A STUDY OF COLLAPSE PHENOMENA OF AN UNDISTURBED LOESS

L'ETUDE DU PHENOMENE DE L'EFFONDREMENT D'UN LOESS NON REMANIE

ИЗУЧЕНИЕ ПРОСАДКИ НЕНАРУШЕННЫХ ЛЕССОВ

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SYNOPSIS. Collapse was studied in the laboratory by testing undisturbed samples of Negev loess. The density of the loess was such that its saturated moisture content was slightly less than the liquid limit and hence the loess was of marginal collapse potential. Tests included conventional and triaxial consolidation, constant volume tests in which the reduced confining pressure for maintaining equilibrium upon saturation was measured and undrained pure deviatoric triaxial compression tests on fully saturated samples in which the pore pressure was measured during shear.

Analysis of the test results showed that the undisturbed loess maintained a quasi-rigid structure even after saturation at low confining pressures. Dilatant properties were observed at low levels of shear stress. In general the tendency for collapse was found to depend on the level of shear stress. At principal stress ratios slightly greater than unity the measured collapse was less than it was for an isotropic stress condition for the same mean stress.

1. INTRODUCTION

A definition of collapse should be general enough to include the whole variety of collapse manifestations. It is proposed that any rapid decrease in volume brought upon by the increase in any one of or combination of the following: water content (w), degree of saturation (S), mean stress (σ_{oct}), shear stress (τ), or pore pressure (u), should be termed collapse. This definition recognizes that collapse of the soil structure, may be triggered by a variety of processes other than wetting. It does not follow that different causes will produce a unique collapse performance. However if the mechanism of the collapse phenomena is similar, the different collapse patterns should be comparable, at least qualitatively.

Using the above definition it is observed that sharp volume reduction following inundation is one sort of collapse while, for example, a rapid increase in pore water pressure during undrained shear, which is typical of this kind of soil, is yet another one. In the first case the collapse occurs under a constant level of applied stress while the water content is the variable, where as in the latter case the water content is kept constant and the stress level is the variable. Despite the seemingly wide gap between the two types of tests, the mechanism of the phenomenon is one and the same, namely the equilibrium, in terms of volumetric stability between the soil structure and the stress field, is impaired drastically. The term volumetric stability in this context, does not necessarily mean no volume reduction since a uniform and modest change in the rate of volume change is not defined as collapse. Thus a necessary condition for collapse (as distinct from continuous volume reduction) is a quasi-rigid soil structure. In the present investigation an attempt is made to investigate the mechanism of collapse in the broad sense, with the aid of controlled laboratory tests.

2. COLLAPSE CRITERIA

The amount of collapse obviously depends on the stress field at the time of wetting. Numerous criteria have been proposed for classifying soils with respect to their tendency to collapse. Most of these criteria refer to a critical density below which collapse is probable. This critical density depends on the Atterburg limits.

A criteria common in Russian literature (Markin, 1969) is as follows: A soil is considered to be susceptible to collapse upon wetting if the in-situ degree of saturation (S) is less than 60% and.... $\frac{e_o - e_{ll}}{1+e_o} > -0.1$

where e_o = in-situ void ratio, and e_{ll} = the void ratio at the liquid limit.

The soil is considered to be prone to swelling upon wetting if the above ratio assumes a value less than -0.3. (Danilov, 1964). It can be shown that the above criteria can be rewritten as

$$\frac{(\gamma o)_d}{(\gamma ll)_d} < 1.1 \text{ prone to collapse}$$

$$\frac{(\gamma o)_d}{(\gamma ll)_d} > 1.3 \text{ prone to swelling}$$

where $(\gamma o)_d$ = in-situ dry density, i.e. weight of solids per unit volume.

$(\gamma ll)_d$ = the dry density of the soil at the liquid limit.

Others consider soil to be susceptible to collapse when the above ratio is less than unity (Gibbs and Bara, 1967).

3. SOIL PROPERTIES

The soil tested was Negev loess from which bulk samples were taken from a pit 1.5 m. below ground surface. The loess was predominantly silt sizes, 10% by weight being sand sizes and 30% by weight smaller than 5 micron. The liquid limit was 31, the plastic limit 16 and the specific gravity 2.74. The natural moisture content (w) was 15% the dry density (γ_d) 1.54 tons/m^3 and the degree of saturation (S) 53.5%.(Zur, 1969). For the soil tested in this investigation $(\gamma o)_d/(\gamma ll)_d = 1.54/1.48 = 1.04 < 1.1$, and the soil may therefore be considered to have a marginal collapse potential.

