The decay of structure and the loss of overconsolidation

La destruction de structure et la disparition de surconsolidation

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ABSTRACT: Naturally deposited clay/sand are mostly found in structured states. In addition those soils are usually at overconsolidated states. In order to describe mechanical behavior of structured and overconsolidated soils super-subloading surfaces are newly introduced to the original Cam-clay model. In the new soil model hardening with plastic volumetric expansion and softening with plastic volumetric compression are both found possible other than the usual hardening with compression and the usual softening with expansion. Both the decay of structure and the loss of overconsolidation proceeds with ongoing plastic deformation, but the former proceeds at a much slower pace than the latter in clay. To the contrary, the decay of structure proceeds much faster than the loss of overconsolidation in sand. The expectation made above is positively accepted through examining numerical simulations of (1)secondary consolidation of clay, (2)undrained shear behavior of clay and sand and (3) rapid collapse of soil structure of loose sand.

RÉSUMÉ: a déposé l'argile. Naturellement, le sable est principalement trouvé dans e' état bien structuré. De plus, ces sols sont souilles overconsol habituellement très solides. Pour décrire le comportement mécanique de modèle è nouveau structuré et solide - les Supers surfaces sous-chargeant sont ont introduits à la Cam-clay originale - modèle en argile. Dans le nouveau sol model qui durcit avec l'expansion volumétrique plastique et softening, il est possible de trouver d'autres comportements que le durcissement habituel avec la compression et l'adoucissement normal avec l'expansion. Les deux : la déchéance de structure et la perte de l'overconsolidation continue avec le difformité plastique progressive, mais le fondateur produit à une allure beaucoup plus lente, que le dernier dans argile. Au contraire, le déchéance de produits de la structure est beaucoup plus rapide que la perte d'overconsolidation dans le sable. L'attente, faite au-dessus, est acceptée à travers examiner positivement les simulations numériques de (1) consolidation secondaire d'argile, (2) ciseau de indrainé comportement d'argile et du sable (3) chute rapide de structure du sol et du sable dégagé.

1 INTRODUCTION

Figure 1 shows a typical 1-D compression behavior of naturally deposited structured clay. The straight line in the figure denotes a normal consolidation line of the fully remolded clay. The compression test of this natural clay was conducted under a finite vertical strain rate with "permeable top and impermeable bottom" boundary conditions. Then the test results of the figure merely shows an overall compression behavior of the specimen during its consolidation procedure. The "element-wise" compression behavior of the clay under fully drained condition should differ, to a certain extent, from this figure. However, Figure 1 still suggests that structured clay is possible to take its state in the "impossible" region of the fully remolded destructured clay, that is, outside the "Roscoe surface", which identifies the demand for a "superloading yield surface" concept for structured soil.

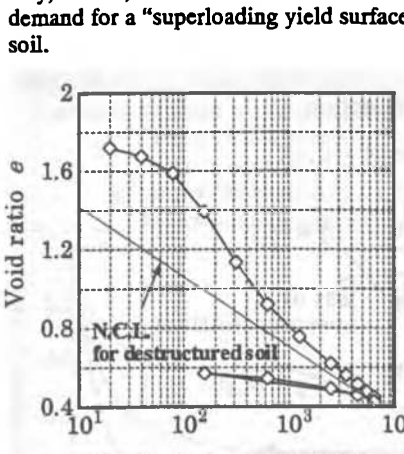

Figure 1. Typical 1-D compression behavior of natural clay.

