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Soil water coupled analysis of land subsidence due to dewatering

Analyse couplée sol-eau d'affaissement du terrain résultant d'un assèchement

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ABSTRACT

A series of one dimensional numerical simulations of land subsidence due to dewatering were performed based on the soil-water coupled finite deformation analysis. The following findings were obtained: 1) when dewatering exceeds a certain level, delayed consolidation with huge settlement is observed, which is concluded as the results of plastic softening of soils with plastic volume compression that occurs below the critical state line in *p'-q* stress space. 2) After the land subsidence, that ground may be fragile against the additional applied load because of the disturbance of soil skeleton structure. 3) When one dimensional multi-layered system is the case, delayed compression/consolidation of lower layers may occur even after the finish of the settlement of upper layers. This is due to the delay of propagation of the increase of effective stress that occurs due to dewatering.

RÉSUMÉ

Une série de simulations numériques unidimensionnelles d'affaissement de terrain résultant d'un assèchement est effectuée sur la base d'une analyse de déformation finie couplée sol-eau. Les résultats suivants ont été mis à jour : 1) Si l'assèchement excède un certain niveau, on observe une consolidation différée avec un tassement considérable qui semble résulter d'un ameublissement plastique du sol avec une compression du volume plastique qui se produit en-dessous de la ligne d'état critique dans l'espace de contrainte *p'-q* ; 2) Après l'affaissement du terrain, le sol est fragilisé vis-à-vis de toute charge supplémentaire en raison de la transformation du squelette de la structure du sol ; 3) Si le cas étudié est celui d'un système multi-couches unidimensionnel, la compression/consolidation des couches inférieures risque même de se produire après le tassement des couches supérieures. Ceci résulte de la propagation différée de l'augmentation de la contrainte se produisant du fait de l'assèchement.

1 INTRODUCTION

Large-scale land settlement as a result of excessive pumping of underground water has become a serious problem in populated areas. With the tightening of pumping regulations the rate of land settlement in Japan has now eased, but past subsidence is irreversible and land that has once sunk does not return to its former level. In a naturally deposited saturated clay soil with a highly developed skeleton "structure" it is not uncommon to find "structural failure" leading to a behavior of plastic compression accompanied by softening even in states where the stress ratio (the ratio of mean effective stress *p'* to deviatric stress *q*) is comparatively low. By means of a soil-water coupled analysis based on an elasto-plastic constitutive equation that has the capability of describing the soil skeleton structure (structure, overconsolidation anisotropy) (e.g. Asaoka et al. 2002, 2000(a)), this paper aims to clarify the mechanism of land subsidence. Figure 1, taken from Ueshita et al., 1990, shows the rate of land settlement in one particularly badly affected part of the Nobi Plain west of Nagoya, in Central Japan, aligned with the yearly variation in underground water pumping in the Nobi Plain area as a whole. Let us first note the characteristic features of the settlement history in this case.

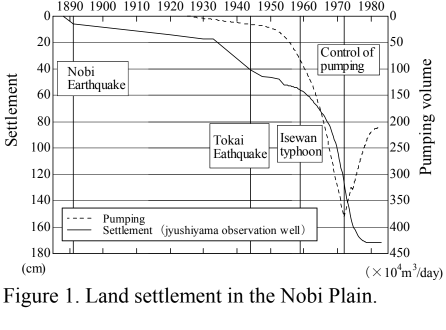


Figure 1. Land settlement in the Nobi Plain.

1) In the 1960s, when the pumping volume suddenly increased, the rate of settlement also accelerated dramatically.
2) Pumping controls were enforced from around 1972 on, but settlement persisted for a while after that.
3) After 10 years of controls the volume of water pumped had declined to half of the maximal amount pumped in 1972, but no rebound was apparent in the lowered ground level.

In what follows, on the basis of these characteristics, a detailed explanation is offered for the long-term settlement behavior of a highly structured naturally deposited clay soil.

2 LOSS OF SOIL STRUCTURE AS AN EFFECT OF A FALLING UNDER GROUND WATER LEVEL

2.1 Calculation conditions

Figure 2 shows the finite element mesh used in the calculation. A one-dimensional deformation is assumed in a clay soil. This clay layer is further assumed to be overlain by a 10m deposit of sand, exerting a load of 182kPa. Below the clay layer is an aqui-

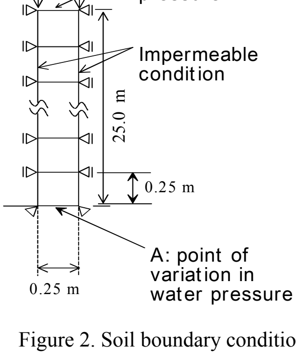


Figure 2. Soil boundary conditions.

