Investigation of landslide failure mechanisms adjacent to lignite mining operations in North Bohemia (Czech Republic) through a Limit Equilibrium / Finite Element modelling approach

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Abstract

Understanding the impact of data uncertainty is a fundamental part of ensuring safe design of manmade excavations. Although good levels of knowledge are achievable from field investigations and experience, a natural geological environment is subject to intrinsic variability that may compromise the correct prediction of the system response to the perturbations caused by mining, with direct consequences for the stability and safety of the operations.

Different types of geoscientific evidence, including geological, geomorphic, geotechnical, geomatics, and geophysical data have been used to develop and perform two-dimensional Limit Equilibrium and Finite Element Method stability analyses of a lignite open-pit mine in North Bohemia (Czech Republic) affected by recent landslides. A deterministic-probabilistic approach was adopted to investigate the effect of uncertainty of the input parameters on model response. The key factors affecting the system response were identified by specific Limit Equilibrium sensitivity analyses and studied in further detail by Finite Element probabilistic analyses and the results were compared. The work highlights that complementary use of both approaches can be recommended for routine checks of model response and interpretation of the associated results. Such an approach allows a reduction of system uncertainty and provides an improved understanding of the landslides under study. Importantly, two separate failure mechanisms have been identified from the analyses performed and verified through comparisons with inclinometer data and field observations. The results confirm that the water table level and material input parameters have the greatest influence on the stability of the slope.

Keywords: Numerical modelling; Limit equilibrium method; Finite element methods; Probabilistic analyses.

1 Introduction

Analysis of slope stability is an important part of the design of human-made excavations and understanding of potential instability or evolution of natural slopes. Several different methods that analyse stability have been developed over the years with added sophistication and detail, thanks to improved knowledge and technological advances, as summarized by Francioni et al. (2017). Nevertheless, the uncertainty of model input data can frequently lead to simplification of methods to reduce the number of variables employed to obtain useful information about failure mechanisms and associated risk analyses. Traditional Limit Equilibrium Methods (LEMs) with relatively simple input(s) are, therefore, still commonly used by engineers and researchers all over the world (Alejano et al., 2011; Zhou and Cheng, 2015; Agam et al., 2016; Deng et al., 2016; Jiang et al., 2017; Salvini et al., 2017). LEMs, a review of which can be found in Duncan (1996) and Stead et al. (2006), are simple methods where stress–strain relations are not considered and where assumptions of internal force distributions are required. According to Morgenstern (1992), the latter is not a major issue in practical use, because different LEMs with different assumptions provide similar results. For Factor of Safety (FoS) calculations, however, instability mechanisms must be assumed a priori and this may be an important limiting factor in certain contexts. To overcome such limitations, more complex numerical methods have been developed in recent years. For example, in Finite Element Methods (FEMs), no assumption needs to be made regarding the failure surface (which is found automatically from shear strain development), failure mechanisms, or internal force distribution (Griffiths and Lane, 1999; Cheng et al., 2007). The development of FEM has allowed applications of stability analysis in complex geological contexts (van den Ham et al., 2009; Francioni et al., 2015; Spreafico et al., 2016; Xie et al., 2016; Fazio et al., 2017) where material deformations are accounted for, but limitations still exist that must be considered, such as long run-times in the case of complex models (Francioni et al., 2014) and the increasing number of variables relative to constitutive models, material parameters, and boundary and initial conditions of a given system (Cheng et al., 2007). These variables all have a significant influence on the development of certain stress/strain conditions within the model. Therefore, although FEMs allow for more complex and potentially more reliable analyses, the level of uncertainty of the input parameters may increase drastically.

Another key difference between LEMs and FEMs is the FoS calculation. Generally in LEM analyses, the FoS is calculated from the ratio of resisting moments to overturning moments, whereas in FEM analyses more complex techniques are applied. In this paper we focus on the Strength Reduction Technique (SRT), which is applied by reducing the shear strength of a material, bringing the model to a limit equilibrium state. Several applications of the SRT can be found in the literature, including Zienkiewicz et al. (1975), Naylor (1982), Matsui and Sun (1992), Ugai and Leshchinsky (1995), Griffiths and Lane (1999), Zheng et al. (2005), Wei et al. (2009), Tschuchnigg et al. (2015), and Ma et al. (2017).

In addition, FEM analyses may be incapable of determining other failure surfaces, which may be only slightly less critical than the SRT solution but still require investigation and potential remediation as part of good engineering practice (Cheng et al., 2007). When using the FEM/SRT method, it is common to have strain localization with the formation of a unique failure surface. Other possible simultaneous failure mechanisms, however, may not be easily identified. This is one of the reasons why Cheng et al. (2007) suggested that LEM and FEM analyses should be performed together as a routine check.

Stead et al. (2006) provided a review of developments of numerical modelling techniques and applications for characterization of complex rock slopes, illustrating how deformation and failure analyses may be undertaken using three levels of sophistication. These levels include conventional LEMs (level I), FEMs (level II), and hybrid methods (level III). In this paper, we have adopted a complementary approach that combines the use of the first two levels of analysis to optimize the workflow and reduce the degree of uncertainty. In open-pit mining operations, understanding the potential impact of data uncertainty within a geotechnical model is necessary to ensure efficient design of a mine. Data uncertainties derive from the recurrent difficulties in correctly predicting the inherently variable properties and characteristics of natural materials, which can be characterized into three groups: geological uncertainty, parameter uncertainty, and model uncertainty.

According to Read (2009), these can be summarized as follows:

Geological uncertainty refers to the unpredictability associated with the identification and geometry of the different lithologies and structures which constitute the geological model and the mutual relationships between them. It encompasses, for example, uncertainties arising from features such as incorrectly delineated lithological boundaries and major faults as well as unforeseen geological conditions.

Parameter uncertainty embraces the unpredictability of the parameters used to account for the various attributes of the geotechnical model. Typically, this includes uncertainties associated with the values adopted for rock mass and hydrogeological model parameters, such as the friction angle, cohesion, deformation moduli, and pore pressures.

Model uncertainty accounts for the unpredictability that surrounds the selection process and the different types of analyses used to formulate the slope design and estimate the reliability of the pit walls. Examples include the various two-dimensional LEMs/FEMs stability analysis methods and the more recently developed three-dimensional numerical stress and displacement analyses now used in pit slope design. Model uncertainty exists if the possibility of obtaining an incorrect result exists even if exact values are available for all the model parameters.

Based on the authors' experience, given the uncertainty present in natural contexts, a minimum FoS of 1.3 is suggested for reasonable assurance of safe slope design. The use of FoS < 1.3 and FoS < 1.5 as criteria is a useful addition to FoS < 1.0 in analyses where FoS = 1.0 is necessarily a small value that does not assure safe design. In this regard, acceptance criteria and interpretations suggested by Priest and Brown (1983), with proposed modifications by Pine (1992), consider a minimum FoS of 1.5 for interpretation of slope stability analyses.

Using a case study from an open-pit mine located in North Bohemia (Czech Republic), this paper demonstrates the use of different geoscientific evidence collected over recent years (geological, geomorphic, geotechnical, geomatics, and geophysical data) to back-analyse the reactivation of the landslide through an approach that involves two-dimensional LEM and FEM stability analyses.

Uncertainty is considered through performing initial sensitivity analyses, which are simple and time efficient because only a single variable is altered at a time, as well as more complex probabilistic analysis. Finally, the developed models are compared with field information, from direct observations to geotechnical inclinometer data interpretation, to calibrate and validate the models, making sure that the results are consistent with real observations. The potential for the presence of two separate failure mechanisms, one associated with deep-seated instability and the other linked to shallow superficial slope deformation, is also investigated.

For this case study, the Rocscience Slide7.0 and RS^2 software applications (Rocscience, 2017a) were used respectively for LEM and FEM analyses. The two-dimensional approach was chosen to decrease the level of model/geological uncertainty given that the case study area has a complex geometry and therefore a representative three-dimensional reconstruction is still difficult to achieve. For this reason, the authors preferred to simplify the analyses to improve the understanding of the dominant mechanism that affects the response of the system. In the authors' experience, complexity should be carefully studied before being included in numerical models, especially if increasing the number of variables reduces the level of control of the model response. Three-dimensional analyses may be performed, however, in further research following improved understanding of failure mechanisms from the two-dimensional simulations. Such back-analyses can help to improve the understanding of landslide processes, evaluate the effects of data uncertainty, and provide guidelines for mine or slope design purposes.

