Geological and geotechnical investigation of a shallow translational slide along a weathered rock/soil contact for the purpose of model development and hazard assessment

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ABSTRACT: A key requirement for the implementation of any effective landslide hazard mitigation plan is the in-depth knowledge of the causes driving the instability. Often these causes are multiple involving not only geological, geotechnical and hydrogeological processes, but also anthropogenic influences. Differentiating between these different factors to identify the principal cause and trigger of a landslide is difficult. This paper presents results from a detailed analysis of one such landslide – the 2002 Lutzenberg landslide in eastern Switzerland, which involved three fatalities. Results obtained through an intensive field investigation combined with numerical modelling revealed that the underlying cause of the slide could be traced to adverse geotechnical and hydrological conditions, triggered through an exceptional precipitation event and the rupture of a water pipeline. Results from the numerical analysis suggest that the pipe didn't only rupture during the landslide event but that it was leaking already prior to failure, thereby acting as one of the key underlying causes.

1 INTRODUCTION

On September 1st, 2002, a strong rain event triggered hundreds of landslide and debris flow in eastern Switzerland (Lateltin et al., 2004). One of these, a small shallow landslide of 2500 m^3 occurred above the village of Lutzenberg, damaging three houses and killing three people. The slide developed along a deforested and cultivated section of slope used for pastureland. Such slopes are extremely common throughout this and other parts of Switzerland and have a high potential for repeated occurrence. Risk evaluation therefore plays a huge role in assessing the hazard level threatening the people and infrastructure located at the foot of these slopes where land use is relatively high. Indispensable to these evaluations is an understanding of the key causes and mechanisms contributing towards an unstable slope condition. Such was the case with the 2002 Lutzenberg slide, where the incidence of fatalities necessitated a detailed study (sponsored by the Swiss Federal Office for Water and Geology).

This paper presents the results from a rigorous geological investigation carried out shortly after the event. The investigation included the determination of the slope, slide body and runout geometries, and the geological, geotechnical and hydrogeological characteristics of the soil and rock materials involved in the landslide. This data was then used to constrain a series of detailed numerical simulations. Results are presented from this numerical analysis, the objective of which was to evaluate and determine which key contributing factors led to the 2002 Lutzenberg landslide event.

2 GEOLOGICAL SETTINGS

The investigation of the 2002 Lutzenberg landslide began with the detailed geodetic and geological mapping of the landslide area and that of the neighbouring slopes (Fig. 1; Table 1). The geomorphologic characteristics of the slope made it obvious that older slide events had occurred west of the investigation area (according to local testimonies, as recent as the early 1900's). These older slides are of similar dimensions to the 2002 landslide, but show signs of having had displaced through more creep-like movements over longer periods of time (as opposed to the sudden catastrophic failure experienced in 2002).

In total, the field investigation included the documentation of 30 soil profiles mapped along the edges of the slide area (e.g. Fig. 2). From these, a geological cross-section was extrapolated through the middle of the landslide body (Fig. 3; see Fig. 1 for position of cross-section). Additional information was gathered from several trial/test pits, positioned at key locations (see Fig. 1), 18 dynamic cone penetration tests and a series of trenches dug as part of a drainage system (constructed after the event to mitigate the rebuilt slope).

Table 1. Identity card for the Lutzenberg landslide

Swiss Coordinates	760400/258450
Total Length	185 m
Release Area Length	75 m
Runout Length	110 m
Width	35 m
Depth	1-3m
Total Surface Area	6500 m^2
Release Area	2625 m^2
Depositional Area	3875 m^2
Volume	2500 m^3
Slope Angle	20-25°
Slide Material	moraine, weathered sandstone
Bedrock	sandstone and marls
Event Time	2 am, September 1st, 2002
Velocity	very quick (~15-20m/s)
Fatalities	3
Damage	3 houses (1 fully, 2 partially)

