Role of hydraulic conductivity on the mechanism of earthquake induced submarine landslides – a CFD-MPM analysis

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**ABSTRACT:**

Submarine landslides can occur in soil types such as clay and sand. The failure mechanism and morphology of these two types of submarine landslides are quite different. Sand failures are typically characterized by sand flow slides, whereas clay failures are characterized by spread, which result from the dislocation and movement of soil blocks. There are significant differences between these types of submarine landslides due to the differences in hydraulic conductivity. It is hypothesized that that the hydraulic conductivity of soil layers is a critical factor in the failure mechanism of seismic-induced submarine landslides. It is, however, unclear how the hydraulic conductivity influences the failure mechanism of seismic induced submarine landslides. Utilizing an advanced numerical technique (coupled Computational Fluid Dynamics and Material Point Method), we simulate the full process of seismic-induced submarine landslides and examine the role of the hydraulic conductivity of the soil in their failure mechanism.

**Keywords:** submarine landslides, Computational Fluid Dynamics, Material Point Method.

# INTRODUCTION

Submarine landslides are a major concern in areas of high seismic activity, as they can cause significant damage to coastal infrastructure and lead to tsunamis. Simulating the full process of a submarine landslide is difficult. This is because sediments behave as solid materials when the slide is triggered and as fluid materials after the slide has failed. In recent studies, particle-based methods have been utilized to simulate submarine landslides, including the Material Point Method (MPM) (Shi et al., 2020), Smooth Particle Hydro Dynamics (Capone et al., 2010), Particle Finite Element Method (Zhang et al., 2019), or Coupled Eulerian Lagrangian method (Dey et al., 2016b). Yet, they used only total stress analysis in classical soil mechanics. As a result, we have yet to be able to quantify the role of hydraulic conductivity in the mechanism of earthquake-induced submarine landslides, even though it is a key factor that influences the failure mechanism of submarine landslides because it governs the change in pore water pressure in the sediment.

To investigate the role of hydraulic conductivity in the failure mechanism of seismic-induced submarine landslides, we adopt the current state-of-the-art numerical technique coupled CFD-MPM model (Tran et al., 2022). In a coupled CFD-MPM method, MPM is used to deal with large deformations in solids or porous media, while CFD is used to analyze fluid dynamics. The MPM model is used for modeling the seabed and debris flows, while the CFD model is used for modeling fluid dynamics (water and air). This method preserves the advantages of both CFD and MPM by combining them together. MPM is able to define more sophisticated solid/soil constitutive models, which are essential for the initiation mechanism of the flow. Through contact laws, such as Coulomb's friction, solids (MPM materials) interact. In a contrast, CFD is the most commonly used method for simulating complex viscous fluid flows involving turbulence (uniform fluctuations in flow) or hydroplaning (debris flows losing friction with the seabed). Overall, CFD-MPM model are able to capture complex mechanisms of the earthquake induced submarine landslides involving solid-fluid interactions.

# problem definition

We consider a base case in this study shown in Figure 1. A 20-meter long slope with a 45-degree gradient is placed within a horizontal and vertical structure. This structure was used as a shaking table to apply earthquake loading. To simplify earthquake loading, we simulated ground shaking for 20 seconds at a peak ground acceleration of 1g and a frequency of 2Hz (Figure 2). Ground motion is expressed in terms of velocity. A magnitude 6 or greater earthquake can produce a similar frequency and peak ground acceleration. In order to highlight the role of hydraulic conductivity on the failure mechanism of earthquake-induced submarine landslides, two simulations are analyzed, including (1) the low hydraulic conductivity case to mimic the clay behavior and (2) the high hydraulic conductivity case to mimic the sand behavior. The hydraulic conductivity is calculated based on the size of the soil grain, the viscosity of the fluid, and the porosity of the soil.

