

ИДЕНТИФИКАЦИЯ НА КОНСТИТУТИВНИ И ГЕОМЕТРИЧНИ ПАРАМЕТРИ НА СКАТОВЕ И ПОТЕНЦИАЛНИ СВЛАЧИЩА

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Абстракт

В практиката, когато се провежда мониторинг на скатове, откоси или потенциални свлачища, данни се взимат главно от повърхността на обекта. По тази причина липсва информация за свойствата на почвата или скалата в дълбочина. От друга страна, при взимане на решения базирани на числена симулация, които да бъдат приети в инженерната практика, трябва моделирането на разглеждания обект да включва достоверни геометрични и материални параметри. Решаването на оптимизационна задача, включваща модела и наличните измервания дава възможност за индиректно добиване на липсващата информация. Настоящата статия разглежда два примера за идентификация на модел с приложение в геотехниката. Получените резултати показват добър потенциал за приложение на оптимизационни алгоритми както за определяне на материалните и геометрични параметри на модела, така и за предварителното планиране на типа и мястото за измерване.

IDENTIFICATION OF CONSTITUTIVE AND GEOMETRICAL PARAMETERS OF SLOPES AND POTENTIAL LANDSLIDES

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Abstract

In practice when monitoring slopes of different sizes a huge number of data is accumulated but it relates usually only to the surface measurements. Therefore in most of the cases there is a lack of knowledge after direct measurements about the slope properties in depth. However in taking decisions or making predictions based on numerical simulations that have sense for the engineering or environmental applications, the possession of information about the slope properties in depth is indispensable. For gaining such knowledge inverse modeling and optimization procedures are well acknowledged. In the present article a critical overview of existing optimization procedures is presented and a numerical experiment is performed in order to evaluate the possibility to identify the sliding boundary, respectively the weathered zone in a given slope. Discussion on the actual stage of the work on a real slope near Reutte (Austria) and the application of the inverse method is also presented.

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1 Introduction

The importance of numerical modeling for better understanding the behavior of complex slopes and potential landslides and for improving the quality of the prediction related to the risk increases continuously in the past 15 years. Beside the improvement of modeling features of numerical codes and elaborating more consistent constitutive models the determination of material and geometrical parameters for the numerical model are of paramount importance for the accuracy of calculation results and consequently for the model predictions.

For determination of model properties there are several approaches used. On one hand the values can be gained by performing measurements in field or doing laboratory tests. Because often these tests are of high cost and time consuming or sometimes not technically possible the data collected rare may serve for having fully determined numerical model. Additionally there are cases when the model parameters can not explicitly be determined from the experimental data and field measurements. On the other hand it is possible to use values from literature or based on expert knowledge in numerical modeling. If present, this is a very fast and simple way to get values. But there is no confidence in correctness for these model parameters.

Optimization techniques provide very good tool for improving the accuracy of the model and thus for getting more reliable predictions. Back analysis comprises the attempt to minimize the deviation between measured and calculated data by iterative adjustment of model parameters that are used by the forward calculation. There are many applications of back analysis for model identification in different branches of science. In geotechnics where often the data is very less and very costly to obtain or the knowledge about the model is provided indirectly and the history is mainly not known back analysis has been well used and several significant contributions have been reported (e. g. GIODA & SAKURAI 1987, SCHANZ et al. 2006, CUI & SHENG 2006)

The chart of the direct approach to the back analysis is shown in Fig. 1. The basic approach consists in choosing an objective function $F(x_1, x_2, \dots, x_N)$ with N parameters to be identified (Fig. 2) that measures the agreement between the available data and the solution of the forward calculation (the model prediction for a given set of parameters). Starting with an initial guess for the parameters the optimization algorithm calls the forward calculation once or several times and extracts the relevant data from the solution of the forward problem to be used in the figure of merit function. The associated objective function value is calculated and the procedure continues up to finding the set of parameters that minimizes the objective function.

In this article we present strategies for back calculation of slope and landslide parameters that are difficult to measure but which are of paramount importance for improving the numerical model and that influence significantly the quality of the model prediction.

