Effects of External Water-Level Fluctuations on Slope Stability

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ABSTRACT

There is a worldwide increasing need of land-use in costal/waterfront areas. All kinds of changes of geotechnical conditions in these areas pose potentially slope instability and jeopardized values of property and life. Soil slopes are affected by water-level fluctuations originating from as well tides and other waves, as non-natural sources such as watercourse regulation for irrigation, freshwater provision, and/or hydropower production. Due to a growing use of non-regulated energy sources (e.g. wind and solar), the need of energy balancing and storage is increasing. Also techniques such as pumped hydropower storage (PHS), which may be associated with significant water-volume changes in the reservoirs, are growing globally. This is expected to involve variations of hydropower reservoir water levels; hour to hour, day to day and/or seasonally. In this paper geotechnical effects of water-level fluctuations on slope stability are reviewed; relevant inter-disciplinary findings are presented, adventurous simplifications and/or inadvertencies are underlined, and potential improvement areas are identified. A lot of research has been carried out focused on coastal erosion; mainly aimed to investigate tide-water influence on slope-profile development, and quantification of sediment production. On the other hand, studies on effects of water-level changes on geotechnical conditions in adjacent soil structures have been predominantly concerning embankment dams. In addition, studies addressing processes in natural slopes and banks are often environmentally oriented, rather than focused on slope stability. Since also water-level rise (not only drawdown) has been shown to significantly influence slope stability, further investigation of processes of suction loss, effects of rapidly increased water pressures, and retrogressive failure development is needed. Long-term views are often missing; analyses tend to involve few rise-drawdown cycles, soil materials are deficiently described, and limited attention is put on constitutive models used. Reliable integration of seepage effects on soil-property changing requires consideration of as well acute effects as long-term changes. Therefore, proper consideration of internal erosion is central. Given the critical relationship between pore pressure, soil strength, and soil-deformation, analyses have to be performed using robust simulation approaches. The terms "simplicity" and "applicability"—promoting use of limit-equilibrium methods—should more often be set in relation to accuracy and robustness provided by use of methods considering also deformations.

KEYWORDS: Water-level fluctuations, reservoir, slope stability

INTRODUCTION

In J. M. Duncan & Wright (2005) it was reminded that an external water pressure acts stabilizing to a slope or to an embankment dam: *"This is perhaps the only good thing that water can do to a slope"*. There is a worldwide increasing need of land-use in costal/waterfront areas (e.g. Singhroy, 1995), whereupon the need to also use sites being unfavorable (from a geotechnical point of view) is increasing. This general trend together with all kinds of potentially changing conditions, means that geotechnical design becomes more and more advanced and challenging; it is necessary to monitor sites, to properly analyze data, and to identify and evaluate potential risks concerning property, environmental, and human values.

Fluctuation of external water levels is one important factor influencing waterfront slopes and adjacent land areas. Sources of such fluctuations may e.g. include tidal water-level variations (e.g. Ward, 1945; Li, Barry, & Pattiaratchi, 1997; Raubenheimer, Guza, & Elgar, 1999), variations caused by wind waves (e.g. Bakhtyar, Barry, Li, Jeng, & Yeganeh-Bakhtiary, 2009), variations caused by other weather-related events (as heavy rainstorms and/or snow melting), and combinations of various phenomena (e.g. Zhang, 2013). Besides the natural phenomena (also including time-dependent soil degradation in terms of e.g. weathering and structural changes), processes caused and driven by human activities are also influencing the stability of waterfront slopes. One such activity, causing water-level fluctuations, is regulation of watercourses, undertaken for water storage enabling irrigation, freshwater provision, and/or hydropower production (e.g. Mill et al., 2010; Solvang, Harby, & Killingtveit, 2012). Due to a growing use of non-regulated energy sources (e.g. wind and solar), the need of energy balancing and energy storage increases (Connolly, 2010). It is furthermore expected to get increased variations of hydropower reservoir water levels; hour to hour, day to day and/or seasonally (Solvang et al., 2012).

Although there are studies and reports presented on this topic—emphasizing potential problems with water level variations—there is a clearly seen predominance of studies focusing on bio-environmental issues; i.e. endangered habitats of plant and animal species (Nilsson et al., 2005) or soil degradation in terms of nutrient dynamics (e.g. Zhao et al., 2014). Thus, direct soil mechanical approaches are few. When it comes to coastal engineering there are many investigations concerning effects of tide and weather on shore slopes and beach surfaces. In Darby, Rinaldi, & Dapporto (2007) it was emphasized that many of the recent studies have been mainly focused on bank geometry. Even though bank sediment erosion is certainly dealt with, there are few studies on the actual fluvial-erosion process itself.

When discussing "fluctuations", time scales and frequencies are to be considered. Concerning coastal erosion, long-term shoreline effects caused by sea-level rise originate from climate changes. In contrast, variations of shorter return times (mentioned above) are more directly relevant for the present study. Analogously, when it comes to watercourses, the time perspective is again of importance. Even though channel development involves as well an external water level as affected soil banks, this kind of long-term overall water-soil interplay (landform evolution) is not what is focused in this study. Rather are so the soil mechanical processes taking place within the slope affected by the water.

Along with processes being potentially changing the stability of a slope (varying ambient conditions), the actual analysis is also important. *Limit-equilibrium* (LE) methods have been used to analyze slope stability for a long time (Duncan & Wright, 1980; Yu et al., 1998; Zheng et al., 2009), and have been unchanged for decades (Lane & Griffiths, 1999). As a consequence of known limitations of LE-procedures, together with significantly increased computational

capacity, more sophisticated and accurate methods have been increasingly requested and developed. Such *deformation-analysis* methods, based on actual limit conditions, are often handled by use of *finite-elements* (FE) tools.

In this paper, geotechnical effects of water-level fluctuation on slope stability are addressed; relevant inter-disciplinary findings are presented, adventurous simplifications and/or inadvertencies are underlined, and potential improvement areas are identified. In order to make it possible to put findings on "water-level fluctuations" (i.e. sources, potential soil mechanical consequences, and slope stability effects) in relation to thoughts and outlooks on actual analysis, some fundamentals of slope-stability analysis procedures are also covered.

WATER LEVEL VARIATION – MODES AND SOURCES

General

The inherent properties of a soil are governed by its history; no matter if the soil is processed (crushed, filled etc.), or if it is naturally occurring (formed by weathering of rock, transported by erosive processes, and finally deposited from water, wind, or ice). Moreover, the properties are influenced by external factors continuously acting on the soil from the time of depositing/placing and onwards. Such factors might include external water loading, development of pore pressures, hydrodynamic impact from water flow (both internal and external), etc. Consequently, any soil volume is always affected by the hydrological conditions. In fact, present water is either (at least) clearly influencing or (more often) completely governing the actual soil properties. Therefore, the interactions between soil and water are highly important in the field of soil mechanics; interplays of water and slopes are to be properly described. Thus, the basic modes of water-level changes are to be defined (see Figure 1). In order to reliably describe a soil profile including the position of the groundwater table, relations between an external water level and the connected groundwater level located "behind" the slope surface, has to be properly expressed.

Long-term natural variations

Sea-level rise is one of the most highlighted and debated direct effect of climate changes. When it comes to the global issue of coastal erosion, water motion taking place along beaches and coasts does potentially cause geotechnical materials to be transported away from the beach. The Intergovernmental Panel on Climate Change (IPCC) is continuously aiming to identifying potential risks, describing processes, and predicting future scenarios concerning ice-sheet instabilities and sea level rise. According to K. Zhang, Douglas, & Leatherman (2004), the long-term effects of elevated sea levels (due to flood and erosion) would cause catastrophic consequences if the "upper bound" is correct (90 cm in the 21st century, based on IPCC's prediction; presented in the "Third Assessment Report").