Asaoka, Nakano and Noda (1998, 2000a, 2000b) introduced a superloading yield surface, together with Hashiguchi's subloading yield surface (Hashiguchi, 1978, 1989), to the original Cam-clay in order to describe mechanical behavior of structured and overconsolidated soils. Fundamental conceptions of the new soil model are explained here in six steps. (1) Fully remolded / destructured and normally consolidated soil is assumed to follow the original Cam-clay model. This is just for the sake of simplicity. (2) Existence of a superloading yield surface is assumed, which is geometrically similar to the Cam-clay yield surface, lying outside the Roscoe surface, denoting the impossible state for remolded soil. The similarity ratio of the Cam-clay yield surface to the superloading yield surface is denoted by R^* ($0<R^*<1$). (3) When the state of stress is on the superloading yield surface, the soil is said to be at normally consolidated state. For the plastic deformation of the normally consolidated soil, the associated flow rule is applied on the superloading yield surface. (4) In order to determine the subsequent superloading yield surface, the material time derivative of R^* is expressed in terms of ongoing plastic deformation, which is called evolution law for R^*. The evolution law describes the fact that soil structure gradually decays as plastic deformation proceeds, which is equivalent to say that R^* is gradually increasing up to 1 when loading and the superloading yield surface finally coincides with the Cam-clay yield surface after complete remolding. (5) Structured soil, initially on the superloading yield surface, becomes overconsolidated soil when unloading. Soil in such overconsolidated state, when reloading occurs, obeys the subloading yield surface through the associated flow rule. The subloading yield surface is again geometrically similar to the superloading yield surface. The similarity ratio of the subloading yield surface to the superloading yield surface is denoted by R, which is also $0<R<1$. Note here that the reciprocal of R gives OCR of the soil. (6) To determine the subsequent subloading yield surface, the evolution law for R is again needed. The evolution law describes the wellknown fact that with ongoing plastic deformation overconsolidated soil gradually reaches normally consolidated state.

In the present study, the difference between sand and clay is discussed from the viewpoint of the difference between the rate of the decay of structure and the rate of the loss of overconsolidation. Essential points of the discussion are as follows: In clay, the loss of overconsolidation proceeds at a much faster pace than the decay of structure, which causes softening with plastic volume compression under a considerably low stress ratio (i.e., small q/p'). The occurrence of softening with volume compression triggers off delayed compression/secondary consolidation. To the contrary, the decay of structure proceeds at a much faster pace in sand than the loss of overconsolidation. When loose sand is the case, initial rapid decay of structure easily causes "compaction" or liquefaction. When medium dense or dense sand is the case, delayed loss of overconsolidation causes hardening with plastic volume expansion even after the occurrence of softening with plastic volume compression. It may be needless to say that hardening with plastic volume expansion and softening with plastic volume compression are both out of the scope of the classical Cam-clay model.

2 A SKETCH OF THE MODEL EXAMINED

Key formulations are given next. For details, *see* Asaoka, Nakano and Noda (2000a). The definitions of R^* and R are simply given in Figure 2, from which

$$f(p',q) + \int_0^t J\mathrm{tr}D^p d\tau + \mathrm{MD}\ln R^* - \mathrm{MD}\ln R$$

$$= \mathrm{MD}\ln\frac{p'}{p_0'^*} + \mathrm{D}\frac{q}{p'} + \mathrm{MD}\ln\frac{R^*}{R} + \int_0^t J\mathrm{tr}D^p d\tau = 0 \qquad (1)$$

gives the subloading yield surface, where M and D are the critical state parameter of the Cam-clay and the dilatancy parameter, respectively, while D^p denotes plastic stretching. J in the equation is the Jacobian determinant of the deformation gradient tensor F.

R^* and R are both increasing to one gradually when loading. As a measure of ongoing plastic deformation the norm of the shear component of plastic stretching $\|D_s^p\|$ is employed, in which

$$D_s^p = D^p - \frac{1}{3}\mathrm{tr}D^p I = \lambda\frac{3S}{2q}\frac{\partial f}{\partial q} \qquad (2)$$

