



Rock mass damage and induced passive depressurisation around open pits

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Abstract

Rock mass damage induced by mining increases the fracture frequency and joint aperture width in the pit walls and rock mass behind open pit mine slopes. The depth and intensity of this mechanical damage relative to the pre-mining state is not well understood and yet is a major factor in the development of slope stability models and operational guidelines. The induced damage can be partitioned into domains or zones. The blast damage zone is essentially a 'free flow' rock mass volume, which transitions quite rapidly into the excavation damage zone, which extends beyond that. In both zones, transient high in situ water pressures are often linked to unstable slope conditions. Whereas rock damage can enhance passive depressurisation in the rock mass, high infiltration rates on the other hand, as one could expect during rainstorm events, will decrease slope stability within the dilated pit rock mass, especially in the blast damage zone-excitation damage zone, by increasing pore pressures for short periods of time. Ice jacking and freshet are additional factors to consider in (sub) arctic environments and can be exacerbated by unfavorable rock fabric orientation. On a local scale, brittle deformation damage zones, in the form of faults, can contribute to slope instability, or enhanced stability because of slope depressurisation, depending on their location and orientation relative to the pit shape and the water sources. In this study, the shapes of the damage zones and their anticipated impact on infiltration and/or passive depressurisation are considered for different pit morphologies, rock mass conditions, in situ stress, and hydrogeological settings. Some unusual hydrological situations, like mining towards rivers and lakes and the potential effects on pore pressures, are also considered. This investigation has resulted in the development of a method to adjust initial hydraulic conductivity values used to estimate transient pore pressure conditions found in rock masses exposed in different pit morphologies and stress regimes as well as discontinuities' orientation relative to open faces within the open pit mine. The changes in K values and pore pressures can then be used to determine hydrogeological influence more accurately on future pit slope stability.

Keywords

rock mass damage zones, hydraulic conductivity adjustment, structural control, slope stability, risk characterisation, scoping level studies

Introduction

From a rock engineering perspective, the effects of groundwater pore pressure around open pits become progressively more important as design studies advance through the different stages of the mining project development, from exploration through to pre-production, production, and into closure. Figure 1 illustrates this idea (Bloem, Barnett, 2022), with the lower study level bars matching the upper model input components spaced from left to right. Lithology, alteration, and structural geology are where most of the data acquisition and knowledge development occurs in the early part of the study life cycle of a project. These parameters are considered 'fixed' in the project timeframe. The transient nature of the input components increases towards the right of Figure 1. Once the initial mineral exploration phase has been completed and the 'extents' have been identified, the project geology model typically gets upgraded, with detailed drilling information, into a comprehensive 3-D litho-structural model with the addition of major faults. It is at this point, normally, where the first estimates of hydraulic conductivity (K, m/s) and potential water inflow and related depressurisation rates are made using the pre-mining rock mass condition as a baseline. Also illustrated in Figure 1 is the relative possibility that the model input components' properties may, and probably will, change throughout the life of mine, and that

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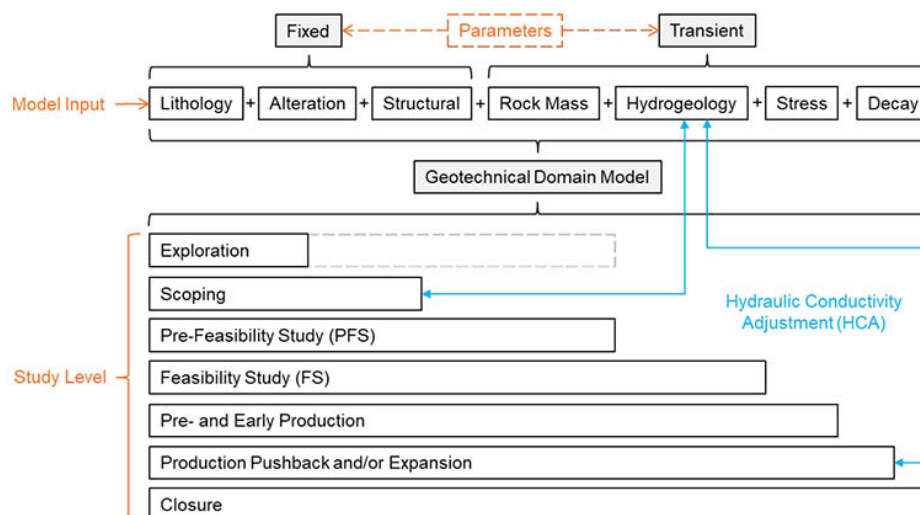


Figure 1—Geotechnical domain parameters and model inputs at different study levels as related to the timeline of open pit development

hydrogeological data acquired during the scoping or pre-feasibility study (PFS) level of the study could potentially be used to estimate the hydraulic conductivity in the disturbed rock mass at some point in the future. The prediction of the K values needs to take in situ stress conditions and potential decay characteristics of the rock mass into consideration.

By unloading the rock mass, which occurs during open pit mining, the in situ stress fields are altered. Rock masses respond differently to these changes depending on orientation and/or magnitude of the stress fields over relatively short periods of time. The rock mass response is typically to undergo deformation, mostly in the form of an increase in fracture frequency and aperture width near the excavated void, a form of induced mechanical deterioration. These changes in turn increase the K of the rock mass and increase both flows out of (passive depressurisation) and into (infiltration) the previously more competent rock blocks. This can, depending on the ambient temperatures and diurnal and annual variations, also stimulate geochemical weathering of the rock mass. These transient effects will both decrease the effective stress (higher pore pressure) while also decreasing the original strength of the rock mass resulting in strength 'decay', which is progressive failure, over time (Bloem, Barnett, 2022). Increased K is linked to the rock mass condition since, in general, the more fractures and potential (dilated) water pathways that exist, the more readily water will passively drain from the rock mass, increasing the effective strength.

Passive drainage and the resulting depressurisation will occur on any rock face. The extent of this effect, however, is not well understood at the pit slope scale because of a lack of available pre- and post-mining data. Therefore, assumptions have been made based on the original work on the damage zone (Hoek, 1994) and

others. This study attempts to build on that with a more detailed look at both the probability of increased fracture frequency and aperture width, and the connectivity for flow, which involves relative orientation and length of discontinuities within the rock mass.