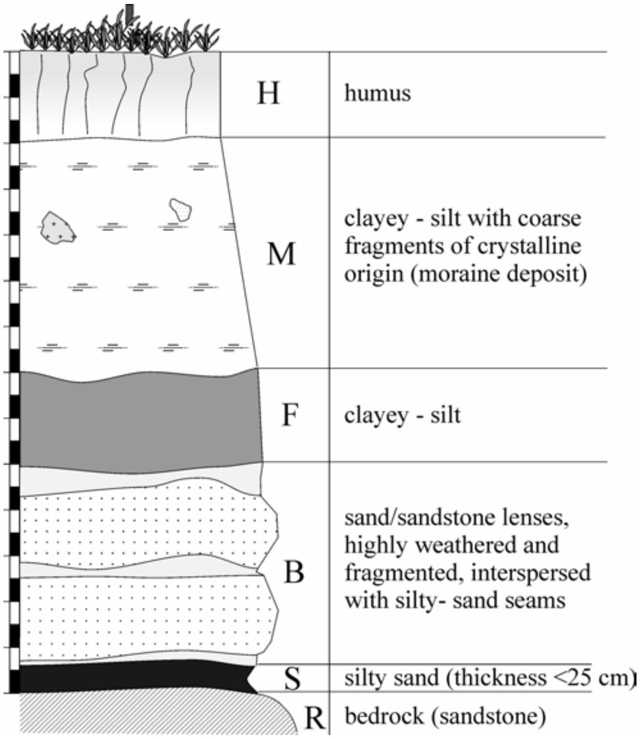
Figure 1. Detailed map of the 2002 Lutzenberg landslide and investigation area.

Results from the investigation revealed that the depth of the soil cover varies from less than 1 m along upper sections of the slope to nearly 5 meters at the slope's foot. The underlying bedrock consists of alternating beds of marl and limey sandstones (from the freshwater Molasse - Aquitanian). The soil strata could be differentiated into five distinct layers (Fig. 2). At surface was a cover of humus, approximately 20 cm thick, which was underlain by a layer of clayey-silt containing coarse crystalline fragments (gravels, stones). This layer was interpreted as being a weathered moraine deposit varying in thickness between 2 and 3 m near the foot of the slope, and thinning out towards the top of the slope. Beneath this layer was found a similar clayey-silt but without the coarse fragments. Below this, forming the interface between the soil layers and the bedrock, was a thin layer (1-25 cm thick) of silty-sand derived from the direct weathering of the sandstone bedrock. This layer was held to be highly significant as it was observed that most of the shear surface had developed within this layer. In addition to the silty-sand layer, in some areas disturbed blocks of the underlying sandstone could be found disengaged and encapsulated within the overlying soil layers (Fig. 2).

Following the field investigation, this data was then used to construct detailed geological cross-sections through the slope failure (e.g. Fig. 3), and to develop conceptual models/scenarios pointing to possible causes of the landslide.

3 GEOTECHNICAL SETTINGS

Geotechnical characterization of the landslide materials was performed through both laboratory and *in situ* testing. Various methods were used and their results were compared in order to obtain values with the greatest degree of confidence possible. In some cases, values were obtained from the literature but generally only for those parameters considered as being of secondary importance.