The Bruun-theory (Bruun, 1988) is a generally accepted mathematical model developed for quantification of relationships between sea-level rise and coastal erosion. The model is assuming a closed material balance system between the shore and the offshore bottom profile. This kind of process is actually about the water-soil interface itself; not necessarily driven by water level changes, but could also be a consequence of water motion along the course; i.e. streaming/flowing (see Figure 1A). Though, a varied mean level imply changed water-levels ranges within which the short-term variations are occurring. In this sense, a rising sea level acts as an enabler of erosion (K. Zhang et al., 2004), whereupon consideration also of long-term changes are of importance. Hupp (1992) presented a channel-evolution cycle in a six-stage model
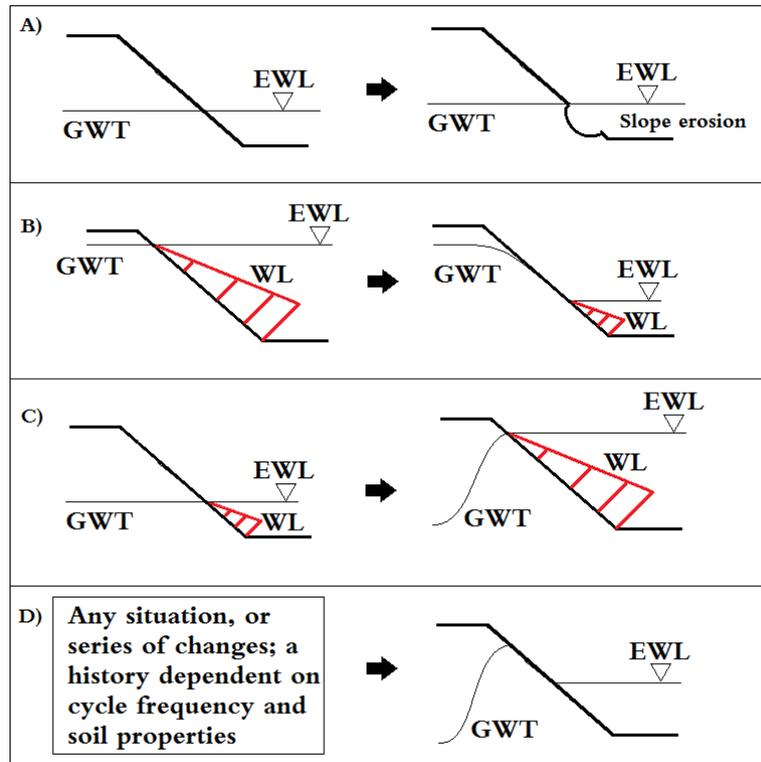
Figure 1: Basic modes of water level change; flowing water (A), water level drawdown (B), raised water level (C), and fluctuating water level (D). In the pictures principle water loads (WL), as well as the positions of the ground-water table (GWT) and the external water level (EWL) are shown.

describing the development from stable conditions, via some time limited landform changing stages, ending up with another stable state (see Figure 2). These examples of long-term effects—as well coastal erosion as channel evolution—are showing clear consequences of water-soil interaction, entailing obvious effects on the beach/bank. Though, henceforth short-term water level variations will be focused.

Short-term natural variations

Sources of natural water-level variations are related to meteorological and geological phenomena. Tide induced water-level fluctuations have been specifically studied for a long time. This including the fact that these kinds of variations are important to beach-sediment transport (erosion) has been further stated and reported by many authors (e.g. Grant, 1948; J. R. Duncan, 1964; Nielsen, 1990; Li, Barry, Parlange, et al., 1997; Li, Barry, & Pattiaratchi, 1997). Besides actual sea-level variations and the mechanical material-transport processes, also the groundwater table on land is affected by the tidal changes (Emery & Foster, 1948; Chappell, Eliot, Bradshaw, & Lonsdale, 1979). Except tidally driven variations, there are also other natural factors that can generate water-level fluctuations. These are e.g. wind (i.e. strong winds, hurricanes etc.), changed atmospheric pressure (causing water movement), and submarine earthquakes (generating waves sometimes propagating landward) (Pugh, 1987).
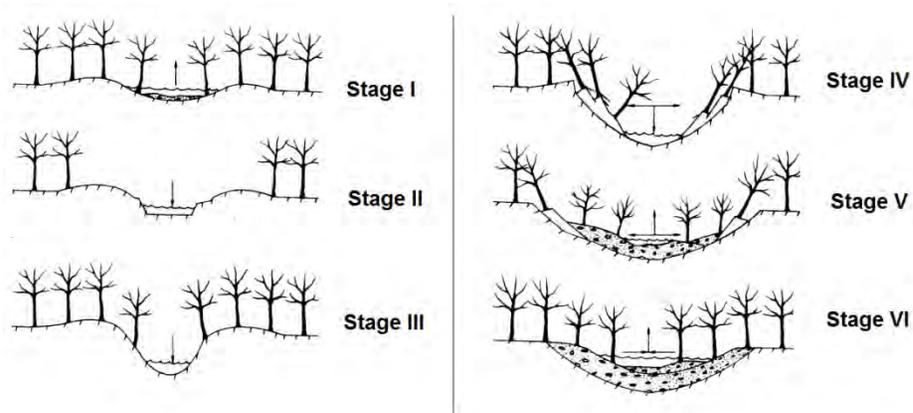
Figure 2: Conceptual model of channel evolution.

The illustrated cycle includes the stages "pre-modified", being of stable nature (Stage I), followed by stages being lasting for limited time periods, including "construction" (Stage II), "degradation" (Stage III), "threshold" (Stage IV), and "aggradation" (Stage V). The cycle ends up with a stage of "recovery", which one is again stable (Stage VI). The arrows are representing the movement direction of the bed (vertically) and the banks (horizontally). The pictures are not to scale. (after Hupp, 1992)

Watercourse regulation

Energy balancing

Besides the effects being immediately related to climate and weather, there are also other climate linked phenomena influencing slope stability. The energy demand is globally increasing and the use of renewable unregulated energy sources (non-fossil sources, naturally regenerated) is strongly growing. In 2011 as much as 19.0 % out of the total global energy consumption came from renewable energy sources (to be compared with 16.7 % for 2010). Moreover, the share of "modern renewables" (i.e. biomass, wind, solar, geothermal heat, hot water, biofuels, and hydropower) was bigger than the share of "traditional biomass" (combusted in inefficient and pollutant systems). (REN21, 2013)

As a consequence of the trends of energy consumption in the recent years, increasingly attention has been given to the importance of use of hydropower reservoirs for energy storage (e.g. Connolly, 2010). The underlying reason—i.e. an increased need of energy balancing—comes from the growth of non-regulated energy sources (e.g. wind and solar) (Whittingham, 2008; Mill et al., 2010; Connolly, 2010). Besides power-distribution issues (including e.g. grid design) and the economic and political aspects, it has been stated that also other effects on the hydropower systems are to be expected (Dahlbäck, 2010). Regarding wind-power development and exploitation being planned, and the following need of hydropower balancing, it was concluded that "this necessarily require that flow magnitudes and water level heights, to a greater extent than previously, will vary between the existing limits" (Svenska Kraftnät, 2008). Different perspectives of potential issues related to more actively operated hydropower plants, causing increased water-level variations in impoundments/reservoirs, are continuously updated through research within CEDREN (Centre for Environmental Design of Renewable Energy). It is highly

expected to get increased variations of the reservoir water levels; hour to hour, day to day and/or seasonally (Svenska Energimyndigheten, 2008; Mill et al., 2010; Solvang et al., 2012).