2 Geological setting

The study area is located in North Bohemia, where the Československá Armáda (ČSA) open-pit mine is located at the edge of the Mostecká Pánev Basin and the crystalline massif of the Krušné Hory Mountains (Fig. 1a).

With a depth of approximately 200 m, ČSA open-pit mine was the deepest mine in Czech Republic until 2009 and is formed by a high anthropogenic slope that passes smoothly (with an inclination of 10–15°) into the steep slopes of the Krušné Hory Mountains behind the margin of the basin (Burda et al. 2011). A schematic geological cross-section of the area is provided in Fig. 1b.

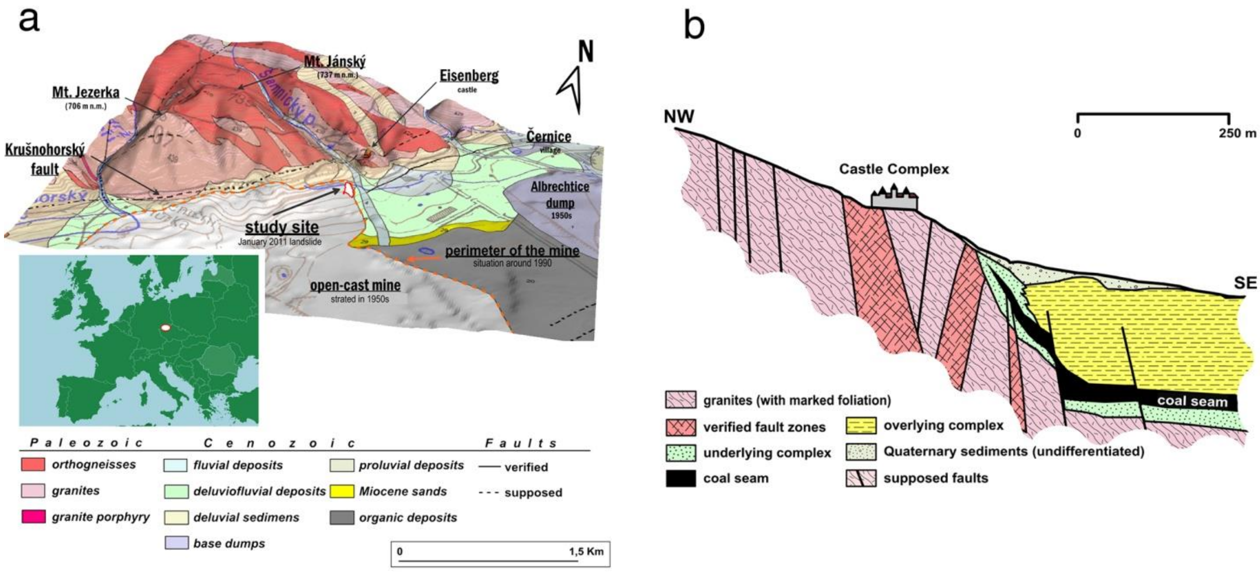

Fig. 1. General topographic and geological overview with inset map showing the study area location (a) and geological cross-section through the edge of the Most Basin and Krusne Hory Mountains (b); modified from Burda et al. (2011, 2013)

The sedimentary basin consists of an Underlying Complex (mostly lower Miocene sandy-clays), the coal seam, and an overlying complex (composed of upper Miocene claystones and Quaternary sediments). Burda et al. (2011) reported that the underlying complex is stratigraphically heterogeneous, with Tertiary clays, sandstones, and sands as well as Cretaceous quartzite, calcareous clays, marlites, and limestones. In addition, volcanic rocks, such as basalts, phonolites, and tuffs, have also been found in this complex. The overlying complex is also made up of clays and sandy-clays with variable occurrence of carbonates (Malkovský, 1985). The Quaternary sediments are comprised of coarse-grained gravel, sandy gravel, and clays with crystalline fragments, with thicknesses ranging from 0.1 to 40 m (Burda et al., 2011).

A dramatic slope deformation which started in 1952 (Rybář, 1997) resulted in the abandonment of the village of Eisenberg, but mining operations continued in the form of open-cast exploitation (Burda et al., 2013). According to Hurník (1982), the removal of millions of tons of overburden material per year (in the 1970s and 1980s) could have caused the elastic lifting of the mountain massif and the destabilization of the upper part of the slope. In this regard, recent studies (Burda et al., 2011; Burda et al., 2013) confirmed an influence of mining, mainly in the mountains' piedmont, where the basin sediments were exposed during excavations.

In January 2011, the area experienced a reactivation of the landslide, which can be related to failure of the overlying Quaternary sediments. This recent failure represented one of the largest flow-like landslides of the Czech Republic (Klimeš et al., 2009; Pánek et al., 2011) and occurred outside the active portion of the ČSA mine, with the landslide material reaching the bottom of the open-pit coal mine (Burda et al., 2013). According to Burda et al. (2013), such reactivation was triggered by a rising water table induced by rapid snowmelt during a period of winter warming. They concluded that the movement accelerations occurred when a theoretical pore pressure of 68 kPa was present at the depth of the shear plane, which was approximately located at the interface between the Quaternary sediments and the Miocene claystones. As far as the drainage is concerned, a system of drainage wells was used in the 1980s and replaced with surface ditches in the 1990s after the mining activities were stopped in this part of the mine.

A detailed map of the mine area affected by the landsliding is shown in Fig. 2, while Fig. 3 shows the 2D Electrical Resistivity Tomography (ERT) profiles (including boreholes, inclinometers, and piezometer data).

