Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering) 2023 24(1):1-5
www.jzus.zju.edu.cn; www.springer.com/journal/11582
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Editorial

https://doi.org/10.1631/jzus.A22MMMiG

Multiscale multiphysics modeling in geotechnical engineering

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1 Introduction

For geotechnical engineering, numerous applications involve multiscale and multiphysics processes, such as internal erosion, hydraulic fracturing, energy piles, municipal waste disposal, production from unconventional oil and gas reservoirs, heat stimulation and depressurization of natural gas hydrate formation, pavement subjected to heating-cooling cycles, contaminant transport, and CO_2 sequestration (Sun et al., 2018; Li et al., 2020; Shao et al., 2020; Yang et al., 2020, 2022; Liu et al., 2021; Qian et al., 2021; Jin and Yin, 2022; Wang et al., 2022b). In the literature, the terminology "multiphysics" always implies two or more physical fields in the so-called thermo-hydro-mechanical-chemical-bio-electrical coupling. Furthermore, the spatial scale of interest may range from the nanoscale to the microscale for material characterization purposes (Bennett et al., 2015), and to hundreds of kilometers for geological and reservoir engineering applications (Durlofsky, 2005; Yan et al., 2020). The time scale can also range from nano-seconds to several hundreds or thousands of years (Borja et al., 2020; Liu and Borja, 2022). Benefitted from the sustained development of computing power and of sophisticated equipment manufacturing, numerical simulations and multiscale laboratory testing are widespread in modern geomechanics. For example, constitutive theories that address suction and temperature dependences (Qiao et al., 2021; Zhu et al., 2021), field equations and poromechanical constants considering poro-thermo-chemo-elasticity or multiple porosity (Cheng, 2016; Yan et al., 2018, 2021; Zhang and Borja, 2021; Zhang Q et al., 2022a, 2022b), and advanced numerical schemes such as the multiscale finite element method-finite volume method (FEM-FVM) (Møyner and Lie, 2016) have been successfully developed. Moreover, this research field has attracted more attention in recent years.

To better highlight the recent research advances in this topic and to give an overview to researchers in similar fields, we are publishing this special feature. Focal points of the special feature include, but are not limited to: (1) understanding the multiphysics processes in granular material by using computational fluid dynamics-discrete element method (CFD-DEM); (2) modeling of unconventional shale gas reservoirs; (3) modeling of dissolution in rocks; (4) modeling of hydraulic fracturing and fracture deformation.

We have invited prestigious scientists in this field to share their expertise, perspectives, and up-to-date investigations. This special feature contains original research articles that cover the various topics mentioned above. In this editorial, we briefly introduce these articles as follows.

Wang et al. (2023) presented a comprehensive study on the process of suffusion in gap-graded granular

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Received Dec. 19, 2022; Revision accepted Dec. 21, 2022;
Crosschecked Dec. 29, 2022

soils, which is always caused by seepage. Suffusion is a typical cause of geo-hazards. Previous studies of suffusion mainly focused on suffusion in homogeneous soil specimens. Wang et al. (2023) investigated suffusion in heterogeneous soils with multiple layers and impermeable zones using a coupled DEM (Liu et al., 2022) and CFD approach. The parameters of the coupling model were first calibrated with the classic Ergun test, and a good match with experiment was obtained. The simulation results first reveal the suffusion mechanism in soils with multiple layers and impermeable zones. It turns out that the cumulative eroded mass is mainly determined by the fines content of the bottom layer. In general, a higher fines content of the bottom soil layer would cause a higher cumulative eroded mass. Furthermore, suffusion is more severe if the fines content of the middle layer is decreased. Impermeable zones inside soil specimens can increase the flow velocity around those zones, thus facilitating the migration of fine particles and intensifying suffusion.