This paper describes a method for the adjustment of K values for the changes in parameters over time, in the form of the hydraulic conductivity adjustment (HCA), and to do this, several main factors are considered in the following order: a) *open pit shape*, b) *fault zones*, c) *rock mass condition* and d) *anisotropy*. The HCA should be looked at as a scoping tool to determine areas that could have enhanced permeability and/or flow potential, both of which will influence infiltration (increases in pore pressure) and passive drainage (decreases in pore pressure) over time.

Open pit shape

The shape of an overall slope as exposed during mining, relative to the in situ stress, regional water table, and flow direction, will influence the flow path and rate at which water moves through the rock mass adjacent to the open pit. For example, in a conical waste rock pile with little or no fines, any water added to the top of the rock pile flows down and outward towards the base's perimeter ($K \approx 1E10^{-2}$ m/s). Undisturbed rock masses ($K \approx 10E^{-14}$ to $10E^{-5}$ m/s) will be considered in this paper for the purposes of the dilation model development and the HCA.

Slope curvature

The low K example of a loosely consolidated rock pile is something like what is seen in unconfined rock masses that are exposed in open pits in the form of convex slopes (bullnoses or ridgebacks), as illustrated in Figure 2. The main difference for the latter, is

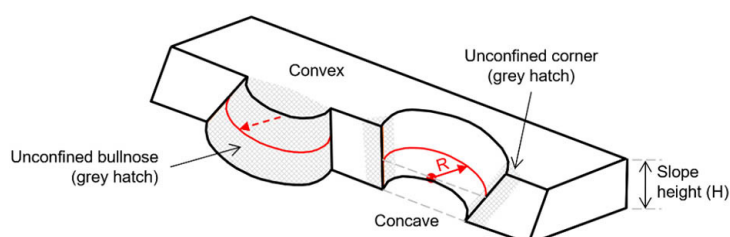


Figure 2—Oblique view of concave and convex slopes, where the slope radius (R) is measured at half of the slope height (H) and H is in the 100 to 1,000 m range

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that the rock blocks will tend to be interlocking, compared to the 'bulked' rock pile. The further the bullnose extends into the open pit, relative to the external shape, the more likely it is to dilate due to lack of confinement, and one measure of this is the ratio between the half height radius (R) and the slope height (H). As R increases relative to H, confinement is removed, and de-stressed – within the excavation damage zone (EDZ) – rock mass conditions are induced. The orientation of the regional in situ stress has no influence on the hydraulic conductivity of a convex slope, because the slope is isolated from the regional stress field and will only be subject to vertical stresses (σ_v) within the bullnose.

Concave slopes tend to remain confined at R/H values less than 1, but as the radius increases further, so too will the de-stressed rock mass at the corners of the concave slope. If the regional principle in situ stress is parallel to the main rock face into which a concave slope is cut, the concave slopes will tend to have reduced hydraulic conductivity at relatively low in situ stress magnitudes. In other words, the relatively low initial K (while being mined) will change as the principal stress rotates around to the vertical and the rock mass dilates parallel to the local minor stress direction perpendicular to the slope. This 'clamping' effect, which does not necessarily damage the rock mass, has been observed (Royle, 2023) around mine shafts in the Athabasca basin of Canada, where most of the water entering the shaft comes from vertical dilated joints oriented parallel to the principal horizontal stress direction σ_H . As the radius of a concave slope increases relative to the height of the slope, it will tend to behave more like a local linear slope with unconfined corners.

Damage and dilation domains

A conceptual model for rock mass damage applied to open pit slope geotechnical studies was developed by Bloem and Barnett (2022) in which four main areas of mechanical weathering induced by open pit mining were identified. These non-discrete 'zones' of damage decrease in intensity outward and away from the excavation, as illustrated in the plan view of Figure 3 and in vertical sections parallel and perpendicular to the principal horizontal stress (σ_H) direction of Figures 4 and 5. These four main rock mass damage and dilation zones within the model, in order of decreasing hydraulic conductivity for the purposes of the HCA, are described as being:

- The **blast damage zone (BDZ)**, which is the rock mass immediately adjacent to the bench face. It extends horizontally from about $0.5H$ for a controlled blast onto a pre-shear line, to as much as $2.5H$ or more for large uncontrolled production

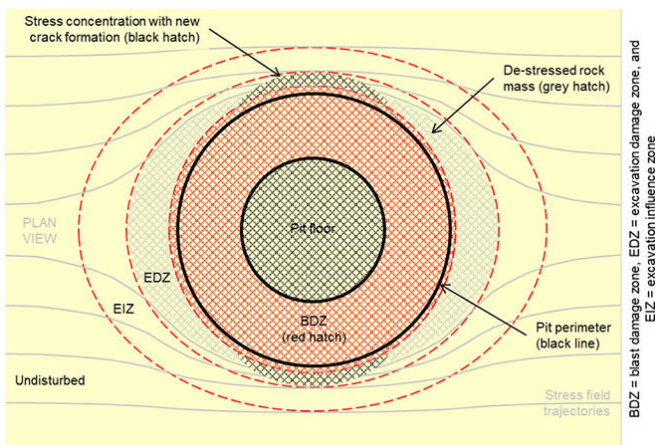


Figure 3—Conceptual model of open pit slope damage and dilation zones relative to the principle in situ stress orientation

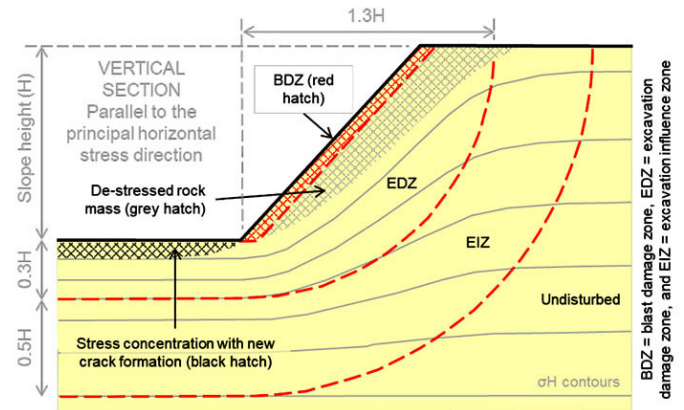


Figure 4—Damage zones parallel to the principal horizontal stress directions. $H \approx 340$ m