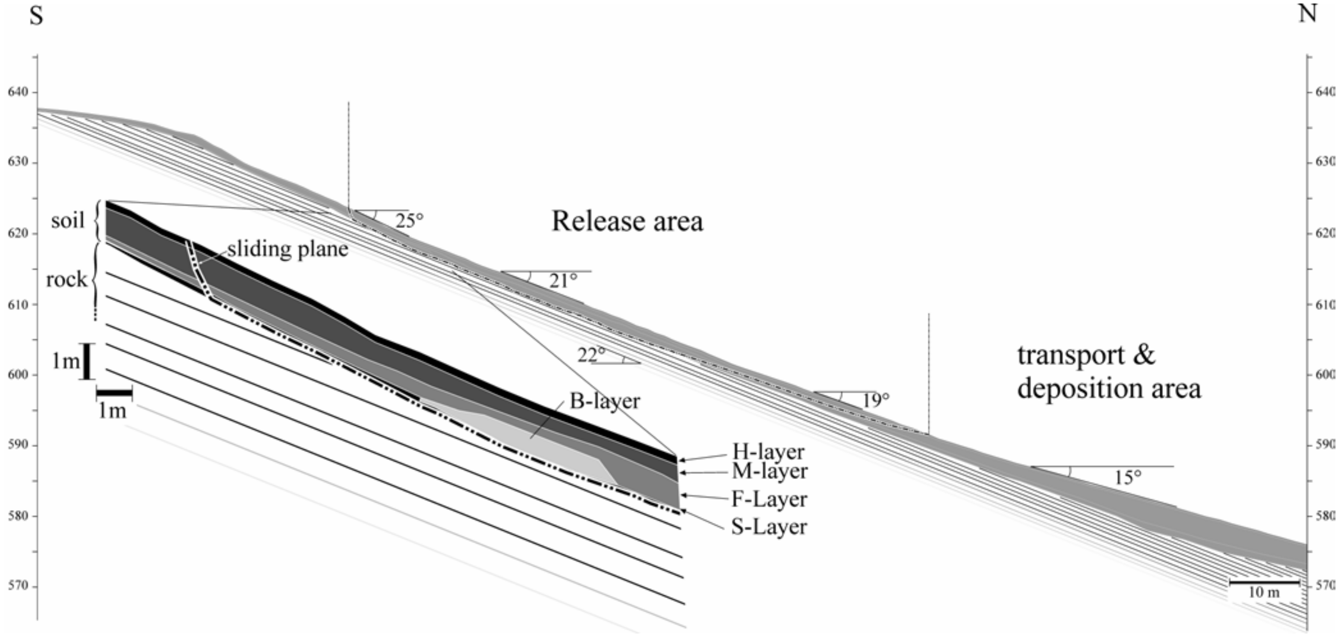


Figure 3. Geological cross-section of the 2002 Lutzenberg landslide taken through the centre of the slide mass.

Figure 2. Soil profile near the slide scarp.

Tests performed *in situ* included two shearbox tests, and numerous penetrometer and shear-vain tests. The two *in-situ* shearbox tests were carried out in trial pits #7 and 8 (near the main scarp; see Fig. 1), using a 25x25x30 cm displacement-controlled shearbox (Fig. 4). Standard laboratory tests were carried out on 13 samples to ascertain grain size distribution and the Atterberg limits. An additional 4 samples were prepared for shearbox and permeability testing. The parameters obtained from these tests are given in Table 2.

4 HYDROGEOLOGICAL SETTING

Throughout the investigation, the hydrological and hydrogeological conditions were believed to have played a prominent role in causing the Lutzenberg landslide. Prior to the landslide, a period of intense precipitation had occurred including 170 mm in one day as was recorded at a nearby weather station (Eggen; Fig. 5). This can be compared to the 1690 mm

Table 2. Geotechnical properties derived from laboratory and *in situ* tests. Parameters derived from the literature for numerical modeling purposes are marked with respect to their source.

	Clayey-Silt	Silty-Sand	Sand-stone
Plastic Limit	25%	28%	—
Liquid Limit	45%	46%	—
Unit Weight [kN/m^3]	20 $^{(1)}$	19 $^{(1)}$	24 $^{(2)}$
Young's Modulus [MPa]	10 $^{(3)}$	10 $^{(3)}$	1000 $^{(2)}$
Poisson ratio	0.4 $^{(3)}$	0.4 $^{(3)}$	0.4 $^{(2)}$
Cohesion [kPa]	14	10/4*	5000 $^{(2)}$
Friction Angle [°]	29	31/28*	35 $^{(2)}$

(1) Swissnorm SN670 010b (2) Goodman, 1980

(3) Das, 1994 * average/minimum values

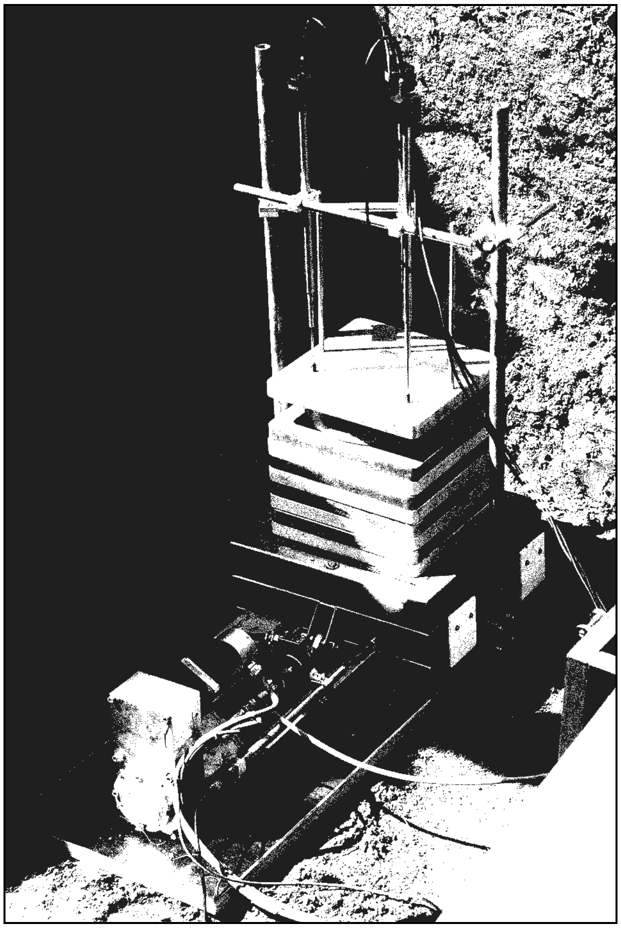


Figure 4. *In-situ* shearbox test performed in test pit #7.

