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Modeling of Soil Water Interaction Using OpenFOAM

Modellierung von Wasser-Boden-Interaktion mittels OpenFOAM

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Strong coupled interactions between the nonlinear soil skeleton and the pore fluid under loading may lead to built-up of pore pressure, yielding material softening and many other soil strength changes. Numerical analysis of such phenomenon however has been a challenging task, due to the difficulty to solve strong coupling effects inside the two-phase physical system, and the lack of reliable constitutive models that capture soil mechanical behaviours accurately. For this purpose, a new finite volume based soil mechanics solver package is developed using open source software – OpenFOAM. This package can solve the modified Biot's equations (Biot 1941 and Zienkiewicz 1982) efficiently and also allows exploring various soil constitutive models in users' needs. Furthermore, the simulation can integrate external hydrodynamic loading straightforwardly due to the wide potentials of OpenFOAM in handling multiphysics. Validation and application cases of the solver package are demonstrated.

Stark gekoppelte Wechselwirkungen zwischen dem nichtlinear reagierenden Korngerüst und dem Porenfluid können bei Laständerungen zum Ansteigen des Porenwasserdrucks führen, was eine Festigkeitsverringerung des Bodens sowie weitere Veränderungen der Festigkeitseigenschaften nach sich ziehen kann. Die numerische Analyse solcher Phänomene stellt von je her eine große Herausforderung dar, aufgrund der außerordentlich schwierigen Lösung der stark gekoppelten Prozesse im Zweiphasen-System und auch mangels zuverlässiger Stoffmodelle zur genauen Berücksichtigung des bodenmechanischen Verhaltens. In Hinblick auf diese Fragestellungen wird auf Grundlage der Open-Source-Software – OpenFOAM – ein neues auf der Finite-Volumen-Methode basierendes bodenmechanisches Lösungspaket entwickelt. Dieses ist in der Lage, die modifizierten Biot-Gleichungen (Biot, 1941 und Zienkiewicz, 1982) effizient zu lösen und erlaubt, verschiedene Stoffmodelle an die Bedürfnisse der Nutzer anzupassen. Aufgrund des breiten Potenzials von OpenFOAM bei der Behandlung gekoppelter physikalischer Prozesse ist das Programmsystem darüber hinaus in der Lage, externe hydrodynamische Belastungen vergleichsweise einfach zu berücksichtigen. Validierungsrechnungen und Anwendungsfälle des Lösungspakets werden vorgestellt.

1 Introduction
Einleitung

A computational model can serve a wide variety of roles, including hypothesis testing, generating new insights, deepening understanding, suggesting and interpreting experiments, doing sensitivity analysis, optimization, integrating knowledge, and inspiring new approaches. With computational soil models playing an increasing role in the advancement of geotechnical engineering, it is important that we recognize the implications of the conceptual, mathematical and algorithmic steps of soil model construction; and comprehend what our models can and cannot do. Soil models cannot replace experiments nor can they prove that particular mechanisms are at work in a given situation. However, they can demonstrate whether or not a proposed mechanism is sufficient to produce an observed soil phenomenon, and they do it in a flexible and cost-reducing way.

It is appealing to me that soil models can help to build a "virtual soil laboratory"(VSL), where we perform comparable soil tests to the real experiments for validation, and afterwards extend to intensively different loading scenarios, soil samples, and geometries, which are originally time-consuming and expensive to do in traditional laboratory. By virtue of being able to translate between soil behaviours and the soil mechanisms that implement them, a VSL enables us to understand not just how the soil is deformed, but why it is deformed in the way it is.

In this article, I would like to present an example of soil model developments applying a specific numerical approach – the finite volume method (FVM). The main focus of the models has been to study the coupled soil skeleton deformation and pore water pressure under different loading mechanisms. The soil models have been implemented and tested during my PhD at Technical University of Denmark (DTU) and post-doc project at Norwegian Geotechnical Institute (NGI), and they have been made as open-source solver package freely available for other researchers with the purpose of open discussions and continuous improvements.

2 An open-source solver package for soil mechanics
Ein bodenmechanisches Open-Source-Lösungspaket

FVM has been an important numerical tool in computational fluid dynamics (CFD) because it is good at treating complicated, coupled and nonlinear differential equations (Jasak and Weller, 2000). However, at the beginning of my research work, it still remained unknown whether importing FVM to model porous nonlinear soil materials is feasible and to what extent its effectiveness is. Thanks to the open source CFD software – OpenFOAM (Weller et al., 1998), I had the freedom to build up my own poro-elasto-plasticity soil solvers using the existing FVM classes and their operator functions. In the following, I shall briefly explain those key components of my solvers, including the global governing equations for the porous soil system, the local soil constitutive models, and the segregated solution procedure.

