Geomechanical Modelling as Central Component of a Landslide Alert System Prototype: Case Study 'Opencast Mine'

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Key words: Opencast mine, landslide analysis, structural FE-model, monitoring system, prediction of displacements

SUMMARY

Impact and risk assessment in a landslide area primarily requires the definition and reliable separation of different kinematic / geomechanical conditions of the slope. In the EU funded project OASYS five decision levels were defined to evaluate the current stability status, and to take adequate measures for instrumentation, monitoring and alerting

Normal operation ⇒ Low Margin Operation ⇒ Warning ⇒ Emergency ⇒ Post Mortem

To provide suitable indicators for allocation of the different levels is one major goal of the analysis of the landslide process and the task of an alert system. Structural models of land-slides, realized with Finite Element software packages like FLAC-2D/3D or Distinct Element methods like PFC2D/3D (from HCITASKA COMPANY) offer very comprehensive possibilities for the analysis and prediction of critical states of the slope. Representing its inner structure, numerical stress distribution indicators (i.e. a factor of safety) can be calculated.

In this paper the creation and combination of a geomechanical FE-model with a geodetic and geotechnical monitoring system of a test-slope is presented. The slope is located within an opencast mine in Northern Germany and is primarily influenced by mass excavation with bucket-wheel excavators.

Using the calibrated FE-model it is possible to predict in each excavation phase the 'normal' reaction (i.e. expected displacements in selected points) of the slope. It is also possible to simulate critical loads and parameter configurations that cause local or global failure events. Comparing the calculations with the empirical observations from the installed monitoring system it can be evaluated whether the slope is going further on to a normal or a critical state which may cause a slide.

The FE-model is planned to act as one central databased component within the prototype of a knowledge based alert system.

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1. INTRODUCTION

The EU funded project OASYS (= Integrated Optimization of Landslide Alert Systems) was located within the fifth framework program and handled by 13 international partners from geology, geomorphology, geodesy and civil engineering. The major goal of the project was to develop a multi-scale concept for the detection, monitoring and alerting of landslide processes (FINAL REPORT OASYS 2006) Within this concept five decision levels were defined to evaluate the current stability status of a slope and to take appropriate measures for monitoring and alerting:

Normal operation ⇒ Low Margin Operation ⇒ Warning ⇒ Emergency ⇒ Post Mortem

To provide suitable indicators for the allocation of the different levels is one important task for the analysis of a landslide process and for an alert system. A typical numerical value is represented by the factor of safety *FS* which is defined as the ratio of stabilizing forces (= shear strength) to destabilizing forces (= shear stress) (WITTKE AND ERICHSEN 2002):

$$FS = \frac{Soil\ Shear\ Strength}{Equilibrium\ Shear\ Stress}$$
$$FS >> 1\ (stable) \xrightarrow{FS} 1\ (failure) \qquad (1)$$

It must be calculated area-wide in different parts of the slope and is very sensitive to external influences (i.e. rain, and other loads) and internal structural changes (CROZIER 1986). To do this structural models of the landslide area represented i.e. by Finite Elements (FE) or Distinct Elements (DE) are very suitable.

One major working package of our institute was to create a realistic static geomechanical FE-model of a selected test-slope (KAMPFER 2005). The model is planned to act as one central databased component within the prototype of a knowledge based alert system. The practical application of the model is related with the following goals:

- To show exemplarily how a geomechanical FE-model can support a monitoring sys-tem concerning investigation and prediction of the deformation processes
- Detection of points of interest with (expected) most significant moving rates for the adequate adaptation of monitoring system and measuring rates => optimization of the measuring design
- Better understanding, interpretation and integration of measured time series (espe-cially focussed on tacheometric and GPS measurements).

- Capability to determine the current state of the slope not only in single points but within an area-wide network of finite elements (grid-width of several meters)
- Capability to predict or simulate normal and critical states (i.e. failure events) of the slope taking into account trigger events like mass excavation, rain etc.
- Capability to determine suitable warning respectively alerting factors for the reliable distinction between the five decision levels.

