

High-performance dynamic solid fluid coupled simulation for large-scale geotechnical earthquake engineering problems

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ABSTRACT: Advances in engineering capabilities has led to the establishment of massive projects in evermore seismically challenging conditions, calling for increased dynamic numerical analysis capacity. This is especially challenging considering the computation demand raised by recent developments in high-fidelity constitutive models, along with the need for solid fluid coupled analysis. The current study develops a high-performance dynamic solid fluid coupled simulation for large scale geotechnical earthquake engineering. A parallel solution framework using the message passing interface (MPI) is developed to harness the power of high-performance computing within the code framework GEOS. A finite element method (FEM) - finite volume method (FVM) coupling approach tailored for parallel computing is proposed to achieve efficient solid fluid coupling simulation, with fully implicit, solid explicit-fluid implicit, and fully explicit algorithms developed for different applications. An advanced plasticity models for soil liquefaction analysis (CycLiq) is implemented within the framework. The computation efficiency of the framework is assessed, showing that the fully explicit FEM-FVM algorithm can achieve dynamic solid fluid coupled analysis for problems exceeding 200 million degrees of freedom. The framework is validated through successful simulation of experiments in the liquefaction experiments and analysis project (LEAP). Applications of the framework for the seismic analysis of large-scale underground structures and earth dams are showcased.

KEYWORDS: Geotechnical earthquake engineering, High-performance computing, Solid fluid coupling, Constitutive model, arge-scale project.

1 INTRODUCTION

With continuously increasing human demand and engineering capacity, more and more mega-sized geotechnical related projects, such as massive underground complexes and tall earth dams, are being planned, designed, and constructed in challenging areas with high seismicity (e.g., China Ministry of Natural Resources, 2020; Han et al., 2016). Such project calls for efficient high-fidelity numerical analysis prowess.

While significant advances have been made over the past three decades for the constitutive modelling of soil under cyclic loading (e.g., Dafalias and Manzari, 2004; Boulanger and Ziotopoulou, 2014; Wang et al., 2014), due to their complexity and computational demand, such plasticity models have largely only been applied to the simulation of relatively simple model tests or heavily simplified versions of real engineering problems.

The progress of high-performance computing has motivated the development of geotechnical engineering oriented parallel computing methods (Yu et al., 2025). Zhao et al. (2024) employed GPU parallel computing to simulate the seismic response of underground structures in single phase soil. Kusakabe et al. (2022) developed a GPU-based method that can achieve over 100 million DOF simulations of seismic ground response using a nonlinear constitutive model. These studies have significantly contributed to the advancement of geotechnical earthquake engineering simulation capabilities. However, these methods usually consider soil as a single-phase material or simplify solid-fluid coupling in porous media via undrained condition assumptions.

The current study proposes a high-performance dynamic solid fluid coupled simulation for large scale geotechnical earthquake engineering. A parallel solution framework using the message passing interface (MPI) is developed to harness the power of high-performance computing within the code framework GEOS. A finite element method (FEM) - finite volume method (FVM) coupling approach tailored for parallel computing is proposed to achieve efficient solid fluid coupling simulation, with fully implicit, solid explicit-fluid implicit, and fully explicit algorithms developed for different applications. An advanced plasticity models for soil liquefaction analysis (CycLiq) is implemented within the framework. The computation efficiency of the framework is assessed, showing

that the fully explicit FEM-FVM algorithm can achieve dynamic solid fluid coupled analysis for problems exceeding 200 million degrees of freedom. The framework is validated through successful simulation of experiments in the liquefaction experiments and analysis project (LEAP). Applications of the framework for the seismic analysis of large-scale underground structures and earth dams are showcased.

2 METHOD

Three main challenges must be overcome to achieve high-performance dynamic solid fluid coupled simulation for large-scale geotechnical earthquake engineering problems: (1) massively parallel framework for the solution of geotechnical problems, (2) efficient solid-fluid coupling solution algorithm, (3) high-fidelity constitutive model for the dynamic response of soil. In this section, we present the methods adopted for each of these challenges.

2.1 High-performance simulation framework

To facilitate large-scale earthquake geotechnical engineering simulation, a high-performance dynamic solid-fluid coupled simulation method for porous media is developed based on the GEOSX platform. The message passing interface (MPI) is employed for CPU based parallel computing. Problems are decomposed into different domains and assigned to different CPU processors for independent solutions. For a specific problem, the solution process typically include the following procedures:

(1) Modeling and meshing: Establishing a geometric model based on the physical model, generating initial discretization of the geometric model, and setting initial and boundary conditions.

