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Research Paper

Application of a Coupled Eulerian–Lagrangian approach on pile installation problems under partially drained conditions

Thorben Hamann [a,*], Gang Qiu [b], Jürgen Grabe [a]

[a] Hamburg University of Technology, Institute of Geotechnical Engineering and Construction Management, Harburger Schloßstraße 20, D-21079 Hamburg, Germany
[b] IMPaC Offshore Engineering, Hohe Bleichen 5, D-20354 Hamburg, Germany

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ABSTRACT

A numerical technique for modeling the soil as a two-phase medium by means of a user material subroutine is presented. The approach is applied to a classical FE analysis in a Lagrangian formulation using an explicit time integration rule and to a Coupled Eulerian–Lagrangian approach. The application of these two approaches to the problem of pile jacking into fully saturated soil under partially drained conditions is investigated and compared to the solution obtained by use of an iterative equation solver. The influence of the installation process as well as the influence of the permeability on the surrounding soil is investigated.

1. Introduction

Offshore seabed or soil in harbor areas is normally fully saturated and can be regarded as a two-phase porous medium. Numerical methods can be a helpful tool for the analysis of the installation process of piles, spudcan foundations, pipelines or sheet pilings. For the analysis, fully coupled FE methods are usually applied to compute the fluid flow through a porous medium over a large time period in case of static or quasi-static loading conditions (e.g. a consolidation analysis). Since fluid flow is usually considered to be a slow process and long periods of time are investigated in an analysis, common FE codes like Abaqus use an iterative equation solver for this kind of analysis. In case of large FE models with relatively short response times as well as for the analysis of extremely discontinuous processes, an explicit equation solver is often preferred due to its computational efficiency [3]. But in common FE codes like Abaqus the use of an explicit equation solver is restricted for modeling only one-phase materials.

Considering the problem of pile installation under drained soil conditions different approaches related to the use of equation solver as well as the formulation in the spatial domain can be found in literature. An implicit integration scheme is applied to calculate the pile jacking process in Grabe and König [6], Sheng et al. [27] and Yi et al. [33]. The numerical results were validated by comparison with the measured pile resistance. However, it is essential to improve the robustness and accuracy of the numerical algorithms to simulate more realistic and complex features as for example piles under cyclic loading, piles with flat ends or piles in soils with excess pore pressure development [27]. Arbitrary Lagrangian Eulerian (ALE) methods [11,13] can be used to improve the robustness of the numerical simulations of pile installation [30] and footing problems [31]. Mahutka et al. [20] presented an ALE model to simulate the vibratory pile driving under cyclic loading using an explicit equation solver. An Eulerian method offered by the commercial package FEAT has been used by Dijkstra et al. [4] to investigate the change of soil conditions near the pile after pile installation. The pile was simulated with a flat end. A Coupled Eulerian Lagrangian (CEL) approach [1], which is based on an explicit time integration formulation, has been developed and implemented in the FE code Abaqus to deal with geotechnical problems involving large soil deformations. The CEL method has been applied by Qiu et al. [23] to simulate the jacking process of a pile into sand and the results were compared to results of a conventional explicit simulation. However, the discussed publications simulated the soil to be under drained conditions. The change of pore water pressure is not taken into account during the penetration of piles.

Accounting for the influence of pore water to the problem of pile installation, Qiu and Grabe [22] used the penalty approach and represented a numerical model using an explicit time integration rule

* Corresponding author.
E-mail address: thorben.hamann@tuhh.de (T. Hamann).

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to simulate the cone penetration test in a saturated fine-grained soil. The soil is simulated to be under undrained conditions. Sabetamal et al. [25] presented a numerical method for modeling fully saturated soil under partially drained conditions and dynamic loading. Within this approach an implicit equation solver is used. The problem of rapid pile jacking as well as the installation of a torpedo anchor are modeled. Recently, meshfree methods are used to analyze the fully coupled hydro-mechanical behavior of saturated porous media [34,26]. By use of a solid and fluid velocity formulation (v–w formulation), Jassim et al. [15] extended the material point method to analyze coupled dynamic, two phase boundary value problems.

The problem of pile installation in fully saturated soil is an example of a large deformation problem, where extremely discontinuous processes in the soil have to be modeled and often large models with relatively short response times are computed. Hence, an explicit equation solver seems to be well suited for this kind of analysis. A numerical technique for modeling the soil as a two-phase medium by means of a user material subroutine is presented in this paper. By use of this technique a common one-phase analysis procedure can be extended to model fully saturated soil as a two-phase porous medium under partially drained conditions. A hypoplastic model is used to describe the behavior of the solid skeleton. The process of pile installation and the effect of consolidation is investigated. The application of this technique in a classical finite element analysis using a Lagrangian formulation with an explicit time integration rule as well as the application in the CEL method is studied. The solution as well as the computational effort of each method is compared to an analysis using an iterative equation solver.