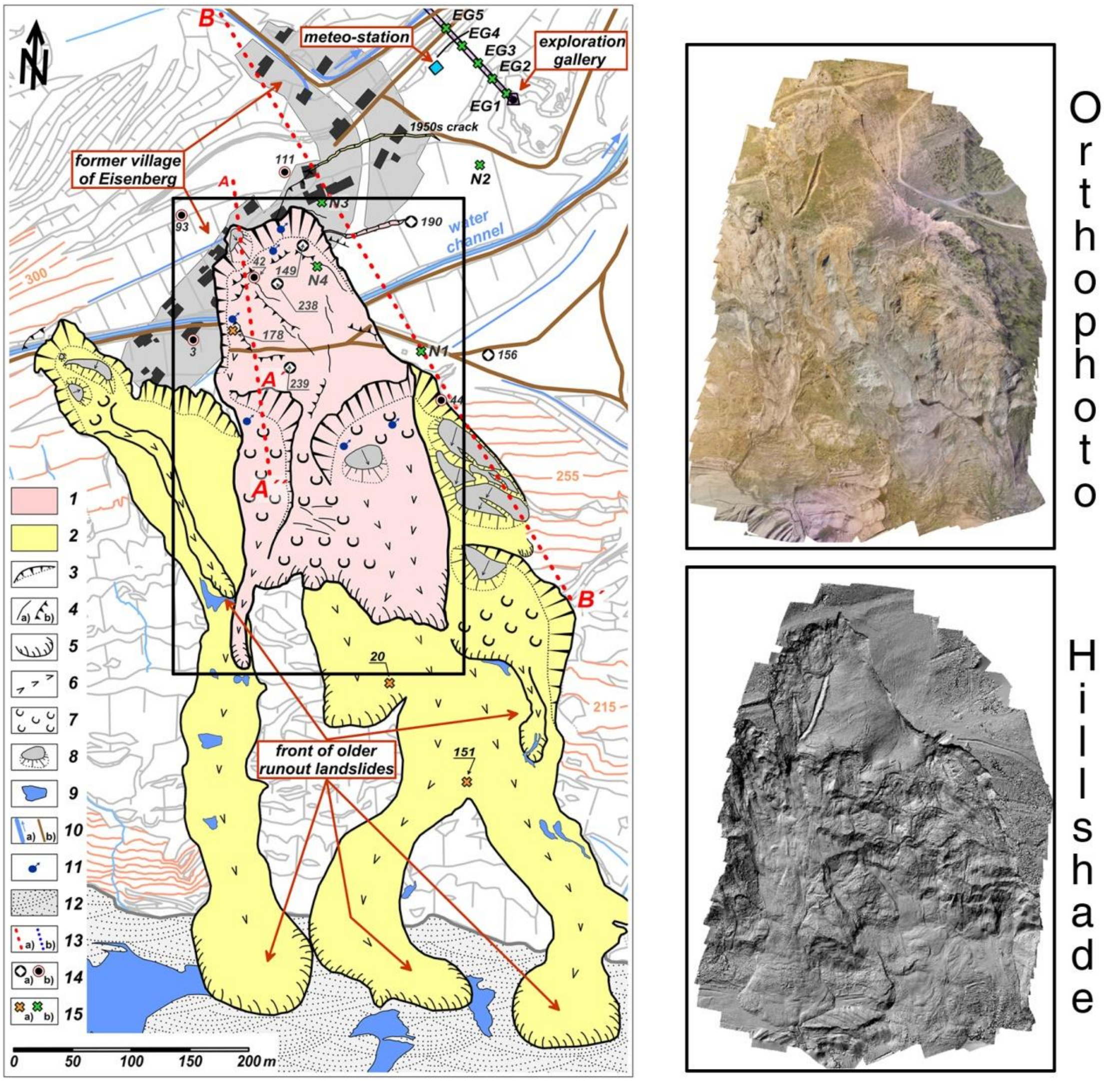

Fig. 2. A geomorphological sketch map of the area around the landslide that occurred during January 2011: (1) the landslide of January 2011; (2) older landslides within the landslide complex; (3) headscarps; (4) (a) tension cracks, (b) tension cracks with vertical offset; (5) accumulation toes; (6) earthflows; (7) landslide accumulation surfaces; (8) landslide blocks within the landslide complex; (9) shallow colluvial depression; (10) (a) brooks and channels, (b) road; (11) spring; (12) dump; (13) (a) ERT profile, (b) longitudinal profile across the landslide; (14) (a) inclinometer borehole (b) structural test hole; (15) observed geodetic points (a) ATR – reflective prism, (b) precise levelling – bench marks (modified from Burda et al., 2013)

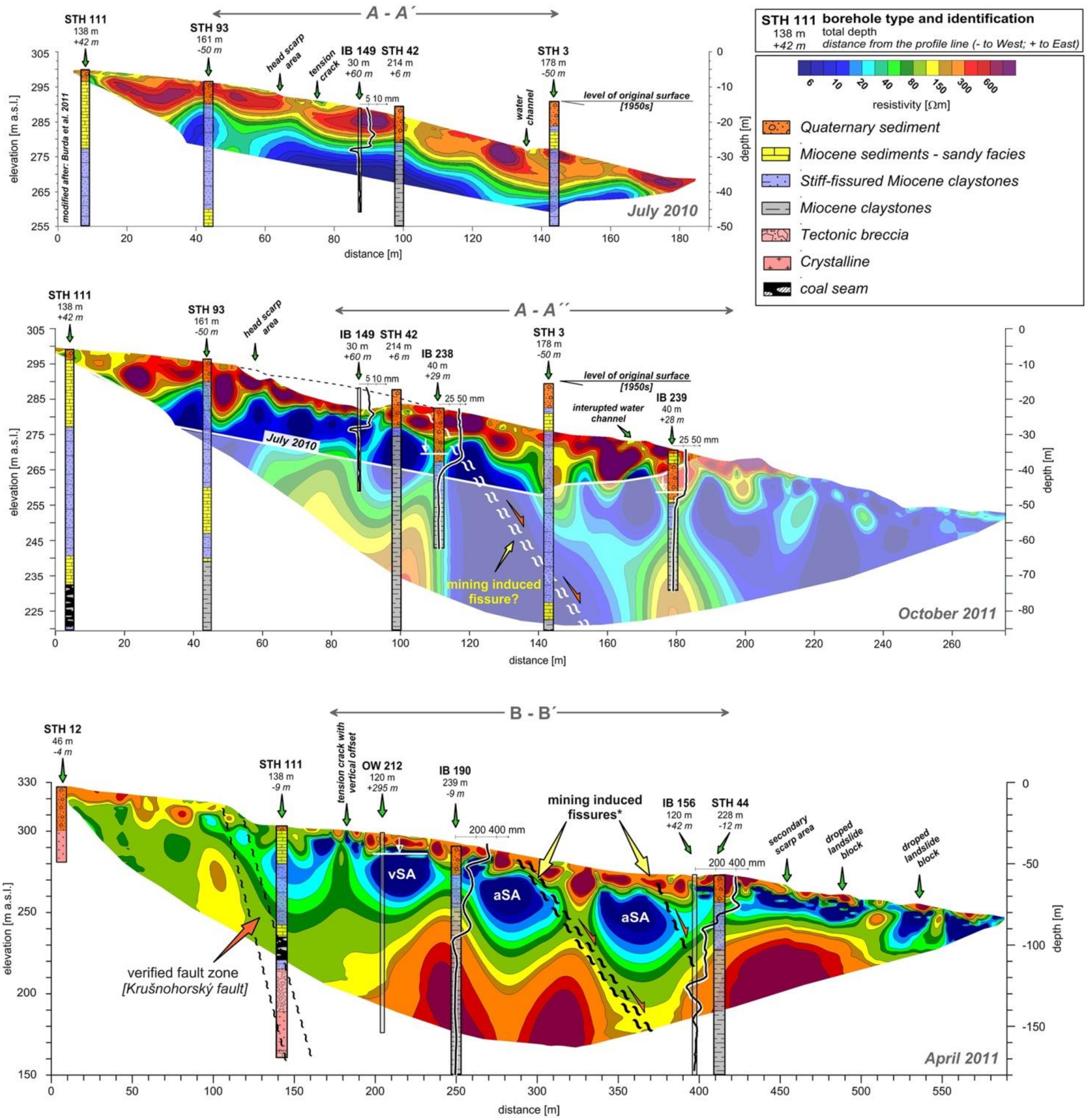

Fig. 3. The ERT profiles taken across the landslide (locations depicted in Fig. 4). STH: structural test hole; IB: inclinometer borehole; OW: observation well; vSA: verified shallow aquifer; aSA: assumed shallow aquifer (from Burda et al., 2013)

As observed from the inclinometers shown in Fig. 3, the failure surface of the reactivated landslide (profile A-A'') can be approximately located at the interface between the Quaternary sediments and the Miocene claystone (at a depth of about 10–15 m). In addition, evidence of the old deeper landslide (dated back to 1952), described as a deep-seated rotational failure (Burda et al., 2013), is present on inclinometers located along profile B-B', which is relatively close to the position of the reactivated shallow landslide. This suggests that the presence of two different failure mechanisms within the study area cannot be excluded.

3 Limit Equilibrium Method analyses

In this study, the focus was on the development of an improved understanding of the landslide reactivated in January 2011, which occurred along profile A-A" depicted in Fig. 2. The 2D model used in the analyses is shown in Fig. 4; it considers the pre-failure shape and has been derived from the geometrical/geological information obtained from Figs. 2 and 3 and the topographic data provided directly by the mine. The profile of the slope has been extended to consider the potential influence of extraction of the lignite at the base of the slope, which in this area is more than 200 m deep. The preliminary LEM analysis regarding the effect of uncertainty was carried out by using the Slide7.0 software and adopting the Mohr-Coulomb linear criterion (with parameters φ and c) and the vertical slice Janbu corrected method (Janbu, 1973). Considering the presence of different geological strata that may influence the shape of the failure surface, a non-circular surface type approach, with the Cuckoo Search method, was adopted. The Cuckoo Search method (Yang and Deb, 2009) is considered a fast and efficient global method of locating non-circular critical surfaces that is not affected by local minimum solutions, which may be possible when using other surface search methods (e.g. block and path search).

