12 Mar 1991, 2:30 pm - 3:30 pm

Deformation of Reconstituted Clay Under Cyclic Loading

S. W. Yan
Tianjin University, China

D. J. Williams
The University of Queensland, Australia

Proceedings: Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, March 11-15, 1991, St. Louis, Missouri, Paper No. 2.29

Deformation of Reconstituted Clay Under Cyclic Loading

S.W. Yan
Associate Professor in Geomechanics, Tianjin University, China

D.J. Williams
Senior Lecturer in Geomechanics, The University of Queensland, Australia

SYNOPSIS Reconstituted soft clay triaxial specimens were prepared by means of vacuum preloading. Both static and cyclic tests were carried out, with the specimens consolidated under different principal effective stress ratios. The test results lend themselves to incorporation in a finite element formulation, which can readily be used for calculating the deformation of soft clay under cyclic loading.

INTRODUCTION

When acted on by cyclic loads, soft clays tend to develop both "dynamic" and permanent deformations. The former are recoverable (elastic) as the loads are released, while the latter develop incrementally as the number of load cycles increases, and are irrecoverable (plastic). Buildings in the Tanggu area (east of Tianjin, People's Republic of China) underwent settlements of up to 300 mm during the Tangshan earthquake in 1976. Semi-submersible drilling rigs working in Bohai Gulf, People's Republic of China, settled 500 to 800 mm as a result of severe storms lasting more than 10 hours. Both of these areas are underlain by thick layers of soft clay. It is therefore important to have a reliable method for evaluating the permanent deformation of soft clay foundations where cyclic loading is expected.

In the field, vacuum preloading is used as a means of strengthening soft clays, particularly offshore. The method can also be used in the laboratory to prepare large homogeneous soil samples for testing. Accordingly, the behaviour of soft clay under the action of cyclic loading was studied in the laboratory using reconstituted soft clay triaxial specimens prepared by means of vacuum preloading.

Both static and cyclic triaxial compression tests were performed, with the specimens consolidated under two different principal effective stress ratios. . The experimental results obtained reveal that there are no fundamental differences between the strength behaviour of soft clay under the action of cyclic loading compared with that under static loading. The constitutive relationships used in analysing static loading can therefore also be used in estimating permanent deformations due to cyclic loading. This enables relatively simple finite element analyses to be used for both loading cases.

DESCRIPTION OF TESTING PROGRAM

Specimen Preparation

Specimens were prepared from reconstituted Xingang (New Harbor) clay taken from Tanggo, People's Republic of China. To ensure that homogeneous specimens were available for the entire series of tests, a vacuum preloading technique was adopted for sample preparation. Initially, a clay slurry with a moisture content of about 71 % was prepared. The slurry was poured into a 1 000 mm by 500 mm by 500 mm container, over which a rubber membrane was placed. The membrane was then sealed air-tight and a pump connected to the container through a pipe to remove the air and excess water from the slurry, as shown in Fig. 1. To accelerate drainage, a geotextile layer was placed adjacent to the inner wall of the membrane. A vacuum pressure of about 70 kPa was maintained at the membrane to preload the sample.

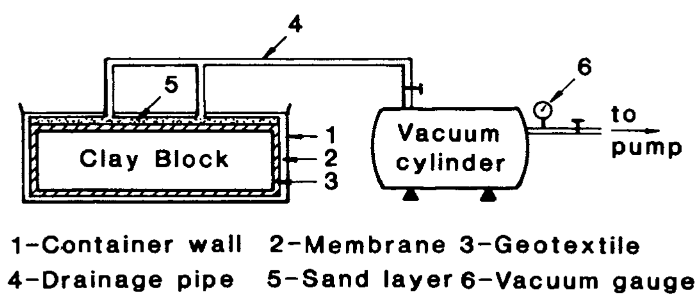

Fig. 1. Scheme for Vacuum Preloading

After 15 days of vacuum preloading, the moisture contents at the upper, middle and lower thirds of the block of clay in the container were 44.4, 45.0, and 45.0 %, respectively, showing that the sample was essentially homogeneous. Representative values for some geotechnical properties of the reconstituted Xiagang clay are listed in Table I.

Testing Procedures

Specimens 50 mm in diameter and 120 mm high, cut from the reconstituted clay block, were used for both the static and the cyclic triaxial compression testing. In the static tests, consolidation under a given confining stress and stress ratio was followed by undrained shearing with pore water pressure measurement. In the cyclic tests, consolidation was followed by undrained cyclic loading, prior to undrained shearing with pore pressure measurement.

