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Fluid-coupled Analysis using Solution Mapping and Remeshing

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ABSTRACT

Mesh-based numerical techniques like the finite element and finite difference method have demonstrated its ability in solving complex time-dependent geotechnical problems. However, the modeling becomes less straight-forward when excessive mesh distortion inevitably occurs when simulating a large deformation problem, for instance pile/cone penetration. Numerical instability may occur which leads to premature termination of the analysis when traditional Lagrangian-based finite element formulation is employed. In the finite element package ABAQUS, numerical approaches like the ALE and CEL method have been built-in to handle the large deformation problems. The approaches have been found successful in performing analysis in a dry medium, where pore fluid is ignored. Yet, problems arise when a fluid-coupled analysis, which is often required in geotechnical engineering, is involved.

In this study, the "re-meshing and re-mapping" methodology of fluid-coupled large deformation finite element analysis is developed and implemented into ABAQUS. The algorithm divides the conventional "*one-step*" analysis into many sub-steps. Within each sub-step, re-meshing and re-mapping of material properties is performed. A fully coupled-consolidation analysis in a hypothetical ground is used as an example to illustrate the capability of such "*adaptive*" method. Development of the surface settlement and excessive pore water pressure with time is compared between the two analyses. Potential applications of the method are discussed.

1. INTRODUCTION

Finite element (FE) is a commonly adopted numerical technique to solve boundary value problems. However, it is well known that a simulation cannot be properly performed when excessive distortion occurs in the FE mesh. The highly distorted mesh may lead to instability problems in which premature termination of the analysis is likely

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to occur. In ABAQUS (Hibbitt, Karlson, & Sorensen Inc., 2008), which is widely adopted by researchers, numerical algorithms are developed to handle the aforementioned problem, like the Arbitrary Lagrangian-Eulerian (ALE) method and the Coupled Eulerian-Lagrangian (CEL) method. The ALE method allows the material to move separately from the mesh, generates new mesh in a given interval and maps quantities from the existing mesh to the newly generated one. The method, in other words, permits large deformation of the domain. The CEL method allows Eulerian material to flow along stiff bodies, thus enabling fluid-structure interaction simulations. Tolooiyan and Gavin (2011) used the ALE method to model a cone penetration test (CPT) in dry sand. Meanwhile, excessive distortion of the FE mesh is prevented by generating new meshes and the analysis is completed successfully. Qiu et al. (2011) used the CEL method to simulate a wide range of geotechnical problems, including strip footing (undrained analysis) and pile jacking (fully drained analysis); where large deformation of the soil domain is involved in both cases. However, transient fluid-coupled responses of the soils involving large distortion are with less focus despite the fact that they are always of the interest to geotechnical engineers.

In this study, it is attempted to prevent excessive distortion of a FE mesh by adopting the method of re-meshing and re-mapping, so-called *adaptive analysis* hereafter. The developed methodology for fluid-coupled large deformation FE analysis is implemented into ABAQUS. Simulation of a consolidating ground in a fully fluid-coupled manner is presented.

2. NUMERICAL MODELING

The saturated normally consolidated ground is modeled by a column of 8-node biquadratic displacement, bilinear pressure, reduced integration axisymmetric elements. The soil column is set to be 1 m by 20 m, with 1 m $\times$ 1 m element size. Roller boundaries are set at the bottom, far end and along the centerline of the domain. The ground water table locates at the ground surface which induces an initial hydrostatic pore water pressure with depth. The initial soil density, void ratio and stresses vary with depth. The saturated soil is assumed to follow well the Modified Drucker-Prager model with a compression cap. Table 1 and Fig. 1 summarize the material properties. In this study, length of transition is set to be zero (by setting α to 0); implying an abrupt change between the shear surface and the compression cap. The consolidation process is initialized by applying a 40 kPa surface load (corresponds approximately to a 2 m height fill) on the ground surface. A fully drained boundary is set at the ground surface.

Fig. 2 shows the algorithm of the re-meshing and re-mapping process – adaptive analysis. Note that the conventional one-stage analysis is referred to as “*one-step*” analysis in this study. The analysis is started by applying a gravity field, and followed by the application of 40 kPa surface load, which induces excess pore water pressure to facilitate the consolidation process. The excess pore water pressure dissipates at the ground surface, and the pore water pressure attempts to return to the initial hydrostatic distribution. Meanwhile, the effective stresses gradually increase and accompany with the ground settlement. The ground settlement is compared to a predefined termination criterion (in this study, a ground settlement limit). The termination criterion is set to be

10% of the initial height of an element; i.e., the analysis is terminated when the ground settles more than 0.1 m. The deformed ground is then used to construct a new mesh (i.e., "*re-meshing*"). The analysis is resumed from the new mesh. At the first increment of the resumed analysis, "*re-mapping*" of the variables from the previously terminated analysis to the new analysis is carried out by the ABAQUS built-in command "*MAP SOLUTION*". The analysis continues until the change in the pore water pressure becomes negligible, such that the steady state response can be claimed.