2.1 Governing equations for porous soil
Grundgleichungen für ein poröses Medium

Here, I extended the classic Biot's theory (Biot, 1941 and Zienkiewicz, 1982) to account for more realistic nonlinear material behaviors of the soil skeleton. The governing equation of the pore fluid flow is formulated as follows:

$$\frac{k}{\gamma_w}\nabla^2 p = \frac{n}{K'}\frac{\partial p}{\partial t} + \frac{\partial}{\partial t}(\nabla \cdot \boldsymbol{u}) \tag{1}$$

where the unknown variable p is the pore fluid pressure and ***u*** the displacement vector of the soil skeleton.

The governing equation of the soil skeleton phase is based on total momentum equilibrium in incremental form. By incorporating the stress-strain relation, small-strain split, and strain-displacement relation below, it is conveniently written as:

$$\begin{cases} \nabla\cdot(\delta\boldsymbol{\sigma}) = \nabla\cdot(\delta\boldsymbol{\sigma}' - \delta p\mathbf{I}) = 0 \\ \delta\boldsymbol{\sigma}' = 2G\delta\varepsilon^e + (K - \frac{2}{3}G)\mathrm{tr}(\delta\varepsilon^e) \\ \delta\varepsilon^e = \delta\varepsilon - \delta\varepsilon^p \\ \delta\varepsilon = \frac{1}{2}[\nabla(\delta\mathbf{u}) + \nabla(\delta\mathbf{u})^{\mathrm{T}}] \end{cases} \tag{2}$$

$$\Downarrow$$

$$\nabla\cdot[G\nabla(\delta\mathbf{u}) + G\nabla(\delta\mathbf{u})^{\mathrm{T}} + (K - \tfrac{2}{3}G)\mathbf{I}\,\nabla\cdot(\delta\mathbf{u})] \\ -\nabla\cdot[K(\delta\varepsilon_v^p) + 2G(\delta\varepsilon_d^p)] - \nabla(\delta p) = 0$$

where the primary unknown variable $\delta\mathbf{u}$ symbolizes the incremental displacement vector of the soil skeleton, and δp the incremental pore pressure. The other two variables: $\delta\varepsilon_v^p$ and $\delta\varepsilon_d^p$ are the volumetric and deviatoric part of incremental plastic strain, respectively.

Eq. (2) has been particularly formulated to fit the 'segregated' solution procedure in FVM. The first term in the equation can be considered as the 'predicted' internal force due to soil skeleton deformation with purely elastic response, while the second term denotes a 'correcting' internal force due to soil skeleton that might undergo plastic deformation, and the third term is the internal force due to pore fluid flow.

Eqs. (1-2) make a set of four equations with four primary unknowns – pore pressure p and incremental displacement vector $\delta\mathbf{u}$.

2.2 Soil constitutive models
Stoffmodelle für Böden

Within the momentum vector equation, Eq. (1), there are nonlinear plastic deformation terms. We need to determine them via proper soil constitutive models. It is necessary to note that a comprehensive collection of constitutive models already exist in the geotechnical community, each of them may target to describe one or more soil features such as dilation, cyclic degradation, anisotropy, large deformation, and among many others. Implementation of such local stress-strain models into the porous soil solver can be straightforwardly done. That is also an advantage of this open-source soil solver package: it can be dynamically expanded by having more user-preferred soil constitutive models depending on the application interests.

2.3 Segregated solution algorithm
Aufgespaltener Lösungsalgorithmus

The four coupled, nonlinear soil equations are discretized using the cellcenter FVM. Readers who are interested in getting more details of the discretization technique are suggested to refer to my article (Tang et al., 2015).