Numerous studies have been carried out related to the Three Gorges Project. Significant water-level changes have been taking place following the regulation activities, and large areas along the reservoir (with a length of approximately 600 km) have been influenced, ending up with landslides (e.g. Cojean & Caï, 2011; Hu et al., 2012).

Pumped hydropower storage

Existing drawbacks and limitations of different energy-storage methods—regarding as well scale as applicability—are continuously identified and compared. The simple energy-storage technology pumped hydropower storage, PHS (or pumped hydroelectric storage, PHES), has been in use since 1929 (Connolly, 2010). A PHS-system consists of two reservoirs of different elevations. During off-peak electrical demand, water is pumped from the lower reservoir to the higher one; during on-peak demand, when the energy need is increasing, the water is discharged through electricity generating turbines (C. Liu et al., 2010). In Deane et al. (2010) it was expressed that "PHES is currently the only commercially proven large scale (>100 MW) energy storage technology". The technology is dependent on suitable geological conditions but is cost effective at large scales (low cost per unit energy); due to its maturity and fast response time, the technology is an attractive option for integration of renewable fluctuating energy sources (Chen et al., 2009; Connolly et al., 2012). In Rognlien (2012) it was meant that some fundamental underlying reasons for increased PHS-focus include environment/climate goals, European cooperation, and nuclear skepticism upcoming worldwide. Moreover, a scenario of practical implementation was presented; giving hints about potential technical conditions. The example included daily water-level variations of the order of 10 m. In 2011, there were about 170 pumped-storage plants (hydropower plants using PHS) operating in Europe and more than 50 new PHS-projects are by 2020 expected to be either under construction or planned (Zuber, 2011).

WATER-LEVEL VARIATION AND SLOPE STABILITY – EFFECTS AND CONSIDERATIONS

Analysis of slope stability

Fundamentals

The stability of a slope is utterly governed by soil properties, stress conditions, and slope geometries. As soon as any activity is taking place that involves changes of at least one of these factors, stability assessments would potentially be needed. As well geometries as data regarding external loading are generally known or determinable. When it comes to soil properties (including hydrological conditions) analysis of natural landforms, banks, and slopes, generally means less information possessed, in comparison to design or analysis of new constructions. Changes of the factors mentioned do cause changes of forces acting on (and within) the soil volume constituting the slope; both driving and resisting forces. Since slope failures are assumed to involve soil movement along a *slip surface*, the approach of driving and resistance is generally about stresses rather than forces; more specifically shear stress and shear strength, respectively.

In turn, the stress state depends on the pore pressure; the effective stress between soil particles is reduced by the pressure of present water. In a situation with fixed conditions (regarding water level, loading, inherent soil properties, and geometry) the pore pressure is

hydrostatic. At occurrence of any changes, the pore-pressure situation is potentially affected. In coarse-grained soils, water is easily moving and the pore-pressure state is not changed; *drained analysis* is performed. In fine-grained soils, low permeability might mean a rate of drainage/water movement being lower than the rate at which the total stress is changed, meaning potential development of increased (excess, non-hydrostatic) pore pressures. Analogously, this could also be the case in coarse-grained soil if the total-stress is changed rapidly enough. In the two latter situations, *undrained analysis* is to be performed. Depending on what kinds of changes being expected and for what time-perspective the stability is assessed, either drained or undrained conditions are most critical. Therefore, both cases are to be considered; *combined analysis* is performed.

Slope-stability evaluation

Quantification of slope stability analyses is mainly about two parts; (1) calculation of the *factor of safety*, and (2) determination of shape and location of the *most critical slip surface*.

Slope stability problems have been quantitatively considered since the 1840s; to a large extent related to the railway constructions projects being run at that time (Ward, 1945). At the early stages of slope-stability analyzing the questions where primarily concerning fine-grained soils; e.g. determination of shear strength of clay, and the study "A slip in the west bank of Eau Brink Cut", including an illustration of a rotational slip surface within a slope mainly consisting of clay, presented by Skempton in 1945. An approach of actually assuming a circular slip surfaces was introduced in 1916 and in the beginning of the 1920s Fellenius presented a fully described analysis method (Krahn, 2003; J. M. Duncan & Wright, 2005). Later, this method has been referred to as the *ϕ=0-method* or the *Swedish circle method*. In Figure 3, a schematic sketch of a circular slip surface of a waterfront slope is shown. There are different approaches used for quantitative stability analysis; *limit equilibrium methods* (LE), and *deformation analysis methods*, often utilizing finite elements (FE).

Limit-equilibrium analysis

LE-methods have been used to analyze slope stability for a long time (J. M. Duncan & Wright, 1980; Yu et al., 1998; Zheng et al., 2009). These methods—been unchanged for decades (Lane & Griffiths, 1999)—are based upon some assumptions and approximations. In J. M. Duncan & Wright (1980) it was emphasized that all equilibrium methods for slope-stability analysis have some characteristics in common: (1) The factor of safety, F is defined as the ratio between the shear strength, τ_f and the shear stress required for equilibrium, τ. Using Mohr-Coulomb's failure criterion (i.e. $\tau_f = c' + \sigma' \tan \phi'$) and also applying the expression for effective stress (i.e. $\sigma' = \sigma - u$), the factor of safety becomes:

$$F = c' + (\sigma - u) \tan(\phi')/\tau \qquad (1)$$

where normal stress and pore pressure are denoted "σ" and "u", respectively, and the strength parameters friction angle, and cohesion (expressed in terms of effective stresses, i.e. for drained situations) are denoted by "ϕ'" , and "c'" , respectively. (2) It is to be assumed that the stress-strain characteristics of the soils are non-brittle, and that the same shear-strength value may be mobilized over a wide range of strains along the slip surface. (3) In order to possibly be able to determine the shear strength using Mohr-Coulomb's failure criterion, all (or some) of the equilibrium equations are used to calculate the average shear stress and normal stress on the slip surface. (4) Since the number of unknowns is larger than the number of equilibrium equations,

assumptions are to be involved.
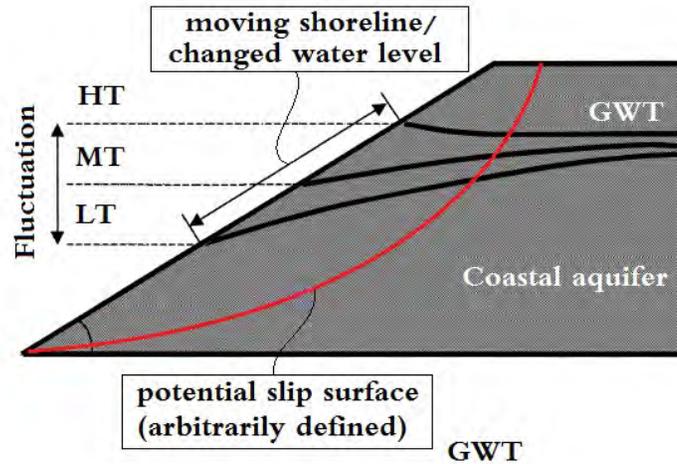
Figure 3:   Schematic sketch of a waterfront slope
High, mean, and low water levels (H, M, and L), positions of the varying groundwater table (GWT), the
range within witch the shoreline is moving, are shown. Moreover, a fictive potential slip surface is drawn.
(Modified after Li et al., 2000)

Moreover, LE-methods may be divided into two groups; *single free-body procedures* and *procedures of slices*, respectively. Within the group of single free-body procedures, there are in turn sub-procedures for various descriptions of the slip-surface geometries. Though, for all of the methods of single-free bodies, the entire soil volume located above the slip surface (as seen in Figure 3-1), homogenous soil profiles are preferable, and external water levels can be considered.

