*Review Paper:*

# Review of Slope Stability Analysis under Drawdown Conditions for Mine Slopes

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## Abstract

*The slope steadiness is influenced by slope configuration, material characteristics and the applied forces interim both internally and externally. These forces encompass the impact of water internally through pore water pressure, seepage forces and externally through hydrostatic and hydrodynamic effects. Examining the slope under various levels of submergence and drawdown illustrates the significant influence of water on slope stability. The presence of water develops effective water pressure in open pit slopes which is more concerned for slope pit designer and geotechnical engineers.*

*This study tried to discuss about the influence of drawdown and rapid drawdown conditions for a mine slope stability in the light of slope stability studies under hydrogeological characteristics. This study includes preliminary generalities considered for drawdown conditions like soil properties, hydraulic properties and drawdown phenomenon.*

**Keywords:** Drawdown conditions, Slope stability, Pore water pressure (PWP), Water seepage.

## Introduction

The stability of a slope inclination is influenced by geometry it possesses, material characteristics and the applied forces. These forces encompass the impact of water, both internally through pore-water pressures and seepage forces, as well as externally through hydrostatic and hydrodynamic effects. Examining the slope under various levels of submergence and drawdown illustrates the significant influence of water on slope stability. The presence of water develops effective water pressure in open pit slopes which is more concerned for slope pit designer and geotechnical engineers[5]. The rapid drawdown scenario is one of the severe loading conditions on slopes.

The practical application of engineering reveals that the stability of neighbouring slopes can be significantly influenced by the conditions of slope drawdown. The transient seepage-induced pore water pressure diminishes the shear strength along the potential sliding surface, potentially leading to slope destabilization. Preventive measures are essential in practical engineering to mitigate slope instability triggered by rapid drawdown conditions[1]. Considering the negative impact of swift drawdown on slope stability, it is essential to incorporate this factor into the design of stabilization measures for dam and reservoir bank slopes[6]. The impact of slopes under varying degrees of submergence and drawdown was initially quantified[4].

Subsequent investigations by researchers[17] delved further into this aspect. They employed limit-state analyses to estimate the factor of safety (FOS) for slopes under different conditions, resulting in the development of charts intended for practical use by engineers. Elevated reservoir levels contribute to slope stability through hydrostatic pressures. A decrease in water level results in two effects: diminished external hydrostatic pressure, reducing stabilization and a shift in internal pore water pressures. To examine drawdown, it is categorized into two distinct groups: Flow methods, which are suitable for relatively permeable slopes and undrained methods, which are employed in slopes with impermeable soil.

In the field of geotechnical literature, there is a comprehensive discussion of procedures related to rapid draw down (RDD) stability analysis for both states. Various methods have been outlined for this purpose[17]. Noteworthy examples of approaches utilizing the total stress method include the Corps of Engineers Method US Army corps[25]. Additionally, illustrations of approaches employing the effective stress approach are those formulated by Berilgen[4] and as well as Duncan et al[8].

## Preliminary generalities

The slope stability (SS) relies on factors such as structure shape, characteristics of the soil and the internal and external dynamic forces acting upon it. The normal preliminaries required for slope stability studies under drawdown conditions are soil properties, hydraulic properties, geometry of the of the slope structure, seismic considerations, monitoring structure system, numerical modeling. The inter relationship is useful for the estimation of conductivity values where direct permeability data are sparse such as in the early stages of aquifer exploration, to simulate the water flow in the soil. Both in the saturated and unsaturated zones, one must be aware of the saturated hydraulic conductivity of the soil. The practical consequences of rapid drawdown, presenting various case histories related to either complete or partial failure of the upstream slope[3] were also explored.

**Soil and Hydraulic properties:** The shear strength characteristics of unsaturated soils can affect a soil slope's stability during a rainy period with a high inrush of water.

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Numerous studies have investigated the uncertainties associated with hydraulic regime for unsaturated soils and their impact on the dependability of slopes under during precipitation events. Alterations in pore water pressure resulting from seepage can induce changes in stresses, subsequently causing deformation in the soil. Modifications in stress levels will impact the seepage process as the alterations in stresses influence soil hydromechanical behaviour including porosity, permeability and water holding confinement.

Slope stability and rainfall circumstances affecting the qualities of the soil are the void ratio which can be used to calculate the coefficients of volume change for solids, $m_1s$ and $m_2s$ (equations 1 and 2):

$$m_1 = \frac{1}{1+e_0} \frac{d_e}{d\,(\sigma_{mean-u_a})} \quad (1)$$

$$m_2 = \frac{1}{1+e_0} \frac{d}{d(u-u_w)} \quad (2)$$

For the study of diversity of soil characteristics, the examination focuses on assessing the impact of uncertainty in the shear strength and hydraulic characteristics of the soil on slope deformation and stability. The results show that prior to the onset of the storm, minor uncertainty in soil strength parameters at the time of the storm contributes to the changes in the safety factor (SF). Following rainfall, the hydraulic properties of soil come into play, influencing pore water pressures and consequently affecting the slope's performance.

