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UNIFICATION OF DESIGN AND CONSTRUCTION OF DEEP EXCAVATION

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SUMMARY

A main factor in the design of excavation in an urban area is the movements. The finite element method provides rational predictions of excavation behaviour, yet practical engineers may find difficulties in applying it to the actual field case. In this study, factors affecting the excavation behaviour are considered in details and the applicability of the finite element method to the actual field excavation cases is presented. Numerical examples are analyzed to provide results of parametric study on the affecting factors.

INTRODUCTION

Thompson and Tanenbaum[1] reported very important remarks on the responsibility for trenching and excavation design. They asserted that the engineering profession should assume total responsibility which means that design cannot be isolated from construction. The design of excavation has been made on the basis of traditional method in which it does not fully account for any soil's local conditions and construction sequences, especially for those of building construction in urban area. According to Thompson and Tanenbaum, ignorance of the subsurface conditions may produce the lowest bid but result in an inferior, more costly and dangerous job in which workmen can be killed and that is why unchanged rate of excavation failures have been occurred.

The solution to those problems of excavation failures is the unification of design and construction practice. To provide the solution, the geotechnical engineer should consider both analytical and practical aspects. The finite element method has been used analytically to predict the movements of earth and earth-supporting structures and produced rational predictions for many actual excavation analyses. However, in simulating the actual field excavation problem by finite element method, it is required to figure out a number of data such as soil conditions and construction sequence which may significantly affect the excavation behaviour. Frequently, it is very difficult to reliably determine the soil strength and deformation parameters for certain reasons of time and expenses. Thus, the designers should make assumptions in predicting the movements and hence the predicted movements are sometimes suspicious to the practical engineers.

Because of those uncertainties, the predicted movements should be checked by the movements observed from field instrumentations and, if any differences found, it should be redesigned on the basis of the measured movements. In this study, some factors affecting the excavation behaviour are mentioned and two actual field excavation problems are analyzed to show the applicability of the finite element method. Finally, numerical examples are presented to evaluate effects of those factors on the earth and earth-supporting structures.

FACTORS AFFECTING THE EXCAVATION BEHAVIOUR

Clough and Mana[2] reported a number of factors affecting the movements of earth and earth-supporting structures in details on the basis of both analytical and practical considerations from considerable experience drawn from case history studies. According to them, those factors are as follows:

1) method of excavation simulation
2) soil modeling procedure
3) soil model parameters
4) problems introduced by construction variables

In this section, the above factors are discussed primarilly in relation with the finite element method developed by author[3] and other factors to be analyzed in this study are mentioned. The developed finite element method satisfies the uniqueness principle postulated by Ishihara[4] and uses nonlinear elastoplastic finite element equations derived from a variational formulation which accounts for time-varying domain and boundaries. The roots of those nonlinear equations are solved by Newton type method using the notion of consistent tangent operator[5] which results in asymptotic quadratic convergence.

Method of excavation simulation

Various methods of excavation simulation proposed so far[6,7,8] have used a step by step or incremental loading procedure and determined the equivalent forces caused by excavation procedure by using interpolation scheme. Higher order elements were proposed by Christian and Wong[6] and Mana[8]. A major drawback of the above procedures is that the solutions thus obtained are sensitive to the choice of equivalent nodal forces. That is due to the violation of total equilibrium. Based on the total equilibrium concept, Ghaboussi and Pecknold[9], and Brown and Booker[10] presented theoretically correct methods of excavation simulation for the problems of excavation in elastic soils.

The method proposed by author adapted the total equilibrium concept and was expanded for the various elastoplastic excavation analyses. The unique solution independent of construction sequence had been obtained for various elastoplastic soils[11]. Thus, from the analytical viewpoint, the excavation simulation algorithm which can appropriately model the actual field excavation problem in relation with actual construction sequence may give reliable results whenever the other factors are correctly handled.

Nevertheless, in view of practical aspects, the finite element method still produces cumbersome troubles as it is applied to the actual field excavation problem. For instance, the practical designers wonder if they should use fairly complicated mesh including actual earth-supporting structural elements. Besides, the element type may have an effect on the excavation behaviour since the earth-supporting structures are relatively stiff compared with the surrounding soils. In this study, those practical aspects are reviewed and analyzed by using actual field excavation problems. The results are presented and discussed later.

Soil modeling procedure

Considerable researches have been being performed on the stress-strain behaviour of soils and a number of models have been being proposed. The simpler models applied to soils are the nonlinear elastic hyperbolic model[12] and elastoplastic von Mises model. The von Mises model has been successfully applied to the analysis of excavation in saturated cohesive soils[2,13].The nonlinear elastic model allows the soil modulus to be adjusted consistently with the shear stress levels and may be successfully applied for the soils showing hyperbolic relations of the stress-strain behaviour.