Procedures of slices were introduced already in the end of the 19th century; stated in e.g. Ward (1945) and Brunsden (1999). In order to simplify the process of determining the driving moments, or to make it possible to consider slip surfaces being non-circular, the soil block is divided into vertical slices The simplest slice procedure, often referred to as *the ordinary method of slices,* was done by Fellenius in the mid-1920s. Only overall moment equilibrium is considered. In *Bishop´s simplified method* also the equation of vertical force equilibrium of each slice is satisfied; in *Bishop´s modified method*, also side forces are considered. All these methods are restricted to only circular slip surfaces. Moreover, there are methods in which only force equilibrium equations are satisfied; e.g. a method presented by Lowe and Karafiath in 1960 (J. Duncan & Wright, 1980). Methods satisfying as well moment equilibrium as force equilibrium (e.g. *Morgenstern and Price's method, Spencer's method,* and *Janbu's generalized procedure of slices)* are applicable on slopes with slip surfaces of any geometry. When stability analyses are performed using LE-methods, consideration of pore-pressure situations are often estimated by simplified methods (Huang & Jia, 2009). This might be done by assuming hydrostatic pore pressures (if there is no flow), use of flow-nets (for steady-state seepage), approximate charts (for transient/unsteady-state seepage), or pore-pressure ratios (as an alternative tool for steady-state seepage consideration or for analytic consideration of development of excess pore pressures due to consolidation).

Deformation analysis

As a consequence of known drawbacks of LE-procedures, together with a computational capacity being continuously increasing, more accurate methods have been gradually more requested and developed. Numerical modeling approaches have been most widely used based on FE-methods; applied to the field of soil mechanics in the mid-1960s (J. M. Duncan, 1996). When using FE-methods the volume/area being analyzed is considered as a continuum whereupon it is discretized to a finite number of sub-volumes/sub-areas (elements) forming a *mesh*. In contrast to the fundamentals of LE-methods, a system analyzed with deformations-analysis approaches is not considered to necessarily be in equilibrium; neither in terms of forces nor moments, but allows for as well strains/deformations as failures. Besides consideration of stresses and geometrical conditions, stress-strain relationships are to be described. This is done by use of constitutive models considering different material properties. Moreover, the key-issue is to as reliably as possible define these constitutive relationships for a certain soil.

When it comes to definition of stability in terms of safety factors, a simulation procedure of reducing the strength until failure occurs is used. This method was firstly used in the mid-1970s (Zheng et al., 2009) and is usually referred to as the *shear strength reduction technique*. The safety factor is defined as when using LE-approaches, i.e. by the ratio between the available shear strength and the shear stress at failure.

In FE-codes, e.g. PLAXIS (2012), this is mathematically handled by expressing ratios of the strength parameters:

$$\Sigma M_{sf} = \frac{c}{c_{reduced}} = \frac{\tan\phi}{\tan\phi_{reduced}} \tag{2}$$

where M_{sf} is a controlling multiplier representing the safety factor, c is the cohesion, ϕ is the friction angle, and the index "reduced" indicates values being successively decreased until failure occurs. However, the definition of actual failure is not always obvious, and there are many different approaches to utilize. Though, the "non-convergence of solutions" is often used for indication of global instability of soil slopes. This is indicated by when a stress state cannot be found to simultaneously satisfy the failure criterion and the global equilibrium (Lane & Griffiths, 2000).

LE and FE – pros, cons, differences

Among the large number of previous studies on various slope-stability issues, a significant share is based on LE-analysis. Still, it is worth mentioning that drawbacks and limitations of LE-methods have been known and evidenced for a long time. For instance, there are difficulties connected to accurately define the position of the slip surface (Ward, 1945), and there are numerical problems potentially met with *Bishop´s modified method* (J. M. Duncan, 1996). An illustrative example of what kind of reasoning that is characteristically justifying use of LE-analysis was seen in Tsai & Yang (2006); an LE-based study focused on landslide prediction combined with consideration of rain-triggering effects. It was referred to several authors and stated: "the infinite slope stability analysis is a preferred tool to evaluate landslides due to its simplicity and practicability".

In J. M. Duncan & Wright (1980) it was emphasized that uncertainties arising from LE-approximations made in the analytical processes, are often less important than those related to definition of geometry and soil properties. However, it was still stated that in some cases the

errors connected to the analysis approximations might be significant. It has been shown that force-equilibrium procedures may give safety-factor values being "significantly affected by the assumed side force inclination"; they may deviate from those calculated by methods satisfying all equilibrium equations, by about 30 % (overestimation). The link existing between LE-approximations and potential errors is generally known and recognized by many authors (e.g. Ward, 1945; Lane & Griffiths, 1999; Krahn, 2003). The accuracy of LE-results has therefore been studied and evaluated in many contexts. Some evaluations have been made by means of direct quantitative comparisons between the results achieved from LE-analysis, and those from methods considering also strains and deformations (e.g. Yu, Salgado, Sloan, & Kim, 1998; Aryal, 2006). Moreover, there are a number of other studies; e.g. J. M. Duncan & Wright (1980), evaluating "computational accuracy", and Donald & Chen (1997), highlighting plasticity consideration. In J. M. Duncan (1996) it was emphasized that there are limitations of many of the accuracy evaluations been performed: "for such an evaluation to be valid, the minimum factors of safety for the different methods should be compared, not factors of safety calculated for arbitrarily chosen slip surfaces. This is because different methods may have different critical slip surfaces". Moreover, the author suggested a comparison approach. Such an approach was used by Aryal (2006). A simple slope geometry was studied, different saturation conditions were analyzed, and external forces were included. LE-calculations were performed with different procedures and FE-calculations were used as a reference. The minimum values for the safety factors obtained were compared. It was concluded that the safety factors calculated with LE-methods were generally higher than those from FE-calculations and that pore-pressure development and seepage estimated in the LE-software was not well agreeing with the FE-results. In Huang & Jia (2009) it was stressed that LE-stability analyses carried out together with simplified methods for seepage-field estimations, are often too rough.

The main problem of use of LE-methods concerns the inability to consider strains and deformations; this affects calculations as well of normal stresses as of pore pressures. Even though "modern" LE-methods consider pore pressures in the equilibrium equations, the absence of changes reduces the accuracy. (Krahn, 2003)

Also FE-calculations may involve uncertainties. Continuum theories and material models might be critical factors (Wong, 1984), as well as FE-mesh size, and element type used (Huang & Jia, 2009). In addition, the choice of model parameters has been found to be sensitive (Aryal, 2006). Despite this, there are many important advantages of FE-methods over "traditional" LE-methods. In Huang & Jia (2009) it was stated that one of the valuable strengths of FE-safety analysis is the possibility to determine shape and location of the failure surface without any guessing needed. The authors also meant that although as well transient as unsaturated flow could effectively be taken into account, the influence of such flow on slope stability (determined by use of the shear strength reduction technique) has been limited investigated; further studies comparing safety factors obtained from LE-calculations and FE-calculations are needed.

Water-level drawdown

When an external water level is lowered, the shoreline (along which the water level intersects with the beach face) moves in the direction outwards from land. Surficial water flow occurs, and so might do surficial soil-material transport; i.e. external erosion. The erosion processes have characteristics being dependent on the soil properties; e.g. grain size, denseness, degree of saturation etc. (Grant, 1948; J. R. Duncan, 1964). Even though sediment-erosion processes are extensively studied, it was concluded in Bakhtyar et al. (2009) that "Most research in this area

deals with the large-scale (tide) problem of sea and aquifer interaction and less attention has been devoted to the response of beach groundwater to the swash motions".