**Monitoring:** In mining operations, maintaining safe and cost-effective slope geometries is crucial. Slope monitoring provides an efficient way to address potential instabilities, offering a practical alternative to conservative and costly design solutions[19,20]. In the realm of geomechanics, the routine monitoring of slope stability (SS) and rock mass movements (RMM) is fundamental. The majority of rock slope failures are linked to creep deformation and complexity is frequently seen in the causes of instability. Accurately predicting the timing of slope failures proves challenging[21-23]. Nevertheless, advancements in modern slope monitoring technology now empower the rapid scanning of expansive moving slopes within minutes, achieving sub-millimetre accuracy[15].

The extraction of rocks has the potential to trigger movements within the rock mass, necessitating vigilant monitoring to avert accidents, to safeguard ore reserves and equipment, to avoid mine closures and in some cases, to prevent the loss of lives. Considerations such as rock mass properties, geological structures and hydrologic conditions assume paramount importance in the formulation of a secure and efficient mining operation. The implementation of an engineered factor of safety becomes imperative for regulating equipment damage and mitigating the risk of injuries resulting from rockfall and slope failure. Balancing this factor of safety is essential to cost control and the adoption of steepened pit walls emerges as a strategy to minimize operational costs through reduced waste removal. As a result, operators at open pit mines are more equipped to handle the fallout from slope failures[5].

**Numerical modelling:** Several researchers have delved into the assessment of slope stability over the years. While numerous methods have been proposed, the limit equilibrium method (LEM) and numerical evaluation (deformation analysis) stand out as the two primary techniques widely employed to evaluate the stability of rock inclined slopes[10,27].

According to Hoek et al[9] the LEM, available for many years, is considered a reliable tool for slope design. It can be used to assess the beginning of failure in slopes under the worst plausible scenario in conjunction with other geotechnical analysis techniques, such as the Mohr-Coulomb failure criterion[14].

Slopes are split into components in the numerical modeling approach and the behaviour of the slope is predicted by modeling the split parts using the stress-strain relationship and deformation parameters. Hammouri et al[7] conducted a study on systematically reducing the shear strength of materials by the factor of safety (FOS) and computed finite element method (FEM) models of the slope until deformations were deemed unacceptably high.

The numerical modeling method for analysing instability in rock slopes has proven instrumental in providing solutions for complex scenarios[16,17,21]. This approach allows for the modeling of plausible rock slope failure mechanisms and makes a thorough examination of rock slopes easier.

**Seepage analysis:** Numerical models are employed to perform both long-term steady-state and transient analyses of seepage in the study. The mathematical representation of the governing differential equation for two-dimensional seepage is articulated as[24]:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(ky \frac{\partial}{\partial y}\right) + Q = \frac{\partial \emptyset}{\partial t} \quad (3)$$

where H is total head, kx is the hydraulic conductivity (K) in the x-direction, ky is the hydraulic conductivity (K) in the y-direction, Q is the applied boundary flux, $\Theta$ is the volumetric water content and time is t.

Primarily, this equation relates the water flow across a two-dimensional elemental volume in both the x and y directions, along with the boundary flux, to the volumetric water content, considering the variability of time. The analysis of stress and deformation in earth structures can be conducted through the utilization of the different numerical modelling programmes like SIGMA/W. This program follows a finite element approach, offering a comprehensive formulation that allows for the examination of both straightforward and intricate problems.

Express the directional strain vector along three axes utilizing engineering shear strain in the following manner:

$$\{\varepsilon\} = \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \end{Bmatrix} \quad (4)$$

In the case of two directions, it is presumed that the strain vector in the z-direction ($\varepsilon_z$) is negligible. Displacements in the field occur due to variations in stress and are directly associated with the strain vector.

The strain matrix for two directions is articulated as[2]:

$$\{\varepsilon\} = [B]\begin{Bmatrix} u \\ v \end{Bmatrix} = \begin{Bmatrix} \frac{\delta N1}{\delta x} & 0 & \frac{\delta N8}{\delta X} & \frac{\delta N8}{\delta y} \\ 0 & \frac{\delta N1}{\delta y} & 0 & 0 \\ \frac{\partial N1}{\delta x} & \frac{\delta N1}{\delta y} & \frac{\delta N8}{\delta X} & \frac{\delta N8}{\delta Y} \end{Bmatrix} \begin{Bmatrix} u \\ v \end{Bmatrix} \quad (5)$$

where $[B]$ is the strain matrix, u is the relocation of nodes in x- direction and $v$ is relocation of nodes in y- direction.

