

投稿論文 (英文)
PAPER

LANDSLIDE PROCESS SIMULATION OF THE CLAYEY SLOPE WITH SAND LENS

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Failure process and large scale material movement of landslide, caused by the presence of a sand lens in the undercut clayey slope, at Ubilci (Yugoslavia) is analyzed by the Extended Distinct Element Method (EDEM). Magnitude of the landslide process caused by changeable clay cohesion during dry and wet season is studied for two hypothetical values of clay cohesion, high and low. The numerical results obtained are in good agreement with the failure surface and the shape of the slope of a real case landslide occurred at Ubilci (Yugoslavia).

Key Words: *extended distinct element method, landslide process, sand lens, clay cohesion, failure surface.*

1. INTRODUCTION

Many cases of landslides in Serbia (Yugoslavia) occur in Neogen clay sediments (Fig.1). These sediments caused that the whole area from the right banks of the rivers Danube and Sava to the central part of Serbia where many settlements and towns like Belgrade, Obrenovac, Smederevo and Pozarevac are located, is endangered by landslides. The same is true of the industrial facilities and infrastructure. The specific characteristics of the Neogen clay sedimentation are occasional appearance of small or big sand segregations in the lens form. This kind of sedimentation sometimes triggers landslide occurrence on slopes, which can be further prompted by human activities that contribute to the destabilization process. In the case of engineering activities, such as undercutting, there is high possibility of the landslide occurrence in the clayey slopes with sand lens. The landslide that is analyzed occurred after artificial undercutting of a clayey slope with sand lens in it, at Ubilci, Yugoslavia, in 1982 (Fig.2).

Different methodologies are used in slope and landslide investigations to define failure surface and shear strength. Various kinds of classical methods (infinite slope analysis¹⁾, 'ordinary' slices method^{8,10)},

etc.), as well as numerical FEM (Finite Element Method)^{4, 12)}, and probabilistic methods¹¹⁾ are applied to analyze shear stress concentration and predict the position and geometry of the failure surface in a slope. These kinds of analysis encounter many difficulties, especially if they consider the large area involved in the process of landslide. Different layers, with inner heterogeneity accompanied by complicated inter-stratific relations demand many approximations during failure surface investigation. Crack propagation and material movement during the landslide process, as well as final geometry of a slope after landslide occurrence, can not be analyzed by FEM or any of the other methods.

In this study, EDEM (Extended Distinct Element Method), a new numerical methodology that provides analysis of the failure process and final failure surface in a slope, as well as material movement and final geometry of the slope after landslide process, is introduced.

2. SAND LENS AND THE PROCESS OF LANDSLIDE

(1) Sand lens

Sand material can appear in layer and bar form, and also in the form of a lens, a so-called "sand

lens". Dimensions of sand lenses vary, from few tens to few hundreds of meters. A sand lens, like other sedimentological forms of sand material, is formed in the continental and continental-margin basins.

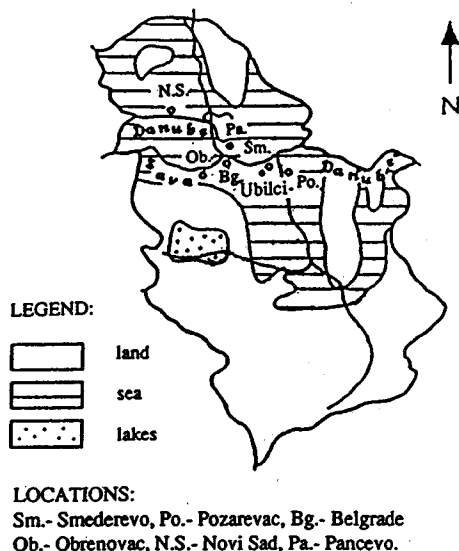


Fig. 1 Paleogeographic map of Neogen (Serbia).

