Numerical Simulation of Landslides through a Stabilised Material Point Method with SANISAND Model

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Abstract

This research presents a new semi-implicit two-phase double-point MPM formulation for modelling large-deformation geotechnical problems such as landslides. The proposed method addresses instabilities in traditional single-point MPM by using distinct sets of material points to model the soil and water phases separately (double-point approach). A modified F-bar technique is derived to stabilise advanced soil constitutive models such as SANISAND, allowing for a more realistic simulation of soil behaviour. The water phase is solved implicitly, enabling significantly longer time steps compared to fully explicit MPM approaches. Landslide examples using the SANISAND constitutive model are presented in this paper, demonstrating the performance of the modified F-bar method and highlighting the importance of the double-point approach.

Introduction

The Material Point Method (MPM) has a very similar formulation to the Finite Element Method (FEM), except that the iteration points (called material points in MPM) are allowed to move independently from mesh, providing the ability of this method to solve large deformation problem without mesh distortion. MPM has become a popular method to solve the geotechnical problem of large deformation. However, the current literature usually uses a basic constitutive model (e.g. Mohr-Coulomb) with a single-point MPM (i.e. use a single layer of material points to represent both soil and water) to model the soil-water coupled problems. Also, instabilities in MPM are usually overlooked. To address these issues, we proposed a new stabilised semi-implicit two-phase double-point MPM formulation. In this paper, we present some numerical examples of landslides using the proposed method with the SANISAND constitutive model to highlight the importance of stabilisation and the double-point method. The details of mathematical derivation, stabilisation method, and validations can be found in our extended paper (Xie et al., 2024).

Numerical Simulations

The SANISAND constitutive model (Taiebat & Dafalias, 2008) is implemented. Fig. 1 shows the validation of the numerical implementation against the original paper. Taiebat & Dafalias (2008) calibrated a set of SANISAND parameters for Toyoura sand with the drained and undrained triaxial tests. We adopt the same parameters for Toyoura sand to study landslides under dry and fully saturated conditions, except that a strength reduction factor 2 is applied (i.e. the parameter $\alpha_c^c = 0.6$) to generate catastrophic landslides. In this study, we also use the following parameters: soil particle density is 2650 kg/m^3, the water density is 1000 kg/m^3, the initial void ratio is 0.65, the initial porosity is 0.4, and initial permeability is 5e10^{-3} m/s.

The geometry and boundary conditions are illustrated in Fig. 2. A 0.05 m wide square mesh with 3^2 material points per cell is used. Rollers and fixed boundary conditions are applied on the side and bottom of the background mesh, respectively. The initial stress conditions are obtained through a gradually increasing gravity load in 1 s while keeping the model elastic. After initialisation, the plasticity suddenly is allowed to generate landslides. The final simulation times are set as 3 and 5 s excluding the initialisation for the dry and fully saturated landslides, respectively. In these times, the movement of landslides becomes negligible.

Discussion and Conclusion

In the case of dry conditions, the performance of the newly proposed modified F-bar stabilisation (Xie et al., 2023; Xie et al., 2024) is evaluated. As shown in Fig. 3, the original F-bar method fails to stabilise the volumetric locking for the dilative SANISAND soil, resulting in even more instability compared with the case without stabilisation. In contrast, the modified F-bar method has excellent performance with SANISAND, and the stress contour becomes smoother after increasing the mesh density. However, a 0.05 m mesh is sufficient for this type of problem. Further refining the mesh does not increase the accuracy significantly, as shown in Figs. 3 (c) and (d).

For the fully saturated landslides, we compared the performance of semi-implicit single- and double-point MPMs. Both methods are stabilised with a modified F-bar method. Fig. 4 shows the simulations of both methods at the final stage. The single- and double-point MPMs generate significantly different results, as shown in Fig. 4. The single-point approach has an unrealistic settlement in the water field. In contrast, the water field in the double-point method is realistic and stable. The soil field (grey material points on the background) between the single- and double-point methods are significantly different as well. The single-point method is stiffer, resulting in an underestimated run-out distance and an overestimated repose angle. These phenomena are consistent with previous findings in MPMs with the Nor-Sand constitutive model (Xie et al., 2024). In addition, the double-point method only increases about 15% of the increment in total computational time.

