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Cyclic Loading on Clays

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SYNOPSIS Experimental results using triaxial undrained cyclic tests on remolded and non remolded clays are exposed. The influence of the clay structure is shown by choosing four clays with different mineralogies (kaolinite, illite, bentonite, marl). Different overconsolidation ratios are used and the fatigue phenomenon is studied in relation to the evolution of the effective stress path.

INTRODUCTION

We here expose a survey of experimental results obtained at the laboratory of soil mechanics of the Ecole Centrale de Paris using triaxial undrained cyclic tests on remolded and non remolded clays.
We have chosen clays with different mineralogies : a kaolinite, an illite, a bentonite and a marl. On each type of material we have followed number of stress paths in cyclic loading, starting from an initial isotropie state. From the results of these tests we are trying to understand the physical mechanisms involved in the fatigue phenomenon and especially to show the important influence of the initial structure on the behaviour during the cyclic loading.

REVIEW OF THE BEHAVIOUR OF CLAYS UNDER UNDRAINED CYCLIC LOADING

When a sample of clay is subjected to some undrained cyclic sollicitations a progressive change appears in the stress-strain relationship during the cyclic loading. It appears differently according to the nature of the sollicitation. Yet as a general rule it corresponds to a reduction of the mechanical properties of the sample (decrease of the shear modulus, residual deformation appears) When the deviatoric stress (q_C) remains of the same sign the significant parameter is the permanent deformation (ε_p). It is the progressive accumulation of this deformation with respect to the number of cycles which respresent the material damage. On the other hand the secant modulus of the cycle depends essentially on the amplitude of the stress and its reduction is still limited and occurs mainly during the first cycles (Fig. 1.)
When the deviatoric stress changes its sign during the cycle there is both an evolution of the permanent deformation and an evolution of the modulus. In this particular case where q_C is symmetrical to 0 (isotropic state) the deformation $_p$ does not vary strongly. It is the amplitude of the cyclic deformation (ε_C) which increases and may grow to large values (a few percents) until the failure of the sample (Fig. 2.).

The heigher the cyclic stress amplitude is, the larger the evolution rate of the clay is. When the stresses are high the deformations may in a few cycles become very large. On he other hand when the stresses are lower we may observe after amore or less important number of cycles a decreased rate of deformation which can lead to the stabilization of the cycle which goes with a stabilization of the effective stress. Therefore a cyclic stress limit does exist below which a state of stabilization of the material in cyclic loading is reached and the value of which changes according to the nature of the clay (Fig. 3.).

