Simulation of Delayed Failure in Naturally Deposited Clay Ground by Soil-water Coupled Finite Deformation Analysis Taking Inertial Forces into Consideration

Simulation de rupture différée d'un sol d'argile naturelle sédimentaire à l'aide de l'analyse des déformations finies de squelette couplé eau-sol en tenant compte de la force d'inertie

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ABSTRACT: A bearing capacity analysis was carried out for a highly structured naturally deposited clay ground using the soil-water coupled finite deformation analysis code ***GEOASIA***, which takes inertial forces into consideration and employs the SYS Cam-clay model, which is capable of describing the work of the soil skeleton structure. The following results and conclusions were obtained. 1) When a ground that exhibited localization of deformation and formation of a circular slip failure accompanied by load reduction as a result of loading by displacement control was loaded by load control, it failed dynamically in association with acceleration motions after reaching the peak load obtained during displacement control. To date, the bearing capacity problem has only been dealt with quasi-statically, but it is essential to take inertial forces into consideration in order to reproduce this type of failure behavior. 2) Using the analysis code, it was possible to reproduce the behavior before, during, and after the delayed failure phenomenon, as well as whether or not there is a load threshold for occurrence of delayed failure. To reproduce this type of phenomenon, a time-dependent constitutive equation is not necessarily required.

RÉSUMÉ : Nous avons effectué l'analyse de capacité portante d'un sol d'argile naturelle sédimentaire ayant développé une structure à l'aide du programme ***GEOASIA*** d'analyse des déformations finies de squelette couplé eau-sol en tenant compte de la force d'inertie, et équipé du modèle SYS Cam-clay qui inclut la fonction de la structure du squelette du sol. Les résultats sont indiqués ci-dessous. 1) La soumission d'une charge au sol par commande de déplacement produit une localisation des déformations et simultanément la création d'une rupture coulissante en forme d'arc alors qu'en soumettant une charge par commande de charge, après avoir atteint le pic de chargement de la commande de déplacement, le sol subit une rupture dynamiquement avec l'accélération de l'activité. Jusqu'à présent, le problème de la capacité portante n'avait été traité que de manière quasi-statique mais afin de reproduire ces comportements de rupture il est nécessaire de prendre en compte de la force d'inertie. 2) Il est possible de reproduire le comportement avant, pendant et après la rupture du phénomène de rupture différée à l'aide du même programme d'analyse du seuil de charge s'il y a rupture différée. Pour reproduire ce phénomène, une équation constitutive dépendante du temps n'est pas forcément nécessaire.

KEYWORDS: Inertial force, Soil-water coupled finite deformation analysis, Delayed failure.

1 INTRODUCTION

Starting in the 1990s, the Nagoya University geo-mechanics group has been engaged in developing soil-water coupled finite deformation analysis employing an elasto-plastic constitutive equation (Asaoka et al. 1994). In 2002, with the goal of developing a constitutive equation capable of handling the full range of mechanical behavior of a wide range of soil textures from clay to sand and intermediate soil, the group proposed the SYS Cam-clay model as an elasto-plastic constitutive equation based on the concept of the soil skeleton structure (Asaoka et al. 2002). More recently, the group developed a soil-water coupled finite deformation analysis code ***GEOASIA*** that accounts for inertial force (Noda et al. 2008), which enables the simulation of ground deformation and failure behavior without having to distinguish between static and dynamic problems.

While the importance of accounting for inertial force is widely recognized in seismic response analysis, the same cannot be said for phenomena that, up to this point, have been handled as quasi-static bearing capacity problems. Thus, in this paper, taking the bearing capacity of a highly structured naturally deposited clay ground as an example, we demonstrate that there are situations in which it is important to account for inertial force, even in the case of phenomena that have traditionally been treated as quasi-static. Furthermore, in order to show the robustness of the soil-water coupled skeleton approach, we again employ the ***GEOASIA*** code to demonstrate the possibility of simulating delayed failure of ground, which previously was explained as a rheological property of the soil skeleton, without having to impose a time dependence on the constitutive equation.

