Analysis of the Structure Suffered Submarine Landslides Using SPH and CEL Methods

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Abstract. Study shows that the submarine landslides have greatly affect the stability and security of subsea production systems, subsea pipelines and other marine structures. Landslides can also take place even though the slope angle is less than 1 °. At present the study of onshore landslide is more, but the study of submarine landslides are very few. The landslides mainly deal with the issues of stability. The analysis of landslide stability mainly use the Galerkin method, discrete element method, SPH and so on. But there is less research on the influence of the subsea structures. When the landslide occurs, fluid characteristics of the landslide are significant, the soils translate into mudflow or debris flow, which is not solid state but fluid. So both SPH and CEL can be used for simulation, this paper uses the CEL and SPH to study the submarine landslide, the comparative analysis of the advantages and disadvantages of both methods is taken on. Both methods are introduced at first, then through calculation, compares the two kinds of calculation methods. It can be seen that the SPH method and the CEL method are basically consistent with the shape of the landslide mass. It shows that both methods are feasible. The results of CEL method is more accurate. When the number of elements of SPH and CEL is few, the calculation time of SPH is shorter than that of CEL, but with the increase of element number, the calculation of the CEL method is more faster. If stress value of Lagrangian structure is required, it is better to choose CEL method. It is useful to further study on submarine landslides on subsea structures.

1. Introduction
Oil and gas developments often require placing subsea equipment, e.g., subsea wells, pipelines and flowlines, foundation systems for floating structures, in areas with sloping seafloors. Submarine slope failures can occur in such areas and create soil slides. Thus we must be concerned about submarine landslides. There are two issues that we need attention, one is the stability of submarine slopes, the other is the effects of submarine landslides on subsea structures. Both issues must be considered in selecting the site for installing and designing seafloor equipments. Slope stability analyses were performed to assess the likelihood of slides being triggered by gravity, rapid sedimentation (underconsolidation) and earthquakes. The analyses revealed that it is unlikely that most of the seafloor slope failures were triggered by gravity loads. Earthquake loading was confirmed as a common trigger, and rapid sedimentation (underconsolidation) was also a likely trigger of many slope failures. It is important to note that the study revealed that a relatively large number of submarine slides occurred on much flatter (less than 10 degree) slopes and traveled much greater distances than slope failures on land[1]. Hydroplaning is one mechanism that may explain such large runout distances[2]. Submarine slides will cause damage to distant subsea equipments. So it should be
clear that once the submarine landslide occurs, how much impact of submarine structures because of the instability of rocks and soils. After the landslides, the soils translate into mudflow or debris flow gradually, and evolve into turbidity finally. It is not solid state but fluid. Both smoothed particle hydrodynamics (SPH) [3] and Coupled Eulerian-Lagrangian (CEL) [4] can be used to describe fluid, so this paper will discuss the influence of landslides on subsea structure by both methods.

2. SPH Method

The SPH method has received substantial theoretical support since its inception (Gingold and Monaghan, 1977) [3]. SPH (smoothed particle hydrodynamics) method, a pure Lagrangian, meshless hydrodynamics method, has been widely applied in numerical simulations in many engineering fields. SPH is a numerical method which is belong to one of meshless (or mesh-free) methods. For these meshless methods, the nodes and elements must not be defined as we normally do in a FEA; instead, only a collection of points are necessary to represent a given body. In smoothed particle hydrodynamics these nodes are commonly referred to as particles or pseudo-particles [5].

SPH is a fully Lagrangian modeling scheme permitting the discretization of a prescribed set of continuum equations by interpolating the properties directly at a discrete set of points distributed over the solution domain without the need to define a spatial mesh. The method's Lagrangian nature, associated with the absence of a fixed mesh, is its main strength. Difficulties associated with fluid flow and structural problems involving large deformations and free surfaces are resolved in a relatively natural way. At its core, the method is not based on discrete particles (spheres) colliding with each other in compression or exhibiting cohesive-like behavior in tension as the word particle might suggest. Rather, it is simply a clever discretization method of continuum partial differential equations. In that respect, SPH is quite similar to the finite element method. SPH uses an evolving interpolation scheme to approximate a field variable at any point in a domain. Smoothed particle hydrodynamic analyses are effective for applications involving extreme deformation. Fluid sloshing, wave engineering, ballistics, spraying (as in paint spraying), gas flow, and obliteration and fragmentation followed by secondary impacts are a few examples. There are many applications for which both the coupled Eulerian-Lagrangian and the smoothed particle hydrodynamic methods can be used [6-9]. In many coupled Eulerian-Lagrangian analyses the material to void ratio is small and, consequently, the computational effort may be prohibitively high. In these cases, the smoothed particle hydrodynamic method is preferred. For example, tracking fragments from primary impacts through a large volume until secondary impact occurs can be very expensive in a coupled Eulerian-Lagrangian analysis but comes at no additional cost in a smoothed particle hydrodynamic analysis.

