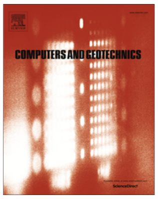
Computers and Geotechnics 70 (2015) 24–40

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo



Research Paper

Recovery-based error estimation in the dynamic analysis of offshore wind turbine monopile foundations

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ARTICLE INFO

Article history:
Received 18 February 2015
Received in revised form 9 July 2015
Accepted 25 July 2015
Available online 7 August 2015

Keywords:
Recovery-based error estimation
Dynamic behavior
Coupled equations
Cyclic load
Offshore foundation

ABSTRACT

Offshore wind turbine foundations are affected by cyclic loads due to oscillatory kinematic loads, such as those from wind, waves, and earthquakes. Monopiles are often used as a foundation concept for offshore windmill turbines. In this study, coupled dynamic equations with the $\mathbf{u}-P$ formulation for low-frequency load are considered for an offshore wind turbine monopile foundation, to present the response in terms of pore water pressure (PWP), stress and strain distribution in an elastic porous medium at regions around the monopile foundation. Different stress recovery techniques based on the Zienkeiwicz–Zhu (ZZ) error estimator namely, super-convergent patch recovery (SPR), weighted super-convergent patch recovery (WSPR), and L_2-projection techniques are also investigated to recover the stresses at nodal points in the finite element method. To estimate errors in the time domain when performing transient simulations, three recovery processes are used with different meshes. The convergence of the dynamic problem is also studied. The results are verified with findings in the literature, revealing that the time period of effective stresses follows the applied load frequency. In conclusion, the history of the shear stress can have an important effect on the shear stress distribution, making it asymmetric in the time domain.

1. Introduction

Recent developments in offshore industries, such as offshore wind turbine foundations and structures for oil and gas extraction, have led to a growing demand for realistic predictions of the dynamic behavior of offshore structures. Offshore wind farms are receiving increasing attention in the quest for renewable sources of energy. As one option for wind turbines, the offshore monopile foundation plays a key role in offshore wind farm design. Monopile foundations bear loads from the seabed and waves, as well as loads that act on the turbine above sea level. Offshore windmill foundations comprise a major part (15–25%) of the total cost of the whole wind turbine structure.

Accomplishing a safe and cost-effective design for offshore monopile foundations requires that dynamic analyses be performed. The dynamic response varies significantly in time and is affected by different parameters, such as the inertia and damping of the monopile structure, and the stiffness and damping of the underlying soil. To achieve the desired results, the soil should be appropriately modeled. Numerical analysis can be the most approachable and straightforward method for dynamic analysis [64,33,1,51,26,13]. Biot [7] offered an important and interesting soil model, establishing governing equations of porous media based on a continuum formulation [7,8]. Zienkiewicz and Shiomi [68] modified the equations of motion in an innovative way, presenting a model for the soil skeleton and pore fluid media that is useful in the numerical context.

Three coupled and dynamic formulations, based on the soil and pore fluid (water) displacements and the pore water pressure (PWP), are the $\mathbf{u}-P-\mathbf{U}$, $\mathbf{u}-P$, and $\mathbf{u}-\mathbf{U}$ equations, where $\mathbf{u}$, P, and $\mathbf{U}$ are the soil skeleton displacement, PWP, and pore water displacement, respectively [67]. Cheng and Jeremić [11] used a fully coupled, inelastic $\mathbf{u}-P-\mathbf{U}$ formulation to simulate the dynamic behavior of piles in liquefiable soils subjected to seismic loading. In the $\mathbf{u}-P$ formulation, if the fluid phase is considered incompressible, then the Ladyzenskaja–Babuska–Brezzi (LBB) condition needs to be satisfied ([9,62,6,2]). In this case, the element type

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http://dx.doi.org/10.1016/j.compgeo.2015.07.012
0266-352X/

for the displacement and pore pressure fields requires special consideration, to prevent volumetric locking [65,67]. The restrictions imposed by the LBB condition exclude the use of elements with equal order interpolation for pressures and displacements. This difficulty can be solved by implementing appropriate stabilization techniques such as the fractional step algorithm which was developed for soil mechanics by Pastor et al. [41]. Later, the generalized fractional step method proposed by Pastor et al. [42], was modified by Li et al. [34]. Recently, Soares et al. [50] described an edge-based smoothed meshfree technique by presenting an independent spatial discretization for each phase of the model. Considering this restriction for monolithic algorithm, a simple model for numerical analyses is the $\mathbf{u}-P$ formulation that neglects the relative acceleration of the fluid with respect to the solid skeleton. This model is especially useful for low-frequency analysis. The contribution of the solid acceleration is neglected in the fluid mass balance; this omission was investigated by Chan [10], who found the omitted contribution to be insignificant.

Prevost [45] incorporated a semi-discrete finite element (FE) procedure with an implicit–explicit time integration algorithm to analyze wave propagation in fluid-saturated porous media, which was modeled in the $\mathbf{u}-P$ format. Zienkiewicz et al. [66] studied the transient and static response of saturated soil, which they modeled as a two-phase material based on the $\mathbf{u}-P$ formulation for porous media. Pastor et al. [43] used a generalized plasticity approach to describe the behavior of soil in the $\mathbf{u}-P$ formulation under transient loading. Elgamal et al. [19,20] implemented the $\mathbf{u}-P$ model for a two-phase (solid–fluid) problem with multi-surface plasticity, using a finite element method (FEM) to highlight the effect of excitation frequency.

