction in strength, or (2) cause such large shear displacements that deformations are readily apparent even though no failure has occurred. Such effects cannot be studied when failure is induced by a single transient stress application.

In order to provide what was considered to be a more realistic simulation of the stress conditions to which soils might be subjected during earthquakes, studies have been conducted at the University of California in which triaxially confined samples of soil have been subjected to a limited series of transient stress applications.

Apparatus

The equipment[9] utilized for these studies is shown in Fig. 1. A soil specimen is subjected to a confining pressure in a triaxial compression cell and loaded by means of a piston and loading yoke. Sustained load is applied to the specimen by placing weights on a hanger attached to the lower end of the yoke. Transient pulses are applied to the yoke by means of an air pressure cylinder mounted below the triaxial cell. For this purpose compressed air is passed through a regulator and stored at constant pressure in a reservoir tank. The tank is connected through a solenoid valve to the pressure cylinder below the triaxial cell. When the valve is open, the air pressure is transmitted through the cylinder and loading yoke to the specimen. When the valve is closed, the air in the pressure cylinder passes through an exhaust pipe in the valve and the load is removed.

The load applied to the specimen is varied by regulating the air pressure in the cylinder. By calibrating the load against the air pressure as recorded by a pressure gage any desired load can readily be obtained.

In order to maintain a constant calibration it is, of course, necessary to eliminate the problem of piston friction both in the pressure cylinder and in the piston of the triaxial cell. In the triaxial cell this difficulty is overcome by the use of ball bushings for the piston and rubber O rings to prevent loss of air pressure; in the pressure cylinder it is overcome by the use of a Bellofram seal - a neoprene diaphragm which fits over the piston and forms a seal between the piston and the cylinder wall. When air pressure is applied in the cylinder the piston moves by rolling the diaphragm away from or back against the cylinder wall.

Application of pressure to the air cylinder is controlled by the spring return solenoid-operated 3-way valve with 3/8-in. diameter port openings. Movement of the valve to admit air to or exhaust air from the pressure cylinder is controlled by a timing unit. Various commercial forms of timing units are available, but a simple mechanical timing unit can readily be constructed by using a synchronous motor to drive a cam and utilizing a microswitch bearing on the cam to send a pulse of the desired duration to the solenoid valve.

The characteristics of all transient stress applications were checked by the use of a Sanborne recorder and an 8-gage, full-bridge dynamometer. The dynamometer was placed between the top of the triaxial cell piston and the loading yoke so that it would be between the specimen and all possible sources of impact. A typical load versus time trace is shown in Fig. 2.

For studies of earthquake effects the stress pulses used have usually been such that the period of a complete loading and unloading cycle was 0.5 second.

Test Procedures and Results

In practice, soils supporting engineering structures are subjected to dead load stresses before the earthquake effects occur. Thus it was decided to conduct the laboratory studies by subjecting each specimen to a sustained stress lower than that required to cause failure, allowing the sample to come to equilibrium and then applying a series of transient stress applications representative of an earthquake (see Fig. 2). In effect, this procedure corresponds to bringing the sample to equilibrium with some known factor of safety (i.e. the ratio of the soil strength in a normal type of test to the applied sustained stress) before the earthquake effects are superimposed.

A typical example of this procedure is illustrated by the test data for a compacted silty clay shown in Fig. 3. A series of specimens of identical composition were first prepared by static compaction to a degree of saturation of 95 per cent. Previous studies have shown that this procedure produces samples having essentially the same strength characteristics as samples prepared by any other compaction method at a lower water content and then brought to a condition approaching saturation by soaking at constant volume.

The strength of the compacted specimens in unconsolidated-undrained triaxial compression tests was first determined using a conventional loading procedure. The stress-strain curve for the soil determined in this way is shown by the dashed line in Fig. 4. For the test illustrated in Figs. 3 and 4 a specimen of the same soil was then loaded to a stress equal to 66 per cent of this strength, corresponding to a factor of safety of 1.5, and allowed to come to equilibrium over a period of 30 minutes. At this stage a series of 100 transient stress pulses, corresponding to an initial stress change of ±35 per cent, were applied and the resulting deformations of the samples were recorded. The progress of deformation with time is shown in Fig. 3 and the stress versus strain relationship for the sample is presented in Fig. 4. For purposes of comparison the strength of the soil when loaded to failure by a single transient stress application is also shown in Fig. 4.

