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Numerical Analysis of Experimental Slurry Trench in Soft Clay

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ABSTRACT: In this paper, experimental sequence of a full-scale test of slurry trench excavation in soft clay is numerically simulated using soil-water coupling finite element analyses. Behavior of pore water pressure; lateral pressure and their influences on deformation and failure of slurry trench are investigated. The effective stress Schofield soil model is utilized for investigating complicated responses of soft clay in active stress-relief condition. Numerical predictions are calibrated with field observations. Parametric study on soil permeability is then described, exposing the strongly time-dependent behavior of trench walls in soft clay.

1 INTRODUCTION

The limit equilibrium method, either with two-dimensional or three-dimensional approaches, has been successfully applied for analyzing the stability of slurry trenches excavated in non-cohesion subsoil. However, its applicability in case of cohesive subsoil is very limited. The complicated behaviors of cohesive soil, especially soft clay, require more synthetic analyses for appropriate solutions.

Finite element method (FEM), featured with soil-water coupling analysis and various soil models, has been used extensively to investigate the problem. Soil-water coupling analyses with effective stress soil models (Ng., 1998) proclaimed the essential aspects of soil behavior that could not be captured with commonly used undrained analyses in terms of total stress. Tamano (1996) made an intensive investigation of field observations from experiments of slurry trench excavation in soft clay which also revealed special issues in behavior of soft clay when lateral pressures acting on the wall were examined separately as pore water pressure and effective horizontal pressure.

Finite element analyses in this study were performed in order to elucidate fundamental behaviors of soft clay surrounding the experimental trench during a slurry level-lowering test. Changes of pore water pressure and lateral pressure in proportion to soil deformation are major elements to be investigated. Yielding and stress paths of subsoil are examined and used to identify the deformation and stability mechanism of slurry trench. It is proved that dissipation of negative excess pore water pressure has essential effects on deformation and collapse of slurry trench walls. Parametric study on soil permeability is carried out to aim at highlighting this issue.

2 EXPERIMENT OF TRENCH EXCAVATION

The experimental slurry trench was excavated in soft clay ground (west of Osaka). Figure 1 shows the sub-

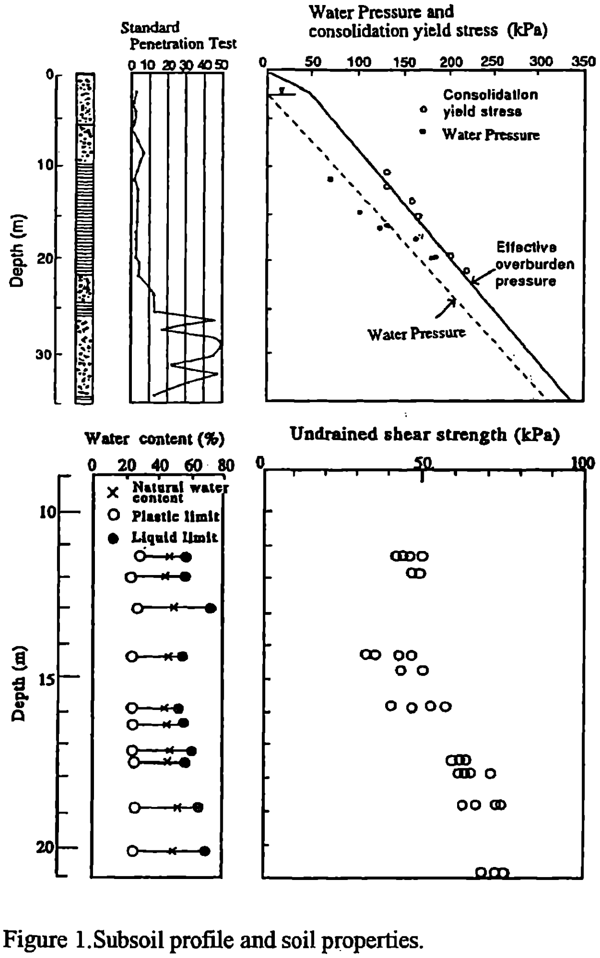


Figure 1.Subsoil profile and soil properties.