References

Taiebat, M., Dafalias, Y.F. 2008. SANISAND: Simple anisotropic sand plasticity model. *International Journal for Numerical and Analytical Methods in Geomechanics* **32**(8): 915–948.

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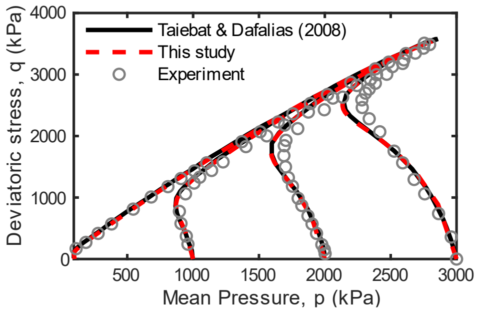

Figure 1. Validation of the SANISAND constitutive model: stress paths of the undrained triaxial test of Toyoura sand under different confining pressures

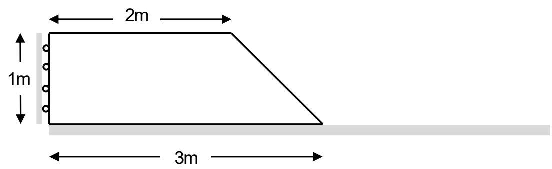

Figure 2. Graphical illustration of the numerical model

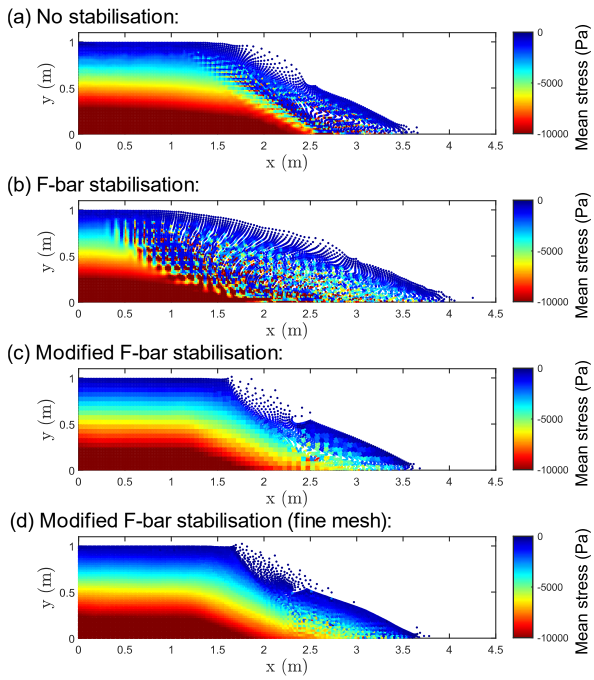

Figure 3. The stress contours of the landslides under dry conditions given by MPM with different stabilisations

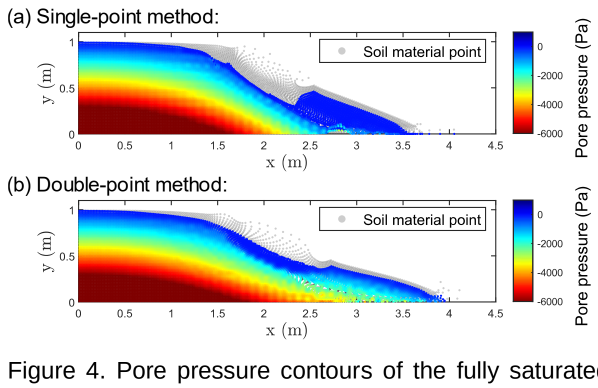

Figure 4. Pore pressure contours of the fully saturated landslides given by single- and double-point MPM