Water Driven Failure of Large Mine Slopes

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Abstract

Water is an important factor in the stability of large mine slopes. Groundwater pressure on a potential failure surface in a slope reduces the effective stress on that surface, which reduces frictional strength of that surface and the Factor of Safety of the slope by as much as 40%. This effect is normally considered in standard slope stability analyses. However, water pressure acting on the surface of a potential failure mass also exerts a lateral driving force, which in saturated slopes generally exceeds the gravitational driving force, and results in a further reduction of the Factor of Safety of more than 50%. This water-drive is rarely correctly considered in standard slope stability analyses. For slopes that can have positive groundwater pressure within them, ignoring water-drive leads to dangerously under-estimating the likelihood of failure. This paper presents the theoretical basis for including water-drive in slope stability analyses, quantifies the magnitude of the failure risk that is introduced by water drive, and provides stabilization strategies that manage those risks.

Keywords: Water drive, large slope failure, slope stabilization

Introduction

Water is an important factor in the stability of large mine slopes (Hoek and Bray 1977). Groundwater pressure on a potential failure surface in a slope reduces the effective stress on that surface, which reduces frictional strength of that surface by as much as 40% (Terzaghi and Peck, 1948). This effect is normally considered in standard slope stability analyses. However, water pressure acting on the surface of a potential failure mass also exerts a lateral driving force, which in saturated slopes generally exceeds the gravitational driving force, and results in a further reduction of the Factor of Safety of more than 50%. This water-drive is often ignored in standard slope stability analyses. For slopes that can have positive groundwater pressure within them, ignoring water-drive leads to dangerously under-estimating the likelihood of failure.

Water Drive in Mine Slopes

Mine slopes in general receive water from precipitation, infiltration, snowmelt, seepage, reservoirs, rivers, and occasionally flooding. When mines are excavated the slope materials are de-stressed, in general allowing fractures to open in the materials near the mined surface. These fractures allow surface water to enter the rockmass. Mine slopes are often made up of low permeability materials, and the water entering the rockmass does not easily drain out of the fractures in the slope, or indeed the slope itself. As a result, mine slope materials at least periodically become saturated and pressurized by groundwater during their operating life.

This slope water has two effects on slope stability. First, the water "floats" the saturated portion of the rockmass, reducing its effective weight to its buoyant weight. This results in a reduction of the normal pressure on sliding surfaces, and a corresponding reduction in the frictional resistance to sliding along potential failure planes. The reduction in strength in saturated slopes is approximately equal to the ratio of the buoyant unit weight to the total unit weight of the slope materials, which for silica rocks is about 0.6, resulting in a reduction of 40% in the frictional resistance of the failure surface. This 40% reduction in the Factor of Safety may result in instability of the slope.

Second, the water "drives" the failure mass by exerting a lateral force on any potential failure surface in the interior of the slope rockmass. Water drive can be understood by considering that the potential failure mass is acting as a "dam", holding back the groundwater behind it from draining from the slope. If the slope is to remain stable, the lateral force exerted by the groundwater on the upstream side of the potential failure "dam" must be resisted, in general by shear force along the potential failure plane. The water-drive force can be large: in a saturated rock slope it is usually substantially greater than the gravitational driving force due to the weight of the rock in the potential failing portion of the slope (Brown 1969). This more than 100% increase in the driving force reduces the Factor of Safety by more than 50%, and may also result in instability of the slope.

I am going to illustrate the water drive problem by looking at the saturated slope in a different light. The slope materials are holding back the force that is exerted on the upstream section of the slope by the groundwater pressure in the un-mined portion of the slope. This is a similar function that a circular or trunnion spillway gate performs for a dam. A picture of the movable portion of such a spillway is presented in Fig. 1(a) (Vortex Hydra 2025). A notable feature of the movable gate is the large size of the bracing that resists the water pressure and holds it in place with a large pivot pin.

The size of the bracing and the pivot to which it is attached is testament to the large lateral load exerted by the water on the gate. And if they are not adequate to the task, then the outcome is starkly illustrated in Fig. 1(b) (Folsom Times 2023). In this case, the water drive is large relative to the weight of the gate, and large relative to the weight of the dam itself. Clearly designers of such gates (and the dams that contain them) need to take that water drive into account. Looking at the trunnion spillway gate as analogous to "slip circle" failure of a slope, it is equally clear that slope design engineers need to take into account the large lateral forces exerted by groundwater pressure acting on the upstream surface of any potential failure mass.

