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Identification of Constitutive and Geometrical Parameters for Slope Instability Modelling – Application to Mountain-Splitting Area Reutte/Tyrol (Austria)

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Back-analysis

Abstract

In practice when monitoring slopes of different sizes a large number of data is accumulated but it is usually restricted only to surface measurements. Therefore in most cases there is a lack of knowledge based on direct measurements of the slope properties with depth. However, when taking decisions or making predictions based on numerical simulations that make sense for the engineering or environmental applications, it is indispensable to possess information about the slope properties with depth. For gaining such information the inverse modelling via optimization procedures is a well accepted and nowadays common tool. In this article, in order to evaluate the possibility to identify the sliding surface and the weathered zone in a given slope, a back analysis of an instable alpine slope is presented based on a numerical/synthetic experiment. The applicability of the back analysis and the performance of the optimization procedure are further demonstrated by an application to a real dip slope near Reutte / Tyrol. Discussion on identification of constitutive and geometrical parameters in both the numerical experiment and the real slope case is given from the point of view of the application of the back analysis to slope stability modelling problems.

Bei der messtechnischen Überwachung von Hanginstabilitäten unterschiedlichster Größenordnungen fallen in der Regel eine Vielzahl von Datensätzen an, die sich jedoch vielfach nur aus Oberflächendaten zusammensetzen. Aus diesem Grund bleiben, trotz aufwändigen Messprogrammen, häufig Fragestellungen zu den Vorgängen unterhalb der Geländeoberkante von instabilen Hängen offen. Allerdings ist eine realistische Darstellung der Vorgänge und Zustände unterhalb der Geländeoberkante unabdingbar, falls auf der Basis eines solchen Modells umweltbedingte oder ingenieurtechnische Voraussagen abgeleitet bzw. Entscheidungen getroffen werden sollen. Zur Gewinnung dieser Informationen wird die inverse Parameterrückrechnung in Verbindung mit Optimierungsalgorithmen vielfach angewendet. In dem vorliegenden Artikel wird die Anwendung von Optimierungsverfahren auf eine Hanginstabilität vorgestellt. Im ersten Schritt wird hierzu am Beispiel eines numerischen Experiments die Möglichkeit der Bestimmung der Mächtigkeit einer Verwitterungszone und deren Eigenschaften untersucht. Im zweiten Schritt werden diese Verfahren auf ein Bergzerreißungsfeld nahe Reutte / Tirol (Österreich) angewendet. Die Diskussion zu der Rückrechnung konstitutiver und geometrischer Parameter wird sowohl für das numerische Experiment als auch für den Hang nahe Reutte für den Aspekt der Anwendung zur Bestimmung von Parametern von Hanginstabilitäten geführt.

1. Introduction

In this paper we examine via numerical modelling a geological-geotechnical situation which typically results in mountain splitting process. The discussion handles the displacement of competent fractured rock masses located on incompetent rock slopes (Fig. 1). These are controlled by bedding planes of competent lithological units, such as thick-bedded carbonates, conglomerates or sandstones. The harder beds are separated into blocks along tectonic fractures or joints and are often overlying weak materials. Often the brittle slab is disintegrated along a set of discontinuities by troughs and cracks into a “rock labyrinth” (e.g. Stepanek, 1992; Simmons et al., 1980; Lotter et al., 1998). Local instabilities of rock blocks at the edge of brittle slabs typically result in large rock slides, especially if the dip slopes are characterized by smooth bedding planes or by intercalated marl or shale horizons that outcrops above the bottom of the valley (Eisbacher et al., 1984). Dip slope failures have led in the past to numerous devastating rock slides (Heim, 1932; Hsü, 1975).

From the numerical modelling point of view, the simulation of mass movements involving large volumes is a special challenge, because normally only fragmentary and/or imprecise geometric, kinematic and constitutive information is available. Additionally, the problem has to be handled as time-dependent, three dimensional and accounting for highly non-linear processes. Usually several million cubic meters large mass movements are involved, yielding the additional need for considering scale effects. That is why material and model parameters obtained from laboratory measurements cannot directly be used. The missing rigorous assessment of the initial stress fields and lacking or imprecise data from deeper zones of the moving masses make the numerical modelling difficult and uncertain. Derived numerical models possess usually a very complex geometry and involve complicated constitutive laws in spite of the introduced simplifications. Such model finally result in time-consuming computations.