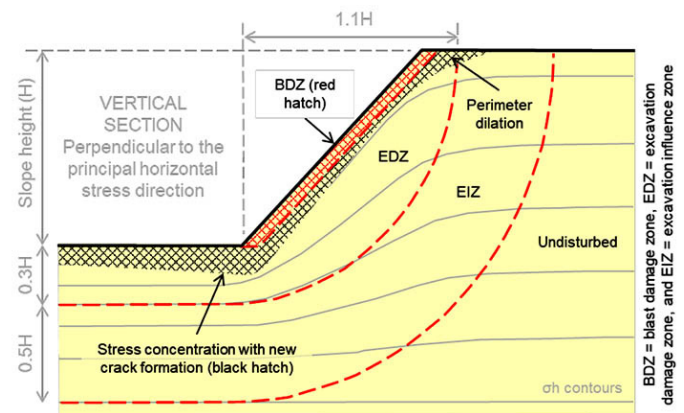


Figure 5—Damage zones perpendicular to the principal horizontal stress directions. $H \approx 340$ m

blasts, where H is the blast hole depth (Hoek, Karzulovic, 2000). A damage value of $D \approx 1$ is currently accepted for a BDZ width of $1H$ in slope stability modelling. This zone displays displaced and loose rock blocks with many new fractures induced by blasting. The BDZ is characterised by 'free flow' water conditions in which the hydraulic conductivity is at a transient peak and pore pressures will decrease to close to atmospheric pressure, assuming fractures do not reclose due to weathering products like clay.

- The **de-stressed rock mass** domain underlies the pit perimeter, above and beyond the influence of the in situ stress field, is unconfined, especially along the axis, which is parallel to the principal in situ stress direction. Vertical stresses are still present, but the rock mass is decoupled from the regional horizontal stress field. Water passes through this domain relatively easily once fractures have dilated parallel to the local vertical stress. Passive dewatering occurs as the rock mass drains and depressurises relatively quickly, forming the base of the initial semi-stable interface of the 'drawdown cone' observed around open pit mines. The extent of the horizontally destressed rock mass will tend to expand over time. This domain is analogous to the natural (pre-mining) dilation of the rock mass due to erosion, glacial rebound, etcetera, with the only difference being that it is induced by mining activity.
- **Excavation damage zone (EDZ)** is the rock mass beyond the BDZ, which experiences post blast dilation because of unloading and new crack formation, and older crack

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dilation as the pit deepens. The rupturing of rock bridges and coalescing of joints by step-path failure lead to the progressive weakening of the rock mass. The extent of this damage can be estimated for stability analysis using Hoek's 'D-factor' system in which $D = 1$ (maximum damage) progressing outward to $D = 0$ (no damage) at the outer boundary of the EDZ. In *fair* ground, under moderate in situ stress conditions, the width of this zone is thought to be between 10% (Stacey et al., 2003) and 30% (Hoek, Brown, 2019) of the depth of the pit. The EDZ has progressively lower hydraulic conductivity, moving outward from the maximum within the BDZ, to lower values at the $D = 0$ position along the excavation damage zone-excavation influence zone (EDZ-EIZ) interface. The EDZ is characterised by an increase in hydraulic conductivity and groundwater flow/depressurisation, which is induced because of the extension strain (Stacey et al., 2003) experienced by the rock mass.

- **Excavation influence zone (EIZ)** is the volume of rock, which forms a buffer between undisturbed rock mass and the zone of geomechanical loss of rock mass strength induced by mining. This zone displays minor changes in in situ stress orientation and magnitude, and hence the pre- and post mining hydraulic conductivity is thought to remain unaltered.
- **Undisturbed rock mass** is that which is beyond the EIZ and is characterised by no changes in in situ stress field orientation or magnitude. The rock mass and hydraulic conductivity properties are essentially static for the life of mine in this zone.

Slope height

As depth increases, so too does the vertical stress which, in undisturbed rock masses, will close off joint apertures, which progressively reduce the available joint-related void space for water flow. This decrease in void space is reflected in a decrease in hydraulic conductivity with depth as noted by Wei et al. (1995) and Jiang et al. (2010). Data collected by SRK illustrating this characteristic is shown in Figure 6. Assuming a bulk in situ rock mass density of around $2,600 \text{ kg/m}^3$, then the 1 MPa load depth is at approximately 40 m, the 3 MPa depth is 120 m, the 9 MPa depth is 340 m, and so on. Using this series, depth categories can be constructed, which in some way reflect the closure of open and soft filled joints with depth. The depth ranges are 0 – 40 – 120 – 340 – 680 – 2,040 m. Beyond 680 m depth, which is approximately 18 MPa load, horizontal and sub-horizontal joints are unlikely to contribute significantly to the hydraulic conductivity of the rock mass and so have the lowest value in the HCA pit depth rating.

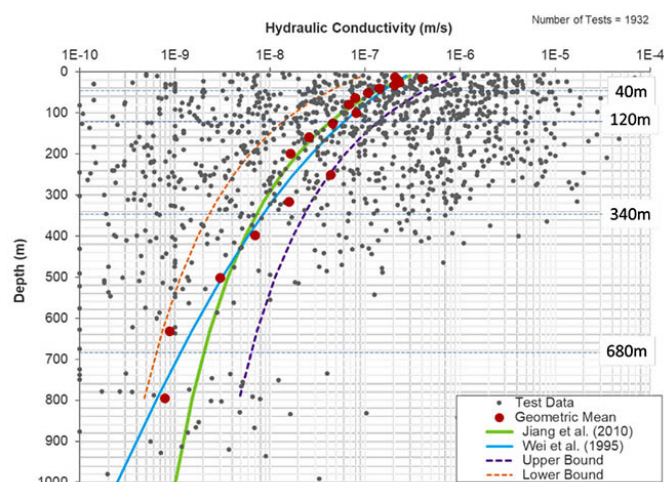


Figure 6—Hydraulic conductivity measurements relative to rock mass depth

Aptly, the geometric range for hydraulic tests in this depth range are approaching $1 \times 10^{-9} \text{ m/s}$, at which point groundwater movement becomes very limited.

Fault zones

Major fault systems are typically a static input parameter into the pit design process with the initial state depending on fault characteristics. For example, faults may be either coherent, have little or no damage zone, or have well developed gouge filled cores with associated damage zones. Mostly, faults with a complex reactivation history tend to have weaker fill material and wider damage zones compared to non-reactivated faults. In all cases, deformation within the EDZ and BDZ during sidewall dilation, will likely result in further weakening of fault damage zones. Depending on the size of the fault, depressurisation deformation may range from the bench to the overall pit slope scale, potentially resulting in wide zones of reduced rock mass quality and increased hydraulic conductivity. Fault systems can therefore have static properties throughout the life of the mine, or in specific cases, may be highly transient (Bloem, Barnett, 2022), with hydrogeological parameters that are more difficult to predict during the life of mine and beyond.