It will be seen that although the maximum applied stress, including the earthquake stress, was less than the normal strength of the soil (in fact the lowest factor of safety attained was 1.12 based on the normal strength and 1.52 based on the transient strength) the soil nevertheless deformed almost 11 per cent during the transient stress applications - an increase in strain sufficient to cause severe distortion in engineering practice.

By reading the strain after different numbers of transient stress applications, the deforming effect of earthquakes of different durations can readily be determined.

Effects of variations in initial stress conditions and in earthquake stress intensities were studied by repeating the same type of test on identical samples using initially sustained stresses corresponding to different factors of safety and transient pulses corresponding to 20, 40 and 60 per cent of the initial sustained stresses. The deformations of the samples during these tests are shown in Figs. 5, 6 and 7.

Fig. 5 shows the effects of single transient stress applications of the various intensities for initial factors of safety ranging between 1.0 and 2.0. The shaded portion of the figure shows the deformation of the specimens induced at stress levels corresponding to the different factors of safety in normal strength tests. The upper curves show the increases in deformation caused by single transient pulses corresponding to 20, 40 and 60 per cent of the initial sustained stress.

Figs. 6 and 7 show similar data for a series of 30 and 100 transient pulses. It is interesting to note that for this soil a single transient pulse equal to 20 per cent of the initial deviator stress causes no appreciable deformation even though the factor of safety may be as low as 1.1. However, it may also be seen that a series of 100 such pulses for the same initial factor of safety will cause an increase in axial strain of about 10 per cent. The significance of increased numbers of stress pulses in producing increased deformation of the soil is readily apparent from a comparison of these figures.

It will be seen from the results presented that for this type of soil the primary effect of the earthquake stress applications is to cause deformations which might be large in magnitude but not to cause a dramatic collapse of the samples. However, failure of soil samples exhibiting large deformation characteristics is usually considered to have occurred when the sample reaches an axial strain of the order of 20 to 25 per cent. It will be seen from Fig. 4 that in a normal strength test the maximum resistance of this soil is reached at an axial strain of about 25 per cent. If this strain is adopted as a criterion of failure, then a variety of combinations of initially sustained stress and earthquake stress intensities which will cause failure of the soil may be determined from Figs. 5, 6 and 7.

For example, reference to Fig. 5 shows that for samples subjected to a single transient stress application failure (or 25 per cent strain) is caused by the following combinations:

Initial Factor of Safety	Transient Stress Increase Based on Initial Sustained Stress
1.02	20
1.065	40
1.17	60

If these stresses are expressed as percentages of the normal strength of the soil and appropriate corrections are made for changes in area of the specimens during the tests, these results lead to the following stress levels producing failure:

Initial Sustained Stress	Transient Stress Increase
96.5	19.7
88	37
73.5	51.5

These values can then be plotted as shown in Fig. 8 to define a portion of the upper curve. By conducting tests at lower values of sustained stress the entire range of combinations of sustained stress and transient stress which will cause failure of this soil can be established. These combinations are shown by the upper curve in Fig. 8.

Repeating this procedure for the test data presented in Figs. 6 and 7 leads to the other curves shown in Fig. 8.

Presentation of the data in this form shows clearly the combinations of initial stress and earthquake stress intensity causing failure for the soil. For single transient stress pulses the combinations of sustained and transient stresses would have to approach about 135 per cent of the normal strength to induce failure. However, for earthquakes inducing about ten major pulses, failure would result when the combined stresses totalled 120 per cent of the normal strength while for earthquakes inducing 100 major pulses failure would occur when the combined stresses totalled only 100 per cent of the normal strength (or whenever a factor of safety of 1, based on the normal strength, was attained).

It should not be imagined that the conditions producing failure shown in Fig. 8 for the compacted silty clay are in any way characteristic of conditions producing failure in other types of soil. A compacted clay is an insensitive material which is not likely to change its strength characteristics appreciably as a result of repeated deformations. With sensitive undisturbed clays on the other hand, repeated deformations will lead to an increase in pore water pressure within the sample and a resulting reduction in strength. Consequently a series of transient pulses is likely to induce failure at lower stress levels than for the silty clay.