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

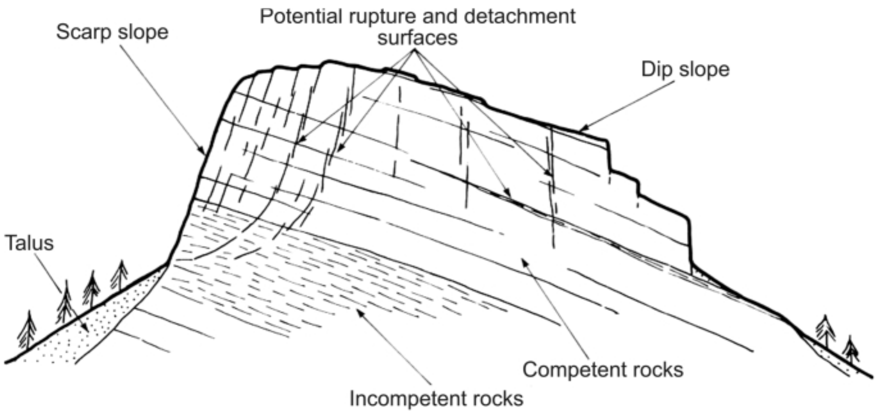

FIGURE 1: Schematic illustration of the geological discontinuities controlling dip slope and scarp slope failures with potential rock avalanche development (Eisbacher et al., 1984).

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 such based on expert knowledge in numerical modelling. This is a very fast and simple way to get values but there is no confidence in correctness of these model parameters.

Optimization techniques provide very good tool for improving the accuracy of the numerical 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. In recent years, due to the availability of sufficiently fast computer hardware, there has been a growing interest in the application to geotechnical modelling of inverse parameter identification strategies in order to make these procedures automated and thus more traceable and objective (reference to, among others, Calvello et al., 2002 and 2004; Carrera et al., 2005; Meier et al., 2006; Schanz et al., 2006). Furthermore, inverse modelling provides statistical information for evaluation of the developed geotechnical model.

Applications of optimization procedures in geotechnics are reported by many authors, e.g. calibration of geotechnical models (Calvello et al., 2002, 2004), or identification of hydraulic parameters based on field drainage tests (Zhang et al., 2003). Already in 1996, Ledesma et al. (1996a) and Gens et al. (1996) applied gradient based optimization methods to a synthetic and a real example of a tunnel drift simulations and to the identification of geotechnical parameters of a cavern in the Spanish Pyrenees (Ledesma et al., 1996b). Malecot et al. (2004) used pressuremeter tests and finite-element simulations of excavation for inverse model-parameter identification. Alternatively to gradient based approaches for solving the optimization problem genetic algorithms are recently intensively used, e.g. in (Levasseur et al., 2007a,b). Feng et al. (2006) applied genetic programming and a Particle Swarm optimization (PSO) algorithm for the determination of the parameters of visco-elastic constitutive models for rocks. As a different aspect of parameter identification, Cui et al. (2006), determined the minimum parametric distance to the limit state of a strip foundation by optimizing a reliability index. Schanz et al. (2006) applied back analysis and PSO technique to geotechnical field projects and laboratory tests, namely multi-stage excavation and desiccation of a sand column. Inverse methods have been already explored in geotechnics regarding slope stability problems. Al Homoud et al. (1997) used the classical lamellae based method and a generalized rigid body method for investigation of a slope in Jordanian. The authors performed a sensitivity analysis and by back calculation they determined the shear strength. Sonmez et al. (1998) used a comparable concept in application to different slopes in Turkey and utilized additionally in their study a non-linear failure criterion. Anisotropic elastic material parameters of several slopes are back calculated by Okui et al. (1997) on the basis of inclinometer data. Constitutive parameters of a creeping slope having failure surface parallel to the ground level and permitting 1D simplification of the governing equations are identified by inverse analysis in Puzrin & Sterba (2006). Feng et al.