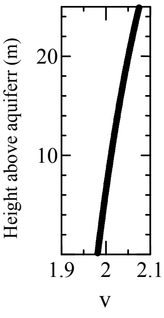


Figure 3. Initial distribution of void ratios in de-structured soil.

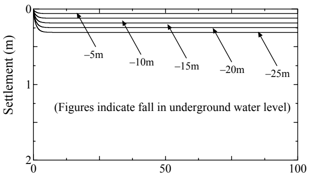
fer, the level of which declines with any diminution of the water pressure at the hydraulic boundary at the base of the clay. For simplicity of calculation let us suppose here that the whole of an assigned drop in level occurs in one day. Table 1 gives the elasto-plastic parameters, evolution parameters and initial conditions of the clay (sand is needed in the chapter 4) as assumed in the calculations. For comparison purposes calculations are performed for two states of clay soil, one structured and one without structure. The initial mean effective stress and void ratio are calculated from the load of the overlying sand layer and the self-weight of the clay. The initial distribution of void ratios can be seen in Fig. 3.

Table 1. Parameter groups.

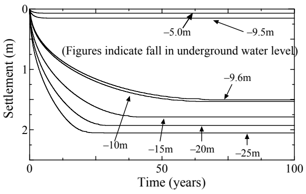
	Clay	Sand
[Elasto-Plastic parameters]		
Compression index $\tilde{\lambda}$	0.13	0.042
Swelling index $\tilde{\kappa}$	0.065	0.012
Critical state constant M	1.2	1.08
Specific volume at p' =98kPa on NCL N	1.97	1.99
Poisson's ratio ν	0.3	0.3
[Evolution parameters]		
Degradation index of structure a	1.5	10.0
b, c	1.0,1.0	1.0,1.0
Degradation index of OC m	7.0	0.04
Evolution index of $\boldsymbol{\beta}$ b_r	0.001	10.0
Limit of rotational hardening m_b	1.0	0.5
[Initial conditions]		
Over consolidation ratio $1/R_0$	1.2	10
Degree of structure $1/R^*_0$	15,1.0	1.0
Coefficient of earth pressure at rest K_0	0.8	0.85
Anisotropy ς	0.231	0.167
Permeability k (cm/sec)	2.0×10^{-9}	4.0×10^{-2}
Density of soil particle ρ_s (g / cm^3)	2.6	2.65

2.2 Calculation results

Figure 4 shows the relation between settlement and time in soils with and without structure. In the soil without structure, the actual settlement will also be no more than a few tens of centimeters. In the structured soil, on the other hand, a mere 10cm drop in the water level from -9.5m to -9.6m produces a settlement that takes more than 60 years to run its course, and in the end is some 7 times larger in scale. Figure 5 shows the relation between settlement and time in the structured soil after the underground water is allowed to fall below the -9.6m level. The lower part of the figure shows pore pressure isochrones for the points (a) to (e) on the curve. The white circles indicate parts of the elements exposed to plastic compression accompanied by softening, the gray-edged line portions show unloading, and the solid black portions hardening. Elasto-plastic compression accompanied by softening occurs in cases where a highly structured soil is additionally subjected to shear deformation. Where the loading (and thus also the underground water level) stays constant, softening in the soil element will occur rather with a generation of excess pore water pressure, which will require unloading onto the other adjoining soil elements. After soil elements have been subjected to compression and shearing in this way, they enter a subsequent stage of hardening with a loss of skeletal structure, which results in a dissipation of the excess pore water pressure. For a closer account of this, the reader is directed to Asaoka et al. (2000(b)) in the References. To sum up, then, we can say that large-scale land settlement is something that occurs when underground water drops beneath a certain level, and this also indicates the existence of a critical threshold value for underground water levels (and for loading) (e.g. Kaneda et al. 2003).



De-structured state of soil



Structured state of soil

Figure 4. Relation between settlement and time.

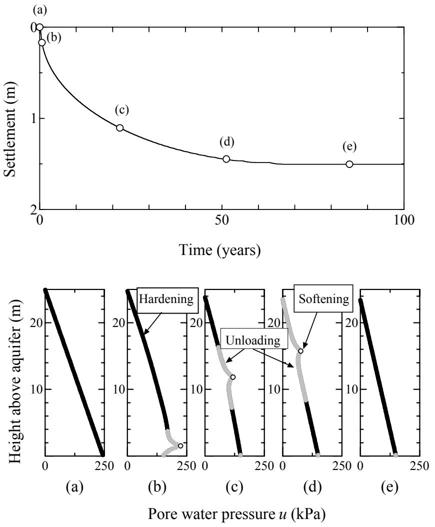


Figure 5. Generation of pre pressure.