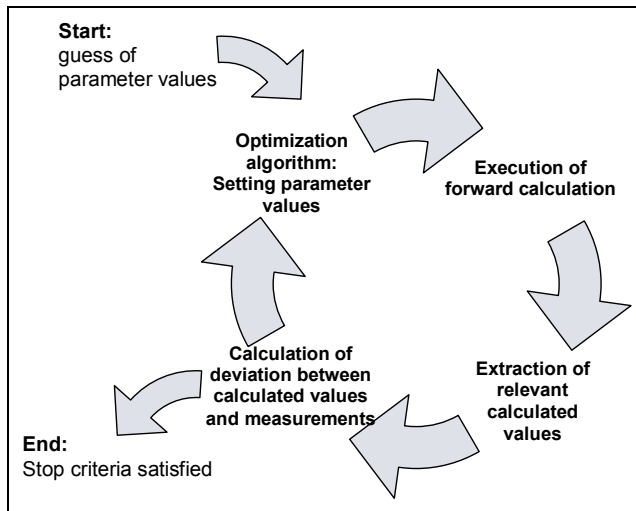


Fig. 1: Basic flowchart for the optimization

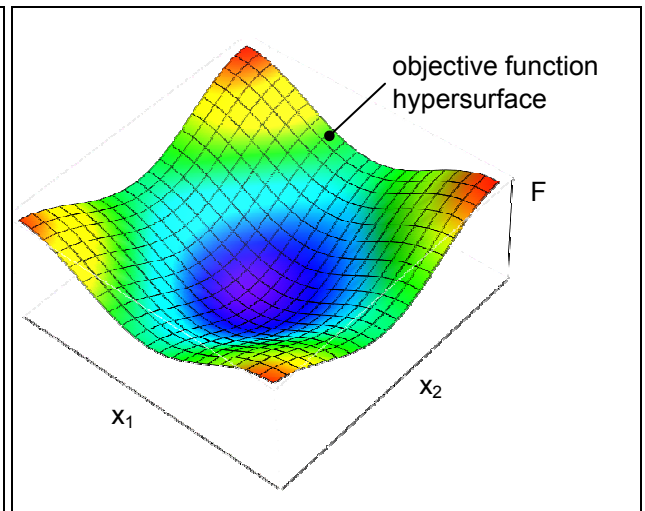


Fig. 2: Objective function topology for two dimensional optimization problem

2 Back analysis of weathered zone depth using inclinometer readings

2.1 Statement of the problem

This application is meant for discussing the possibility to determine the boundary between weathered and non-weathered zones if data from surface displacement measures or data from inclinometers are given. The numerical model of the slope with the instrumented two inclinometers is depicted in Fig. 3. Loading to the slope has been introduced by adding and consequently excavating a layer of material filling the valley at the slope's toe. The slope is supposed to consist of two layers. The material composing the upper layer is considered as to be weathered. The next assumption in the model is that the material properties of the weathered material improve with depth as linear function of the distance from the slope surface. At the boundary between weathered and non-weathered materials there is a continuity of the material properties. Schematically it is given in Fig. 3 as distribution diagram of the selected material parameters. A 2D model of the considered slope has been built in the finite element program ABAQUS/Standard. The used mesh and the boundary conditions for the geostatic equilibrium step are shown in Fig. 4. The boundary condition at the bottom of the model has been modified for the consequent calculations steps and no horizontal displacements are allowed, modeling this way the contact with possibly very rough rock base surface.

The filling material of the layer above the toe valley is excavated by ramped in time elevating of the whole piece and this way quasistatic unloading of the slope is modeled. The resulting displacements are printed out to be compared with inclinometers readings and this way the solution of the forward problem serves as objective function for the optimization procedure.

The material model chosen for this example slope comprises linear elasticity and Mohr-Coulomb plasticity. The filling material of the layer imposing the load at the toe of the slope is taken to be linear elastic. The material model parameters listed in Tab. 1 are used for gaining synthetic data for

the consequent back analysis. Fig. 5 shows the resulting distribution of displacements that has been used instead of real inclinometer measurements. In the following this solution for displacements is called measured displacements.

2.2 Verification of the optimization procedure

This section presents the verification of the procedure for back analysis of the weathered zone depth and the material parameters of the non-weathered layer using the known material parameters at the slope surface and the measured displacements by two inclinometers. There are three parameters of the model to be identified: the values of the Young's modulus (E_{nw}) and the friction angle (φ_{nw}) for the non-weathered material and the depth of the weathered zone (t). The trusted zone for the parameters to be back calculated is defined by the given in Tab. 1 constrains. The merit function $F(E_{nw}, \varphi_{nw}, t)$, that has to be minimized relates the measured and calculated displacements. For the optimization the least-squares fit is used and for the minimum search the particle swarm algorithm with ten individuals (EBERHARDT & KENNEDY 1995) is applied. Six different sets of parameters have been used for the procedure verification. Sets 1 and 2 use the measured displacements at the top of inclinometer 1 and inclinometer 2 respectively (see Fig. 3). Set 3 combines set 1 and set 2. Sets 4 and 5 use the displacements along the inclinometer 1 or inclinometer 2 respectively and set 6 is composed by the displacements at all nodes along the both inclinometers. Fig. 6 presents a subsection of the objective function for sets 3 and 6. When compared the two subsections shown in Fig. 6 it is evident that for set 3 (Fig. 6b) the objective function is less smooth and the log deviation varies within larger interval. This fact influences the calculations cost for obtaining the best fit. The report for optimization runs using sets 3 and 6 is given in Tab. 2. The data set 6 contains the most data possible to gain from the two inclinometers which gives smoother objective function and the comparison shows that the optimization performed using this set is the most efficient. However utilizing measurement on the top of both inclinometers is sufficient for successful back analysis of the requested model parameters. If set 1 or set 2 is used in the merit function no reliable parameter set has been obtained. It means that only having the measurements at the top of one of the inclinometers it is not possible to back calculate the depth of the weathered zone and the properties of the non-weathered material. The reason for that is the existence of non uniqueness of the inverse problem. It has been recognized that adding data to the merit function the number of computation steps for obtaining the best fit decreases.