When it comes to slope stability, as well large-scale drawdown effect of changed external loading situations as hydrodynamic phenomena within the slope, are to be considered. Drawdown of an external water level is usually impairing the stability situation. The process of having the water level rapidly lowered is described and investigated by many authors (e.g. Lane & Griffiths, 2000; J. M. Duncan & Wright, 2005; Yang et al., 2010; Pinyol, Alonso, Corominas, & Moya, 2011), and simply referred to as *rapid drawdown*. Pore pressure gaps—increased hydrological gradients—are potentially occurring under certain circumstances; i.e. as soon as a water-level change comes about rapidly, and the geology of a site is unfavorable. Such pore-pressure gaps combined with a decreased (or fully vanished) supporting water load, may obviously lead to reduced slope stability. Studies on this phenomenon are mostly focused on earth-fill dams, rather than on waterfront slopes in general. This predominance notwithstanding, the connection between rapid drawdown, vertical infiltration, and slope stability was generally highlighted in Yang et al. (2010). The study was based on laboratory testing of rapid drawdown in a column prepared with two soil layers (clayey sand over medium sand). Pore-pressure development was logged with time elapsed. The soil properties considered were—besides permeability—specific gravity, liquid limit, plasticity index, dry density, void ratio, porosity, and water content at saturation. Some of the results obtained are shown in Figure 4; pore pressures plotted against the depth (elevation) with different curves for different times elapsed. The results did clearly confirm and show potential outcomes of rapid drawdown; pore pressures remained high and gradients occurred. Consequences of rapid drawdown—and the fact that pore pressures are potentially delayed compared to the external water level—have been shown to include outward seepage, tension cracks developed, and finally slope failure (Jia et al., 2009). This was shown in a large-scale experiment with a slope built up inside a tank. The slope consisted of sandy silt, the water level inside the tank was changed by valves installed, and instrumentation installed was registering soil suction, pore-water pressure, horizontal and vertical stresses, slope-inclination changes, vertical displacement, and water flow. The slope was failing along a rotational slip surface, and the mechanism was found to be retrogressive; three clearly separated blocks where found to come loose at different times, but still sharing the same rotational slip surface.

The earliest tools used to take into account different degrees of submergence of a slope (i.e. different water levels), consisted of charts (Morgenstern, 1963). In the following decades further investigations were done; still utilizing LE-methods for expression of the safety factors. This—including the limitations of LE-analysis being again stressed—was reported in Lane & Griffiths (2000) and Huang & Jia (2009). Nowadays, these kinds of problems are also approached using FE-tools (e.g. Lane & Griffiths, 2000; Pinyol et al., 2011).
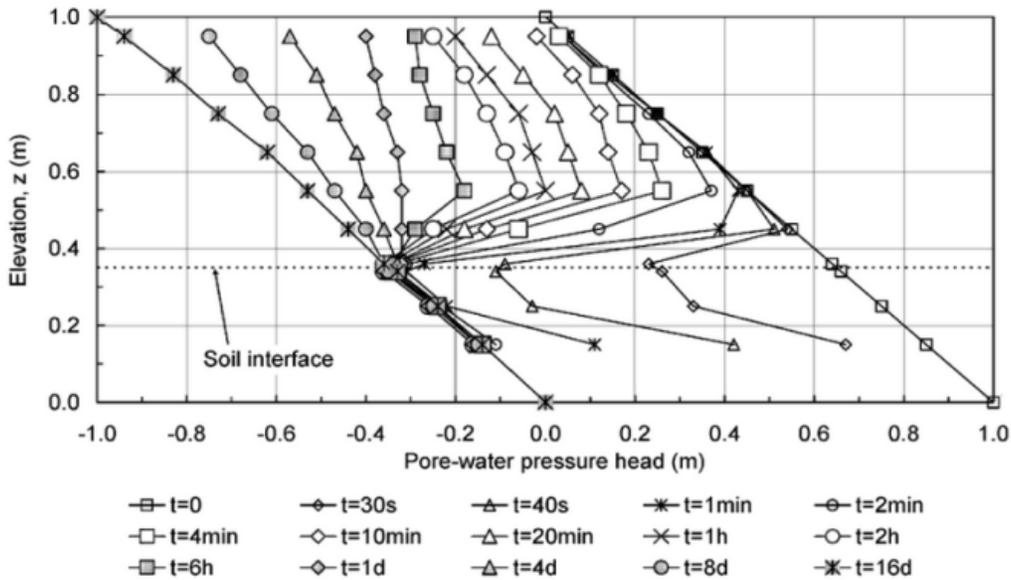
Figure 4: Results from column rapid drawdown tests performed through a soil sample consisting of a finer soil layer (clayey sand) put over a coarser soil layer (medium sand). Pore-water pressures at different depths (elevations) are plotted at different times. The soil interface is represented by the dotted line (Yang et al., 2010)

Water-level rise

Also rising of a water level might cause problems; among studies concerning the Three Gorges Dam site (e.g. Cojean & Caï, 2011), reduced slope stability during periods of water-level rise has been noticed. Generally, water-level rise has been shown to cause stress redistributions due to external loading (as well increases as reductions, in various directions), wetting induced issued such as loss of negative pore pressures, and seepage effects. Subsequently, these changes have been shown to potentially cause loss of shear strength, soil structure collapse, and development of settlements and/or slope failure. In a large scaled model test reported in Jia et al. (2009) (an instrumented soil slope built up inside a tank), the water level was raised 4 m during 192 h. The displacement measurement showed vertical settlements at the crest (and by depth) developing almost linearly during the first period of water-level rising. Further on, the settlement rate was continuously decreasing during the remaining time. The authors assigned the vertical settlements to wetting-induced soil collapse. Moreover, the soil located under the sloping surface was found to be collapsing gradually during the water-level rise. Suction values registered did clearly show abrupt drops occurring immediately when the water level reached the measure points. The horizontal total stresses were gradually increasing during the rise. In contrast, the vertical stresses were at first increasing, and peak-values were noted. Thereafter, gradual reductions were seen; asymptotically leveling out until the end of the rise. The authors found the initial increase of vertical stresses to be caused by presence of entrapped air, together with occurrence of stress concentrations caused by the early observed differential settlements. Development of these, in turn, was explained by the wetting; i.e. entrapped air was replaced by water. Loss of negative pore-pressures and subsequent loss of shear strength did obviously immediately cause soil structure collapse/failure. Development of the total stresses was assigned

to homogenization of the slope body; increased horizontal stresses caused by an increased water load, and vertical stresses gradually returning to the start values. It was emphasized that a delayed change of pore pressure inside a slope—relative to the change of the adjacent external water level—results in significant movements of water within the soil-slope body. Thus, the seepage forces were found to adversely affect the stability. The seepage-instability relationship was also confirmed in Tohari, Nishigaki, & Komatsu (2007).

Water-level fluctuation: drawdown-rise combinations

When it comes to cyclic water-level fluctuations, the fundamentals for each phase of rise and drawdown respectively are obviously the same as for these changes occurring separated. Though, there are important peculiarities linked to recurrence, i.e. actual cycling. Since one of the key-issues of evaluating the effects of cyclic water-level fluctuations on slope stability concerns water-flow patterns—not at least description of groundwater motion—*hydrological modeling* is highly important. Furthermore, any movement of a groundwater level is impacting the geotechnical conditions; the history of stress and strain changes is central. Consideration of such development concerns *hydro-mechanical coupling*.

Hydrological modeling

General

The transition process during which a dry or moist soil changes from being not fully saturated (unsaturated) into saturated conditions has been subject of research all since Bishop (in the end of the 1950th) proposed an effective-stress expression considering also partially saturated conditions (e.g. Fredlund & Morgenstern, 1977).

