SOME DYNAMIC BEHAVIORS OF UNDISTURBED COHESIVE SOILS FROM LABORATORY TESTS

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SYNOPSIS

Dynamic triaxial compression tests were carried out under several loading conditions on the cell pressure, frequency and magnitude of the axial pressure, on cohesive soils in the range of 0.5 kg/cm^2 to 16.0 kg/cm^2 of static unconfined compressive strength. By the tests under the stationary stress waves, following results are obtained; the plastic strain induced by repeated stress converges on a certain strain or progresses to the failure according to the magnitude of the stress; dynamic modulus of elasticity, coefficient of viscosity, Poisson's ratio and dynamic strength are related to the static strength and the loading conditions.

SYMBOLS

σ_a = mean value of the effective axial repeated stress (kg/cm^2).
σ_o = amplitude of the effective axial repeated stress (kg/cm^2).
ε_a = mean axial strain (%). ε_o = amplitude of axial strain (%).
ε_p = plastic axial strain (%). t = time (sec).
E_m, E_v = dynamic modulus of elasticity in case where Maxwell's model or Voigt's model is assumed respectively.(kg/cm^2).
η_m, η_v = dynamic coefficient of viscosity in case where Maxwell's model or Voigt's model is assumed respectively.(kg·sec/cm^2).
ω = circular frequency (1/sec). φ = loss angle.
Q^{-1} = loss tangent

INTRODUCTION

The purpose of this report is to present the appropriate mechanical behaviors of undisturbed cohesive soils under earthquake load. From results of an experimental study, plastic strain, elastic constants, yield and strength are obtained in dynamically. The behaviors are affected to the static strength, friquency and magnitude of repeated stress, confining stress and anisotropy of the soils. The results will be usefull on the dynamic design of structures considered with earthquake.

APPARATUS

Dynamic triaxial compression test equipment used for this report is illustrated in Fig. 1. The tube specimen is confined with water pressed by air and loaded vertically through a loading shaft by oil pressure. Confining pressure is adjusted statically by means of air

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valve with pressure gauge, and axial load is adjusted statically or oscillatory by means of servomechanism and oscillator.

Axial stress, axial strain, volumetric strain and pore water pressure are amplified and recorded on an electro magnetic oscillograph paper. Maximum speed of the paper feed is 1.0 m/sec, and timing lines at each 1/100 sec. are marked.

TEST PROCEDURE

The tested soils were got from nine different locations near Tokyo. These soils are classified to clay, silty clay, silty loam and silty clay loam. The static unconfined compressive strength were in the range of o.5 kg/cm^2 to 16.0 kg/cm^2. The specimens were cutted off from large block samples and trimed to 50 mm diameter, 125 mm height and in the directions of vertical, horizontal and oblique angle 45 deg. in order to see the effect of the direction in ground to mechanical behavior.

At least three specimens trimed to each direction from one block sample were tested by statical loading under different confined pressures from 0 to 3 kg/cm^2. Dynamic loading tests were carried out under same confined pressures as the static tests. Repeated axial pressure was sine curve shaped stationary load and the frequencies were taken some appropriate values from 0.3 Hz to 30 Hz to each soil.

Every soils were deformed plastically with repetition of the stress, and the plastic strain by each stress wave reduces under less stresses than a endurance limit, but under more stresses than the limit, plastic strain increases to failure. This behavior is classified into five tipical curves on the relation of the plastic strain and logarithmic number of the stress pulses, asshown in Fig. 2. These are; 1. the increment of the plastic strain obtained by one pulse of the dynamic stress decreases to zero gradually and the total plastic straines converge to a certain value. 2. The increment of the plastic strain by each pulse decreases gradually and the curve is oblique straight line. 3. once the increments of the plastic strain decrease to zero, and thereafter increase to failure suddenly. 4. the increments of the plastic strain decrease gradually as the curve is a straight line, and thereafter increase to failure suddenly. 5. the increments of the plastic strain increase to failure and the curve decline.

Accordingly, it seems that behaviors of soils could be researched from the three points of view as follows; 1. the mechanical behavior before plastic strain converges to a critical value. 2. the stationary elastic response after plastic strain converges to the critical value. 3. the mechanical behavior of yield and failure.