A comparison of the combinations of sustained and earthquake stresses inducing failure in undisturbed samples of San Francisco Bay mud (a saturated, slightly organic silty clay having a sensitivity of about 8) and the compacted silty clay is shown in Fig. 9. It will be seen that the strength of the more sensitive soil under single transient stress pulses is somewhat higher and under repeated transient stress pulses somewhat lower than for the compacted clay. In fact, the combinations of stress conditions producing failure cover a much wider range. It is noteworthy that for this type of soil only 10 transient pulses are required to cause failure when the combined sustained and transient stresses total 100 per cent of the normal soil strength; and for 100 stress repetitions failure can occur when the total stress is only 80 per cent of the normal strength.

Conclusion

In conclusion it should be pointed out that the strengths of these clays, which vary quite greatly in type, under simulated loading conditions do not differ too greatly from the strength value determined in a normal type of compression test. The test data show that for the compacted clay a total stress between 100 and 120 per cent of the normal strength would probably be required to cause failure under reasonably simulated earthquake loading conditions while for the sensitive undisturbed clay a total stress between 80 and 100 per cent would probably be required. Thus it would appear that designs including both sustained and earthquake stresses and providing a factor of safety against soil failure exceeding unity for the compacted clay and exceeding about 1.15 for the undisturbed clay, based on the normal strength of the soil, are likely to provide assurance that there will be no catastrophic collapse of the soil during an earthquake. However, large shear deformations of the soil can be expected to occur if the combined stresses produce factors of safety approaching these values.

The results also show that soil strength under the simulated earthquake loadings is appreciably less than that indicated by transient tests on soils but also considerably more than that indicated by long-term vibratory tests. It is believed that the test conditions used in the study are more closely analogous to earthquake loading conditions than either transient or long-term vibratory tests and thus the results may serve to reconcile in some measure the widely conflicting opinions concerning soil strength during earthquakes which, based on these other test procedures, have been adopted by engineers in different parts of the world.

Acknowledgment

The cooperation of Mr. C. K. Chan in obtaining the test data presented in the paper and of Mr. G. Dierking, who prepared the figures, is gratefully acknowledged.

References

1. Mogami, T. and Kubo, K., "The Behavior of Soil During Vibration", Proceedings, Third International Conference on Soil Mechanics and Foundation Engineering, 1953.

2. Mogami, T., Nakase, A. and Yamaguchi, H., "The Change in the Yield Value of Soil when Vibrated", Report on Researches and Investigations, 1953 - Japanese Committee on Soil Mechanics and Foundation Engineering.

3. Mogami, T., Yamaguchi, H. and Nakase, A., "On the Dynamical Behavior of Soils", Report on Researches and Investigations, 1954 - Japanese Committee on Soil Mechanics and Foundation Engineering.

4. Casagrande, A. and Shanon, W. L., "Research on Stress-Deformation and Strength Characteristics of Soils and Soft Rocks under Transient Loading", Publication Graduate School of Engineering, Soil Mechanics Series No. 31, Harvard University, 1948.

5. Seed, H. B. and Lundgren, R., "Investigation of the Effect of Transient Loading on the Strength and Deformation Characteristics of Saturated Sands", Proceedings, American Society for Testing Materials, vol. 54, 1954.

6. Whitman, R. V., "The Behavior of Soils Under Transient Loading", Proceedings, Fourth International Conference on Soil Mechanics and Foundation Engineering, 1957.

7. Whitman, R. V., "Testing Soils with Transient Loads", Conference on Soils for Engineering Purposes, Mexico City, December, 1957, American Society for Testing Materials, Special Technical Publication STP. No. 232.

8. Hampton, D., "Effect of Rate of Strain on the Strength of Remolded Soil", Report No. 17, Joint Highway Research Project, Purdue University July, 1958.

9. Seed, H. B. and Fead, J. W. N., "Apparatus for Repeated Load Tests on Soils", Preprint No. 88a, Annual Meeting of American Society for Testing Materials, Atlantic City, June, 1959.