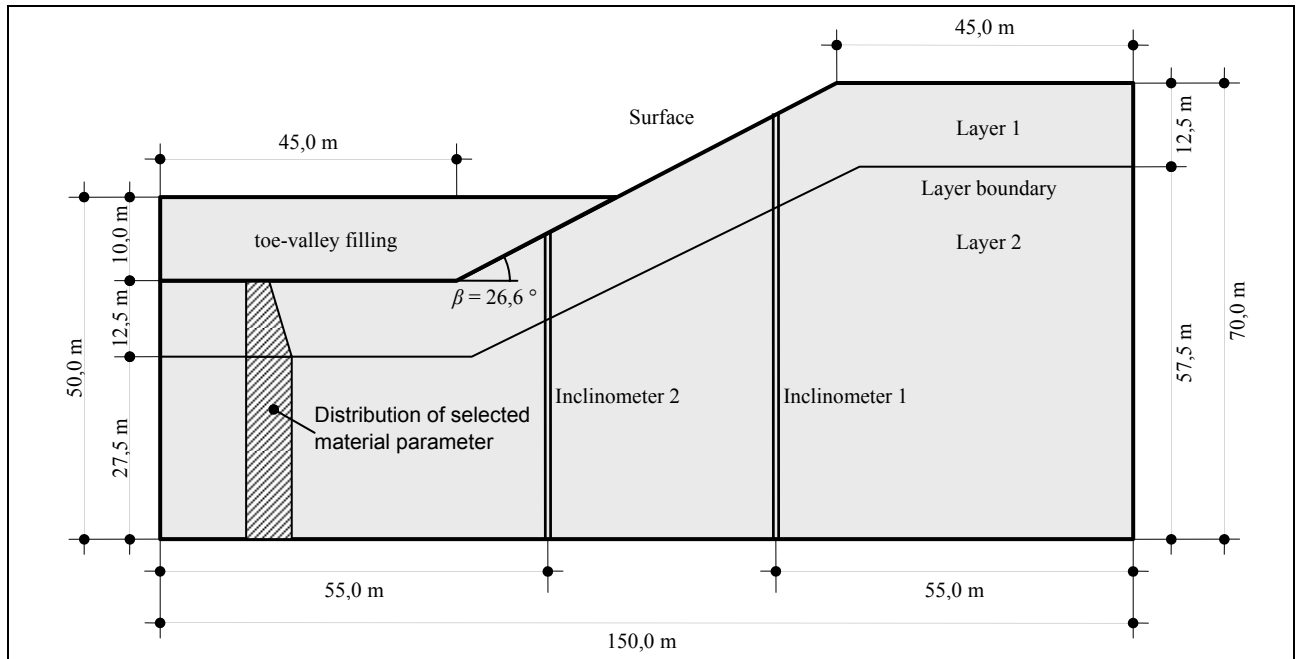


Fig. 3: The model for a numeric experiment of releasing the slope toe-valley filling

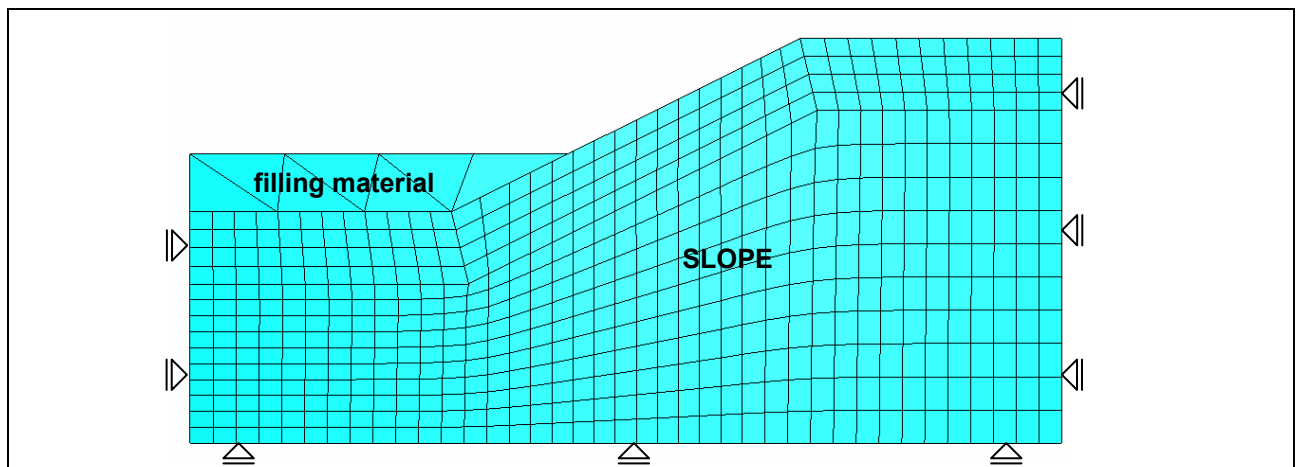


Fig. 4: FE mesh and boundary conditions for the step to remove of the filling material

Tab. 1: Material parameter of the reference simulation

| Parameter | Unit | Value | Trusted zone |
|---|----------------------|-------|----------------|
| for synthetic data | | | |
| Slope | | | |
| density | [kg/m ³] | 2200 | |
| Young's modulus at the surface E_{surf} | [N/m ²] | 1E+08 | |
| E_{nw} | [N/m ²] | 7E+08 | 5E+08 to 1E+09 |
| Poisson's ratio ν | [-] | 0.3 | |
| friction angle φ_{nw} | [°] | 30 | 25 - 35 |
| friction angle φ_{surf} | | 30 | |
| cohesion c | [N/m ²] | 1E+04 | |
| depth of layer boundary t | [m] | 12.50 | 7.5 to 17.5 |
| toe valley filling | | | |
| density | [kg/m ³] | 2200 | |
| Young's-modulus E | [N/m ²] | 7E+09 | |
| Poisson's ratio ν | [-] | 0.3 | |