SPH method was a newly emerged method for the applications in the geotechnical engineering fields [8]. In abaqus, the finite element model (Figure 1) can be converted into the SPH model (Figure 2) easily.

3. CEL Method

In the ninetieths Lagrangian and Eulerian approaches were combined together in the new approach called coupled Eulerian-Lagrangian (CEL) [4]. The CEL method was initially applied to fluid-structure interaction problems. Coupled Eulerian-Lagrangian approach may be also applied to geotechnical problems [10].
If a continuum deforms or flows, the position of the small volumetric elements changes with time. These positions can be described as functions of time in two ways: (a) Lagrangian description: the movement of the continuum is specified as a function of its initial coordinates and time. (b) Eulerian description: the movement of the continuum is specified as a function of its instantaneous position and time.

In simulations with Lagrangian formulation the interface between two parts is precisely defined and tracked. In these simulations large deformation of a part leads to hopeless mesh and element distortion. In Eulerian analysis a Eulerian reference mesh, which remains undistorted and does not move, is needed, to trace the motion of the particles. The advantage of a Eulerian formulation is that no element distortions occur. Disadvantageously, the interface between two parts cannot be described as precise as if a Lagrangian formulation is used. Numerical diffusion can happen during the simulation [11].

In a traditional Lagrangian analysis nodes are fixed within the material, and elements deform as the material deforms. Lagrangian elements are always 100% full of a single material, so the material boundary coincides with an element boundary.

By contrast, in an Eulerian analysis nodes are fixed in space, and material flows through elements that do not deform. Eulerian elements may not always be 100% full of material—many may be partially or completely void. The Eulerian material boundary must, therefore, be computed during each time increment and generally does not correspond to an element boundary. The Eulerian mesh is typically a simple rectangular grid of elements constructed to extend well beyond the Eulerian material boundaries, giving the material space in which to move and deform. If any Eulerian material moves outside the Eulerian mesh, it is lost from the simulation.

Eulerian material can interact with Lagrangian elements through Eulerian-Lagrangian contact; simulations that include this type of contact are often referred to as coupled Eulerian-Lagrangian (CEL) analyses. This powerful, easy-to-use feature of Abaqus/Explicit general contact enables fully coupled multi-physics simulation such as soil-structure interaction.

Eulerian analyses are effective for applications involving extreme deformation, up to and including fluid flow. Eulerian-Lagrangian contact allows the Eulerian materials to be combined with traditional nonlinear Lagrangian analyses.

For general geotechnical problems, a Lagrangian mesh is used to discretize structures, while a Eulerian mesh is used to discretize the soil (Figure 3). The interface between structure and soil can be represented using the boundary of the Lagrangian domain. The Eulerian mesh, which represents the soil that may experience large deformations, has no problems regarding mesh and element distortions.

4. Comparative Analysis of Both Methods

The numerical model is established by ABAQUS software. The slope angle of landslide is 60°, the soil density is assumed to be 2.0g/cm³, the friction angle is 20°, and the cohesion is 6.19kPa. Assuming that the structure is an elastic steel tube with a density of 7.85g/cm³, the SPH model and the CEL model are established respectively, as shown in Figure 3 and Figure 4. Both model sizes and the material parameters are the same. And the number of elements divided is the same.

One of the differences between the submarine landslides and landslides on land is that the submarine landslides may have hydroplaning effect, which causes submarine landslides have large runout distances because of low friction in the process [2]. So for the convenience of calculation, the seabed is set rigid body, and ignore the friction between the seabed and landslide mass.