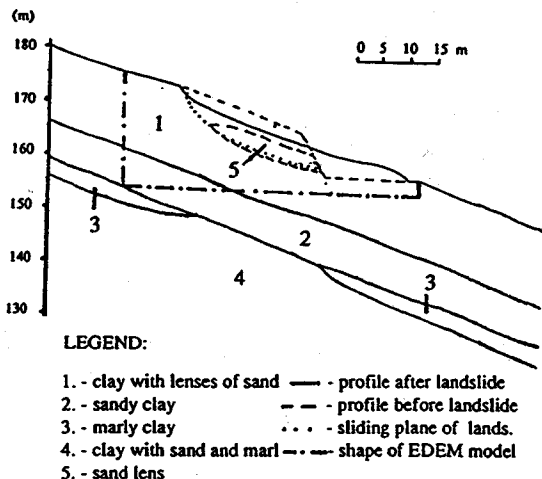


Fig. 2 Profile of slope Ubilci after landslide occurrence (1982).

Distribution and dimensions of sand lens segregations are caused mainly by the session variation of energy flow in rivers and deltas. It is a specific characteristic of continental margin basins that the changeable energy flow of transported material in the wide offshore area leads to a situation where the lithofacies of gravel, sand and clay

material vary respectively in the width as well as distance from the coast. Because of that, the sand lens as a specific sedimentological form with small dimensions can appear surrounded by gravel or clay facies, especially in the zone between sand and gravel, and sand and clay lithological facies. The same type of sedimentary process occurred in Yugoslavia during the Miocene and younger Neogen periods, with the deposit of clay material that occasionally incorporates sand lenses (Fig. 1). Consequently to the lithological base in this area, there are many landslides. Usually, they occurred because of the low shear clay resistance, but a certain number are caused by the presence of sand lenses in the clay material. A special case was the landslide that occurred in Ubilci (1982), after undercutting a clayey slope incorporating a sand lens for the purpose of building a road (Fig. 2).

(2) Ubilci landslide

Ubilci, close to Smederevo town, is part of a wide belt which extends from the right banks of the rivers Danube and Sava to the central part of Serbia; it is known for many cases of landslides. Usually they occur in Neogen clay material, but some of them are caused by the presence of sand lenses.

The base of the Ubilci slope is composed of a different type of clay material with enclosed sand lens. Their stratigraphic superposition is obtained by geoelectrical investigation after slope undercutting (Fig. 2). After slope undercutting, the material above the sand lens, as well as the lens itself, starts sliding with time. We apply the present method to the simulation of this kind of sliding.

3. NUMERICAL ANALYSIS

(1) Extended Distinct Element Method (EDEM)

The conventional Distinct Element Method (DEM), proposed by Cundall ²⁾, has been used in movement of blocky rock system. In this method each element is regarded as a rigid body. A Voigt-type dynamic model of the contact point was created; it was composed of an elastic spring and a dashpot. Based on Newton's law, independent equations of motion for each element were established. By solving all equations of motion progressively, step by step, the motion of elements in time domain can be followed.

$$m_i \ddot{x} + C_i \dot{x} + F_i = 0 \quad (1)$$

$$I_i \ddot{\phi} + D_i \dot{\phi} + M_i = 0 \quad (2)$$

where F_i and M_i are sum of all forces and moments acting on the particle i . C_i and D_i are damping coefficients; x and ϕ are displacement vector and angular displacement.

To simulate the behavior of continuous media the conventional DEM has been widely extended by the EDEM simulation program (Iwashita, Hakuno 1990). In this method, the continuity of the model is provided by the introduction of pore-springs to represent surrounding fill material. During the process of the simulation destruction of the pore show the fracture process in the media.

Cohesion in EDEM, c_{EDEM} , is modified real cohesion, c , by parameter b which depends of configuration of element assembly and particle radians⁹⁾.

$$c_{\text{EDEM}} = c \times b \quad (3)$$

(2) Parameters

Basically, the data used in parameter estimation for the EDEM model of the Ubilci landslide were obtained by geophysical and geomechanical investigation by the "Geosonda"⁵⁾ company in the Ubilci neighborhood, and in other areas with similar lithologic units. The geological column of Neogen and Quaternary sediments, obtained by drilling investigation, with lithologic units and their geophysical and geomechanical characteristics, is shown in Table 1.

Geomechanical characteristics of the clay and sand sequences from the upper part of the geological column are used to obtain the clay and sand parameters for EDEM simulation. Because clay is more elastic than sand, the numerical parameter β which defines critical elongation of pore-springs for clay is bigger than in the case of sand material (Table 2).