## Drawdown Phenomenon for Slope failure

In the context of mine slope stability, a drawdown scenario refers to the lowering of the water level in a pit or mine which can have significant implications for slope stability. Any soil slope experiences a drawdown condition when its outer slope is partly or totally submerged and a sudden decrease of the free water level occurs after a long period of average water level as shown in fig. 1. Under normal conditions, the water level plays a crucial role in stabilizing the forces exerted on the slope. Nevertheless, in the event of a sudden drawdown, the slope undergoes two primary effects.

Initially, there is a decrease in the external hydrostatic pressure responsible for stabilization and subsequently, there is a alteration in the internal water pressure[15]. In the examination of slope stability analysis under drawdown conditions, the focus is primarily on two scenarios: (1) when the internal section of the free surface is horizontally positioned at the level just before the initiation of water drawdown, or during a gradual drawdown or partial submergence, wherein the internal section of the free surface has stabilized at the new level[20].

The configuration of the slope, the characteristics of the soil and the forces exerted on it, both internally and externally by the slope structure, contribute to its overall geometry. Internal and external forces, such as pore pressure and surface water pressure, are instances that can impact the slope stability, with potential implications from both hydrostatic and hydrodynamic viewpoints[4].

Because of changes in the water level, the slope experiences the development of both seepage-generated pore pressures caused by transient flow and stress-induced excess pore pressures. Over time, these excess pore pressures dissipate, leading to consolidation[26]. The dissipation rate of elevated pore pressures and the reduction in seepage-induced pore pressures are contingent upon the drawdown rate as well as the hydraulic conductivity and compressibility nature of the slope materials[18].

In soils characterized by high permeability, stress-induced pore pressures typically dissipate during drawdown. Conversely, in soils with low permeability, there is a disparity in the dissipation rates between seepage-generated and stress-induced pore pressures in response to external water level changes. As a result, either partial or total undrained soil behaviour is likely to be observed.

**Application of Geo-studio for Slope Study Analysis:** Geo-Studio is a professional simulation and calculation software that has evolved over decades. Its development began in the 1970s under the guidance of Professor Fredlund. Today, after more than 60 years of continuous improvement, it is recognized as a leading software in geotechnical engineering, renowned for its precision, efficiency and comprehensive functionality.

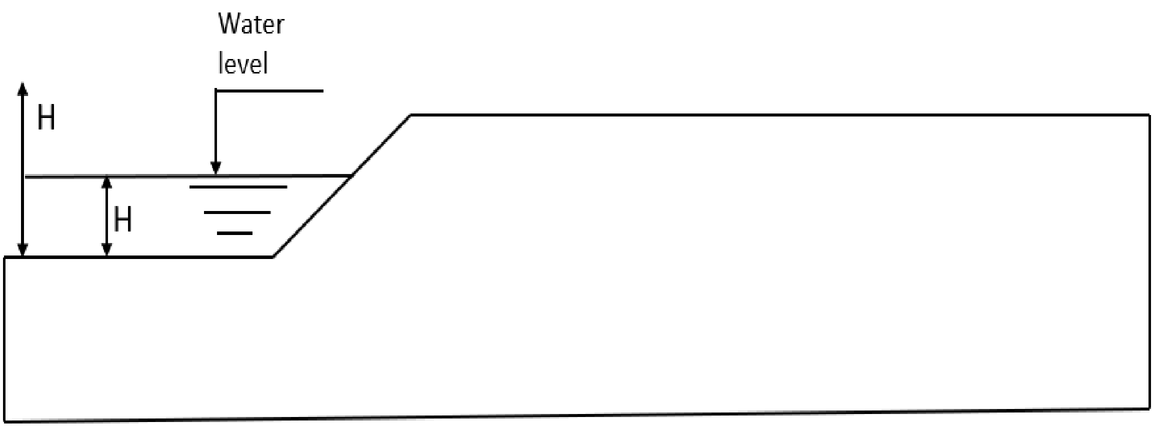


**Figure 1: Schematic line diagram of drawdown condition for slope analysis[9].**

This versatile software is widely used across various engineering disciplines including:

- Slope stability analysis and support
- Mechanical properties of unsaturated soils
- Groundwater seepage analysis
- Impact of drainage ditches and water injection wells on seepage flow.