For many soils the endurance limit were nearly equal to the values of the static strengths, but for weak soils as the static strength is less than 1.0 $kg/cm^2$and yield point is indistinct, the limits were considerably less than the static strength. Under repeated loads less than 70 % of the static strength, the plastic strains of many soils increased to a certain value, however in the weak soils increments of the plastic strain were almost stationary value and the failure didn't occur suddenly.

When the maximum value of the repeated stress is less than about 70 % of the static strength, the behavior of soils may be considered to be in stationary state. In this research, dynamic elastic behavior was observed to the amplitude of the repeated stress from 1/3 to 2/3 of the static strength of the soil. The range of amplitude corresponds to the stress of soil under the foundation occured by the earthquake design load in Japan.

The relation of failure surfaces of a soil in ground and the test specimens are shown in Fig. 3. In the figure, the case where the angle between the axis of principal stress and the failure surface is 45 deg. is shown. On the tested samples, the direction of failure surface was not in a specific direction of ground.

Influence of the pore water pressure to the effective stress during stationary response was negligible small.

Response of soil to the repeated load in the range mentioned above may be substituted by a model consisted of some combinations of elastic spring and dashpot. When Maxwell's model or Voigt's model is assumed, the coefficients can be estimated from the test results on the response amplitudes and phase differences between the load and the response.

By Maxwell's model, under the stress $\sigma = \sigma_a - \sigma_o \cos\omega t$, ($\sigma_a \geq \sigma_o$) the strain is represented as follows;

$$\varepsilon = \frac{\sigma_a}{E_m} + \frac{\sigma_a}{\eta_m} t - \varepsilon_o \cos(\omega t - \varphi) \quad \text{from} \quad \dot{\varepsilon} = \frac{1}{E_m}\dot{\sigma} + \frac{1}{\eta_m}\sigma$$

where $\varepsilon_o = \frac{\sigma_o}{E_m}\sqrt{1 + \frac{E_m}{\eta_m^2 \omega^2}}$, $\varphi = \tan^{-1}\frac{E_m}{\eta_m}\omega$

if $\varepsilon_p, t, \sigma_o$ are given,

$$_c\eta_m = \frac{\sigma_o}{\varepsilon_p} t$$

and if $\sigma_o, \omega, \varepsilon_o, \varphi$ are given,

$$E_m = \frac{\sigma_o}{\varepsilon_o \cos\varphi} \quad , \quad \eta_m = \frac{\sigma_o}{\varepsilon_o \cdot \omega \cdot \sin\varphi}$$

By Voigt's model, under the stress $\sigma = \sigma_a - \sigma_o \cos\omega t$, the strain is represented as follows;

$$\varepsilon = \frac{\sigma_a}{E_v} - \varepsilon_o \cos(\omega t - \varphi) \quad \text{from} \quad \eta_v \dot{\varepsilon} + E_v \varepsilon = \sigma$$

where $\varepsilon_o = \frac{\sigma_o}{\sqrt{\eta_v^2 \omega^2 + E_v^2}}$, $\varphi = \tan^{-1}\frac{\eta_v \omega}{E_v}$

if $\varepsilon_o, \sigma_o, \omega, \varphi$ are given

$$E_v = \frac{\sigma_o \cos\varphi}{\varepsilon_o} \quad , \quad \eta_v = \frac{\sigma_o \sin\varphi}{\varepsilon_o \omega}$$

Damping of the soil is represented by loss tangent $Q^{-1} = \tan\varphi$ either model, where φ is the phase difference between the load and the response.

TEST RESULTS

PLASTIC STRAIN Static yield strain decreases rapidly with the increase of static strength, but when the static strength is more than 2 kg/cm^2, the yield strain doesn't so much vary. The curve 1 in Fig.4 shows the fact. The relation between the plastic strains occured by a same number of repetition of the stress and the static strength has a similar tendency to that of the yield strain and the static strength.

The plastic strains occured by 10 pulses of the stresses of 90 % and 70 % of the static strength are shown by curves 2 and 3 in Fig.4.

DYNAMIC MODULUS OF ELASTICITY was not so much affected from assumed model. In some soils the value increases slightly with increase of frequency, but the variation is not so large.

Modulus of elasticity is related with the static strength and the range of stresses. In the case where the range of repeated stress is in 1/3 to 2/3 of static strength of thelsoil, dynamic modulus of elasticity has a certain value between the static modulus and dynamic modulus estimated by means of the theory of elastic wave using the results of elastic wave test on ground, as shown in Fig. 7. The result may be caused by the rate and the range of stresses.