In both cases a numerical parameter α for setting up pore-springs is the same. Considering the specific position of the sand lens in the surrounding clayey material of the Ubilci slope, because of infiltration between sand grains, it is suppose existence of some kind of fill material which shows very low cohesion ($c_{\text{EDEM}} = 5.0 \text{ N}$). A very small value of pore spring is used for pore material to detect failure zone in sand lens during simulation only. The other mechanical and geophysical characteristics of sand lens are the same as common sand material.

Basically, considering mechanical characteristics of the clay from the upper part of the geological

column in Table 1, for EDEM simulation we used two hypothetical types of clay material:

A) with high cohesion: $c_{\text{EDEM}} = 1.5 \times 10^4 \text{ N}$ and

B) with low cohesion: $c_{\text{EDEM}} = 0.75 \times 10^4 \text{ N}$

Table 1 Geological column (obtained by drilling in Ubilci neighborhood) with geophysical and geomechanical characteristics of stratigraphic units.

depth (m)	age	weight (kN/m^3) wet, dry	effective angle of friction ϕ' (deg.)	effective cohesion c' (kN/m^2)	long. waves propag. V_p (m/s)	trans. waves propag. V_s (m/s)
0						
5	al3	19	30	0	300-500	190-200
10		19 13-15	19-20	10	1500	100
15	al2	20 14-16	20-25	0	1500	200-250
20		21-22 16-17	30-35	0	1500	250-300
25	Q2	19-20 15-17	15-20	5-10	1900	350
30		22 17-18	30	10	2100	500
35	al1	19-20 18	25	30	1800	400
40		22 16-18	35	10	2100	500
45		19-20 15-18	30	5	1900	350
50	P1	19-20	25-30	5	1600	200
55		21	25	100	1800	350
70	M3	19-20	18-22	100-150	1900	450

This is because water presence in unsaturated clay decreases apparent clay cohesion c^s while effective clay cohesion c' and effective angle of inner friction ϕ' remain unchangeable. Relation between degree of saturation in soil and apparent cohesion can be found using Bishop's²⁾ relation for effective stress:

$$\sigma' = \sigma - u_a + \chi(u_a - u_w) \quad (4)$$

where σ' - effective stress, σ - total stress, u_a - pore air pressure, u_w - pore water pressure and χ - parameter changing from zero to unity depending on degree of saturation.

Employing Mohr-Coulomb criterion for shear strength τ_f in case of effective stress:

$$\tau_f = c' + \sigma' \tan \phi' \quad (5)$$

Substitution of equation (3) to equation (4) shear strength is:

Table 2 Parameters used

		Clay	Sand
Element density		$1.7 \times 10^3 \text{ kg/m}^3$	$1.4 \times 10^3 \text{ kg/m}^3$
Element spring	Normal direction	$2.59 \times 10^9 \text{ N/m}$	$1.57 \times 10^8 \text{ N/m}$
	Shear direction	$1.28 \times 10^8 \text{ N/m}$	$2.4 \times 10^6 \text{ N/m}$
Damping constant	Normal direction	$7.1 \times 10^5 \text{ Ns/m}$	$1.3 \times 10^5 \text{ Ns/m}$
	Shear direction	$1.57 \times 10^5 \text{ Ns/m}$	$2.2 \times 10^4 \text{ Ns/m}$
Coefficient of friction between elements		0.26	0.35
Stiffness of pore springs	Normal direction	$1.29 \times 10^8 \text{ N/m}$	15.7 N/m
	Shear direction	$6.4 \times 10^5 \text{ N/m}$	4.8 N/m
Criterion for setting up pore springs (α)		1.3	1.3
Criterion for failure of pore springs (β)		1.005	1.001

$$\tau_f = c' + (\sigma - u_a) \tan \phi' + \chi(u_a - u_w) \tan \phi' \quad (6)$$

writing

$$c^s = \chi(u_a - u_w) \tan \phi' \quad (7)$$

shear strength is:

$$\tau_f = c' + c^s + (\sigma - u_a) \tan \phi' \quad (8)$$

Here apparent cohesion is expressed using Bishop's relation, but during experimental work some authors use different expression for apparent cohesion:

$$c^s = f(u_a - u_w) = \frac{a + b(u_a - u_w)}{c + d(u_a - u_w)} \quad (9)$$

where a, b, c and d are constants to be determined. From these relations it is visible that apparent cohesion is function of suction ($u_a - u_w$).