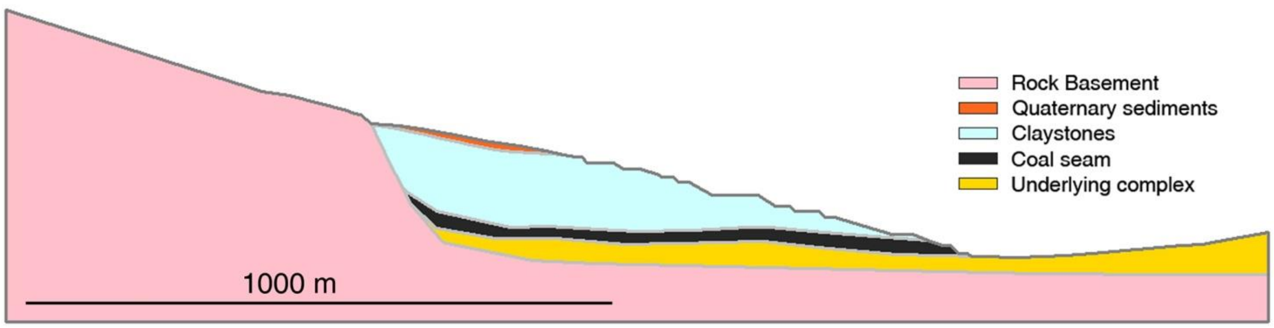

Fig. 4. Longitudinal profile used for the stability analysis (no vertical exaggeration is applied)

3.1 Deterministic and sensitivity LEM analyses

For this case study, given the detailed geometrical information such as borehole data and ERT profiles, the major source of uncertainty is associated with data input relating to the material properties (parameter uncertainty).

The first step of the sensitivity analysis was to vary the parameters across a range of values, observing the effect on the final calculated FoS. Using this methodology, it is possible to determine which parameters have the most influence on the stability of the slope. For a sensitivity analysis in Slide7.0 it is necessary to determine relative (distance from the mean value) minimum and relative maximum values across which the analysis can be performed. This can also be expressed in terms of two or three standard deviations away from the mean value. The values used (Pichler, 1989) in the sensitivity analysis, based on the mine operator’s laboratory test data (taken from boreholes within the ČSA mine, where the majority of the geotechnical investigation focused on the basin–mountain contact area) and model calibration, are shown in Table 1 (the reported parameters are intended as peak effective values). As observed, the properties indicate relatively poor to weak geotechnical materials that explain the rotational movement indicated in previous analyses, which would tend to exclude pure discontinuity-controlled failure mechanisms.

Table 1
Sensitivity analysis: Relative MINIMUM and MAXIMUM values for each geological formation

Material	Property	Mean	Rel. Min.	Rel. Max
Rock basement	Cohesion (kPa)	1000	500	500
Rock basement	Unit weight (kN/m^3)	25	5	5
Rock basement	Phi (°)	42	5	5
Quaternary sediments	Cohesion (kPa)	5	5	5
Quaternary sediments	Unit weight (kN/m^3)	20	5	5
Quaternary sediments	Phi (°)	27	5	5
Claystones	Cohesion (kPa)	100	50	50
Claystones	Unit weight (kN/m^3)	20	5	5
Claystones	Phi (°)	18	5	5
Coal	Cohesion (kPa)	50	25	25
Coal	Unit weight (kN/m^3)	14	5	5
Coal	Phi (°)	25	5	5
Underlying complex	Cohesion (kPa)	40	20	20
Underlying complex	Unit weight (kN/m^3)	20	5	5
Underlying complex	Phi (°)	24	5	5

The water table was also initially considered in the deterministic analysis, whose results (mean values) and associated sensitivity analysis are provided in Fig. 5.

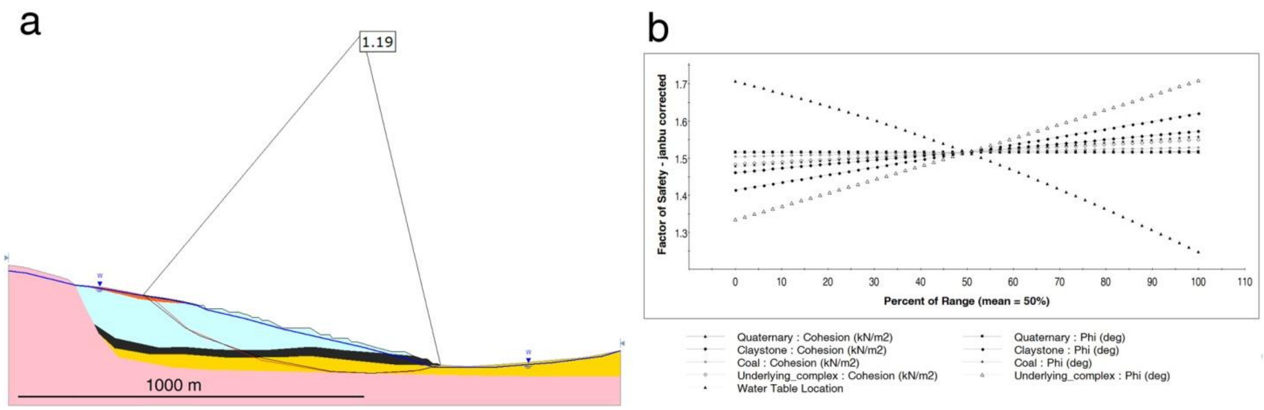

Fig. 5. Slide7.0 LEM deterministic stability analysis results with indication of global minimum FoS (a) and LEM sensitivity analysis results (b) (no vertical exaggeration is applied)

As observed in Fig. 5, the failure surface with the minimum FoS is a deep-seated surface that passes through the underlying complex, coal seam, and claystone layers. The analysis undertaken has not provided a good representation of the shallow failure surface that developed at the interface between the Quaternary sediments and the claystone layer. In addition, it can be seen that the modelled water location has the greatest influence on the FoS results. In particular, if the effect of water in the slope is removed, the FoS rises to about 1.7.

According to Burda et al. (2013), the permeability of the claystone layer is highly variable and is influenced by continuity and thickness, mainly in the upper part of the geological formation, and by the varying properties of the clay. The inclusion of a water table in the simulation, however, leads to a low FoS (< 1.3), which, given the uncertainty of some input data, may indicate potential deep instability at an overall slope scale. In this context, the uncertainty related to the water distribution in the slope is a major issue. The results of Pletichová (2006) and 2D ERT interpretations highlighted by Burda et al. (2013) concur in identifying the presence of a high-resistivity layer formed by permeable slope deposits (Quaternary sediments) that overlie a water-saturated zone, probably corresponding to the altered claystone. At the base of this zone, another high resistivity area exists that most likely relates to impermeable (< 10–8 m s^{-1}) dry compact claystones. Therefore, the altered permeable claystone level is likely to hold water, resulting in perched or raised water pressures and thereby creating an ideal sliding plane for the landslide. Consequently, it is possible to hypothesize that deep water infiltration may also be precluded (at least in part) by the impermeable claystone level. Other parameters that showed the highest influence on the FoS are the friction angle of the underlying complex and the friction angle and cohesion of the claystone. This highlights the importance of good site investigation to establish, where possible, the range of variation of material strength parameters.

3.2 Probabilistic LEM analysis

In general, the sensitivity analyses indicated that the most critical situation in this model is relative to a deep-seated failure surface that involves the underlying complex, coal seam, and claystone levels and shows little to no evidence of a shallow landslide involving the Quaternary sediments. Consequently, probabilistic stability analyses were carried out in two stages: with initial focus on an overall slope scale and subsequent evaluation of the shallow near-surface Quaternary strata.

In a probabilistic analysis, it is possible to associate a statistical distribution to the model input parameters, accounting for the degree of uncertainty in the parameter values. In Slide7.0, input data samples are randomly generated based on the user-defined statistical distribution. This results in a distribution of the FoS from which the probability of failure for the slope can be calculated. The default random sampling in Slide7.0 is the Latin Hypercube Sampling method (used for this analysis). With reference to the Slide7.0 user manual (Rocscience 2017b), the Latin Hypercube method is based on "stratified" sampling, with random selection within each stratum. Typically, an analysis using 1000 samples obtained by the Latin hypercube technique will produce comparable results to an analysis of 5000 samples using the Monte Carlo method.

In this case, the probabilistic analysis is focused on the claystone and underlying complex parameters (highlighted by previous sensitivity analysis results), including (Fig. 6a) and excluding (Fig. 6b) the water content in the deeper levels (claystones, coal seam, and underlying complex, according to previous interpretations from Pletichová, 2006, and Burda et al., 2013).