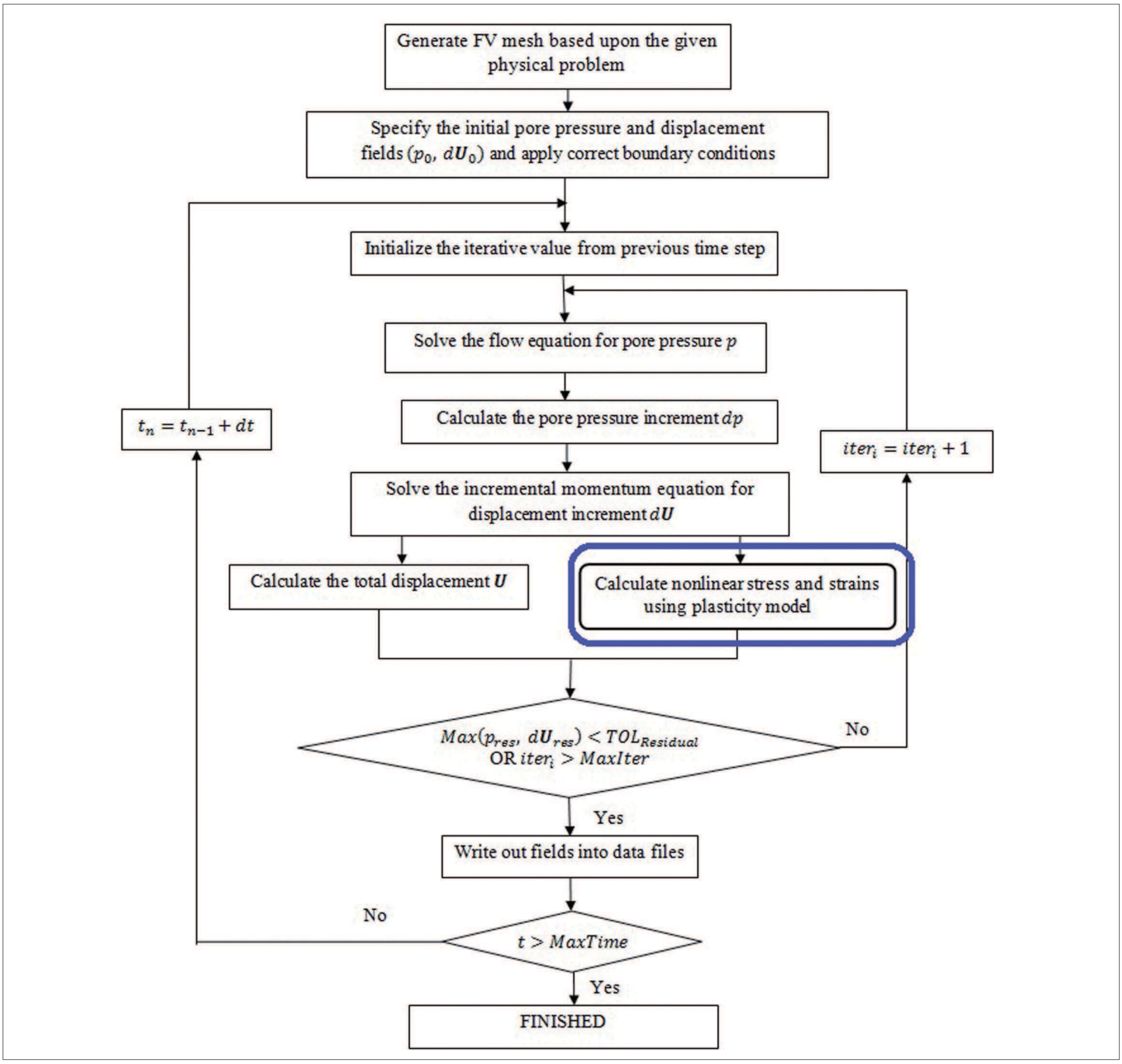


Figure 1: The global iterative 'segregated' solution procedure
Bild 1: Das globale iterative „aufgespaltene" Lösungsverfahren

The discretized equations are solved sequentially for each unknown following the order: first the pore pressure p and then the three components of $\delta\mathbf{u}$ in parallel.

After solution of all four unknowns is performed, one iteration is completed and unless a converged solution is obtained, the explicit source terms are updated using the new solutions and next iteration proceeds.

Fig. (1) depicts such segregated solution algorithm. The blue outlined box highlights the flexible choice of local constitutive model in the solver.

3 Simulation examples
Berechnungsbeispiele

After the built-up of soil solvers, I carried out a few simulation examples to test their validity and applications.

The first two, Sections 3.1 and 3.2, are aimed at validating the accuracy of the FVM method on simple poro-elasto-plasticity and cyclic poro-elasto-plasticity soil models. The third case (Section 3.3) illustrates the application of the solver on a real-life offshore engineering problem: a 3-D gravity based foundation standing on seabed under wave loads.