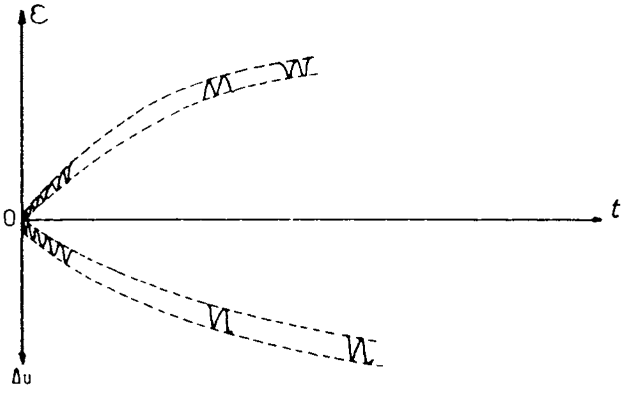

Fig. 1. One-way cyclic triaxial test

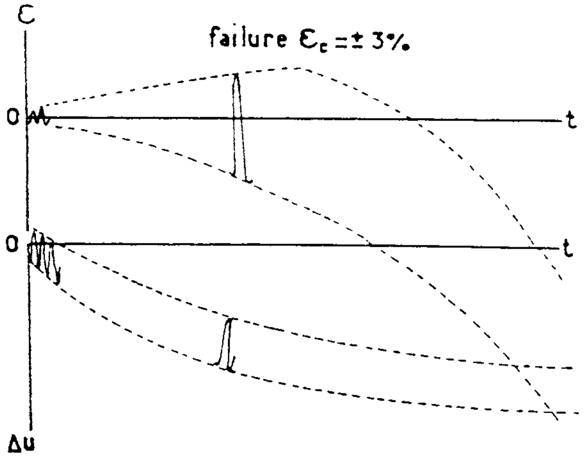

Fig. 2. Two-way cyclic triaxial test

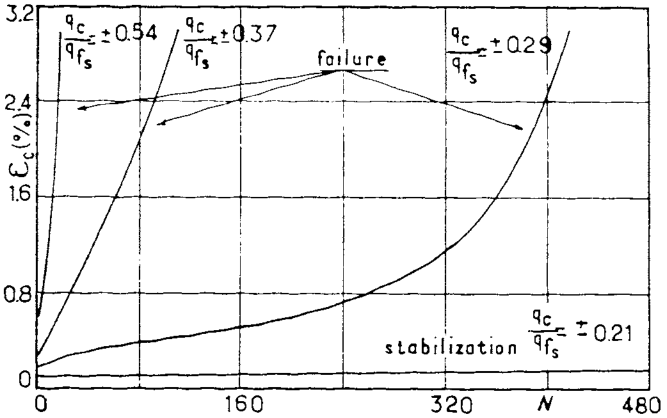

Fig. 3. Two-way triaxial tests at different constant cyclic stresses

In order to represent the behaviour of a clay under cyclic loading we may draw through the use of constant cyclic stress tests the isodeformation curves in a (q_c - log N) plane. We obtain a family of curves equivalent to the Wohler ones used for the metal fatigue (Fig. 4.).

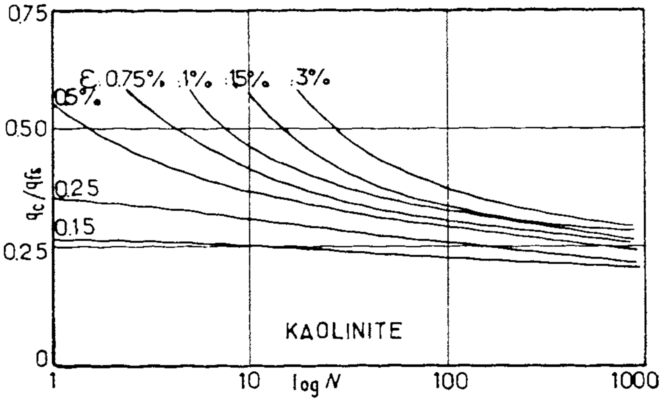

Fig. 4. Isodeformation curves. Two-way cyclic triaxial tests

These curves are dependant on some parameters. We shall in the next two sections examine the role played by the initial structure of the clay.

INFLUENCE OF THE CLAY MINERALOGY

The clay mineralogy determines its particules arrangement and therefore is an important factor of the initial structure. From a mechanical point of view an initial arrangement may be modified by an external stress changing the equilibrium of the system. The less stable the initial arrangement is the more numerous the possibilities of evolution are. Under cyclic loading it will be easier for the particles arrangement to modify itself in the case of a floculated arrangement than in the case of a dispersed one.
In order to illustrate the last remark we have taken three materials of a different mineralogy prepared in the laboratory : a kaolinite which has non-oriented structure; an illite and a bentonite wiich have oriented structures. The bentonite has a more important adsorbed water layer than the illite.
We have performed on each clay several cyclic tests and we have drawer the isodeformation curves in the plane (q_c - log N). The results show a very different behaviour for each of the three clays tested. We have summed them up on the following curves : the figure 5 shows the ± 3% cyclic deformation curves. They are extremely different although the original deformations are almost identical between the kaolinite and the bentonite and smaller for the illite.

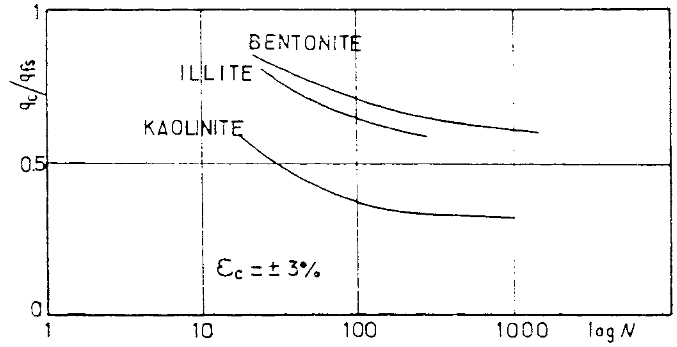

Fig. 5. Influence of the mineralogy on the isodeformation curves

On the figure 6 we have drawn the evolution of the cyclic deformation for three tests with a value of the ratio q_c/q_{fs} approximatively constant. We can see that the evolution of the kaolinite is very fast and gives large deformations (ε_c = ± 3% for 19 cycles). The illite on the contrary evolue slightly during the 300 first cycles. Then the cyclic deformation amplitude increases rapidly up to ± 3% for N = 400 cycles.
The evolution of the bentonite is the slowest of the three the ± 3% deformation being only reached for N = 1300 cycles.