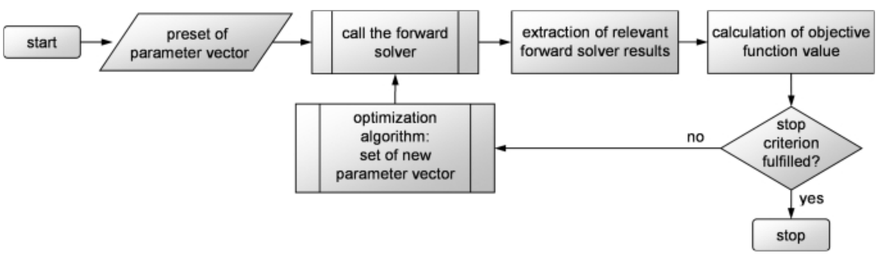

FIGURE 2: Basic flowchart for the back analysis.

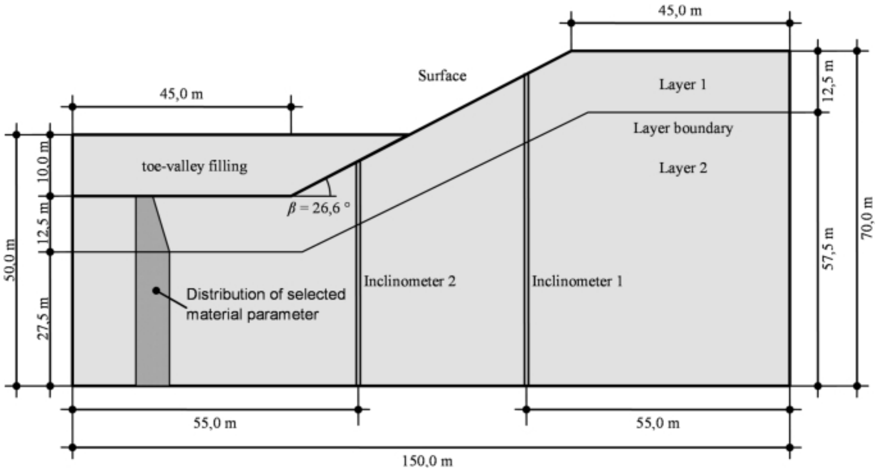

Figure 3: The model for a numerical experiment of releasing the slope toe-valley filling.

(2000) and Deng et al. (2001) presented inverse displacement analyses of a very steep rock slope in China based on genetic algorithms. In the later paper a combination of FEM - simulation and neural network is used as a forward calculation. Cheng et al. (2007) carried out a performance study on heuristic optimization algorithms for location of noncircular critical slip surface in slope stability analysis (SSA). The use of a modified PSO method for the determination of a critical slip surface in SSA is described by Cheng et al. (2008). Sun et al. (2008) shows the application of a genetic algorithm to a similar problem.

All cited references agree on the fact that back-calculation of model parameters by means of optimization routines has considerable potential in the field of geotechnics if an appropriate forward calculation depending on adequately realistic model assumptions is provided. In this context, PSO approach is a powerful tool for finding parameter sets that best represent the reference data by means of acceptable numerical robustness and calculation time costs. Detailed review of the properties and characteristics of the PSO approach is available in the literature (e.g. Clerc, 2006, or Meier, 2008). It is important to mention that the PSO is not a global optimization technique in general. In case of presence of multiple minima of the objective function the PSO may converge to a local suboptimal solution. Although the PSO posses-ses the ability to recover single particles from local minima, if another member of the swarm locates less value of the objective function.

The chart of the direct approach to the back analysis is shown in Fig. 2. The basic approach consists in choosing an objective function $f(x_1, x_2, ..., x_n)$ that measures the agreement between the available data and the solution of the forward calculation (the model prediction for a given set of parameters $x_1, x_2, ..., x_n$). Starting with 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 objective function. 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 influence significantly the quality of the model prediction.