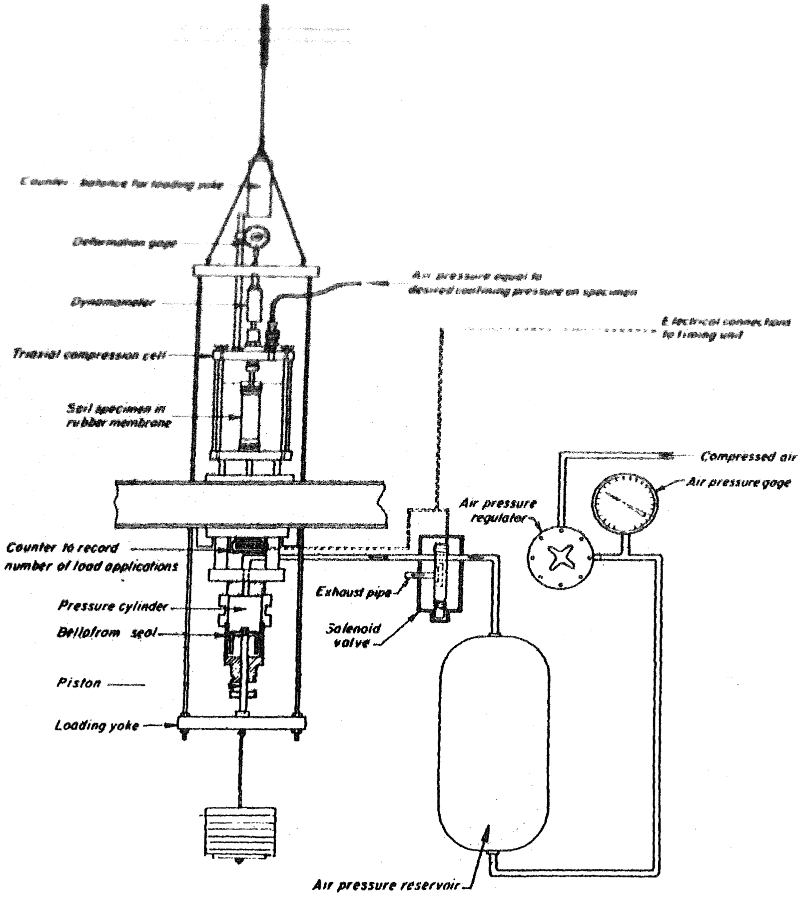

Fig. I -EQUIPMENT FOR TESTING SOIL SPECIMENS UNDER SIMULATED EARTHQUAKE LOADING.