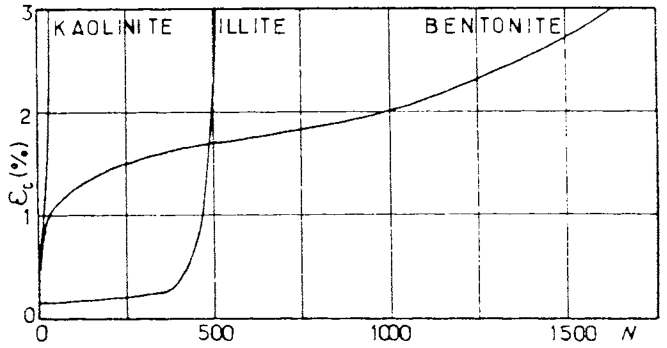

Fig. 6. Two way cyclic triaxial tests. Influence of the mineralogy

The difference observed between the illite and the bentonite is linked to the importance of the adsorbed water layer which can also be assessed by the following ewample. We have tested the kaolinite with a pore water with the Na ion normally concentrated (the marine sediments are generally in these conditions). The sodium ion has a large radius of hydratation and thus will increase the adsorbed water layer. It will contribute by this fact to create a more oriented structure. The maximal resistance (q_{fs}) determined by the triaxial monotonous test is not modified. The figure 7 shows the comparaison between the results obtained on the saltless kaolinite and on the kaolinite NaCl (N) for a same value of q_c/q_{fs}. The difference in the behaviour appears clearly. The evolution of the deformation and of the pore pressure is slower with the kaolinite NaCl (N) case for identical starting values.

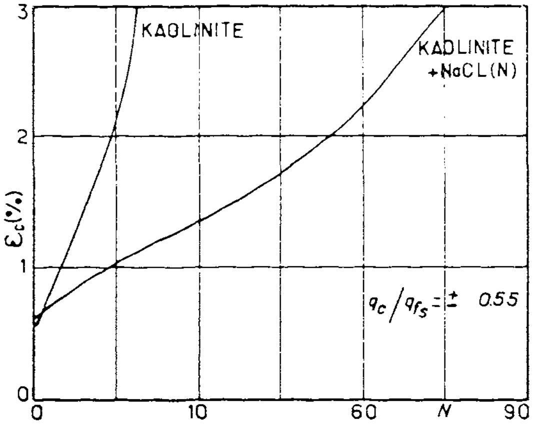

Fig. 7. Influence of the cation of hydratation on the evolution of the kaolinite under cyclic loading

Therefore we can classify the clays according to their initial particules arrangement into the following categories : a sensitive material; a half-sensitive material and almost not sensitive material to the cyclic loading. Some cyclic tests have been performed by the Norwegian Geotechnical Institute on Drammen Clay (1975). It is a clay composed essentially of Feldspar and Hydromica slightly altered and with a rather small (45 to 65%) Clay content (< 2 μ). It is thus very similar to the illite with respect to the type of materials and to the kaolinite as regard to the fact that materials are slightly altemed and that it is a sandy clay. The results obtained by the N.G.I. confirm our analysis. The curve ε_c = ± 3% in the plane (q_c - log N) is between the kaolinite curve and the illite one.
The initial structure will play an important part in the clay sensitivity to cyclic loading. It will influence essentially the rate of evolution of the phenomenon (the number of cycles). We can say that the mechanical behaviour of the clay under cyclic loading will depend on the type of particles organization as welle as on the material density and on the characteristics and the density of the interparticular forces linked to the importance of the adsorbed water layer (influence of the hydratation radius of the cations within the pore water).

