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COUPLED SOIL-STRUCTURE INTERACTION MODELING AND SIMULATION OF LANDSLIDE PROTECTIVE STRUCTURES

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Abstract. Within the past two decades, mass movements hazards involving fast and large soil deformation have increased significantly in frequency and magnitude due to their strong relation to climate changes and global warming. These phenomena often bring along rocks, debris, and heavy materials that can extensively damage and destroy the landscape and infrastructures, causing devastating economic loss, and often, human casualties. The risk of future disasters continues to escalate with the increase of real estate development in suburban areas, including mountainous regions. Further assessment and prediction on such disasters and their countermeasures are, therefore, in high economic demands. One of the most intuitive ways is to install protective structures in mountain slopes and valleys that can hold the materials brought by the moving landslides. While the current state of the art of landslide prediction using numerical methods has been mainly dominated by the development of advanced geomechanical models suited for different types of soil materials, e.g. multi-phase unsaturated soil model, this study focuses more on the interaction of such phenomena with the installed protective structures. Here, an implicit formulation of material point method (MPM) is implemented to model the landslides considering finite strain assumption. Furthermore, a staggered coupling scheme with traditional Finite Element Method (FEM) is proposed to simulate accurately and robustly the dynamic force and displacement coupling of soil-structure interaction (SSI). All developments of the method are implemented within the *Kratos-Multiphysics* framework [1] and available under the BSD license (https://github.com/KratosMultiphysics/Kratos/wiki). In the future works, more adequate consideration of coupling scheme and material models considering damage and fracture will be investigated before conducting a real-scale landslide simulation.

1 INTRODUCTION

Landslides and other mass movements often carry huge rocks and heavy materials that may, directly or indirectly, cause damage to structures and the landscape. These phenomena are also extremely dangerous and often bring huge losses of lives and properties, resulting in a great economic loss, in particular, in rainy mountainous regions or in major earthquake zones. According to the United Nations Office for Disaster Risk Reduction (UNISDR) and the Centre for Research on the Epidemiology of Disasters (CRED), from 1998 to 2017 [2], landslides and other mass movement hazards have been responsible for 18,779 deaths worldwide, with more than 4.7 million citizens affected, and more than US$ 5.2 billion economic losses. The risk of future disasters is predicted to continue to escalate with the increase of real estate development in suburban areas, including mountainous regions. Even if nothing can be done in a short time to avoid the disasters, protection structures should be designed, or improved, as such that it can minimize the damage induced by the dynamic soil forces.

In this study, the dynamic interaction between landslides and protection structure is selected as a target issue, and it is numerically represented by using a staggered coupling of implicit Material Point Method (MPM) and Finite Element Method (FEM). Introduced by [3, 4] as the extension of Particle-In-Cell (PIC) method [5], the MPM has gained a remarkably increasing popularity due to its capability in simulating solid mechanics problems, which involve historically dependent materials and large deformations. As one of the fully Lagrangian particle methods which combines the strengths of Eulerian and Lagrangian methods, MPM has been utilized in various civil engineering applications, mostly in the analysis of moving discontinuities and large deformation systems such as the free-surface environmental flows with breaking, splash, and fragmentation; those which are difficult to simulate by using traditional FEM due to its mesh distortion issues.

Although MPM has been proven to work robustly for problems involving large deformation materials, the accuracy of the integration done in the particle quadrature is significantly lower than the Gaussian quadrature, which is used in the traditional FEM. It, therefore, produces less accurate and efficient solutions when being used to simulate problems with small deformation in comparison to the ordinary FEM. It is always desirable to combine the FEM with MPM to take respective advantages of these two methods, in particular for soil-structure interactions (SSI) problems.

The objective of this study is to develop an accurate implicit MPM formulation to simulate three-dimensional landslides and SSI considering a robust contact and coupling strategy. Although there were numerous research done to tackle large deformation soil and SSI problems by using MPM, almost all of them are formulated in an explicit way which is easy to implement and computationally less costly. There are, however, still limited research done for the implicit MPM formulation. By using the implicit approach, imposition of nonconforming boundary conditions can be done easily, such as by utilizing the penalty approach. Moreover, the formulation can be smoothly coupled with structural analysis studies by using purely MPM or coupled with other available methods suitable for structural analysis, such as FEM. To achieve the aforementioned motivation, the Kratos-Multiphysics proposed by [1], which is an open-source software available under the BSD license, has been used and continuously developed to treat multi-physics coupling phenomena. This framework allows us to establish a seamless coupling strategy between MPM and FEM, and possibly with other Lagrangian methods in the near future.

