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INCORPORATING THE EFFECTS OF GROUNDWATER AND COUPLED HYDRO-MECHANICAL PROCESSES IN SLOPE STABILITY ANALYSIS

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INTRODUCTION

The presence of groundwater in a rock or soil slope mass can have several destabilizing effects, for example those related to freeze-thaw, weathering, seepage forces and/or erosion (either at the slope's toe or internally through piping). Although some of these processes may be treated in a slope stability analysis, they generally require the use of complex techniques that are applied in a highly conceptual fashion (EBERHARDT *et alii*, 2004). Instead, it is usually only the counterbalancing effect of pore pressures described through the effective stress relationship that is taken into consideration in most slope stability analyses.

Slope stability analyses involve three main procedures depending on the importance and complexity of the slope geology - kinematic, limit equilibrium and numerical. The first stage should always be a kinematic assessment of the feasibility of varied slope failure mechanisms; this is especially important in the case of rock slopes. Such analyses are usually undertaken using stereographic techniques that check for daylighting structures and whether sliding is possible assuming a particular friction angle. Pore and/or joint water pressures are not considered as kinematic analyses solely focus on the spatial configuration and alignment of persistent discontinuities, bedding/foliation planes and other similar structures.

Having identified the potential failure mechanism, limit equilibrium and numerical modeling codes may then be employed to investigate the influence of groundwater on the stability state of the slope. Variations in how these methods are applied generally depend on the objectives of the analysis and the quality of the field observations and *in situ* monitoring data available to constrain the analysis. For most analyses, the key data constraint is the location of the groundwater table as determined through piezometer readings or field observations of surface springs.

Table 1 presents a selection of the common techniques used in slope stability analysis, highlighting the required input data, and both the advantages and limitations of the methods with respect to the incorporation of groundwater. This paper will review these techniques (limit equilibrium, finite-element and distinct-element) using several case histories to illustrate their use and the influence of groundwater and coupled hydro-mechanical processes on slope failure mechanisms.

LIMIT EQUILIBRIUM APPROACHES

All limit equilibrium techniques share a common approach based on a comparison of resisting forces/moments mobilized and the disturbing forces/moments. Methods may vary, however, with respect to the slope failure mechanism in question (e.g. translational or rotational sliding), and the assumptions adopted in order to achieve a determinate solution. The presence of groundwater is treated by these methods as a disturbing force that counteracts the normal forces acting across a potential slip surface and the frictional strength enabled by means of these normal forces; in the case of unsaturated groundwater conditions, i.e. negative pore pressures, the effect can be positive. In performing an analysis, pore pressures are calculated as a function of the location of a specified water table relative to the sliding plane. Alternatively, a pre-specified pore pressure distribution may be defined. Recent developments in commercial limit equilibrium codes have worked towards combining finite-element derived groundwater analyses with a “method of slices” solution, to more accurately calculate pore pressure distributions and magnitudes throughout the landslide mass.

In soil slopes, most analyses assume drained conditions, although undrained soil slope conditions may also be treated using a '$\phi = 0$' analysis (e.g. SIMONS *et alii*, 2001). It should be noted that undrained soil slope conditions are generally only applicable to temporary short term engineered slopes, where the total stress state may be rapidly increased, for example during the construction of an embankment. In natural slopes, rapid loading causing an undrained condition may arise during an earthquake, leading to liquefaction. Rigorous treatments of liquefaction potential are now available through commercial codes that couple finite element derived dynamic stress conditions and generated pore-water pressures with limit equilibrium method of slices analyses (GEO-SLOPE, 2003).

In rock slopes, limit equilibrium analyses may provide a useful "first step" where failure occurs along well-defined discrete discontinuities. The assumption of an assumed water table in rock slopes without due consideration of the flow properties of the individual joint sets must however be treated with caution and used only as an indicator or in sensitivity analyses.