Table 1. Material properties of the hypothetical ground.

Variable	**Magnitude**
Unit weight (kN/m^3)	18
d	0
β	45^o
R	1
α	0
K	1
κ (swelling gradient in the v-lnp' plane)	0.01
Poisson's ratio	0.2
Permeability (m/day)	2×10^{-6}
Void ratio at ground surface	1.2
OCR	1

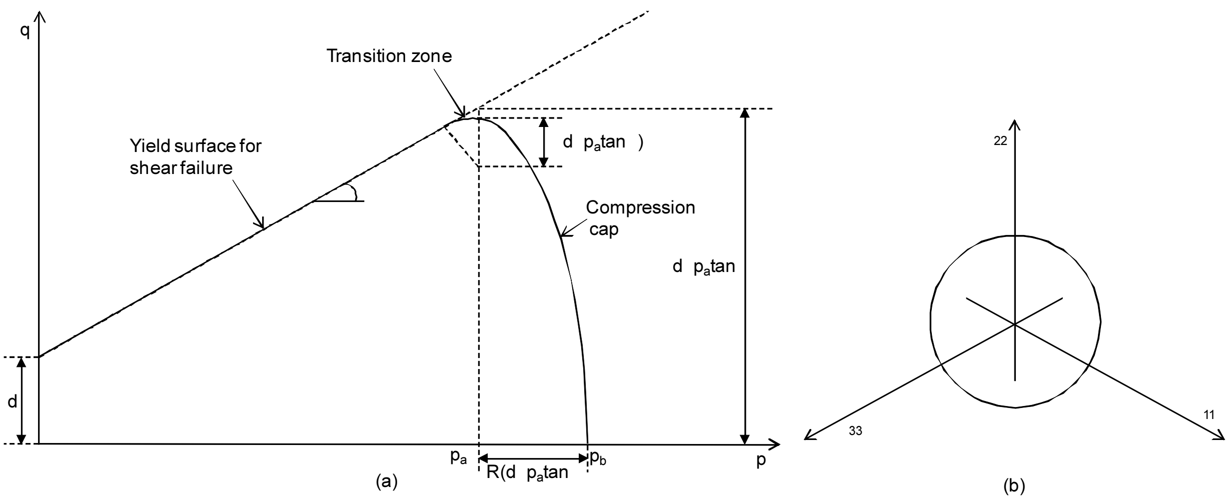

Fig. 1 Yield surface in (a) p-q plane, (b) π-plane.

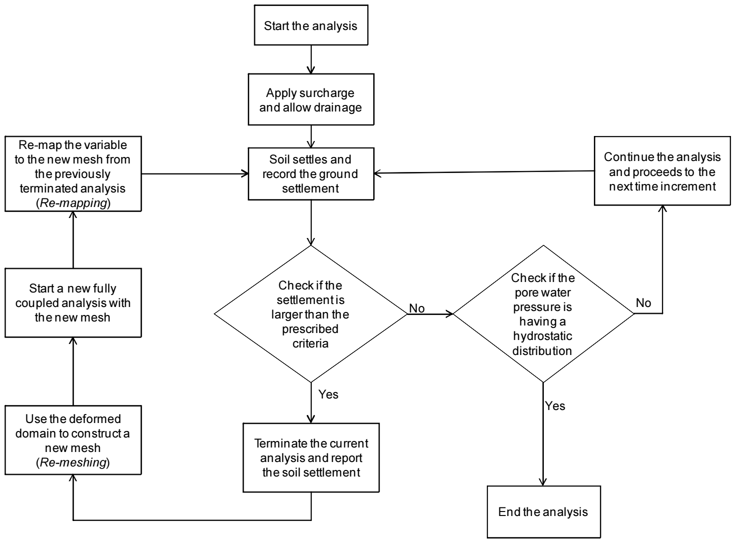

Fig. 2 Algorithm of the re-meshing and re-mapping process.

3. RESULTS AND COMPARISONS

Fig.3 shows the development of ground settlement with time by the *adaptive* and *one-step* analyses. The analysis completes when the change in the pore water pressure is negligibly small (1×10^{-4} kPa) (i.e., steady state is essentially reached). In total, five meshes are re-generated in the *adaptive* analysis. The settlement increases monotonically as expected. The final settlement predicted by the proposed algorithm is almost identical to the conventional *one-step* analysis. Despite the slight difference in the rate of consolidation, the *adaptive* analysis shows comparable ground response when compared to the *one-step* one.