(2) Domain decomposition: Partitioning the initial mesh into different computational domains with the goal of balancing the computational load for each domain. METIS is implemented for partitioning of unstructured mesh with any geometric shape based on the multilevel recursive bisection, multilevel k-way, and multi-constraint partitioning schemes (Karypis and Kumar, 1998).

(3) Neighbor construction: The GEOSX framework adopts an overlapping domain decomposition approach, where overlapping regions are used for data communication between

adjacent computational domains. Hence, neighborhood construction and initialization of the ranking for the elements and nodes are required, and the communication units in the overlapping region are given a ghostRank.

(4) Parallel solution: For different computational domains, corresponding solvers are employed on each computational core, with communication of the solution results at communication units based on ghostRank to facilitate rapid communication between different computational domains.

(5) Mesh reconstruction: Integrating the results obtained from parallel solution to reconstruct the complete model and corresponding simulation results, facilitating post-processing.

2.2 FEM-FVM solid-fluid coupling solution

For the dynamic simulation of saturated soil, an explicit finite element method-finite volume method (FEM-FVM) solid-fluid coupled method is proposed. Compared with the traditional FEM u-p solid-fluid coupled method, this method guarantees mass conservation of porous fluid and offers great parallel computation efficiency. The solid phase is discretized using FEM. The fluid solver is discretized using FVM. The forward Euler method is adopted for computational efficiency.

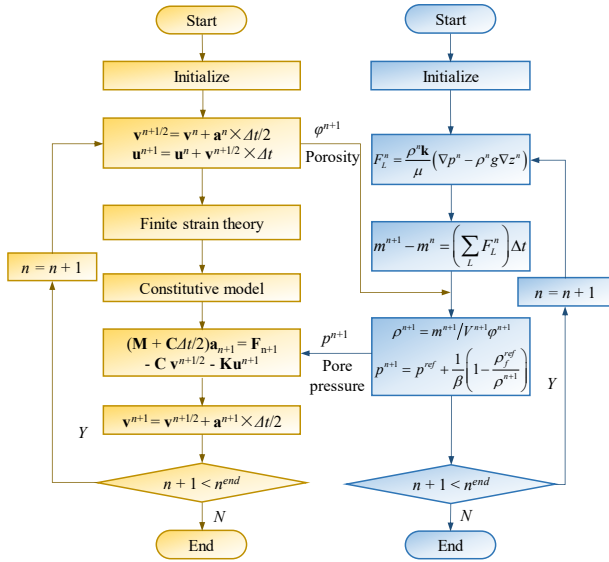


Figure 1. Explicit FEM-FVM solid-fluid coupling solution procedure.

The solution procedure is illustrated in Figure 1, and follows:

(1) Initialization: Set initial parameters including porosity, pore pressure, and permeability matrix, etc., and initialize solvers.

(2) Update solid displacement: Solid velocity and displacement are obtained through acceleration integration and velocity integration. Subsequently, solid strain increments, solid volume, and porosity are solved. Thereafter, the updated volume and porosity are transferred from the solid solver to the fluid solver.

(3) Update fluid pore pressure: Element fluid mass is solved by the filtration equation, and fluid pore pressure is determined based on fluid equation of state. Thereafter, the updated pore pressure is transferred from the fluid solver to the solid solver.

(4) Update solid acceleration: Solid stress is obtained through solving the constitutive model, and solid acceleration is determined based on mixture balance equation with fluid pore pressure.

(5) Update solid velocity: Updated solid velocity is obtained through integrating the updated acceleration.

The use of a fully explicit solid-fluid coupled scheme, along with explicit algorithms for solid and fluid phases, avoids the need to solve large system-of-equations, thus improving parallel computation efficiency. Although the explicit approach usually demands smaller time steps compared with the implicit methods, it matches the natural need for relatively small time steps in dynamic seismic analysis considered for this study.