Effect of confining stress to dynamic or static modulus of elasticity may be estimated by the use of increased static strength with the confining stress.

As the test results on the specimens trimed in the directions of vertical, oblique angle 45 deg. and horizontal in ground, it is obtained that the order of values of moduli of elasticity was the same order as above, but the variation was not so much as over the range of the scatter on the tested soils.

DYNAMIC POISSON'S RATIO in the range of stationary response was not different from the static value regardless of confining stress, magnitude of repeated stress, frequency and direction of specimen.

Dynamic and static Poisson's ratios of soils were related with static strength and closed mutually, as shown in Fig.9 .

DYNAMIC COEFFICIENT OF VISCOSITY η_m and η_v were reduced rapidly with increasing of frequency. There is a large difference between the coefficients assumed Maxwell's and Voigt's models. When Maxwell's model is assumed, the coefficient estimated from creep strain $c\eta m$ was quite different from the value ηm estimated from loss angle, and was not affected from frequency. The coefficient of viscosity $c\eta m$ of a certain weak soil specimen trimed horizontal was about a quater of the values of vertical or 45 deg.'s one.

The coefficient $c\eta m$ is related with the static strength as shown in Fig. 10 .

Loss tangent Q^{-1} don't so much vary with the friquency, and the directions of specimen. The value of loss tangent Q^{-1} is related with the static strength as shown in Fig.8 .

YIELD During plastic strain increases to failure, envelope of the peaks of repeated strains was similar to the static curve as shown in Fig. 12. Envelope of the peaks of the curve of pore water pressure and the axial strain was also similar to static curve.

The increment of plastic strain per one pulse was minimum at the strain near the static yield strain. It is suggested that the dynamic yield point is this point. Dynamic yield stress was about five per cent smaller than the dynamic strength in case of soil specimen broke by the same number of cycles as yield, as shown in Fig.14 .

Poisson's ratio become 0.5 after yield to failure.

FAILURE The ratio of the dynamic strength to the static strength was related to the number of repetitions till failure.

Dynamic failure was mostly caused slide at shearing face as static failure.

Under a certain ratio in per centage, S_n, of the repeated stress to the static strength, soil break after a number, N , of repeated cycles. The relation between logarithms of S_n and N is represented by a linear line as shown in Fig.14 . Then the line is determined by S_1 and the inclination α. Standard deviation to the line was about 20 % to most of tested soils and scatter was large. S_1 were about 200 % to 90 %, and it should seem that larger S_1 value is obtained to the soil of larger static strength.

When soils had static internal friction or broke in a few number of cycles, dynamic internal friction was larger than the static value, whereas when soils had no static internal friction or broke after many number of cycles, dynamic internal friction was equal to the static value.

CONCLUSION

By the dynamic triaxial compression tests, it is found that the dynamic behaviors of soil may be related with the static strength, the range of repeated stress, and the progress of plastic strain.

When the test results are used in the dynamic analysis of structures, it should be taken care that the moduli of elasticity estimated from static test, dynamic tests,and elastic wave test differ fairly in the value, and the value of coefficient of viscosity varies by the selected Model.

REFERENCE

1. Seed, H.B.; Clay strength under earthquakes loading conditions. 1966, Journal ASCE
2. Seed, H.B.; Cyclic strain characteristics of clay. 1968, Journal ASCE
3. Ohkubo,Terasaki; Physical properties and rate of elastic wave of rock. 1971, Soils and Foundations (Japanese)
4. Enami,A.,Abe,T.; Dynamic triaxial compression test of a silty loam. 1969 Proc. of AIJ
5. 6.7. Enami,A., Ohhashi,M.; Research on dynamic tryaxial compression characteristics of cohesive soils. 1970,71,72. Proc of symposium of AIJ.

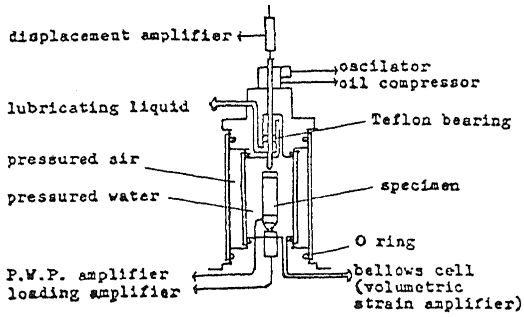

FIG. 1 Main features of the dynamic triaxial compression apparatus.