In figure 1 the basic architecture of the knowledge based alert system is shown. Using the calibrated FE-model the prediction respectively simulation of the (possibly critical) behaviour of the slope and its geomechanical parameters are planned to be used as input for the systems knowledge base. The additional consideration of hybrid expert knowledge will help to evaluate the databased results (inference) and to make the knowledge based decision to change from one alert level to the next one.

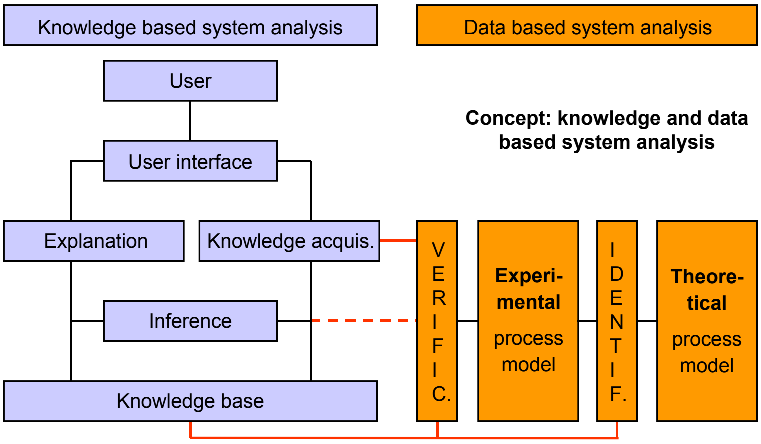

Figure 1: Concept of an alert system with a combination of knowledge and databased system analysis (EICHHORN 2005)

The functionality of the databased part is concretised in figure 2. It is exemplarily shown how a static geomechanical model can work to detect deviations from the normal behaviour of the slope. According to the selected study site opencast mine (see section 2), the main trigger events are assumed to be successive artificial excavation steps at discrete times t_k.

Using the calibrated FE-model it is possible to predict in each excavation phase the normal reaction (i.e. expected displacements in selected points) of the slope. It is also possible to simulate critical loads and parameter configurations that cause local or global failure events and to define and evaluate (plausibility) related levels of critical deformations. Comparing the calculations with the empirical observations from the installed monitoring system it can be evaluated whether the slope is going further on to a normal or a critical state which may cause a slide. Hereby one suitable indicator can be the gradient of the measured time series.

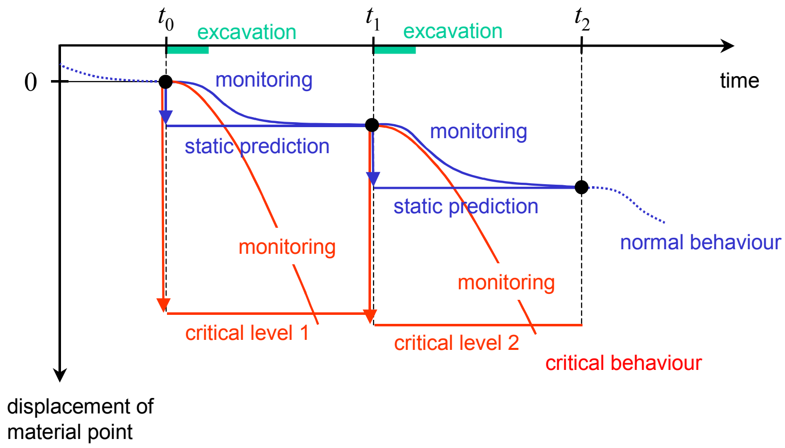

Figure 2: Usage of a static geomechanical model as deformation predictor with mass excavation as main influence factor (EICHHORN 2005)

2. SELECTED STUDY SITE

An opencast mine in Northern Germany was selected as suitable study site. Within this mining area a test-slope with significant trigger events (mass excavation by bucket-wheel excavators) was selected for permanent monitoring and the creation of the geomechanical model as essential precondition for an alert system prototype. In figure 3 the profile of the test-slope and one part of the permanent monitoring system are shown.