TABLE I. Representative Values for Some Geotechnical Properties of Reconstituted Xiagang Clay

Water content	w	45 %
Liquid limit	w_L	43 %
Plasticity index	I_P	19.1 %
Specific gravity	G_S	2.75
Unit weight	γ	17.5 kN.m^{-3}

Both the static and cyclic triaxial tests were carried out with two different consolidation effective stress ratios $R = \sigma_{1'}/\sigma_{3'}$; namely, R = 1 (isotropic) and R = 1.5 (anisotropic). In the cyclic tests, two different frequencies f of cycling were used; namely, f = 1.0 Hz and f = 0.5 Hz. Cycling was applied in stages of increasing load level. In the first stage of each test, a cyclic stress σ_d of 25 kPa was applied 300 times. In subsequent stages, the cyclic stress was increased by an amount $\Delta\sigma_d$ (given in Table II), and applied 300 times, with failure occurring during either the third or fourth stages.

The cyclic triaxial test conditions are summarised in Table II. In most of the tests, the specimens were normally consolidated (that is, the confining stress was larger than the vacuum pressure). In no cases were the specimens more than lightly over-consolidated. The loading sequence used in the cyclic triaxial tests is shown diagramatically in Fig. 2. Cycling under undrained conditions led to the development of excess pore water pressure, and the corresponding decrease of effective confining stress, leading to the eventual failure of the specimen.

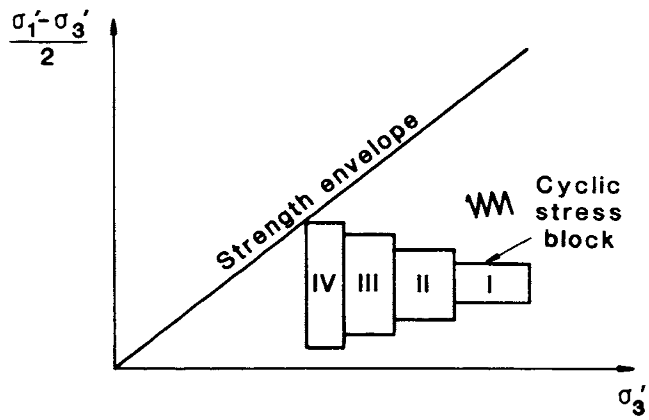

Fig. 2. Cyclic Loading Stress Path

A static triaxial test can be considered as a special cyclic test with f = 0.0. The confining stresses adopted in the sixteen static triaxial tests were identical to those used for the cyclic tests (Table II).

TABLE II. Cyclic Triaxial Test Conditions

Specimen No.	Confining stress $\sigma_{1'}$ (kPa)	$\sigma_{3'}$ (kPa)	$\Delta\sigma_d$ (kPa)	f (Hz)
1	80	80	15	1.0
2	100	100	15	1.0
3	120	120	20	1.0
4	150	150	20	1.0
5	80	80	15	0.5
6	100	100	15	0.5
7	120	120	20	0.5
8	150	150	20	0.5
9	75	50	10	1.0
10	100	67	10	1.0
11	120	80	10	1.0
12	150	100	10	1.0
13	75	50	10	0.5
14	100	67	10	0.5
15	120	80	10	0.5
16	150	100	10	0.5

CUMULATIVE STRAIN, STRENGTH AND EFFECTIVE STRESS

Figures 3(a) and (b) show the cumulative axial strain ε_c and the cumulative pore water pressure u_c, with increasing number of cycles N, for a representative specimen. Figure 3(a) illustrates that ε_c increases with N nearly linearly. The strain develops very slowly when the magnitude of the cyclic stress is small. With increasing magnitude of the cyclic stress, the accumulation of strain becomes increasingly rapid.

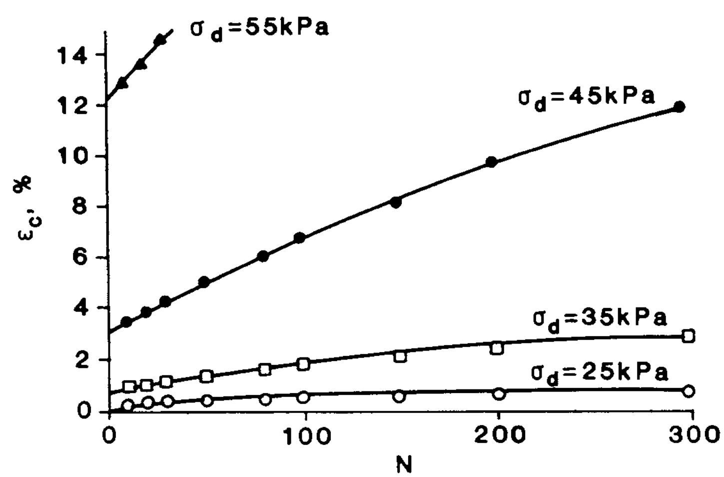

Fig. 3(a). Cumulative Axial Strain ε_c Versus Number of Cycles N at each Cyclic Stress Level

Immediately the cyclic stress level is increased, u_c increases very rapidly, and then increases more slowly.