Cumulative fault damage zone width

To characterise the relative influence of faults on the rock mass and the hydraulic conductivity, five classes are proposed (as illustrated in Figure 7) based on the cumulative fault and associated damage zone thickness. These range from a rock mass with no fault damage to a highly faulted rock mass with an extreme cumulative faulted

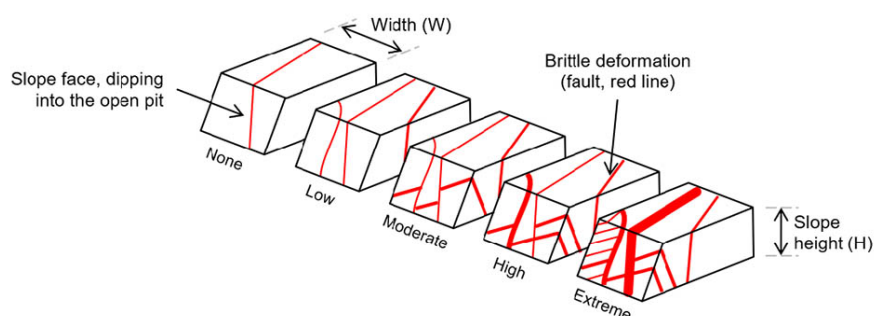


Figure 7—Cumulative damage zone width classes, ranging from none to extreme for the hydraulic conductivity adjustment. Slope H and W are in the 10 to 1,000 m range

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contribution. The cumulative fault damage zone width can also be viewed as a percentage of the width of the face, in which case the 'extreme' damage cumulative width on the slope would exceed 33%.

Fault orientation versus pit slope

Fault orientation relative to the pit slope face is an additional factor that will influence the opening of new, or the dilation of existing faults, both of which have the potential to increase groundwater flow. This could lead to increased seepage for daylighting structures at the pit face resulting in depressurisation, or transient enhanced infiltration resulting in increased pressurisation.

Five orientation classes are provided (Figure 8), ranging from perpendicular to parallel with the pit slope. The most influential faults are those which hydraulically connect the slope face to large reservoirs of water, either in the backwall rock mass volume or the pit crest. If faults perpendicular to the slope do not dilate because of unloading, an increase in K leading to augmented depressurisation is unlikely, whereas parallel faults (or tension cracks) are likely to be more open, but not necessarily have a connected flow path to the slope face to allow for seepage losses to drain away the infiltrating water. The latter case may have little impact on passive depressurisation but does impose a risk of rapid infiltration during heavy rainfall and increases in pressures, leading to slope instabilities. Fault angles between these two endpoints will allow for both passive drainage to reduce pressures, and to drain-off rain events (although probably at a slower rate than infiltration increases pressures temporarily).

Rock mass condition

In open pits, the initial rock mass condition at time-zero (t_0) is not necessarily what it will be as the excavation approaches final depth (t_n). Decay of rock mass strength is not unusual over time. It is more pronounced in weaker and/or altered rock masses in temperate climates, ones with a wet/dry season, and those with pronounced freshet. By unconfining a rock mass, as illustrated in Figures 2 to 5, the local in situ stress fields are altered. When this occurs, the rock mass undergoes deformation, often in the form of increased fracture frequency and/or aperture near the excavation face (as observed in zones of increased stress near the pit floor as well). These effects decrease the rock mass strength and will ultimately result in some form of strain weakening (strength decay) over time. In mountain top mining, for example, relatively few new cracks are formed compared to high horizontal stress environments, but the pre-existing joints dilate, and step-path failures are induced as the rock mass 'relaxes'. This results in an increase in the total volume of void space and hydraulic conductivity. The parameters that change can be estimated using well-known measures as described in the following, like *intact rock strength* (Bieniawski,

1989), among others, and *rock quality designation* (Deere, 1964). In addition, weathering will change over time, and the in situ stress will reorient itself around the advancing open pit shape.

Intact rock strength

Intact rock strength is commonly measured using unconfined compressive strength (UCS) testing, and the results for 'rock' range from 1 to more than 250 MPa. Most rocks fall into the 50 to 100 MPa range at or near the Earth's surface. Rocks that are weaker than 25 MPa break much more readily than those that are significantly stronger (> 250 MPa). For the purposes of the HCA, RMR89 (Bieniawski, 1989) ranges have been used to represent intact rock strength, and all rocks that are stronger than 250 MPa have been assigned the same rating value (of 1). Strong rocks, when broken, will tend to retain their joint apertures, while weaker rocks' joint apertures will tend to close over time as the intact rock structure decays.

Rock quality designation

Rock Quality Designation (RQD) is a measure that was introduced by Deere (1964) to characterise rock mass strength for engineering purposes. It is calculated as the sum of the length of the intact pieces of rock (> 0.1 m in length) for each drill run, expressed as a percentage. RQD is included in, and correlates to some degree, with Bieniawski's (1976, 1989) rock mass rating system. Although field data do not show a strong correlation of high K to low RQD, potentially due to lack of connectivity and other factors, RQD has been included as part of the HCA rating system to provide a broad-brush estimate of the 'brokenness' of the rock mass, with ranges from 100 to 99%, 99 to 75%, 75 to 20%, and 20 to 0%.