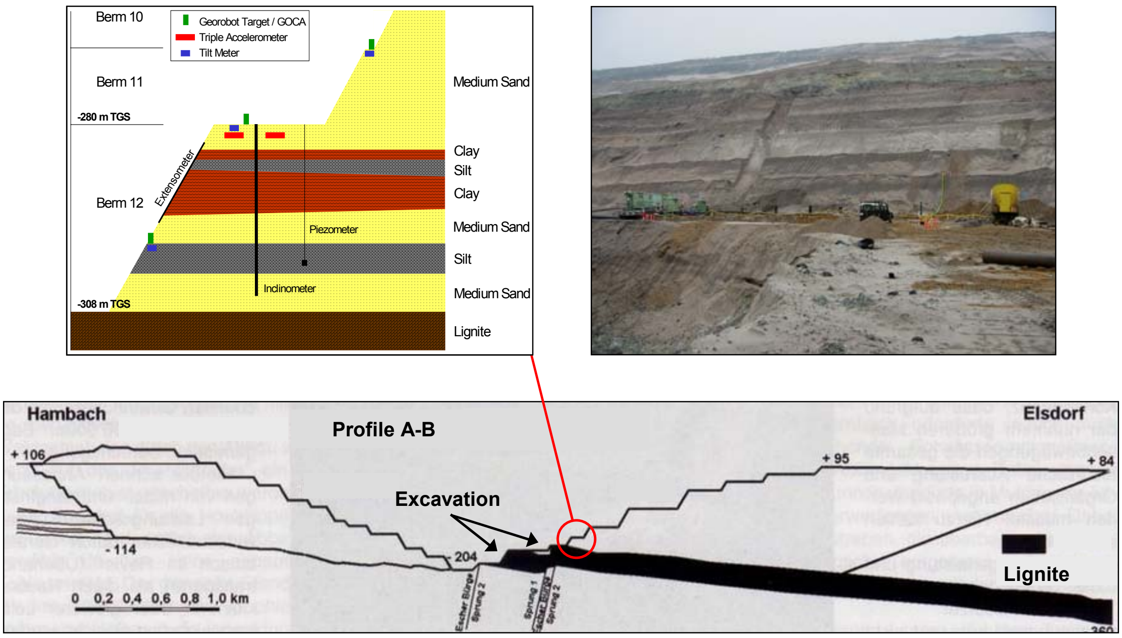

Figure 3: Test-slope with installed geotechnical monitoring system in opencast mine

The profile shows the different excavation steps whereby the boundaries are represented by berms. The whole area is monitored by a network of tacheometric (GEOROBOT) and GPS (GOCA) measuring points (see figure 4).

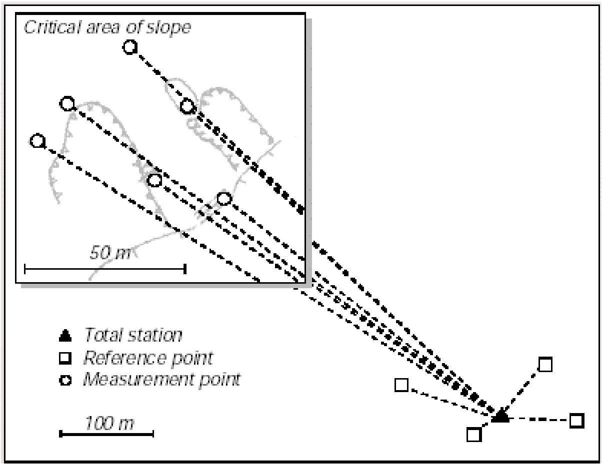

Figure 4: Monitoring system GEOROBOT and GOCA (PRADER 2003)

In addition geotechnical sensors are located at berm 12 in a depth between –280 and –308 m (measured from Top Ground Surface = TGS of the slope) directly over the lignite layer. Expecting an increasing excavation activity caused by the decomposition of the lignite and related mass movements this location was classified as a special area of interest.

3. GEOMECHANICAL FE-MODEL

3.1 Basic Design

For the creation of the geomechanical model the FE-software FLAC-3D (FLAC = Fast Lagrangian Analysis of Continua) from HCITASCA was used. This software is very common for static geomechanical modelling and enables the calculation of critical stress distributions and related failure events. It is based on the finite difference method, this means a linear relationship between external/internal forces and the displacements in defined nodal points. Principally a slope can be divided into 2-D or 3-D finite elements which represent the elastic behaviour by the specification of realistic material properties.