Clough and Mana performed an analysis to facilitate comparison of the results using the different soil models and showed similar predicted behaviour irrespective of the soil model if appropriate soil parameters can be chosen. However, they observed that the magnitudes of the elastic moduli needed for accurate modeling of observed behaviour were significantly influenced by the soil modeling technique. In this study, various models are adapted to show the effects of those on the excavation behaviour. The models considered are nonlinear elastic hyperbolic model, Drucker-Prager model[14], and critical state model[15].

The parameters used in various models could be obtained from the laboratory test results. The laboratory tests are usually performed under triaxial compression condition, yet the actual field condition could have various other stress paths than those of the triaxial compression condition. Thus, even though some models represent good agreement with the results obtained from the laboratory tests, they cannot properly simulate the actual field behaviour unless the model shows good agreements for various stress-paths results. Unfortunately, even a model which can properly represents all the behaviours for all possible stress-paths is not available yet. This fact simulates researchers to suggest a universal constitutive model for all types of soils. However, the more accurate the model is, the more complicated it is, and it requires vast amount of parameters only obtainable from the experimental tests. Accordingly, this is the most unknown factor which the practical designer should be required to compare the predicted movements with those measured from the field instrumentations.

Soil model parameters

As mentioned in the last section, the number of parameters required to describe a soil model depends on the complexity of the model. Even if we use a simple model, the predicted movements are often very sensitive to the values of the parameters. Those parameters can be obtained by experience, field tests, or laboratory tests. The decision depends on the size and importance of the project. In this study, actual field excavation problems are analyzed to show how to determine the soil parameters and how to use it to predict final excavation induced movements in the cases that there is little knowledge on the soil strength and deformation parameters. Several numerical examples are investigated to show which parameters are significantly affecting the movements of earth and earth-supporting structures for various soil models.

Construction variables

Construction variables represent unanticipated construction problems or changes. Such an unanticipated problems may be caused by changed construction sequence, unexpected surcharge loads, overexcavation before installation of any supporting systems, etc. An example was reported by Murphy et al[16] showing the effects of unexpected surcharge load. Clough and Tsui[17] mentioned in their paper that the advantages of tied-back wall over braced wall could be the construction restriction of overexcavation in tied-back wall.

Any unexpected change in excavation system should be taken into account in the analysis and the practical designer should consider the revised construction procedure to make correction on the original design. In this study, the effects of overexcavation on the behaviour of anchor system are considered by using numerical examples of excavation in various elastoplastic soils. The construction sequence effects are also considered in the actual field problem and numerical examples.

Other factors

Besides the above factors, the stiffness of supporting structures, inclination of the anchor, and prestressing of the supporting system may have some effects on the movements of earth and earth-supporting structures. Hanna and Kurdi[18] studied an anchored flexible retaining wall in sand and concluded some effects of those factors in their paper. Clough and Tsui presented the effects of prestressing load of anchor on the wall deflections. Only significant factors are considered in this study.

APPLICATION OF F.E.METHOD TO ACTUAL FIELD CASES

In this section, two field excavation cases are analyzed by using the developed finite element excavation simulation technique to show the applicability of the method. In the field excavation, some instrumentations were installed to observe the behaviour of the earth and earth-supporting structures. They are inclinometers, load cells, strain guages and piezometers. The measured values are compared with the predicted ones.

Asia cement building excavation

This field excavation problem was analyzed to show the applicability of the finite element method to predict the movements of excavation system. Some factors mentioned in previous sections are considered in this example problem. Fig.1 shows the plan view of the excavation site and locations of some instrumentations. The excavation proceeds up to the depth of 20.3m to utilize the underground space. Fig.2 represents the subsoil condition and the mesh used in the numerical analysis. The problem was assumed to be plane strain and Drucker-Prager model was used to simulate the soil behaviour. In first step, the mesh includes the anchor elements and the other supporting elements and uses 8-node isoparametric elements to model the actual excavation system as closely as possible(Fig.2). This mesh requires huge amount of input data and storage requirement which make it almost impossible to use in practice. The complication of the mesh comes from the inclined anchor system and the actual soil stratification. Since much simpler mesh is preferred in practical application, the alternatives are suggested.

Before mentioning the suggestion, the designer of the actual excavation system has little knowledge on the soil strength and deformation parameters which may significantly affect the movements of the excavation system. Hence, to determine the parameters, the observed data from the field instrumentation are selected. Fig.3 shows the displacement profile measured from the inclinometer No.1, observed after 16 days from the installation of the inclinometer. The inclinometer was installed on Jan.9,1990 when the excavation proceeded upto the depth of 8.5m. Thus, the displacement profile represent only differences from the initial reading and do not represent the actual wall movements. Besides, the bottom point of the inclinometer was assumed to be fixed in the inclinometer reading, but the actual movement of the fixed point may be occurred even though the rock stratification has a large elastic modulus.