3.1 2-D strip footing
Zweidimensionales Streifenfundament

The strip footing case setup is as follows: a smooth, perfectly flexible, uniformly loaded, permeable strip footing acts on a layer of soil resting on a smooth rigid base. In order to completely define the problem, it is assumed that there is no horizontal force on any vertical section; and plain strain condition has been considered. This test case was originally examined by Small et al. (1976) to investigate elasto-plastic consolidation using FEM. A comparable simulation in a commercial FEM software Abaqus was also performed.

For the assessment of model performance, Figure 2 clearly indicates that the excess pore pressure starts to dissipate as long as plastic deformation occurs and results in dilation.

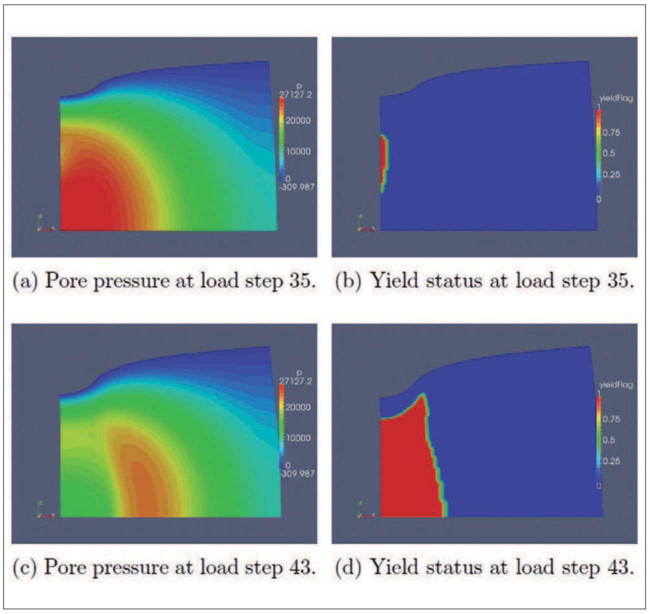


Figure 2: Nonlinear soil-pore fluid coupling, loading rate ω = 1.43

Bild 2: Nichtlineare Kopplung von Boden und Porenfluid, Belastungsgeschwindigkeit ω = 1,43

Figure 3 presents the FVM predictions: the lowest level of footing bearing capacity under fast speed undrained condition (full impact from the high amount of excess pore pressure); and thereafter a gradual increase of the capacity along with the decreasing load speed (gradual dissipation of the excess pore pressure).

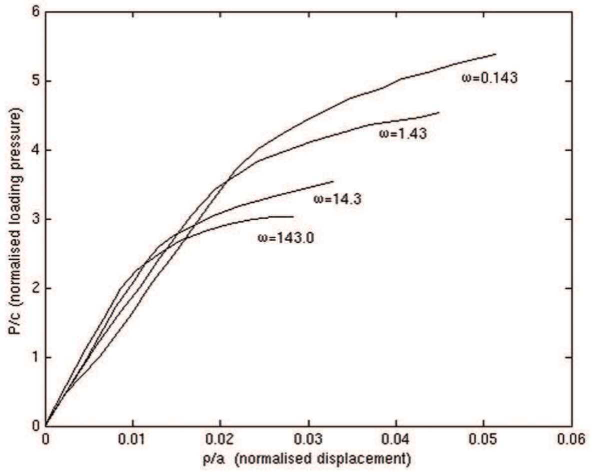
Such results agree well with the other two FEM solutions. The simulated results explain the influence of the generated excess pore pressure on the soil effective stresses and in turn the soil strength.

3.2 3-D simple cyclic pressure loading

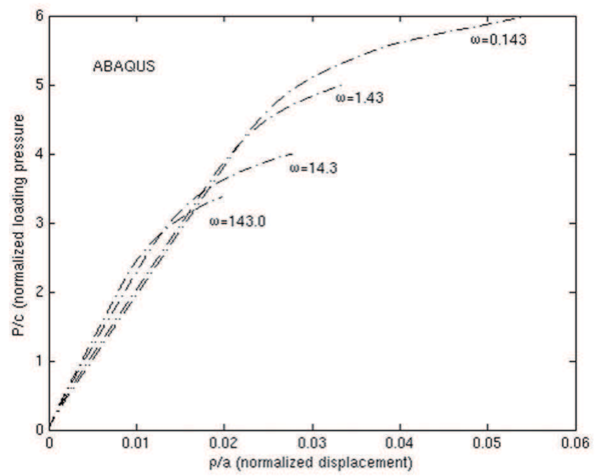
Dreidimensionale einfache zyklische Druckbelastung

Excess pore pressure accumulation under cyclic loading and in consequence full/partial liquefaction of the seabed is a major concern for offshore foundations' stability. In order to validate my cyclic soil constitutive model, I simulated typical cyclic undrained triaxial tests in experiments performed in NGI.

