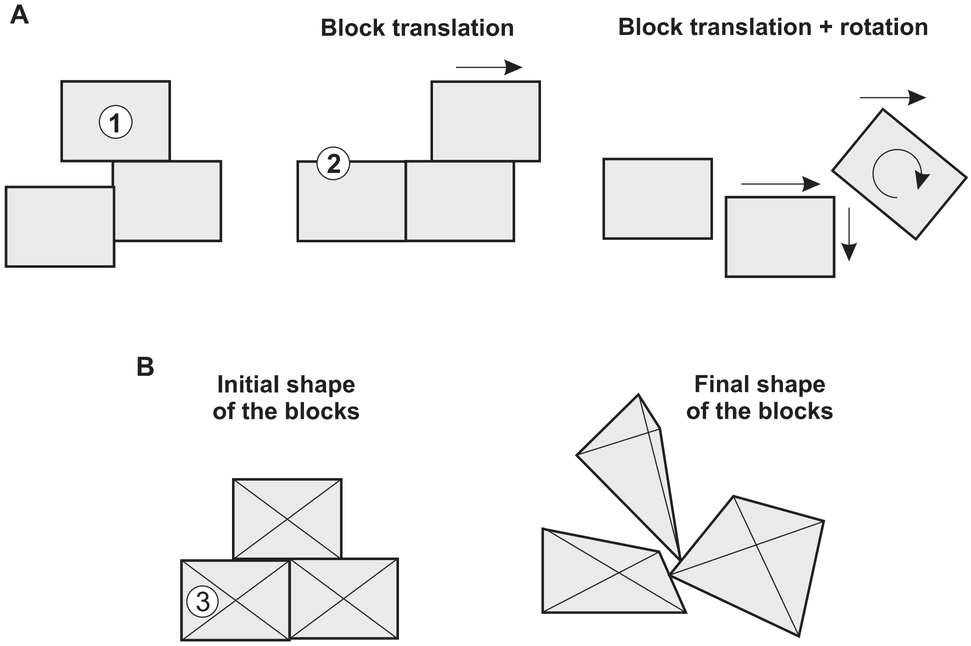

Fig. 4. Explanation of possible deformations and displacements of the blocks

A — rigid model; **B** — fully deformable model

ties. There are two options, when the block body is considered. In the more simple models, block material can be treated as rigid, i.e. its elasticity modulus is equal to infinity. In the second option, fully deformable block-material deforms and in the consequence the shape of the block can change. The schemes on Figure 4 explain the differences in the behaviour of these two models. First assumption means that any displacements in the system occur only due to the movement along or perpendicularly to the interfaces (discontinuities). Such kind of model is applied in case of blocks built of hard rock, divided by sets of joints. Second model can be taken into account, if the system of blocks, built of relatively weak rock, is considered.

Rigid block (Fig. 4A) deforms in translational and (or) rotational mode. Deformable block is divided into zones, which can change their shape causing the change of the block shape (Fig. 4B). As it is seen on the Figure 4B, final system seems to be very different in comparison with the initial one.

NUMERICAL SIMULATION OF THE LANDSLIDE MOVEMENT

LANDSLIDE IN A DIABASE QUARRY

General site inspection suggested that the main reason of the landslide development was connected with the sand movement. Thus, the main task of numerical calculations concerned the explanation of the deformation mechanism and the role of the diabase settlement in this process.

The model geometry is presented on Figure 5. Central cross-section of the landslide was chosen for model construction and numerical simulation. Discontinuities in the diabase are modelled in accordance with the real orientation and spacing of joints. Sand discontinuities are rather "artificial". However, it can be assumed, that the simulation of the sand layer overall behaviour approximately agrees with the reality, as the dimensions of sand blocks are sufficiently small. It was also assumed that the blocks were rigid. Therefore, failure processes were only possible along or across the discontinuities, in shear or tension respectively. The set of parameters describing their properties is shown in Table 1.