Analysis Method	Groundwater input	Advantages	Limitations
Limit Equilibrium	Multiple water tables/piezo-lines. Pore water pressure ratio (Ru & Hu coefficients). Total/pressure head and pore pressure grid points. Saturated and anisotropic permeability. Unsaturated permeability models. User-defined permeability models. Nodal inflow/ outflow. Ground water boundary conditions. Steady state or transient groundwater analysis.	Simple and reduced input requirements. Applicable to circular slope failures in soil and rock slope failures along discrete planes, wedge or structurally defined non-circular surface. Rapid sensitivity analysis to show influence of water pressure. Can import/incorporate data from finite element groundwater flow codes. Probabilistic analyses possible. Unsaturated conditions may be considered. Can be readily incorporated with GIS techniques.	Assumed failure mechanism. Factor of safety calculations give no indication of instability mechanisms. Pore pressure distribution assumptions may be simplistic in jointed rock. Strains and intact failure not allowed for. Influence of water pressures on failure mechanism not considered. Time effects ignored or difficult to analyse (progressive failure, drawdown, etc.). Groundwater flow analysis needed to adequately consider influence of seepage forces.
Continuum Modelling *(e.g. finite-element, finite-difference)*	Water table and boundary conditions (pore pressure/ flux/inflow/outflow). Saturation (i.e. saturated or unsaturated analysis). Fluid bulk modulus and density. Moisture content and negative pressure head. Isotropic permeability, permeability tensors, permeability/porosity – volumetric strain relation. Poroelastic parameters (α, β). Steady state or transient coupled analysis.	Uncoupled or fully coupled hydro-mechanical models. 3-D coupled modelling possible. Flow/no flow analyses. Consolidation. Single phase or two phase flow. Useful for modelling effect of seepage forces. Can incorporate creep deformation and dynamic analysis. Output includes effective stress, head and pore pressure contours, displacements, failure zones, seepage vectors. Particle tracking and history points.	Users must be well trained, experienced and observe good modelling practice. Need to be aware of model/software limitations (e.g. boundary effects, mesh aspect ratios, symmetry, hardware memory restrictions). Availability of groundwater input data generally poor with scale dependency problems. Required input parameters not routinely measured. Inability to model effects of highly jointed rock. Can be difficult to perform sensitivity analysis due to run time constraints.
Discontinuum Modelling *(e.g. distinct-element, discrete-element)*	Water table and boundary conditions (pore pressure/ flux/etc.). Fluid pressure and gradients, fluid bulk modulus and viscosity. Intact yield strength and elastic constants. Joint contact hydraulic aperture, initial saturation and pore pressure. Joint spacing, trace length and gap length. Joint shear strength and stiffness properties.	Allows for block deformation and movement of blocks relative to each other. Can model complex behaviour and mechanisms (combined material and discontinuity behaviour, coupled with hydro-mechanical and dynamic analysis). No flow, steady state and transient coupled flow. Output includes joint fluid flow and velocity, flow vectors and pore pressure.	Experienced user required to observe good modelling practice. General limitations similar to those listed above. Must be aware of scale effects. Need to simulate representative discontinuity geometry (spacing, persistence, etc.). Limited data on required joint properties available. Most experience with uncoupled or partially coupled analyses. Only fracture permeability considered-intact rock assumed impermeable.

Table 1 - Conventional and advanced methods of groundwater-based slope analysis

EXAMPLE APPLICATION - USOY ROCKSLIDE DAM

The application of a limit equilibrium analysis generally involves the objective of testing the sensitivity of a slope to fluctuations in the groundwater table, for example those that occur following a heavy rainfall event, and the potential for such fluctuations to trigger a catastrophic failure. Several different incrementally increasing water tables may be analyzed producing a different factor of safety for each. The water level above which an acceptable factor of safety is not attained is then deemed the critical threshold.