Slope stability under water drive

A powerful example of the effects of water drive on slope stability was the subject of the author's applied graduate research (Brown 1969). This study evaluated the stability of large slopes in the lignite coal measures of the Latrobe Valley in southeast Australia. The lignite in the coalfields reaches depths of 300 m, with a 15 m veneer of overburden. Beneath the lignite is a horizontal 10 m layer of clay, which in turn overlies a fine-grained sand aquifer, originally pressurized to the ground surface. Mining of the coal resulted in large-scale lateral and vertical movement of the mine slopes ("batters"), which disrupted the bucket-wheel and conveyor-belt coal-winning operation and the dewatering operations on which they depended. This in turn threatened the stability and safety of

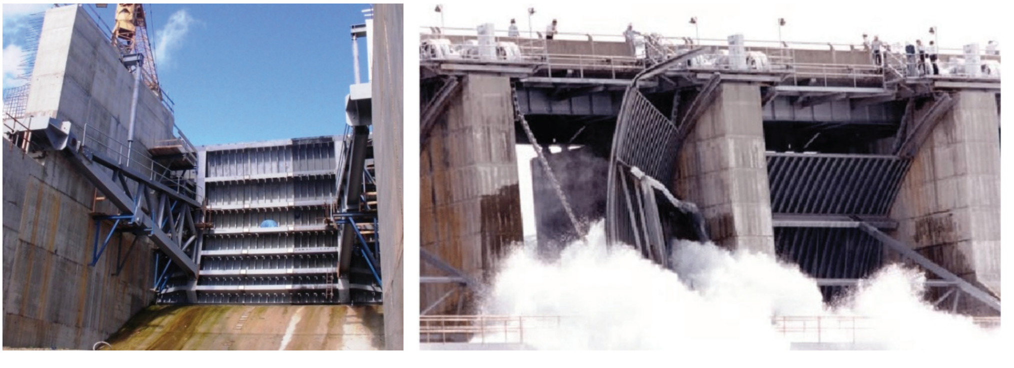
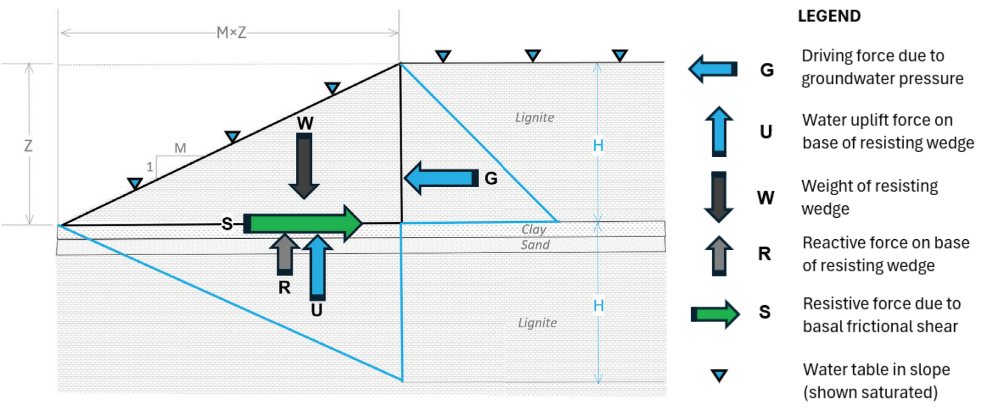


Figure 1 (a) Radial spillway gate (Vortex Hydra) (b) Failure of Folsom Dam Gate 3 (Folsom History).