4. EXPERIMENTAL PROGRAM

Collapse being a volumetric phenomenon, it may be studied either by measuring upon saturation the actual volume change under various stress fields or by measuring the reduction in stress field required to maintain constant volume. For soils that possess the capacity to collapse even after being fully saturated, tendencies for volume change may be monitored by measuring pore pressure developed during undrained shear. It should be noted that the constant volume technique is more fundamental since the void ratio does not vary as the test proceeds.

The equipment used consisted of rigid ring consolidation apparatus for an initial series of tests and Bishop type triaxial apparatus for all remaining tests.

The following tests were performed:

a) Rigid ring consolidation tests on undisturbed samples first loaded at natural water content followed by inundation at various stress levels. For comparison, rigid ring consolidation tests were also performed on fully saturated samples sedimented from a slurry and tested at the same initial dry density as the undisturbed samples.

b) A series of triaxial consolidation tests on undisturbed samples. The samples were first consolidated at their natural moisture content at three mean stress levels and then saturated during which the volume change ("collapse") was measured. At each mean stress level tests were performed at three ratios of major (σ_I) to minor (σ_{III}) principal stress.

c) As b) above, but upon the introduction of increments of water, the mean stress was reduced so as to maintain constant volume.

d) Undrained pure deviatoric triaxial compression tests on samples saturated at low confining pressures. Pore pressure was measured during shear at constant volume.

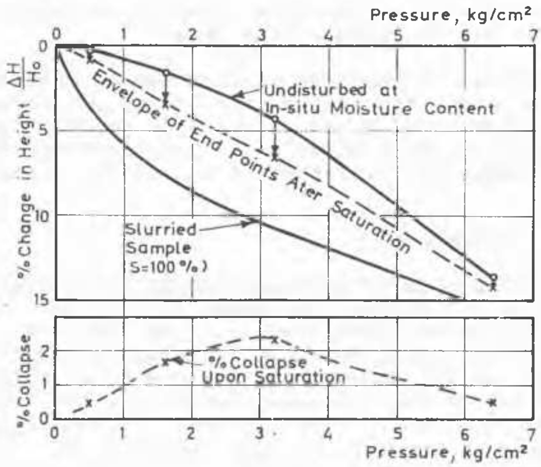

Fig. 1. Study of Collapse in Consolidometer (Rigid Ring)

5. TEST RESULTS AND ANALYSIS

a. The results of the one dimensional rigid ring consolidation tests are shown in Fig. 1. Four undisturbed samples were loaded to 0.5, 1.6, 3.2, and 6.4 kg/cm^2 respectively and then inundated with water. Shown on the plot are the percent change in height versus applied pressure at in-situ moisture and the envelope of end points after saturation. On the same plot are shown the results for a slurried sample having the same initial density. After saturation the void ratio of the undisturbed samples remains higher than that of the slurried sample up to pressures as high as 6.4 kg/cm^2. This behaviour indicates that the quasi-rigid structure of the loess is at least partially maintained even after collapse upon saturation.

It may be assumed that loess which subsides upon saturation less than one percent in laboratory consolidation tests under a particular stress can be considered to be non subsident for the same vertical stress in the field. (Goldshtein, 1969). This stress may be considered to be a measure of the "residual" strength of the bonds between the silt particles after saturation. Several investigators report field evidence supporting the above. (Dranikov, 1967; Kodryanova, 1969). It may be seen that for the loess tested the threshold stress is about 1.0 kg/cm^2 and at stresses below this level the quasi-rigid nature of the bonds between the silt particles is maintained even after saturation. (Goldshtein and Makarenko, 1970).

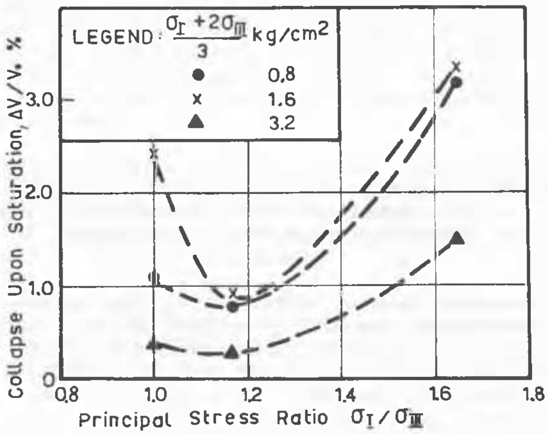

Fig. 2. Influence of Principal Stress Ratio on Percent Volume Collapse Upon Saturation