2 ANALITICAL CONDITIONS

The simulations were performed using the soil-water coupled finite deformation analysis code ***GEOASIA***, which accounts for inertial force, mounted with the SYS Cam-clay model to represent the work of the soil skeleton structure. The finite element mesh and boundary conditions used in the simulations are presented in Figure 1. Computations were conducted under two-dimensional plane strain conditions. We examined the loading of a rigid frictional foundation, represented in the simulations by imposing linear constraint conditions (distances constant and angles constant; Asaoka et al. 1998) on the nodes constituting the foundation. In order to prevent asymmetrical motion of the foundation due to slight numerical errors, we fixed horizontal displacement of the central node of the foundation and imposed direction constant condition. The material constants used in the simulation were adjusted to reproduce the elasto-plastic behavior of a typical clay soil (degradation rate of overconsolidation is greater than the degradation rate of structure, and development of anisotropy is slow). In the initial stage prior to analyzing the bearing capacity problem, we simulated the consolidation following the removal of a load (98.1 kPa) from the surface of a normally consolidated clay ground with highly developed structure and anisotropy up to the achievement of a steady state. The bearing capacity analysis was performed on the overconsolidated ground that was not affected by the surface load (material constants and initial values were estimated based on Noda et al. 2007). Loading was accomplished in two ways, either by controlling the displacement or by controlling the load. In the displacement controlled case, a forced vertical displacement was imposed on the central node of the foundation at a sufficiently fast rate (10^{-5}cm/sec) to ensure little migration of pore water within the ground. In the load controlled case, a load was added to the central node of the foundation at a rate of 0.015 kPa/sec. The loading rate, in this case, was adjusted so that the total time required to reach the peak load obtained by displacement control would be approximately the same as in the displacement controlled case.

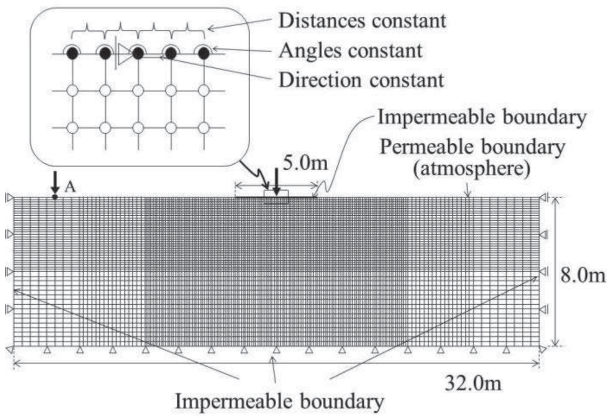


Figure 1. Finite element mesh and boundary conditions.

3 BEARING CAPACITY ANALYSIS UNDER DISPLACEMENT AND LOAD CONTROLLED CONDITIONS

In this paper, the bearing capacity analyses were conducted under both the displacement controlled and load controlled conditions employing a "quasi-static" approach, whereby the inertia term is ignored and only the equilibrium of force is taken into consideration, and a dynamic approach, whereby time integration of the equation of motion enables the handling of dynamic problems. In so doing, we demonstrate the need to account for inertial force when simulating the behavior, which includes accelerated motion, of soil undergoing failure.

3.1 Displacement controlled case

Here we consider the effect of inclusion (or omission) of the inertial term in the displacement controlled case. The relationship between load and settlement and the shear strain distributions are presented in Figures 2 and 3, respectively. First, it is evident that inclusion (or omission) of the inertial term has little or no effect on the simulation outcome. This is because, in the displacement controlled case where the foundation is moved at a constant velocity, the resulting ground acceleration is negligible and can, for all practical purposes, be ignored. Furthermore, it can be seen that, in the displacement controlled case, the deformation is localized and results in the development of a circular slip failure accompanied by load reduction. Such behavior characteristically occurs when a highly structured naturally deposited clay ground experiences rapid loading, with the soil components above the slip line exhibiting softening accompanied by plastic compression (Noda et al. 2007). In addition, it can be seen how the load increases a second time when displacement continues to be imposed after the initial reduction in load. As is evident from the upheaval of ground on either side of the foundation, this can be attributed to uplifting of the slipped soil mass and can be said to be the result of finite deformation.

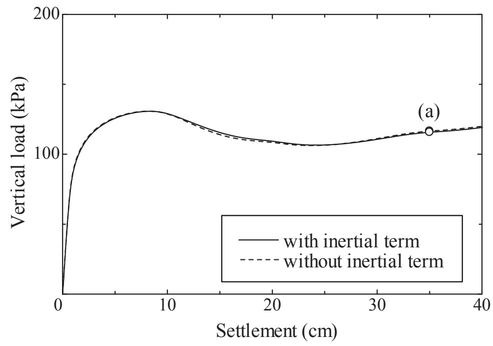


Figure 2. Relationship between vertical load and settlement (displacement controlled case).