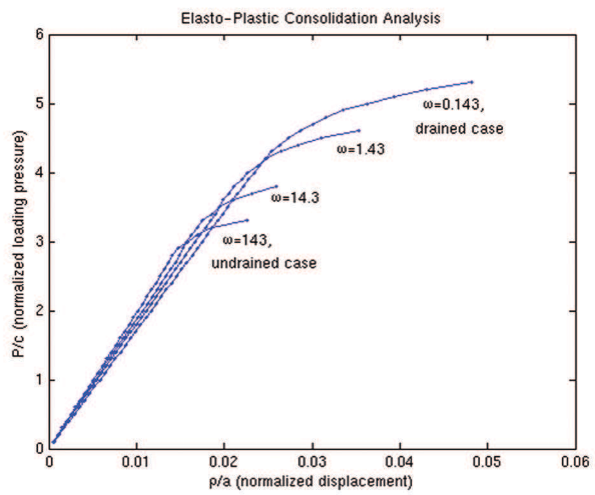
Figure 4 below shows a well-captured cyclic response of the soil stress path and stress-strain behaviour.



(a) FEM results of Small et al.



(b) FEM results in Abaqus



(c) FVM results in OpenFOAM

Figure 3: Bearing capacities of the footing under different loading rates

Bild 3: Tragfähigkeiten des Fundaments bei verschiedenen Belastungsgeschwindigkeiten

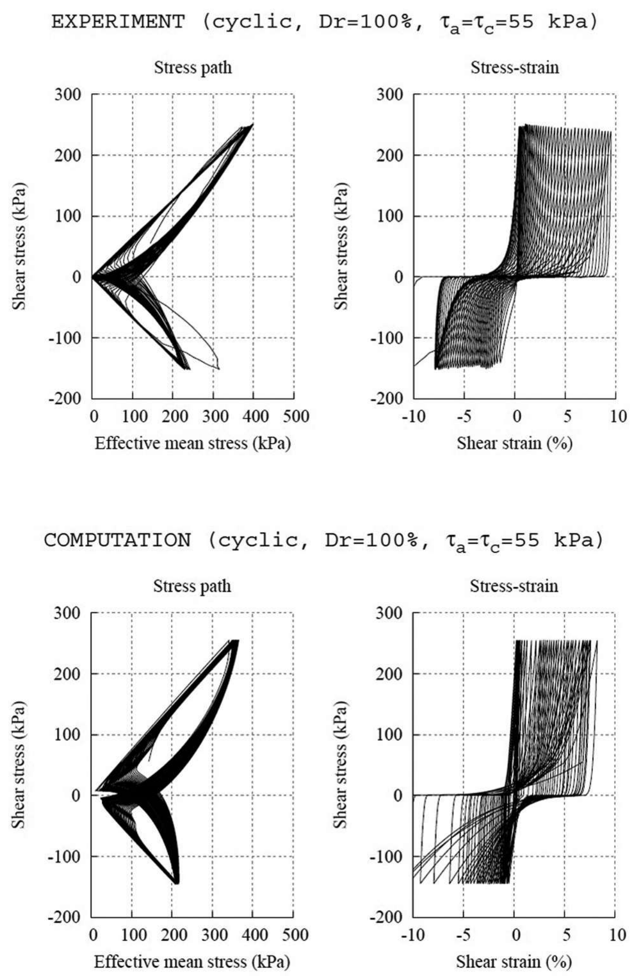


Figure 4: Experimental vs. Simulated stress path and stress-strain curve in cyclic undrained triaxial tests on full soil sample

Bild 4: Spannungspfad und Spannungs-Dehnungskurve aus undränierten zyklischen Triaxialversuchen an einer ganzen Bodenprobe – Vergleich von Versuch und Berechnung