Researchers have attempted to solve these coupled equations by various numerical methods. For example, Lu and Jeng [35] investigated the porous soil which governed by the $\mathbf{u}-P$ formulation, using the boundary element method. Maghoulaet al. [37] applied a boundary integral formulation for dynamic behavior analysis of unsaturated soils. Khoshghalib and Khalili [30] used a meshless radial point interpolation to solve the fully coupled Biot's equations. Soares [49] formulated an edge-based smoothed weak meshless formulation by Delaunay triangulation to perform an iterative dynamic analysis of linear and nonlinear fully saturated porous media. Zhang et al. [63] formulated a coupling material point method to predict the dynamic response of saturated soil and the contact/impact behavior between saturated porous media and solid bodies. Samimi and Pak [47] solved the $\mathbf{u}-P$ formulation by applying the Element-Free Galerkin method. Irzal et al. [27] implemented an isogeometric analysis to predict the behavior of a deformable fluid-saturated porous medium, using non-uniform rational B-splines.

To improve the efficiency of numerical approaches, it is important to calculate and reduce the errors. For as long as physical events have been computationally simulated, the numerical error of such calculations has been a major concern. Discretization error is inherent in these simulations, arising from the discretization process of the continuum domain. As a result, not all of the information characterized by the partial differential or integral equations can be obtained. Especially for the dynamic analysis of complex problems with many degrees of freedom, adaptive refinement procedures need to be used. This requirement is because of the limitations of the speed and memory of available computers. The mesh size should be refined in regions where there are large gradients in the changes between the nodal variables. The error can be in conjunction with the adaptive refinement procedure to obtain the desired accuracy for design purposes with less computational effort.

In 1910, Richardson [46] presented the first report of a practical approach for estimating numerical error, utilizing the finite difference method. Subsequent researchers used the FEM for this purpose. The FEM has a well-developed theory for error estimation. To date, many reliable methods for estimating the error in the global energy norm have been proposed, using either residuals- or recovery-based methods. Tang and Sato [53,54] and Tang and Shao [55] studied error estimation and adaptive mesh refinement on seismic liquefaction, seeking to improve the numerical results for large deformation in a soil–pile interaction problem. They used a FE and finite difference coupled dynamic method for liquefaction analysis of saturated soil. The $\mathbf{u}-P$ formulation was used for the governing equations, which described the coupled problem in terms of soil skeleton displacement and excess pore water pressure. Nazem et al. [39] used an h-adaptive FEM to tackle the penetration and indentation problems of geomechanics in the presence of inertial forces. They compared three alternative error estimation techniques, based on the energy norm, the Green–Lagrange strain, and the plastic dissipation.

Earlier studies on offshore monopile foundation have considered three-dimensional simulation (see e.g. [14,33]), and several authors have emphasized the importance of using a non-linear material model [24,52]. However, in this study the ZZ error estimator is applied for a two-dimensional (2D) model with an elastic constitutive model. These simplifying assumptions make some shortcomings such as ignoring bending of pile, different drainage paths and dilatancy out of the plane. But in order to investigate small displacements and get some desired outputs such as the estimation of the regions with higher numerical error, the 2D model may be applicable. Also, serviceability requirements for offshore wind turbines only allow rotations of 0.5° at the mudline. For such small rotations, soil behavior is controlled by elasticity rather than plasticity. Essentially, small settlement and rotation of foundations are controlled by linear elastic soil behavior as it was mentioned by Achmus et al. [1].

In the dynamic analysis of monopile foundations, complex changes occur in the displacement, stress, and pore pressure fields of the $\mathbf{u}-P$ coupled equations due to the fluid–soil interaction. The error must be estimated to identify zones that are affected by insufficient mesh size. To the best of the authors' knowledge, no dynamic analysis of offshore foundations has been performed by considering different stress recovery techniques-namely, super-convergence path recovery (SPR), weighted super-convergence path recovery (WSPR), and L_2-projection to implement the Zienkiewicz–Zhu (ZZ) error estimation. The mentioned post-processing procedures have not been employed for the coupled $\mathbf{u}-P$ equations which can highlight the distinction of the present study. Moreover, the convergence rates are compared for the different recovery procedures. Thus, it motivates the authors to perform comprehensive error estimation for the coupled $\mathbf{u}-P$ equations. Indeed, it then paves the way to implement different adaptive refinement procedures based on the implemented error estimation methods, finally leading to the lower computational costs for modeling two phase media such as saturated soil.

This study considers a 2D offshore monopile foundation (Fig. 1), surrounded by a linear-elastic saturated soil and subjected to cyclic load. The plane strain condition is invoked by having small deformation of the soil. Symmetry is assumed with respect to the horizontal axis and the center line of the monopile. This work aims to investigate the effects of stress recovery techniques on the ZZ error estimation in the time domain, by employing the FEM in the $\mathbf{u}-P$ equations. Displacement and pore water pressure fields are investigated in the time domain for a saturated soil.

Following this brief introduction, Section 2 contains the governing coupled $\mathbf{u}-P$ equations of the saturated soil and its FEM discretization process. The recovery-based ZZ error estimation and the SPR, WSPR, and L_2-projection stress recovery procedures are addressed in Section 3. The time discretization of the coupled