Weathering

Weathering of rock is a response to changes in the pressure, temperature, moisture, and the chemical environment in which it was formed (Fell et al., 2015) compared to the mined exposure. This is broadly expressed as mechanical changes in the rock mass, which tend to precede the chemical weathering processes. The rate at which weathering occurs, and the effect it has on the discontinuity void network, depends on the pre-mining rock mass composition and strength, as well as local hydrogeological and atmospheric conditions. For example, silicates are more stable than carbonates, sulphides, and clay minerals, with the latter often losing mechanical strength over relatively short periods of time of no more than a few years, depending on the rock type, moisture, and temperature range that they are being exposed to. In altered, weak, and/or argillaceous rocks, weathering processes will tend to decrease the hydraulic conductivity and the fines will 'clog' the flow path along fractures (and throats between pores) as they are transported through the

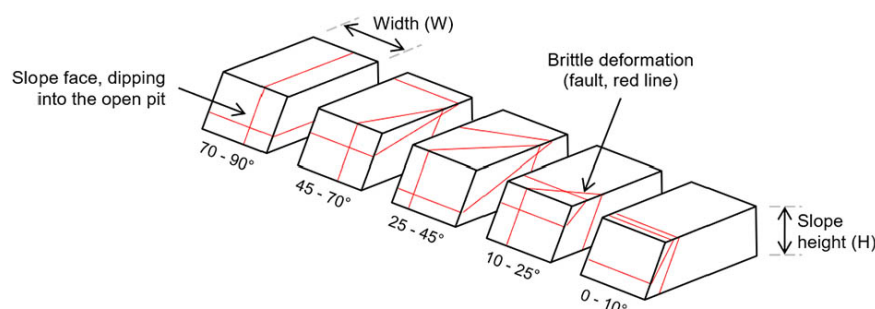


Figure 8—Fault zone orientation relative to the slope face, within ranges used for the hydraulic conductivity adjustment. Slope H and W are in the 10 to 1,000 m range

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network. In hard or unaltered rock masses the influence of long-term decay is likely to increase K as joints and fractures that do open are more likely to stay open and not clog. The weathering rating classes used to describe the existing and/or anticipated rock mass conditions for the HCA, are those of Bieniawski (1989), in which the rock mass can be considered as being decomposed, highly weathered, moderately, slightly, or not weathered at all (none).

In situ stress

It has been demonstrated by Stacey (1973) and others, that the in situ stress field orientation varies around open pits. The shape of the damage zones, especially the EDZ and EIZ, depend on the terrain within which the open pit is mined (Figure 9) and the stress fields reorient themselves around the damage zones. In mountain-top environments the principal regional horizontal in situ stress (σ_H) is low because valley-floors create stress shadow zones at higher elevation, the rock mass tends to be unconfined, and most of the potential EDZ is made up of 'loosened' rock blocks around and below the pit. Dilation occurs in these environments as progressive, albeit slow (on the time scale of years to decades in *very-poor* to *fair* ground) vertical load induced 'slumping' ($\sigma_v \gg \sigma_H$). In these cases, relatively few new joints are formed beyond the BDZ, and deformation is expressed as bulking of the rock mass as it 'relaxes' in place. There is no indication in mountain top mining that a significantly concave down EDZ develops, which means that water entering the system as rainfall or snow melt, will flow down and outwards towards lower elevations at the base of the geomorphologically de-stressed rock mass.

In valley bottom environments where the horizontal in situ stress ($\sigma_H \gg \sigma_h > \sigma_v$) concentrates at the lowest part of the opening (Piteau 1970, Fell et al., 2015), damage induced by compression and upward movement of the rock mass in the floor (Matheson, Thomson 1973, Bell 1996, Hunt, 2005) of the pit tends to occur. This is like what is observed in drillholes advanced into highly stressed rocks, where borehole breakouts form perpendicular to the maximum in situ stress (σ_H). The amount of damage depends on the maximum in situ stress direction and magnitude relative to the intact rock strength and the pit shape. The weaker the rocks are, relative to the in situ stress magnitude, the more existing crack tips will extend, and newer cracks will be formed, which could increase the hydraulic conductivity of these zones as the joints coalesce, and rock bridge rupturing occurs. The in situ stress classes used for the HCA are based on the ratio between the principal horizontal stress (σ_H) and the vertical stress (σ_v). For laterally unconfined conditions, like on mountain tops, the stress conditions will have the relationship $\sigma_v \gg \sigma_H$, while at the high stress extremes seen in

valley bottoms below sea level, the stress concentration will be $\sigma_H \gg \sigma_v$.

Ice jacking

Ice jacking is a common modifying action caused when water infiltrates joints, fractures, or bedding, and then freezes and 'expands' the aperture during sub-zero temperature conditions in winter. This phenomenon is commonly observed in road cuts and causes bench scale damage in pits that can lead to spalling and localised instabilities. As this is mostly a 'skin' effect of no more than 5 to 10 m deep and not found at all pit locations, it has not been added to the Ratings table (see Table 1). Instead, in cases where this is a significant contributing factor, the HCA rating total can be reduced by up to 5 points to account for this localised effect.

Anisotropy

Foliation and bedding typically develop high-continuity anisotropic joint networks within rock masses, which can have significant influences on the BDZ, EDZ, and ultimately, the hydraulic conductivity surrounding open pits. For HCA purposes, a continuum from bedding-dominant to a foliation-dominant situation is considered. Bedding is usually dominant in low grade sedimentary metamorphic and orogenic terrains where deformation intensity is low. As deformation intensity increases, bedding is progressively overprinted by foliation (cleavage), and at high strains foliation becomes dominant with primary bedding no longer being preserved. The influence on the BDZ and EDZ by anisotropy is further influenced by bedding and foliation types, foliation, and bedding orientation relative to pit slope orientations, and the regional stress. High K can be expected to be correlated with an open bedding and certain (open) foliation types, where foliation and bedding orientations are perpendicular to pit slopes and parallel to regional stress.

Joint length

Joints behave as pathways for water flow, and the longer (or more persistent) they are, the more pronounced their influence can be. Joints are, for engineering purposes, rock mass discontinuities with little or no cohesive strength and have no visibly discernable lateral offset, which is characteristic of 'faults'. Even though some joints can be slickensided and do, therefore, have evidence of displacement across the plane, they are considered 'joints' and not micro-faults. Joint lengths can vary from a few centimetres, as in crackle-breccias, to several tens of metres or more in length, as is often seen in bedding parallel jointing. There is no direct relationship between joint length and aperture, but there is anecdotal evidence that in non-foliated ground, long and rough textured joints tend to have

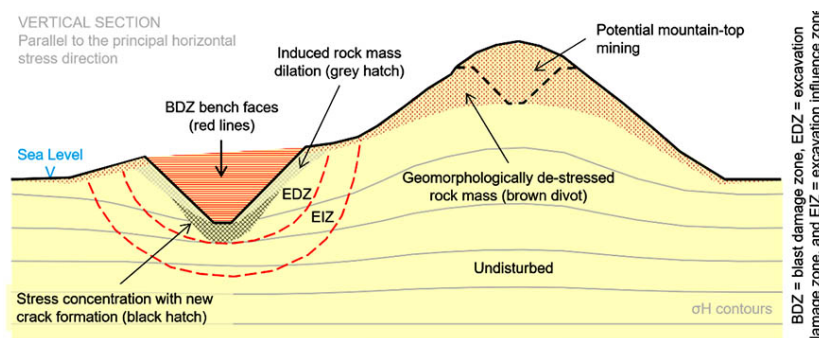


Figure 9—Vertical section parallel to the principal horizontal stress direction of open pits at different relative elevations, showing the damage zone shapes. Pit depth $\approx$ 900 m

