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To cite this article: KCh Kozhogulov et al 2018 IOP Conf. Ser.: Earth Environ. Sci. 134 012032

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Prediction of slope stability based on numerical modeling of stress–strain state of rocks

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Abstract. The paper presents the developed technique for the estimation of rock mass stability based on the finite element modeling of stress–strain state of rocks. The modeling results on the pit wall landslide as a flow of particles along a sloped surface are described.

The National Security Concept approved by the President of the Kyrgyz Republic on June 12, 2012 points at the risk of increase in number and scale of natural and induced emergencies. Also, it is emphasized that the methods and means currently available for responding and preventing such emergencies display insufficient efficiency.

Today, there are more than 5000 landslide-hazardous sites revealed in the Republic. Landsliding initiates both on natural mountainsides and on slopes of technical structures. Out of a few open pit mines in the Republic, Kumtor gold mine is the largest. It is highly important to ensure stability of pit walls, dumps and embankments. Moreover, it is necessary to maintain steadiness of canyons and hydroelectric dams. Naturally, it is required to predict stability of artificial slopes along mountainous roads in the country.

The landslide on the slope of Bishkek–Balykchy road on August 12, 2015 inflicted considerable damage to economy. By a lucky chance, no people were injured in that accident on the road with the heaviest traffic between two regions and the capital of the country.

\textbf{Figure 1.} Landslide, Bishkek–Balykchy road.
The Kyrgyz-Russian Slavik University develops a rock mass stability estimation procedure based on numerical modeling of stress state of rocks. Modeling involves the finite element method. The calculation uses a multi-processor computation cluster (super computer), which enables solving complex spatial and dynamic problems.

Landslide simulation is performed with the designed software system *LandslideModeller*. This system is mean for numerical modeling of slides and falls using structural dynamic equations discretized in space. To check the landslide prediction reliability, *LandslideModeller* algorithms were tested with the known numerical solutions from the available mathematical models of landslide processes.

The mathematical models available for calculating velocities and amplitudes of displacements [1–3] are grouped with regard to approaches to the mechanism of slide initiation and growth: я оползней:

— viscoplastic medium models;
— hydraulic models;
— granular medium models.

Small mud slides are described by the first group models. The second group models use complicated equations including dry friction between slide layers and friction between the slide body and floor. The common feature of the models in this group is the representation of a slide flow by a liquid with non-Newtonian properties. Such models sufficiently accurately describe flows saturated with clay or mud, with well coherent particles which cannon collide. The models based on the theory of granular media [4–6] use an assumption that a slide flow is composed of separate particles (grains) of different size. A granular medium is a set of discrete particles subjected to satisfy conditions that:

— the particles are sufficiently many to generate a flow;
— the high concentration of particles ensures their frequent collisions.

Within the period of interaction between particles, their collision is represented by a damping system of mass and spring with friction oriented along a line tangent to the contact point of particles. Motion of each particle in the landslide flow is described by the second-order differential equation with regard to the contact interaction of particles and taking into account external bulk forces. The effective friction coefficient is an increasing function of shear velocity, and material, which lays atop landslide at the beginning of the process, remains atop in the end of landsliding. In full scale conditions, this statement is valid for large particles on the surface of landslide at the beginning of its displacement. More complex models of granular media take into account interaction of particles depending on which forces—viscous or colliding—have higher influence on the landslide flow dynamics.

In the given study, landslide was modeled as a flow of particles over an inclined surface. Initially, it is assumed that the displacing portion splits into flow of particles downward the slope. Interaction with air on side edges is negligible. The flow motion is subjected to the force of gravity. The external mass inflow is assumed absent. The landslide motion is described using the system of Navier–Stokes equations and the law of mass conservation [7–8]:

\[
\begin{align*}
\frac{Du}{Dt} + \frac{1}{\rho} \frac{\partial P}{\partial x} &= \mu \nabla^2 u, \\
\frac{Dv}{Dt} + \frac{1}{\rho} \frac{\partial P}{\partial y} &= \mu \nabla^2 u, \\
\frac{Dw}{Dt} + \frac{1}{\rho} \frac{\partial P}{\partial z} &= \mu \nabla^2 u + g, \\
\frac{D\rho}{Dt} &= 0,
\end{align*}
\] (1)
where \( x, y, z \)—Cartesian coordinates; \( u, v, w \)—components of the velocity vector \( \mathbf{u} \); \( t \)—time; \( \rho \)—flow density; \( P \)—pressure; \( \mu \)—viscosity; \( g \)—acceleration of gravity.