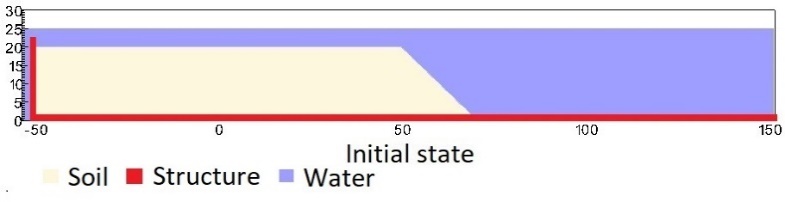
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Figure . Geometry of the base case slope

Chart

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Figure . Ground acceleration profile, frequency of 2Hz and magnitude of 1g

# COUPLED CFD-MPM ANALYSIS

## Soil-Water-Structure interaction

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Figure . Schematic of soil-water-structure interaction

We implemented the coupled CFD-MPM model in the Uintah computational framework (Tran et al., 2022) to capture the triple interaction between soil-water-structure. The CFD approach is derived from the implicit continuous-fluid Eulerian method (ICE). In ICE, all state variables are located at the cell/body centers. The state variables at cell centers are given in the vector form of the material *r* including mass, velocity, internal energy, temperature, pressure, volume fraction and specific volume. The MPM approach adopted the generalized interpolation technique from Bardenhagen and Kober (Bardenhagen & Kober, 2004). This method was validated with laboratory experiments (Tran et al., 2017a; Tran et al., 2017b) and large-scale landslide (Tran & Sołowski, 2019). To couple MPM with ICE, the state variables of MPM material points including mass, velocity, temperature and effective stress are mapped to cell centers using generalized interpolation technique. Then, the following governing equations are solved at the Eulerian background mesh:

*Mass Balance Equation*

|  |  |  |
| --- | --- | --- |
|  |  | (1) |

*Momentum Balance Equation for fluid*

|  |  |  |
| --- | --- | --- |
|  |  | (2) |

*Momentum Balance Equation for fluid*

|  |  |  |
| --- | --- | --- |
|  |  | (3) |

The last term is the momentum exchange between materials with dragging force . Apart from mass and momentum balance equations, we also solve the energy balance equations but not presented here in, all implicitly. This is also combined with the generalized Poisson’s equation to compute the fluid pressure for compressible fluid materials.

## Momentum Exchange

For the momentum exchange between fluid flows and porous media, we assume that the drag force is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (4) |

where is the average grain size of the grains, the solid volume fraction is , the fluid viscosity is , Re is the Reynolds number and the relative velocities of soil grains and fluid is . The function is given as:

|  |  |  |
| --- | --- | --- |
|  |  | (5) |

where the low Reynold coefficient is:

|  |  |
| --- | --- |
|  | (6) |

In case the Kozeny Carman formula is used. The hydraulic conductivity can be express as:

|  |  |  |
| --- | --- | --- |
|  |  | (7) |

Here the hydraulic conductivity can be controlled by adjusting the grain sizes. Two grain sizes are selected for the numerical analysis (1) = 0.5 mm and (2) = 1e-4 mm to mimic the hydraulic conductivity of sand and clay.

## Soil Models

A non-associated Mohr-Coulomb model is used for the soil, with a Young's modulus of 10 kPa and Poisson's ratio of 0.3 and zero cohesion. The mobilized friction angle is governed following the softening curve (Figure 4) with the peak friction angle of 45 degrees and the residual friction angle of 10 degrees. The mobilized dilatancy angle is calculated from the Row-stress dilatancy as follow:

|  |  |  |
| --- | --- | --- |
|  |  | (8) |

Shape, rectangle

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Figure . Mobilized friction angle in Mohr Coulomb model

The contact between horizontal plane and the soil is the frictional contact with the friction coefficient of 0.1. No artificial damping is applied in the simulation. The contact between vertical plane and the sand is considered to be smooth with zero friction coefficient.

## Fluid equation of state models

The equation of state establishes relations between thermodynamics variables. For the air, the equation of state for the perfect gas is adopted while for the water, a simple linear equation of state can be written as:

|  |  |  |
| --- | --- | --- |
|  |  | (9) |

where reference pressure = 1 atm = 101325 Pa, reference temperature = 10°C, reference density = 999.8 kg/m3, the bulk modulus of water = 2 GPa, and the water thermal expansion = 0.18 °C-1. This equation matches well with the state of the water (Figure 5).

Chart, scatter chart

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Figure . Equation of state for water

Under gravity, the density of the water at the surface is 999.8 kg/m3 at the pressure of 1 atm. At the top boundary, the air has a density of 1.17 kg/m3 at the atmospheric pressure of 1 atm. At 5 Celsius degrees, air and water have viscosity of 18.45e-3 mPa s and 1 mPa s respectively. On all boundary faces, the symmetric boundary condition is imposed, while the Neuman boundary condition is imposed at the top boundary for pressure (dp/dx = 0 kPa) and density (d/dx = 0 kg/m3). The mesh size is 0.25 x 025m with 300852 element cells and 142316 material points.