The material statistics are provided in Table 2.

Table 2
Statistical properties used in the probabilistic analysis for each geological formation

Material	Property	Distribution	Mean	Std. Dev.	Rel. Min.	Rel. Max.
Claystones	Phi (°)	Normal	18	1.66	5	5
Claystones	Cohesion (kPa)	Normal	100	16.6	50	50
Underlying complex	Phi (°)	Normal	24	1.66	5	5
Underlying complex	Cohesion (kPa)	Normal	40	6.6	20	20

Without evidence for any other distribution, a normal distribution was adopted in this case study, with Standard Deviation (Std Dev) values estimated using the following equation (1):

$$\sigma = \frac{\text{HCV} - \text{LCV}}{6} \quad (1)$$

where HCV is the highest conceivable value of the random variable and LCV is the lowest conceivable value of the random variable (Duncan, 2000).

Results of the probabilistic analyses are given in Fig. 6.

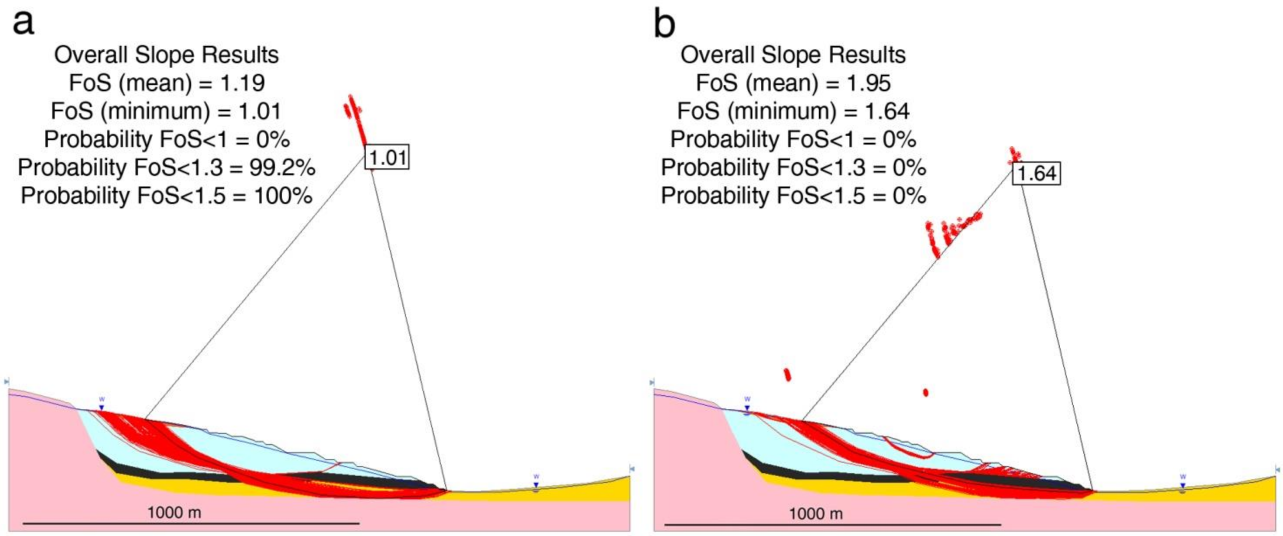

Fig. 6. Results of Slide7.0 LEM probabilistic analyses performed including (a) and excluding (b) the effect of the water table at deeper levels (claystone, coal, underlying complex) (no vertical exaggeration is applied)

Again, the critical failure surfaces, depicted in Fig. 6, do not refer to the Quaternary strata but possible deep-seated instability on an overall scale is highlighted. The results indicate, however, a 99% probability of FoS < 1.3 in “wet” conditions and a 0% probability of FoS < 1.3 in “dry” conditions.

3.3 Focus on the instability of Quaternary deposits

The results illustrated so far show how the lowest FoS values refer to possible instability at an overall slope scale and do not replicate the superficial landslide observed at the mine site associated with the Quaternary sediments. In detail, the failure surfaces that involvet the Quaternary deposits show a minimum FoS of 2.13, with a 0% probability of failure, even considering a minimum FoS of 1.5.

Analysis of the data (not shown) indicates that even with a combination of low friction angle and high water table, FoS values lower than 2 are not obtained within the Quaternary sediments. This result does not match field observations, where instability on superficial strata has been detected, and a more in-depth study of the parameters of the Quaternary layer is required. For clarity, a possible hypothesis, based on what is stated in Burda et al. (2013) concerning the presence of an altered permeable claystone level at the bottom of the Quaternary sediments (mainly detected through 2D ERT surveys and analysis of landslide deposit material), needs to be explained before undertaking further simulations. It is possible that in the case of abundant water infiltration, because of precipitations and snow melting during spring time, this altered claystone level may become saturated and water flow parallel to the slope may occur at the interface with an impermeable level in the claystone. Considering the low depth of this level (10–15 m) with respect to the length of the slope (more than 200 m), it is possible that under these circumstances the slope approaches a condition similar to an *infinite saturated slope*. For a saturated slope in this condition, the critical slope angle is about half that of a completely dry slope ($\tan\alpha_{crit} \sim 1/2 \tan\varphi$).

To try to simulate this effect, a new layer with a low friction angle (about half of that of the claystone, 9°) at the base of the Quaternary sediments was included in the model. This is aimed at simulation of the superficial alteration of the claystone layer, which could respond as a saturated soil. Results of the analysis are shown in Fig. 7. Although the natural variability of the altered layer is unknown, this analysis provides an initial starting point to assess its potential impact on the shallow landslide.

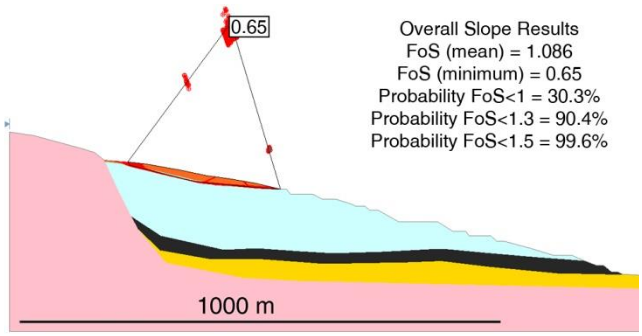

Fig. 7. Result of Slide7.0 LEM probabilistic analysis focused on Quaternary sediments (no vertical exaggeration is applied)

It is possible to see that the FoS in this case is closer to what is expected from field observations, with up to 99.6% probability of failure considering a minimum FoS of 1.5. Complex slope movements, with different deformation mechanisms, cannot be fully replicated and simulated with LEM analysis. This is because plastic deformation and degradation of material properties are not considered in such an analysis. Deformations of the deeper geological strata could have played a role in triggering the rapid and shallow landslide reactivated in January 2011. Therefore, more complex numerical modelling analyses should be carried out to fully understand the implications of the observed landslide at the mine site. An example of such analysis is described in the next section.

4 Finite Elements Method analyses

The analysis was carried out using the 2D FEM analysis software RS^2, following the same logic as the previous Slide7.0 analyses. Using the available material properties, a Mohr Coulomb failure criterion was adopted for the analyses. To simulate the plastic response of the different materials, the values highlighted in Table 3 have been adopted (approximate test data, subjected to calibration):

Table 3
Young's modulus and Poisson's ratio utilized in the RS^2 FEM analysis

Material	Young's Modulus (MPa)	Poisson's Ratio
Rock basement	100000	0.2
Quaternary sediment	200	0.3
Claystone	5000	0.25
Coal seam	1000	0.3
Underlying complex	200	0.3

To simulate the progressive mining activity undertaken at the case study site, 18 excavation stages have been included in the numerical analysis.

4.1 Deterministic FEM analysis

In keeping with previous results, the first FEM deterministic analyses have been carried out using the same profile as shown in Fig. 4, initially considering the presence of water in all geological strata (Figure 8a) and then confining it only to the Quaternary sediments (Figure 8b). The results of these analyses, which allow consideration of the effect of water level on the model, are shown in Fig. 8.