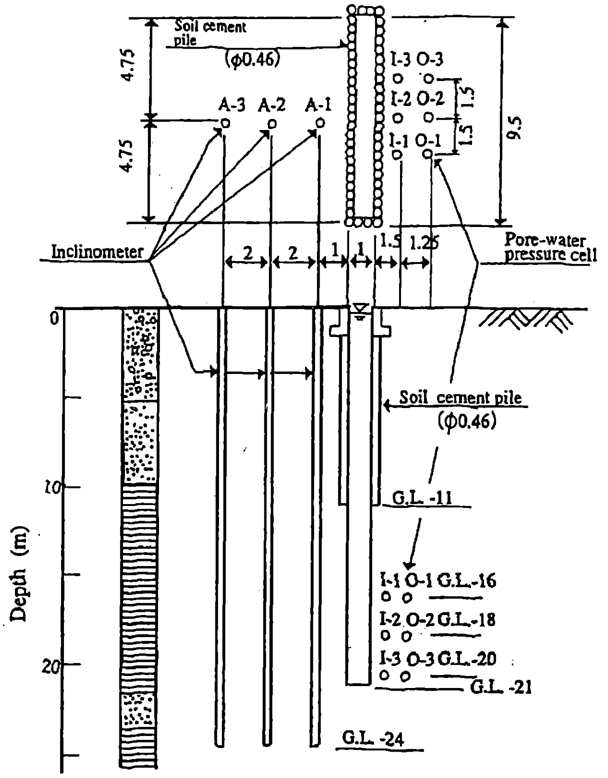


Figure 2.Experimental trench excavation
(plan, cross section and location of measuring instruments).

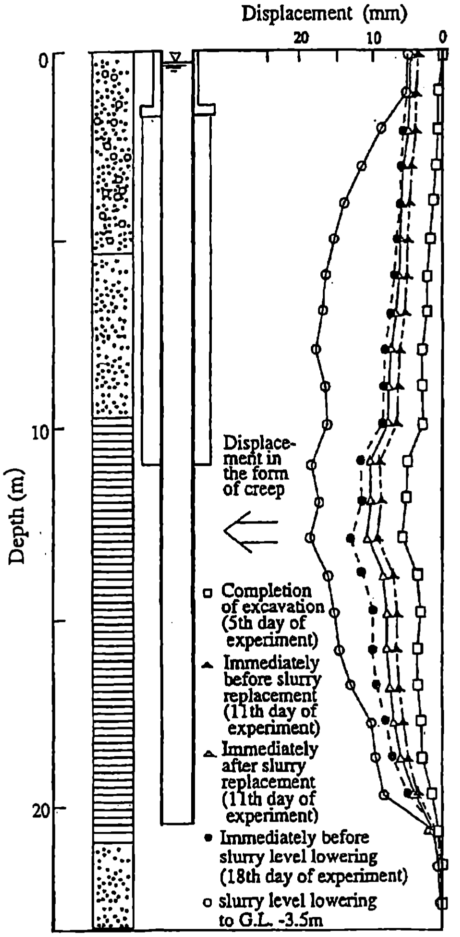


Figure 3. Subsoil displacement (at measuring point A-1).

soil profile and soil properties. The subsoil stratum consists of a backfill material layer to G.L.-5.0m reclaimed on a loose sand layer. The alluvial clay layer locates between G.L.-9.8m and G.L.-21.8m, comprises normally consolidated clay with natural water content of 40-50%, liquid limit of 50-70%, plastic limit of 20-27% and undrained shear strength of 29-73 kPa. At greater depth is a stiff sand layer with N>40. The pore water pressure was observed close to hydrostatic condition and ground water table situated at G.L.-2.6m.