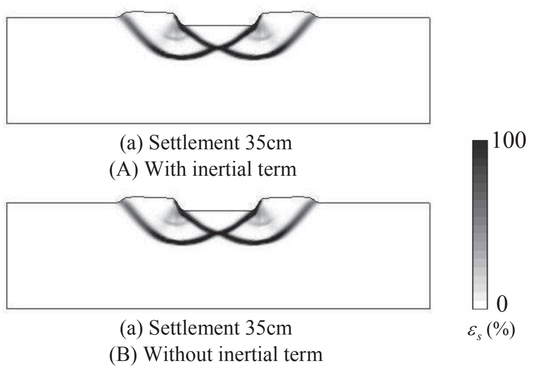


Figure 3. Shear strain distributions (displacement controlled case).

3.2 Load controlled case

Next, we examine the effects of the inertial term in the load controlled case. The relationship between load and settlement is presented in Figure 4. The results for the displacement controlled case (with inertial term) are shown in the same figure. The quasi-static approach not accounting for the inertia term only allows simulation up to point (a) in Figure 4, which represents the peak load in the displacement controlled case. In contrast, the dynamic approach enables the simulation to continue beyond the point of peak load in the displacement controlled case. We see that the load continues to cause nearly constant settlement, and the load begins to increase again after a certain point. The shear strain distributions corresponding to time points (a) to (c) in Figure 4 are presented in Figure 5. In the simulation including the inertial term, the deformation is localized, resulting in development of a circular slip line similar to that observed in the displacement controlled case. The time histories of vertical acceleration, velocity, and displacement (positive in the downward direction) for the central node of the foundation are presented in Figure 6. (Only velocity data is shown for the quasi-static analysis.) It can be seen in the dynamic analysis that accelerated motion begins after point (a) on Figure 6, which represents the peak load in the displacement controlled case. After reaching a peak, acceleration transitions to deceleration and motion once again converges to approximately zero through repeated cycles of acceleration and deceleration. In accordance with this acceleration history, velocity reaches a peak and thereafter converges to zero. During this time, displacement continues to increase, resulting in settlement on the order of 80 cm. A mere 2 to 3 seconds are required for this movement to occur. The majority of the nearly-constant settlement due to load seen in Figure 4 occurs during this short time. Meanwhile, it can be seen in Figure 6 (B) that velocity increases rapidly even in the case of the quasi-static

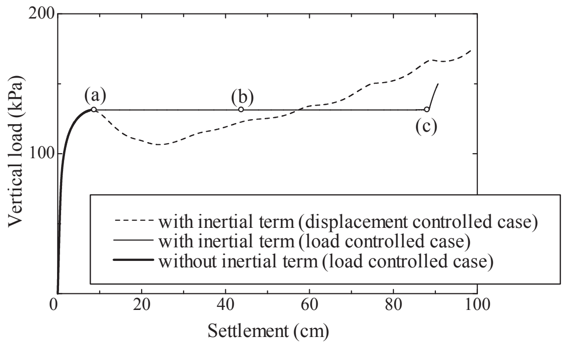
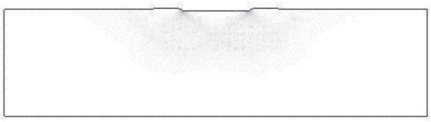
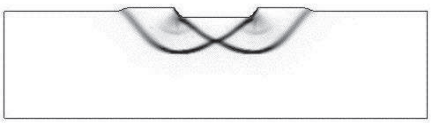


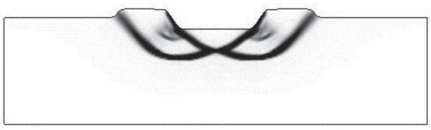
Figure 4. Relationship between vertical load and settlement (load controlled case)

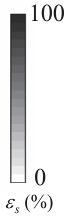


(a) Commencement of accelerated motion
(just prior to failure)



(b) During accelerated motion
(during failure)



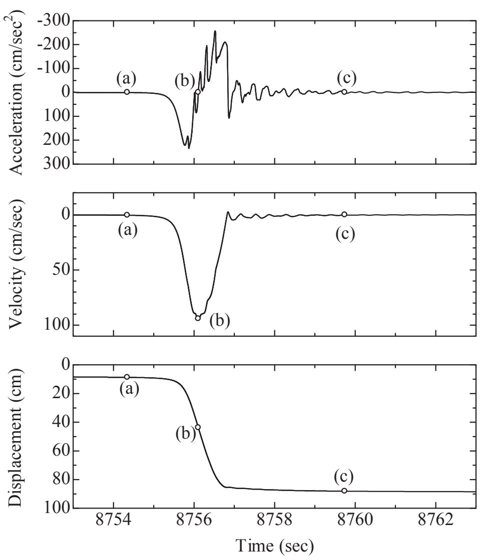


(c) Cessation of accelerated motion
(immediately after failure)
(A) With inertial term