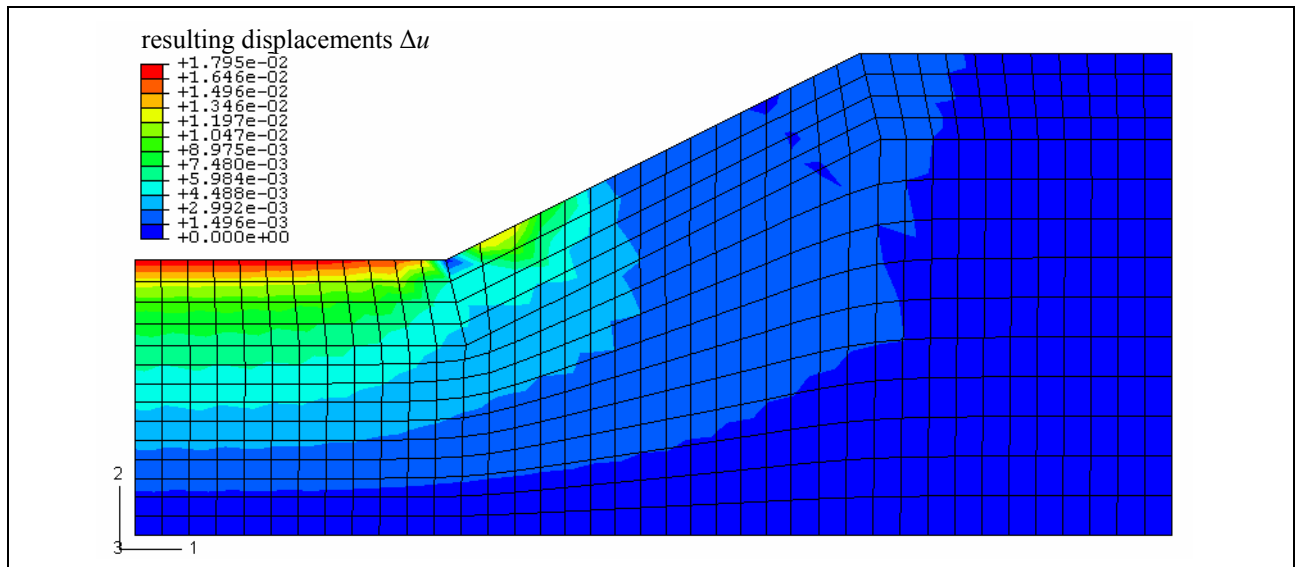


Fig. 5: Distribution of displacements after removing the filling material used as synthetic data.

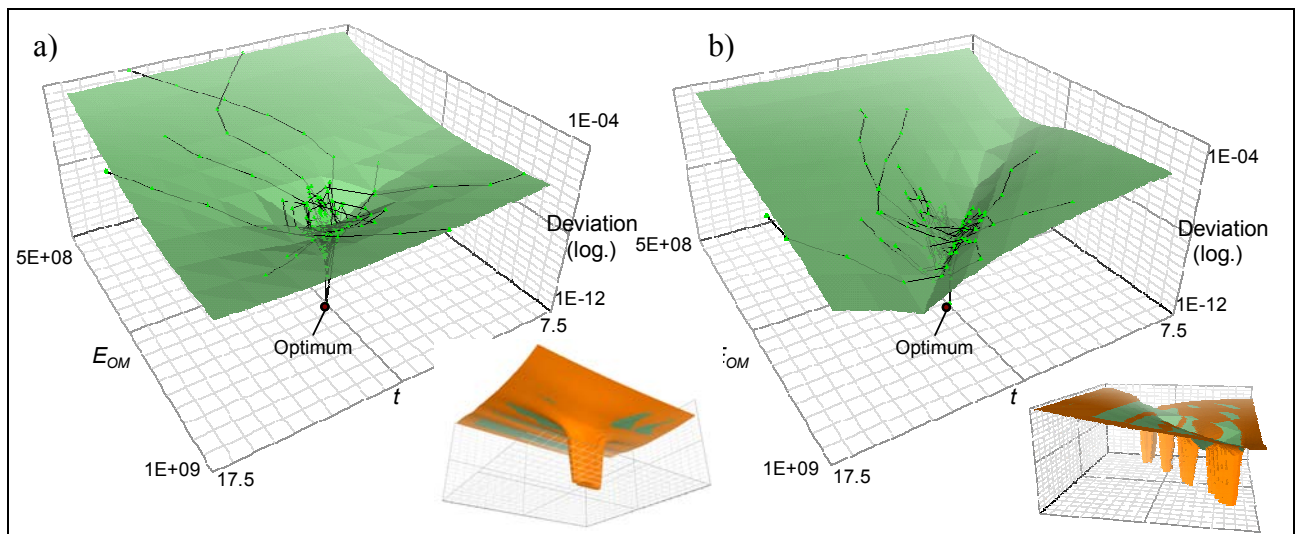


Fig. 6: Subsections of the objective function a) using set 6; b) using set 3.

Tab. 2: Comparison of the computation costs for obtaining the best fit (Particle Swarm Optimizer)

| Reference data | Calculation steps | Function calls |
|----------------|-------------------|----------------|
| Data set 6 | 35 to 40 | 350 to 400 |
| Data set 3 | 50 to 55 | 500 to 550 |

3 Identification of the jointed rock model parameters

3.1 Geomechanical characterization of the problem

As a second example of landslide parameters identification we chose a numerical simulation to determine the limestone (“oberer alpiner Muschelkalk”) disintegration features. The numerical model has been done based on geological and geometrical data from an unstable slope in Austria. The Hornbergl / „Fauler Schrofen“ area with the “Murenbach” torrent is situated in the Northern Calcareous Alps approx. 10 km southwest of Reutte (Tirol) in a chain of mountains, which frames the Reutte basin at a length of 6 km. The topographic map is given in Fig. 7. The tectonically

structured and unstable lime-alpine geological setting together with a snow- and rain-laden climate result in an above-average number of floods, debris flow and rock fall events, mountain spreading fields and rockslides (cliff falls). Consequently carried out protective measures have cost to this day about 11 million euros. Opening of cracks, formation of spreading zones, and rock falls accompanied by debris flows (e. g. events taking place in 1975, 1982 and 1983) as well as rockslides/cliff falls (1976) clearly indicate mountain splitting mechanisms. Since 1967 there were several events that took place in the 7 large and several smaller torrents located in this region. Following ALBRECHT 1999 these are:

- 7 large debris flow events causing severe damage to settlement areas;
- rockslide/cliff fall in 1976 at „Fauler Schrofen “ (approx. 100 000 m³);
- several small rockslides / cliff falls (means fall: 10⁴ to 10⁶ m³) or block falls (fall: 10² to 10⁴ m³);
- several small-scale debris flow events.