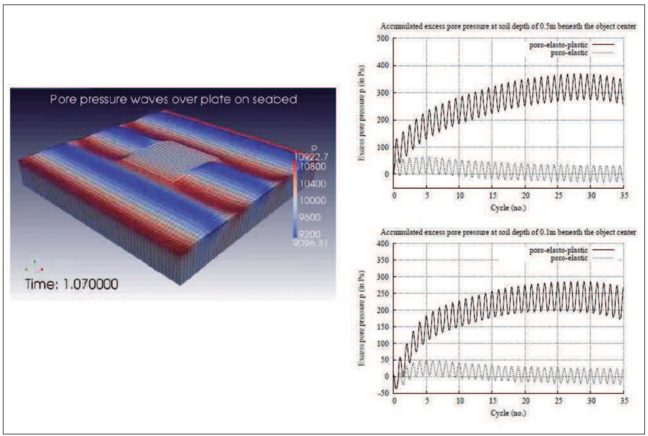


Figure 5: Simulated pore pressure evolution in seabed under cyclic wave loading; the impermeable structure sits steadily in the centre of simulated seabed domain

Bild 5: Berechnete Entwicklung des Porenwasserdrucks am Meeresboden unter zyklischer Wellenbelastung; das undurchlässige Bauwerk befindet sich in einer unveränderlichen Lage in der Mitte des modellierten Meeresbodenbereiches

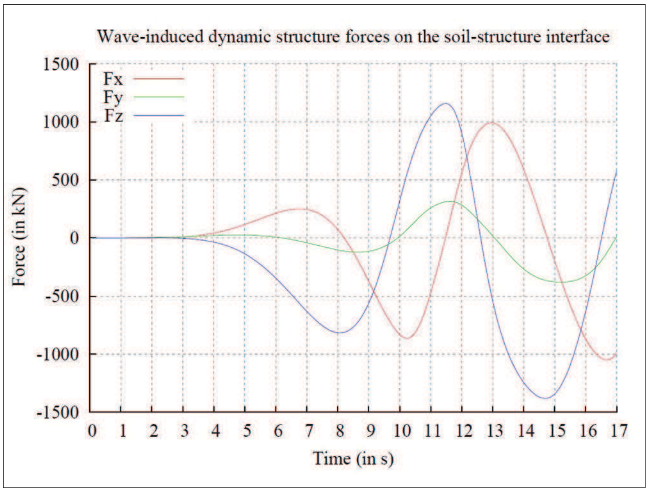


Figure 6: Combined structure force loading on the soil-structure interface

Bild 6: Kombinierte Belastung durch das Bauwerk an der Boden-Bauwerk-Grenzfläche

With the calibrated soil parameters, a hypothetical case of standing wave pressure acting on top of porous sea floor is also explored here. The simulated excess pore pressure variations, cycle by cycle, at two different soil depths have been plotted in Figure 5. Results from the classic Biots theory, i.e. the poro-elastic model, are also presented for comparison. The poro-elastoplastic model predicts a gradual accumulation of excess pore pressure inside the soil corresponding to a gradual decrease of pore volume, while the simple poro-elastic model, which has constant pore volume only captures the steady state pore pressure variation.

3.3 Gravity-based offshore foundation
Schwerkraftfundament für Offshore-Bauwerke

This test case consists of three computational domains: a numerical wave tank 86 m long and 42.5 m wide, a grounded gravity base structure with hexagonal geometries, and an underlying porous seabed 10 m thick. The novelty of such simulation lies in the integration of CFD, structural analysis, and porous soil calculations and allows interface coupling between these different physical systems.

In Figure 6, the total forces created at the structure bottom, namely the dynamic wave loads transferred through the structure to the underlying soil, are plotted. The magnitudes of the shearing forces – F_x denoted by red and F_y by green – are quite comparable to that of the normal force F_z (blue). This demonstrates that the soil underneath the structure is subjected to significant combined loading effects from the structure response.

Figure 7 presents different screenshots taken from the simulated domains. The upper left panel depicts the calculated free surface of water waves, in which the presence of the structure significantly modified the wave motion around it. The upper right panel shows the generated wave pressure load on the gravity structure and porous seabed surface. Such loading condition is highly nonlinear and three-dimensional, partly due to the disturbance effect of the structure and also due to the directional spreading of natural waves. This complex wave pressure loading environment is impossible to get from analytical solutions based on wave theory, but can readily be estimated from advanced CFD wave solvers.