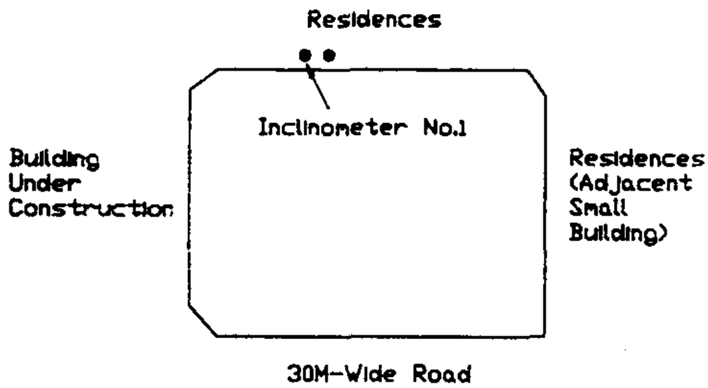

Fig.1 Plan view of excavation site and locations of instruments(Asia cement)

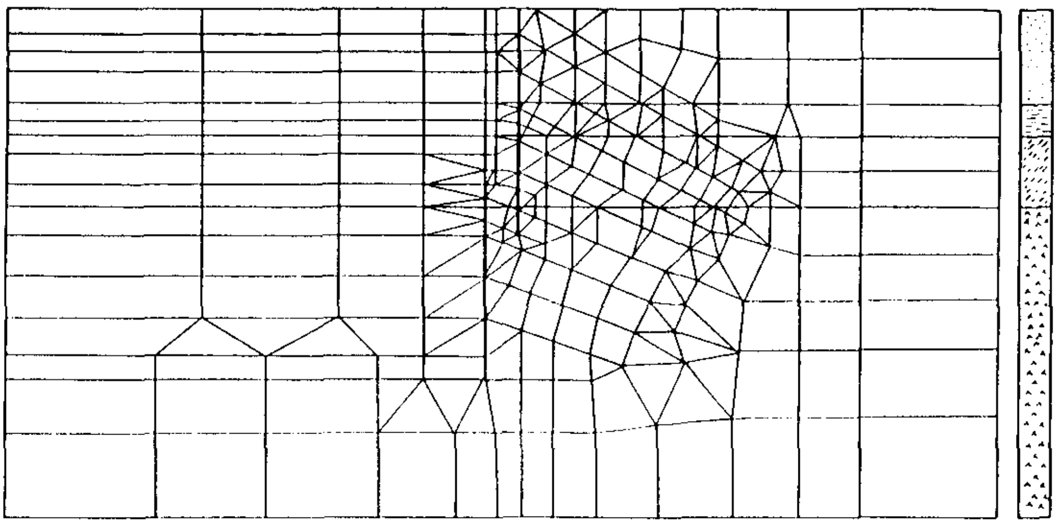

Fig.2 Mesh and subsoil condition

In this study, the parameters were selected to have close agreement with the measured displacement profile and they are shown in Table 1. With those parameters, the actual shapes of earth movements could be obtained corresponding to any excavation stages and those are drawn in Fig.4. The figure also shows the predicted difference in displacement profile after installation of the inclinometer. With those selected parameters, the final excavation-induced movements are predicted and Fig.5 shows the result with measured displacement profile. Those are in good agreement.

Now, the alternatives are mentioned to make the complicated mesh much simpler. First, the anchor elements are replaced by spring elements having same rigidity and inclination with the actual anchor system and then the final excavation-induced movements are calculated. Fig.6 shows the result and represents that a little bit small amount of movements are predicted for the alternative case. This fact was also reported by Clough and Tsui and in their paper they reasoned that for all conditions being equal the anchorage movement with soils caused the tied-back wall to move further than the spring supported wall(braced wall).

Table 1. Soil strength and deformation parameters

	E (t/m²)	ν	c (t/m²)	φ(°)
Sand	800	0.35	0	30
Weathered Rock	1000	0.33	0	33
Weak Rock	2000	0.30	5	37
Hard Rock	20000	0.25	10	40

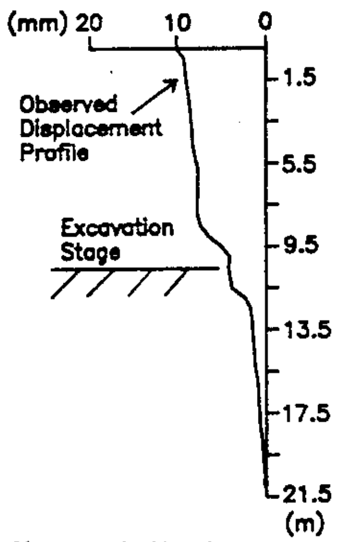

Fig.3 Observed displacement profile (Inclinometer No.1)