Similarly, the fluctuations in water level behind an earth dam or landslide dam may be tested for its influence on stability of the dam. Such is the concern in the case of the Usoi Landslide Dam in the Pamir Mountains of Tajikistan. The Usoi Landslide dam was created in 1911 following an earthquake that triggered a massive landslide that blocked a valley creating a lake, Lake Sarez, 60 km long and more than 500 m deep (ALFORD & SCHUSTER, 2000). Due to high regional seismicity and the large volume of water the dam confines, questions have been raised regarding the potential for catastrophic collapse, an event that could threaten between 7000-35000 inhabitants down the Panj River Valley (IVES & PULATOVA, 2000). destroy villages and infrastructure in the Amu Darya River basin inhabited by more than 5 million people.

Figure 1 shows a method of slices limit equilibrium analysis of the Usoy Dam employing a Morgenstern-Price/General Limit Equilibrium solution (FREDLUND & KRAHN, 1977). Pore pressures for the analysis were imported from a finite element analysis assuming a lake level 536 m above the base and toe of the slope (or 34 m below the maximum crest of the dam). Two different slip circles and their respective Factors of Safety are shown for slope failures ranging in size from the smallest, but most critical slip surface, to one that could breach the entire dam. Little is known about the internal structure of the landslide dam and therefore several assumptions are required regarding the dam's strength and flow characteristics. For the analysis shown in Figure 1, it is assumed that the dam foundation is more impervious than the overlying landslide material and that the composition of the dam would primarily involve fine-grained material overlain by a carapace of coarser rockslide debris. The lowermost diagram in Figure 1 contains the results for a sensitivity analysis in which the influence of a major earthquake is accounted for (equated in terms of horizontal acceleration). In terms of the influence of groundwater in this case, the Factors of Safety calculated are 25% lower than if the analysis is performed dry. Given the uncertainty attached to the assumptions adopted in slope analysis, and the efficiency of computer-aided limit equilibrium analyses, probabilistic techniques can also be employed for which statistical distributions of the different input parameters can be defined to account for their uncertainty.

NUMERICAL APPROACHES

Limit equilibrium analyses are limited by their inability to account for material deformation or yield, factors which help to provide insights into potential slope failure mechanisms (EBERHARDT, 2004). In cases where the consideration of complexities relating to geometry, material anisotropy, non-linear stress-strain behavior, in situ stresses and/or the presence of coupled processes (e.g. pore pressures, seismic loading, etc.) are deemed important, numerical modeling methods should be employed. There exists a wide range of numerical codes for the analysis of slopes, ranging from continuum techniques (e.g. finite element), ideally suited for soil slopes, to discontinuum techniques (e.g. distinct element), which are more applicable to rock slopes where both discontinuities and intact material deformation contribute to the development of an instability.

Numerical techniques incorporate an array of means for assessing the importance of groundwater in a slope stability analysis. Many of these, especially in the case of a continuum analysis, are similar to those previously discussed for a limit equilibrium analysis. In rock slopes, high-risk situations may require the characterization of discontinuity-controlled groundwater flow. This may either be done using a continuum groundwater flow code (assuming equivalent rock mass approaches and varying permeability) or preferably discontinuum codes with varying discontinuity properties such as joint permeability, spacing, persistence and aperture. Analyses may be undertaken using either uncoupled, partially coupled or fully coupled flow-mechanical models.

EXAMPLE CONTINUUM APPLICATION-LUTZENBERG SHALLOW LANDSLIDE

When multiple factors (heavy rain, weakened slope, anthropogenic factors, etc.) influence the failure of a slope, it is often difficult to evaluate which factors formed the primary contributing cause/trigger. The 2002 Lutzenberg landslide in eastern Switzerland was one such case in which various potential causes could be inferred (VALLEY *et alii*, 2004). The landslide occurred during a period of heavy precipitation and involved a shallow soil slip of 2500 m^3 along a weathered rock bedding plane resulting in three fatalities. Such slopes are extremely common throughout Switzerland and have a high potential for repeated occurrence.