Plan and cross-section of the experimental trench excavation, indicating the locations of measuring instruments and measuring points, are described in Figure 2. The trench panel was 1m wide, 9.5m long and was excavated to 21m deep in 5 days. Slurry with unit weight of 10.6 kN/m^3 was maintained at G.L.-0.3m during trench excavation process. A wall of soil cement piles, diameter of 0.46m, was installed through the backfilling material and loose sand layer to protect the trench wall from damage during the test. Displacements of subsoil adjacent to trench wall were observed by three inclinometers at 1m, 3m and 5m away from the trench wall, between G.L.-0m and G.L.-24m. Six pore water pressure cells were installed at G.L.-16m, G.L.-18m and G.L.-20m, 1.5m and 2.75m away from the opposite trench wall.

The test procedure is summarized in Table 1. The slurry level-lowering test was conducted from the 18th day to the 20th day, during which slurry level was successively lowered to G.L.-3.5m in three stages. Rapid increases of subsoil displacement were measured within 4 hours maintaining slurry level at G.L.-3.5m ~ G.L.-3.0m. After being raised back to G.L.-1.5m, the slurry level was again swiftly lowered to G.L.-3.5m. Inclinometer measurements indicated excessive displacements of subsoil and the slurry level had to be raised back to G.L.-0.3m in order to prevent the trench walls from collapsing. Recorded maximum displacement of subsoil was 28mm.

Some of the field data are described in Figure 3 and Figure 4. More details of the experimental results

Table 1. Test procedure.

Stage	Construction and experimental test operations	Unit weight of slurry (kN/m^3)	Elapsed time (hours)
1	Excavate to G.L. –21.0m	10.6	120
2	Maintain slurry level at G.L.–0.3m	10.6	144
3	Replace slurry	10.3	168
4	Start slurry level lowering test		
4.1	- lower to G.L. – 1.5m	10.3	2
4.2	- lower to G.L. –2.5m		2.5
4.3	- lower to G.L. –3.5m		4
4.4	- raise back to G.L. –3.0m		3.5
4.5	- raise back to G.L. – 1.5m		11.5
4.6	- lower to G.L. –3.5m		0.5
4.7	- raise back to G.L. –0.3m		~

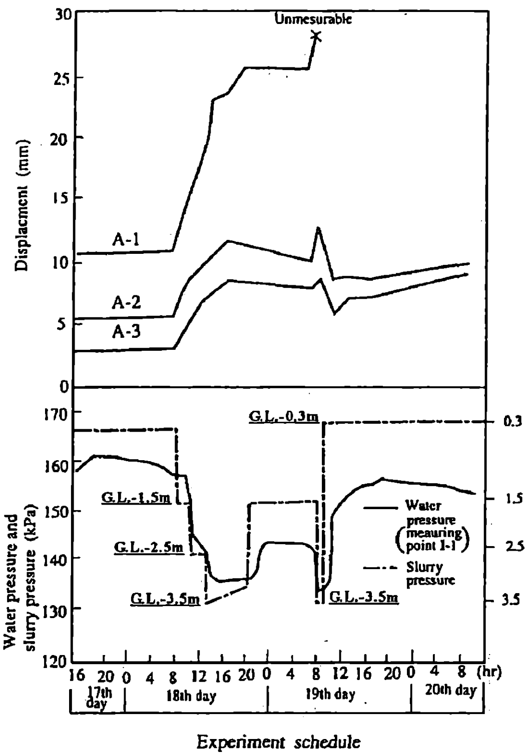


Figure 4. Variations of subsoil movement and water pressure during slurry leveling test (G.L.-16.0m).