2 GOVERNING EQUATIONS

2.1 Strong Form

Consider a body $\mathscr{B}$, which occupies an initial domain Ω at time $t = 0$ of a three-dimensional Euclidean space $\mathscr{E}$, with a regular boundary $\partial\Omega$ in its *reference* configuration. A deformation of $\mathscr{B}$ is defined by a one-to-one mapping as:

$$\varphi : \Omega \to \mathscr{E} \, . \tag{1}$$

This maps each material point at initial configuration $\mathbf{X} \in \Omega_0$ in the body $\mathscr{B}$ into a spatial coordinate in *deformed* configuration $\mathbf{x} \in \Omega_t$ as:

$$\mathbf{x} = \varphi\left(\mathbf{X}\right) = \mathbf{x}\left(\mathbf{X}, t\right) \, , \tag{2}$$

which also represents the location of the same material point in the deformed configuration of $\mathscr{B}$. The region of $\mathscr{E}$ occupied by $\mathscr{B}$ in its new configuration can be denoted similarly by:

$$\Omega_t = \varphi\left(\Omega_0\right) \, . \tag{3}$$

The governing equations, i.e. the mass and the momentum conservation equations, can be written as:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} + \rho\nabla\cdot\mathbf{v} = 0 \qquad \text{in}\, \varphi(\Omega)\, , \tag{4}$$

$$\rho\mathbf{a} = \nabla\cdot\sigma + \rho\mathbf{b} \qquad \text{in}\, \varphi(\Omega)\, , \tag{5}$$

where $\mathbf{b}$ is the volume acceleration and σ is the symmetric *Cauchy stress* tensor. The kinematic variables $\mathbf{a}$ and $\mathbf{v}$, which are the second and the first material derivatives of displacement $\mathbf{u}$, are the acceleration and velocity, respectively. The balance equations above are to be solved numerically in a three-dimensional field $\Omega \subseteq \mathcal{R}$, within the time range $t \in [0, T]$, considering the following *Dirichlet* and *Neumann* boundary conditions:

$$\mathbf{u} = \bar{\mathbf{u}} \qquad \text{on}\, \varphi\left(\partial\Omega_D\right) , \tag{6}$$

$$\sigma \cdot \mathbf{n} = \bar{\mathbf{t}} \qquad \text{on}\, \varphi\left(\partial\Omega_N\right) , \tag{7}$$

where $\mathbf{n}$ is the outward surface unit normal vector, while $\bar{\mathbf{u}}$ and $\bar{\mathbf{t}}$ are the corresponding Dirichlet and Neumann boundary displacement and traction, respectively.

2.2 Weak Form and Linearization in Spatial Form

In order to solve the momentum balance equation, which was previously written in its *strong* or derivative form, the *weak* or integral form of equation (5) should be derived by employing the principle of virtual work [6]. To do that, equation (5) is, first, multiplied by an arbitrary *test function* $\mathbf{w}$, such that $\mathbf{w} = \{\mathbf{w} \in \mathscr{V} | \mathbf{w} = 0 \,\text{on}\, \varphi(\partial\Omega_D)\}$, where $\mathscr{V}$ is the *space of virtual displacements*. By using the divergence theorem the weak form of momentum balance can be obtained and written as:

$$R(\mathbf{u}, \mathbf{w}) \equiv \int_{\varphi(\Omega)} \sigma(\varepsilon(\mathbf{u})) : \nabla^s \mathbf{w} \mathrm{d}v - \int_{\varphi(\Omega)} \rho\left(\mathbf{b} - \ddot{\mathbf{u}}\right) \cdot \mathbf{w} \mathrm{d}v - \int_{\varphi(\partial\Omega_N)} \bar{\mathbf{t}} \cdot \mathbf{w} \mathrm{d}a = 0 \qquad \forall \mathbf{w} \in \mathscr{V} . \tag{8}$$

Equation (8) is valid for any kind of strain definitions, including the infinitesimal one. Since, in the current work, strong material and geometric nonlinearities are involved, a linearization of the weak form is, therefore, necessary, and thus, the Newton-Raphson method, which is based on Taylor's theorem, is used to approximate the solution iteratively. The algorithms of the solving strategy implemented in MPM fashion are explained in detail by [7, 8, 9] considering an implicit time integration scheme of the Newmark-beta method.

3 STAGGERED SOIL-STRUCTURE INTERACTION COUPLING

In the current study, a staggered two-way strongly coupled SSI scheme is implemented [10] considering a dynamic relaxation scheme. The SSI interface is implemented to first transfer the soil impact force acting on the structure $\mathbf{F}_{\mathrm{s}\to\mathrm{st}}$ to the structural solver. The force transferred will further cause deformation on the structure, and this deformation $\mathbf{u}_{\mathrm{st}\to\mathrm{s}}$ will be then sent back to the soil solver as a response to the given force. This process of transferring and receiving information, namely force and displacement, is then continued in an iterative loop until certain convergence criteria are satisfied, or until the maximum number of iterations is reached (see figure 1 for the illustrative description). Here, the convergence criteria must preserve the continuity of displacement and velocity (or the Dirichlet conditions) as well as the equilibrium of forces or tractions (the Neumann condition) at the boundary Γ between the structure and the soil domain. Here, a penalty-based method is utilized and proposed to impose inhomogeneous Dirichlet condition in the MPM and to approximate contact force at the SSI interface. Note that the discretization of the soil and the structural interface maybe nonconforming, as two different numerical methods are employed, i.e. the MPM and FEM, to discretize the soil and structural domain independently. Therefore, a mapping procedure between the two staggered systems [11] is needed to translate all the scalar or vector quantities required in the coupling.