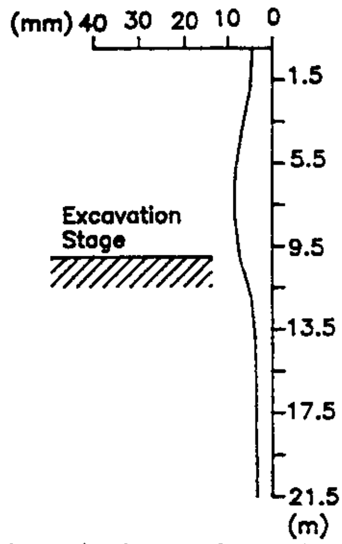

Fig.4 Actual shape of earth movement

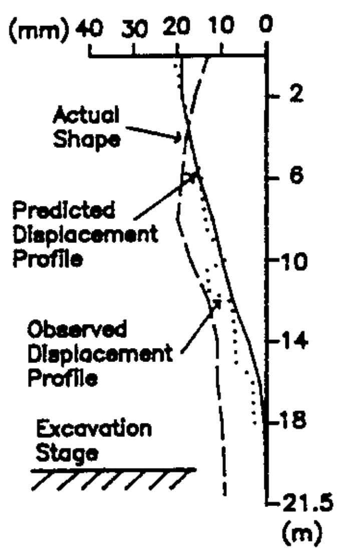

Fig.5 Final excavation-induced movement

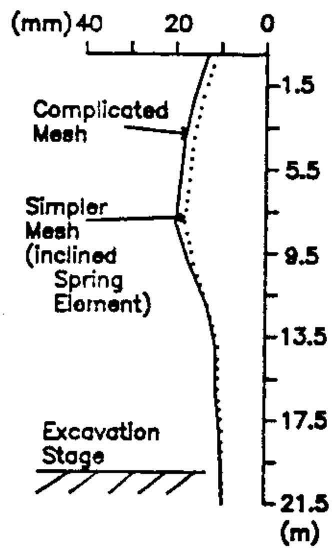

Fig.6 Displ. profile with simpler mesh(Hori. spring element)

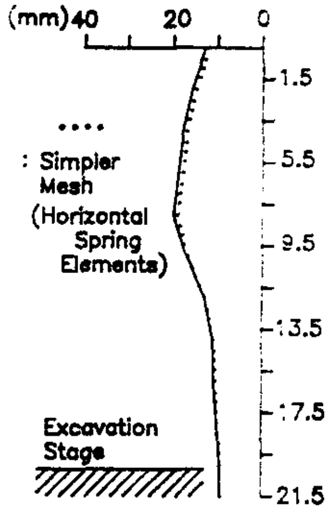

Fig.7 Displ. profile with simpler mesh(Incl. spring element)

According to the results of Fig.6, the anchor elements are now replaced by spring elements in horizontal direction. Fig.7 shows the result and also the result from the complicated mesh including the anchor elements. The final excavation-induced movements are in fairly good agreement. Accordingly, for practical analysis, the horizontal spring elements can substitute for the actual inclined anchor elements in this case and hence much simpler mesh can be used to represent the actual anchored excavation problems.

Kidokgyo hall building excavation

From the results of Asia cement building excavation problem, much simpler mesh can now be used to analyze this excavation problem. Fig.8 and Fig.9 show the plan view of the excavation site and the mesh and subsoil condition used in the analysis, respectively. Again, the observed displacement profile is selected to determine the soil parameters. In this case, the inclinometers were installed before the excavation proceed (on May 30,1990). The selected soil parameters are shown in Table 2.

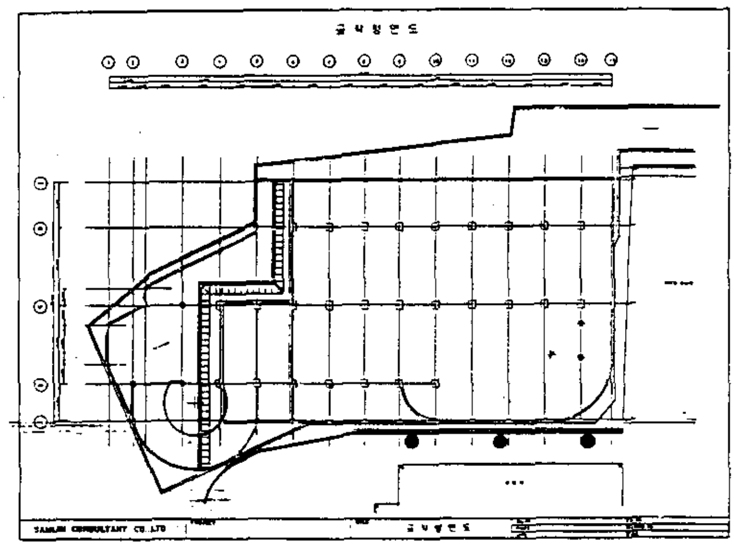

Fig.8 Plan view of excavation site and locations of instruments(Kidokgyo Hall)

Using the soil parameters, final excavation-induced displacement profile was calculated and Fig.10 shows the results.