One source of increased pore pressures is precipitation and following infiltration. Even though this means a wetting front moving downwards (which is not the case when the saturation conditions are changed due to a varying external water level) the hydrological processes are similar. The slope stability is influenced by the patterns of pore-pressures changes (governed by hydraulic properties of the soil and the initial volumetric moisture content), and by precipitation patterns (Cai & Ugai, 2004). Despite the climatological part of precipitation consideration, the main issue of properly consider effects of suction loss, change of shear strength, and different water-flow types, on landslide susceptibility, has been shown to concern hydrological modeling. In the model in Iverson (2000) details regarding transient and variably saturated groundwater flow was not completely included. In Tsai & Yang (2006) Iverson´s model was questioned, the authors proposed a modified version, but suggested however further development. In Olivares & Tommasi (2008) water retention curves were determined from laboratory results, and steady-state and transient seepage analyses were carried out. Though, in these studies slope stability was evaluated by use of LE-calculations. In Olivares & Tommasi (2008) the soils were classified using strength parameters, natural water content, degree of saturation, initial void ratio, and liquid limit (for those soils being finer). Modeling results were compared with in-situ measurement values and found to be in agreement provided that the highest saturated permeability values from laboratory test were used, together with water-retention curves from field measurements.

In J. R. Duncan (1964) the term *swash-backwasch zone* was used for definition of the beach slope area being exposed to seawater in motion. It was stated that the backwash of the temporarily risen water causes erosion of the beach material (seawards), more than does the incoming water. This since the velocity of landward moving water tends to be decreased due to

infiltration and water volume reduction, whereas outgoing water volumes mostly move on saturated soil, get extra water added from the effluent zone, and therefore become accelerating. It has been suggested that rapid fluctuations of a phreatic level within a sandy beach swash zone is governed by occurrence of local jumps in pore-pressures (Turner & Nielsen, 1997). Thus, the authors did suggest that phreatic-level changes are caused by downward infiltration, rather than by upward water flow. Furthermore, it was stressed that conclusions in previous studies—suggesting that saturation characteristics of a soil bed is varying (i.e. is altering between wet and dry) at water table fluctuations—might be wrong.

An obvious fact is that the groundwater table is lagging behind the external water level (Emery & Foster, 1948; Chappell et al., 1979). In Li, Barry, & Pattiaratchi (1997) it was claimed that there are important drawbacks in formerly defined models used for description of groundwater behavior. They stressed that many models are based on the one-dimensional Boussinesq's equation—i.e. shallow free water-flow theory (e.g. Parlange et al., 1984; Nielsen, 1990)—involving non-physical assumptions; e.g. that the beach-face water table is to be coupled with the adjacent external water level. Moreover, the authors meant that many FE-approaches earlier presented did involve drawbacks due to simplifications and inefficiency, and presented a model based on the boundary element method (BEM). The model was allowing for decoupling the exit point from the sea level, taking seepage dynamics into account, and was showing good agreement with measured field data. Regarding quantities for description of the soil (or rather soil state), porosity, water content in the unsaturated zone, and thickness of the capillary fringe, were considered and incorporated in the model. In Li, Barry, & Stagnitti (2000), an approach based on findings presented in Raubenheimer et al. (1999) was suggested. The model took into account also spring-neap tidal water table fluctuations (SNWTF); variations with two frequencies. As an extension to consideration of moving boundaries and SNWTF, Teo, Jeng, Seymour, Barry, & Li (2003) suggested an analytical method for avoiding the beach-slope inclination dependence. They derived a higher-order solution for tide-induced water table fluctuations; later additionally improved by Stojsavljevic, Jeng, Seymour, & Pokrajac (2012). In the latter study (analytical), the soil properties were still just approximately considered/described; only porosity and hydraulic conductivity were used. Both of these quantities were moreover assumed to be constant.

Recent approaches are questioning traditional numerical methods for simulation of water flow; i.e. those being based on gridding and meshing of the models. Instead, *mesh-free methods* (MFree) may be used. Thomas, Eldho, & Rastogi (2013) presented a study comparing MFree with FE used for analysis of a groundwater-flow problem. They concluded that the MFree-results were in god agreement with analytical solutions to the problem; better than were the FE-results. They did underline that MFree-methods are meant to be a good alternative to finite difference methods (FDM), FEM, and BEM. In Swathi & Eldho (2013) it was confirmed that "High costs in creating a grid/mesh, low accuracy of prediction, difficulty in adaptive analysis are few of the shortcomings of these methods".

Hydro-mechanical coupling

In Huang & Jia (2009) it was stressed that fully coupled consolidation calculations should be further studied. Coupled hydro-mechanical behavior can possibly be considered in existing FE-codes. In such processes, calculations of deformations and groundwater flows with time-dependent boundaries have to be simultaneously carried out. Since as well saturated as partially saturated conditions have to be properly handled, consolidation has to be modeled also for unsaturated soils. For description of unsaturated soils, as well elastoplastic soil-skeleton behavior as suction dependency, have to be considered. Moreover, the suction dependence concerns both

degree of saturation and relative coefficient of permeability (e.g. Fredlund et al., 1994). Recent models considering influences of soil mechanical properties on the hydraulic behavior are usually based on the dependency of the soil-water characteristic curves on soil volume, soil density, or volumetric strain (Sheng, 2011). In this study—a review of principles of modeling unsaturated soils—it was also concluded that "when coupling the hydraulic component with the mechanical component in a constitutive model, it is recommended to take into account the volume change along soil–water characteristic curves. Neglecting this volume change can lead to inconsistent prediction of volume and saturation changes."

There are very few studies applying hydro-mechanical coupling found in the literature. The main aims of such studies have often been to address issues occurring in the fluvial environment (i.e. in the sediment transfer system). These are generally connected to sediment loading problems, sources of contributes to a river's sediment budget, changed river shapes caused by sedimentation etc. (e.g. Darby et al., 2007; Fox et al., 2007; R. Grove, Croke, & Thompson, 2013). In Darby et al. (2007) it was presented a method for performance of a coupled simulation of fluvial erosion and mass wasting. The method used to consider the dynamics of bank erosion involved simulations coupling a fluvial erosion model with FE-seepage analysis and LE-stability methods; the mass wasting was simulated to occur as a series of failure episodes. Even though that study was limited to cohesive riverbanks, and mainly aimed to find a method to properly quantify bank derived sediment volumes, the testing and modeling did involve both particle-size characterization and soil-strength consideration.

The shortfall notwithstanding, some studies on large-scale reservoir fluctuations are found in the literature. For instance, it was found that the stability of a reservoir slope constituted by sand and silt was more directly governed by hydraulic conductivities than by water-level change velocities (Liao et al., 2005). For evaluation of reservoir-fluctuation effects on a silty slope, the importance of negative pore pressures, friction resistance, and water-load support was highlighted in Zhan, Zhang, & Chen (2006). In that study, saturated-unsaturated seepage analysis was combined with LE-stability analysis. Also in Shen, Zhu, & Yao (2010) examination of "reservoir water-level fluctuation" included analysis of one cycle of rise and drawdown, carried out by means of LE-calculations. In Galavi (2010) hydro-mechanical theories used in FE-modeling were presented. Comparisons and evaluations performed showed good agreement between the results obtained from the numerical FE-calculations and those from analytical solutions. In Kaczmarek & Leśniewska (2011) effects of groundwater-level-changes on a flood bank core was modeled. Stability and seepage were considered by FE-analysis. Though, the study was only briefly described and neither the input nor the outcomes were satisfactorily presented.

Seepage – internal erosion

Fundamentals observed

Since water-level drawdowns or rises (i.e. fluctuations) affect hydraulic gradients, flowing are potentially induced within the soil volume. Thus, the individual soil particles become subjected to water loads/forces. Moreover, depending on the characteristics of the soil skeleton (i.e. the particle-size distribution, denseness/degree of packing, particle shape etc.), the material is more or less susceptible to particle movement/washout. In the context of embankment dams, this kind of process is known as *internal erosion*.