3 ONE-DIMENSIONAL NUMERICAL SIMULATION OF A SINGLE CLAY LAYER

3.1 Calculation conditions

As the behavior to be investigated here is that of a structured soil, the initial conditions are chosen to match those occurring in the structured state. More particularly, the aim is to simulate the kind of behavior in Fig. 1. In this calculation, the water level is first made to drop to -20m over a period of 47 years, then allowed to recover to -10m over the 10 years that follow, and finally held constant. If the Fig. 1 level of subsidence for 1925 is counted as 0m, the calculation thus simulates the settlement for all years since.

3.2 Calculation results

Figure 6 presents the yearly variations in the rate of settlement and the fall in the underground water level. After passing the vicinity of point (b), the settlement curve goes into a dramatic fall. As explained in section 2, this is because the lowering of the underground water level has crossed a threshold into a region where plastic compression begins to co-occur with soil softening. Moreover, this settlement goes on occurring for some time after the water level starts to recover again (1972), giving us much the same pattern we remarked on above in section 1 (characteristic 2)). Figure 7 shows isochrones for the pore water pressure at points (a) to (j) on the settlement curve in Fig. 6. At points (h) and (i), where the water level is in recovery, there is swelling in the area where the soil approaches the hydraulic boundary condition (the deeper region of the clay layer), but as the water level recovery is still insufficient the overall effect of plastic compression accompanied by softening remains dominant, so that settlement continues for a while more with no sign of a rebound. Figure 8 represents the states in the soil after settlement has ended (t = 100 years in Fig. 6). v (= 1+e) in this figure is the void ratio, $1/R$ is the overconsolidation ratio, R^* is the degree of structure ($0 < R^* < 1$: a small value of R^* shows a highly structured soil), K is the coefficient of earth pressure at rest, and $|\boldsymbol{\beta}|/m_b$ stands for the degree of anisotropy. All of the distributions are non-homogeneous in the direction of depth. At a certain depth in the soil, a boundary point appears at which the states of distribution show a discontinuity.(e.g. Kaneda te al. 2003).

3.3 Observations on the state of the soil after consolidation

3.3.1 Comparison of numerically simulated "soil test" results with in-situ data

We now look in a little more detail at the state of the soil after settlement has occurred. To investigate this, soil elements are chosen at nine different depths in the soil for the point in time (47 years in Fig. 6) where the underground water depletion reaches a maximum. The data calculated are degree of structure, overconsolidation, stress ratio, anisotropy and void ratio. The constitutive equation is then used to arrive at a simple calculation of the one-dimensional compression and undrained shear stress responses. Figure 9 (upper row) presents a rearrangement of these computed results following the depth direction in the soil. The lower shows actual land survey results obtained in 1973 from the Nanyo district in Nagoya, where land subsidence was extreme (e.g. JGS chubu branch 1998). These actual data include only four levels of depth, but if attention is paid to the distributions just above and below the arrowed line in the figure panels a discontinuity will be found in the depth direction. While this is admittedly only qualitative evidence, it can be seen to resemble the numerically computed results.

3.3.2 Continuing fragility of soil after settlement

Regarding the historical influence of past settlement, a common-sense reasoning might seem to be: "Since soil settlement is a kind of consolidation caused by a lowering of the underground water level, once the level is restored again the result ought to be equivalent to the loading and unloading of a weight. The ground is put into an overconsolidated state, which is effectively the same as a pre-loading effect, and must result in an improvement of the soil." In this section, we are now going to see why this argument fails to apply to a naturally deposited clay soil with a high degree of structure. As for the water level variation, let us also assume, once again, that the underground water is first made to fall to -20m after 47 years, and then restored completely to its original level. At the 80 year point, a load of 34.5kPa is exerted on the soil surface. The calculated results of these changes are given in Fig. 10. For comparison, the figure also has a curve for a similarly loaded soil that has not undergone a history of water depletion. The settlement in this pristine soil comes to no more than about 12cm, but in the soil with the depletion history, delayed settlement persists for some 55 years before ending at a level around 86cm lower than the recovery level after the previous phase of settlement. Figure 11 shows isochrones of the pore water pressure in this soil with a water depletion history, taken at points (a) – (e) in Fig. 10. We see the same kind of effect as in Fig. 7, with plastic compression leading to softening accompanied by pore water generation, and the same upward propagation as in Fig. 8, beginning in the area of the discontinuity boundary and then moving higher. Figure 12 shows the in-situ one-dimensional compressive response of one element (marked "I") in Fig. 11, calculated for the two soils with and without the history of water depletion.