2. Back analysis of weathered zone depth using inclinometer readings

2.1 Statement of the problem

In this first numerical example we validate our general approach to identify model parameters by back analysis of synthetic measurements. This application can also be found in Meier et al. (2006) and 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 displayed in Fig. 3 as dis-

Parameter	Unit	Value for synthetic data	Constraints
Slope			
density	[kg/m³]	2200	
Young's modulus at the surface E_{surf}	[N/m²]	1E+08	
E_{nw}	[N/m²]	7E+08	5E+08 to 1E+09
Poisson's ratio v	[-]	0.3	
friction angle φ_{nw}	[°]	30	25 - 35
friction angle φ_{surf}	[°]	30	
cohesion c	[N/m²]	1E+04	
depth of layer boundary t	[m]	12.50	7.5 to 17.5
toe valley filling			
density	[kg/m³]	2200	
Young's-modulus E	[N/m²]	7E+09	
Poisson's ratio v	[-]	0.3	

Table 1: Young's modulus - NO -

tribution diagram of the selected material parameters. A 2D model of the considered slope has been built within the finite element program ABAQUS/Standard. The used FE-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, modelling 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 quasi-static unloading of the slope is modelled. The resulting displacements are printed out to be compared with inclinometer readings and this way the solution of the forward problem serves as measurement data in the objective function for the optimization procedure.

The material model chosen for this example comprises the linear elasticity and the 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 in the forward problem for gaining synthetic data for the consequent back analysis. In the following the displacements obtained as solutions of the forward problem using the parameters in Tab. 1 are called measured displacements.

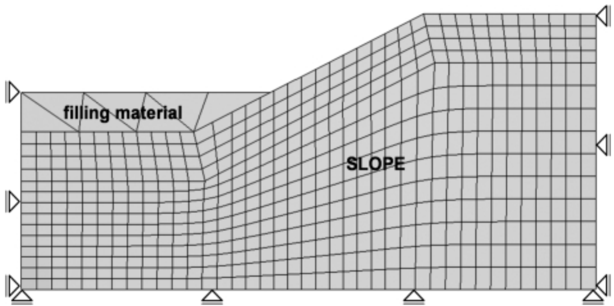

Figure 4: FE mesh and boundary conditions for the step to remove of the filling material.

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 constraints. The objective function $f(E_{nw}, \varphi_{nw}, t)$, that has to be minimized compares by means of least-squares the measured and calculated displacements. Particle swarm algorithm with ten individuals (Eberhardt et al., 1995) is applied for finding the minimum of f. Six different sets of data have been used for the procedure verification. Sets 1 and 2 use the measured displacements at the top of respectively inclinometers 1 and 2 (see Fig. 3). Set 3 combines set 1 and set 2. Sets 4 and 5 use respectively the displacements along the inclinometers 1 and 2 and set 6 is composed by the displacements at all nodes along the both inclinometers. Fig. 5 presents a section of the objective function for sets 3 and 6 with φ_{nw} set to the value for synthetic data (φ_{nw} = 30°). When comparing the two subsections shown in Fig. 5 it is evident that for set 3 (Fig. 5b) the objective function is less smooth and it varies within larger interval. This fact influences the calculation costs 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 and it gives smoother objective function and the most