2.3 The CycLiq elasto-plastic constitutive model

The unified plasticity model for large post-liquefaction shear deformation of sand (CycLiq model, Wang et al., 2014) is adopted and implemented to simulate the dynamic response of soil in geotechnical earthquake engineering problems. The model has been extensively validated against element and model tests and applied to various soil dynamics applications (He et al., 2020; Wang et al., 2023; Li et al., 2025). Detailed presentation of the model formulation can be found in Wang et al. (2014) and is not repeated here for brevity.

3 VALIDATION AND PARALLEL PERFORMANCE

The proposed high-performance dynamic solid fluid coupled simulation method is validated against the LEAP-2017 centrifuge tests on a sloping ground model conducted at Zhejiang University (ZJU) (Manzari et al., 2020). The centrifuge test model used in LEAP is presented in Figure 2 (a). The model surface inclination angle is set at 5°, and the sand is saturated Ottawa F65 sand. The three tests simulated in this study, ZJU1-ZJU3, used sand at relative densities of 64%, 45%, and 82%, respectively. The details of the test setup and the constitutive model parameter determination process is reported in He et al. (2020).

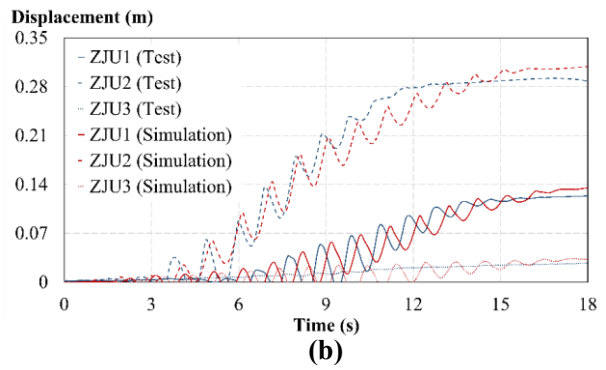
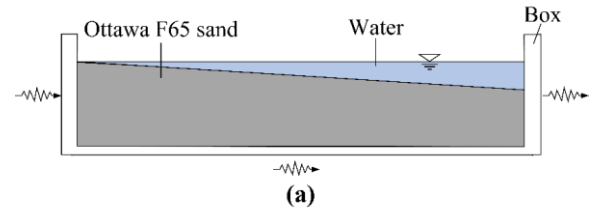


Figure 2. Simulation of LEAP-2017 centrifuge tests on sloping ground: (a) centrifuge test setup; (b) soil surface lateral displacement at the center of the slope.

Figure 2 (b) compares the simulated and test soil surface lateral displacement at the center of the slope, showing good agreement between simulation and test results. The proposed method can successfully simulate the dynamic response of saturated ground under seismic loading.

To evaluate the parallel performance of the proposed method, a 1D consolidation problem is solved using different number of model degrees-of-freedom (DOFs) per core and different number of cores. The scalability, which is the computation time ratio between one core and a number of cores

for a fixed number of DOFs per core, is used to assess the parallel performance. The results are presented in Figure 3.

The scalability of the solution initially decreases with increasing number of cores, but tends to stabilize after about 400 cores. The scalability of the solution generally increases as the DOFs per core increases. This is due to the increased proportion of communication overhead when the computation load for each core is relatively small. For the largest problem solved in this validation case, over 200 million DOFs (212,549 DOFs/core, 1000 cores), the scalability of the solution can reach 80%, highlighting the excellent parallel performance of the proposed method.

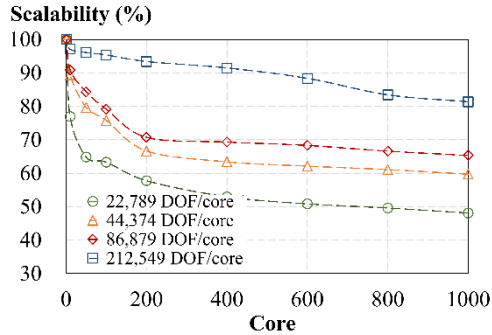


Figure 3. Parallel computation performance of the proposed method for solving a consolidation problem.

4 APPLICATION FOR LARGE-SCALE GEOTECHNICAL EARTHQUAKE ENGINEERING PROBLEMS

4.1 Underground complex seismic analysis

The Beijing Municipal Administrative Center Transport Complex (BMACTC) is an underground railway, subway, business, and commercial hub. It consists of three main underground structure sections with a total underground floor area of 1.28 million square meters and is directly connected with eight aboveground structures. The main station section has 3 underground floors, reaching a depth of 31.15 m. The distribution of the aboveground structures is shown in Figure 4. For natural lighting, the station is designed with three large openings passing through B1 to B3 in the main station section. These openings account for approximately half of the overall width of the structure.