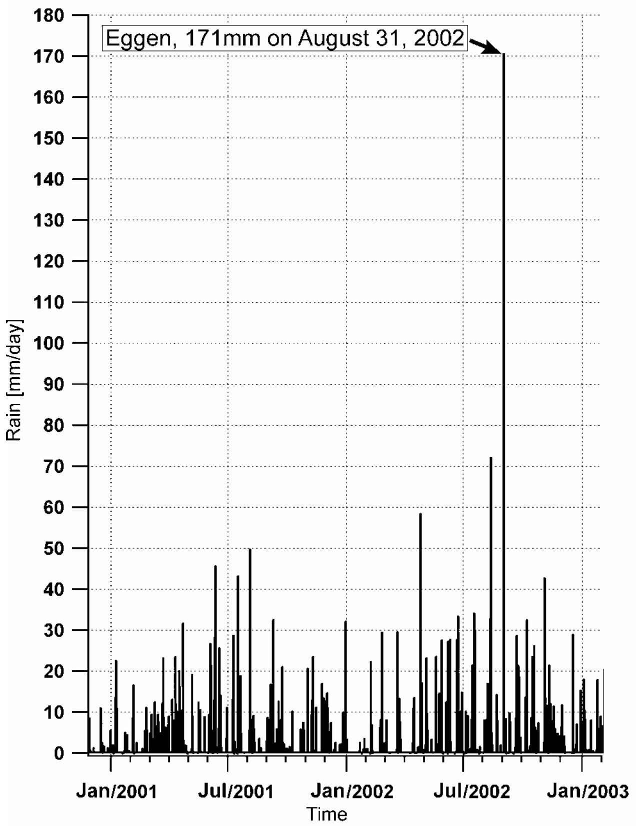


Figure 5. Precipitation recorded at Eggen weather station near Lutzenberg

total precipitation recorded for all of 2002. This exceptional rain event was regarded *a priori* as the principal trigger of the landslide.

The slope hydrogeological conditions revealed during the investigation were also seen as being unfavourable. Laboratory testing of soil permeability indicated that the silty-sand layer was considerably more permeable (1E-07 m/s) compared to that of the overlying and underlying layers (1E-09 m/s). As such, the silty-sand layer forms a confined interval of preferential flow along which elevated pore pressures could easily arise. The location of the shear plane within this interval therefore pointed to a scenario in which the pore pressures within the silty-sand reached a critical level (i.e. critically diminished effective stresses), triggering the detachment of the soil mass above it.

The attainable pressure within the silty-sand layer was viewed as being a function of the overall slope dimensions, for which a maximum of a few hundred kPa could be estimated (currently, a hydrogeological monitoring system has been implemented in order to validate this estimation). Another disconcerting factor was the presence of a broken water pipe found near the head of the slide. The question that then followed was did the pipe break before or during the landslide?

Several different scenarios were then deemed possible:

1) The water pipe had no influence on the failure. The principal cause and trigger of the landslide were the heavy rainfall events;
2) The heavy rainfalls induced small slope displacements that led to the rupture of the water pipe, which in turn triggered the catastrophic failure of the slope;
3) The water pipe had been broken for a long period of time and had been leaking, gradually weakening the slope until catastrophic failure was triggered by heavy precipitation.

The Eternit$^{\copyright}$ water pipe had a diameter of 100 mm and was connected to a reservoir to provide water for 10 local residences. No notable loss of water pressure had been detected prior to the slide event (i.e. prior to September 1st, 2002), although this could not be established with any certainty as the reservoir was not instrumented.

The water pipe was positioned along the soil-bedrock interface. In some places it was trenched into the weathered sandstone bedrock, and in other places it was located solely within the soil. At the point where one of the side scarps of the landslide developed, it was sheared on one side as the pipe exited a rock trench to continue within the soil (Fig. 6).

Figure 6. Photo of the broken water pipe where it intersected the western side scarp of the slide body.

Assuming the pipe was leaking prior to sliding, the elevation difference between the reservoir and the location of the broken water pipe would allow for a maximum pressure of 500 kPa. Due to pressure losses into the formation, a steady state pressure of 100 kPa was estimated as being more realistic.