The investigated in this study area is located in the forehead of the “Lechtaldecke” nappe, which has been overthrust onto the “Allgäudecke” nappe. Banked limestone of the “Lechtaldecke” nappe build up the “Fauler Schrofen” mountain that is the upper layer of “Alpiner Muschelkalk” (“oberer alpiner Muschelkalk”). The overthrust zone between these rocks and the underlying “Allgäuschichten” layers is formed by the “Reichenhall” beds (“Reichenhaller Schichten”) and crosses the slope at a depth of approx. 200 m in its upper part and approx. 100 m in the lower part, as it is illustrated in Fig. 8 (ALBRECHT 1999, MEIER et al. 2005). The limestone packages of the upper “Alpiner Muschelkalk” are characterized by clearly marked and persistent parallel to the slope discontinuities. These, as well as two further sets of discontinuities, both more or less perpendicular to them, show in part marly interstitial covers. It has been recently observed at the upper part of the slope, above the detachment zone that has been formed in 1976, the appearance of cracks, some decades of meters long and up to 1m wide. Wide spreading zones at the mountain crest show opening rates of up to 85 mm/a (Fig. 8).

3.2 Description of the numerical model

A 2D model of the considered slope has been built in the finite element program ABAQUS/Standard. The modeled area is depicted in Fig. 9. Instead of the “Allgäuschichten” zone a boundary condition for the displacements has been introduced. This is reasonable as the latter part of the slope does not experience much deformation as compared to that included in the numerical model. On the other side the slope instability is govern only by the properties of the materials that are comprised by the chosen model in Fig. 9. Within the left and right range of the model the boundaries are selected in such a way that to avoid inducing tension.

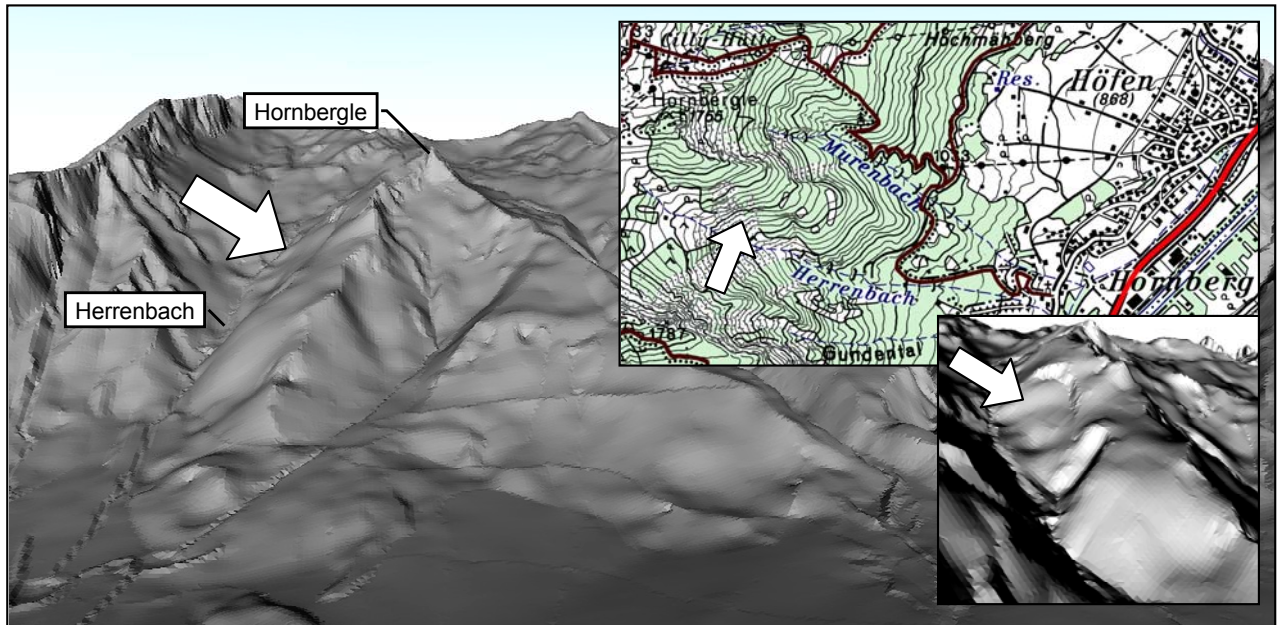


Fig. 7: Situation of the mass movement at „Faulen Schrofen “with Reutte/Tirol (3D surface model with topographic map)