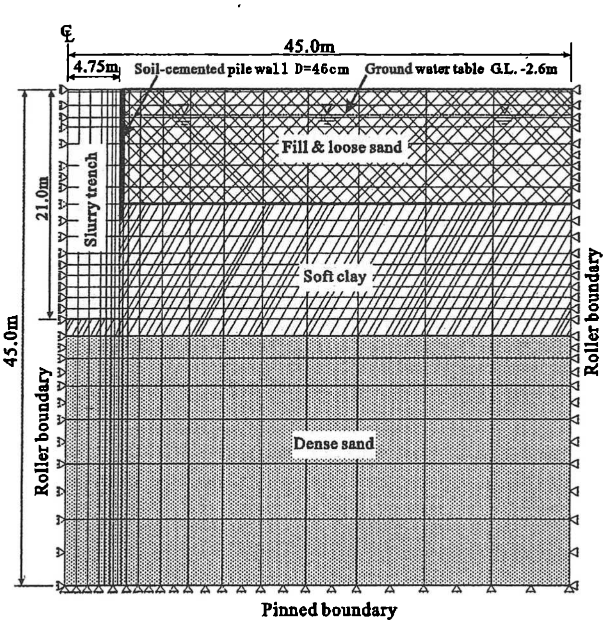


Figure 5. Finite element model and boundary conditions.

Table 2. Input parameters for backfill, sand layers & soil-cemented pile.

Soil parameters	Fill layer	Stiff sand	Soil - cemented
Elastic modulus, Eo (kPa)	1.0E+04	2.6E+04	6.0E+04
Poisson's ratio, ν	0.35	0.3	0.3
Internal friction angle, $\phi(^0)$	27	35	25
Drained cohesion, C' (kPa)	0	0	50
Bulk unit weight, γs (kN/m^3)	18	18	18

were reported by Tamano (1996). Figure 3 shows subsoil displacement adjacent to trench wall during the test at measuring point A-1. The trench wall had been observed quite stable until the slurry level was lowered to G.L.-3.5m from which it started deforming excessively in form of creep.

In figure 4, the measured pore water pressure showed a behavior closely corresponding to slurry pressure. It was interpreted (Tamano, 1996) that subsoil body deformed (compressed or expanded) very sensitively to the changes of slurry pressure. And because the subsoil behaved nearly saturated and undrained, these changes are then directly reflected by the variations of pore water pressure. This theoretical issue is visually demonstrated by the experimental data and, as will be described in the next section, also well reproduced by numerical analyses.

3 NUMERICAL ANALYSES

3.1 Finite element mesh and soil modeling

Analyses described in this paper were performed using the FEM program Sage Crisp, which features fully soil-water coupling analysis together with effective stress constitutive soil models.

The 3-D slurry trench panel was approximated in axisymmetric analyses; the trench was modeled as a cylinder with diameter of 9.5m, equivalent to the long edge of the trench panel (Tan, 1999). Figure 5 shows the finite element mesh, displacement and pore water boundary conditions. The lower horizontal boundary and the vertical boundary on the right side were set sufficiently remote from the excavation zone. For initial condition, ground water table was set at G.L-2.6m and the initial pore water pressures was assumed to be hydrostatic equilibrium.

Backfill material and sand layers were modeled by elastic-perfectly plastic Mohr-Coulomb soil model (Table 2). A Cam clay soil model proposed by Schofield, which incorporates the Cam clay yield surface on the wet side, and the Hvorslev surface and a no-tension cut-off on the dry side, was utilized to model the soft clay layer. Soil parameters used in the primary analysis are summarized in Table 3.

3.2 Initial stresses

The initial lateral effective stresses were estimated from the effective overburden pressure with coefficient of lateral pressure K_0 in normal consolidation condition (OCR =1; K_0 =1-sinϕ'). Size of Cam clay yield locus p'_c is also an essential input parameter of the model. It was evaluated from the initial effective stresses and an assuming ageing factor K_a=1.05, taking into account ageing effects.

Table 3. Input parameters for soft clay layer.