Results of experimental tests for unsaturated DL clay silt obtain by Huang ⁶⁾, on Fig.3 show how increase of water content in soil decreases apparent cohesion due to suction. The changeable water content in soil produces change in material density, but it is neglected because it does not have significant influence on simulation results.

The behavior of the undercut Ubilci slope for two hypothetical values of clay cohesion is investigated.

The behavior of the undercut Ubilci slope for two hypothetical values of clay cohesion is investigated.

In both cases the sand lens is treated with the same mechanical characteristics, because the water

influence on the mechanical characteristics of sand material is not significant, as is the case with clay material.

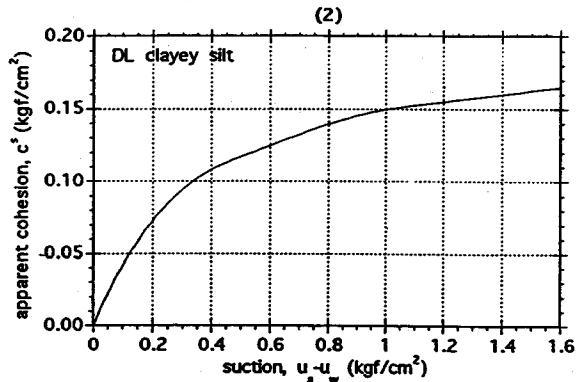
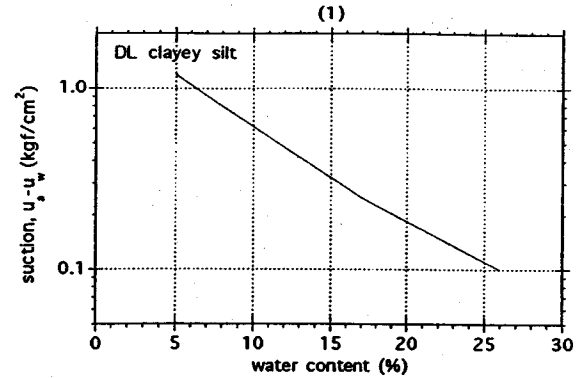


Fig.3 On diagram (1) and (2) it is shown correlations between suction and water content in the soil and apparent cohesion (Huang, Y. ⁶⁾)

Estimation of parameters based on experimental data for both cases is done according to Meguro and Hakuno⁹⁾, Table 2. Propagation velocities of longitudinal V_p and transversal V_s seismic waves which are used as the base for stiffness estimation in Ubilci clayey slope are higher than in sand material, what caused higher stiffness in clay.

4. MODELING OF THE SLOPE

In the process of EDEM modeling, the part of Ubilci slope (Fig.4), enclosed by the interrupted line (Fig.2), with high (A), and low (B) cohesion, was modeled.

Stratigraphically, the EDEM model of the slope Ubilci is simplified in comparison to the real profile. In the EDEM model sandy clay is omitted because mechanical characteristics of this material and its location in the model have no significant influence on the landslide process.

The granularly and mineralogically heterogeneous clay material at Ubilci slope, created in the process of sedimentation, and the homogenous sand material are represented in the model by two types of particle distribution: log-normal for clay material and uniform for sand material. Grain dimensions in clay material vary up to more than 100 times¹³⁾, or more in the case with changeable distribution of carbonate component. Carbonate cementation between fine grains makes them bigger as is the case in Ubilci clayey slope. Considering this, and CPU time required for simulation, range of diameter of clay elements is reduced. Particles that represent clay and sand material in EDEM model are used proportionally bigger than in reality. Minimum diameter of clay material is 0.48 m and maximum is 1.20 m, value of sand particle diameter is 0.60 m. The EDEM model of Ubilci slope is composed of 1272 particles, of which 1175 represent clay material and 97 represent sand material. The sides and the bottom of the model are provided with 157 fixed wall elements with a diameter of 0.50 m.