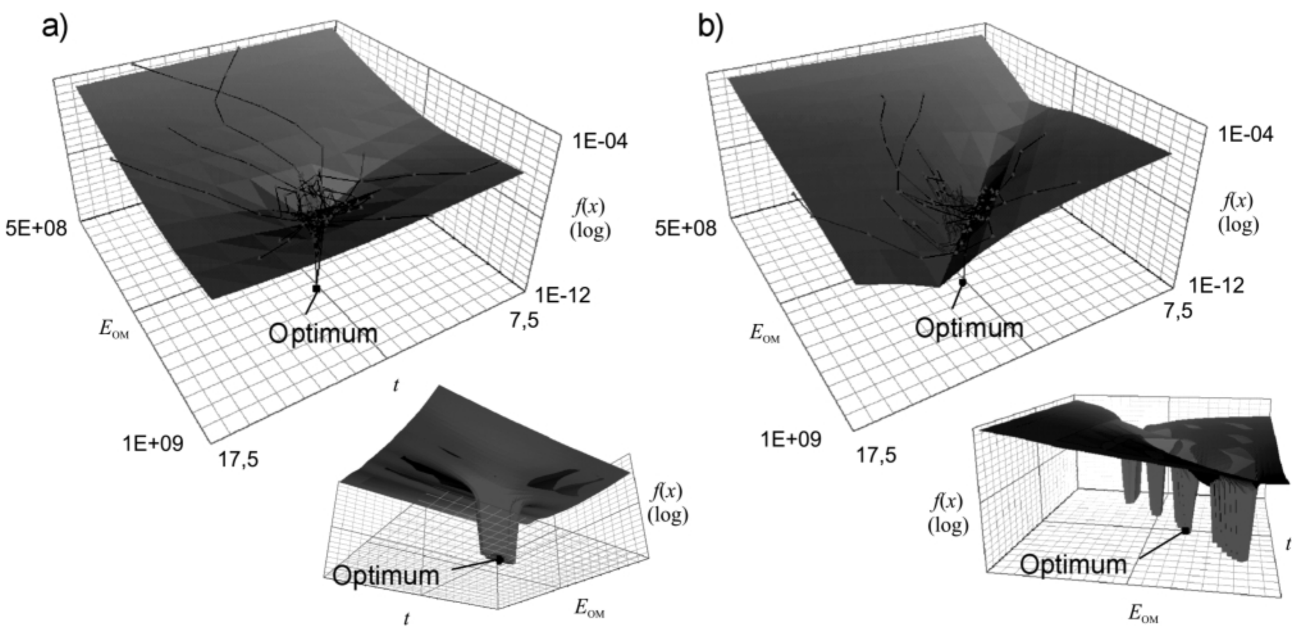

Figure 5: Subsections of the objective function a) using set 6; b): using set 3.

efficient optimization procedure. However, utilizing measurement on the top of both inclinometers is sufficient for successful back analysis of the requested model parameters, while if set 1 or set 2 are used in the objective function, no reliable parameter set can be obtained. This means that only having the measurements at the top of one of the inclinometers it is not possible to calculate back the depth of the weathered zone and the properties of the non-weathered material. The reason for that is the non uniqueness of the inverse problem solution. It has been observed that with adding data for the back analysis the number of computation steps for obtaining the best fit decreases.

Reference data	Calculation steps	Obj. function calls	Approximate calculation time*
Data set 6	35 to 40	350 to 400	17.5 h to 20 h
Data set 3	50 to 55	500 to 550	25 h to 27.5 h

* On a computer with 3 GHz CPU and 2 GB RAM the forward solution takes approximately 3 minutes. Calculation time required by PSO algorithm can be neglected. Because no parallelisation is used the total execution time can be calculated by multiplying the number of objective function calls by the run-time to obtain one forward solution.

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

Parameter		Value
Cliff fall debris		
density	[]	2200
Young's modulus	[]	5E+03
Poisson's ratio	[-]	0.3
friction angle	[°]	40
dilatancy angle	[°]	0
cohesion	[kN/m²]	10
Detachment zone		
density	[kg/m³]	2600
Young's modulus	[MN/m²]	5E+03
Poisson's ratio	[-]	0.3
friction angle	[°]	40
dilatancy angle	[°]	5
cohesion	[kN/m²]	20
"Reichenhall" beds ("Reichenhaller Schichten")		
density	[kg/m³]	2200
Young's modulus	[MN/m²]	5E+04
Poisson's ratio	[-]	0.3
"Partnachmergel" (marls)		
density	[kg/m³]	2600
Young's modulus	[MN/m²]	5.0E+04
Poisson's ratio	[-]	0.3
Limestone: "Oberer Alpiner Muschelkalk", non-weathered		
density	[kg/m³]	2600
Young's modulus	[MN/m²]	5E+04
Poisson's ratio	[-]	0.3
Limestone: "Oberer Alpiner Muschelkalk", weathered (jointed material model)		
Density	[kg/m³]	2600
Young's modulus E_{OM}	[MN/m²]	5E+03
Poisson's ratio v	[-]	0.3
Joint system 1 (parallel to slope surface) / Joint system 2 (perpendicular to slope surface)		
friction angle φ_1 / φ_2	[°]	40 / 42
dilatancy angle ψ_1 / ψ_2	[°]	10 / 12
cohesion c_1 / c_2	[kN/m²]	350 / 400

Table 3: Material parameters for the numerical model of Reutte slope.