INFLUENCE OF THE OVERCONSOLIDATION RATIO

The most important fact is the evolution of the pore pressure. In the case of a normal consolidation or weakely overconsolidation we always have a pore pressure increase and we can say that the evolution of clays under cyclic loading will depend essentially on a decrease of the effective stresses. As a matter of fact the evolution of the pore pressure and the evolution of the cyclic or residual deformation are linked together. The appearance of large deformations occurs when the state of effective stresses linked with the cyclic stress maximum reaches the critical state line defined by the classical monotonous tests. So the decrease of the mechanical properties of the clay appears here as being essentially determined by the decrease of the effective stresses (Fig. 1 and 2). On the other hand the overconsolidated samples show smaller increases or even no increase at all, as well as some diminutions for high overconsolidation ratio. Thus the nature of the fatigue is different. It is a solid fatigue type linked to the grain-to-grain contacts. The material structure plays in that case an important role. This explains the fact that according to the type of the clay the overconsolidation effect can be different. It can be beneficial by slowing down the phenomenon (at same values of q_c/q_{fs}) or not. It is difficult to establish a general conclusion. Yet it appears that the highly overconsolidated clays (> 10) are less able to resist to the cyclic loading.
We have taken examples of cyclic tests performed on kaolinite and bentonite normally consolidated and overconsolidated (OCR = 4). For both materials one cyclic stress limit exists below which the evolutions are very close (in both cases : normally consolidated and overconsolidated) leading to the stabilization when the cyclic deformations remain less than 2°.
Past this stress limit the overconsolidation has an opposite effect. For the kaolinite the normally consolidated sample will be clearly more sensitive and will deform itself under cyclic loading much more rapidly than the overconsolidated one (figure 8).

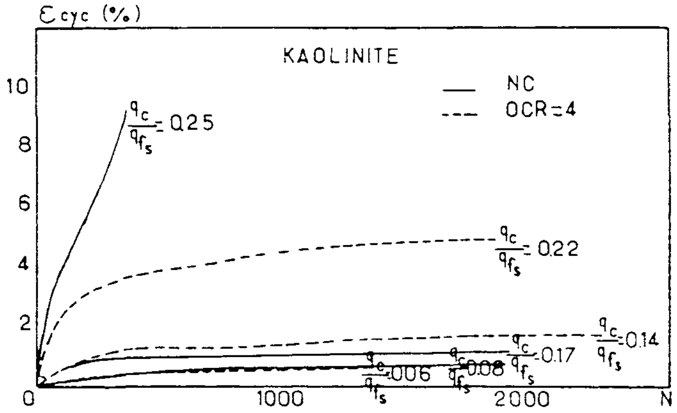

Fig. 8. One way cyclic triaxial tests with different O.C.R. on the kaolinite

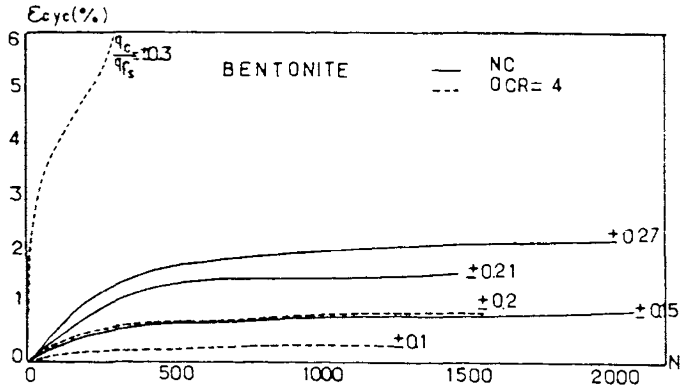

Fig. 9. One way cyclic triaxial tests with different O.C.R. on the bentonite

The opposite phenomenon occurs with the bentonite (Fig.9). We can for all these tests follow the evolution of the effective stresses with the ratio $\eta = q_{cmax}/p$

$q_{cmax} = q_m + q_c$, $p = \sigma_1 + 2\sigma_3/3 = q_{cmax}/3 + \sigma_{3o} - u$

The variation of η depends only on the pore pressure during the cyclic test.
On the example of the figure 10 we can see that this ratio the initial value of which is established by the state of material at the end of the creep tests at q_m increases at the same time for the normally consolidated sample and the overconsolidated one. But the final value remains far from M.
On the other side when the ratio q_c/q_{fs} is increased the initial values of η increase also. But in that case the evolutions are different according the overconsolidation ratio. For the normally consolidated kaolinite the impor-

tant increase of the pore pressure gives an increase of η which will reach the critical value M after a given number of cycles the sample being then submitted to large deformations.