The use of $\|D_s^p\|$ for the evolution laws of R^* and R is again just for the sake of simplicity, through which a simple closed form expression for M_s is obtained, *see* Eq.(6). Thus, the evolution laws for R^* and R are expressed here

$$\dot{R}^* = JU^*\sqrt{\frac{2}{3}}\|D_s^p\|, \qquad U^* = \frac{1}{\mathrm{D}}R^*(1-R^{*m^*}) \qquad (3)$$

and

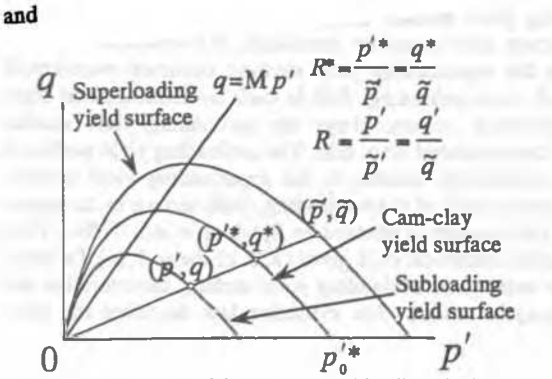

Figure 2. Cam-clay model with super-subloading yield surfaces.

$$\dot{R} = JU\sqrt{\frac{2}{3}}\|D_s^p\|, \qquad U = -\frac{m}{\mathrm{D}}\ln R \qquad (4)$$

respectively. U^* and U in these equations are both positive scalar function of R^* and R. In Eqs.$(3)_2$ and $(4)_2$ m^* and m are degradation parameters of structured states and overconsolidated state, respectively. The greater those variables, the faster the decay of those state.

Substituting evolution laws into consistency condition, and applying the associated flow rule, the plastic multiplier λ is obtained in terms of stresses as follows:

$$\lambda = \frac{\dfrac{\partial f}{\partial T'}\cdot\dot{T}'}{J\dfrac{\mathrm{D}}{p'^2}(\mathrm{M}_s p' - q)} \qquad (5)$$

in which

$$\mathrm{M}_s = \mathrm{M}\left(1 - \frac{\mathrm{D}U^*}{R^*} + \frac{\mathrm{D}U}{R}\right) \qquad (6)$$

is now a new critical state parameter. The new critical state line $q=\mathrm{M}_s p'$ is found to be the watershed between hardening and softening. Note also here that the critical state parameter M in a classical Cam-clay model is a material constant, while the new critical state parameter M_s is a variable. When loading, the M_s is increasing/decreasing with ongoing plastic deformation.

3 DIFFERENCE BETWEEN CLAY AND SAND

In principle, there are two processes from structured and overconsolidated state to destructured and normally consolidated state. Clay loses its overconsolidation first and therefore M_s comes down first. After that the M_s is increasing gradually to M with the decay of structure, which may need considerably large shear deformation. This is schematically illustrated in Figure 3. Structure of clay remains long.

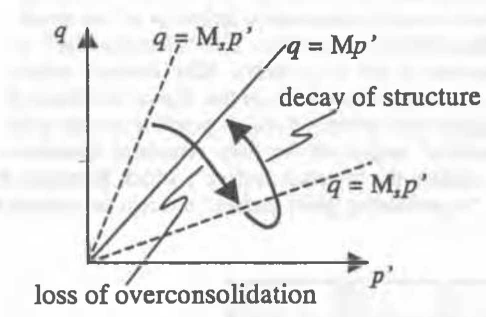

Figure 3. Typical clay behavior.

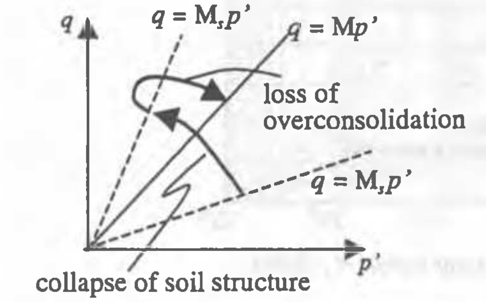

Figure 4. Typical sand behavior.

In sand, to the contrary, the decay of structure proceeds very easily/rapidly even with a relatively small plastic deformation.