Soil parameters (Schofield model)	
Slope of compression line in v-lnp' space, λ	0.25
Slope of unload/reload line in v-lnp' space, κ	0.025
Critical void ratio, e_{CR}	3.00
Slope of critical state line in q-p' space, M	1.05
Poisson's ratio, ν	0.3
Bulk unit weight of soil, γ_s (kN/m^3)	16
Vertical permeability, k_v (m/s)	3.0E-09
Horizontal permeability, k_h (m/s)	1.0E-08
Slope of Hvorslev surface in q-p' space, H	0.6
Slope of no-tension cut-off in q-p' space, S	2

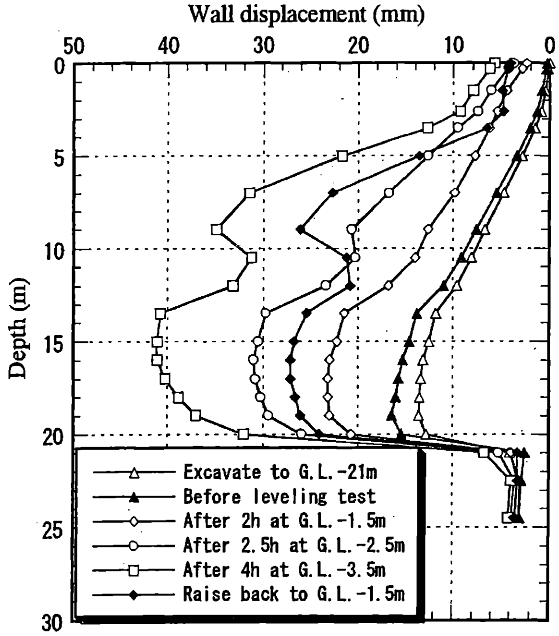


Figure 6. Predicted trench wall displacement profiles.

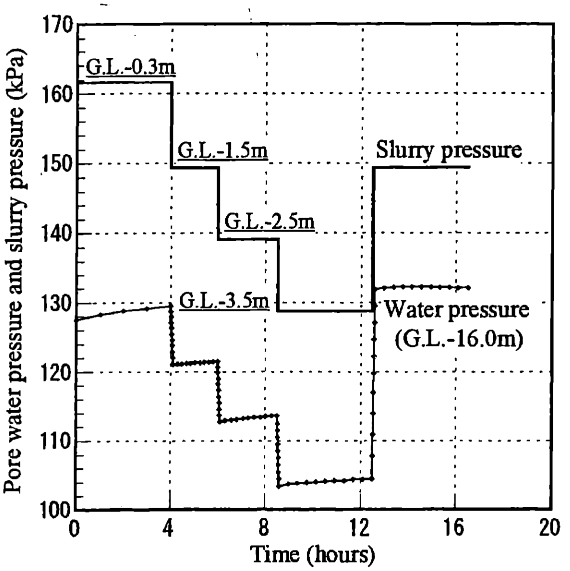


Figure 7. Response of pore water pressure to changes of slurry pressure (predicted at G.L.-16.0m).

3.3 Test procedure simulating & analysis cases

In the analyses, trench excavation and experimental test processes were simulated by corresponding analysis increment blocks which consisted multi increments with appropriate time-steps to fit the non-linear time-dependent behavior of soil.

Along with a primary analysis (case 1) as described above, three additional analysis cases (case 2 to 4) were also performed. In case 2, the slurry level was lowered further from G.L.-3.5m to G.L.-5m and maintained at that depth for couple of days. This analysis case aims to observe and examine more prominently the failure mechanism of soft clay while trench wall displaces excessively.

Permeability of soft clay layer was increased 10 times in analysis case 3, serving as a parametric study on the effects of time factor on subsoil deforming and failure. This parametric study considers the variety of soil permeability and drainage condition in real soil profile. Undrained analysis (case 4) was performed to compare with case 2 and case 3.