5 NUMERICAL MODELLING

Based on the detailed site investigation, a working hypothesis was developed with respect to the landslide cause and trigger (Fig. 7). In it, the silty-sand layer acts as a confined aquifer along which elevated pore pressures (i.e. artesian conditions) may arise during periods of high precipitation. These increased pore pressures would result in a significant reduction in effective stresses along the soil-bedrock interface. Whether these pore pressures could reach destabilizing levels naturally, was investigated through a series of limit equilibrium and finite element models. Only the numerical modelling results are presented here, as the limit equilibrium analysis produced similar but less informative results.

Numerical modelling was performed using a commercially validated fully coupled hydromechanical finite-element code, Visage (VIPS, 2003). The continuum mesh was constructed with extended boundaries to eliminate boundary effects. In the model, the geological profile was simplified to include three soil layers, combining those with similar geotechnical characteristics and properties as measured through the laboratory and *in situ* testing. These include an upper clayey-silt/moraine layer, the thin silty-sand layer and the bedrock base. This allowed for the construction of a more accurate, efficient and manageable finite-element mesh.

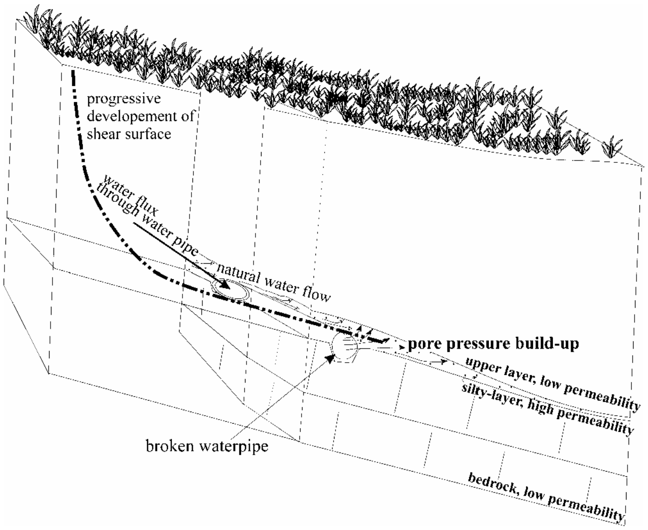


Figure 7. Working hypothesis for the primary cause of failure.

The resulting model incorporated 4450 9-noded higher-order elements with maximum aspect ratios of 5:1. Relevant soil properties were varied between the average and lower bound values derived from the different tests performed. A Mohr-Coulomb elasto-plastic constitutive model was selected to model soil yield. This selection was based on test data availability and the objective at hand (i.e. to model failure <u>initiation</u> and to ascertain its underlying cause).

To ascertain the cause of failure, models were run testing different scenarios with increasing degrees of complexity. Initial models were evaluated assuming dry slope conditions, with later scenarios assuming fully saturated conditions (i.e. coincident with a period of heavy precipitation). The final scenario tested included the added influence of a leaking water pipe. For each scenario, the average and minimum values for the silty-sand (Table 2) were used and the respective results compared to field observations. Depending on the fit, or the assumptions required to achieve a fit, the model scenario was then validated or rejected (Fig. 8).

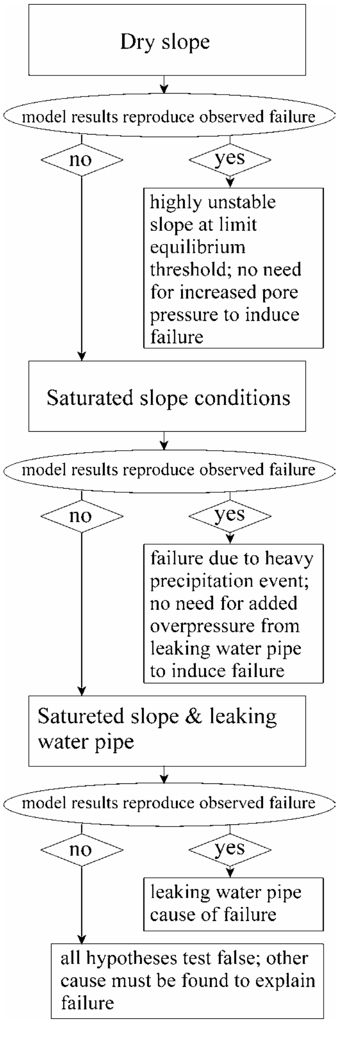


Figure 8. Modelling procedure and scenarios tested to determine cause of slide.