In this example, the effects of element type is also investigated by using 4-node and 8-node isoparametric elements for the soils and supporting systems. According to Fig.11, the 8-node element type is predicting much larger displacements

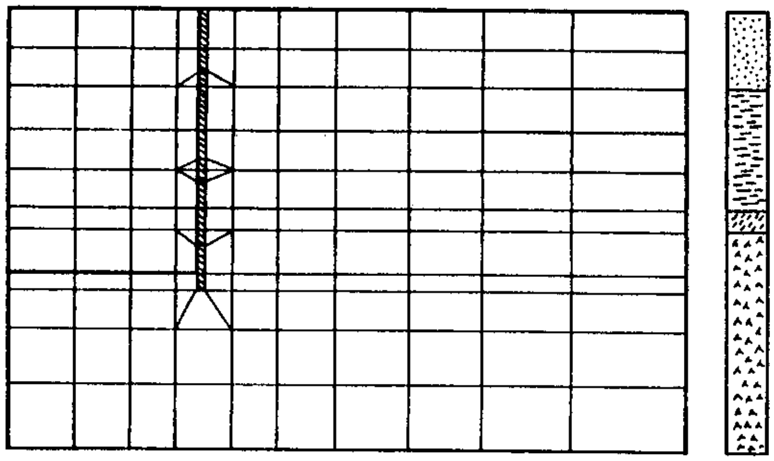

Fig.9 Mesh and subsoil condition

Table 2. Soil strength and deformation parameters (8-node isoparametric elements)

	E (t/m²)	ν	c (t/m²)	φ (°)
Residual Soil	30	0.35	0	30
Weathered Rock	40	0.33	0	35
Weak Rock	5000	0.25	5	38
Hard Rock	50000	0.25	10	40

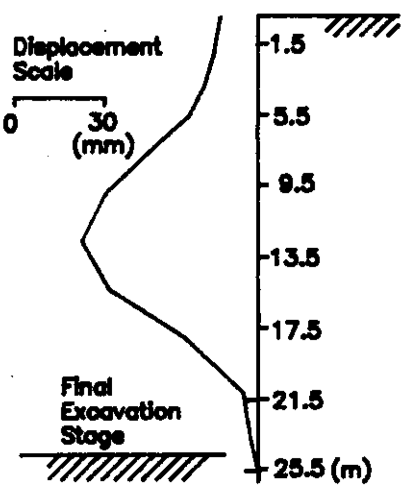

Fig.10 Final excavation-induced movement (8-node element)

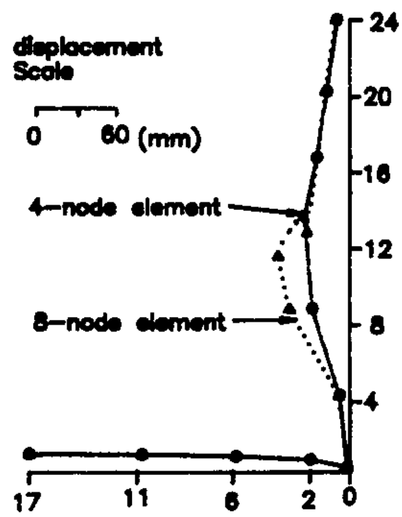

Fig.11 Effects of element type

NUMERICAL EXAMPLES FOR PARAMETRIC STUDY

In previous section, the developed finite element method of simulating excavation problems was applied to the actual field excavation cases and it is concluded that the algorithm reasonably predicts the movements of earth and earth-supporting structures. Thus, the method may be used to make parametric study of anchored or braced excavation problems. The factors mentioned in previous sections are considered in numerical examples to show the effects of those on the excavation behaviour. Fig.12 shows the mesh used in the numerical analyses.