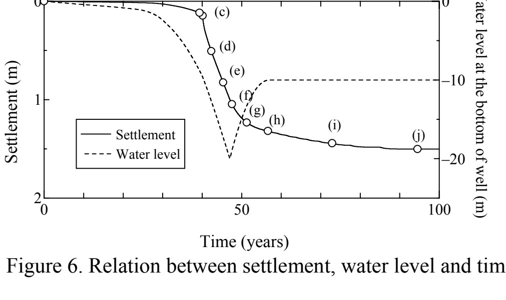


Figure 6. Relation between settlement, water level and time.

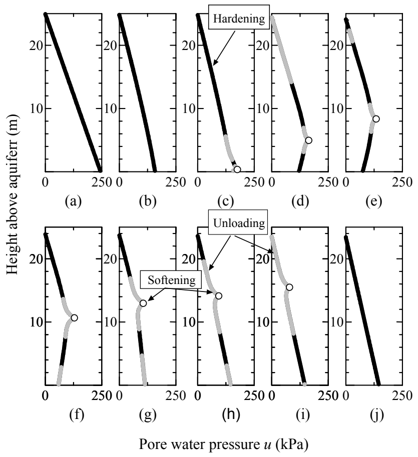


Figure 7. Generation of pore pressure.

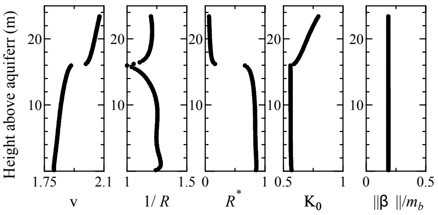
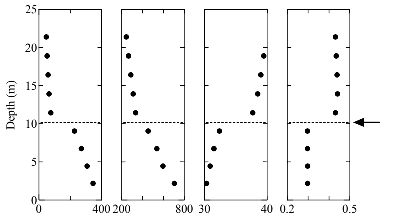
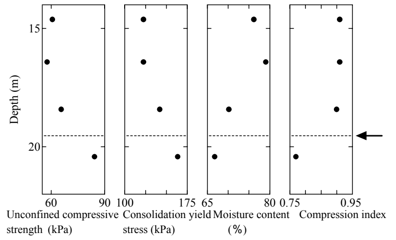


Figure 8. Soil property distributions after consolidation (100 years).



Numerical simulated "soil test" results



In-situ survey results (Nanyo district, Nagoya, 1973)

Figure 9. Comparison of simulated "soil test" with actual survey results.

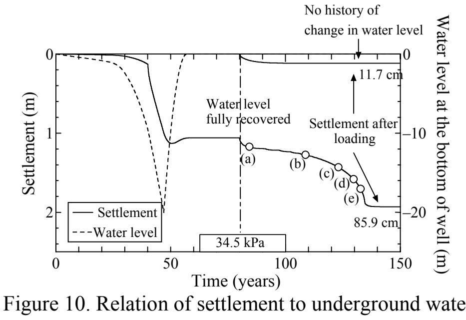


Figure 10. Relation of settlement to underground water level and time.

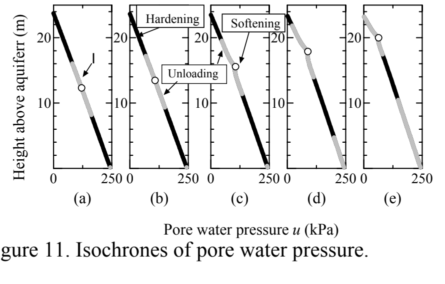


Figure 11. Isochrones of pore water pressure.

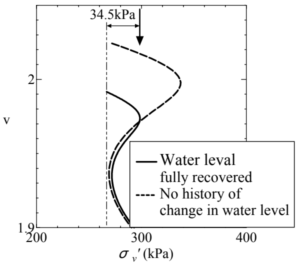


Figure 12. Response to one-dimensional compression test.

It is clear from this figure how a previous history of change in the underground water level, preserved in the form of soil disturbance, leads to a reduced reserve of so-called "preconsolidation stress." In contrast, a soil which has no depletion history of this kind will not undergo softening when subjected to a surface load.

