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論 文 内 容 要 旨

Large-scale tsunamis triggered by submarine or/and subaerial landslides lead to terrifying natural disasters. This type of tsunami is a rare event but causes severe global damage and can be extremely deadly to community residents. However, the process of such an event is not well understood due to the existence of multiple physical phenomena. Although some model experiments were reported in the past, it is practically impossible to reproduce the actual phenomenon on the scale of the experiment, and the mechanism by which the experiment and the actual phenomenon occur may not be the same. Therefore, it is necessary to develop effective numerical simulation methods that can properly evaluate the complex mechanical behavior involved in the generation of tsunamis due to landslides.

Mesh-based schemes, such as the finite element method (FEM), have been widely used for modeling complex coupled solid-liquid problems in the past, and their robustness and efficiency have been demonstrated in solving various geotechnical engineering problems. However, these schemes inevitably require complex re-meshing algorithms and are therefore not suitable for solving complex large deformation problems in the solid phase. On the other hand, meshless or particle-based methods, such as the smoothed-particle hydrodynamics (SPH) method, particle finite element method (PFEM), and material point method (MPM), have been developed rapidly due to their robust capabilities in handling large deformations nowadays widely used. Among the three methods, we note the superiority of MPM over the other particle-based methods. Indeed, since MPM has a similar mathematical structure to FEM, the advantages of FEM will be retained. Also, unlike PFEM, MPM does not require re-meshing to avoid severe mesh distortion thanks to the combined use of the Lagrangian description and Eulerian grids. Moreover, unlike SPH, there is no need for neighbor particle search for MPM, reducing computational costs. Because of these advantages, MPM has contributed to the remarkable development of the field as a method of choice for many researchers.

Within the MPM framework, two approaches are proposed to study the interaction between solid and liquid phases: (1) the two-phase single-point approach and (2) the two-phase double-point approach. The governing equations used by the two approaches are not the same. Compared with the first approach, in which the formulation is derived by reference to the solid configuration, the second approach uses two sets

of material points to separately represent the solid skeleton and the liquid phase. Thanks to this, the motions of each phase can be expressed separately and applied to solve more diverse problems, such as seepage, over-topping, and transportation. Since we have our sights set on simulating a tsunami generated by a submarine or/and subaerial landslide, which requires the rough movements of water and soil phases to be represented, the second approach is considered more suitable.

However, in most of the coupled solid-liquid MPM algorithms, the liquid phase is assumed to be weakly compressible, since the MPM was originally developed mainly with a focus on large deformation problems for solids. Many of these existing analysis methods suffer from pressure oscillation, and free surface instability, and involve a high computational cost due to the large bulk modulus of water when an explicit time integration is adopted. For single-phase problems, there have been some remedies for dealing with incompressibility that yield stable solution schemes for MPM calculations of incompressible fluids. Nevertheless, only a few attempts have so far been made at managing incompressibility for solid-liquid MPM. In addition, the dynamic addition or deletion of water particles is more complicated when it comes to problems containing inflow or outflow boundaries. In view of such issues, a class of stabilization schemes with an Eulerian description provides a simpler process and therefore has clear advantages in terms of calculation cost and accuracy. Thus, a novel scheme needs to be developed to couple the FEM with MPM to simulate granular mass-water interactions. Here, the "granular mass" is a synonym for "soil structure" in this study.

Moreover, a fully 3D simulation of the entire process, including the tsunami generated by landslides and offshore wave propagation, is accompanied by a significant increase in degrees of freedom and often becomes unrealistic in terms of computational costs. In view of this, 2D computations have been widely used for simulating large-scale offshore wave propagation because of their technical simplicity and lower computational costs compared to fully 3D computations. Several studies of landslide-triggered tsunamis using the shallow-water (SW) model have been conducted thus far and have demonstrated the high capability in characterizing wide-range offshore wave propagation due to landslides. Even though 2D approaches are capable of simulating tsunami propagation over a wide area, there are limitations in the performance of representing 3-D effects of submarine landslides that are necessary to obtain more reliable inputs of tsunami propagation to coastal areas. Thus, it is preferable to consider a suitable combination of 2D and 3D analyses to accurately and efficiently represent the entire process of a submarine/subaerial landslide-induced disaster.