The BMACTC is located between the North canal and Yunchaojian river, within over 100m thick layered soil mostly consisting of sand interbedded with silty clay. The groundwater is relatively shallow, at 8.2 m. At the location of the site in Beijing, the 10% exceedance probability in 50-year hazard level peak ground acceleration (PGA) is 0.2 g.

For the simulation of the problem, the soil is modeled with coupled tetrahedral FEM-FVM elements using the CycLiq model, while the structure is modeled with single phase tetrahedral FEM elements using linear elasticity. The entire model comprises 13,020,902 tetrahedral elements and 2,763,083 nodes. As there are three degrees of freedom per FEM node for the solid phase and an additional pore pressure degree of freedom per FVM element, the total degrees of freedom of the model amount to 16,875,959.

The details of the numerical model and simulation results have been discussed in Yu et al. (2025). Figure 4 presents the typical simulation results of structure horizontal and vertical displacement. The horizontal displacement is taken at the moment of maximum underground structure deformation at $t = 3.2$ s, as shown in Figure 4 (a). The station section experiences greater lateral displacement than the east and west sections due

to the existence of large openings. The displacement of the underground structure on the side with the aboveground structure is observed to be greater. The vertical displacement is illustrated for the base of the underground structure at the end of shaking at $t = 20$ s, as shown in Figure 4 (b). Significant spatial variability of vertical displacement is also observed.

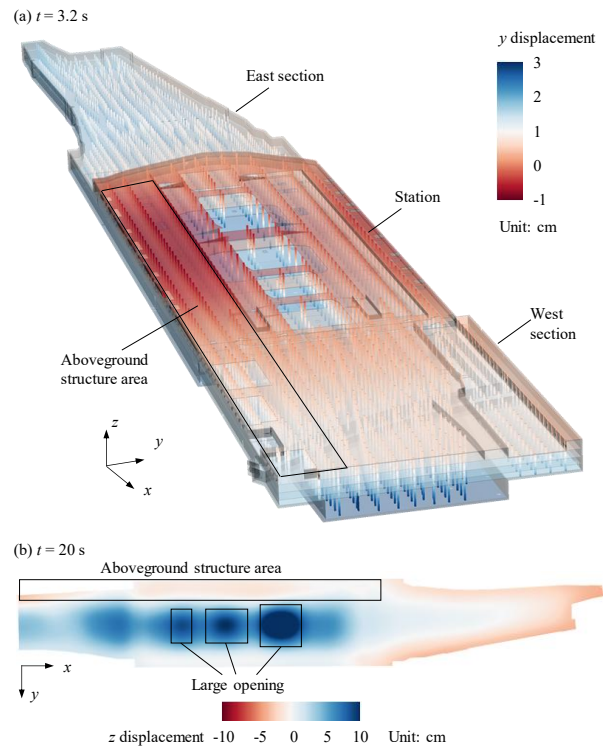


Figure 4. Simulation results for the seismic response of the BMACTC: (a) Horizontal displacement of the underground structure at the maximum structure deformation at $t=3.2$ s, (b) vertical displacement of the base of the underground structure at the end of shaking at $t = 20$ s.

Figure 5 illustrates a colormap of the excess pore pressure ratio at 20 s for typical cross sections. The distribution of the excess pore pressure ratio at cross sections a and c are similar. The excess pore pressure ratio of saturated sand layers reaches nearly 0.5, indicating that the soil has significantly softened but has not yet reached liquefaction. The excess pore pressure ratio shows a clear layering phenomenon, mainly caused by the interlayering between sand and clay as shown in Figure 5 (c). The excess pore pressure ratio in the sand layers shows a lighter color and is greater, while the excess pore pressure in the clay layers shows a darker color and is generally smaller, which is typical of sand and clay response.

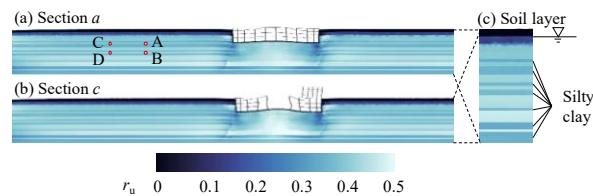


Figure 5. Excess pore pressure ratio in the soil for cross sections a and c at 20 s (deformation magnified 100 times). (a) Cross section a, (b) cross section c, (c) soil layer and water level.