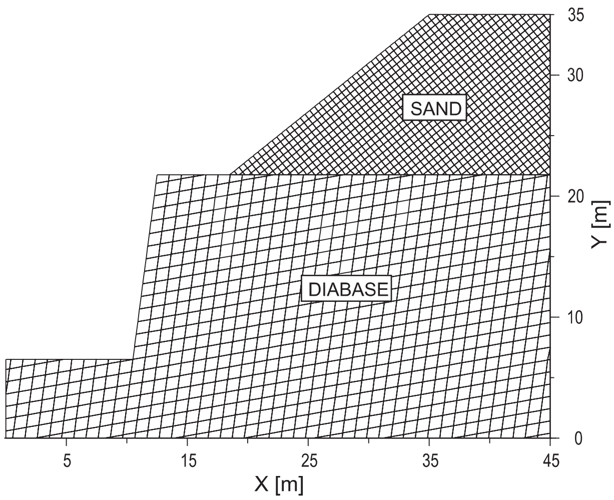

Fig. 5. Cross-section for the numerical simulation of the landslide movement

Table 1

Mechanical parameters of the model

Layer	Discontinuity	Normal stiffness k_n	Shear stiffness k_s	Cohesion c_s	Tension strength R_{rs}	Friction angle Φ_s	Dilation angle Ψ_s
		[MPa/m]	[MPa/m]	[kPa]	[kPa]	[°]	[°]
Diabase	Dip 10° (SZ)	250	250	10	5	8	0
	Dip 10° (DZ)	250	250	15	10	20	0
	Dip 80° (SZ)	250	250	10	15	15	0
	Dip 80° (DZ)	250	250	15	10	20	0
Sand	SZ	250	250	5	0	25	0
	DZ	250	250	15	5	30	0

SZ — shallow zone; DZ — deep zone

The simulation results in form of illustration of landslide development during the selected stages are shown on Figure 6. Based on these results, it is possible to describe both the failure processes and their order:

— diabase blocks lowering and sliding, especially along steeply inclined discontinuities — beginning at the slope base, to the top of diabase zone;

— enlarging this process into deeper regions of the slope;

— creation of the free space between lowered diabase blocks and sand overburden;

— sliding and rolling of the sand particles, following continuous settlement of the diabase zone;

— covering the diabase zone by sand particles;

— slope surface smoothening.

It generally means that the sand movement has a secondary character, following the diabase failure. This conclusion has a practical consequence. Before the calculations were performed, it was decided that removing the sand overburden is necessary for the diabase wall stabilisation. The results proved that such operation would not give expected effects.

The results also show, that the application of discontinuous model was proper, as the displacements of some blocks reached tens of metres; it would be impossible to simulate such large movements using a continuous approach. Moreover, final shape of the landslide body was similar to this observed in the nature.