The main information base for the 2-D FE-model was the geological profile S75 with the state from 19.03.2004. It is a vertical cut through the selected test-slope along its line of steepest gradient (see also figure 3). This profile and related technical plans and documentations were used for the geometrical (number, spatial distributution and shape of elements) and physical design (material parameters, initial and boundary conditions, etc.) of the model.

In figure 5 the geological profile S75 is shown. The geology of the test-slope consists of several horizontal arranged sediment layers with a thickness from ca. 2 to 10 m. These layers contain three dominant material classes: medium sand, clay and silt. They are situated over a lignite layer with a mean thickness of ca 60 m.

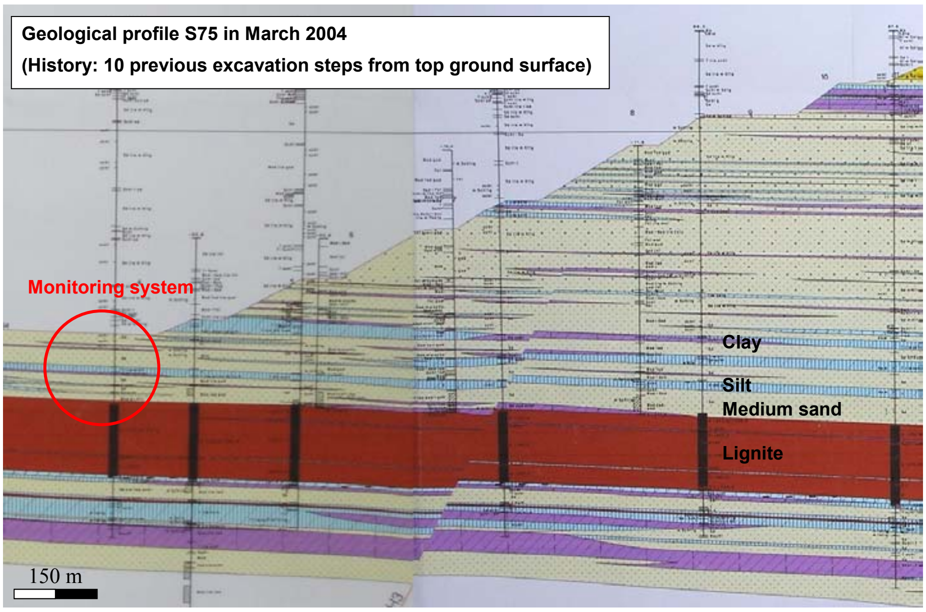

Figure 5: Geological profile as main database for the FE-model

The geological plan also shows a history of ten excavation steps (starting from TGS) and the resulting berms with a mean height of ca. 30 m as previous trigger events in march 2004. The area of the geotechnical monitoring system (which was installed in winter 2004/05) is still unexcavated. Its excavation was done by two further excavation steps 11 and 12. Finally step 13 went down directly into the lignite layer. This step was the last trigger event to be considered within the calculation workflow of the geomechanical model.

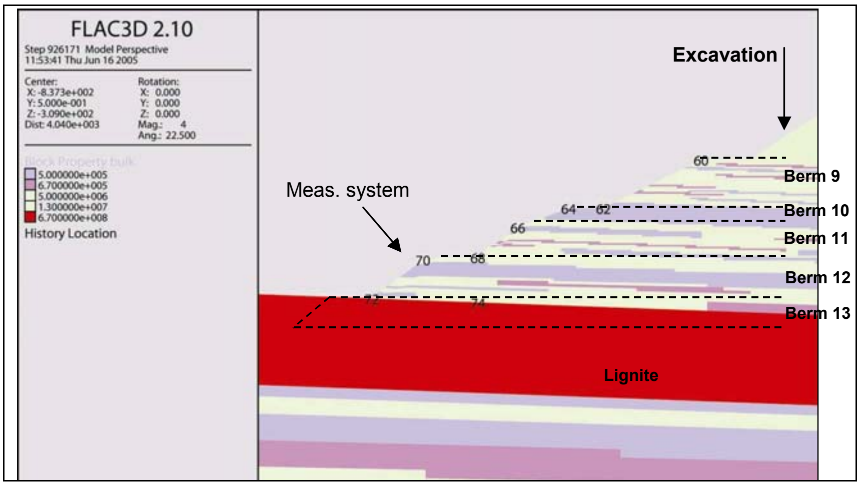

Figure 6: 2-D FLAC-model with selected points of interest (history points)

The final design of the slope model is shown in figure 6. The progress of horizontal and vertical displacements was calculated in selected history points which are distributed all over the model. Some of these model points are situated next to monitoring points (i.e. GEOROBOT targets) and are suitable for direct comparison with the displacement data.