The submarine landslides modeled with particles and CEL interact with the subsea structure modeled with finite element via contact. The contact interaction is the same as any contact interaction between a node-based surface and an element-based. Both general contact and contact pairs can be used. And apply gravity to the the whole models.

For CEL, The subsea structure is modeled with conventional Lagrangian continuum elements with reduced integration (S4R), which is a 4-node doubly curved thin shell, whereas the soil body is meshed using Eulerian elements (EC3D8R), which is a 8-node linear eulerian brick, reduced integration hourglass control.

For SPH, The subsea structure is modeled with conventional Lagrangian continuum elements with reduced integration (S4R), whereas the soil body is meshed using PC3D. Rigid body structures are established to Limit particle overflow.
The results obtained by both methods are shown in Figure 5 and Figure 6. The deformation of the landslide mass obtained by both methods at the same time is shown in the following figures.
Figure 5. Comparison of calculation results (side view).

Figure 6. Comparison of calculation results (vertical view).

It can be seen that SPH and CEL are basically consistent with the shape of the landslide mass calculated at the same time. The simulation calculation result is coincidence with the actual state. The following Figure 7 shows the stress time history curves of the same node on the subsea structure affected by landslide, which is calculated by the two methods.

Figure 7. Stress comparison of the same node.

As shown above, the Mises stresses of the same node have the same trend. With the impact of the landslide, the stress increases gradually, reaches the peak and then decrease. But there are also obvious differences between both results. The stress curve calculated by SPH vibrates greatly. There are noticeable noises. But the stress curve calculated by CEL relatively smooth. The maximum stress calculated by SPH is much larger. The stress peaks calculated by SPH appear earlier, and then the stress is lowered and increased again. The stress decreases after the second peak points. But there is only one stress peak for the CEL results. The curve obtained by CEL method is smoother, and there is no maximum change. From the result, it can be concluded that the CEL calculation is reasonable relatively.
As shown Stress nephogram of structure (Figure 8), the maximum stress position calculated by CEL remains in one spot, which is located near the root of the structure faced to the landslide. But the maximum stress position calculated by SPH is in the different positions, and irregular position change. The table (Table 1) and figure (Figure 9) below shows the calculating time difference between the two methods.

**Table 1.** Comparison of the CPU time.

| Method | Step time | Element | CPU time |
|-------|-----------|---------|----------|
| CEL   | 0.1       | 12      | 239.6    |
| SPH   | 0.1       | 12      | 164.8    |
| CEL   | 0.1       | 24      | 1143.4   |
| SPH   | 0.1       | 24      | 1429.5   |

![Figure 8. Stress nephogram of structure.](image)

Figure 8. Stress nephogram of structure.

When the number of elements of SPH and CEL is few, the CPU time of SPH is shorter than that of CEL, but with the increase of element number, the SPH method will spend more time than the CEL method.

The following figure (Figure 10) shows the contrast of result with different mesh number.

![Figure 9. CPU time of different mesh number (SPH and CEL).](image)

Figure 9. CPU time of different mesh number (SPH and CEL).
After the mesh refinement, the distribution is more regular. At the same time, it also shows that the Mises stress of SPH is lower, and is closer to the result of CEL calculation. As shown in Figure 11 and Figure 12, by comparing the stress value of the same node under the condition of the different number of elements, it can be seen that the finer the mesh, the smaller the value.

As shown in the above, for SPH, although after refined mesh stress is reduced, but the results still have more noise. So if stress value of Lagrangian structure is required, it is better to choose CEL method.

5. Conclusions

It can be seen that the SPH method and the CEL method are basically consistent with the shape of the landslide mass. The computational result is coincidence with the actual state. Both methods can be good computation tools for the submarine landslides simulation. The Mises stresses of the same node have the same trend, but under the condition of the same elements number, the results of CEL method is more accurate.

When the number of elements of SPH and CEL is few, the calculation time of SPH is shorter than that of CEL, but with the increase of element number, the calculation of the CEL method is more faster. And if stress value of Lagrangian structure is required, it is better to choose CEL method.
This paper try to discuss the calculation method of the influence of the structure due to the landslide, which is useful to further study on submarine landslide on Subsea structures.

6. References

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