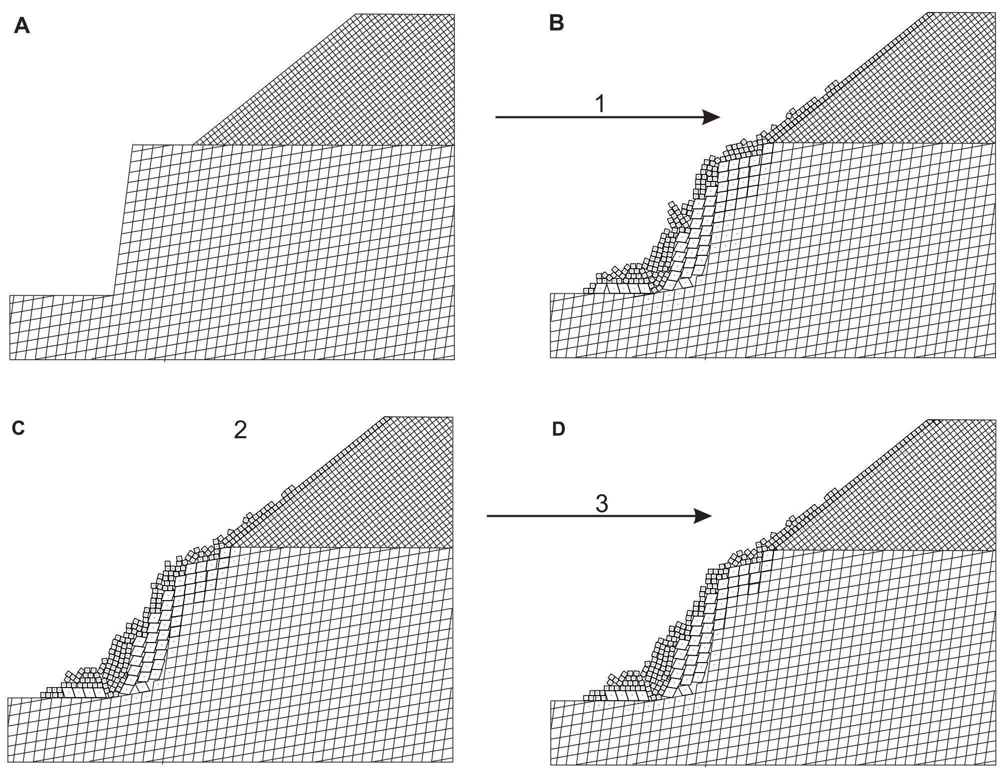

Fig. 6. Selected stages of the landslide development

A — initial stage; **B**–**D** — selected stages of the progressive landslide deformations

LANDSLIDE IN ITALIAN DOLOMITES

Initiation and progression of the Passo della Morte landslide were connected with the retreat of ice from the valley during the last period of the glaciation's epoch. Huge rock falls and toppling failures developed in the first stage (see Fig. 2, stage 1). Due to these phenomena, the dip angle of the moving body surface significantly decreased and the character of the process changed. Movement continued by sliding in the direction 2 (see Fig. 2) and finally stabilisation was reached. Gradual weakening of the rock medium as well as water filtration into the loosened rock mass in difficult climatic conditions caused reactivation of the deformations. However, the movement direction nowadays (direction 3 on Fig. 2) is different than in the earlier stages. The movement distance in some parts of the slope is equal to hundreds of metres, and application of the continuous model would be very improper. Thus, UDEC was chosen to analyse this process.

The task of UDEC analysis was to simulate the movement in direction 3 (shown on Fig. 2) and to explain the mechanism of deformations occurring from the initiation of sliding until today. This work is not finished yet, but some promising results have already been obtained. Serious difficulties resulted from uncertainties regarding input data, i.e. geomechanical parameters describing the medium properties. It is highly probable that the material properties in the past were more or less different than they are at present, but due to the lack of information an assumption of constant properties was accepted. In practice, it was only one possibility for verification of the simulation appropriateness, namely, comparison of the final slope shape — simulated and measured.

Initial and final stages of the landslide are presented on Figure 7[3]. Fully deformable blocks were chosen in this case. Simulation procedure of the process was performed for decreasing thickness of the ice cover. Although this process in natural conditions was continuous, it was impossible to follow such way in calculations. Thus, the process was divided into four stages. In each of them, one ice slice was removed and calculation carried out until equilibrium was reached. Large movement distances of the blocks and changes of their shapes are clearly visible. The geological structure, especially arrangement of the layers in the slope is in final stage significantly different in compari-