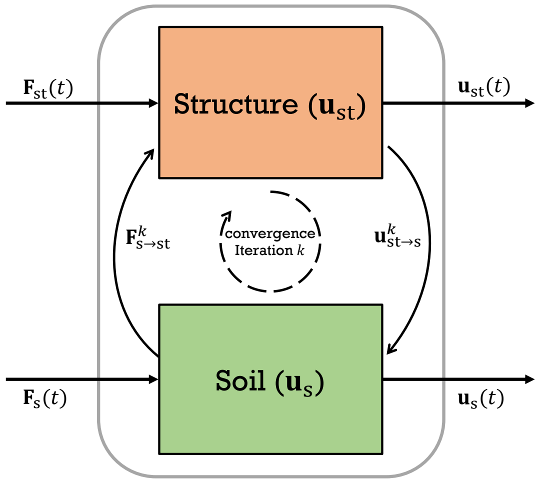

Figure 1: Two-way strongly coupled SSI: Schematic description.

4 NUMERICAL EXAMPLE

In order to test the performance of our staggered coupling of MPM with FEM a similar model to the one created by [9] is constructed by using the proposed SSI interface. The initial geometry for the staggered MPM-FEM coupling can be seen in figure 2. In this validation, the material parameters specified in table 1 is considered. Here, two tests with mesh size h = 0.005 and 0.0025 m are performed to check the mesh-convergence effect in comparison with the result obtained by [9].

The staggered coupling simulations are performed considering a strongly coupled formulation, where a series of iteration is performed to reach a certain convergence of Dirichlet and Neumann conditions at the soil-structure interface. For the MPM simulations, structured triangular meshes are used to generate particles, as such that the initial arrangement is the same with the monolithic SSI simulation done by [9], with MP/cell = 3, while, unstructured triangular background grids are used to perform the MPM computa-

Table 1: Granular flow simulations with an obstacle: Material data.

Material type	Density [kg/m^3]	Young's modulus [kPa]	Poisson's ratio	Friction angle [°]	Cohesion [kPa]	Dilatancy angle [°]
Soil	2650	840	0.3	19.8	0.0	0.0
Structure	1100	1000	0.0	Neo-Hookean hyperelastic material		

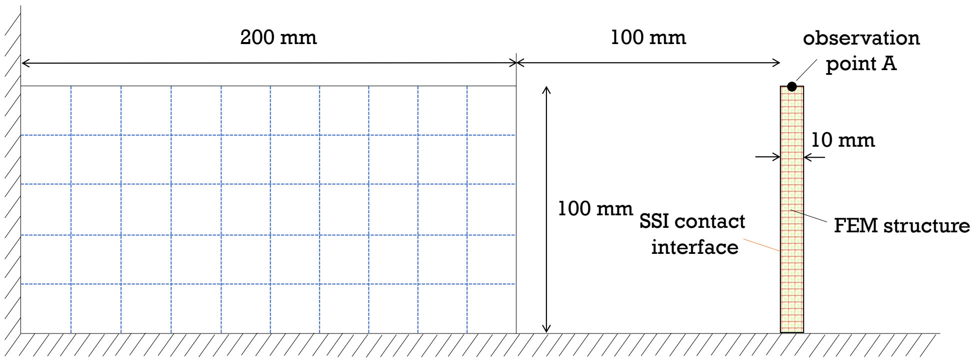

Figure 2: Granular flow simulations with an obstacle: Initial geometry for staggered MPM-FEM coupling.

tions. Moreover, as the approximated contact forces are often over-estimated at the first coupling iteration, a relaxation method based on the multi-vector update quasi-Newton (MVQN) approach [12] is assumed in this case to ensure and accelerate the convergence of the SSI iteration. Last but not least, for the strong coupling iteration settings, the maximum coupling iteration is set to be 20, and both of the absolute and relative tolerances are set to be 10^{-5}.

In figure 3 and 4, it can be observed that the simulation results show a very good qualitative agreement with the monolithic MPM-MPM SSI simulations done by [9] with respect to the conducted mesh convergence study. Here, the displacement of the staggered simulations, in particular for h = 0.0025 m, shows a higher peak than the one obtained by [9], even though at the end of the simulation the displacement shows a lower displacement. Moreover, the staggered SSI displacements also vibrate with higher amplitude and longer period. These differences in the obtained results are mostly caused by the different contact conditions assumed between the two coupling approaches. Unfortunately the current results are not yet validated with any experiments, and thus, further verification and validation test are planned to be performed in the near future.