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Table 1

Parameters and ranges of values with their relative weightings to estimate hydraulic conductivity adjustments for open pit damage and rock mass dilation

Parameter		Influence	Ranges of Values				
<u>Shape</u> of open pit Rating = 30	Slope curvature	DP	Concave R << H	Concave R ≈ H	Linear	Convex R ≈ H	Convex R << H
	Rating		14	10	6	3	2
	Damage domain	DP	None	EIZ	EDZ	BDZ	Loose
	Rating		10	6	3	2	1
	Slope height (m)	DP, K	< 40	40 - 120	120 - 340	340 - 680	> 680
	Rating		6	3	2	1	0
<u>Fault zones</u> relative to slope orientation Rating = 30	Cumulative fault damage width (m)	DP	Little	Low	Moderate	High	Extreme
	Rating		20	14	10	6	3
	Intersection (°)	DP	0 - 10	10 - 25	25 - 45	45 - 70	> 70
	Rating		10	6	3	2	1
<u>Rock mass</u> condition Rating = 20	Intact rock strength (MPa)	K	> 250	100 - 250	50 - 100	25 - 50	< 25
	Rating		1	2	3	4	5
	Rock Quality Designation (RQD)	K	> 99	99 - 95	95 - 75	75-20	< 20
	Rating		5	4	3	2	1
	Weathering	K	None	Slightly	Moderate	High	Decomp
	Rating		1	2	3	4	5
	In-situ stress	DP, K	σv >> σH	σv > σH	σH = σv	σH > σv	σH >> σv
	Rating		5	4	3	2	1
<u>Anisotropy</u> (bedding, foliation, fabric), relative to slope orientation Rating = 20	Joint Lengths (m)	K	< 1	1 - 3	3 - 10	10 - 20	> 20
	Rating		10	8	6	4	2
	Fracture frequency (FF/m)	K	< 1	1 - 3	3 - 10	10 - 30	> 30
	Rating		5	4	3	2	1
	Intersection (°)	DP	0 - 10	10 - 25	25 - 45	45 - 70	> 70
	Rating		5	4	3	2	1
Influence, where DP = passive depressurization, and K = hydraulic conductivity			Little	Low	Moderate	High	Extreme

wider apertures. For the purposes of classification of lengths for the HCA, the RMR89 standard (Bieniawski, 1989) standard has been used in which the categories are <1 m, 1 to 3 m, 3 to 10 m, 10 to 20 m, and >20 m.

Fracture frequency

The frequency at which joints are encountered in scan-line mapping or drilling, as measured in counts per metre (FF/m), reflects the amount of jointing within the rock mass. Interconnected joints behave as pathways for water flow, and the longer (more persistent) and possibly more dilated they are, the more pronounced their influence potentially can be on passive depressurisation in an open pit environment. An extreme condition exists within rock mass rating systems in which, as the number of joints per metre approaches 40, being an end-member situation, any additional joints have little or no added cumulative impact on the behaviour of the rock mass. For example, 30 joints per metre is approximately what one would expect to record for an RQD of about 20%. Following on from this, an RQD of 75% has a fracture frequency of approximately 10, while the linear approximation of RQD at the low end of the spectrum is FF/m ≈ 3 (RQD ≈ 95%). At the point where FF/m ≈ 1, a rock mass would be considered undisturbed and 'intact' from a typical mining engineering perspective – and

this is the second from lowest increment proposed for the HCA's FF/m classification, where RQD ≈ 99%. These FF/m classification categories (> 30, 30 to 10, 10 to 3, 3 to 1, and <1) are used for the HCA and could potentially be used to represent the rock mass damage zones presented in Figures 3 to 5, if calibrated using the base of the drawdown cone in open pit mines.

Fabric orientation, discontinuity length, and continuity

For groundwater to flow through the fractures, there needs to be a continuous (but possibly tortuous) flow path to a discharge point on the pit face. Figure 10 illustrates how discontinuity orientation becomes critical to discharge as the angle approaches 90° relative to the pit face – and even though the concept is scale-independent, a scale has been provided for context. Figure 10 also shows that at angles less than 10° it may have little impact on the ability to drain the rock mass within the timescale of mining but could be influential in short term transient events such as rainfall or snow melt.

Hydraulic conductivity adjustment

Rock disturbance factor

Using the parameters described in the aforementioned, a method is proposed for adjusting K values using a rock disturbance factor

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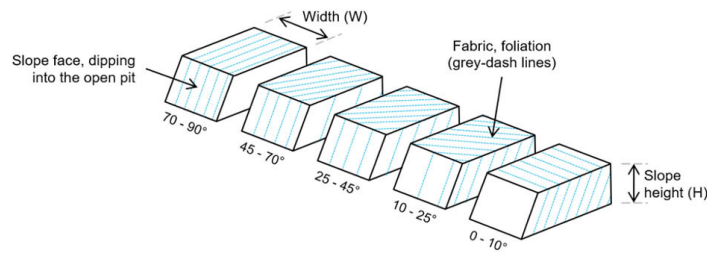


Figure 10—Dominant anisotropy (bedding, foliation, fabric) relative to the slope face orientation, within ranges used for the hydraulic conductivity adjustment. Slope H & W are in the 10 to 1,000 m range