The underlying problems of internal erosion have been addressed; fundamental theories have been investigated and tools/measures for practical implementation have been developed (e.g. Sherard et al., 1984; Kenney & Lau, 1985; Lafleur et al., 1989; Foster & Fell, 2001).

The material removal has been shown to cause increased seepage flow/leakage through dams, development of settlements at dam crest (sink holes), creation of weak zones, and in some cases also slope failure. Based on the nature of the initial phase of the material washout, internal-erosion modes are divided into three groups; *concentrated leak, backward erosion*, and *suffusion*. The two former ones may occur as soon as there is a seepage flow present being sufficiently strong to remove and carry soil particles from the structure; concentrated leak is progressing from the source of water towards the exit point, whereas backward erosion means erosion progressing in the other direction. Suffusion, on the other hand, concerns material instability caused by a soil-material composition being adverse in terms of particle-size distribution (e.g. Fell et al., 2003). In addition, also the term suffosion is used. In Moffat, Fannin, & Garner (2011) the two related phenomena suffusion and suffosion are explained, and the distinction is clarified; the former implies pure particle removal, whereas the latter process also causes a soil-volume change (due to loss of fines).

In Fell, MacGregor, Stapledon, & Bell (2005) four conditions being relevant for internal erosion to possibly occur, were listed. Three of them concern the erosive process generally: (1) there must be a seepage flow path (and a source of water), (2) there must be erodible material within the flow path (and the seepage flow forces have to be of such nature that the material can possibly be carried by the water, and (3) there must be an unprotected exit (making escape of the eroded material particles possible). For piping to occur (4) the material being piped (or the material directly above) must be able to form and supporting "roof".

A number of studies have been carried out aimed to optimizing filtering properties of soils; i.e. searching for optimal interfaces between different soil types, designed to inhibit particle migration (Kenney & Lau, 1985; Lafleur et al., 1989). Except the filtering itself, i.e. whether there are exit points enabling soil particle migration, or not, the influence of gradients has been researched. In Al-Taie et al. (2014) hydraulic conductivity changes were put in relation to changed gradients, including possible consolidation effects. The study was showing that hydraulic conductivities of filter materials consisting of sand and silt were increasing with raised gradients. The authors were suggesting that the high pressure did probably open up the voids within the filter material, whereupon the conductivities became increased.

Since constructed (man-made) dams are designed to be functional and stable for long times, all kind of deterioration and loss of performance is highly unwanted. Tailings dam—built for long-term storage of deposited waste material produced in the mining industry—are designed to stand by for thousands of years. In Bjelkevik (2005) it was underlined that there are a lot of naturally formed geological formations (often made up by moraine), impounding lakes or serving as banks along rivers or other watercourses. In a reported investigation taken out by the Geological Survey of Sweden in 2002, it was stated that such natural landform structures most probably can serve as long-term hydraulic barriers without being subject to erosion, despite aging and deterioration (Jantzer, 2009). Moreover, hydraulic-gradient dependence on internal-erosion susceptibility of soils, was investigated in Jantzer (2009). Results from pore-pressure measurements performed within a geological formation separating two lakes with water levels of different heights were analyzed. It was found that the assumed shape of the water table (initially expected to connect the two lakes), did not agree with what was actually the case (based on measurements). One possible reason of the finding was that the upper lake was not at all connected to the lower one through the formation (initially assumed to serve as a hydraulic barrier), but instead possibly connected to another lake situated further away, having an even lower water level. Consequently, the potential of long-term erosion resistance of natural formations could not be reliably evaluated.

Also more recently developed natural damming formations have been investigated. In Meyer et al. (1994), a landslide blockage—a dam constituted by soil originating from a debris avalanche—was focused. The study was taken out only 14 years after the creation of the dam, and addressed the potential for development of erosion due to seepage. The dam had been blocking runoff water since its emergence, whereupon a lake had been formed. The author discussed *seepage erosion* collecting the three phenomena *heave* (upward movement of a soil volume subjected to a high seepage gradient); *piping* (removal of soil along discontinuities); and *internal erosion* (removal of fine particles into coarser ones). For evaluation of heave and piping, vertical and horizontal hydraulic gradients were measured and compared to critical gradients calculated. Evaluation of 3) was carried out through material-property analysis. They found the dam being stable, but suggested further monitoring. Though, they underlined that landslide dams (i.e. natural formations) are generally homogenous and have not been systematically compacted as man-made embankment dams. In Costa & Schuster (1988), these peculiarities of natural dams were said to be potentially increasing the susceptibility to internal erosion.

Consideration

Among recent studies some have been addressing not only definition of different erosion processes and filtering, but also the importance of detection of erosion and the difficulty of reliably model the processes. In Rönnqvist (2007) a method for assessment of the potential for sinkhole development in dams with cores made of glacial till was discussed. The fundamental approach was based on putting together results from a comprehensive screening of Swedish zooned embankment dams, with existing and generally accepted filter criteria. The author was underlining that the method/tool been developed and proposed could provide qualitative indications, and that existing criteria for the actual filter design should not be disregarded. Other studies addressing the topic in terms of identifying signs of initiated internal erosion and predicting time for continued development (e.g. Fell et al., 2003), are based on peculiarities of zoned embankment dams.

There is a need of method improvements to be done in order to completely noninvasively make rapid detections, and also to accurately quantify seepage-related hydraulic soil parameters in earth-fill dams (Ikard et al., 2013). The study was aimed to evaluate geophysical (geoelectrical) methods for reliable detection of anomalous (concentrated) seepage within a dam-body. The self-potential method (SP) was used together with direct current (DC) resistivity measurements. SP-measurements provide results directly related to the Darcy velocity, whereas the DC-measurement results provide information about the soils' electrical conductivities (being dependent to porosity and moreover needed for interpretation of SP-results). A small embankment dam exhibiting internal concentrated seepage was imaged. Data analysis and laboratory tests were performed and potential seepage paths were identified. Even though the results were found to be reasonable, and the method therefore useful, elements of roughness and estimation were incorporated.

The difficulty of describing the mechanical process of soil-particle removal due to seepage forces has been stressed by many authors; the topic is moreover increasingly researched. It has been concluded that erosion would be possibly modeled using DEM, but then would be required either a fluid model coupled, or a method for description of the pore network to be included in the models (Shire & O'Sullivan, 2012). The latter alternative for erosion simulation was highlighted also in Reboul et al. (2010). According to the authors, a central part of modeling transport processes in granular materials is to compute the cumulative constriction size distribution (CSD), i.e. the void-network geometries. The model proposed only requires information about particle-

size distribution, and extreme void ratios of the soil material. Even though limitations were identified, the methodology was found promising. In Shire & O'Sullivan (2012) internal soil stability was micromechanically assessed by DEM-modeling, whereas the approach in Reboul et al. (2010) concerned probabilistic determination of CSD. Both studies were based on the assumption of perfectly spherical particles. In Hicher (2013) predictions of the mechanical behavior of granular materials being subjected to particle removal, were made. The numerical model presented was considering stress-strain relationships, elasticity and plasticity of soil (the latter using Mohr-Coulomb plastic law), and sliding resistance connected to void ratio. The model was applied on internal-erosion processes and the results obtained were found to be in agreement with real observations done. It is worth mentioning that modeling approaches based on assuming soil particles to be spherically shaped might importantly reduce the reliability of the results; there are effects of particle shape on mechanical properties of soils Cho et al. (2006). The relevance of such relationships, including the possibility to quantify the shape was presented in Rodriguez & Edeskär (2013) and Rodriguez, Edeskär, & Knutsson (2013).