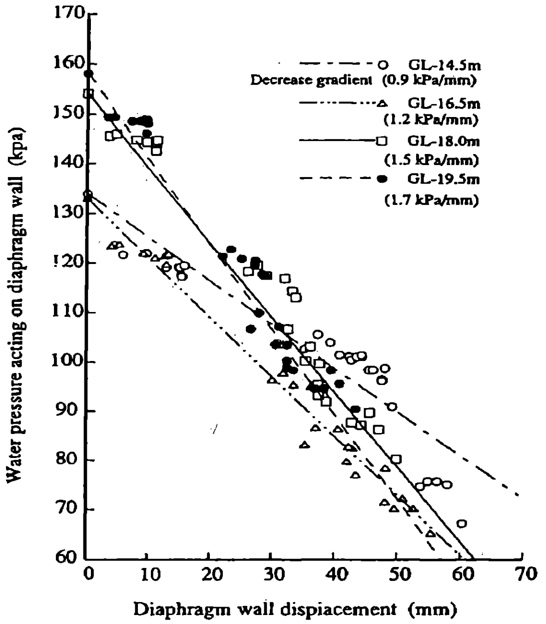
4 ANALYSIS RESULTS & DISCUSSIONS

4.1 Primary analysis results (analysis case 1)

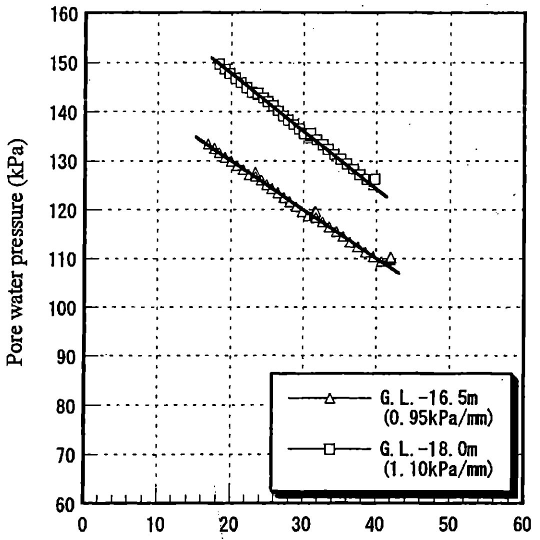
Figure 6 shows the displacement profile of the trench wall at instants of slurry level-lowering stages. The predicted displacements are generally larger than field observations but in a reasonable approximation. While plastic deformations of subsoil are well predicted, its behavior at small-strain is not appropriately captured. This has been known as backwardness of conventional Cam clay soil models and could only be surmounted by utilizing advanced soil models.

Nevertheless, the predicted trend of wall displacement well resembled that of the experiment. Very analogously to field observations, the trench walls are predicted quite stable. Then it starts displacing outrageously only when the slurry level is lowered to G.L.-3.5m. Maximum displacement exceeds 40mm. At the same time the soil-cemented pile wall is also predicted to undergo large deflection, coinciding with the occurrence of open cracks along the pile wall which is actually observed at the experiment site.

Figure 7 presents predicted variations of pore water pressure of a point close to the trench at G.L.-16m together with the evaluated slurry pressure at the same elevation. The predicted tendency of pore water pressure's response is seen in good agreement with the experimental data as described in Fig. 4. Hence, behavior of pore water pressure is proved appropriately illuminated in soil-water coupling analyses. Because in undrained or nearly undrained loading conditions, variations of lateral pressure are mainly attributed to variations of pore water pressure, sensitive re-



(a) Field data of experimental diaphragm wall excavation.



(b) Analysis results (at G.L.-16.5m and G.L.-18.0m).

Figure 8. Correlation between wall displacements and water pressure acting on the wall.