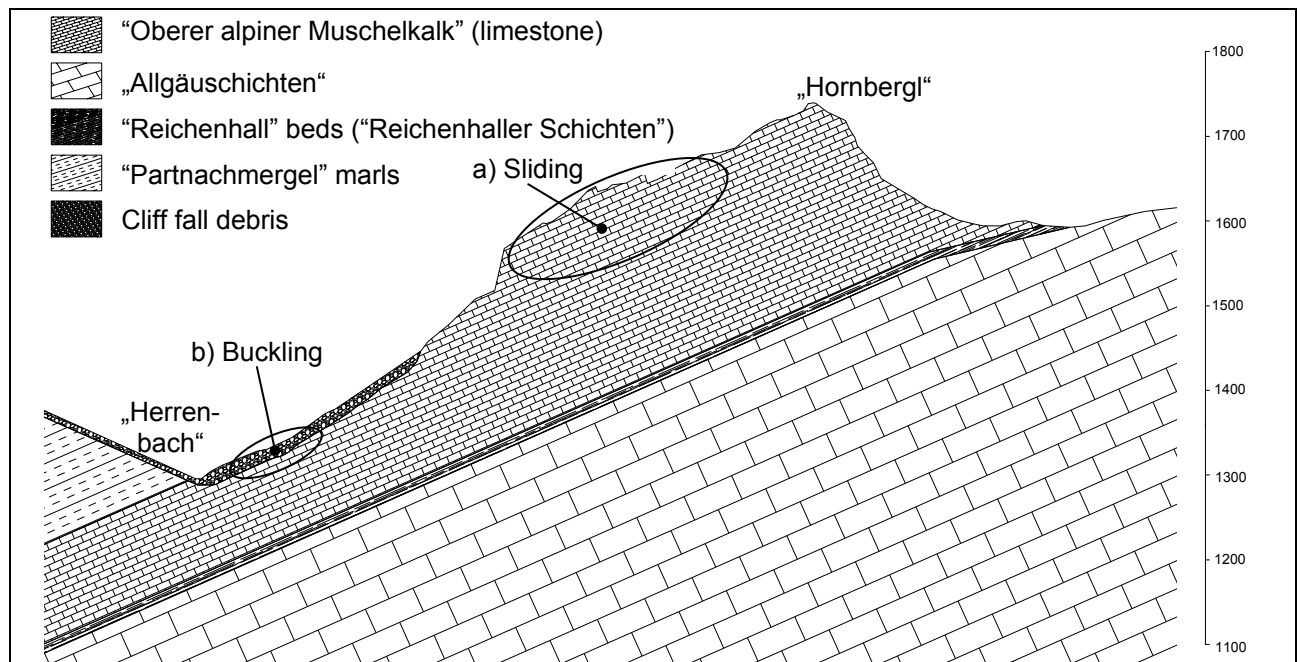


Fig. 8: Engineering-geological sketch within the range of the rockslide of 1976

As the material “Oberer alpiner Muschelkalk” mainly composing the upper body of the slope is known to be disintegrated due to weathering, the constitutive law selected for its behavior description is „jointed material model“ as provided in ABAQUS/Standard model library (see ABAQUS Online Documentation and ZIENKIEWICZ & PANDE 1977 for the model description). The jointed material model assumes the spacing of the joints of a particular orientation to be sufficiently close compared to characteristic dimensions in the domain of the model and therefore the joints can be smeared into a continuum of slip systems. Thus the jointed material model provides a continuum model for materials containing a high density of parallel joint surfaces in different orientations. Based on geological investigation done for the considered slope it is supposed that the weathered “Oberer alpiner Muschelkalk” contains two systems of high density parallel joint surfaces. The joint

system 1 has planes of weakness parallel to the slope surface and for the joint system 2 the joint planes are perpendicular to the slope surface. The material behavior of the bulk material is taken to be isotropic and elasto-plastic obeying the Drucker-Prager failure criterion. The joints behavior is described by the Mohr-Coulomb failure criterion and for a given joint system a (in our case $a = 1, 2$) the failure surface for sliding on joint system is defined by:

$$f_a = \tau_a - p_a \cdot \tan \varphi_a - c_a = 0 \quad (1)$$

with: τ_a the shear stress along the failure plane for the system a

p_a normal stress on the failure plane for the system a

φ_a the friction angle for system a

c_a the cohesion for system a

The synthetic data for the verification of the optimization procedure for determining the model parameters for “jointed material model” have been obtained by solving the boundary and initial value problem depicted in Fig. 9 and using the material parameters for the involved 6 different materials as they are listed in Tab. 3.

First the geostatic equilibrium step is performed with fixed displacements at all nodes. The initial stress is calculated using the user subroutine SIGINI and taking $K_0 = 1 - \sin \varphi$, where φ is chosen such that minimizes the displacements that take place after the consequent steps during which a stepwise release of the constrain on the nodes displacement has been done. The next step in the simulation is to decrease the Young’s modulus and the friction angle for the weathered “Oberer alpiner Muschelkalk” material. The new values are $E_{OM} = 700 \text{ MN/m}^2$ and $\varphi_1 = \varphi_2 - 2^\circ = 30^\circ$. This imposes displacements to put the model back at equilibrium. The displacements at four nodes as they are given in Fig. 9 are printed out and these data are used for the later on performed optimization. Fig. 10 shows the displacements distribution after the last step of the procedure to simulate the weathering of the “Oberer alpiner Muschelkalk” material. These data are later called measured data.

3.3 Verification of the optimization procedure

Next we present verification of the procedure to back calculate the material properties of the jointed material model using the measured displacements at four points on the slope surface. For obtaining the best fit the least square regression is used. The merit function compares the measured and calculated displacements at the four chosen nodes (see Fig. 9). As in the previous example the particle swarm optimizer (PSO) with ten individuals is used for determine the minimum of the objective function. The trusted zone for the PSO is given as it follows: $E_{OM} \in [2\text{E}+02 \dots 5\text{E}+03] \text{ MN/m}^2$ and $\varphi_1 \in [25^\circ \dots 40^\circ]$. The friction angle for the joint system 2 is given as $\varphi_2 = \varphi_1 + 2^\circ$ and the dilatancy angle is $\psi_a = \varphi_a - 30^\circ$ if $\varphi_a > 30^\circ$ or elsewhere $\psi_a = 0$. Fig. 11 presents the objective

function topology and one can see that in this case the particle swarm (black lines with green triangles) tends to go to the optimum point. The performance of the PSO is such that it gives after 8 steps including 80 calls of the forward calculation values of the identified parameters close to the true one, namely $E_{OM} = 7.14E+02 \text{ MN/m}^2$ and $\varphi_I = 30.1^\circ$ and after 18 steps (180 calls of the forward calculation) already the optimum solution is obtained with $E_{OM} = 6.99E+02 \text{ MN/m}^2$ and $\varphi_I = 30^\circ$. Decreasing the values of E_{OM} and the friction angles for the two joint systems raises the problem with calculation time for achieving the equilibrium during the forward computation. To improve the convergence a higher value for the stabilization factor “dissipated energy fraction” (ABAQUS Online Documentation) is introduced. By default this factor has a value of $2E-04$ and controls the used damping factor for the energy dissipation. For this application we used a value of $2E-03$ for the dissipated energy fraction.