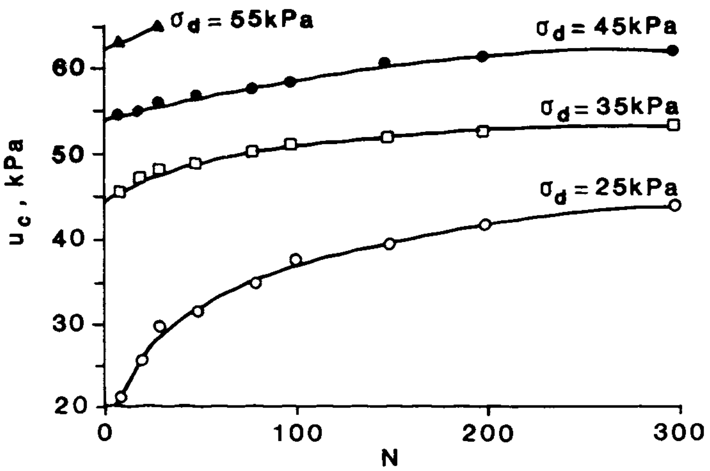

Fig. 3(b). Cumulative Pore Water Pressure u_c Versus Number of Cycles N at each Cyclic Stress Level

It is well known that normally consolidated (and lightly over-consolidated) clay subjected to static loading exhibits unique relationships between effective stresses, deformations, and the strength of the soil. As shown in Fig. 4, u_c resulting from cyclic loading can be normalised with respect to the mean effective stress $\sigma_{m'}$ (where $\sigma_{m'} = 1/3\ [\sigma_{1'} + 2\ \sigma_{3'}]$), and the results represented by one curve. This curve is independent of the magnitude of the confining stress, the loading method, and the magnitude and frequency of the cyclic loading. However, it does depend on R.

According to the principle of effective stress, if the average total stress is unchanged, any increase in pore water pressure is equal to the decrease in effective stress. Fig. 4 shows that the relationship between $u_c/\sigma_{m'}$ and ε_c is unique for a given R. Therefore, since the average total stresses do not change during each test, the relationship between the effective stress, normalised by $\sigma_{m'}$, and ε_c is also unique for a given R.

Although it has been reported that cyclic loading can reduce the strength of a soft clay, tests on undisturbed soft clay carried out by Janbu (1985) showed no strength reduction due to prior cyclic loading. The test data compared in Fig. 5 illustrate that the "dynamic" effective stress strength parameters $c_{d'}$ and $\phi_{d'}$ (0 and 25 °, respectively) determined following cyclic loading are indistinguishable from the static strength parameters c' and ϕ'. This is provided the same failure criterion is adopted both for axial strain in static triaxial tests and for cumulative axial strain in cyclic triaxial tests, these being the irrecoverable strains in each case.

FINITE ELEMENT FORMULATION

Under the action of cyclic loading, the pore water pressure within a soil deposit increases. In most earthquake and storm-loading of soft clay deposits, the effect of consolidation during cyclic loading can be ignored since the permeability of a clay is very low and the duration of cyclic loading is usually short (from a few minutes to several hours). In this paper, only cumulative strain and pore water pressure are considered. The deformation caused by the dissipation of cumulative pore water pressure after the end of cyclic loading can be estimated by any suitable consolidation theory.

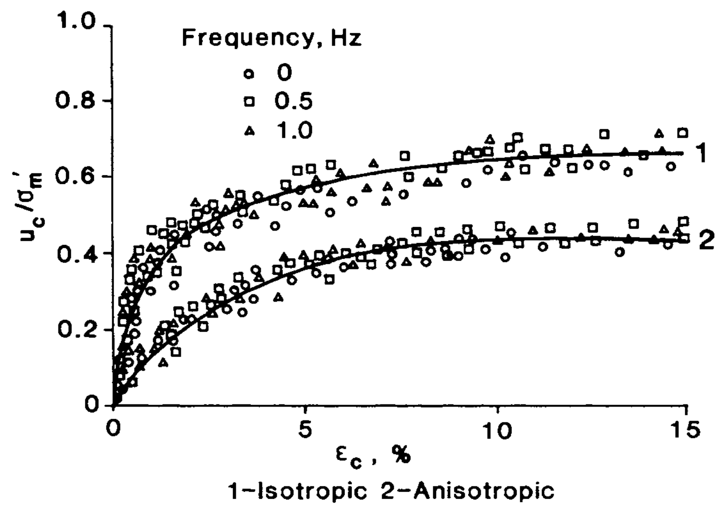

Fig. 4. Cumulative Pore Water Pressure Normalised by Mean Effective Stress $u_c/\sigma_{m'}$ Versus Cumulative Axial Strain ε_c