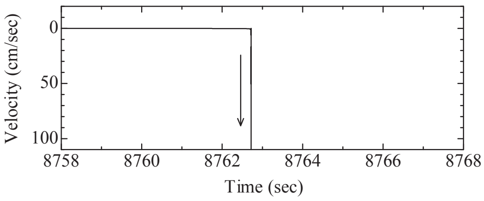
Figure 5. Shear strain distributions (load controlled case)

simulation resulting in partial failure. However, the velocity increase is more sudden than in the simulation accounting for the inertia term and dissipates instantaneously, precluding further calculation. The velocity change calculated using the approach accounting for the inertia term results in a maximum acceleration on the order of 0.25g, much more moderate than that predicted in the quasi-static analysis. Naturally, this is because the inertial force resists changes in motion. The upheaval of ground on both sides of the foundation after failure can be confirmed in Figure 5. In finite deformation analysis, it can be imagined that this upheaval plays a significant role in the transition from accelerated motion to static motion.

Next, comparing the results of the displacement and load controlled cases in Figure 4, we see that the behavior predicted is the same up to the point of peak load (a) for the displacement controlled case. We understand the accelerated motion observed in the load controlled case occurring after achieving the peak load in the displacement controlled case as resulting from external forces that cannot be accounted for statically. If we change our perspective to that of an observer moving with the foundation, the inertial force can be said to be an apparent force that compensates for the deficit in the equilibrium of forces. Whereas the behavior predicted in the load controlled case coincides with that for the displacement controlled case up to the initiation of accelerated motion at point (a), it can be seen that the behavior at the conclusion of accelerated motion (point (c)) is not consistent with the relationship between load and settlement predicted in the displacement controlled case. This is because the soil elements undergo a different stress history in failure involving accelerated motion and failure due to static forces.



(A) With inertial term



(B) Without inertial term

Figure 6. Time history of acceleration, velocity, and displacement of the central node of the foundation (load controlled case)

4 SIMULATING DELAYED GROUND FAILURE

In order to simulate delayed failure, we increased the vertical load up to 125, 126, 127, 128, 129, and 130 kPa under the load controlled condition and then left the load in place. Taking the discussion in the previous section into consideration, we performed an analysis using the approach accounting for inertial force.

The resulting relationship between the vertical load and settlement is presented in Figure 7 (corresponding to symbols (a)-(c), (a)', (a)" in Figures 7 to 10, respectively). It is evident that there is a significant difference between the settlement for final loads up to and including 127 kPa and those greater than or equal to 128 kPa. The relationship between the elapsed time during a constant load and the displacement velocity in the central part of the foundation is presented in Figure 8. In the case of final loads greater than or equal to 128 kPa, similar to the other cases, the settlement initially and gradually approaches convergence, but at a certain point the displacement velocity increases rapidly, after which the settlement again approaches convergence. The shear strain distribution for the 128 kPa load after point (c) at which the displacement velocity increases rapidly is presented in Figure 9. It is evident in the 128 kPa load case that delayed failure has occurred. As can be seen in Figures 7 and 8, delayed failure occurred for all loads greater to or equal to 128 kPa. Meanwhile, for all loads up to and including 127 kPa, the consolidation continuously approached convergence. The existence of a threshold load value above which failure occurs and below which failure does not occur has long been verified through experiments on triaxial samples (e.g. Murayama & Shibata 1956). Up to this point, such phenomena observed in saturated soils have been treated as a rheologic property of soil and have been described using viscoplastic constitutive equations. In contrast, the results presented here demonstrate that delayed failure and the existence of a threshold load value for the occurrence (or lack thereof) of delayed failure can be simulated as a soil-water coupling effect without having to impose a time dependence on the soil skeleton. The time history of vertical acceleration of the central node of the foundation around the time of delayed failure for the 128 kPa load case is presented in Figure 10. Similar to the behavior observed in the load-controlled case in Figure 6, it is evident that the behavior during failure involves accelerated motion. As such, it is necessary to account for inertial force in order to reproduce the behavior that occurs during this delayed failure. Furthermore, in the 128 kPa load case presented in Figure 8, the momentary increase in displacement velocity followed by a secondary convergence indicates a return to static consolidation following the convergence of accelerated motion. Thus, the soil-water coupling effect is particularly important in understanding the consolidation behavior before and after failure, and the effects of inertial force are particularly important in understanding the dynamic failure experienced under constant load. It should be kept in mind that even if it is possible to reproduce the behavior of the ground right up to the point of failure by using a time-dependent constitutive equation, if the analytical tool used to solve the boundary value problem does not account for inertial force, it will not be possible to reproduce the behavior after that point.