3 Identification of the jointed rock model parameters for the unstable slope Reutte/Tyrol

3.1 Geomechanical characterization of the problem

As an example of landslide model-parameters identification we chose to determine the disintegration features of limestone material ("Oberer Alpiner Muschelkalk") encountered in Tyrol. The numerical model has been done based on geological and geometrical data on unstable slope in the mountain splitting area Reutte/Tyrol in Austria. The Hornbergl / „Fauler Schrofen" area with the "Murenbach" torrent is situated in the Northern Calcareous Alps approx. 10 km southwest of Reutte in a chain of mountains, which frames the Reutte basin at a length of 6 km. The topographic map is given in Fig. 6. The tectonically structured and unstable geological setting together with a snow- and rain-loaded climate result in an above-average number of floods, debris flow and rock fall events, and existence of 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 have been 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 m^3);
- several small rockslides / cliff falls or block falls;
- several small-scale debris flow events (1982: 40 000 m^3).

The investigated slope is located in the forehead of the Lechtal Nappe, which has been overthrusted onto the Allgäu Nappe. Layered limestone of the Lechtal Nappe builds up the "Fauler Schrofen" mountain, i.e. the

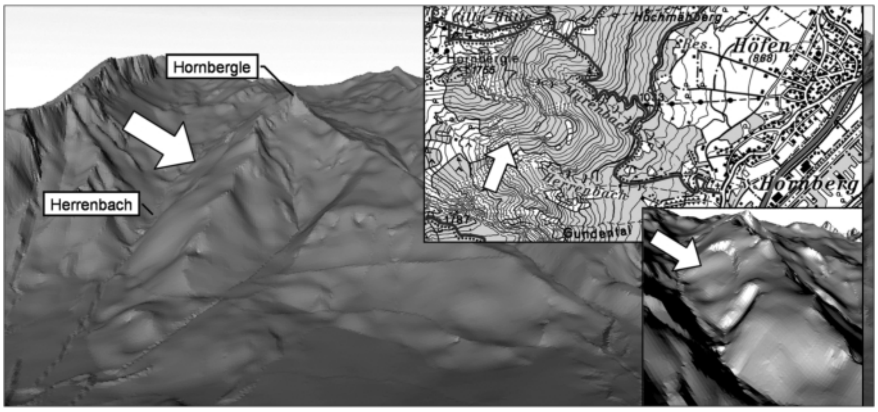

Figure 6: Situation of the mass movement at „Faulen Schrofen " Reutte/Tyrol (3D surface model with topographic map).

upper layer of "alpiner Muschelkalk" ("Oberer Alpiner Muschelkalk", Albrecht, 1999). 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. 7 (Albrecht, 1999; Meier et al., 2005). The limestone packages of the upper part of the "alpiner Muschelkalk" are characterized by clearly marked and persistent dipping downhill bedding surfaces. Between the thick bedded limestone there are embedded semi-indurated marl layers (thickness some cm) which alternate with small rock connections which bridge the ductile marl layers. Additionally, we have two joint systems perpendicular to the bedding surfaces. It has been recently observed at the upper part of the slope, above the main scarp that has been formed in 1976, the appearance of cracks and trenches, some decades of meters long and up to 1m wide. The wide spreading zones at the mountain crest show opening rates of up to 85 mm/a (Fig. 7; Moser et al., 2009). In summary the style of block movement involves dipping downhill slippage and creep of intact huge blocks along a weaker surface without appreciable rotation.

3.2 Description of the numerical model

A 2D model of the considered slope has been built within the finite element programme ABAQUS/Standard. The modelled area is depicted in Fig. 8. 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. Moreover the slope instability is governed mainly by the properties of the materials that compose the model in Fig. 8. Within the left and right range of the model the boundaries are selected in such a way to avoid inducing tension.