CONCLUDING DISCUSSION

Water-level fluctuations

Since water-level rise is causing important threats and problems when it comes to environmental values (habits, plants, animals, etc.), these are generally the most highlighted and investigated issues. On the other hand, among engineers being focusing on slope stability, drawdown is generally more often considered as more undesirable. Moreover, concerning effects of water-level fluctuations on slope stability, there are obviously more studies focusing on drawdown than those focusing on rise related issues. In addition, long-term perspectives on cyclic fluctuations, and studies including plastic deformations and soil property changes (degradation, washout etc.), are very few.

The results obtained in Jia et al. (2009) did confirm some known processes: settlement development, stress redistributions, homogenization, delayed pore-pressures changes, gradient changes, seepage, and failure. However, the fact that the results obtained did only concern one rise and drawdown phase, respectively, does open up for further questions: (1) What would have been the outcome if the same test had been carried out with the water level initially located at its maximum, where after the drawdown had been run as the "first" change? (2) If the slope had not failed during the drawdown, how would another rise-drawdown cycle have been ending up? The lack of tests performed makes it desirable to further investigate the processes of suction loss, effects of rapidly increased pressures in existing cracks, retrogressive failure development etc.

When interpreting findings and conclusions from previous studies, it is important to be aware of existing peculiarities and disparities of different processes and scales. For instance, in simulations it might be of some value to consider the proven difference in "erosion capacity" of water moving landward and that of water moving outward from a slope being exposed to a fluctuating water level; an actuality related to degree of saturation, explained in J. R. Duncan (1964). Though, for application on reservoir-bank slopes, this theory of external-erosion susceptibility (being reduced with increased degree of saturation), has to be merged (and balanced) with what is the case for suffusion and other seepage processes.

Regarding the large scale—i.e. in situations with hillsides instead of beaches, and water-level changes of regulated watercourses instead of waves and tides—there are few studies that stick to actual fluctuation. Among the ones that according to the paper titles aim to consider "variations" and "fluctuations", most attention has anyway normally been put on the drawdown phase (e.g.

Liao et al., 2005). Moreover, those that certainly include also rise are commonly looking at only one fill-drawdown cycle (e.g. Zhan et al., 2006; Shen et al., 2010).

In most studies addressing flow modeling issues, soil properties are considered by involving only a few parameters; permeability and/or conductivity disregarded, soil material characteristics are only exceptionally specified and strength/stiffness properties strikingly rarely. Therefore, the coupling between soil deformation, pore-pressure development, and water flow conditions are often deliberately overlooked or incidentally missed. This is probably to some extent explained by the fact that research published within the framework of groundwater modeling is often aimed to describe systems of more or less stationary/non-changeable nature; i.e. moving water and fixed/unchanged soil structures. Although the aims might be varying, and the soil types investigated of different natures, the fundamentals of hydro-dynamical coupling should be interdisciplinary applicable.

Seepage and internal erosion

Similar to the rapid-drawdown phenomenon itself, also internal erosion has been primarily approached considering earth-fill dams. Though, the criteria listed in Fell et al. (2005)—needed to be fulfilled for internal erosion to occur in embankment-dams—would probably be applicability also on natural stream banks. Once having two water levels of different elevations (potentially connected) present in soil, there will be gradients (potential seepage flows). Furthermore, potential water paths are undoubtedly present in any porous materials, and flows through any soil volume may lead to erosion of fine-grained fractions. In a soil volume where flowing water is present, there are (by definition) "exits". Moreover, the geology and the particle size distribution do govern whether these potential exits are "unprotected" or not. Even though embankment-dam conditions generally mean potential presence of very high hydraulic gradients, also natural conditions would be of interest; not at least considering gradient changes, stress redistributions, recurrence, and long-term effects.

According to some findings concerning the properties/peculiarities of natural geological formations serving as hydraulic barriers is interesting. Though, long-term stability of such formations is perhaps not always a consequence of extraordinary good erosion-resisting conditions, but possibly sometimes a result of changed patterns of phreatic-line connections (e.g. Jantzer, 2009). To this discussion should be added also the interesting thoughts presented in Costa & Schuster (1988); i.e. that peculiarities of natural dams (e.g. homogeneity) are potentially increasing the susceptibility to internal erosion. However, stationary conditions seen in natural hydraulic barriers are not comparable to bank slopes facing fluctuating water; the latter conditions mean gradient changes and horizontal flows. Moreover, all the components needed to initiate (and later continue) internal erosion-like processes are potentially present.

Even though internal erosion has been a topic of research for a long time, there are still unsolved issues connected to the complexity of the process; especially when it comes to physical description and modeling. It is obvious that in studies focused on "internal erosion" in the context of man-made embankment dams, the complexities and the lack of reliable simulation methods have been repetitively and clearly stressed. On the other hand, within the field of erosion and sedimentation of stream banks—research that is generally aimed to quantify sediment production (and subsequent issues)—there are numerous reported approaches considering "seepage erosion". The views of how the erosion should be described and simulated seem to be different. This is probably because of the fact that the ultimate goals are not the same; *sediment quantification* versus *physical description of soil material migration*. In turn, perhaps this explains the severe lack of interdisciplinary exchange of knowledge and available measures.

Despite recent progress seems to open up for implementation of hydrodynamic models, further studies are still needed. The complexity of combining models of solid particles and fluids is well-known but still not fully solved. For instance, modeling approaches based on soil particles represented by spheres are probably importantly reducing the analysis reliability.

Slope stability

Historically, the general view on the LE-methods has been optimistic and praising. Drawbacks are certainly identified and presented, but actual limitations are often scaled down or neglected; this typically by use of arguments pointing at other important uncertainties. For instance, LE-method inaccuracies are put in relation to soil-property uncertainties, or numerical uncertainties of FE-modeling. However, since pore-pressure conditions are directly dependent on deformations (in analyses with pore water present), the strengths of deformation analysis become important and obvious for the reliability. In particular, when stability-analysis is to be carried out combined with seepage analysis, LE-procedures often cause problems. Unfortunately, there are examples of somewhat contrived result interpretations, made in order to show upon agreement, and applicability of LE-analysis.

In addition to advantages such as increased reliability of slope-stability evaluations, properly modeled hydro-mechanical processes would also provide improved assessments/quantifications of coastal zones being influenced by water-level fluctuations.

ASPECTS TO BE FURTHER CONSIDERED

- The lack of studies addressing slope stability issues related to watercourse regulation—i.e. the predominance of studies on pure bioenvironmental issues—is contributing to an unbalanced picture. Relationships between effects of hydrological changes on slope stability, and human safety—i.e. the central role of geotechnical perspectives—should be clarified.

- Since water-level rise (not only drawdown) has been shown to significantly influence slope stability, together with the obvious lack of studies, it would be desirable to further investigate the processes of suction loss, effects of rapidly increased water pressures (as well in pores as in other discontinuities), retrogressive failure development etc.

- Many of the studies, intended to evaluate effects of water-level fluctuations, actually are not. In order to fully consider altering hydraulic gradients, stress-strain changes, and waterfront influence zones, long-term views should be central; analysis of several rise-drawdown cycles, detailed description of soil materials, and more attention put on constitutive models used, is needed.

- The coupling between soil deformation, pore-pressure development, and water flow conditions are often deliberately overlooked or incidentally missed. Regarding as well general pore-pressure consideration, as specific seepage modeling, interdisciplinary approaches would be beneficial for further improvements.

- In order to reliably incorporate effects of seepage on soil-property changing, as well acute effects as long-term changes has to be considered. Therefore, effects of water-level fluctuations on slope stability are highly dependent on description/modeling of internal erosion.

- Given the important and critical connections involving pore pressure, soil strength, soil-deformation development, pore-pressure change (and so on), analyses have to be performed using robust simulation approaches. The terms "simplicity" and "applicability" (promoting

use of LE-methods) are therefore to be related to accuracy and robustness of methods considering also deformations; especially for systems of soil and moving water.

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