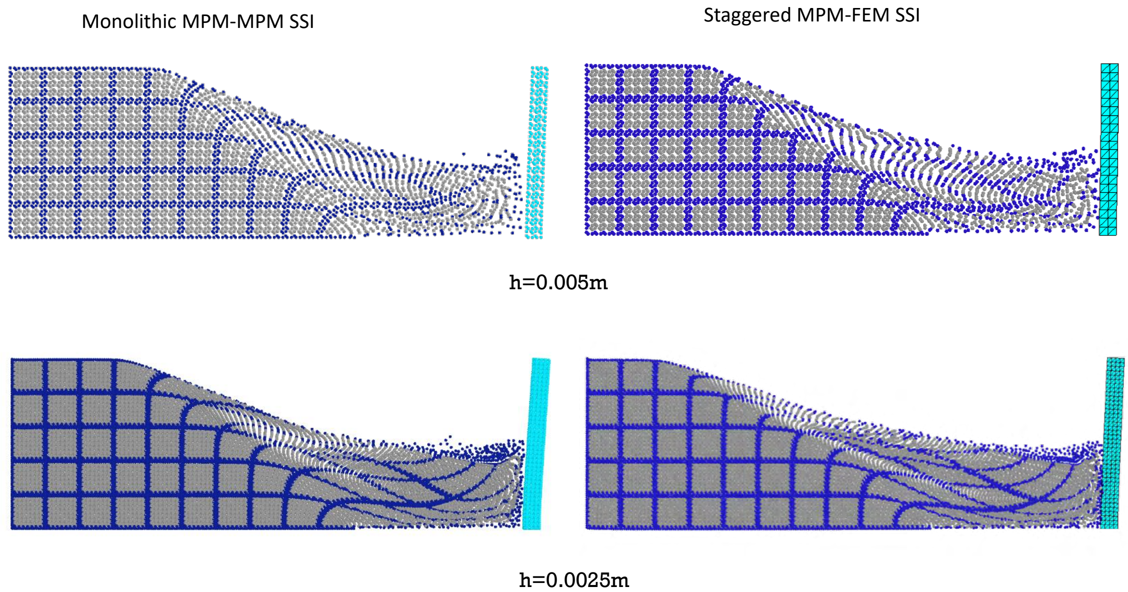

Figure 3: Granular flow simulations with an obstacle: Comparisons of deformed configuration at t = 0.5 s between the monolithic MPM-MPM [9] and the proposed staggered MPM-FEM SSI tests.

5 CONCLUSIONS

A staggered coupling scheme to simulate soil-structure interaction problems is presented in the current study by using a coupled implicit material point and finite element method. The staggered coupling technique allows us to utilize the best of each numerical method: the MPM for large and non-linear soil deformation, and the FEM for an accurate evaluation of structural dynamics. Implicit MPM can then be connected to the FEM to adequately simulate fast landslides hazards interacting with complex civil structures with protective purposes. Nevertheless, some future works are necessary to improve the accuracy and quality of the numerical results, such as by improving the numerical stability or reducing the computational cost of the simulations. This will allow to use out apporach to predict real-scale landslide hazards involving complex multi-phase flows of particles with different sizes.

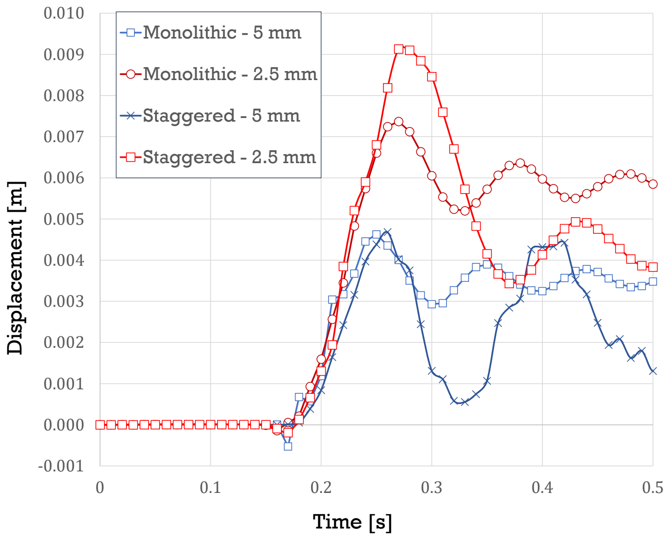

Figure 4: Granular flow simulations with an obstacle: Comparison of structural displacement at point "A" upon impact between the monolithic [9] and the proposed staggered SSI coupling.

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