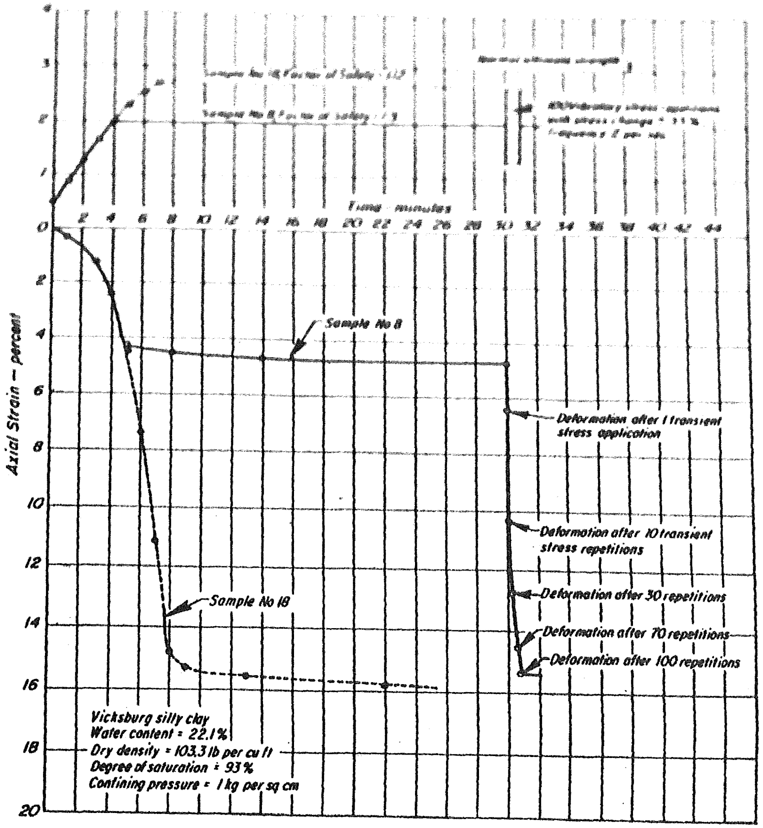

Fig. 3-CHANGES IN STRESS AND DEFORMATION WITH TIME DURING SIMULATED EARTHQUAKE LOADING TEST ON SILTY CLAY.

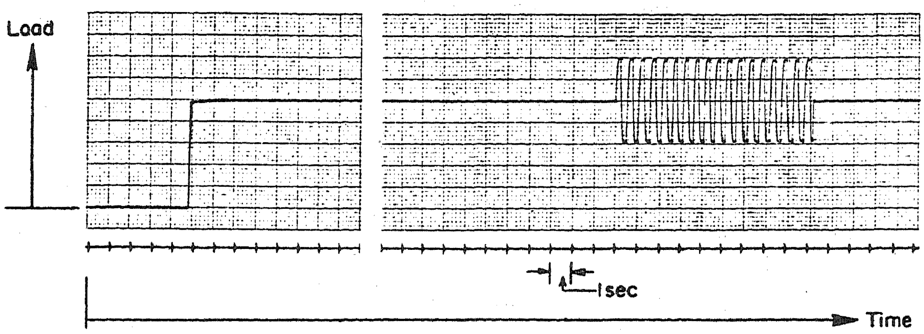

Fig. 2 – TYPICAL PATTERN OF LOAD APPLICATION IN SIMULATED EARTHQUAKE TEST.

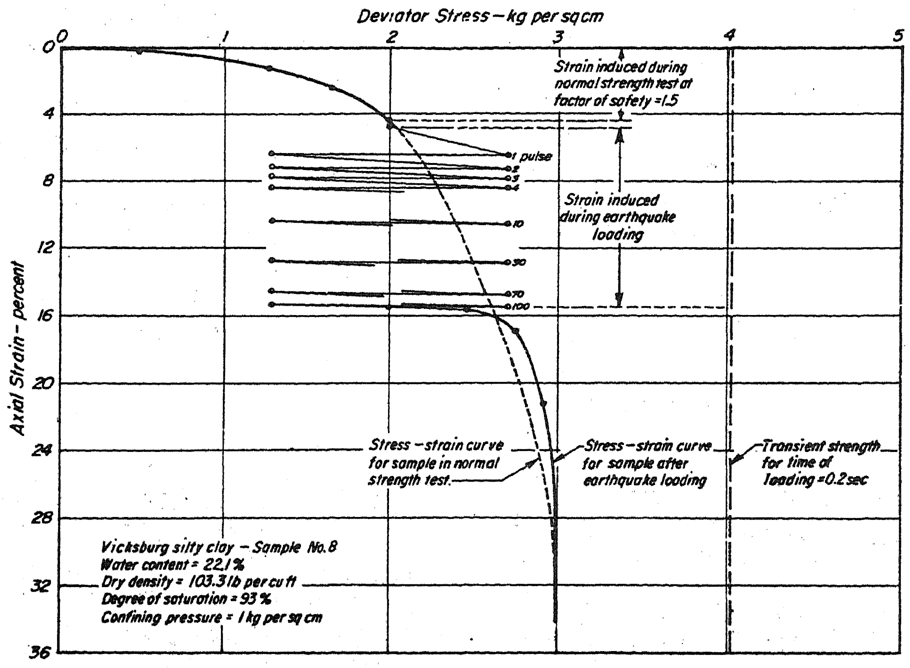

Fig. 4 – STRESS vs STRAIN RELATIONSHIP IN SIMULATED EARTHQUAKE LOADING TEST ON SILTY CLAY.