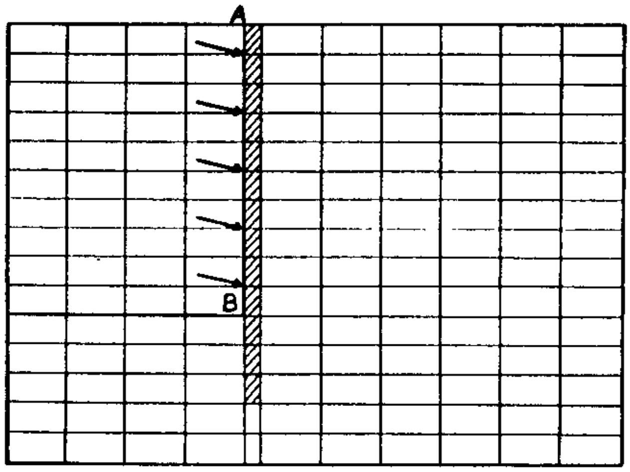

Fig.12 Mesh used in numerical analysis

The 4-node isoparametric elements are used to simulate the soil and slurry wall for simplicity and the problem was assumed to be plane strain. The effects of the method of excavation simulation on the excavation behaviour were already discussed and the results were presented in the actual field case application analyses. In this section, the other factors are considered in details.

Excavation analysis with hyperbolic model

In this section, the numerical example is used to present parametric study results in which the soil is assumed to behave according to the nonlinear elastic hyperbolic model. The model parameters used in the analysis are shown in Table 3.

Table 3. Hyperbolic model parameters

K	n	$P_a(t/m^2)$	K_b	m	$c(t/m^2)$	ϕ	R_f	K_{ur}	$\Delta\phi$
150	0.25	10.3323	150	0.0	0.0	30	0.9	250	0.0

The slurry wall element was assumed to be elastic with $E=1000t/m^2$ and $\nu=0.25$. To see the sensitivity of the final excavation-induced movements by change in construction sequence, the left corner 40 elements are removed in several steps. Fig.13 shows the final excavation-induced movements of nodes A and B(Fig.12) for each step. According to the figure, the errors for one step solution is not insignificant and one step analysis overestimates the movements. It is due to that unless the precise actual construction sequence is modeled, the resulting movements could be overestimated if the soil is assumed to behave according to the hyperbolic model.

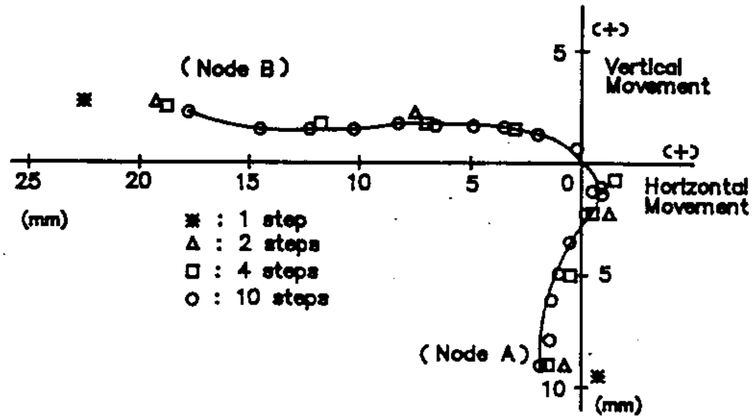

Fig. 13 Final excavation-induced movements of nodes A and B

Now, the anchored excavation system is analyzed to show the effects of overexcavation on the load of the anchors. The alternatives previously mentioned are used to simulate the anchor system and five anchors are used to support the slurry wall as shown in Fig. 12. Fig. 14 shows the predicted load of anchor No. 1 and Fig. 15 represents the max. excavation-induced displacement as the overexcavation proceed, respectively.

