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Runout of submarine landslide simulated with material point method*

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Abstract: Most of the present knowledge on submarine landslides relies upon back-analysis of post-failure deposits identified using geophysical techniques. In this paper, the runout of slides on rigid bases is explored using the material point method (MPM) with focus on the geotechnical aspects of the morphologies. In MPM, the sliding material and bases are discretised into a number of Lagrangian particles, and a background Eulerian mesh is employed to update the state of the particles. The morphologies of the slide can be reproduced by tracking the Lagrangian particles in the dynamic processes. A real case history of a submarine slide is back-analyzed with the MPM and also a depth-averaged method. Runout of the slides from steep slopes to moderate bases are reproduced. Then different combinations of soil and basal parameters are assumed to trigger runout mechanisms of elongation, block sliding and spreading. The runout distances predicted by the MPM match well with those from large deformation finite element analysis for the elongation and block sliding patterns. Horst and grabens are shaped in a spreading pattern. However, the current MPM simulations for materials with high sensitivities are relatively mesh sensitive.

Key words: Submarine landslide, runout, morphology, material point method, large deformation

Introduction

Submarine landslides are one of the most hazardous geological threats to subsea infrastructure, since they can transport vast volumes of sediments across continental slopes. Velocities of the slides can be up to 20 m/s, reaching final runout distances of hundreds of kilometers[1]. Most of the present knowledge on submarine slide relies upon back-analysis of post-failure deposits identified using geophysical techniques. Although various conceptual models have been proposed to analyze the runout mechanisms of slides, work on the runout process and evolution of morphologies remains limited. A variety of failure patterns have been reported: retrogressive failure in the Storegga slide generated a series of grabens and ridges[2], failure starting from the toe and progressing towards the head scarps was found together with compressional and extensional distortion[3], and out-runner blocks were observed in the Tampen slide[4]. In this paper, the runout of submarine slides is simulated using the material point method (MPM). A real case history of a submarine slide is back-analysed with the MPM and also with a depth-averaged method (DAM). The runout morphologies predicted by the two methods are compared. Then different combinations of soil and seabed parameters are explored to trigger runout mechanisms of elongation, block sliding and spreading. The runout distances predicted by the MPM are compared with those from large deformation finite element (LDFE) analysis.

1. Methodology

The MPM, originating from the particle-in-cell method in computational fluid dynamics[5], can be regarded as a combination of finite element and meshfree methods. It possesses an inherent advantage for large deformation problems such as runout of landslides[6] and large-amplitude displacements of structural elements in soil[7], by means of discretising soil as Lagrangian particles. The material mechanical and kinematic properties (mass, volume, density, velocities, momentum, deformation gradients and stresses) are recorded and updated at the particles, and an Eulerian

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mesh is used for calculation in each incremental step only. Since the mesh is fixed in space, mesh entanglement such as occurs in conventional finite element methods is avoided. An in-house MPM program was developed, which stems from an open-source package Uintah[8] but was enhanced with a novel contact algorithm "Geo-contact"[9] and a GPU parallel computing strategy[10]. The updated Lagrangian calculation in explicit integration is based on the generalised interpolation material point method presented in Ref.[11].

The interaction between the slide and rigid base was considered with the "Geo-contact" by adjusting the nodal velocities of the slide. The slide and base might be in contact at specific nodes if both of their masses projected onto the nodes are non-zero. For a specific slide node in contact, the normal velocity v^n was eliminated, and the tangential velocity v^t was reduced by

$$\Delta v^t = \min\left(v^t, \frac{\tau A \Delta t}{m}\right) \tag{1}$$

where τ is the maximum shear stress on the interface, A and m are respectively the area and mass represented by the node, Δt is the time increment, determined through the Courant-Friedrichs-Lewy stability condition. In the following simulations, the tangential behaviour of the slide-base interface is regarded as: (1) No-slip: the slide is fixed at the interface with τ limited only by the strength of adjacent material. (2) Frictional: a maximum shear stress τ, potentially lower than the strength of adjacent material, is specified along the interface.

Strain-softening and rate-dependency of the undrained shear strength of slides are expressed in multiplicative (Eq.(2)) or additive (Eq.(3)) form according to

$$s_u = s_{u0}\left\{[\delta_{\mathrm{rem}} + (1-\delta_{\mathrm{rem}})\mathrm{e}^{-3\xi/\xi_{95}}] + \eta\left(\frac{\dot{\gamma}}{\dot{\gamma}_{\mathrm{ref}}}\right)^n\right\} \tag{2}$$

$$s_u = s_{u0}[\delta_{\mathrm{rem}} + (1-\delta_{\mathrm{rem}})\mathrm{e}^{-3\xi/\xi_{95}}]\left[1 + \eta\left(\frac{\dot{\gamma}}{\dot{\gamma}_{\mathrm{ref}}}\right)^n\right] \tag{3}$$

where s_{u0} is the threshold shear strength, δ_{rem} the strength ratio between the fully-remoulded and intact state (i.e., inverse of sensitivity S_t), ξ the cumulative plastic shear strain with ξ_{95} the plastic shear strain required to achieve 95% of remoulding, η the viscosity coefficient and n the shear-thinning index, $\dot{\gamma}$ the shear strain rate and $\dot{\gamma}_{\mathrm{ref}}$ the reference shear strain rate. In Eq.(2), strain-softening is only imposed on the threshold shear strength of the soil but not the rate-dependent portion[12]. This may be reasonable for a soil-fluid mixture, as strain-softening is considered for the soil and rate-dependency for the fluid. In contrast, the multiplicative expression in Eq.(3) implies that strain-softening is imposed on both the threshold shear strength and the rate-dependent portion. The two adjustments are therefore multiplicative in nature. This seems more appropriate for soil from a geotechnical perspective.

In all simulations with the MPM, a 4×4 particle configuration was allocated for each element fully occupied by particles prior to the calculation. The particle density was finer than the 2×2 particle configuration used in Refs.[9] and [10], to improve the numerical accuracy. The acceleration of gravity was $g = 9.81\,\mathrm{m/s^2}$. The Poisson's ratio of the soils was taken as 0.49 to approximate constant volume under assumed undrained conditions. The Young's modulus was taken as $100 s_{u0}$. The time step Δt was determined by a Courant number of 0.3.

The DAM uses layer-integrated governing equations to describe the conservation of mass and momentum[13], simplifying 2-D runout into a 1-D problem. This simplification is acceptable for large scale events, where shallow water approximations to the Navier-Stokes equations are acceptable for overall behaviour of the runout. This approach is especially attractive on computational efficiency, requiring orders of magnitude less effort than other approaches. The volume of mass is discretized into a number of Lagrangian elements, which are solved, for example, using an explicit time-marching finite difference scheme. Each element advances at the local layer-averaged velocity. The thickness of each element is computed at the midpoint, but the volume remains constant.

The large deformation finite element (LDFE) approach used in the following study is the one termed "remeshing and interpolation technique by small strain (RITSS)" developed at the University of Western Australia[14,15]. The basic procedure is to divide the runout of the slides into hundreds or thousands incremental steps. The time step must be sufficiently small that all slide elements maintain acceptable shape during each step, then an updated Lagrangian calculation in the implicit integration scheme is performed. After that, the deformed slides are remeshed and the stresses and material properties at integration points and the nodal velocities and accelerations are mapped from the old mesh to the new mesh. The commercial finite element package, Abaqus, was used to conduct mesh generation and Lagrangian calculations.

2. Back-analysis of a real case

A real case history of submarine escarpment failure in the southern Mediterranean (The information of