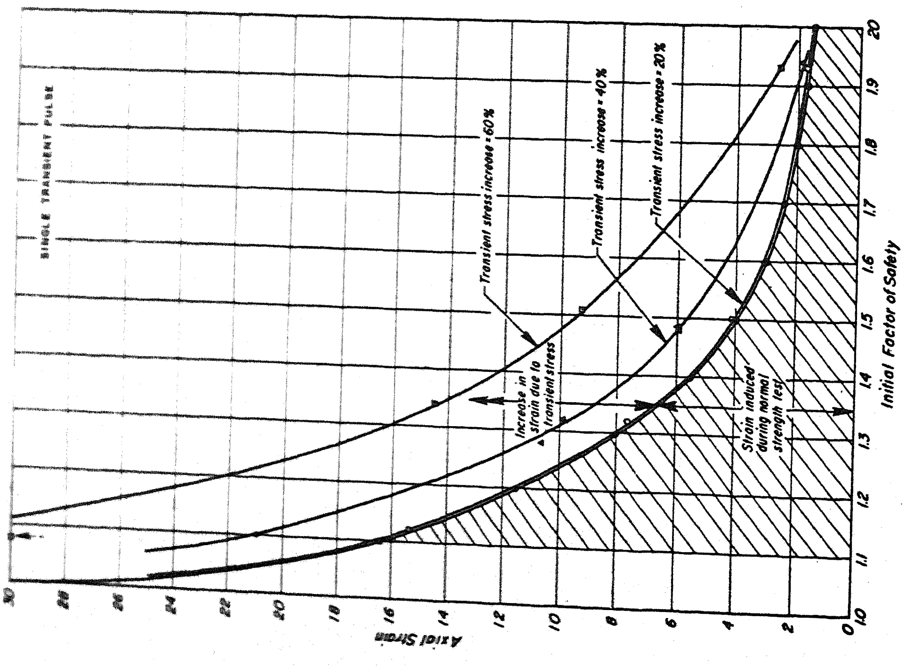

Fig. 5–SOIL DEFORMATIONS INDUCED BY VARIOUS COMBINATIONS OF SUSTAINED AND TRANSIENT STRESSES.

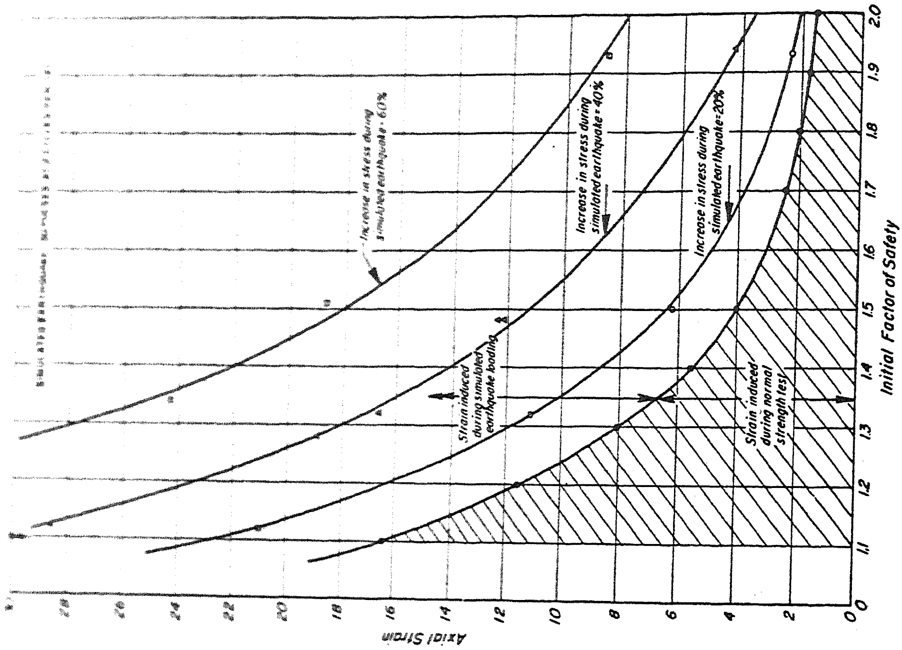

Fig. 6–SOIL DEFORMATIONS INDUCED BY VARIOUS COMBINATIONS OF SUSTAINED AND VIBRATORY STRESSES.