The process of simulation started only by influence of gravity.

5. RESULTS OF SIMULATION

(1) The case of high cohesion

After start during all 6.25 (s) of simulation material did not move significantly. Only sand material close to the undercut surface moved, as did

a few particles just above these sand particles. Results during 6.25 (s) of the simulation are shown in Fig.5.

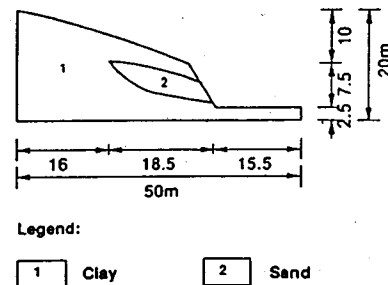


Fig.4 Model for landslide Ubilci simulation.

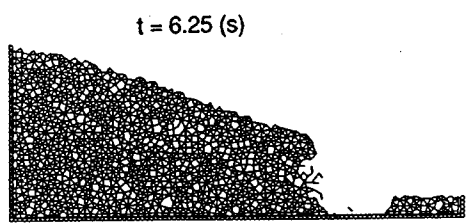
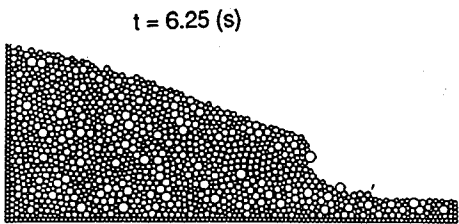
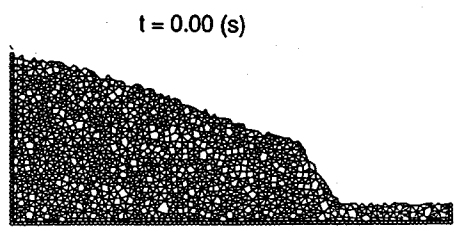
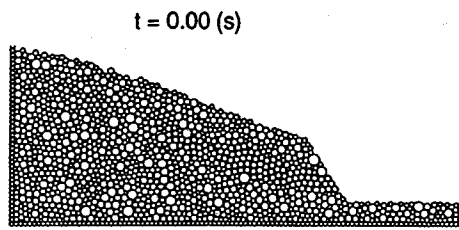
(2) The case of low cohesion

The appearance of first cracks was followed by rather fast destruction of pore springs throughout sand lens, while clay material previously broken off at the top of the lens started sliding downhill. After 3.50 (s) destruction of the clay material started slowly in the lower part. Then the pore springs were destroyed, the compact clay mass was cut into a few blocks and finally, all the clay material was destroyed. Distribution of clay and sand material after the sliding process is shown in Fig.6.

6. DISCUSSION

Methodology used in this study provides for the investigation of complicated superposition relations between geological units and their influence on slope stability. However, during the process of modeling, complicated relationship between geological units can be simplified if it has no influence upon results. In the case of Ubilci landslide results obtained by EDEM simulation indicate that log-normal and uniform distribution of particles used for modeling clay and sand lens material respectively, was satisfactory to explain their inner characteristics.