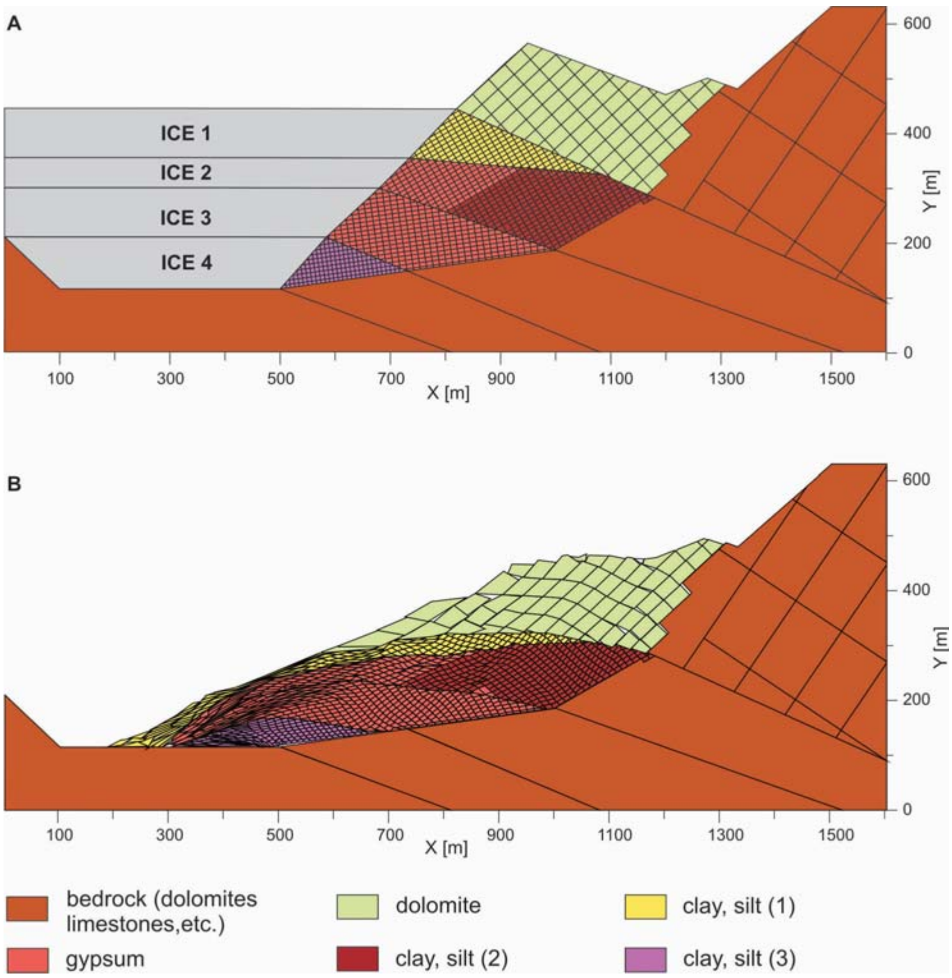

Fig. 7. Development of the Passo della Morte landslide

A — initial stage; **B** — final (present) stage

[3] Cross-sections were elaborated by geologists from the Istituto della Ricerca per la Protezione Idrogeologica CNR, Padova, Italy

son with the initial situation. The calculation results allow understanding the reasons of these changes.

As it was mentioned above, next trials of calculations will be carried out and their results compared with the results of some measurements performed on the slope (e.g. inclinometric measurements). Therefore, the example presents rather the possibilities of the distinct element method than the final, fully reliable solution.

FINAL REMARKS

Two examples of landslide simulation with the help of discontinuous modelling illustrate the possibilities and advantages of this approach. The model could be satisfactorily used both in the case of fractured mass built of hard, competent rock (rigid block model) and weak rock (fully deformable block model). In the first example: landslide in a diabase quarry, first model was applied, and in the second one: the Passo della Morte landslide, fully deformable blocks were assumed.

Discontinuous modelling could also be used in the flysch rock mass. Particularly sandstone flysch is suitable for application of such approach, although — as the second example proves — weak rock mass can be also modelled using this method. The landslides of different kinds and dimensions can be considered, especially in cases of large displacements.

It should be underlined that the numerical simulation can help geologists to interpret phenomena and forms observed in the nature. It means that the co-operation between geologists and engineers can give fruitful results. The examples presented in the paper confirm this conclusion.

In frames of co-operation between Istituto della Ricerca per la Protezione Idrogeologica CNR, Padova, Italy and Institute of Hydroengineering PAS Gdańsk, Poland.

REFERENCES

ITASCA C.G., 2004 — UDEC 4.0 user's manual. Minneapolis.