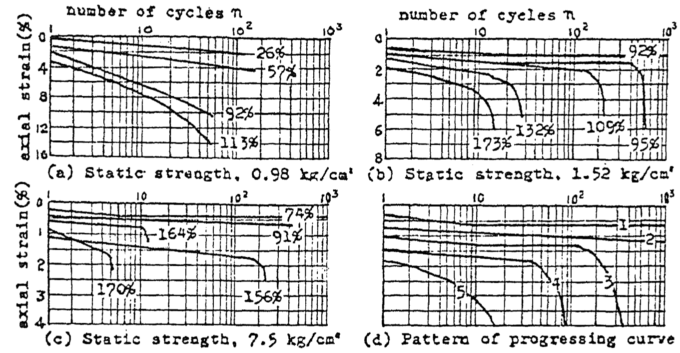

FIG. 2. Classification of the progress of plastic strain due to the repeated stress. Values (%) in Fig. represent the ratio of repeated stress (max.) to static strength.

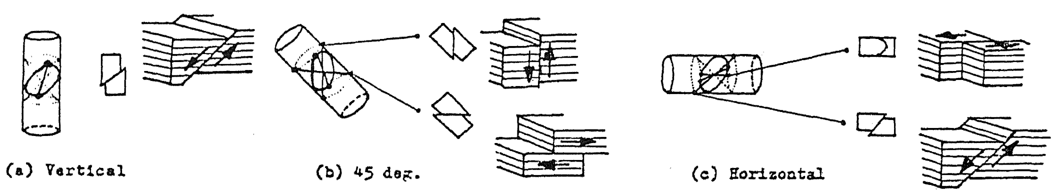

FIG. 3. Probable angles of the failure surfaces of specimens trimed to various directions in the ground.
(a) The failure angle of the specimen trimed vertically are 45 deg. in the ground.
(b) The angles of the 45 deg. specimen are varying between vertical and horizontal in the ground.
(c) The angles of the horizontal specimen are varying between vertical and 45 deg. in the ground.

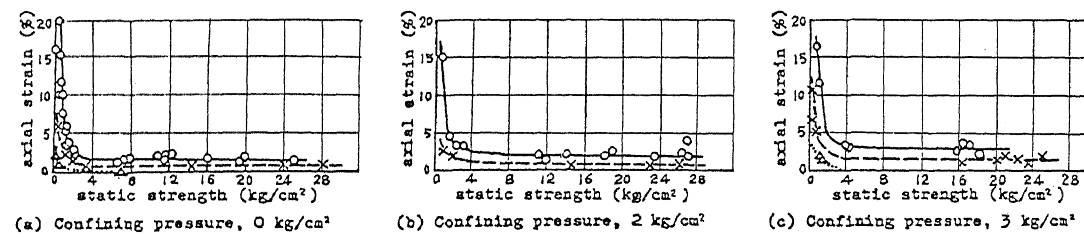

FIG. 4. Relationship between yielding strain, plastic strain due to the repeated stress in 5 seconds, and static strength.

1. —o— static yield
2. --x-- repeated stress equal to 90% of static strength
3. ...△... repeated stress equal to 70% of static strength