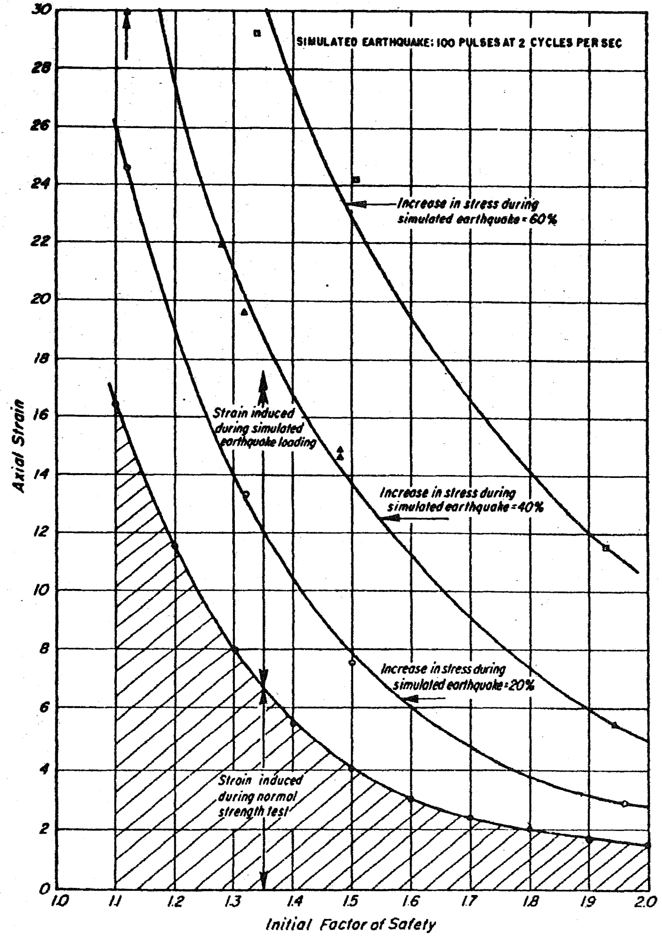

Fig. 7 - SOIL DEFORMATIONS INDUCED BY VARIOUS COMBINATIONS OF SUSTAINED AND VIBRATORY STRESSES.

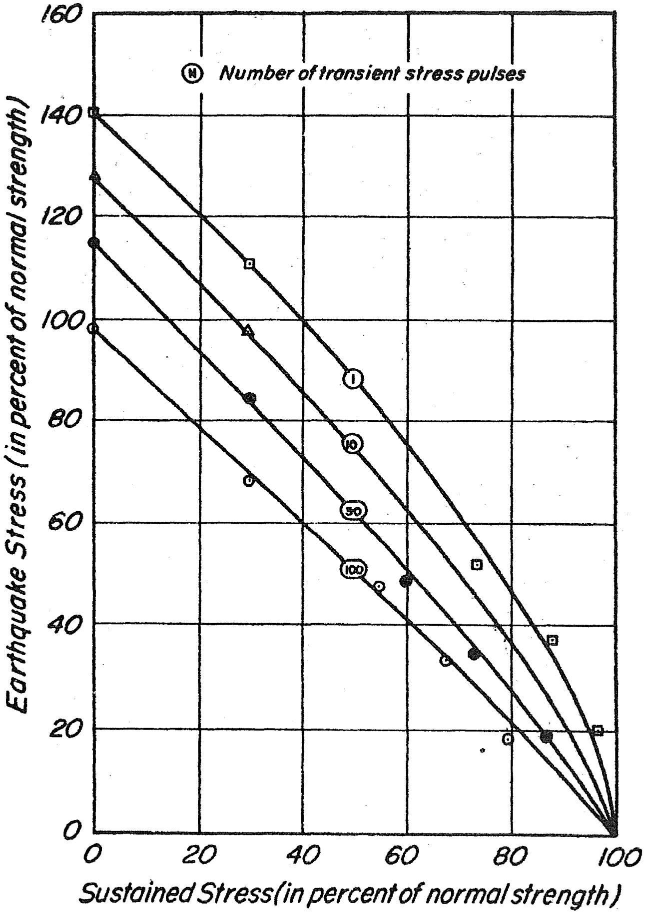

Fig. 8 - COMBINATIONS OF SUSTAINED AND VIBRATORY STRESS INTENSITIES CAUSING FAILURE IN COMPACTED SILTY CLAY.