As the material "Oberer Alpiner Muschelkalk" mainly composing the upper body of the slope is known to be disintegrated due to lateral spreading and weathering, the constitutive law selected for its behaviour description is "jointed material model" as provided in ABAQUS/Standard model library (see ABAQUS Online Documentation and Zienkiewicz et al., 1977, for the model description). This material model reproduces the real behaviour by means of smearing the discontinuities. 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 parallel joint surfaces of high density. Based on geological investi-gation 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 behaviour of the bulk material is taken to be isotropic and elasto-plastic obeying the Drucker-Prager failure criterion. The joints behaviour 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:

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

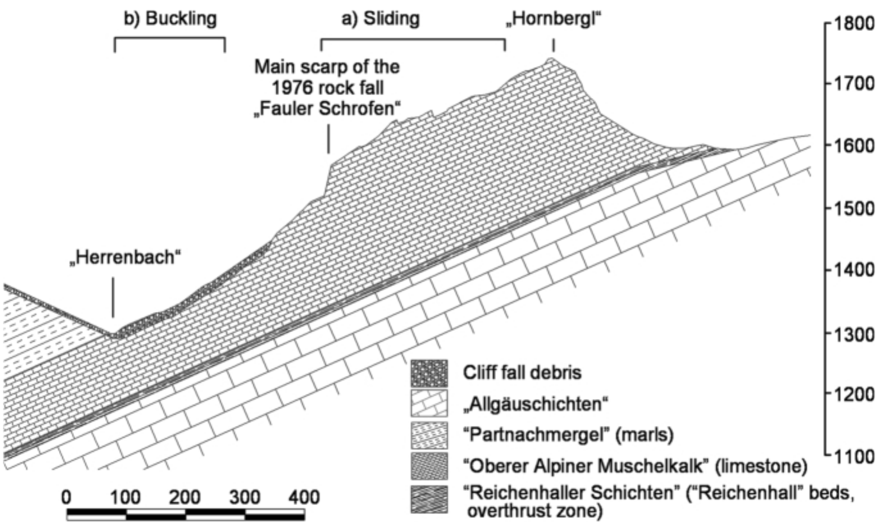

Figure 7: Engineering-geological profile within the range of the rockslide in 1976.

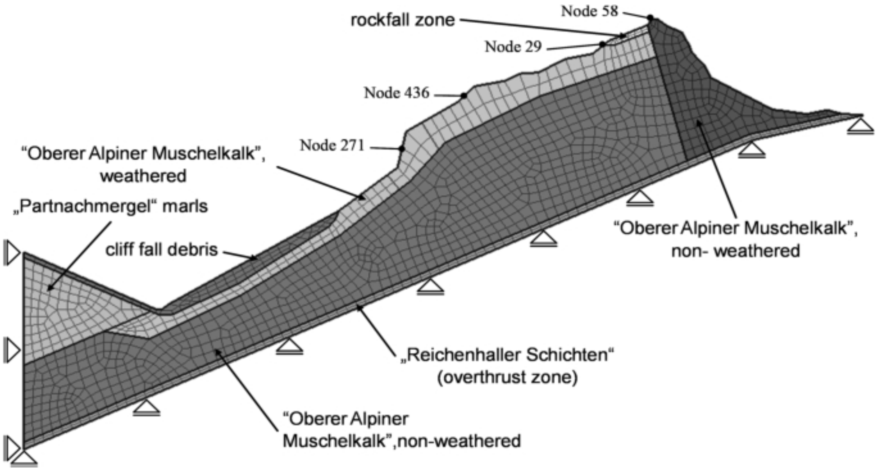

Figure 8: The 2D FE-modell for the Reutte slope.

weathering of the "Oberer Alpiner Muschelkalk" material. These data are further called measured data.

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; f_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. 8 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 constraint 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 MN/m² and $\varphi_1 = \varphi_2 - 2° = 30°$. This imposes displacements to put the model back at equilibrium. The displacements at four nodes as they are given in Fig. 8 are printed out and these data are used later in the performed optimization. Fig. 9 shows the displacements distribution after the last step of the procedure to simulate the weathering of the "Oberer Alpiner Muschelkalk" material. These data are further 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 objective function compares the measured and calculated displacements at four nodes (see Fig. 8). As in the previous example the PSO with ten individuals is used to determine the minimum of the objective function. The trusted zone for the PSO is given as it follows: $E_{OM} \in$[2E+02… 5E+03] MN/m² and $\varphi_1 \in$[25°… 40°]. The friction angle for the joint system 2 is given as $\varphi_2 = \varphi_1 + 2°$ and the dilatancy angle is $\psi_a = \varphi_a - 30°$ if $\varphi_a > 30°$ or elsewhere $\psi_a = 0$. Fig. 10 presents the objective function topology and it can be seen that in this case the particle swarm (black lines triangles) tends to go to the optimum point. The performance of the PSO is such that after 8 steps including 80 calls of the forward calculation it gives values of the identified parameters close to the true ones, namely E_{OM} = 7.14E+02 MN/m² and φ_1 = 30.1° and after 18 steps (180 calls of the forward calculation) already the optimum solution is obtained with E_{OM} = 6.99E+02 MN/m² and φ_1 = 30°. 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 used. 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".