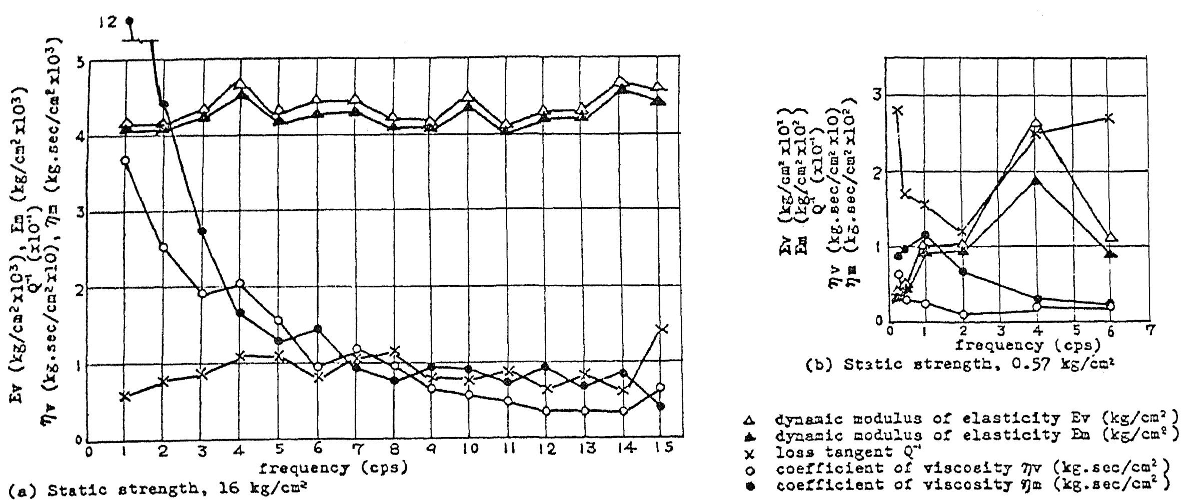

FIG. 5. Variation of the dynamic constants of soils with increasing of the stress frequency.

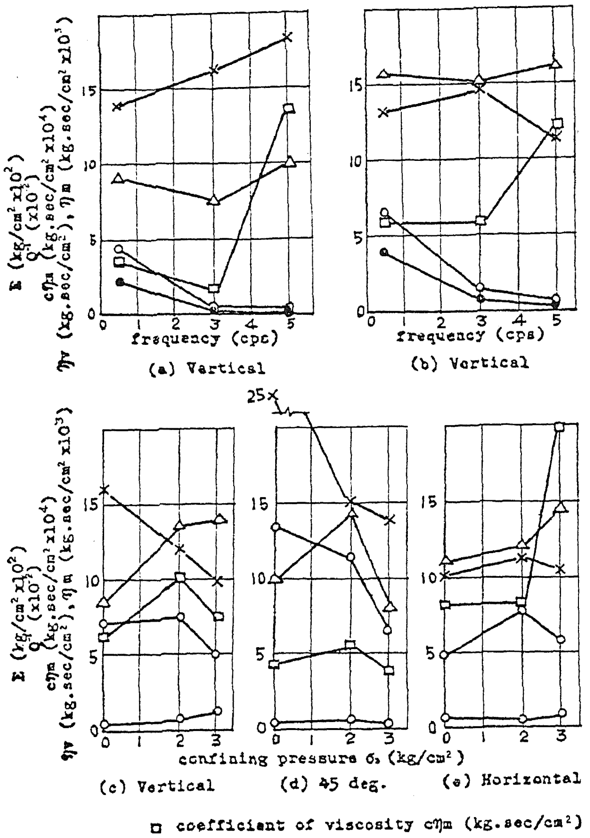

FIG. 6. Variation of the dynamic constants with the confining pressure and the direction in the ground. (Frequency 3Hz, static strength qu=2.35 kg/cm².)

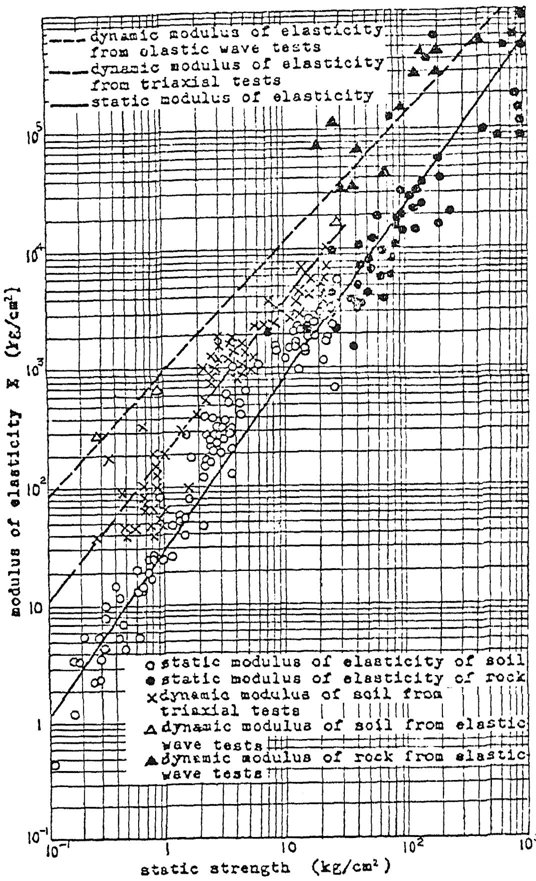

FIG. 7. Relationship between the static strength and the modulus of elasticity.