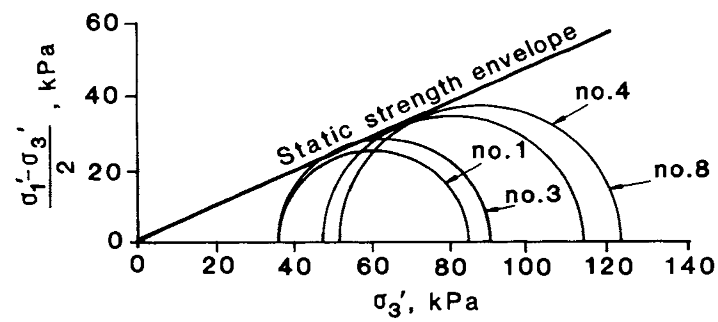

Fig. 5 Comparison Between "Dynamic" Mohr Circles for Tests 1, 3, 4 and 8, and Static Strength Envelope

As has been shown in Fig. 4, for saturated normally consolidated (and lightly over-consolidated) soft clay, whether under static or cyclic loading, a given cumulative pore water pressure (normalised by the average consolidation pressure) corresponds to a unique permanent axial strain. N cycles of cyclic load applied to a saturated soft clay specimen will give rise to a given u_c and a given ε_c. Alternatively, if a deviator stress $(\sigma_{1'} - \sigma_{3'})$ applied to the same specimen gives rise to the same pore water pressure, then the same axial strain would be expected. Therefore, a complicated dynamic deformation problem can be reduced to a simple static one, which is much easier to analyse. Using this approach, a finite element analysis can be applied as follows:

(1) Estimation of Cumulative Pore Water Pressure

The following equation is given by Janbu (1985) to evaluate the value of u_c developed in a saturated soft clay subjected to cyclic loading.

$$u_a = A.\log_{10} N + B \qquad (1)$$

where "u_a", is the cumulative pore water pressure, "N", is the number of cycles, and "A" and "B", are experimental constants related to the consolidation stresses.

(2) Equivalent Deviator Stress Change

The following equation gives an empirical relationship between pore water pressure and deviator stress (Qian, 1988).

$$u = (\sigma_1 - \sigma_3)/3 + C.(\sigma_1 - \sigma_3)^2 \qquad (2)$$

where "u", is the pore water pressure, and "C", is an experimental constant. Equation (2) allows calculation of the deviator stress needed to induce a given pore water pressure equal to that due to a particular level of cyclic loading.

(3) Stress - Strain Relationship

Any suitable constitutive relationship can be used for calculating the cumulative (plastic) deformation of soft clay subjected to cyclic loading.

(4) Nodal Force Transformation

The nodal force transformation may be expressed as

$$\{\Delta P\} = - \int_V [B]^T.\{\Delta\sigma\}.dV \qquad (3)$$

where "$\{\Delta P\}$", is the incremental nodal force vector, "[B]", is the geometry matrix, "$\{\Delta\sigma\} = (\sigma_1 - \sigma_3)$", is the incremental deviator stress calculated using Equation (2), and "V", is the volume of the soil element.

For a design storm or earthquake, the magnitude, frequency, and number of cycles of load can be selected. Then u_c of a soil element can be predicted using Equation (1), and this can be converted using Equation (2) into an equivalent deviator stress. Using Equation (3), the equivalent deviator stress can be transformed to nodal force vector form. The finite element procedure can then be performed in the usual way.

CONCLUDING REMARKS

1. The use of vacuum preloading provides an excellent means of preparing homogeneous specimens. No special equipment nor heavy loading facilities is required.

2. The relationship between the effective stress, normalised by $\sigma_{m'}$, and ε_c under cyclic loading is unique for a given R.

3. The effective stress strength parameters for reconstituted Xingang clay, determined following cyclic loading, are identical to those determined in static triaxial tests.

4. Based on the above conclusions, normal finite element analysis procedures involving static loading can be used to calculate the permanent deformation of saturated soft clay subjected to cyclic loading.

REFERENCES

Andersen, K.H. (1980), "Cyclic and Static Laboratory Tests on Drammen Clay", Proc. ASCE, J. Geot. Eng. Div., Vol. 106, No.GT5, 499-529.

Janbu, N. (1985), "Soil Models in Offshore Engineering", Geotechnique 35, No.3, 241-281.

Qian S.Y. (1988), "Pore Water Pressure Performance in Triaxial Testing", Chinese Geotechnical Engineering J., Vol.7, No. 1, 1-9 (in Chinese).