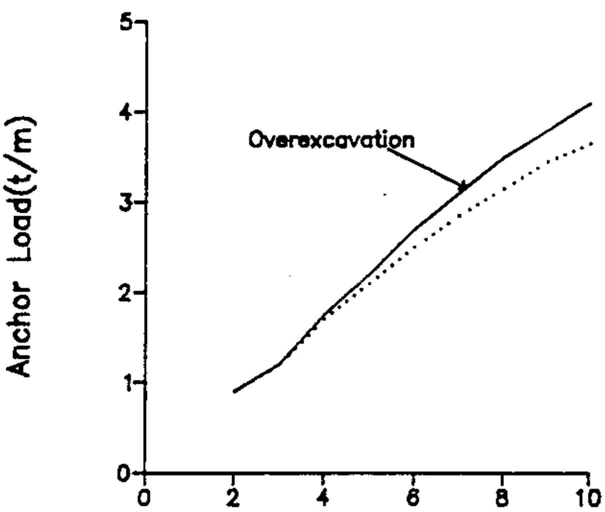

Fig. 14 Predicted load on anchor No. 1

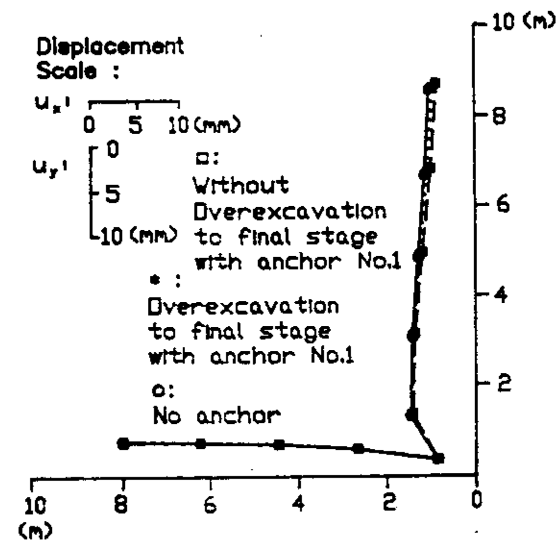

Fig. 15 Final excavation-induced movement

According to Fig. 14, the anchor loads shows the differences when the overexcavation depth exceeds 1m. Fig. 15 results in that with only the anchor No. 1 the max. final excavation-induced displacement could not be reduced even though the effect is not significant for this case. Thus, overexcavation over the depth of 2m could significantly affect the excavation behaviour if the excavation system is not stable without any anchors. Finally, Fig. 16 shows the calculated net earth pressure as well as at rest pressure(K_o=0.5). From the figure, prestressing the anchor with 0.25γH may largely reduce the resulting displacements.

Excavation analysis with Drucker-Prager model

The sensitivity of the final excavation-induced movement by change in construction sequence was reported by author for the case of Drucker-Prager model[3]. Fairly insensitive results were observed for various steps of construction sequence. In this study, the other factors are considered for this elastoplastic model.

The limitations of the Drucker-Prager model have been discussed by Christian and Desai[19]. The use of this yield model with the associative flow rule implies very large extensional volumetric plastic strains which is not observed experimentally even for dense sands. Some problems can be solved by using a nonassociative flow rule. The numerical example is analyzed to show this effects on the final excavation behaviour. To fully account for this effects, the soil parameters are chosen to guarantee that the initial gravity load alone already caused the soil to plastify. Fig. 17 represents the results that resulting displacement profile could significantly affected by the used flow rule and the overestimated volumetric plastic strain could result in much larger displacements.

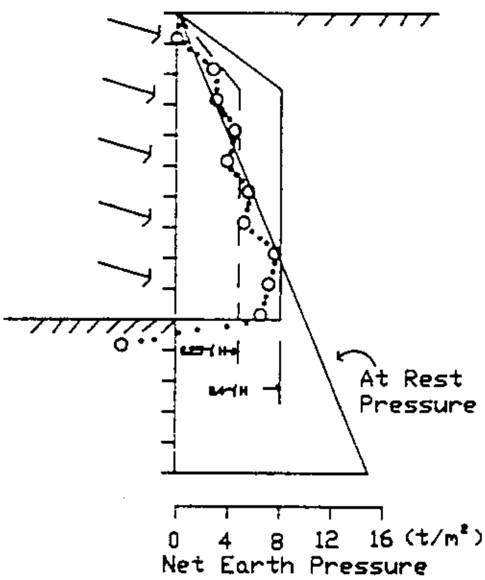

Fig. 16 net earth pressure

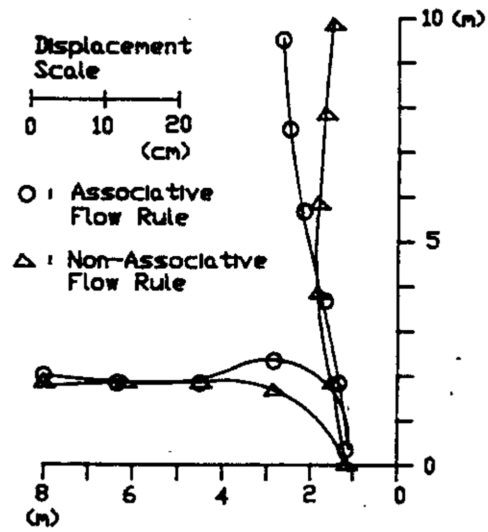

Fig. 17 Effects of flow rule

Fig. 18 shows the effects of overexcavation on the anchor load. In this example, the overexcavation effects are apparently presented, showing large difference in anchor load as the overexcavation proceed. Overexcavation to the depth of 2-3m already caused the anchor load over the final excavation-induced load without overexcavation. Fig. 19 shows the calculated net earth pressure at final excavation stage. Again, $0.20\gamma H$ pressure diagram could represents approximate pressure diagram and hence the prestressing stress of the anchors may produce much smaller displacement.