WATER DRIVEN BLOCK SLIDING FORCE DIAGRAM



DEFINITIONS

WATER FORCES
G Water drive due to groundwater
U Uplift force due to groundwater
DIMENSIONS
Z Height of slope failure wedge
T Thickness of slice
H Groundwater head
M Slope (M horizontal : 1 vertical)

ROCK FORCES
W Weight of resistive wedge
R Reaction on base of resisting wedge
S Shear resisting force due to friction
PARAMETERS
γw Unit weight of water
γr Unit weight of solid granular particles
ϕ Effective stress friction angle
s Degree of saturation of slope

ANALYSIS OF FACTOR OF SAFETY OF SLOPE AGAINST WATER DRIVEN G

DRIVING FORCE
The groundwater backed up behind the slope exerts a force (G) on the resisting wedge:

1) $\mathbf{G} = \tfrac{1}{2}\,\gamma_w\, H^2\, T$

For partial saturation (s), we have: H = s Z, so equation 1 becomes:

2) $\mathbf{G} = \tfrac{1}{2}\,\gamma_w\, s^2\, Z^2\, T$ where s = degree of saturation of the slope

RESISTING FORCE
The force resisting displacement of the Resisting Wedge is friction on the base of the wedge. Available base friction shear force is given by the Mohr-Coulomb relation (Hoek & Bray, 1977):

3) $\mathbf{S} = (\mathbf{W} - \mathbf{U}) \tan \phi$

The weight of the resistive wedge is given by:

4) $\mathbf{W} = \tfrac{1}{2}\,\gamma_r\, M\, Z^2\, T$

The groundwater upthrust on the base of the Resisting Wedge is given by:

5) $\mathbf{U} = \tfrac{1}{2}\,\gamma_w\, s\, M\, Z^2\, T$

Accordingly, the expression for the Resisting Force **S** is:

6) $\mathbf{S} = \tfrac{1}{2}\,(\gamma_r - \gamma_w\, s)\, M\, Z^2\, T \tan \phi$

FACTOR OF SAFETY
The Factor of Safety is the factor which available shear force (**S**) exceeds driving force (**G**):

7) $\mathbf{FoS} = \mathbf{S} / \mathbf{G} = [\tfrac{1}{2}\,(\gamma_r - \gamma_w\, s)\, M\, Z^2\, T \tan \phi] / [\tfrac{1}{2}\,\gamma_w\, s^2\, Z^2\, T]$

Simplifying, the FoS is found to be:

8) $\mathbf{FoS} = \mathbf{S} / \mathbf{G} = (\gamma_r/\gamma_w - s)\,(M/s^2) \tan \phi$

Figure 2 Slope stability model for the Latrobe Valley coalfields (after Brown 1969).

the towns, highways, rivers, and reservoirs adjacent to the mines, as well as the reliability of coal supply to mine-mouth power plants (Sullivan 2008).

All analysis methods applied to the slope at the time (including method of slices slip circle and finite element numerical analysis) incorrectly showed a high degree of stability for the slope and predicted little movement after the initial elastic strain accompanying the unloading of the slope due to mining (Brown 1969). In order to determine what mitigation is required to stabilize the mine slopes a simple force balance slope model was developed and proved able to explain the observed movement. The development of the model is presented in full in Fig. 2.

The factor of safety (FoS) against water-driven failure of the slope is given by (Fig. 2):

FoS = Resisting force / Driving force = $(\gamma_r/\gamma_w - s)(M/s^2)\tan\phi$

The typical clay in the Latrobe Valley has an effective stress friction angle (ϕ) of 13.5°, the lignite has a relative unit weight ($\gamma r/\gamma w$) of 1.12, and typical slopes are cut at 3H:1V (M = 3) (Brown, 1969). When the slope is saturated (s = 1), which is the worst-case situation that occurs, we have:

FoS = Resisting force / Driving force = $(1.12 - 1) \times (3/1^2) \times \tan(13.5°) = 0.09$

When the slope is thus saturated, the water drive easily exceeds the resistance offered by the clay beneath the lignite, and the lignite moves laterally towards the mine for as long as water is supplied to and retained behind the moving coal mass. This movement disturbs the coal mass and can lead to catastrophic collapse of the mine slope.

To prevent these progressive movements becoming disruptive of operations and causing the coal slopes to collapse, it was necessary to determine how much the water drive needed to be reduced to create stability (FoS ≥ 1). Using the same parameters as above, the slope saturation that just keeps the slope stable is 60%:

FoS = Resisting force / Driving force = $(1.122 - 0.60) \times (3/0.60^2) \times \tan(13.5°) = 1.04$

Based on this finding, horizontal drains were installed along all final mine batters at multiple levels, the underlying aquifers were dewatered, and all surface water reservoirs and streams were required to be located no closer than the mine depth from the mine crest. Movements largely ceased, and production continued without serious stability incidents for 40 years.