4.2 Rockfill dam on thick sandy deposit

Recently, an increasing number of high earth dams have been constructed on thick deposit in areas with high seismicity. For the seismic analysis of high earth dams on soil deposits, it is important to conduct high fidelity large-scale simulation

considering the plasticity of soil and solid-fluid coupling in porous media. The method proposed here is applied to the simulation of the seismic response of a hypothetical earth core rockfill dam on thick sandy deposit.

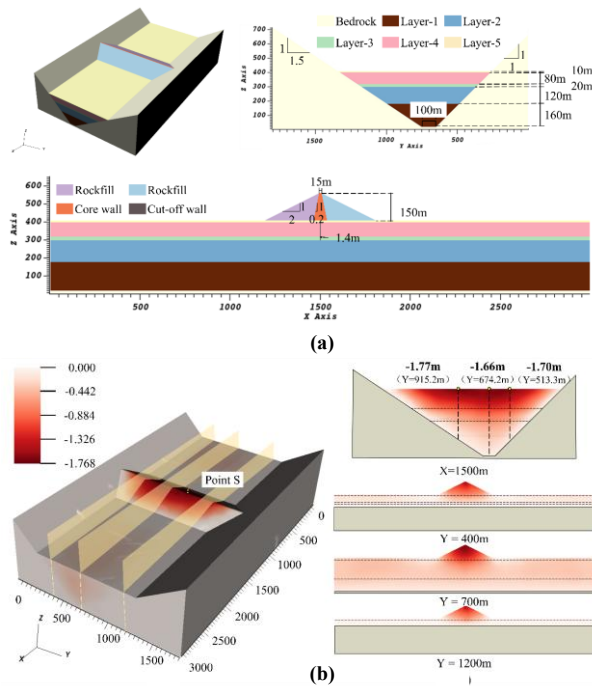


Figure 6. Simulation of a rockfill dam on thick deposit: (a) model geometry and geotechnical conditions, (b) simulation results for post-earthquake settlement.

The hypothetical dam-deposit model used in the study are detailed in Figure 6. There are five layers of deposit upon the bedrock, with the deepest location reaching 390m of deposit. The dam is 150m height, with a top width of 15m and a top length of 1450m. The cut-off wall penetrates through layers 5, 4, and 3 from the base of the core wall, reaching a depth of 110m and has a thickness of 1.4m. The model is discretized using tetrahedral elements, reaching a total of 11,928,107 elements and 17,988,653 DOFs.

Figure 6 (b) shows the post-earthquake settlement of the dam and foundation deposit. Interestingly, the greatest settlement of the dam crest does not occur at the center of the dam, where the deposit is the thickest. Rather, the settlement is the greatest near half way towards the abutment from the center of the dam. This is largely due to the attenuation of seismic wave at the center considering the accumulation of excess pore pressure, resulting in weaker dynamic response of the dam. Near the abutment, the dynamic response of the dam is stronger, resulting in greater overall settlement even though the thickness of the deposit is less.

5 CONCLUSIONS

This study proposes a high-performance FEM-FVM solid-fluid coupled dynamic simulation framework for large-scale geotechnical earthquake engineering problems. Parallel simulation is achieved using the MPI interface and METIS mesh partitioning, and communication between partitions is achieved using a ghostRanking approach. Dynamic solid-fluid coupling analysis for porous media is achieved using an explicit FEM-FVM solution algorithm, providing high stability and efficiency. The CycLiq elasto-plastic constitutive model is implemented for soil modeling.

The proposed method is validated against centrifuge shaking table test results from LEAP-2017, showing successful simulation for the seismic response of sloping saturated sandy ground. The parallel performance of the method is evaluated, achieving 80% scalability for the solution of an over 200 million DOFs consolidation problem using 1000 cores.

The method is applied to the simulation of two large-scale earthquake geotechnical engineering problems, including a large underground structure complex in sandy ground and a tall rockfill dam on thick deposit. The results of the large-scale simulations highlight the advantage of achieving high-resolution and high-fidelity integrated analysis of such problems, revealing the unique seismic response of the systems.

6 ACKNOWLEDGEMENTS

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