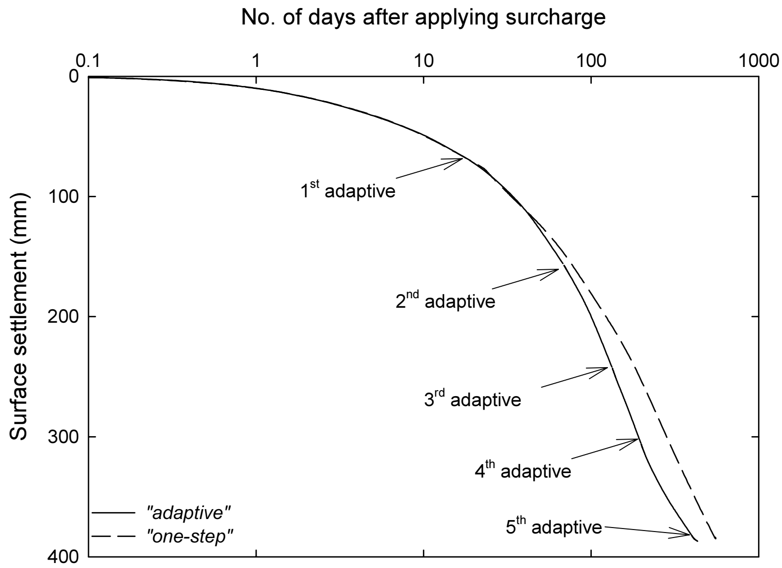

Fig. 3 Ground surface settlement profiles of *adaptive* and *one-step* analysis.

Fig. 4 shows the comparison of pore water pressure distribution between the two analyses during different stages of the consolidation process; i.e., at U equals 0%, 35%, 75% and steady state (U close to 100%) where U is the average degree of consolidation. It is calculated from the ratio of the difference between the initial and current excess pore water pressure to the initial excess pore water pressure over the ground. The response of pore water pressure is essentially the same for both analyses, indicating correct mapping of pore water pressure between the analyses. At the beginning of consolidation (i.e. U equals 0%), the pore water pressure equals to hydrostatic distribution plus the magnitude of surcharge. The pore water pressure dissipates fast at the ground surface (i.e. drainage boundary) during the early stage of consolidation (i.e. U equals 35%). As expected, the pore water pressure returns to hydrostatic distribution at the steady state.

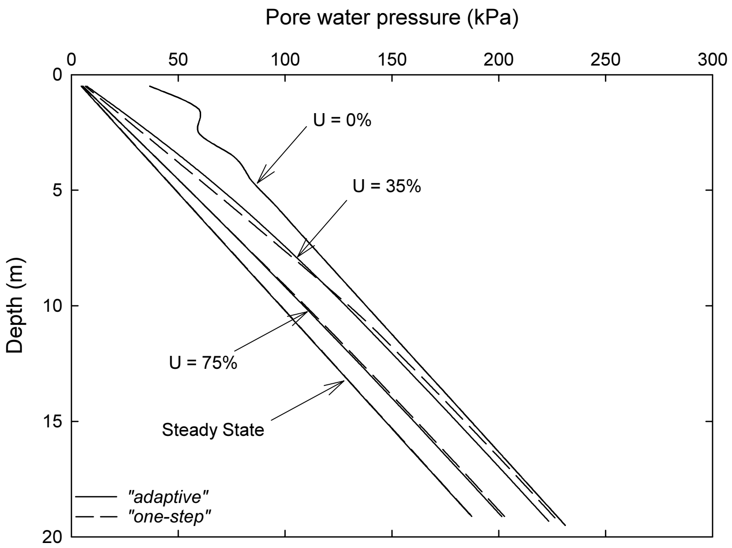

Fig. 4 Pore water pressure distribution of different analyses at different stages of the consolidation: U = 0%, U = 35%, U = 75%, steady state.

CONCLUDING REMARKS

The conventional Lagrangian-based finite element formulation is of limited application when large distortion occurs. As a result, a more advanced adaptive approach should be adopted. The developed “re-meshing and re-mapping” algorithm in saturated porous medium is implemented into the FE package ABAQUS. A consolidation-coupled analysis on a hypothetical ground is performed as an illustrative example. The developed ground settlement and pore water pressure are close to the conventional *one-step* analysis. It is expected that this method can be applied to complex fluid-coupled soil-structure interaction problems involving large mesh distortion, such as penetration of hard objects (e.g., cone penetrometer and pile) into a saturated porous media.

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