3.2 Calibration of the Model

To obtain realistic calculation results which were suitable for comparison with the monitoring data an adaptation of the FE-model to the real deformation process was required. This model calibration contained

- the adaptation of the initial and bounday values of the model
- the adaptation of the physical parameters.

In geomechanical modelling it is very common to do this with try and error methods. This means comparing the calculated moving rates of selected history points with available monitoring data and adapting the geometrical and physical model parameters to fit. In our case especially GOCA data, GEOROBOT data and the results from precise levelling were used which cover the slope in a wide range and provide information about the absolute moving rates of the measuring points.

4. FIRST CALCULATION RESULTS

In this section some of the FE prediction results after model calibration are presented. The selected history points 68 and 70 are situated close to the installed geotechnical monitoring system. Their 2-D movements are referenced to a local (x,z)-coordinate system (= slope coordinate system, see figure 7) which is defined by the geometrical design of the FE-model.

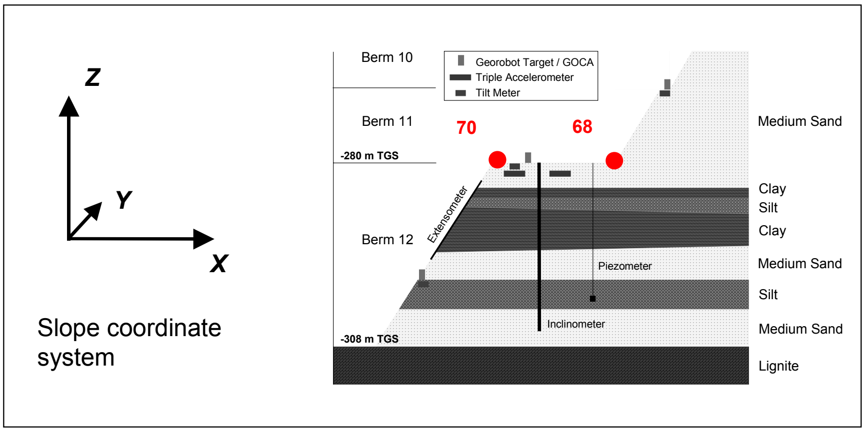

Figure 7: Location of history points 68 and 70

In figure 8 the predicted displacements of history point 68 as reaction to all 13 sequentially executed excavation steps are shown. The horizontal (x) and vertical (z) deviations are related to a static state before excavation step 1. The axis of abscissae represents the excavation depth starting from TGS (0 m) and going down to the lignite layer (≈ -310 to -370 m).

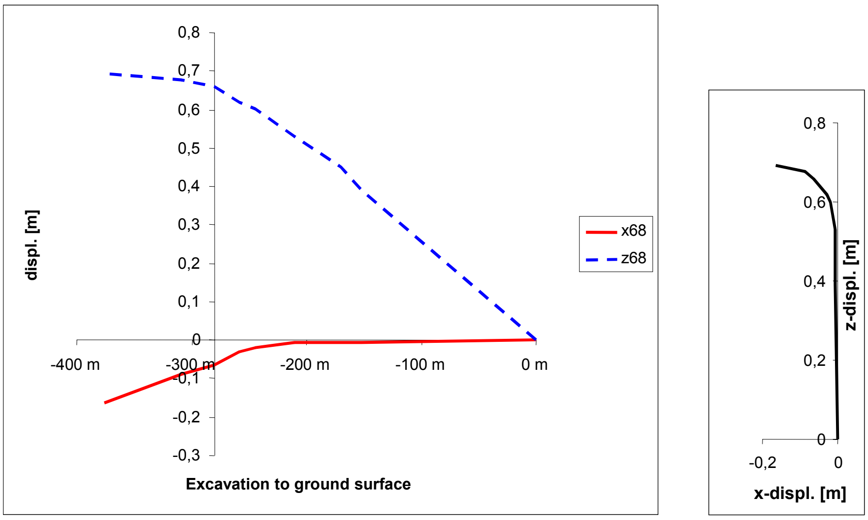

Figure 8: Prediction of horizontal (*x*) and vertical (*z*) displacements of history point 68