However, overconsolidation remains long. When the sand is initially at a loose state with structure, M_s is increasing up first with a sudden collapse of structure, and then the M_s comes down very slowly to M with a gradual loss of overconsolidation, *see* Figure 4.

Since q=Mp' line is the watershed between plastic volume ompression and plastic volume expansion, then softening becomes possible even with plastic volume compression when M_s < M. Conversely, when M_s > M, hardening may occur even with plastic volume expansion.

4 SECONDARY CONSOLIDATION OF NATURAL CLAY

Even when the clay is initially at overconsolidated state, the M_s comes down very rapidly after some amount of plastic deformation, *see* Figure 3. Therefore, even in 1-D consolidation with relatively low stress ratio, softening becomes possible with plastic volume compression. In case of softening, "coefficient of consolidation" becomes negative and then not dissipation but generation of excess pore pressure should be observed during consolidation procedure. As the decay of structure proceeds, M_s is increasing to M gradually, that is, with the passage of time the clay now exhibits hardening. However, before hardening begins, the clay can not dissipate excess pore pressure, which causes delayed compression/secondary consolidation.

A typical oedometer test in laboratory is numerically simulated in this section. Material constants and necessary initial values of clay are tabulated in Table 1. At three loading stages A, B and C, the vertical load was kept constant so that the clay specimen underwent 1-D consolidation under constant load application. Three settlement behaviors are given with time in Figure 5.

Delayed compression can be clearly observed at loading stage B, pore pressure isochrones for which are given in Figure 6. Arrows in the figure indicate the points where softening occurs with excess pore pressure rise.

5 UNDRAINED SHEAR BEHAVIOR OF CLAY AND SAND

Typical undrained triaxial compression tests on clay and sand are numerically simulated in this section. Tabulated in Table 2 are the elasto-plastic soil parameters together with m^* and m. Necessary initial conditions of the soil are also given in the table. Clear distinction between clay and sand should be observed in the clear differences in m^* and m. The loss of overconsolidation proceeds at much faster pace in clay, while the decay of structure, at much faster pace in sand. Concerning the initial value of R^*, it should be noted here that, in dense sand, initial structure that had ever existed when the sand was loose has already been totally decayed due to the densification process. Therefore R^* =1 is assumed from the beginning in dense sand. This topic will be discussed in the next section.

Computed results of the undrained shear behaviors of normally consolidated and overconsolidated clays and one medium dense sand are given in Figures 7 and 8, which are superimposed upon the experiment results.

Table 1. Material constants and initial conditions.

Compression index $\tilde{\lambda}$	0.131
Swelling index $\tilde{\kappa}$	0.075
Critical state constant M	1.53
Poisson's ratio ν	0.3
Degradation parameter of structure m^*	0.5
Degradation parameter of overconsolidated state m	10.0
Initial specific volume v_0	2.19
Initial value of $1/R^*(1/R_0^*)$	20.0
Initial overconsolidation ratio $1/R_0$	100.0
Soil permeability k(cm/sec)	7.8×10^{-9}

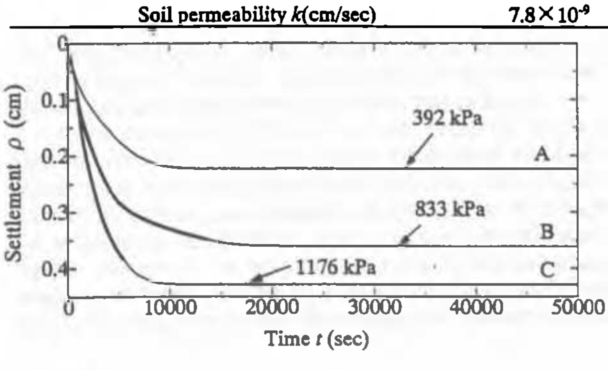

Figure 5. Secondary consolidation.