Then a new mine operator decided to cease draining the lignite and to extend mining close to a local river. This precipitated the 6 million cubic meter failure shown in Fig. 3 (Melbourne Age 2009). Fortunately, the failure occurred at about 2 am and no mine personnel were injured. However, the State of Victoria was deprived of a substantial portion of its electrical power generation capacity for months and the estimated cost of the outage and repair of the mine was in the billions of Australian dollars (Sullivan 2008).

Could a water drive failure happen in a hard rock mine? A typical hard rock mine has an effective stress friction angle (ϕ) of 35°, a relative unit weight (γ_r/γ_w) of 2.5, and typical slopes are cut at 1H:1V (M = 1). When the slope is saturated (s = 1) we have:

***Figure 3** Failure of one Latrobe Valley Open Pit slope due to water drive (Photos: Melbourne Age).*

FOS = Resisting force / Driving force = (2.5 – 1) × (1/1^2) × tan (35°) = 1.05

Still barely stable, and this is for a saturated slope with water drive alone, and horizontal sliding with a vertical crack behind the mine slope. Add in an angled fracture behind the slope, slope on the sliding plane, a coating of alteration residue on the rock joints, and some active pressure from the slope above, and that portion of the slope fails.

It appears that the collapse of the Bingham Canyon Mine in Utah in 2013 is an example of this kind of progressive failure, at least in part water driven. This mine is one of the largest in the world. To maintain stability on the slopes it incorporates an extensive mine water control system including dewatering wells, horizontal drains, and drainage tunnels (Dunn 2013). However, despite these precautions the slope was continuously moving, and failed catastrophically twice in rapid succession during the 2013 spring thaw and snowmelt (AGU 2013a). The failures occurred in almost the only portion of the slope that had no water pressure mitigation (Dunn 2013). The run out of the resulting rockslide or "sturzstrom" (literally "rock storm", per Scheidegger 1973) demolished equipment, haul roads, and operations in the mine (Fig. 4). Comprehensive real-time monitoring warned of the failure so that no life was lost (AGU 2013a). The cost of replacing equipment, rehabilitating the mine, and lost production has been estimated to be in the billions of dollars (AGU 2013b).

So, what is the lesson to be learned here? It is that water drive can provide a large force behind a saturated mine slope, which can overwhelm frictional resistance and create an unstable slope, with potentially catastrophic consequences. Any slope designer must take water drive forces into explicit consideration. Don't rely on standard slope stability packages to do it for you, because many of them do not, or do not do it correctly. Indeed, one of the most commonly used slope stability packages says of water drive: "Seepage forces in a stability analysis can create considerable confusion. The concept of seepage forces is easy to comprehend, but including seepage forces in a limit equilibrium stability analysis is fraught with misunderstanding. … [N]o attempt should be made to manually add seepage forces via concentrated point loads." (GeoSlope 2010, p. 32, 34).

Before you put your Engineer's Stamp on your computer-generated mine design, I strongly recommend that you perform a robust check on the admittedly convincing pictures that your computer analysis produces, to ensure that water drive is correctly considered. If you need assistance in this computation, I also recommend using the methodology pioneered for use in the mining industry by Evert Hoek (Hoek and Bray, 1977). The analysis presented in Fig. 2 of

***Figure 4** Landslide at Bingham Canyon Mine which occurred on April 10, 2013 (Photo: Ravell Call, Deseret News).*

this paper is a simple – but robust – example of the use of this methodology applied to slope safety under water drive.

Conclusions

1. Water drive caused by groundwater pressure behind mine slopes is a powerful factor in mine slope instability.
2. Water drive must be explicitly included in mine slope design.
3. Water drive must be explicitly included in mine slope stability mitigation.

Acknowledgements

This paper has been prepared with thanks as a tribute to Evert Hoek, who died last year after a lifetime lovingly creating and leading the science of mining rock mechanics. Evert taught me that geomechanics is both an engineering science and an art. He brilliantly and elegantly simplified it so that it is accessible to everybody in mining, allowing the larger, safer, deeper, steeper and more productive mines that provide the metals and the power for the ongoing industrial revolution that we all rely upon.

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