**Case studies from literature**

**a) Case study of Xinchang slope in Lanping County, Yunnan Province, China[24]:** GEO-Studio software is applied to simulate and analyse the slope stability under different rainfall conditions. The software is utilized to explore various aspects of slope mechanics including the seepage field, stress field, displacement field and stability coefficient of the slope. Specifically, the study employs three modules of GEO-Studio: SEEP/W for seepage analysis, SIGMA/W for volumetric stress analysis and SLOPE/W for slope stability analysis. The research focuses on understanding how internal seepage changes affect slope stability, particularly in the context of dynamic rainfall conditions.

The findings indicate that the volumetric water content and saturation of shallow soil increase rapidly with rainfall, leading to changes in pore water pressure, shear stress and total displacement, which ultimately influence the stability coefficient of the slope. The software's capabilities allow for a comprehensive evaluation of these factors, providing a theoretical foundation for assessing slope stability and designing prevention and control measures for similar engineering cases [13].

**b) Analysis of seepage for Kongele earth dam of Bagdad, Iraq[8]:** Geo-Studio utilizes the finite element method (FEM) to analyse seepage, allowing for detailed modelling of complex geometries and material properties of the dam. This method helps in accurately predicting the flow of water through the dam and its foundation under different scenarios, such as when the reservoir is empty or at normal and maximum water levels[10]. The software enables the analysis of steady-state conditions, which is essential for understanding the long-term behavior of seepage through the dam. This includes defining hydraulic conductivity for different parts of the dam and setting appropriate boundary conditions.

SEEP/W provides tools for visualizing the results of the seepage analysis including the phreatic line, pore water pressure distribution and hydraulic gradients. This visualization aids in understanding the flow paths and potential areas of concern within the dam structure.

**c) Geo Studio software to analyse the soil slope of Kottayam County, Kerala province, India**: This study engages with the analysis of soil slope stability utilizing GeoStudio software, assessing various parameters such as height, inclination and water level that impact soil stability. The research focuses on a specific area in Elamkadu, Kottayam, which has experienced notable landslides, particularly in 2018 and 2021. By applying geotechnical engineering principles, the research focuses on a specific area in Elamkadu, Kottayam, which has experienced notable landslides, particularly in 2018 and 2021. By applying geotechnical engineering principles, soil samples were collected and subjected to laboratory testing to ascertain key properties. The data gathered were instrumental in calculating the Factor of Safety (FOS) across different conditions, with particular emphasis on changes in slope height, angle and water level, thus illustrating the relationship between these factors and soil stability.

**d) Khassa Chai Dam in Iraq:** A numerical approach through the Finite Element Method (FEM) analysed the mechanisms of seepage and the resultant slope stability under different evacuation scenarios. Utilizing a numerical approach through the Finite Element Method (FEM), the study analysed the mechanisms of seepage and the resultant slope stability under different evacuation scenarios.

GeoStudio software was used to quantify water flux dynamics and the impact of varying drawdown rates on stability, revealing that prolonged or rapid drawdown significantly threatens the integrity of the dam's upstream slope[7]. The study enumerated specific scenarios, highlighting that longer drawdown periods often allow for sufficient time for pore water pressure dissipation, mitigating some adverse effects compared to rapid evacuations[12].

## Conclusion

The stability of slopes under drawdown and rapid drawdown conditions is a multifaceted issue influenced by several key factors. The interplay between soil properties, hydraulic characteristics, slope geometry and external forces, including changes in water levels, creates a complex environment that can lead to slope failures. Understanding and monitoring these variables are crucial for predicting and mitigating the risks associated with slope instability in such conditions.

- The stability of a slope is heavily impacted by factors such as slope geometry, soil characteristics, applied forces and the presence of water, having a significant impact.
- Drawdown and rapid drawdown conditions impose severe loading on slopes, leading to slope failures. Changes in water levels, whether elevated or reduced, contribute to these failures by exerting hydrostatic pressures.
- Factors influencing drawdown conditions encompass soil properties, hydraulic characteristics, slope geometry, structural attributes, seismic considerations, monitoring systems and numerical modeling.

- In drawdown conditions, soils are characterized by high permeability typically dissipate stress-induced pore pressures.
- In soils with low permeability, there will be a difference in the rates of dissipation between seepage-induced and stress-induced pore pressure when reacting to external changes in water levels.

These conditions result in significant loading on slopes, creating a dynamic environment where hydrostatic and seepage pressures vary. Understanding these behaviours is essential for slope design optimization. By investigating these factors, mine slope designs can be optimized to improve stability and reduce failure risks. Monitoring systems and numerical modelling also aid in real-time risk assessment and management.

Slope stability analysis under drawdown conditions can be a great influence in understanding the soil behaviour which helps to better optimum mine slope designs.

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