Yan et al. (2023) considered the hydraulic fracture deformation hysteresis in the simulation of gas production, since its effect on the performance of CO_2 huff-n-puff has not been well understood in previous studies. In their study, an efficient hybrid model (Yan et al., 2018), which consists of a single porosity model, a multiple porosity model, and an embedded discrete fracture model (EDFM), is applied to model shale matrix, natural fractures, and hydraulic fractures. In flow equations, the Peng-Robinson equation of state (PR-EOS), extended Langmuir isotherms, and Fick's law are adopted to describe the gas properties, multi-component adsorption, and molecular diffusion, respectively. In the solid deformation portion, a loading-path dependent constitutive model is applied to describe the deformation hysteresis of hydraulic fractures. After that, the modified fixed-stress sequential implicit method is used to solve the resulting model, in which the FVM and the stabilized eXtended finite element method (XFEM) are used to discretize the fluid flow and solid deformation equations, respectively. Numerical results show that the hydraulic fracture deformation hysteresis negatively affects the CO_2 huff-n-puff performance. The effects are sensitive to or dependent on the initial conductivity of hydraulic fracture, production pressure, starting time of huff-n-puff, injection pressure, and huff-n-puff cycle number.

Laouafa et al. (2023) concerned the dissolution of rocks sensitive to water. These rocks usually contain many evaporites. Depending on the configuration of the site and the location of the rocks, the fluid flow and the associated dissolution can lead to surface subsidence and, for instance, the formation of sinkholes and landslides. In their work, the authors presented a numerical model that describes the dissolution process in geotechnical engineering. In the model, the physical interface between the fluid and the rock (porous medium) is represented by a diffusive interface of finite thickness. The authors also briefly described the steps for upscaling, i.e., from the microscopic scale (pore scale) problem to the macroscopic scale (Darcy scale) problem, similar to those in (Coussy, 2004; Luo et al., 2014). The numerical applications focus on saline and gypsum rocks: the effect of dissolution in the vicinity of a soil dam or slope and the partial dissolution of a gypsum pillar by a thin layer of water are analyzed. These theoretical examples show the approach's relevance and potential in the general framework of geotechnical problems.

The hydraulic fracture initiation around a horizontal perforation was investigated by Zhang et al. (2023) by using a thermo-poro-elastic model that considers the physical interactions between fluid flow and heat transfer. A numerical model based on the FVM (Zhang et al., 2023) is proposed for simulating fracture initiation of the rock around a perforation, which takes the effect of stress sensitivity into consideration. Results show that when the perforation azimuth rises, a longer injection time and a higher fluid pressure are required to satisfy the fracture initiation criterion. In addition, when the wellbore wall is impermeable, contours of fluid pressure exhibit an oval shape around the perforation site. In contrast, when the wellbore wall is permeable, the fluid pressure spreads outwards like there is a line mass sink. Furthermore, stress sensitivity of permeability and porosity increases fluid pressure and permeability in the area surrounding the well. In the future, more advanced fracture initiation criteria could be included (Liu, 2018; Wang et al., 2022a).

We think this special feature will provide a good insight into many different kinds of multiphysics processes in geotechnics, which are solved by a variety of numerical methods such as CFD-DEM, FVM, and FEM. These numerical methods are still the most popular choices in modern engineering calculations and commercial software. As the actual processes may be much more complex than we expect, our explorations never come to an end. We hope this special feature will enhance the understanding of multiscale and multiphysics processes in geotechnics and, at the same time, may promote more interdisciplinary international collaborations in the future.

Acknowledgments

This work is supported by the Research Grants Council (RGC) of the Hong Kong Special Administrative Region Government (HKSARG) of China (No. N_PolyU534/20).

Author contributions

Zhenyu YIN conceived and edited the draft of manuscript. Qi ZHANG performed the literature review and completed the first draft of the manuscript. Farid LAOUAFA edited the draft of the manuscript.

Conflict of interest

Zhenyu YIN, Qi ZHANG, and Farid LAOUAFA declare that they have no conflict of interest.

References

Bennett KC, Berla LA, Nix WD, et al., 2015. Instrumented nanoindentation and 3D mechanistic modeling of a shale at multiple scales. *Acta Geotechnica*, 10(1):1-14. https://doi.org/10.1007/s11440-014-0363-7

Borja RI, Yin Q, Zhao Y, 2020. Cam-Clay plasticity. Part IX: on the anisotropy, heterogeneity, and viscoplasticity of shale. *Computer Methods in Applied Mechanics and Engineering*, 360:112695. https://doi.org/10.1016/j.cma.2019.112695

Cheng AHD, 2016. Poroelasticity. Springer, Switzerland. https://doi.org/10.1007/978-3-319-25202-5

Coussy O, 2004. Poromechanics. John Wiley & Sons, Ltd., Chichester, UK. https://doi.org/10.1002/0470092718

Durlofsky LJ, 2005. Upscaling and gridding of fine scale geological models for flow simulation. Proceedings of the 8th International Forum on Reservoir Simulation, p.1-59.