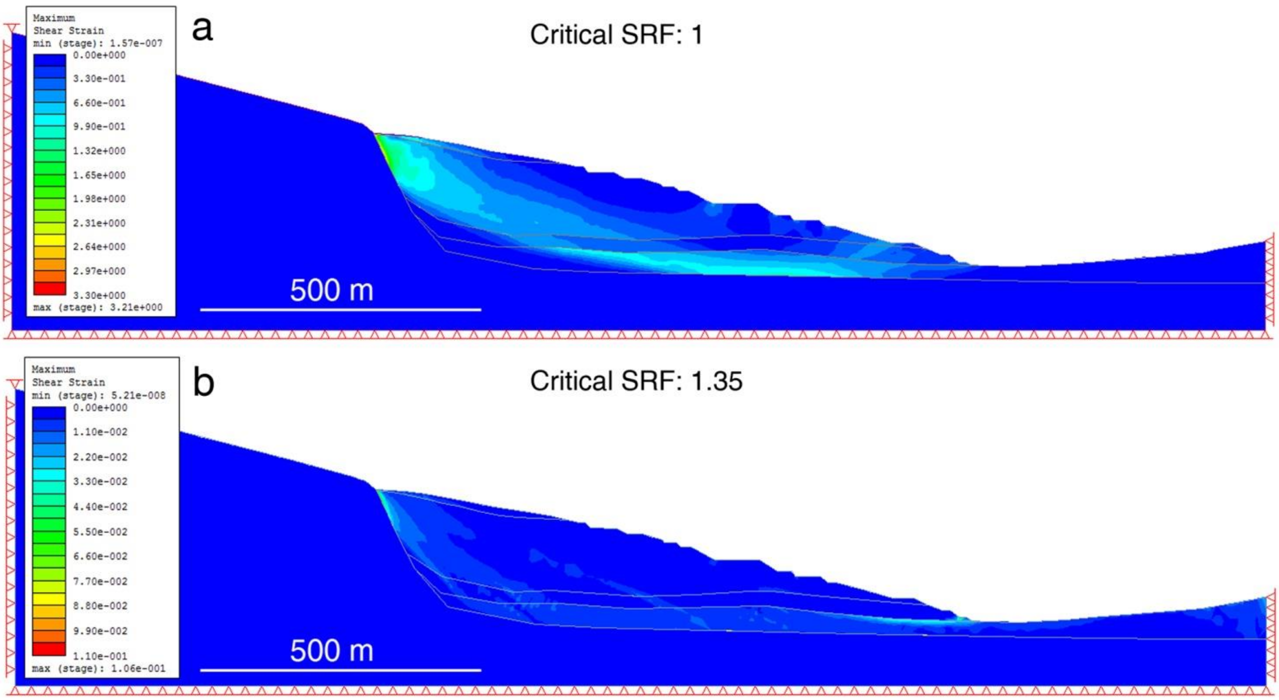

Fig. 8. Shear strain development depicted in preliminary RS^2 numerical modelling (no vertical exaggeration is applied)

In this case, the analyses show the development of shear strain values in deeper strata, similar to that observed from the LEM analysis. The critical detected values of the Shear Reduction Factor (SRF, calculated with the SRT; in this work SRF and FoS are used as synonyms for convenience) are equal to 1 and 1.35. The inclusion of water content in deep levels leads to very low values of the critical SRF (1) and high values of shear strain that do not match field observations. Moreover, no indication of the shallow landslide highlighted earlier in the Quaternary sediments exists. Therefore, in a similar way to what was performed with LEM analyses, a new model RS^2 was created including the altered claystone level. The slope was considered dry, with a low friction angle (9°) assigned to the altered claystone to simulate the effect of the water flow on the strength properties of the material. The result of the analysis is shown in Fig. 9.

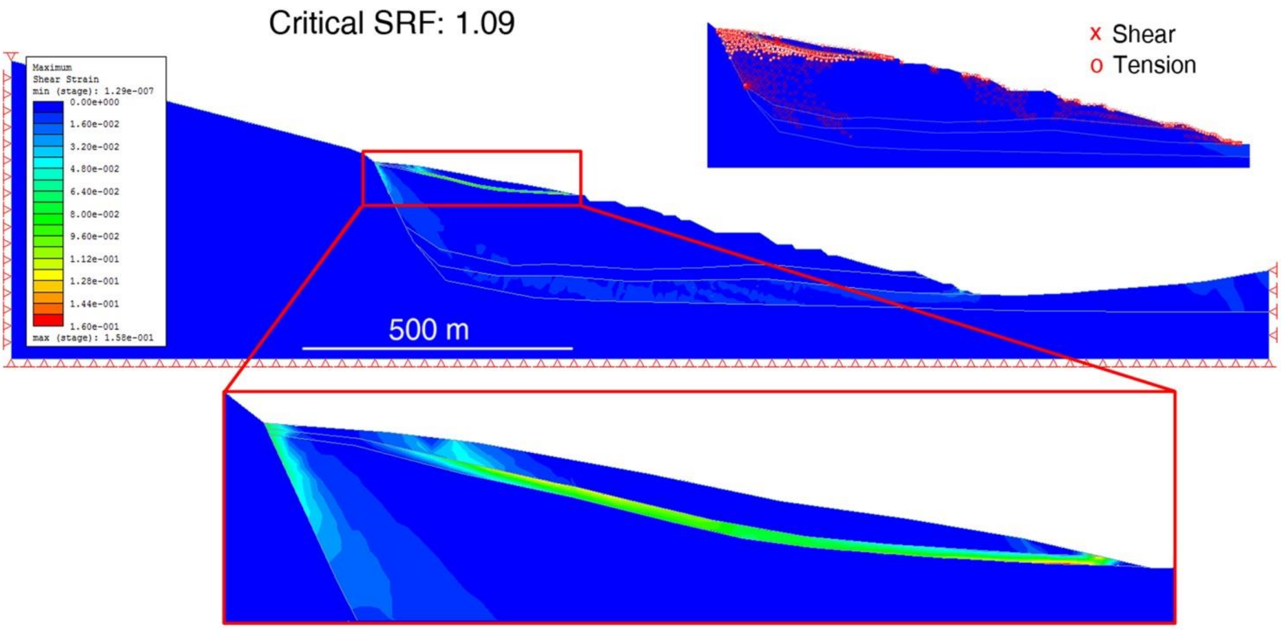

Fig. 9. Shear strain development depicted in preliminary RS^2 numerical modelling (no vertical exaggeration is applied)

The critical SRF value in this case is 1.09 and replicates the observed shallow landslide affecting the Quaternary sediments, indicating that the two different failure mechanisms (shallow landslide and deep-seated movements) have different FoS values of 1.35 (Fig. 8b) and 1.09 (Fig. 9), respectively.

To understand the reliability of these results, inclinometer data have been used for comparison. In this case, two sets of inclinometer data were selected (Fig. 10): IB149 (in the landslide area) and IB156 (near the landslide area). Locations of the two inclinometers are shown in Fig. 2. Even if the last readings date back to 2004, they still provide useful information. The IB149 inclinometer data suggest the location of a shallow landslide associated with deformation at approximately 12 m below the surface. IB156 suggests two distinct deformation horizons, one related to the shallow landslide and the other at depth that may be indicative of deep-seated instability.

It should be noted that the two inclinometers do not reach the same depth. IB149 (inclinometer 1), located in the landslide area, reaches a depth of only approximately 30 m whereas IB156 (inclinometer 2) reaches a depth of 120 m. The data from the two different inclinometer locations were simulated and analysed during the numerical simulation in RS². The results of the simulation are shown in Fig. 10 (data were collected in stage18, the last excavation stage). The modelled deformation reflects the shallow and deeper movements observed in the inclinometer boreholes.