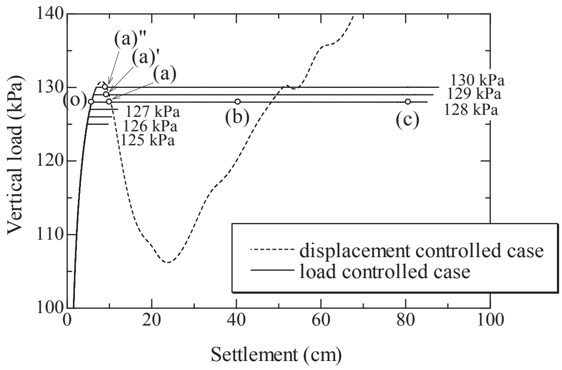


Figure 7. Relationship between vertical load and settlement (load constant case)

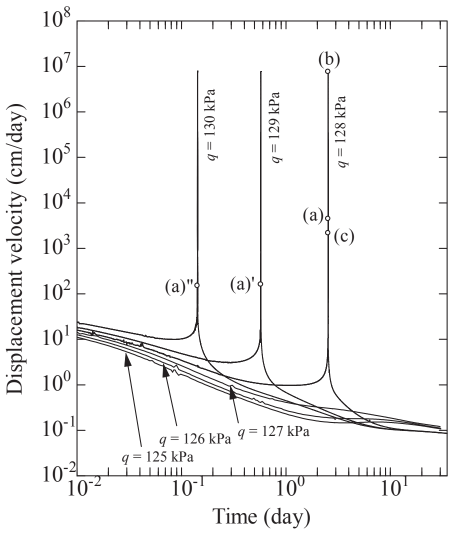


Figure 8. Relationship between time and displacement velocity (load constant case)

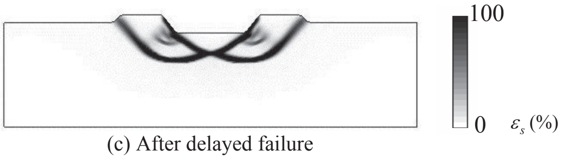


Figure 9. Distribution of shear strain (load: 128 kPa)

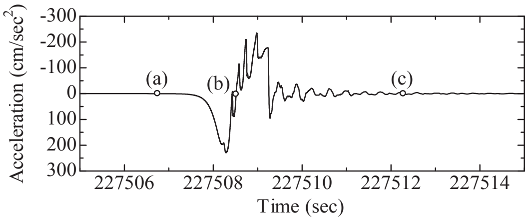


Figure 10. Time history of acceleration of central node of foundation (load: 128 kPa)

5 CONCLUSIONS

In this paper, a bearing capacity analysis was carried out for a highly structured naturally deposited clay ground using the soil-water coupled finite deformation analysis code ***GEOASIA***, which takes inertial forces into consideration and employs the SYS Cam-clay model, which is capable of describing the work of the soil skeleton structure. The following results and conclusions were obtained.

1) When a ground that exhibited localization of deformation and formation of a circular slip failure accompanied by load reduction as a result of loading by displacement control was loaded by load control, it failed dynamically in association with acceleration motions after reaching the peak load obtained during displacement control.
2) To date, the bearing capacity problem has only been dealt with quasi-statically, but it is essential to take inertial forces into consideration in order to reproduce this type of failure behavior.
3) Using the analysis code, it was possible to reproduce the behavior before, during, and after the delayed failure phenomenon, as well as whether or not there is a load threshold for occurrence of delayed failure. To reproduce this type of phenomenon, a time-dependent constitutive equation is not necessarily required as an inherent nature of soil skeleton.
4) For the delayed failure phenomenon, the soil-water coupling effect is particularly important for the consolidation behavior before and after failure, and inertial effects are particularly important for the dynamic failure behavior while a constant load is maintained.

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