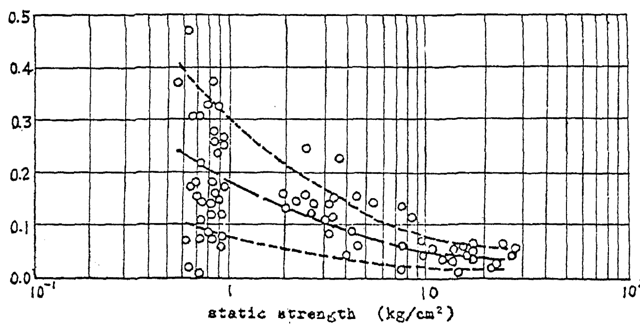

FIG. 8. Relationship between the static strength and the loss tangent.

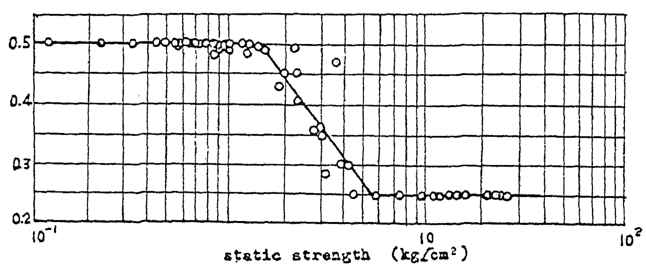

FIG. 9. Relationship between the static strength and the Poisson's ratio. Poisson's ratio of dynamic and static are almost same before yield.

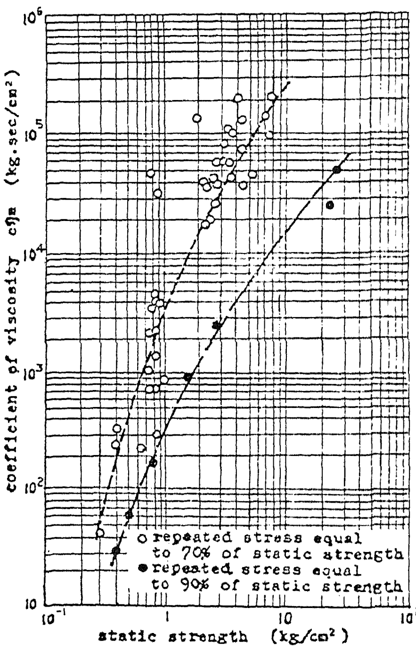

FIG. 10. Relationship between the static strength and the coefficient of viscosity.

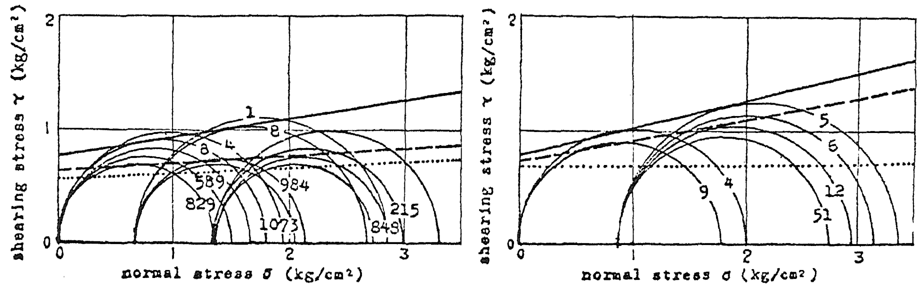

FIG. 11. Dynamic and static internal friction. Numbers (N) in Fig. represent the number of cycles to failure.