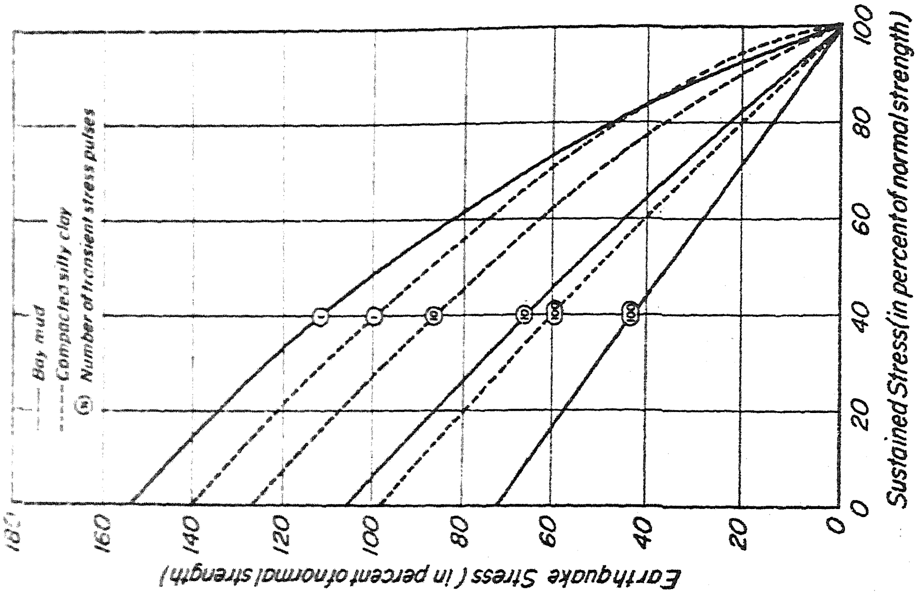

Fig.9-COMPARISON OF STRESS CONDITIONS CAUSING FAILURE FOR COMPACTED AND UNDISTURBED SAMPLES OF SILTY CLAY.

DISCUSSION

H. Matsuo, Kyushu University, Japan:

1. Didn't you observe the phenomena of thixotropy?

2. How much was the acceleration of vibration applied in your experiment?

H. B. Seed:

The compacted specimens of silty clay used in the tests were prepared by static compaction and stored for a period of several weeks before testing. Previous studies 1, 2 have shown that samples of this soil prepared by static compaction possess only slight thixotropic characteristics and that there is very little gain in strength with time after several weeks. These factors were considered in planning the testing program and it is not thought that the results of tests on this soil are significantly influenced by thixotropy.

The samples of San Francisco Bay mud were obtained by undisturbed sampling and were tested in the undisturved condition (shear strength about 400 lb per sq. ft.). However on remolding, which causes a considerably less of strength (sensitivity about 8), they do exhibit substantial thixotropic characteristics.

The tests described in the paper were conducted using controlled stress pulses and measurements were made of the resulting deformations at different stages in the tests. However the rate of deformation of the samples during the tests was not determined.

S. Murayama, Kyoto University, Japan:

Does the factor of safety vary according to the duration of pulse applied?

H. B. Seed:

The deformations of clay soils under repeated stress applications depend on many factors including the number and duration of the stress applications. For an equal number of stress pulses, our studies show that deformation increases with increased duration of pulse. Thus excessive distortion or deformation of a clay will be induced by fewer pulses when the pulses are of long duration rather than short duration. This might well be interpreted as causing a reduction in the factor of safety of the soil.

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1. Seed, H. B. and Chan, C. K., "Thixotropic Characteristics of Compacted Clays", Journal Soil Mechanics and Foundations Division, American Society of Civil Engineers, October, 1957.
2. Mitchell, J. K., "Fundamental Aspects of Thixotropy in Soils", Journal Soil Mechanics and Foundations Division, American Society of Civil Engineers, June, 1960.