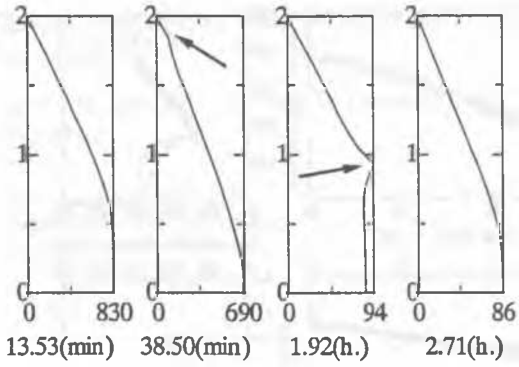

Figure 6. Excess pore pressure rise due to softening.

Table 2. Material constants and initial conditions of clay and sand.

	clay	sand
Compression index $\tilde{\lambda}$	0.25	0.0419
Swelling index $\tilde{\kappa}$	0.045	0.016
Critical state constant M	1.43	1.24
Poisson's ratio ν	0.3	0.3
Degradation parameter of structure m^*	0.1	1.8
Degradation parameter of overconsolidated state m	10.0	0.04
Initial specific volume v_0	2.33(2.47)	1.92
Initial value of $1/R^*(1/R_0^*)$	6.6(8.0)	4.5
Initial overconsolidation ratio $1/R_0$	1.3(5.7)	12.7
Soil permeability k(cm/sec)	7.8×10^{-9}	4.1×10^{-2}

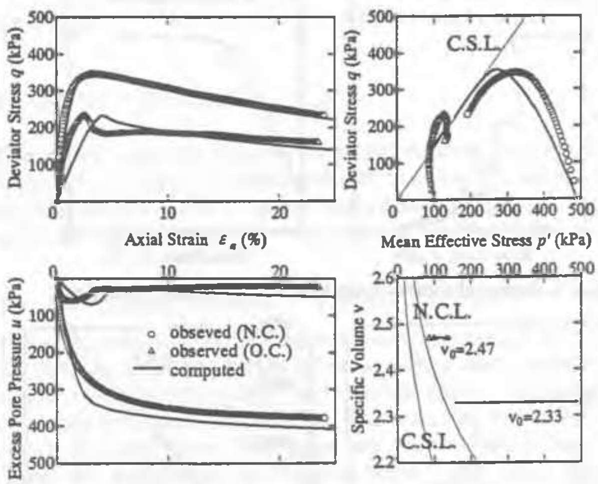

Figure 7. Undrained shear behaviors of clays.

6 SUDDEN COLLAPSE OF STRUCTURE IN LOOSE SAND

Two different behaviors of loose sand under repeated shear stress application are examined next. One is under fully drained condition and the other, under perfectly undrained condition. One may imagine sand compaction and sand liquefaction, respectively. Material constants with m and m^* are the same as

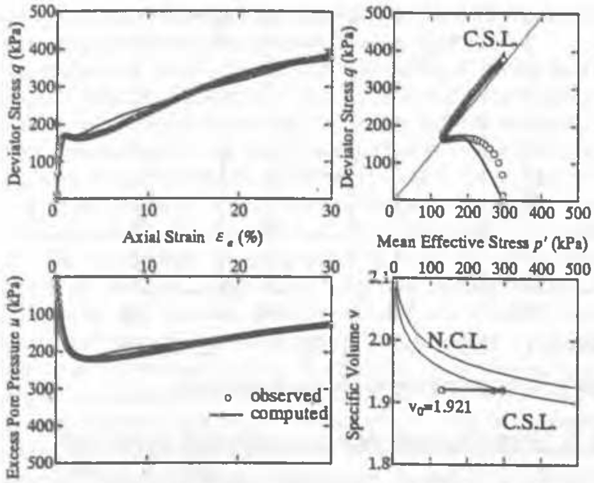

Figure 8. Undrained shear behaviors of medium dense sand.