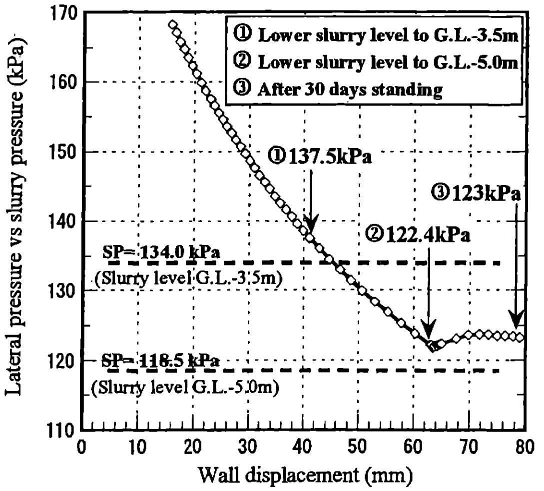


Figure 9. Correlation between wall displacements and lateral pressure.

sponse of pore water pressure to changes of slurry level confirms its essential role in the deforming and failure of slurry trenches.

Figure 8a shows the experimental correlation between wall displacement and water pressure. The measured data was extracted from field data of a braced diaphragm wall full-scale experiment in the same soil profile with the trench excavation. The plots indicated rather conformable linear correlations. With the assumption that behavior of subsoil adjacent to a slurry trench would be similar to that of subsoil in retaining side of a braced diaphragm wall excavation while the wall undergoes small deformations, experimental linear correlations were established that clarifies the behavior of water pressure and identifies the stability mechanism of slurry trenches (Tamano, 1996).

Analysis results (see Figure 8b) present the same trend of pore water pressure's behavior. The decreasing gradients of water pressure in proportion with wall displacement are 0.96 kPa/mm and 1.1 kPa/mm, well comparable with the experimental data of 1.2 kPa/mm and 1.5 kPa/mm, at G.L.-16.5m and G.L.-18m, respectively. The gradients will depend on initial value of pore water pressure, soil plasticity and rate of soil deforming. In practice, these decreasing gradient can be used to primarily estimate the required displacement of trench wall to attain equilibrium at which the lateral pressure, total of effective horizontal pressure and pore water pressure, reduces to the slurry pressure (at the corresponding elevation). The larger the difference between initial value of lateral pressure and slurry pressure, the more extensively the trench wall is forced to displace. Finally, either an equilibrium state is established or the trench wall displaces excessively and proceeds to collapse. This failure mechanism is further discussed in the next section.

4.2 Failure mechanism

Analysis case 2 was carried out to investigate the failure mechanism more prominently and to follow up the stress path of subsoil during its yielding. The slurry level was pretended being lowered to G.L.-5m. At the moment, rapid displacement of trench wall is predicted, maximum of 66mm (at G.L.-14.5m). The displacement is then seen to increase steadily during standing time, leading to the collapse of the trench wall.

Figure 9 shows the decrease of total horizontal stress (lateral pressure acting on the wall) of a point in soft clay at G.L.-16.5m, close to the trench wall, during the slurry level-lowering test. At either point ① or point ②, the reduced total horizontal stresses are a little larger than the referenced slurry pressures. Thus, equilibrium states have not been approached and trench wall is not in stable condition: progressive displacement is in great potential to occur. It is confirmed by additional displacements observed after 2 days the slurry trench left standing. During this period, dissipation of negative excess pore water pressure is observed to associate with corresponding reduction of effective horizontal stress which results no significant changes of lateral pressure (point ③).

Figure 10 describes the distribution of yield zone in subsoil after the slurry level was lowered to G.L.-5m. Within a large zone of about 10m, the soft clay is predicted "hardening on sub-critical (wet) side": in *p'*-*q* space, the soil stress state moves upwards, reaches Cam clay yield surface and follows the surface towards critical state line. A section of subsoil close to the trench wall suffers sufficient change in deviatoric stress that takes it onto the rupture-Hvorslev surface. As negative excess pore water pressures continues to dissipate, stress state of more soil element leaves the critical state and continues to soften on Hvorslev surface (see Figure 11).