(RDF) to account for the changes in the individual parameters, as listed in Table 1. Once the changes in the input parameters have been estimated (Ratings Δ), the RDF can be calculated and used to determine the hydraulic conductivity adjustment (HCA), which results in the modified K value (K') used for that domain and pit slope design sector of the slope. It is important to recognise that there is some cross correlation between individual parameters, and how they can affect K in the rock mass (for example, fracture length will affect slope drainage and infiltration differently depending on fracture orientation relative to the slope's open face) but this has been done so that various scenarios can be dealt with. The initial approach to determining the RDF is to use a simple summation of the parameters, as described in Equation 1 and illustrated in Table 1, to estimate the Ratings Δ for a specific rock mass volume within the open pit slope. The RDF is described in Equation 2:

$$\text{Rating } \Delta = \text{Shape}(30) + \text{Faults}(30) + \text{Rock Mass}(20) + \text{Anisotropy}(20) \quad [1]$$

$$\text{RDF} = \frac{100 - \text{Rating } \Delta}{100} \quad [2]$$

Hydraulic conductivity adjustment calculation and application

The RDF can be used to adjust the initial (t_0) hydraulic conductivity measurements (K) to the estimated values that take the changes in the rock mass and pit slope characteristics (Ratings Δ) into account at t_n . The adjusted hydraulic conductivity (K') is K to the power of RDF, as shown in Equation 3:

$$K' = K^{\text{RDF}} \quad [3]$$

RDF values can range from 0.001 (no adjustment) to 0.23 (extreme decreasing adjustment), but can also increase to above 1.00 in situations where the hydraulic conductivity is reduced by confinement or clogging/closure of joints. Two examples are provided in Appendix 1, the first (A) in which pre-mining data is used to estimate conditions during mining, and the second (B) in which data collected in one part of the pit is used in a different (deeper and more confined) location relative to the original K-measurement location relative to the pit shape. The overall workflow for calculating the HCA is:

- Measure the t_0 hydraulic conductivity (K) or estimate it from similar areas and rock mass conditions.
- Rate the potential changes to the parameters, based on knowledge of the location in which the decayed rock mass will occur within the pit, and calculate the rock dilation factor (RDF).
- Apply the RDF to the t_0 K value to calculate the expected t_n hydraulic conductivity.

The HCA arrived at by using this method can be used as a guide to the possible hydraulic conductivity of the rock mass at t_n .

Several iterations should be done, using slightly different parameter estimates so that the sensitivity of individual parameters can be assessed for each rock mass volume of interest. As the parameters can change significantly around an open pit, the RDF needs to be reviewed carefully to ensure the parameter ratings are appropriate. For example fracture dilation will change substantially as the testing location moves from the BDZ into the EDZ, and then into the EIZ.

There are some situations that are not easily dealt with by the HCA but can be done with experience and engineering judgement. A good example of this is fractures parallel to a slope versus tension cracks. The slope-parallel fractures are expected to dilate because of unloading within the EDZ, in turn increasing infiltration, but ultimately this results in only a small increase in passive drainage. On the other hand, tension cracks above instabilities, which are also parallel to the slope, can significantly increase passive drainage in the local area. Another situation that is complex is the orientation of the principal in situ stress field relative to a fracture plane or foliation direction – if in compression rather than tension (dilated) relative to the anisotropy or fabric of the rock mass, they will behave differently. Unloading within the EDZ domain can be thought of as having the effect of dilating all of the fractures within the rock mass, but this effect could potentially be overridden by an increase in the in situ stress field's magnitude for those fracture planes oriented perpendicular to the principal stress orientation direction.

Impacts of hydraulic conductivity adjustment on slope stability analysis

Hydrogeological predictions and/or numerical modelling are used to determine the likely transient pore pressure distribution of the general rock mass (and specific geotechnical domains and pit design sectors) for use in stability modelling. To do so, assumptions need to be made on how the rock mass will change and be affected by passive drainage, which results in depressurisation and recharge, which reduce or even reverse depressurisation. These assumptions are influenced by changes in rock mass permeability, highlighting the need for a better understanding of how hydraulic conductivity evolves within rock slope domains over time. The HCA is useful in conceptualising, explaining, and justifying any proposed changes in K values when doing a pit slope model of an interim pushback or an end-of-life mine model.

Recharge (water pressure increase)

Rivers and lakes: The presence of water bodies near the pit slope have the potential for recharging or maintaining higher pore pressures in the rock mass (as illustrated in Figure 11). This could be exacerbated in cases where fractures form parallel to the slope, which will allow infiltration but could hinder passive drainage and result in increased pore pressures at depth.

Freshet, snow melt, and storm events: The influence of rapid snow melting, or significant precipitation events can cause considerable, if

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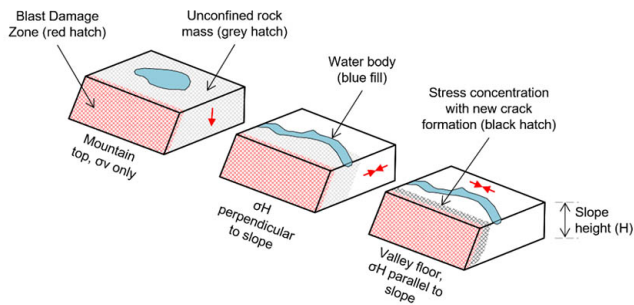


Figure 11—Open pit faces advancing towards water bodies in different dominant in-stress regimes, where $H \approx 120$ m in these examples

only temporary, increases in pore pressures in rock slopes, especially if vertical tension cracks are present. These rapid infiltration events can have significant impacts on the rock mass, an example of which is illustrated in Figure 12, where a 55 m increase in pressure was measured at a glacially formed natural slope of approximately 700 m height in northern British Columbia, Canada. The Figure 12 measurements are based on calibrated vibrating wire piezometer (VWP) sensors. At this location, vertical fracturing and dilation are thought to have been caused by the relaxation of the rock mass after the ice mass receded (melted) and is considered analogous to the unloading observed in EDZs in open pits. In situations where significant tension crack development has occurred along pit crests, the HCA rating total should be reduced by up to 10 points to account for this localised perimeter influence.

Discussion

The conceptual model developed for the open pit damage and dilation zone shapes is based on homogenous material types with simple stress field trajectories. It is recognised that rock masses are inhomogeneous and anisotropic, so too are the stress fields surrounding them, which can be deflected locally by large brittle deformation features, fabric, and so on. In general, though, as an open pit is mined progressively deeper, water flow occurs mostly through joints close to the current pit face in the rock mass, and as the vertical load (σ_v) increases, so the hydraulic conductivity (K) decreases.

Large brittle deformation features, like faults, can be considered as representing 'broad' discontinuities, which behave according to their 'fill' material and the fracture frequency of their damage zones. Foliation can also direct flow (along open planes), which is a form of anisotropic behaviour. At the one extreme, blast damage and rock mass dilation increases fracture-counts and aperture, respectively, which often leads to increased flow, while at the other extreme, depth closes off discontinuity-related void space, which

significantly reduces the hydraulic conductivity. These and other local variations in the discontinuity void shapes, whilst in situ stress direction and magnitude can influence the dilation of joints, which can induce anisotropic flow in and around open pits. This is not well understood at this point and needs further study.