According to the above-described background, the objectives of this study can be summarized as follows:

- Suppressing the afore-mentioned instabilities in the liquid phase (pressure oscillation, free surface instability, and high computational cost) that often arise in the solid-liquid coupled MPM algorithm.
- Combining the 3D and 2D analyses to reduce the computational cost while maintaining accuracy that is capable of handling tsunami simulations caused by large-scale landslides.
- Introducing high-performance computing techniques to speed up the 3D domain calculation and make it suitable for real-world hazard problems.

For the first objective, we propose a hybrid method of MPM and FEM capable of expressing the complex interaction between granular masses and liquids. The proposed method is formulated based on porous media theory, in which saturated soil is considered a continuum composed of the soil skeleton and the liquid phase. The MPM is applied to the governing equation of the solid phase by the Lagrangian description, whereas the stabilized FEM is applied to the governing equation of the liquid phase in the Eulerian frame. Also, a free surface is captured by using the phase-field method. In addition, MPM and FEM use the same spatially fixed grid, to which B-spline basis functions are introduced for spatial discretization.

For the second objective, since the original domain overlapping method only considers fluid flow and therefore uses the same low-order interpolation function for the 2D and 3D domains. However, the MPM-FEM hybrid method commonly uses high-order B-spline basis functions for both fluid and solid motions to suppress the cell-crossing error that often arises when using the MPM with low-order basis functions, while low-order interpolation is adopted for 2D SW simulations. Thus, the existing 2D-3D FEM cannot be applied as is unless the difference in interpolation orders is taken into account when passing variables. In this context, we proposed a new variable passing scheme in the domain overlapping method when combining the 3D MPM-FEM hybrid method for coupled soil-water analysis and the 2D FEM for SW analysis. Here, the modification to be highlighted against the original domain overlapping method is to properly pass the water level and flow rate in consideration of the difference in basis functions between the 3D and 2D analysis methods. Specifically, the mass and flow rate balances are imposed on the connection boundary between the 2D and 3D domains, on which the positions of control points of B-spline basis functions employed in the MPM-FEM hybrid scheme and those of nodes for linear basis functions for the 2D FEM are not necessarily coincident.

For the third objective, although we try to reproduce the large-scale simulation as closely as possible using the strategies mentioned above, it is important to note that the existing algorithms have not been fully optimized. As a result, we cannot fully maximize the advantages of parallel computing for optimal performance. In other words, we are limited to validating our proposed methods using data from small-scale laboratory experiments. In view of such issues, we introduce the dynamic load balancing technique for MPM to mitigate the computational imbalance between computed ranks caused by the unbalanced distribution of the material points as much as possible, while retaining the computed ranks for FEM unchanged since it tends to a relatively balanced domain decomposition during the calculation. The implementation of this strategy ensures that MPM and FEM can maximize and maintain their respective computing efficiency itself, thereby improving the computational efficiency of the whole algorithm.

The present dissertation is outlined as follows:

- **Chapter 1** give a detailed introduction and objectives of this study.
- **Chapter 2** presents an MPM-FEM hybrid analysis method for simulating granular mass-water interaction problems, in which the granular mass causes dynamic motion of the surrounding water. While the MPM is applied to the solid (soil) phase whose motion is suitably represented by the Lagrangian description, the FEM is applied to the fluid (water) phase that is adapted for the Eulerian

description. Also, the phase-field approach is employed to capture the free surface. After the accuracy of the proposed method is tested by comparing the results to some analytical solutions of the classical consolidation theory, several numerical examples are presented to demonstrate its capability in simulating fluid motions induced by granular mass movements.