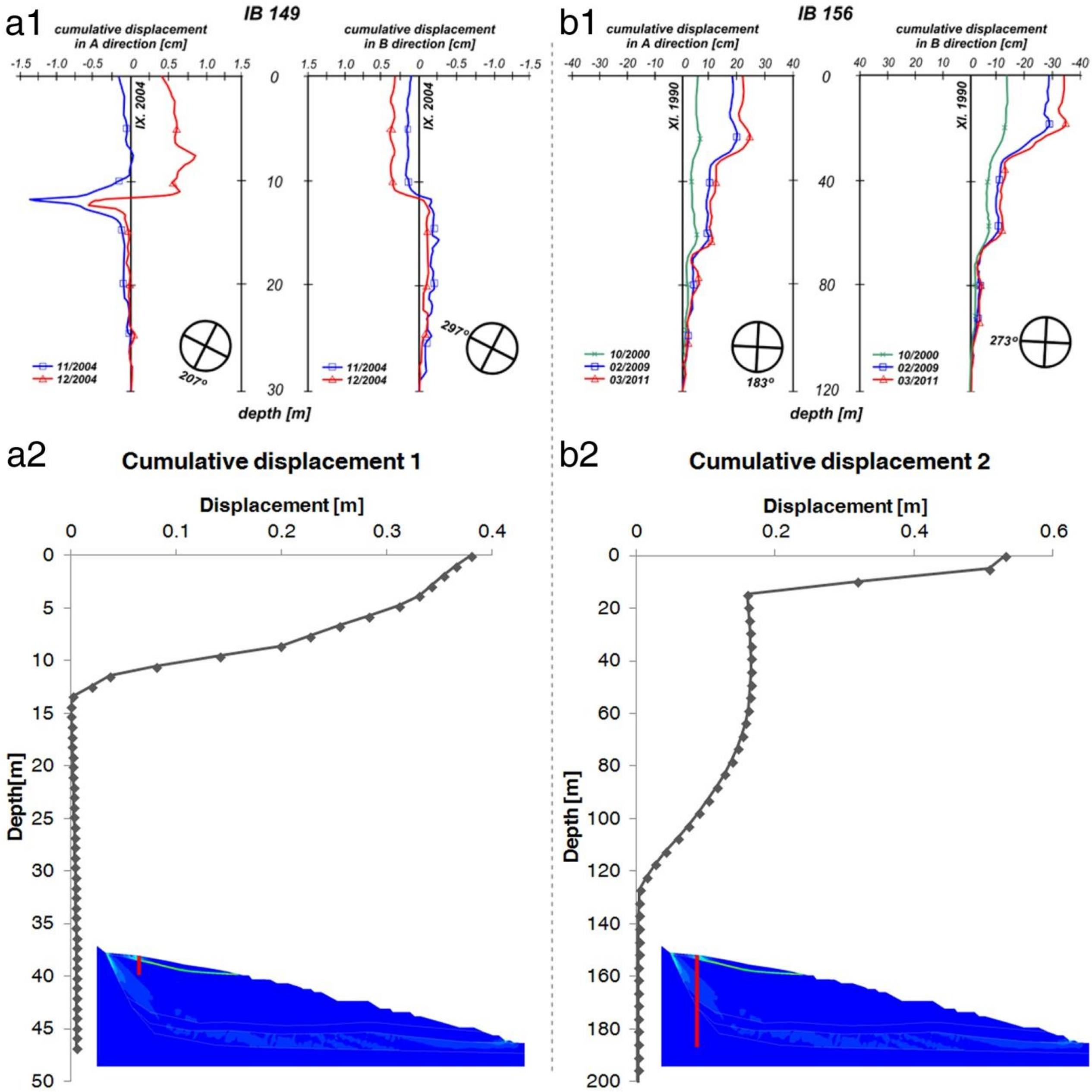

Fig. 10. Selected inclinometer boreholes – cumulative displacement (IB 149, a1, was placed within the landslide body; IB 156, b1, was placed near the January 2011 landslide) and the results of RS² inclinometer borehole analysis 1 (a2) and 2 (b2); inset profiles show approximate inclinometer locations

4.2 Probabilistic FEM analysis

Given the uncertainty of the input data discussed in this report, further analyses were required. A probabilistic analysis was performed, similarly to the previous LEM sensitivity analyses, using the parameters shown in Table 4.

Table 4
Statistical properties used in the probabilistic analysis for each geological formation

Material	Property	Distribution	Mean	Std. Dev.	Rel. Min.	Rel. Max.
Altered Clay	Phi (°)	Normal	9	1.33	4	4
Claystone	Phi (°)	Normal	18	1.66	5	5
Claystone	Cohesion (kPa)	Normal	100	17	50	50
Underlying complex	Phi (°)	Normal	24	1.66	5	5

Following the same logic as the previous probabilistic analyses, the random sampling method used was the Latin Hypercube, with 1000 samples. A normal distribution was also incorporated, with SD values estimated using Equation (1).

The results of the probabilistic analysis are given in Fig. 11.

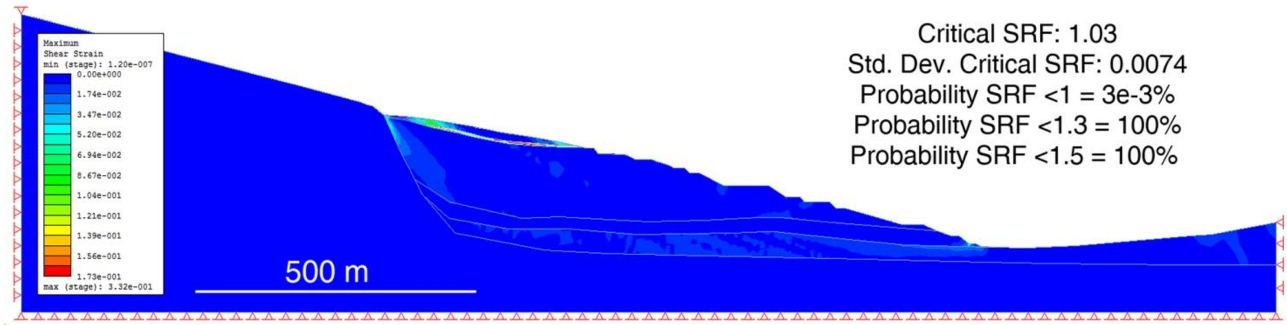

Fig. 11. Shear strain development depicted in probabilistic RS^2 numerical modelling analysis (no vertical exaggeration is applied)

Figure 11 shows a low critical SRF of 1.03 with a probability of failure of 100% considering a minimum FoS of 1.3. It should be noted that this critical SRF refers to the shallow landslide (critical area of maximum instability), but as noticed from all the simulations performed, a deeper failure surface has the potential to be activated. RS^2 allows consideration of a search area to define the potential location of different SRF factors, excluding the external area from the calculations. To investigate the critical SRF at an overall slope scale, a new simulation was then performed excluding the contribution of the Quaternary sediments and altered claystone layer. Utilizing this new configuration, the modelled critical SRF is 1.37, the probability of failure considering FoS < 1 is 0%, the probability of failure considering a minimum SRF of 1.3 is 0.17% and the probability of failure considering an SRF of 1.5 as a minimum acceptable value for a safe design is 100%.

5 Discussion

The approach adopted during the investigation utilized LEM and FEM stability analyses for the evaluation of different landslide failure mechanisms affecting an open-pit lignite mine. The approach reduces uncertainty by using sensitivity and probabilistic analyses to identify the critical factors that influence the results of analyses. The LEM results have then been compared with the results of FEM analyses.

The initial sensitivity analyses based on LEM indicated that the parameters that have the greatest influence on the results of the stability analyses are related to the properties of the underlying complex and claystone layers, in addition to the influence of water levels on the claystone layer (Fig. 5). LEM probabilistic analysis, considering the influence of water at depth, provided a minimum FoS of 1 with a probability of FoS < 1.3 of 99.2%, whereas the same analysis performed excluding the effect of the presence of water at deeper levels showed a minimum FoS of 1.64 with a probability of FoS < 1.3 of 0%. This latter result agrees with field observations, where no indication of a recent deep failure surface is evident. In addition, the initial analyses did not replicate the presence of the shallow landslide that is affecting the upper part of the slope of the ČSA mine. Analysis focused on the response of the Quaternary sediments indicates an FoS of 2.1 for a possible failure surface to develop at the interface between the Quaternary and claystone layers. Therefore, taking into account 2D ERT evidence and previous studies, it has been hypothesized that a weathered claystone level may occur between the Quaternary sediments and the claystone layers. In the case of abundant rainfall and snow melting during spring time, this altered claystone level may become saturated and water flow parallel to the slope may occur at the interface with the underlying impermeable claystone. This may drastically reduce the friction angle of the material, triggering potential instability (because of a *saturated infinite slope* condition). The analysis shown in Fig. 7 indicates that in such a situation the FoS for the shallow Quaternary instability agrees with field observations, with a minimum FoS of 0.65, a probability of FoS < 1.3 of 90.4%, and a probability of FoS < 1.5 of 99.6%. The results suggest that in the case of abundant precipitation, if a water flow parallel to the slope occurs because of the impermeable barrier caused by the claystone, a condition of instability could be induced in the superficial strata of the slope.