b. The above phenomenon was further checked by a series of triaxial consolidation tests on undisturbed samples at natural moisture and density. Each sample was consolidated at natural moisture under a particular value of total mean stress [1/3 (σ_I + 2σ_{III})] and principal stress ratio (σ_I/σ_{III}). The samples were then inundated with water and the volume decrease under the same stress was measured. Test results are shown in Fig. 2. As can be seen the volume collapse upon saturation was about 1.0 percent for a mean stress of 0.8 kg/cm^2 for principal stress ratios of 1.0 and 1.3, whereas for the same mean stress the volume collapse upon saturation increased to over 3 percent when the principal stress ratio was 1.65. An increase of volume change with increasing principal stress ratio for constant mean stress has been measured both in the laboratory and in the field by several investigators. (Stanculescu, 1967; Limize and Kratsov, 1969). However, Fig. 2 indicates that the minimum volume change was not measured at a principal stress ratio of unity but rather at a principal stress ratio of 1.17. This result is a further indication of the quasi-rigid nature of the bonds even after saturation, with the soil exhibiting apparent dilating (vol. increase) characteristics at low shear stress levels.

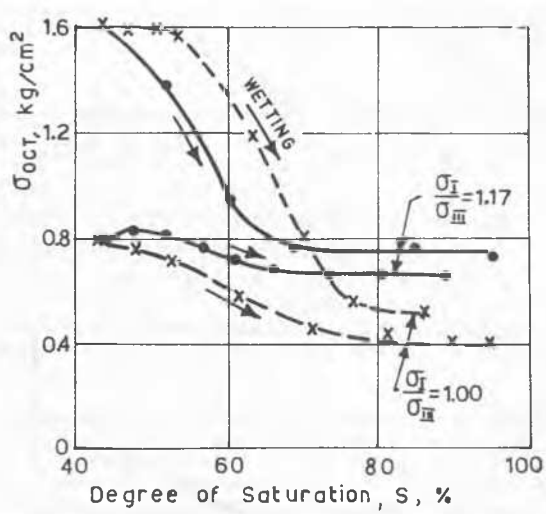

Fig. 3. Equilibrium Octahedral Normal Stress Versus Degree of Saturation for Incremental Wetting at Constant Volume

c) The influence of shear stresses on collapse phenomena was studied further in a series of constant volume tests on undisturbed samples. The samples were consolidated at a particular level of mean normal stress (σ_{oct}) and a particular value of the principal stress ratio. Water was then introduced in increments, and the mean normal stress reduced sufficiently to maintain constant volume. The test results showing the equilibrium mean stress (σ_{oct}) as a function of the degree of saturation (S) is shown in Fig. 3 for two initial values of σ_{oct}, i.e. 0.8 and 1.6 kg/cm^2, each at principal stress ratios of 1.00 and 1.17.

Several features are worth noting. For both initial mean normal stresses (σ_{oct}) of 0.8 and 1.6 kg/cm^2 the final equilibrium σ_{oct} at close to full saturation was higher for a principal stress ratio of 1.17 than for a principal stress ratio of unity. The same reresults are shown on Fig. 4A on a σ_I versus $\sqrt{2}\sigma_{III}$ plot, where the stress paths followed during saturation are shown. The increased rigidity associated with a low level of shear stress shown in Fig. 2 in the volume change tests is here shown in Fig. 4B for the constant volume tests.

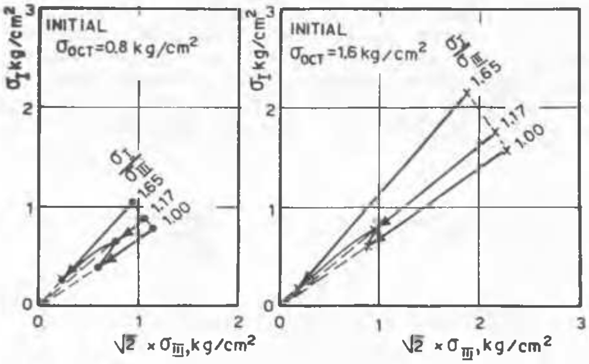

Fig. 4A. Stress Paths in $\sigma_I - \sqrt{2}\sigma_{III}$ Plane for Constant Volume Upon Saturation