The particle-in-cell method transforms basic motion equation to the equations for interacting particles. It is assumed that all interactions between particles are limited to a finite volume \( r_e \), and no interaction takes place beyond this radius. In this case, computational complexity of recalculating an unknown function at each time step equals \( O(NM) \), where \( N \)—total number of particles; \( M \)—number of interacting particles. The unknown function is presented as a finite sum of Dirac’s functions \( \delta \):

\[
\phi(r) = \sum_{i}^{M} m_i \frac{\rho_i}{\rho_i} \delta(x-x_i),
\]

where \( m_i, \rho_i, x_i \)—mass, density and position of a particle \( i \), respectively.

In accordance with Eq. (2), the slide flow density is given by:

\[
\rho(r) = \sum_{i}^{M} m_i \delta(x-x_i).
\]

The pressure of the landslide flow is calculated using the equation of state:

\[
P = P_0 + k (\rho - \rho_0),
\]

where \( P_0, \rho_0 \)—pressure and density of landslide in rest.

For the momentum conservation equation, it is necessary to express a gradient’s operator and a Laplace operator used to calculate forces of pressure and viscosity applied to particles. The pressure and viscosity forces are given by:

\[
F_{i}^{\text{press}} = \sum_{j}^{M} m_j \frac{P_j + P_i}{2 \rho_j} \nabla \delta_{\text{press}}(r_i - r_j),
\]

\[
F_{i}^{\text{visu}} = \mu \sum_{j}^{M} m_j \frac{u_i - u_j}{\rho_i} \nabla \delta_{\text{vis}}(r_i - r_j),
\]

where \( r_i, r_j \)—positions of interacting particles \( i \) and \( j \), respectively.

The weight functions for the pressure, viscosity and other members are calculated as:

\[
\nabla \delta_{\text{press}}(r) = \frac{45}{\pi r_e^6} (r - \frac{r^3}{3}) \frac{r}{r_e^4},
\]

\[
\nabla \delta_{\text{press}}(r) = \frac{45}{\pi r_e^5} (r - \frac{r^3}{3}) \frac{r^4}{r_e^5},
\]

\[
\delta(r) = \frac{345}{64 \pi} (r^2 - \frac{r^4}{4})^3.
\]

Beyond the radius of interaction between particles, \( r_e \), all functions equal zero. The boundary conditions are materialized with the help of immobile boundary particles. It is assumed that the flow particles locate at a distance \( d \) from the boundary particles. A particle \( i \) approaching the boundary closer than \( d \) is assumed to undergo the force of pressure in the line \( \hat{n}(r_i) \) from the side of the boundary particle. In this case, the force of pressure is:

\[
F_{i}^{\text{press}} = m_i \frac{\Delta t}{dt^2} = m_i \left( d - \left| \frac{r_i}{r_i} \right| \right) \frac{\hat{n}(r_i)}{dt^2},
\]

where \( \left| \frac{r_i}{r_i} \right| \)—distance between particle \( i \) and the boundary particle.

This method needs no smooth solution and uses a nonuniform 3D grid for the modeling. Each time iteration includes the sequence of steps:
—determination of interaction radius \( r \) for each particle;
—calculation of flow density and particle velocities;
—recalculation of particle positions by the Euler scheme.

The algorithm has been implemented and then used for the 3D discrete modeling of landslide flow motion (Figure 2). The profile of the landslide is presented be a set of elements. The frontal plane of the landslide is inclined to horizon at an angle of 45º, the grains are 0.5 m in size. The maximum horizontal displacements are generated at the right bottom of the frontal plane of the landslide in all stages of the flow development. The maximum vertical displacements are observed in the upper portion of the model.

The displacements change their relative values as the landslide develops. The horizontal displacements exceed the vertical movements in the initial stages of the landslide activation, which the vertical displacements dominate over the horizontal displacements later on. Figure 3 demonstrates the results of modeling pitwall landslide.

Figure 2. Modeling landslide motion in the PIC method.

Figure 3. Modeling pitwall landslide.
Conclusion
The authors have developed the procedure to model landslide motion without the requirement of the solution smoothness and applicable with the nonuniform spatial grid. The modeling procedure makes it possible to estimate stability of a landslide, its volume and flow distance. Using the procedure, 3D discrete modeling of landslide and fall of pitwall has been carried out.

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