The soil at yield is swelling and softening. During standing time, lateral pressure is seen to level off and therefore, we can reckon that the progressive displacement of trench wall is mainly attributed to the expansion of soil body while softening. Yet, the rate of soil softening in this condition is fully controlled by the dissipation of negative pore water pressure. Accordingly, time-dependent behavior of pore water pressure strongly influences the performance of trench wall. It should be strictly considered in numerical analyses of slurry trench excavation in soft clay.

4.3 Time-dependent parametric study

The progressive behavior of soft clay set off the essential roles of time-dependent factors on deformation and stability of trench wall. Table 4 compares the results of three analyses with different soil permeability. Obviously, undrained analysis badly underestimates trench walls' progressive displacement either when the standing time unexpectedly increases which may occur in practice because of bad weather and/or poorly controlled construction's management. This also awakes cares to estimate accurately actual drainage condition of subsoil for appropriate predictions of slurry trench performance.

5 CONCLUSIONS

It is concluded from this numerical study that:

1. Dissipation of negative excess pore water pressure causes progressive displacement of trench walls. When standing time is long enough, trench wall might collapse after excessively displacing due to soil softening.
2. Displacement and failure of slurry trench in soft clay are strongly time-dependent which cannot be reproduced by undrained analyses. In addition, in soil-water coupling analyses, soil permeability and drainage condition should be cautiously considered.

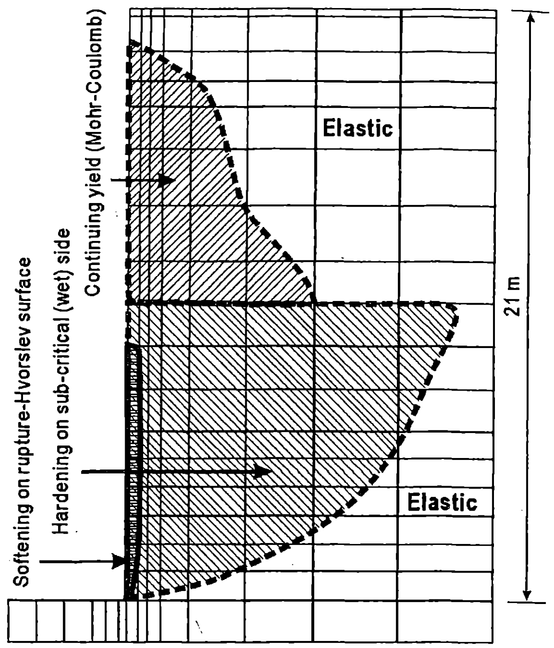


Figure 10. Soil yieldingwhen slurry level was lowered down to G.L.-5.0m (analysis case 2).

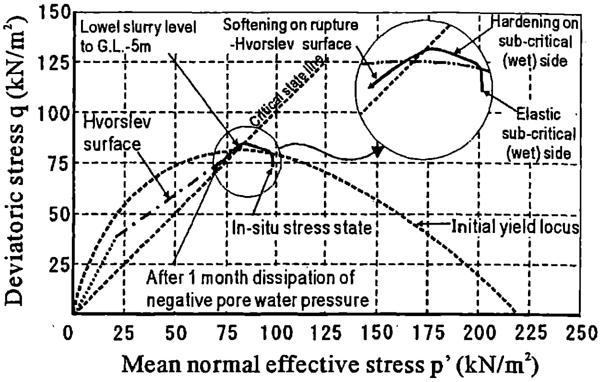


Figure 11. Stress path of a soil element close to trench wall, at G.L.-16.5m (analysis case 2).

Table 4. Wall displacements with various soil permeability.

Analysis stages (slurry level)	Wall displacement (mm)		
	Case 2	Case 3	Case 4
	k_h=10^{-8}m/s	k_h=10^{-7}m/s	undrained
Slurry level at G.L.-3.5m	42	47	39
Slurry level at G.L.-5.0m	66	71	62
After 2 days at G.L.-5.0m	70	113	65

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