The point shows a nearly linear rising (≈ 0,7 m) and no significant horizontal movement until the lignite layer is reached by the excavation process. After this a reduction of the vertical movement can be observed. In addition the point starts a horizontal move out of the slope with a rate of ≈ -0,15 m.

The predicted rising of point 68 is the normal behaviour as a result of unloading effects caused by excavation and the related mass extraction. It is fitting the precise levelling results and the GEOROBOT data collected in this area. The horizontal movement is assumed to be induced by a horizontal sliding of the slope on the lignite layer. This interpretation is supported by the examination of the borehole inclinometer data (PRADER 2005). Summarizing it can be stated that there are no significant signs for any unstabilities in this part of the slope.

Considering the predicted move of history point 70 a local failure event can be observed (see figure 9). The event starts when the lignite layer is reached by the excavation process and causes a sudden horizontal move out of the slope and a vertical sagging of ≈ –1,5 m in each component. Finally the movement stabilizes itself. Referring to geotechnical experts these local instabilities represent normal behaviour and can not be evaluated as critical for the slope. But this example is very suitable to show how critical states of the slope with area-wide failures in clusters of history points could be predicted by the FE-model.

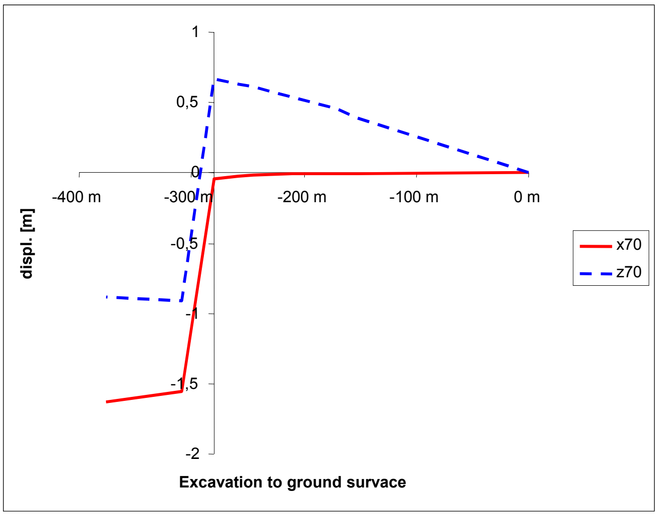

Figure 9: Prediction of a local failure event in history point 70

5. CONCLUSIONS

In conclusion the creation of a geomechanical 2-D FE-model can be evaluated as positive for the investigation and understanding of the internal physical structure of deformation processes related with the selected test-slope. The causative relationship between triggers (mass excavation by bucket-wheel excavators) and the slopes reaction (displacements in nodal points of the FE-grid) is sucessfully established and allows predictions of the expected deformations with a realistic magnitude. Defining in principle arbitrarily situated history points these predictions are not restricted to single cutouts of the slope but can be performed area-wide. In this respect the FE-model represents a flexible extension to the localised monitoring system.

An early evaluation of a possible risk potential can be performed by the detection of failure events (i.e. sagging of the grid geometry) and the calculation of a stable or unstable progress. The calculation of the internal distribution of normal and shear stresses can be used as input for numerical safety factors like (1).

Alternative calibration strategies and the integration of the FE-model into a knowledge based alert system will be subject of further investigations.

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- 3 years project member: “Analysis of dynamic deformation processes” (IAGB and IFW)
- 1 year project member: “Car navigation” (IAGB, DaimlerChrysler)
- 3 years project manager: “High precision DTM calculation” (IAGB, DaimlerChrysler)

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