2. Numerical method

Three different finite element analysis procedures are used to model the process of pile jacking into fully saturated soil. A classical finite element analysis in a Lagrangian formulation using an iterative equation solver provided by the finite element software code Abaqus/Standard [3]. The second approach (Abaqus/Explicit) is also a classical finite element analysis in a Lagrangian formulation, but uses an explicit time integration rule. The third approach (Abaqus/CEL) applies the Coupled Eulerian–Lagrangian method provided by Abaqus and uses an explicit time integration rule. The first procedure (Abaqus/Standard) allocates the numerical modeling of fully saturated soil by use of build-in features. The second and third approach, generally limited to a one-phase material, are extended by use of a user-subroutine for constitutive models to allow for the modeling of the soil as a two-phase material. This approach is described more in detail in the following. The numerical solutions of the three approaches are compared with each other to evaluate their application to coupled pore fluid diffusion and stress analysis of geotechnical boundary value problems. The first approach provided by Abaqus/Standard serves as reference.

2.1. Abaqus/Standard

The FE code Abaqus/Standard provides an analysis procedure for a coupled pore fluid diffusion and stress analysis of geotechnical boundary value problems limited to quasi-static loading conditions. The analysis procedure uses an iterative linear equation solver applying the newton method to solve the equilibrium equations [3]. Therefor, the simulation is broken into a certain number of time increments. By use of an iterative equation solver the approximate equilibrium of the system of equations is achieved iteratively at the end of each time increment until a given tolerance value is reached. The soil is considered as a multiphase medium. The fluid flow of up to two fluids through a porous medium can be modeled using the principle of effective stress. Fully saturated and partially saturated conditions can be considered. The FE mesh is attached to the solid phase. The fluid flows through the mesh. For the solid phase most of the implemented constitutive models, e.g. linear elastic model and Mohr–Coulomb model as well as user defined constitutive models such as hypoplasticity model, can be applied. To describe the fluid flow a continuity equation for the mass of the wetting fluid in a unit volume of the medium is used. Forchheimer's flow law (Eq. (1)) as well as a Darcy flow (Eq. (2)) as a special case of the Forchheimer's flow law can be applied. In the following only a Darcy flow is considered.

$$\boldsymbol{v}_{ws}(1+\beta\boldsymbol{v}_{ws}) = \frac{\kappa}{\mu_w}(-\nabla p_w + \rho_w \boldsymbol{b}) \tag{1}$$

$$\boldsymbol{v}_{ws} = \frac{\kappa}{\mu_w}(-\nabla p_w + \rho_w \boldsymbol{b}) \tag{2}$$

where $\boldsymbol{v}_{ws}$ is the fluid velocity relative to the solid skeleton, β is a permeability coefficient of Forcheimer's flow law, κ is the intrinsic permeability, μ_w is the dynamic viscosity, p_w is the pore pressure, ρ_w is the density of the fluid and $\boldsymbol{b}$ is the body force per unit mass (gravity).

2.2. Abaqus/Explicit

The explicit equation solver of Abaqus/Explicit generally solves the equation of motion without a damping term (Eq. (3)) at each node of the FE model [3]:

$$\boldsymbol{M}\boldsymbol{a}_s + \underbrace{\boldsymbol{K}\boldsymbol{u}_s}_{\boldsymbol{F}_{int}} = \boldsymbol{F}_{ext} \tag{3}$$

where $\boldsymbol{M}$ is the lumped mass matrix, $\boldsymbol{a}_s$ are the nodal accelerations, $\boldsymbol{K}$ is the stiffness matrix, $\boldsymbol{u}_s$ are the nodal displacements, $\boldsymbol{F}_{int}$ is the nodal internal force vector and $\boldsymbol{F}_{ext}$ is the nodal force vector due to an applied external load. The explicit equation solver uses an explicit central-difference integration rule for integration in the time domain. The solution of displacements $\boldsymbol{u}_s^{t_{i+1}}$ at the end of the current time increment Δt_i can be calculated using known values of acceleration $\boldsymbol{a}_s^{t_i}$ at the beginning of the current time increment and known values of velocity $\boldsymbol{v}_s^{t_{i-0.5}}$ at the midpoint of the previous time increment Δt_{i-1} (Eqs. (4) and (5)).

$$\boldsymbol{v}_s^{t_{i+0.5}} = \boldsymbol{v}_s^{t_{i-0.5}} + \frac{\Delta t_{i-1} + \Delta t_i}{2}\boldsymbol{a}_s^{t_i} \tag{4}$$

$$\boldsymbol{u}_s^{t_{i+1}} = \boldsymbol{u}_s^{t_i} + \Delta t_i \boldsymbol{v}_s^{t_{i+0.5}} \tag{5}$$

where $\boldsymbol{v}_s^{t_{i+0.5}}$ are the nodal velocities at the midpoint of the current time increment and $\boldsymbol{u}_s^{t_i}$ are the nodal displacements at the beginning of the current time increment. The nodal accelerations $\boldsymbol{a}_s^{t_{i+1}}$ at the end of the current time increment are calculated applying the equation of motion (Eq. (6)).

$$\boldsymbol{a}_s^{t_{i+1}} = \boldsymbol{M}^{-1}\left(\boldsymbol{F}_{ext}{}^{t_{i+1}} - \boldsymbol{F}_{int}^{t_{i+1}}\right) \tag{6}$$

Hence, no iteration is necessary. By using a lumped mass matrix the inversion of the mass matrix is trivial. Thus, the explicit dynamic procedure performs a large number of very small time increments efficiently. The central-difference operator is conditionally stable, if the time increments are less than a critical time increment Δt_{crit} (Eq. (7)). The critical time increment depends on the characteristic element length L_e and the dilatational wave speed c_d and is computed for each time step.

$$\Delta t_{crit} = \frac{L_e}{c_d} \tag{7}$$