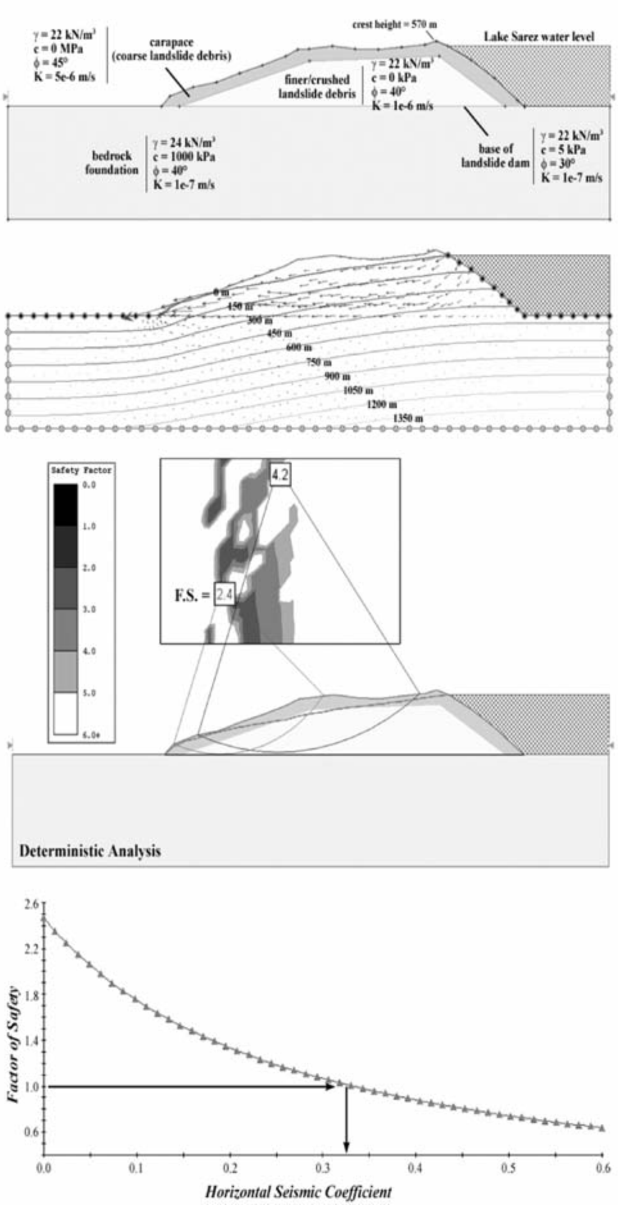

Figure 1 - Limit equilibrium analysis of the Usoi landslide dam, showing from top to bottom: the problem geometry and material assumptions; finite element derived hydraulic head contours and flow vectors imported into the limit equilibrium analysis; deterministic analysis adopting a Morgenstern-Price solution; and a sensitivity analysis plotted with respect to the horizontal seismic coefficient, showing the potential for failure for values greater than 0.325

Results based on an integrated strategy combining geological and geotechnical *in situ* investigations with numerical modeling, showed that failure may not have occurred solely through the effects of heavy precipitation. A series of fully coupled hydro-mechanical 2-D finite-element models were used to ascertain the cause of failure by testing different scenarios with increasing degrees of complexity, from dry slope conditions, to fully saturated slope conditions (i.e. coincident with heavy precipitation events), to a final scenario where the influence of a leaking water pipe was added. Depending on the fit of the modeling results to those observed in the field, or the assumptions required to achieve a fit, the model scenario was then either validated or rejected.

Results from the finite element analysis suggest that a fully saturated slope, representing the conditions expected following a period of heavy precipitation, could not fully explain the Lutzenberg slope failure alone. Instead, models that included the simulation of a leaking water pipe produced the overall best fit (Figure 2). These results, corroborated by observations made in the field, were therefore used to suggest that a 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 (VALLEY *et alii*, 2004). 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.