The bottom left one plots the pore fluid flow direction induced in the seabed at a time when a wave trough is passing by the gravity structure. There are notable upwards pore fluid flows created underneath the structure. The bottom right panel shows the contours of the wave-induced shear stress measurement in the seabed soil and the upper gravity structure.

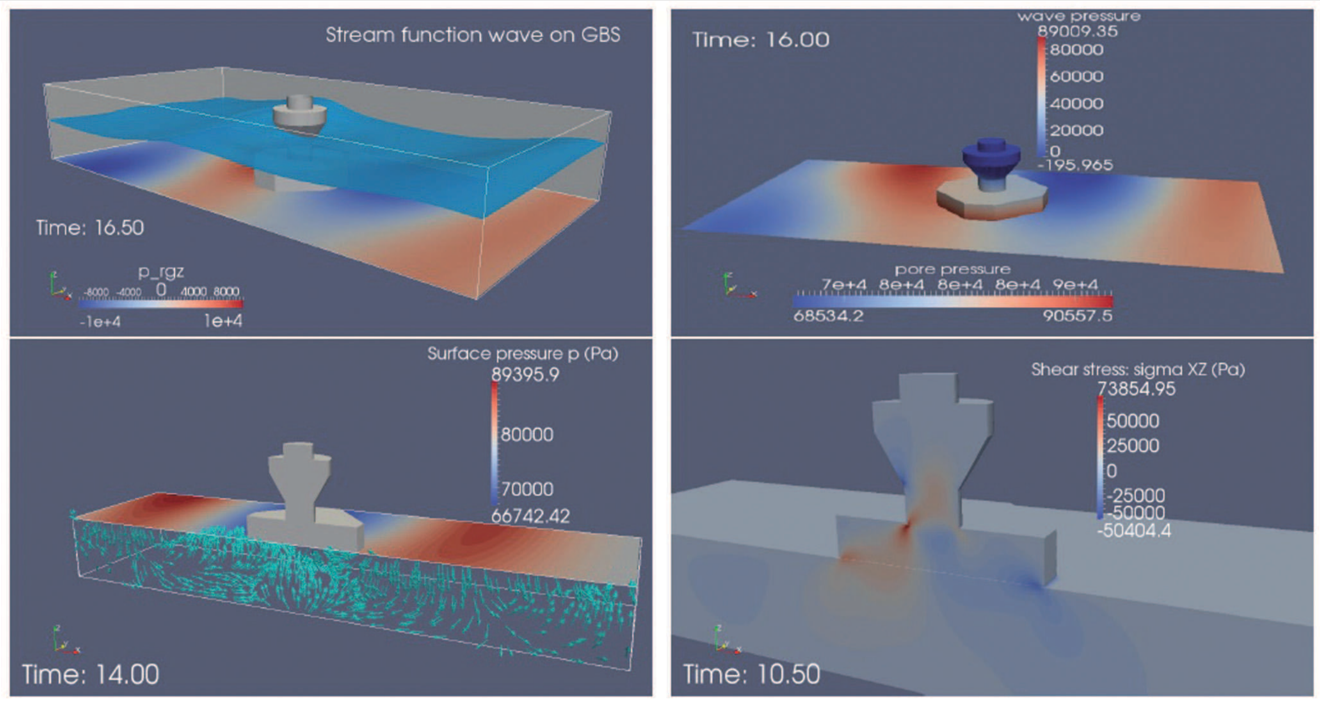


Figure 7: Free surface waves passing by an elastically deformable gravity-based structure standing on a porous seabed
Bild 7: Freie Oberflächenwellen, die an einem auf einem porösen Meeresboden stehenden, elastisch verformbaren Schwerkrafttragwerk vorbeiströmen

4 Conclusions
Zusammenfassung

The simulation cases presented in this article serve as brief examples on how the solver package can be used for modelling different soil behaviour and loading conditions. I believe that there are more potentials for this solver package to be applied in the wide range of geotechnical applications, due to the flexibility and open-source feature of OpenFOAM which freely supports from pre-processing (mesh generation), parallel computation, as well as post-processing (visualization).

Being a code developer, there is great freedom in creating new classes and functions tailor-made for the physics of your interest; whereas being a user, different application cases either purely for soil mechanics or for multi-physical topics where both fluid and solid is involved can be set up efficiently. The discussions are open and welcome.

5 References
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