Figure 9 shows the modelled results assuming a dry slope, for which the silty-sand shear strength parameters required for failure were back calculated. As expected, these values were unrealistically low (c=10 kPa, ϕ = 5°). Moreover the dry slope model predicted a failure surface developing in the lower half of the slope, much further down than that of the actual failure.

When the model assumed fully saturated slope conditions (Fig. 10), failure could be achieved using feasible strength properties but lower than those obtained during testing. Again, as in the previous case, the modelled failure initiates and develops along the lower half of the slope and not where the actual failure had occurred. Thus, a failure scenario involving a fully saturated slope, representative of the conditions that would be encountered during periods of heavy precipitation could not fully explain the Lutzenberg slope failure.

The final model scenario included a fully saturated slope, arising due to heavy rainfall, and a leaking water pipe. The leaking water pipe was incorporated into the model as a 100 kPa pore pressure source that was allowed to diffuse outward into the slope. Results from this scenario (Fig. 11) produced the best fit by far. As before, the shear strength values used coincided with the minimum values obtained through the in situ and laboratory tests. With respect to the location and dimensions of the failure surface, a near exact fit was obtained between the model and the actual slope failure.

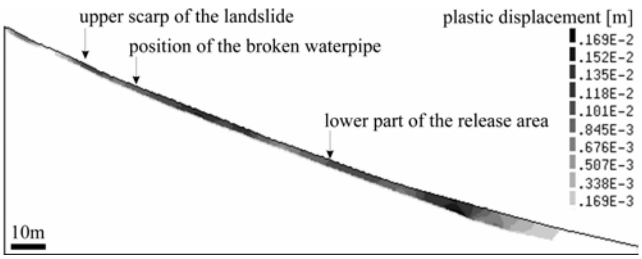


Figure 9. Model results assuming a dry slope. Back-calculated shear strength values required for failure were unrealistically low (c = 10 kPa, ϕ= 5°).

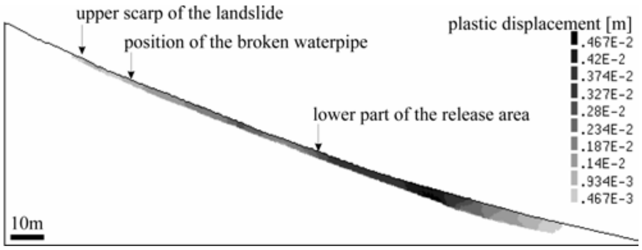


Figure 10. Model results assuming fully saturated slope conditions. Results in this case incorrectly predict the extent of the failure surface.

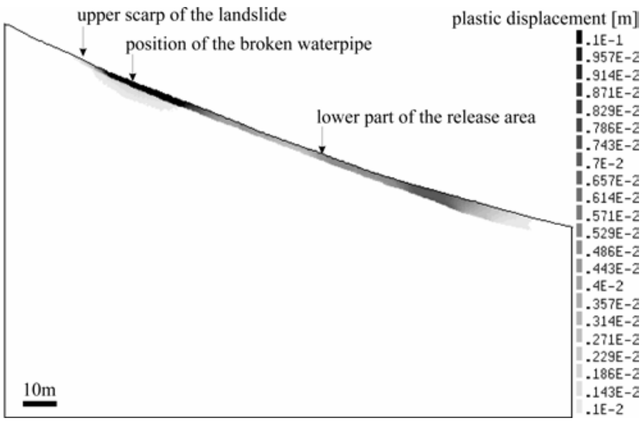


Figure 11. Model results assuming a fully saturated slope with a leaking water pipe.

6 CONCLUSION

When multiple factors (heavy rain, weakened slope, anthropogenic factors, etc.) influence the failure of a slope, it is often difficult to evaluate which factors were the primary contributing cause/trigger. The case study of the 2002 Lutzenberg landslide was one such case in which various potential causes could be inferred. Results based on an integrated strategy combining intensive fieldwork together with *in situ* testing and numerical modelling, showed that in the case of the Lutzenberg slide, failure may not have occurred through the effects of heavy precipitation alone. Instead, numerical modelling results suggest that the leaking water pipe was responsible for a permanent saturation of the unstable mass, and that heavy precipitations then triggered the fatal landslide.

These results demonstrate the value of performing an integrated analysis for which each of the different components of the study is planned with the other components in mind. In doing so, this allowed for a better comprehension of the landslide failure mechanism, which can be carried forward in planning future mitigation measures to be applied to similar slopes in the region.

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