EXAMPLE DISCONTINUUM APPLICATION - CAMPO VALLEMAGGIA

The Campo Vallemaggia landslide, a deep-seated creeping landslide in the south-central Swiss Alps, involves a 300m deep, complex structure consisting of schists and gneisses sub-divided into distinct blocks by a series of extensive faults (BONZANIGO *et alii*, 2000). The hydrogeology of the landslide is dominated by strongly anisotropic flow through discontinuities and especially along high conductivity fault zones. When combined with regional topographical controls, these structures result in upward directed seepage forces at the base of the slide body. Instrumentation records showed that when pore water pressures exceeded an apparent threshold, sudden accelerations of the slide mass occurred; velocities returning to background levels as the pore pressures dissipated.

Given the risk to communities located on the unstable slide mass, mitigative measures were undertaken. This involved the construction of a deep drainage adit within the undisturbed rock below the creeping slide mass, from which drainage boreholes were drilled into the slide base. Total discharge on completion of the adit, at the end of 1995, was approximately 50 l/s decreasing to 30 l/s by 1998. This resulted in an immediate reduction in water head of 150 m and the almost complete cessation of downslope movement. Despite this apparent success, skepticism arose as to the true effectiveness of the deep drainage solution due to the relatively small water outflows measured from the drainage gallery and competing arguments that the instability was the result of continuous erosion at the slide's toe. Numerical modeling was therefore undertaken to explore the mechanisms and effects that drainage may have had on stabilizing the slope. The study was performed using a distinct element code through which a fully coupled hydro-mechanical analysis was undertaken where the controlling influence that rock mass structure played in both the kinematics and groundwater flow could be explicitly modeled.

The coupled hydro-mechanical modeling procedure used can be summarized as follows: i) Pore pressures were introduced to the model using a water table based on site investigation data; ii) The model was stepped to a steady state and modeled pore water pressure histories for varied locations compared to those recorded in the field; iii) Strength properties along the failure surface were varied, where together with the addition of pore water pressures, an unsta-

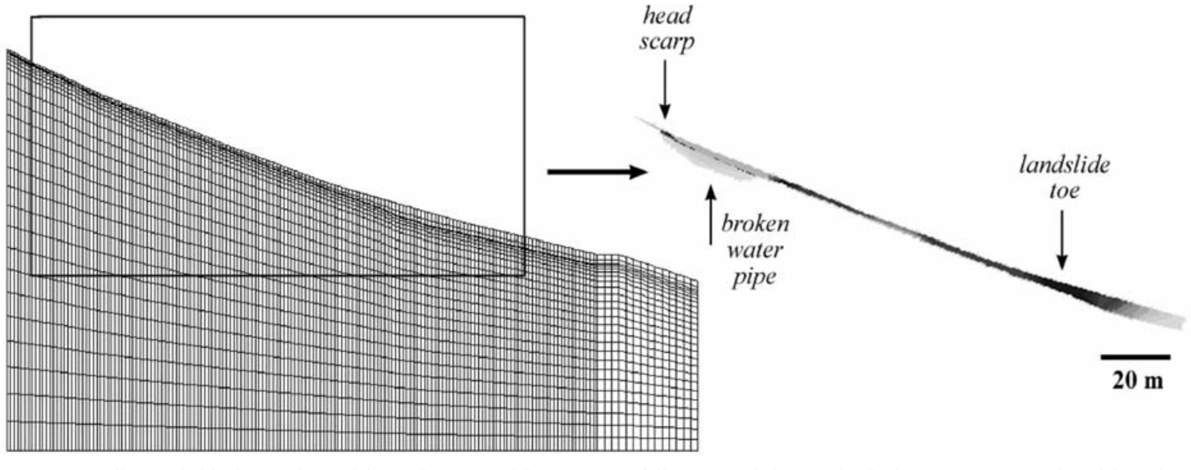

Figure 2 - Fully coupled hydro-mechanical finite-element model, assuming a fully saturated slope with a leaking water pipe, and model results in the form of plastic yielding (used in this case to indicate initiation and development of the shallow translational soil slope failure). Superimposed on these results are arrows pointing to the mapped locations of the landslide head scarp and toe