Jin YF, Yin ZY, 2022. Two-phase PFEM with stable nodal integration for large deformation hydromechanical coupled geotechnical problems. *Computer Methods in Applied Mechanics and Engineering*, 392:114660. https://doi.org/10.1016/j.cma.2022.114660

Laouafa F, Guo JW, Quintard M, 2023. Modelling and applications of dissolution of rocks in geoengineering. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 24(1):20-36. https://doi.org/10.1631/jzus.A2200169

Li KQ, Li DQ, Liu Y, 2020. Meso-scale investigations on the effective thermal conductivity of multi-phase materials using the finite element method. *International Journal of Heat and Mass Transfer*, 151:119383. https://doi.org/10.1016/j.ijheatmasstransfer.2020.119383

Liu GZ, Dai JC, Wang P, et al., 2022. Analysis of the breakage parameters of railway ballast based on the discrete element method. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, in press. https://doi.org/10.1631/jzus.A2200019

Liu HY, 2018. Wing-crack initiation angle: a new maximum tangential stress criterion by considering *T*-stress. *Engineering Fracture Mechanics*, 199:380-391. https://doi.org/10.1016/j.engfracmech.2018.06.010

Liu YJ, Yin ZY, Wang LZ, et al., 2021. A coupled CFD-DEM investigation of internal erosion considering suspension flow. *Canadian Geotechnical Journal*, 58(9):1411-1425. https://doi.org/10.1139/cgj-2020-0099

Liu YX, Borja RI, 2022. Time scales in the primary and secondary compression of soils. *International Journal for Numerical and Analytical Methods in Geomechanics*, 46(8):1383-1408. https://doi.org/10.1002/nag.3350

Luo H, Laouafa F, Guo J, et al., 2014. Numerical modeling of three-phase dissolution of underground cavities using a diffuse interface model. *International Journal for Numerical and Analytical Methods in Geomechanics*, 38(15): 1600-1616.

https://doi.org/10.1002/nag.2274

Møyner O, Lie KA, 2016. A multiscale restriction-smoothed basis method for high contrast porous media represented on unstructured grids. *Journal of Computational Physics*, 304:46-71. https://doi.org/10.1016/j.jcp.2015.10.010

Qian JG, Zhou C, Yin ZY, et al., 2021. Investigating the effect of particle angularity on suffusion of gap-graded soil using coupled CFD-DEM. *Computers and Geotechnics*, 139:104383. https://doi.org/10.1016/j.compgeo.2021.104383

Qiao YF, Tuttolomondo A, Lu XB, et al., 2021. A generalized water retention model with soil fabric evolution. *Geomechanics for Energy and the Environment*, 25:100205. https://doi.org/10.1016/j.gete.2020.100205

Shao JL, Zhang Q, Wu XT, et al., 2020. Investigation on the water flow evolution in a filled fracture under seepage-induced erosion. *Water*, 12(11):3188. https://doi.org/10.3390/w12113188

Sun X, Luo H, Soga K, 2018. A coupled thermal–hydraulic–mechanical–chemical (THMC) model for methane hydrate bearing sediments using COMSOL Multiphysics. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 19(8):600-623. https://doi.org/10.1631/jzus.A1700464

Wang P, Ge Y, Wang T, et al., 2023. CFD-DEM modelling of suffusion in multi-layer soils with different fines contents and impermeable zones. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 24(1):6-19. https://doi.org/10.1631/jzus.A2200108

Wang ZY, Zhang Q, Zhang WQ, 2022a. A novel collaborative study of abnormal roof water inrush in coal seam mining based on strata separation and wing crack initiation. *Engineering Failure Analysis*, 142:106762. https://doi.org/10.1016/j.engfailanal.2022.106762

Wang ZY, Jin YF, Yin ZY, et al., 2022b. A novel coupled NS-PFEM with stable nodal integration and polynomial pressure projection for geotechnical problems. *International Journal for Numerical and Analytical Methods in Geomechanics*, 46(13):2535-2560. https://doi.org/10.1002/nag.3417