# Numerical Results

We compare simulations with the same input parameters except for the grain size Dp. For the high hydraulic conductivity cases (sand), the grain size is 0.5mm (= 0.5 mm) while for the low hydraulic conductivity cases, the grain size is 1e-4 mm ( = 1e-4 mm). For both cases, we demonstrate the entire process and the mechanism of earthquake-induced submarine landslides and draw attention to the differences in the mechanisms.

*Diagram

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*Figure 6. Shear strain development for high permeability and low permeability cases*

## High hydraulic conductivity case (sand)

As a result of the high hydraulic conductivity, the slope collapsed right after the initial seismic event, and the failure mechanism is classified according to the updated Varnes classification as a sand flow slide (Hungr et al., 2014). The slope inclination after the landslide is less than 10 degrees (around 8 degrees), which is equivalent to the residual friction angle of the soil after the landslide. It is important to note that the shear band keeps developing rapidly during the shaking and slowly after the shaking is over. There is a possibility that this is due to the secondary effect caused by the waves. The final inclination of the shear band is around 20 degrees (Figure 6).

It is estimated that the wave generated by the slide is around 2-3 m in the direction of the slide. In the event of landslides, the excess water pressure slighly changes during shaking. However, this pressure quickly returns to hydrostatic pressure due to the high hydraulic conductivity of the soil during landslides. (*Figure 7*).

## Low permeability case (clay)

For the case of low hydraulic conductivity, the first shear band developed right after the initial event of the seismic event. The failure mechanism in this case is characterized as spread according to the updated Varnes classification (Hungr et al., 2014). The mechanism involves the formation and dislocation of undisturbed soil blocks with inclined shear bands. Based on the simulation, the slide-scare morphology of the submarine clay slide was similar to the seabed morphology of the Storegga slide, which is known to be the world's largest landslide (see Figure 8).

*Graphical user interface, diagram, application, Word

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*Figure 7. Pore water pressure development for high permeability and low permeability cases*

In addition, we demonstrate the advantages of using effective stress analysis over total stress analysis when capturing the failure mechanism for the undrained clay slide. In the total stress analysis, one limitation is that the tip of the simulated horst was around 90 degrees (Dey et al., 2016a; Tran & Solowski, 2019) , whereas, in the field, this angle was approximately 60 degrees. Based on the numerical results, the tip of the simulated horst is approximately 60 degrees (see Figure 6).

The wave generated from slide is around 2-3 m towards the slide direction. Unlike the high hydraulic conductivity case, the negative excess water pressure was increase sharply during the onset of the shear band. This is a typical dilatancty behavior when the soil is sheared rapidly in the low hydraulic conductivity condition. After the seismic event, the excess pore water pressure continues to dissipate leading to the slow run-out of the debris materials continuing moving towards.

A close up of a snake

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Figure 8*.* Seabed near the Storegga slide area (Gauer et al., 2005)

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Figure 9*.* Tip of the horst on the field (Locat et al., 2015)

# ConCLUSIONS

We present a numerical approach that combines CFD-MPM to capture the complicated triple interaction between soil, water, and structure. We also show the completed process of earthquake induced submarine landslides including (1) earthquake triggering mechanism, (2) the onset of the shear band with the development of pore water pressure, (3) progressive failure mechanism, and (4) submarine landslide induced wave to final deposition.

The hydraulic conductivity also plays an important role in the failure mechanism of earthquake-induced submarine landslides. As a result of the high permeability of the material, the mechanism is characterized as a sand flow slide with rapid movement of the saturated debris material. When hydraulic conductivity is low, the mechanism is characterized as a spread with the dislocation and formation of soil blocks. We also capture a more realistic tip angle of the horst in comparison to the one-phase model previously presented.

This research can be used to better understand the failure mechanisms of submarine landslides and to develop better methods for predicting and mitigating their potential damage. It is necessary to conduct further research in order to better understand the complex relationship between hydraulic conductivity, soil properties, and the failure mechanisms of submarine landslides, in order to improve the prediction of landslide susceptibility and to improve coastal zone management.

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