4. Conclusions

The ability of iterative back analysis to identify slopes material and geometrical model parameters is verified by 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. In

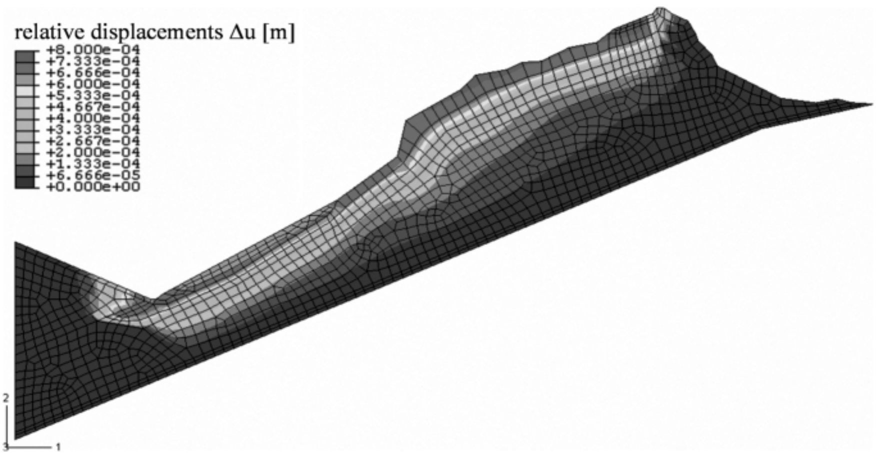

Figure 9: The distribution of the displacements after degradation of the jointed material properties.

this way the synthetic experiment has been used for better understanding which inclinometer data would be sufficient for the unique geometrical and material model identification. The second example considers a real natural slope. Analyzing several measurements on the slope surface in conjunction with simplifying assumptions regarding the geological situation, it is shown that the material properties featuring the degradation of jointed rocks due to weathering can be identified. 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. It can be concluded that back analysis is a useful tool for improving the quality of the numerical model and for increasing the confidence in the predictions regarding the behaviour of slopes as well as in the landslide risk analysis.

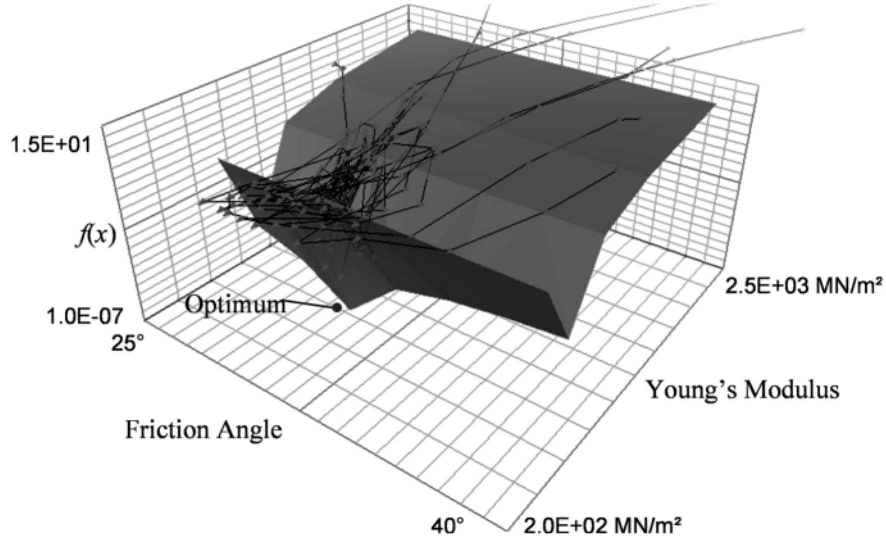

Figure 10: The objective function topology and the particles' paths.

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