4 ONE DIMENSIONAL NUMERICAL SIMULATION OF A MULTI-LAYERED MODEL SOIL SYSTEM

4.1 Calculation conditions

Alluvial plains often consist of multiple layer systems of alternating sand and clay. This section reports a calculation performed on the assumption of a multi-layer soil system having five layers each of clay and sand. This choice of layer composition is modeled on alluvial soils in Shanghai, on the lower reach of the Yangtse River. The boundary conditions are shown in Fig. 13 as in the single-layer example above. A load of 91kPa is assumed to be exerted on the upper surface of clay 1 layer. The elasto-plastic and evolution parameters of clay and sand are presented in Table 1. The initial conditions of clay are shown in Table 2. For the sand, the parameters are the same in all five layers, and the values chosen (overconsolidation ratio 10, and a low degree 1 of structure) are sufficiently dense for consolidation in the sand layers to be treated as negligible in comparison with the state of the clay. The behavior of the soil is investigated as the level of the first aquifer is made to fall from its position of 34m under initial ground level (point "A" in Fig. 13). The water level is first made to fall to a level of -27m over 39 years, after which it recovers to -15m over 10 years and is finally kept steady.

Table 2. Initial conditions of clay.

	$1/R_0$	$1/R^*_0$	k (cm/sec)
Clay 1 layer	1.45	12	3.0×10^{-7}
Clay 2 layer	1.29	10	3.0×10^{-7}
Clay 3 layer	1.05	12	3.0×10^{-7}
Clay 4 layer	1.05	9	3.0×10^{-7}
Clay 5 layer	1.03	8	3.0×10^{-7}

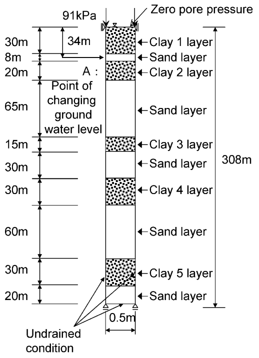


Figure 13. Boundary conditions.

4.2 Calculation results

Figure 14 shows the rates of settlement in clay 1 to 4 layers and at the ground surface, together with the variations in the underground water level, over a period of 400 years. The lowering and recovery of the water level can be seen to lead to settlement in clay 1 and 2 layers. Then, when the water level is held constant, clear evidence of settlement begins to appear in 3 layer at around t = 110 years, and in 4 layer at around t = 260 years, and surface subsidence is found to exceed 5m over wide areas. Furthermore, this subsidence shows no sign of ending even after 400 years. Figure 15 shows isochrones of pore water pressure taken at points along the surface settlement curve. At points (a) and (b) we see plastic compression and soil softening accompanied by a rise in the pore water pressure in clay 1 and 2 layers. Then, with the maintenance of the water level at a constant -15m, the effective stress becomes gradually propagated to the lower regions of the soil, until at (c) and (d) a rise in pore pressure becomes evident in 3 and 4 layers. The isochrones for 5 layer have been omitted from the figure since, for this amount of fall in water level, no influence is felt that far down in the soil. What is clear from the figure, however, is that a drop produced in the water level in this way has an effect on deep regions of the soil for a considerable length of time.

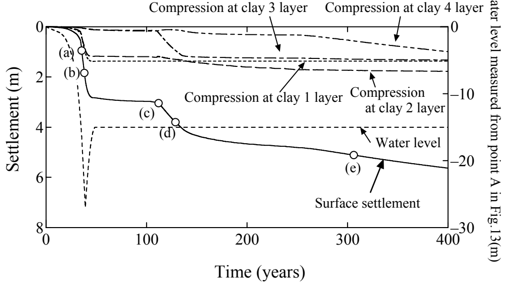


Figure 14. Relation between settlement, water level and time.

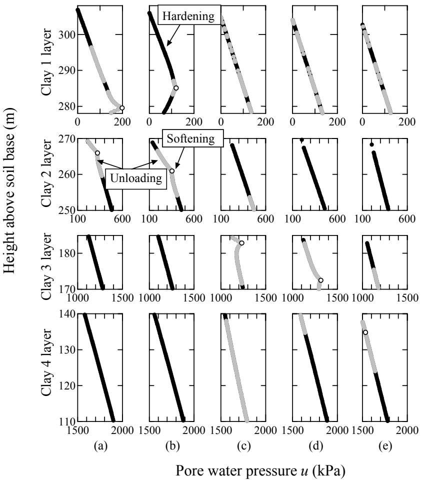


Figure 15. Isochrones of pore water pressure.

5 CONCLUSION

The study has shown that the fall in an underground water level can lead, by way of plastic compression accompanied by soil softening, to large-scale delayed settlement over a long period of up to several centuries. It also points to the possibility that a soil once exposed to subsidence of this kind may remain vulnerable to fresh loading in the future.

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