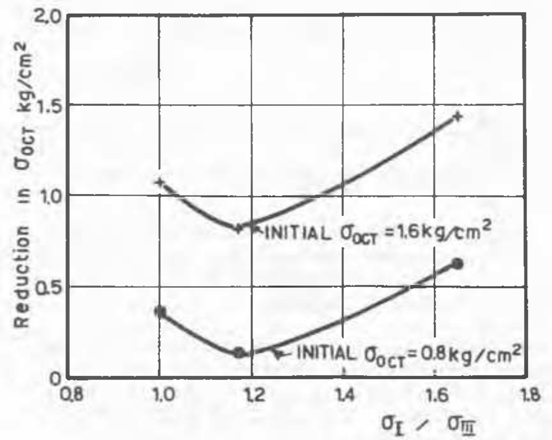

Fig. 4B. Reduction in σ_{oct} Required for Constant Volume Upon Saturation at Various Principal Stress Ratios

It is interesting to note from Fig. 3 that the tendency for collapse as evidenced by the reduction in σ_{oct}, required to maintain constant volume, continued until a degree of saturation of 70%-80% was reached. Other investigators have suggested that collapse continues until a degree of saturation of 60% is reached, (Goldshtein and Makarenko, 1970). Of special interest is the slight tendency for swelling as evidenced by the increase in σ_{oct} required to maintain constant volume prior to collapse exhibited by the sample that had an initial stress of σ_{oct} = 0.8 kg/cm² at a σ_I/σ_{III} of 1.17. This tendency for swelling continued until the degree of saturation reached 50% and then was followed by a tendency for collapse.

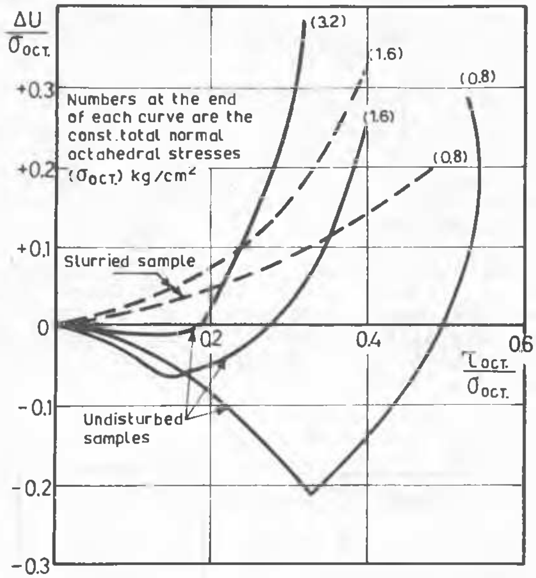

Fig. 5. Dimensionless Pore Pressure Curves for Undrained Pure Deviatoric Axial Compression on Fully Saturated Samples

d) The quasi-rigid structure of the undisturbed loess is maintained even after saturation. It is therefore possible to study collapse phenomena during undrained shear of saturated specimens by measuring pore pressure, (Zur and Wiseman, 1969).

The triaxial compression tests were performed while maintaining a constant mean stress (σ_{oct}) so that the pore pressure developed was in the first approximation due to changes in the shear stresses only (τ_{oct}).

The tests were performed by incremental axial loading, the confining pressure being reduced accordingly, so that the total mean stress on the sample remained constant. Plots of pore pressure developed ($\Delta u/\sigma_{oct}$) versus applied shear stress (τ_{oct}/σ_{oct}) are shown for both undisturbed and slurried samples in Fig. 5. The slurried samples were tested at two levels of σ_{oct}, i.e. 0.8 and 1.6 kg/cm², while the undisturbed samples were tested at three levels of σ_{oct}, i.e. 0.8, 1.6 and 3.2 kg/cm². The slurried samples showed a continuous and gradual increase of pore pressure as the shear stresses were increased. The undisturbed samples, on the other hand, showed strong evidence of the quasi-rigid structure even after saturation. This effect is most marked at the low σ_{oct} of 0.8 kg/cm². The pore pressure decreased with increasing shear stresses up to a value of τ_{oct}/σ_{oct} of about 0.3, implying a sufficiently "dense" structure to give rise to dilatency (tendency for volume increase) followed by a rapid collapse of the structure as the cohesive bonds are broken

6. CONCLUSIONS

The main findings of the study are that the loess maintains a quasi-rigid structure even after saturation and that collapse behavior depends not only on the increase of the degree of saturation and the mean stress level but on the shear stress level as well. The decrease in collapse potential at low shear stress levels as compared to hydrostatic stress conditions is particularly worthy of note. This latter phenomena was found to exist for all the widely different methods of testing employed.

All tests were carried out on undisturbed samples of Negev loess whose density is such that it may be considered to have a marginal collapse potential. Though the findings are only applicable quantitatively for the loess tested it is believed that the test methods used and the trend of the results are of more general applicability.

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