Yan X, Huang ZQ, Yao J, et al., 2018. An efficient numerical hybrid model for multiphase flow in deformable fractured-shale reservoirs. *SPE Journal*, 23(4):1412-1437. https://doi.org/10.2118/191122-PA

Yan X, Huang ZQ, Zhang Q, et al., 2020. Numerical investigation of the effect of partially propped fracture closure on gas production in fractured shale reservoirs. *Energies*, 13(20):5339. https://doi.org/10.3390/en13205339

Yan X, Sun H, Huang ZQ, et al., 2021. Hierarchical modeling of hydromechanical coupling in fractured shale gas reservoirs with multiple porosity scales. *Energy & Fuels*, 35(7): 5758-5776. https://doi.org/10.1021/acs.energyfuels.0c03757

Yan X, Liu PY, Huang ZQ, et al., 2023. Effect of hydraulic fracture deformation hysteresis on CO_2 huff-n-puff performance in shale gas reservoirs. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 24(1):37-55. https://doi.org/10.1631/jzus.A2200142

Yang J, Yin ZY, Laouafa F, et al., 2020. Three-dimensional hydromechanical modeling of internal erosion in dike-on-foundation. *International Journal for Numerical and Analytical Methods in Geomechanics*, 44(8):1200-1218. https://doi.org/10.1002/nag.3057

Yang J, Yin ZY, Liu YJ, 2022. Multiphysics modelling of backfill grouting in sandy soils during TBM tunnelling. *Acta Geotechnica*, in press. https://doi.org/10.1007/s11440-022-01528-2

Zhang PF, Xu XG, Hua YJ, et al., 2022. Effects of the outlet pressure on two-phase slug flow distribution uniformity in a multi-branch microchannel. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 23(1):68-82. https://doi.org/10.1631/jzus.A2100135

Zhang Q, Borja RI, 2021. Poroelastic coefficients for anisotropic single and double porosity media. *Acta Geotechnica*, 16(10):3013-3025. https://doi.org/10.1007/s11440-021-01184-y

Zhang Q, Yan X, Li ZH, 2022a. A mathematical framework for multiphase poromechanics in multiple porosity media. *Computers and Geotechnics*, 146:104728. https://doi.org/10.1016/j.compgeo.2022.104728

Zhang Q, Wang ZY, Yin ZY, et al., 2022b. A novel stabilized NS-FEM formulation for anisotropic double porosity media. *Computer Methods in Applied Mechanics and Engineering*, 401:115666. https://doi.org/10.1016/j.cma.2022.115666

Zhang Y, Hou SH, Mei SH, et al., 2023. FVM-based numerical simulation method for hydraulic fracture initiation in rock around a perforation. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 24(1):56-63. https://doi.org/10.1631/jzus.A2200203

Zhu QY, Zhao TY, Zhuang PZ, 2021. Thermal strain response of saturated clays in 1D condition. *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)*, 22(3):182-187. https://doi.org/10.1631/jzus.A2000152

Introducing Guest Editor-in-Chief and Guest Editors:

Guest Editor-in-Chief

Zhenyu YIN has been an Editorial Board Member of *Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)* since 2019. Prof. YIN is currently a full Professor of Geotechnical Engineering at The Hong Kong Polytechnic University (China). Prof. YIN received his B.Eng. in Civil Engineering from Zhejiang University (China) in 1997, followed by five years of engineering consultancy at the Zhejiang Jiahua Architecture Design Institute (China). Then, he obtained his M.Sc. degree and Ph.D. degree in Geotechnical Engineering at the Ecole Centrale de Nantes (France) in 2003 and 2006, respectively. According to the Web of Science, Prof. YIN has published over 250 articles in peer-reviewed international journals with an H-index of 50. He is the Associate Committee Member of the Granular Materials Committee in ASCE; Associate Editor of *European Journal of Environmental and Civil Engineering* and *Geotechnique Letters*, and Editorial Board Member of some top journals in the field of soil mechanics and geotechnical engineering (*Canadian Geotechnical Journal*, *International Journal of Geomechanics ASCE*, *Soils and Foundations*, *Acta Geotechnica*, *Transportation Geotechnics*, *Computers and Geotechnics*, *GeoRisk*, etc.).

Guest Editors

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