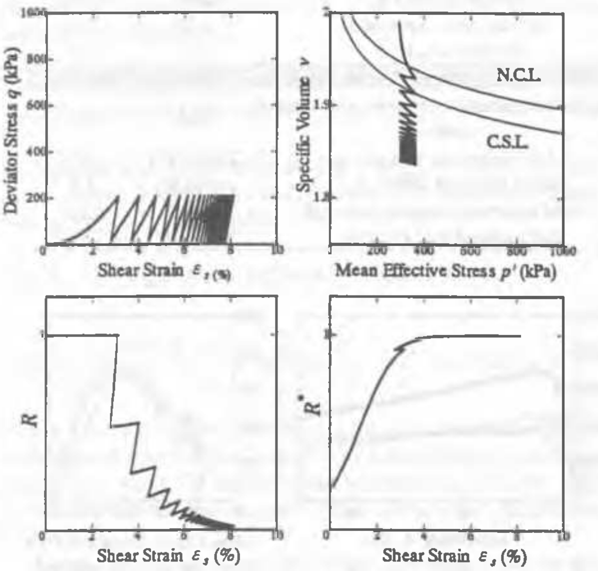

Figure 9. Repeated shear of loose sand in fully drained condition.

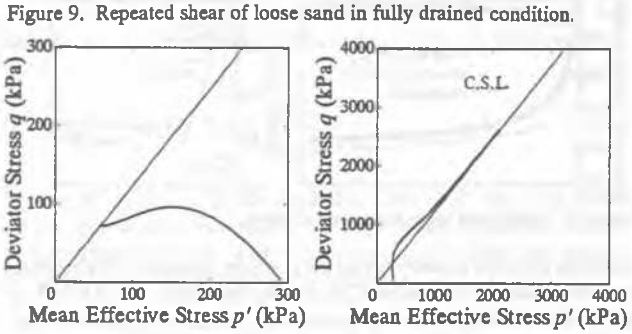

Figure 10. Undrained shear behavior before and after "compaction".

those in Table 2. Initial overconsolidation ratio of the loose sand is assumed to be one.

Figure 9 shows a typical compaction procedure of loose sand. The shear stress application is repeated until the OCR exceeds 100. Necessary number of repetition was less than 30. The comparison in the undrained shear behavior of the sand before and after compaction is given in Figure 10.

Undrained behavior of the same loose sand under repeated shear stress application is given in Figure 11. After several repetitions the plastic volume compression reaches Equilibrium State with plastic volume expansion and the sand arrives at a steady state.

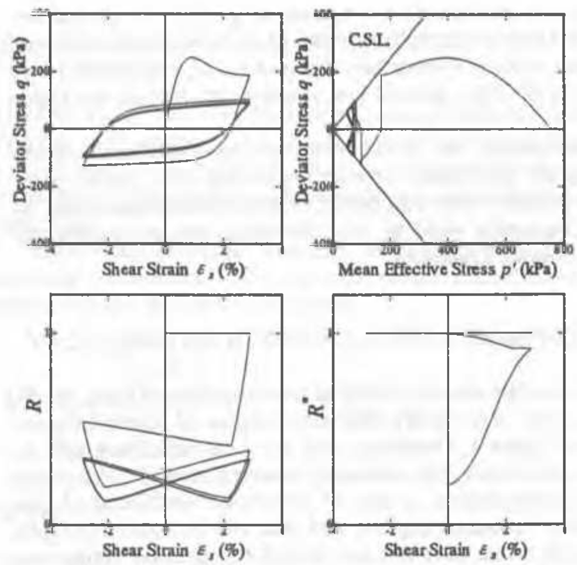

Figure 11. Repeated shear of loose sand in perfectly undrained condition.

7 CONCLUSION

Through numerical simulations, together with fundamental experiments, the expectation is positively accepted that in clay loss of overconsolidation proceeds much faster than the decay of soil structure and in sand, vice versa.

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