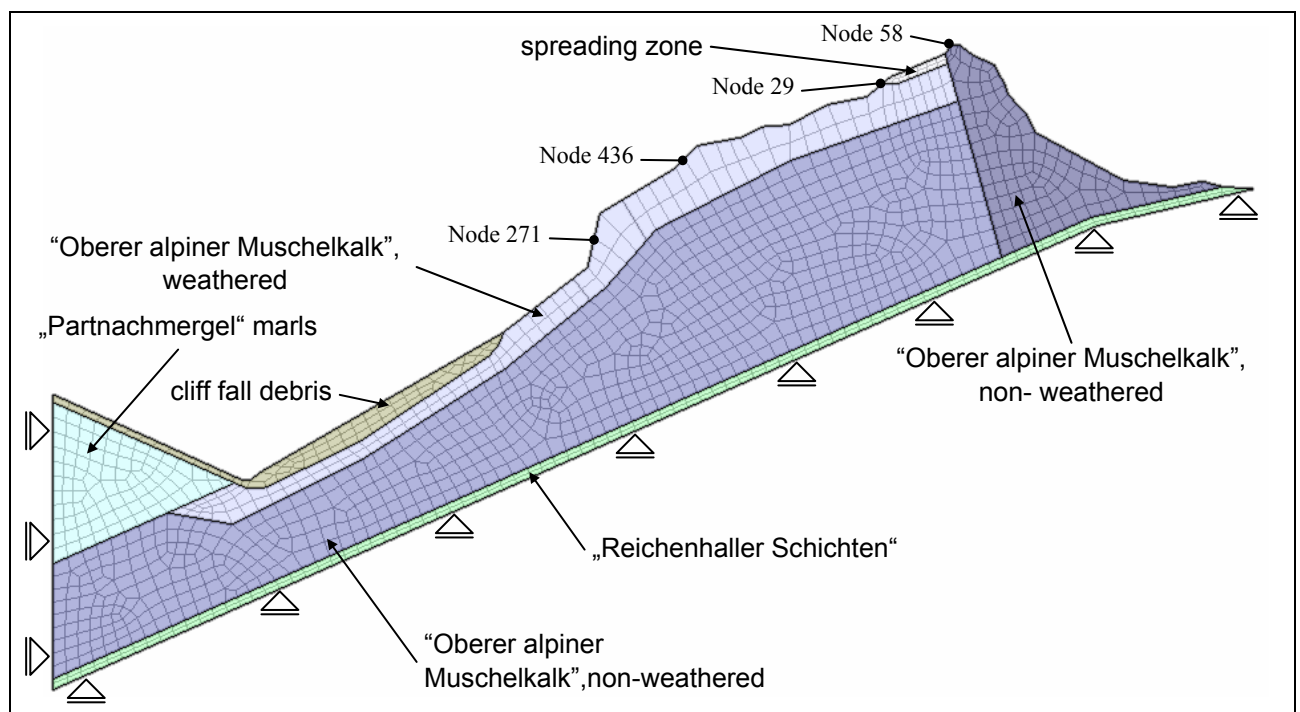


Fig. 9: The 2D-modell for the Reutte slope

Tab. 3: Material parameter of the numeric model Reutte (empirical values)

| Parameter | | Wert |
|--|----------------------|-----------|
| <i>Cliff fall debris</i> | | |
| density | [-] | 2200 |
| Young's modulus | [-] | 5E+03 |
| Poisson's ratio | [-] | 0.3 |
| friction angle | [°] | 40 |
| dilatancy angle | [°] | 0 |
| cohesion | [kN/m ²] | 10 |
| <i>Spreading zone</i> | | |
| density | [kg/m ³] | 2600 |
| Young's modulus | [MN/m ²] | 5E+03 |
| Poisson's ratio | [-] | 0,3 |
| friction angle | [°] | 40 |
| dilatancy angle | [°] | 5 |
| cohesion | [kN/m ²] | 20 |
| <i>"Reichenhall" beds ("Reichenhaller Schichten")</i> | | |
| density | [kg/m ³] | 2200 |
| Young's modulus | [MN/m ²] | 5E+04 |
| Poisson's ratio | [-] | 0.3 |
| <i>"Partnachmergel" marls</i> | | |
| density | [kg/m ³] | 2600 |
| Young's modulus | [MN/m ²] | 5,0E+04 |
| Poisson's ratio | [-] | 0.3 |
| <i>Limestone: "Oberer alpiner Muschelkalk", non-weathered</i> | | |
| density | [kg/m ³] | 2600 |
| Young's modulus | [MN/m ²] | 5E+04 |
| Poisson's ratio | [-] | 0.3 |
| <i>Limestone: "Oberer alpiner Muschelkalk", weathered (jointed material model)</i> | | |
| Density | [kg/m ³] | 2600 |
| Young's modulus E_{OM} | [MN/m ²] | 5E+03 |
| Poisson's ratio ν | [-] | 0.3 |
| <i>Joint system 1 (parallel to slope surface) /</i> | | |
| <i>Joint system 2 (perpendicular to slope surface)</i> | | |
| friction angle φ_1 / φ_2 | [°] | 40 / 42 |
| dilatancy angle ψ_1 / ψ_2 | [°] | 10 / 12 |
| cohesion c_1 / c_2 | [kN/m ²] | 350 / 400 |