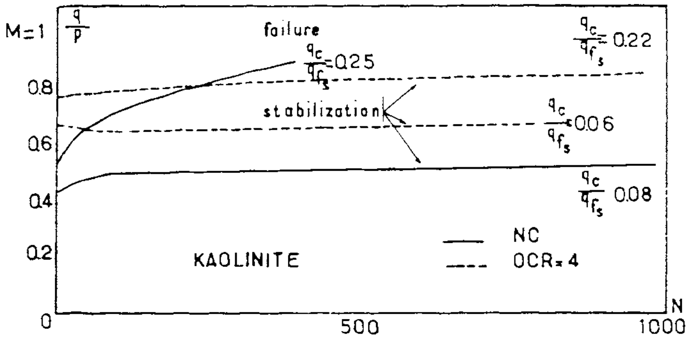

Fig. 10. Influence of the O.C.R. on the evolution of the ratio q/p. One way cyclic triaxial tests on the kaolinite

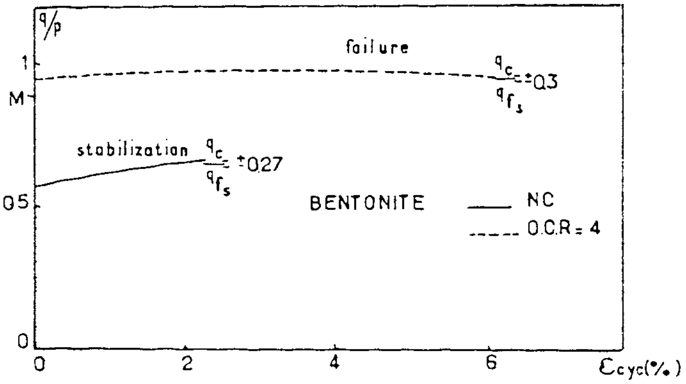

Fig. 11 ; Influence of the O.C.R. on the evolution of the ratio q/p. One way cyclic triaxial tests on the bentonite

As far as bentonite is concerned we have the opposite phenomenon (Fig. 11). In the normally consolidated case the increase of the pore pressure is still limited the bentonite being less sensitive to the cyclic loading. The ratio η then increases slightly and becomes stable at a value lower of M. In the overconsolidated case the value of η during the first cycle is above M. The state of the material under effective stresses stands beyond the critical state line. While the pore pressure (and so η) vary slightly the deformations increase clearly according to the number of cycles. A true fatigue phenomenon exists which is probably related to the propagation of micro fissures inside the sample, of destructions of the interparticular contacts leading to the failure through the concentration of the weak zones and the creation of a failure surface because since the beginning of the cyclic test the sample is in a favourable state to the propagation of unstabilities inside the material without a change of the effective stresses being necessary.
We obtained similar results with some tests realized on natural samples of marl. The residual deformations increase with the number of cycles until the sample failure while the pore pressure remains practically constant. When η is greater than M the residual deformations increase until the sample fails. We have in that case M = 1,55 and η = 1,8 practically constant during the whole test.

CONCLUSION

The results shown in the different sections have allowed us to decribe some evolution mechanisms of clays under cyclic loading linked to their initial structure (both physico-chimical and mechanical history).
In the physico-chimical history we can regroup the mineralogy the cations in the pore water, the sedimentary deposits history (alteration, calcareous..). It is essentially the parameters that are going to determine the clay structure. We saw that the initial arrangement of the particles and the intensity of their interparticles forces will influence the evolution of the clay under cyclic loading. This evolution will be faster in the case of a floculated arrangement than in the case of a dispersed one. In the same way the presence of cations while modifying the interparticles forces value gives a more or less important sensitivity of the clayed material to the cyclic loading.
In the mechanical history we can regroup the nature of the consolidation (overconsolidation ratio), the water contain....The most important point is the variation of the pore pressure. In the normally consolidated case there is always an increase in the pore pressure and thus the failure during the cyclic loading is related to the reduction of the effective stresses. It is possible to obtain with somewhat highly overconsolidated samples slight variations of the pore pressure and even some decrease when the sample is strained and a subsequent failure of the sample occurs when the deformations become larger.
It seems that in these conditions the nature of the fatigue phenomenon changes. In the second case it is a purely solid fatigue related with grain-to-grain contacts and to the propagation of weak surfaces during the successives loadings.

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