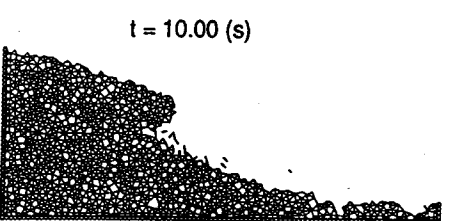
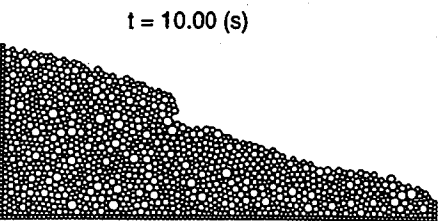
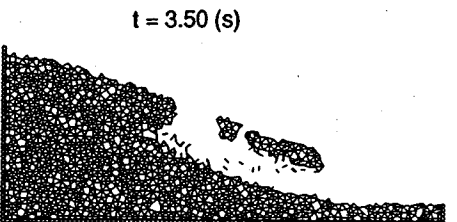
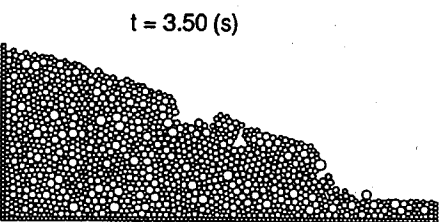
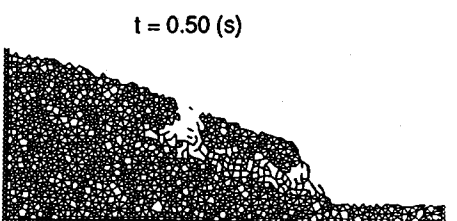
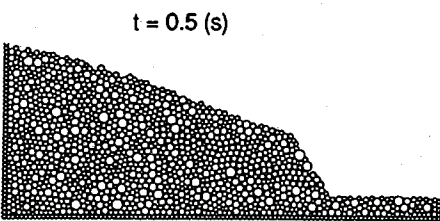
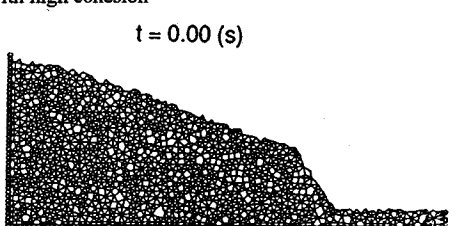
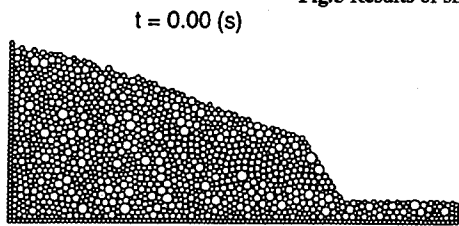
To make EDEM model of the Ubilci slope considering its geomechanical characteristics and the objective of this study, it was necessary to approximate the whole process of clay saturation and the nonhomogeneity of the clay cohesion distribution to the two hypothetical values of cohesion: high and low. As can be seen, these approximations have not had a significant influence upon the simulation results.



Particles

Pore springs

Fig.5 Results of simulation case with high cohesion



Particles

Pore springs

Fig.6 Results of simulation case with low clay cohesion

EDEM simulations show that sand lens influences landslide process with its mechanical properties and geometry.

7. CONCLUSION

Results obtained by EDEM modeling and analysis of the case with clay cohesion $c_{\text{EDEM}} = 0.75 \times 10^4$ N agreed well with the actual situation of landslide Ubilci in the following:

1) location of the top of the landslide obtained by simulation corresponds well to the location of the top of the actual landslide;

2) geometry of the failure surface obtained analytically is in good agreement with the geometry of the actual case;

3) geometry of the whole landslide after the sliding process is similar in both the real and simulated cases.

4) Clay cohesion influence on the magnitude of slope destruction and material movement can be seen by comparing results of simulation of the case with clay cohesion $c_{\text{EDEM}} = 1.5 \times 10^4$ N (Fig.5) to the case with clay cohesion $c_{\text{EDEM}} = 0.75 \times 10^4$ N (Fig.6). In the first case, with clay cohesion $c_{\text{EDEM}} = 1.5 \times 10^4$ N, we have small material movement and slope destruction only at the undercut surface. But in the case with clay cohesion $c_{\text{EDEM}} = 0.75 \times 10^4$ N, the process of the landslide takes all parts of the slope above the sand lens, including the sand lens itself. Also in this case there is big material movement that covers almost all the road surface.

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レンズ状砂層を有する粘土質傾斜地の地滑り過程シミュレーション

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1982年にUbilci(ユーゴスラビア)で発生した地滑りは人為的にアンダーカットの施された粘土質の傾斜地の内部にレンズ状の砂層が存在したことにより誘発された。この地滑りの発生過程とそれに伴う大規模な物質移動を拡張された個別要素法(EDEM)を用いて解析した。その際乾季と雨季とで変化する粘土の粘着力が地滑りの規模にどのように反映するかを調べるために2種類の粘着力値を仮定した。

数値計算の結果はUbilciで生じた地滑りの実際の地滑り面や地滑り後の傾斜地の形状をよく再現できることが確かめられた。