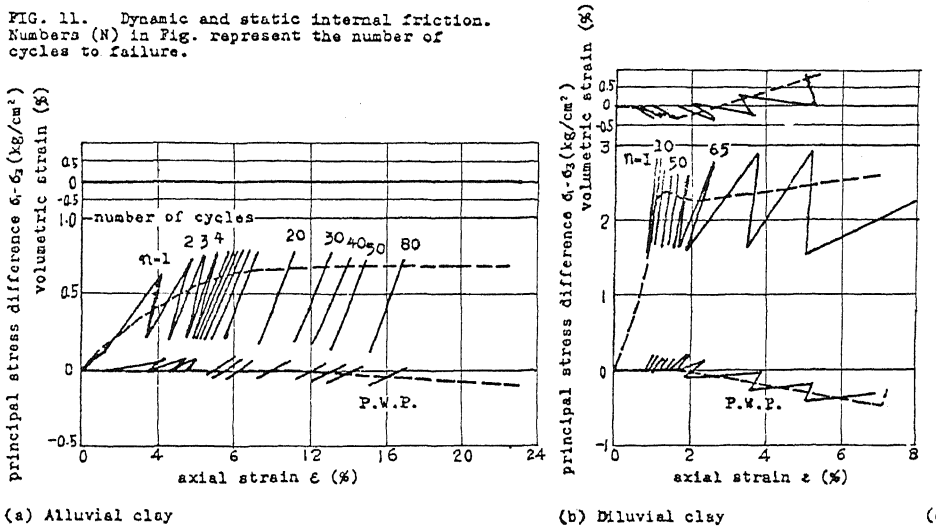
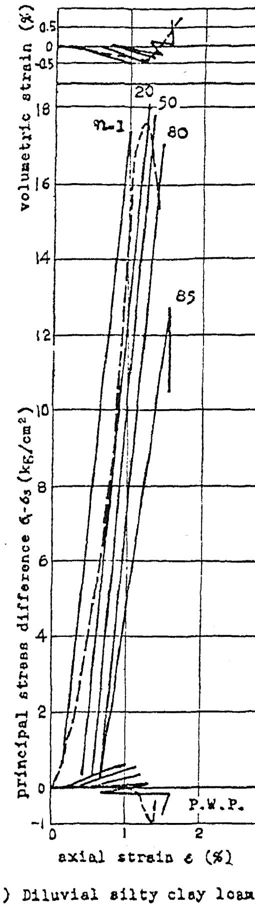

FIG. 12. Dynamic and static stress-strain curve, volumetric strain-axial strain curve, and pore water pressure-axial strain curve. Dynamic behavior is similar to the static one.

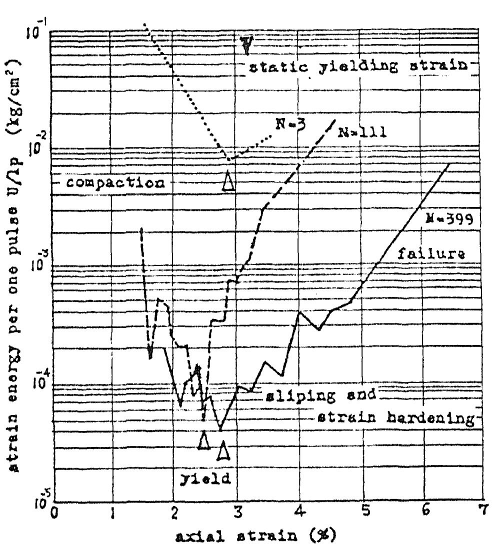

FIG. 13. Transition of strain energy per one pulse with the axial strain. Static strength, 1.25 kg/cm².

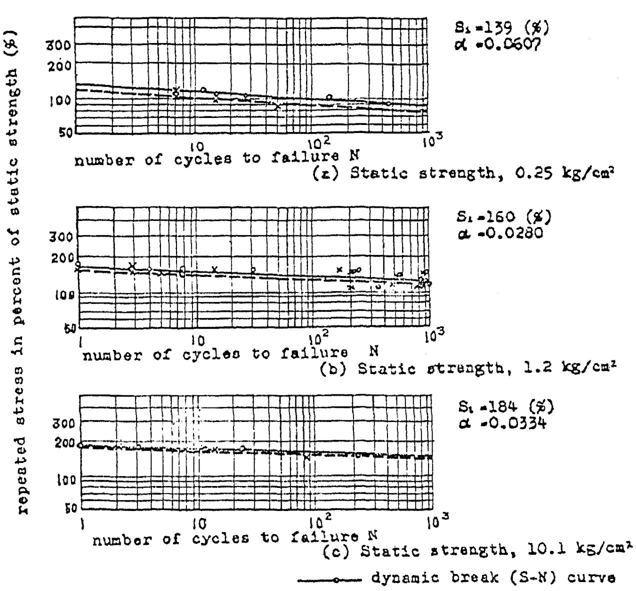

FIG. 14. Relationship between the repeated stress and number of cycles to yield or failure.