Transient factors are seldom incorporated into slope stability models during the early stages of investigation, such as the scoping or PFS-FS levels, despite their potential significance. The HCA has been developed not only as an aid for the conceptualisation of how transient parameters influence water flow around open pits, but it could also be used for water flow simulations to assess how well the slope might depressurise with time or be impacted by recharge events.

Conclusions

The hydraulic conductivity adjustment (HCA) method has been developed for open pit mining environments and is an initial attempt at understanding and quantifying the multivariant effects of rock mass and geotechnical influences on passive depressurisation of pit slopes during mining. The method tries to provide geotechnical engineering practitioners with a semi-quantitative way of domaining the hydrogeological behaviour of rock masses within and around open pits.

It is proposed that hydraulic conductivity (K) measurements, acquired or estimated for undisturbed pre-mining rock masses, can be defensibly adjusted for planning and modelling purposes using geological and engineering judgement, to reflect a later-date (K') situation in which rock mass damage and/or dilation has occurred. Inputs to the HCA include 'fixed' and 'transient' input parameters. On the fixed end of the spectrum, the intact rock strength is relatively easily measured and does not change much for the life of mine (other than in chemically altered rocks), whereas fracture frequency or in situ stress and rock mass decay can change rapidly and are sometimes more difficult to quantify. As the project advances and open pit shapes change, transient parameter characterisation becomes increasingly critical. The use of instrumentation, along with updated drilling and characterisation programmes, is strongly recommended. No previously published data describing rock mass strength decay and the associated water flow around open pits to adequately calibrate the HCA have been found, and therefore underground excavation damage zone characterisation work was used to develop this conceptual model. Fortunately, field-based K profiles were available, which enabled estimation of the likely range of K to K' variations. These profiles formed the basis of the initial calibration dataset for the HCA.

Overall, it is recommended that geotechnical domains be established inclusive of mining induced damage zones to allow for

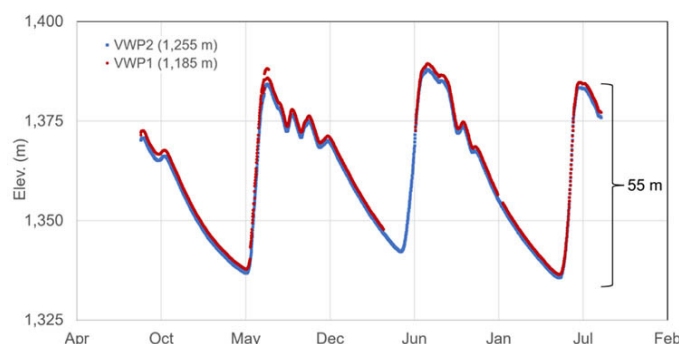


Figure 12—Influence on pore pressure due to rapid snow melt in natural rock face with subvertical fracturing and vertical tension cracks (northern British Columbia, Canada)

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the quantification of the rock mass strength and the influence on hydraulic conductivity over time. Even though HCA estimates of future conditions can be made for any point in the mining project life cycle, the first choice for slope stability modelling data input should always be the use of rock mass and hydraulic conductivity data acquired within the present phase of the project. With sufficient calibration over time, use of this method could potentially enable the identification of the primary factors affecting the hydrogeological influences on pit slope stability in specific mining environments.

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Appendix 1

These example calculations are based on the parameters and ratings provided in Table 1. Note that two parameters have an inverse effect on K, in other words, their ratings increase from left-to-right in Table 1. These inverse ratings are in the Rock Mass Rating (max total = 20) section and are the values used for rating intact rock strength and weathering.

Example A – Mining estimate using pre-mining data

In this example, K is estimated within an EDZ, based on pre-mining data collected within the same rock mass volume of interest (VOI). It is assumed that the **t0** rock mass' K was determined during the PFS or FS, and now the **t1** VOI will be 100 metres behind the open pit mining face, within a linear slope in the distressed zone 100 m below the pit perimeter. Where there is no change in the parameter, it remains the same and thus cancels out (for example, in *Faults* below):

If t0 K	= 1.0E ⁻⁶ m/s	
Shape	= (14 – 6) + (3) + (3) = 13	drillhole to pit shape change
Faults	= (20 – 20) + (10 – 10) = 0	no change in faults
Rock Mass	= (3 – 3) + (4 – 3) + (2 – 3) + (4 – 4) = 0	changes in RQD and weathering
Anisotropy	= (8 – 6) + (4 – 3) + (5 – 1) = 7	dilation of joints, orientation
Rating Δ	= 13 + 0 + 0 + 7 = 20 =	see eqn. 1
RDF	= (100 – 20) / 100 = 0.80	see eqn. 2
Then t1 K'	= K ^ RDF = 1.0E ⁻⁶ m/s ^ 0.80 = 1.6E ⁻⁵ m/s	see eqn. 3

Example B – Location within existing pit

In this example, the location of the rock mass volume of interest (VOI) relative to the pit shape changes such that the rock mass at the new location is more competent than the initial location tested. The change in ratings can be used to estimate the “upgrade” in rock mass and resulting decrease in K. The **t0** rock mass' K was determined within the EDZ behind a convex slope at 50 m depth, and the **t1** VOI being considered is 100 m behind the face, within a concave slope at a depth of 200 m, with a modest decrease in FF/m and anisotropy.

If t0 K = 1.0E ⁻⁶ m/s		
Shape	= (3 – 10) + (3 – 3) + (3 – 2) = -6	locations change in the pit
Faults	= (10 – 14) + (10 – 10) = -4	fewer fault intersections
Rock Mass	= (4 – 4) + (3 – 4) + (3 – 1) + (1 – 4) = -2	increases in rock mass strength
Anisotropy	= (4 – 8) + (2 – 4) + (2 – 3) = -7	confinement related changes
Rating Δ	= -6 – 4 – 2 – 7 = -19	see eqn. 1
RDF	= (100 – (-19)) / 100 = 1.19	see eqn. 2
Then t1 K'	= 1.0E ⁻⁶ m/s ^ 1.19 = 7.2E ⁻⁸ m/s	see eqn. 3