Excavation analysis with critical state model

The critical state model is simple yet capable of replicating actual behaviour of soils, especially for soft cohesive soils. The sensitivity of the final excavation-induced movements by change in construction sequence was also reported by author[20] and several other effects were considered by Borja [21]. According to Borja, the predicted movements are very sensitive to the poisson's ratio since this with bulk modulus calculates the elastic shear modulus. Also, since the bulk modulus is assumed to relate with the recompression index, the excavation-induced movements are also very sensitive to it[3]. Fig.20 and Fig.21 represent those effects on the final excavation-induced movements, respectively.

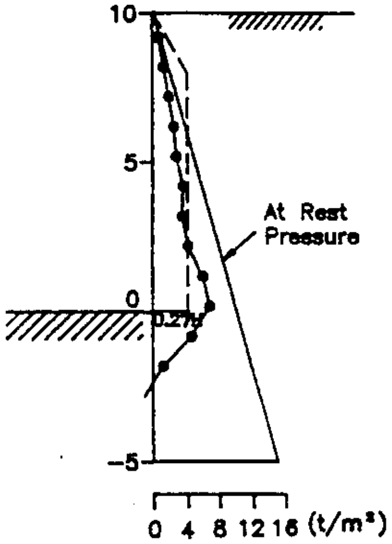

Fig.18 Net earth pressure

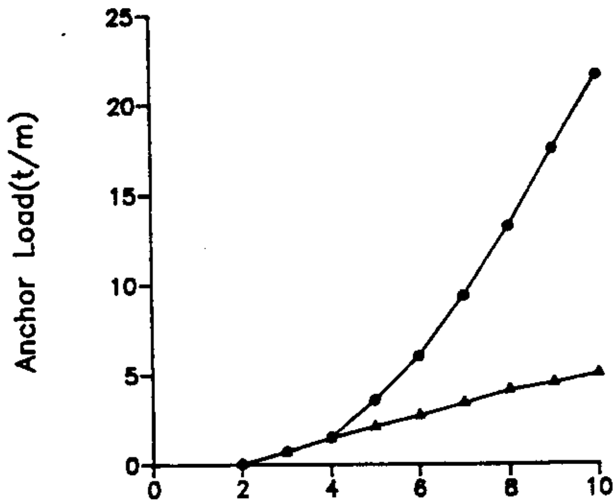

Fig.19 predicted load on anchor No.1

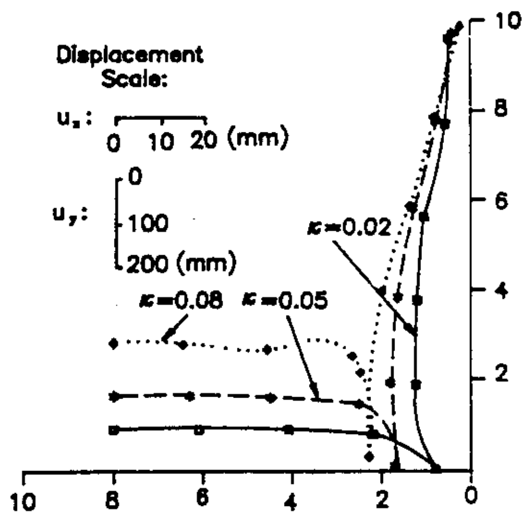

Fig.21 Effects of recompression index

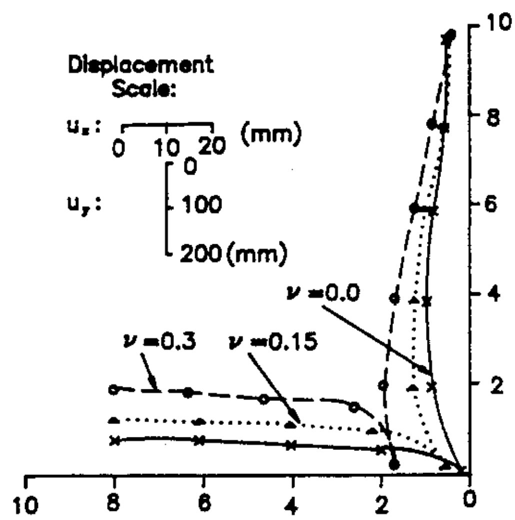

Fig.22 Effects of poisson's ratio

CONCLUSIONS

An accurate, stable, and efficient finite element algorithm for nonlinear incremental excavation problem was used to show the applicability to actual field case and to evaluate the effects of affecting factors on the excavation behaviour. The finite element method fairly well predicts the movements of excavation whenever the affecting factors are appropriately considered. Based on the results from parametric study, the variation of the affecting parameters largely affects the final excavation-induced movements and the supporting system.

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