The results of FEM analyses, shown in Fig. 8, indicated that the presence of high levels of the water tables leads to a low FoS value, which does not match field observations and confirms that deep water infiltration may be precluded or limited by impermeable barriers in the claystone layer. In addition, the FEM analysis did not replicate the shallow landslide involving the Quaternary sediments. Therefore, the analyses shown in Figs. 9, 10, and 11 were performed, excluding the influence of water at depth and including the altered claystone level with low friction angle to simulate the effect of water flow parallel to the slope caused by the underlying impermeable claystones. Using this configuration, the presence of two possible instability mechanisms was highlighted: the development of high values of shear strain at the base of the Quaternary sediments, with the possible formation of tension cracks in the upper part of the slope (lower inset map of Fig. 9) and potential development of deep-seated failure in shear within the claystones (upper inset map in Fig. 9). The critical SRF, calculated with a probabilistic approach, is 1 (Fig. 11) with a probability of failure close to 0 for SRF < 1 and a probability of failure of 100% for SRF = 1.3. This refers to the critical condition of the shallow landslide, whereas the critical SRF of the deep failure surface is equal to 1.37, with a probability of SRF < 1.3 of 0.17% and a probability of SRF < 1.5 of 100%. In this case, the two failure mechanisms found in the case study area were correctly identified by FEM analysis, but different simulations had to be performed to discern the critical SRF of the two phenomena. To summarize the results obtained, and for the purpose of comparison, Table 5 shows the probability of failure using the final configuration of the model (including the altered claystone level and excluding water infiltration at depth), mean and minimum FoS values, and standard deviation of FoS (only possible with RS^2 software) obtained with Slide7.0 and RS^2. A distinction is made in Table 5, separating FoS values for the shallow and deep-seated landslides.

Table 5
Comparison of Slide7.0 and RS^2 results in terms of FoS

Landslide	Software	Probability of failure < 1.3	Probability of failure < 1.5	Mean FoS	Minimum FoS	Std. Dev. FoS
Shallow	Slide7.0	90.4%	99.6%	1.08	0.65	–
Shallow	RS^2	100%	100%	–	1.03	0.007
Deep	Slide7.0	0%	0%	1.95	1.64	–
Deep	RS^2	0.17%	100%	–	1.37	0.02

The results show good agreement between the different stability analyses, LEM and FEM. In detail, the FEM stability analysis appears to be more conservative for the possible deep landslide. Such results, when considering the advantages and limitations of both approaches, confirm the importance of using different methods for the interpretation of modelled results. In this case, modelled plastic deformations of the different materials appear to play an important role in simulation of the landslide, and therefore FEM analyses are particularly useful for obtaining an improved understanding of the instability mechanism.

The modelled results show good agreement with field observations, inclinometer data, and previous studies at the mine (Burda et al., 2011; Burda et al., 2013), confirming the reliability of the analyses performed and indicating the capability of the FEM approach to recognize different failure mechanisms in a single model. The inclinometer data were particularly useful for validation of the modelled results. From Fig. 10 it is clear how the results from modelled inclinometer 1 match what was observed in IB149, with displacements occurring at the interface between Quaternary sediments and claystones. This movement could affect the altered clay level indicated previously. In this context, it is interesting to note that a limited deeper movement (1–2 cm) is observable at depth and also illustrated in the modelled inclinometer 2. This result is similar to that of IB156, located in the vicinity of the landslide under study, in an area that experienced instability problems because of deep claystone deformation in the past. Both IB156 and inclinometer 2 show deformation in both the deep strata and at the interface of the Quaternary sediments/claystone. Interaction between the shallow and more deep-seated instability cannot be ruled out.

The hypothesis matches previous observations by Burda et al. (2011, 2013), which can be summarized as follows:

– "Immediate triggering factor for the landslide activity in the study area is the water saturation of landslide material, due to a combination of high cumulative rainfall and snow melt water that results in water table increase."[1]

– "Movement accelerations always occurred when the water table rose above -10.25m, which corresponds to a theoretical pore pressure of 68 kPa at the depth of the shear plane."[2]

– "The transported and accumulated material consists primarily of Quaternary debris but also includes weathered Tertiary clays (i.e., altered claystone level). This fact, along with profiles over the headscarps, indicates that the slip surface passes through Tertiary claystones and that this occurs not only at the interference of Quaternary and Tertiary sediments."[3]

– "Investigation revealed markedly conductive part of the claystone in the Tertiary complex. It is probable that the extremely conductive part of these clays, situated at an average depth of 14 to 15 m, is conditioned by weathered and water-saturated clays and represents an assumed water-bearing shear plane"[4] whose base "is associated with high resistivity zones that most likely reflect impermeable ($<10^{-8}$ m s^{-1}) dry compact claystones. This creates an ideal sliding plane for the landslide (also confirmed by inclinometric boreholes)".[5]

In summary, the most critical condition of the slope is related to the shallow landslide activated by intense rain precipitation and snow melting. According to the results of the stability analysis, it is unlikely that the effect of pore pressure could trigger a superficial movement of the landslide in the Quaternary sediments. Instead, the presence of an altered claystone level, immediately above the impermeable claystone layer, could provide water flow parallel to the slope, decreasing the strength properties of the altered layer, leading to a condition of instability on the superficial strata of the slope. Moreover, the presence of weathered Tertiary clays in the landslide accumulated debris material supports this hypothesis.

The results of the back analysis, however, also show the possible presence of a deeper instability, which has already been noted in the past in the vicinity of the area under study but could not be detected by inclinometers on the reactivated landslide area because of the low depth. Because the modelled FoS of the possible deep movement is between 1.3 and 1.5, further investigation is recommended to assess the likelihood and consequences of any likely

[1] Burda et al., 2011, page 1468
[2] Burda et al., 2013, page 372
[3] Burda et al., 2011, page 1467
[4] Burda et al., 2011, page 1471
[5] Burda et al., 2013, page 371

instability. Further site investigation is also required to fully understand the water levels within the slope. In addition, the application of remote sensing techniques, such as interferometry or LiDAR, would also be beneficial for monitoring possible future slope displacements and validation of numerical modelling results.

6 Conclusion

Limit Equilibrium and Finite Element analyses have been used to assess the effects of data uncertainty for back analysis of previous slope instability at a lignite operation in the Czech Republic. The case study provides valuable insight into the effects of the geological parameters and model uncertainty. A sensitivity analysis was undertaken to understand the controlling influences of input parameters on the model response. The results highlight that water table level and material input parameters have the greatest influence on the stability of the slope. The potential for deep-seated instability and shallow Quaternary sediment landsliding has been investigated. More detailed probabilistic analysis suggests that a minor possibility of deep-seated instability exists.

The observed shallow landslide within Quaternary sediments was not initially well replicated with either Limit Equilibrium or Finite Element analyses. The results of further analyses suggest that the claystone at the base of an altered clay level could act as an impermeable barrier, establishing water flow parallel to the slope that decreases the strength properties of the altered layer (similar to a saturated "infinite slope" condition). In this situation, the critical slope angle could be approximately half that of the same dry soil, a condition sufficient to create instability. The presence of weathered Tertiary clays in the landslide accumulated debris suggests that the possible shear plane involved the altered claystone level. A minor possibility of deeper instability was also detected, and therefore two different failure mechanisms were identified. The modelled results were shown to be in good agreement with observed inclinometer data.

The investigation allowed an improved understanding of the landslide activity at the ČSA open-pit mine site, and the increased level of knowledge provides improved hazard assessment and data for mine-planning purposes. To conclude, the importance of performing sensitivity and probabilistic analyses through the approaches of Limit Equilibrium and Finite Element analyses is highlighted within the analyses undertaken. Complementary use of both approaches is recommended for routine checks on model response and associated results.

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