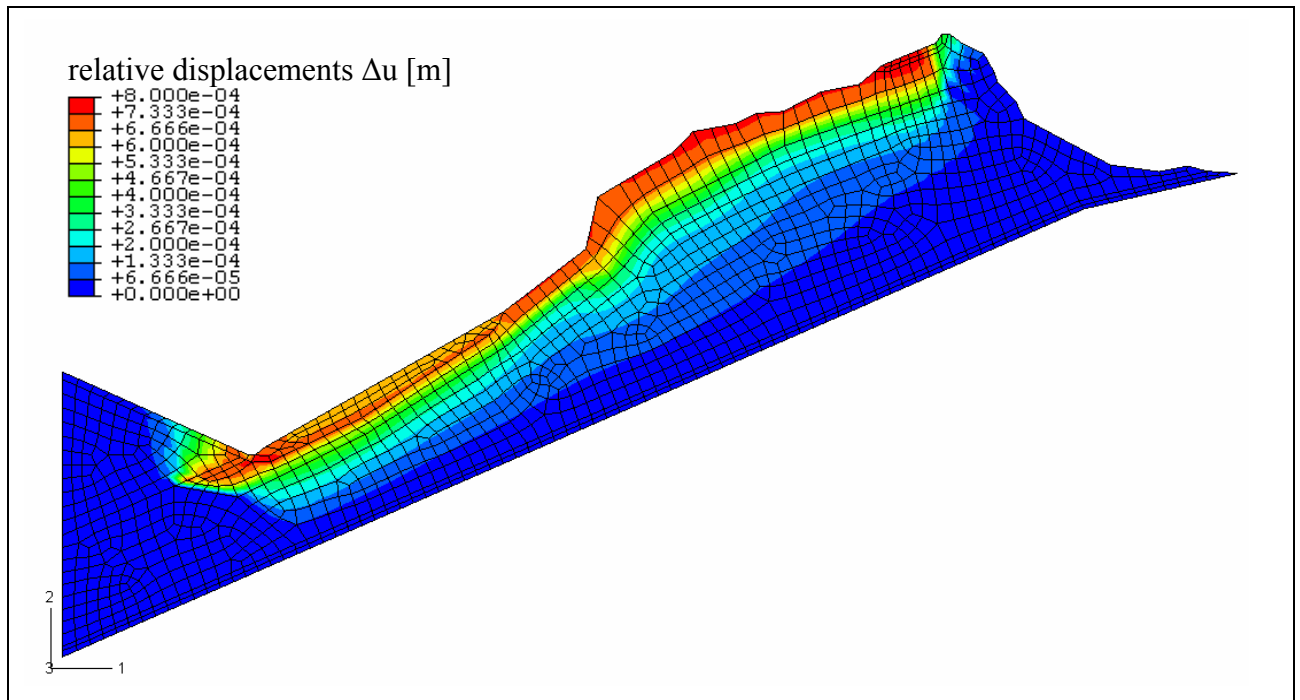


Fig. 10: The distribution of the displacements after reduction of the jointed material properties.

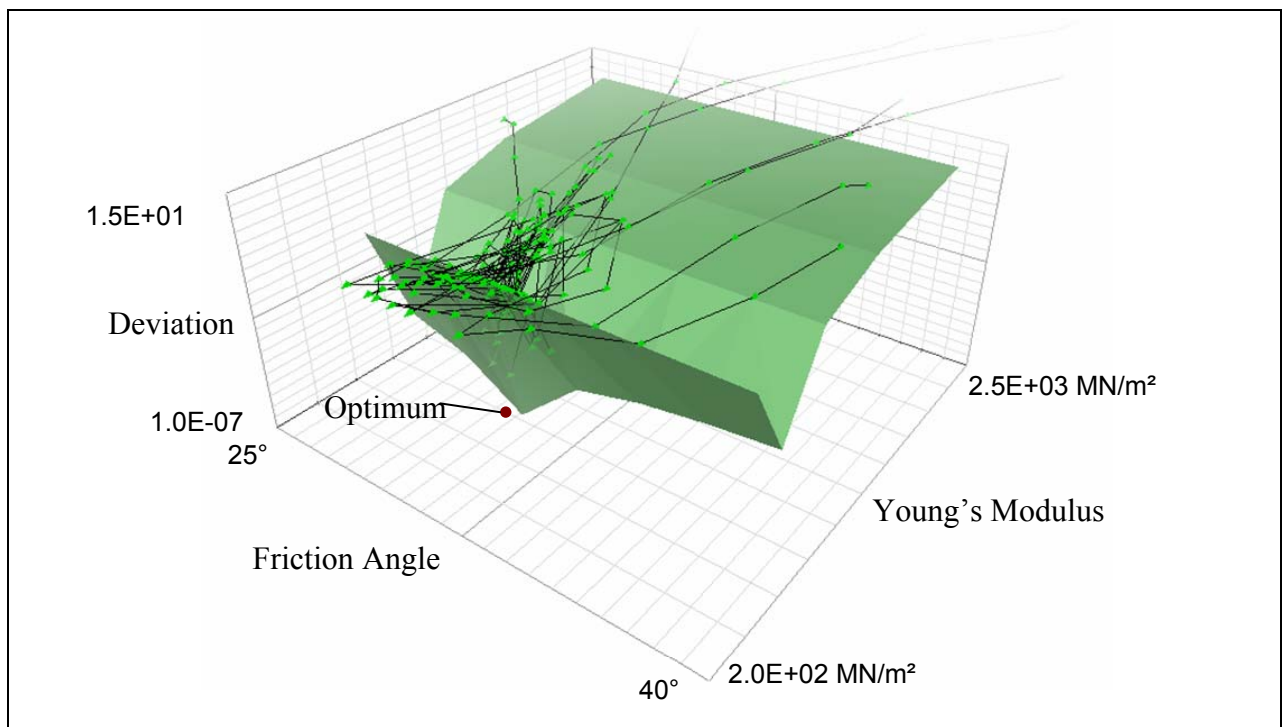


Fig. 11: The objective function topology and the paths of the Particle Swarm method

Conclusions

The ability of the back analysis for slope material and model parameter identification is verified based on two examples. The first example is related to the identification of the depth of weathered zone based on inclinometer readings. Different possibilities for data to be used in the optimization procedure are discussed. It is shown that not in any case the optimum solution of the inverse problem can be found. At least two inclinometers have to be instrumented in order to back calculate the weathered zone depth. This way the synthetic experiment has been used for better understanding

which inclinometer data would be sufficient for the unique model identification. The second example demonstrates that having some four measurements on the slope surface and some simplifying assumptions regarding the geology situation and material structure it is possible to determine the material properties degradation due to weathering. The obtained results clearly show that back analysis may be of importance in both determining the material and model parameters and for giving hints regarding measurement instrumentation. This way the quality of the numerical model predictions regarding the behavior of slopes and potential landslide risk analysis may be significantly improved.

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