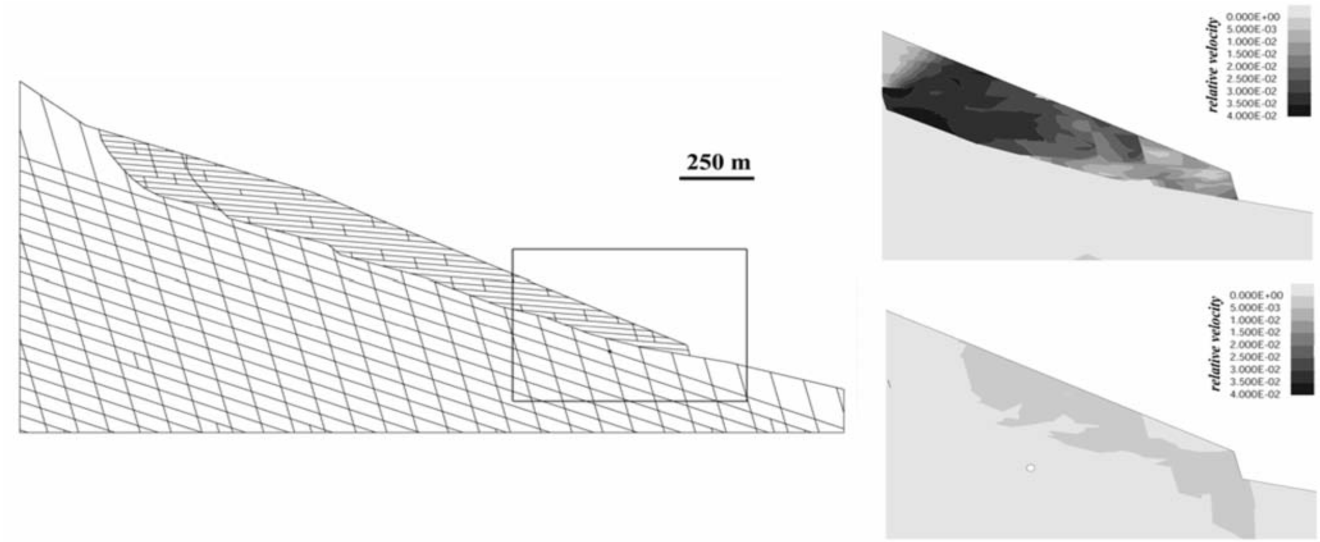

Figure 3 - Coupled hydro-mechanical distinct-element model of Campo Vallemaggia, showing slope velocities before (right-upper) and after (right-lower) deep drainage

ble slope state was created and movements could be compared to those recorded in the field; iv) Drainage of the slide mass is enabled through the modeled opening of the drainage adit.

Opening of the adit resulted in an abrupt termination of the modeled downslope velocities (Figure 3). With respect to tunnel inflows the model showed that very little drainage is required for stabilization to be achieved (approximately 10-20 l/s). These magnitudes were in agreement with the observed tunnel inflows. In terms of the underlying contributing mechanisms, the distinct element models show that in the case of fracture permeability, where storativities are low, large water inflows through drainage are not necessary to achieve significant reductions in head.

CONCLUSIONS

Groundwater is recognized to be the critical factor in many, if not most, slope failures. Considerable research has been undertaken on the use of limit equilibrium and numerical methods in slope design and analysis. A concerted research effort, however, is required to improve our understanding of groundwater flow in soil and rock slopes and its coupled influence on slope deformation. Further progress in the application of these techniques requires additional constraints with improved slope characterization and site investigations. Similarly, improved instrumentation of groundwater in unstable slopes is needed in order to provide important constraints for numerical analysis.

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