- **Chapter 3** presents a 2D–3D coupling strategy to bridge 3D MPM–FEM hybrid and 2D SW simulations for reproducing the entire process of a landslide-triggered tsunami, ranging from tsunami generation to offshore wave propagation, with relatively low computational costs. Specifically, considering the difference in basis functions between the 3D and 2D analysis methods, we devise a novel variable passing scheme in the domain overlapping method, in which a slightly overlapped domain enables the generated wave to pass through the connection boundaries with as little discrepancy as possible. For the tsunami generation stage in the 3D domain, the MPM–FEM hybrid method is adopted. In this method, the 3D governing equation of the solid phase is solved with the MPM, whereas the well-established 3D stabilized FEM is applied to that of the fluid phase in an Eulerian frame. Additionally, the phase-field method is employed to track the free surface of the 3D fluid domain. On the other hand, the SW equation that represents the offshore wave motion in the 2D domain is solved by the 2D stabilized FEM. Several numerical examples are presented to demonstrate the effectiveness of the developed scheme in properly passing the data from 3D/2D to 2D/3D domains.
- **Chapter 4** presents a high-performance computing technique to speed up the 3D MPM–FEM hybrid method proposed in Chapter 2. For the solid phase, we introduce the dynamic load balancing (DLB) technique for MPM, which dynamically or adaptively adjusts the partition of the calculation domain based on the distribution of material points to mitigate the imbalance situation of the particles in all ranks throughout the calculation. For the fluid phase, we keep the size of the FEM computational ranks unchanged since the calculation of FEM in various ranks tends to be in a relatively balanced state. Several numerical examples are presented to verify the effectiveness of the DLB technique for the MPM–FEM hybrid method and its capability with a view to large-scale simulations.
- **Chapter 5** gives the concluding remarks and the future work.

論文審査結果の要旨

海底地すべりは、海底斜面上の堆積物が外力によって滑り落ちる自然現象であり、海底ケーブルや海底パイプラインの切断、大規模な津波の発生などを誘発する災害である。これらの問題の解決には、数値解析が重要な役割を担うことに疑う余地はない。本研究では、海底斜面の崩壊・流動とそれに伴う津波の発生、およびその後の津波伝播の連続したすべてのプロセスを精度よく表現するために、2D-3D 連成による地すべり誘発津波の MPM-FEM ハイブリッド解析手法を提案している。本論文の構成は以下の全 5 章になる。

第 1 章は緒言である。

第 2 章では、先行研究で課題とされていた流体の自由表面の数値不安定性、水圧の不安定性、高い計算コストなどの問題を克服するために、MPM-FEM ハイブリッド法を提案している。多孔質体理論に基づき、土・水混合体の挙動を飽和土の土骨格と間隙水に分離し、固相と流体相からなる 2 相の連続体の重ね合わせとして考えている。その際、固相には MPM を採用し、流体相には安定化有限要素法 (Stabilized FEM) を採用している。いくつかの実験の再現解析を通して提案手法の表現性能が例証されている。

第 3 章では、海底地すべりに起因した津波の再現解析の計算コストを削減するために、3 次元 MPM-FEM ハイブリッド法と 2 次元浅水長波 FEM の接続領域における変数の受け渡し方法を提案している。海底地すべりの発生とそれに伴う海面変動を 3 次元 MPM-FEM 連成解析手法で表現するのに対し、沖合領域での津波の伝播を 2 次元浅水長波で表現することで、いくつかの室内実験に対して精度の良い再現解析を実現している。

第 4 章では、3 次元 MPM-FEM 解析を高速化するために、最新の高性能計算手法を実装している。固相には動的負荷分散 (Dynamic Load Balancing) を実装し、粒子分布に応じて計算格子の領域分割を動的に変化させ、各プロセスが所持する粒子数を均等にすることによって計算量、通信量の偏りを解消することに成功している。一方、常に空間固定の均等格子で計算が行われる流体相は、プロセスに対する負荷の偏りは小さいため、動的負荷分散が不要であるが、B-spline 基底を用いる MPM との通信を工夫している。いくつかの数値解析例を通してこの高速化手法の有効性を確認している。

第 5 章は結論である。

本論文の以上の研究成果は、数値流体力学と固液連成現象の解析手法の発展に大きく寄与し、土木工学や計算科学の分野への貢献が大きいと判断される。よって、本論文は博士(工学)の学位論文として合格と認める。