

QAJARAN OPEN-PIT OVERALL SLOPE STABILITY ASSESSMENT UNDER UNLOADING CONDITIONS BASED ON THE STRESS REDISTRIBUTION THEORY

V.V. Hovakimyan

"Lernametalurgiai Institute" CJSC

Under low - confinement conditions, the extension crack initiation lower and interaction upper bounds in the in-situ rock mass within the Qajaran open-pit South-West overall slope presented with hydrothermally altered and weathered monzonite and granodiorite is assessed. As an integral part of the large open pit projects, it is essential to estimate the in-situ rock mass strength and the expected failure mechanism as accurately as possible, taking into account the stress relaxation in near-surface rock mass. In an excavation-induced unloading condition, it has been shown that the extension crack propagation mechanism is a function of low confinement condition which, in turn, leads to low in-situ rock mass strength. The global failure mechanism in the fractured rock mass of the overall slope has been theoretically assessed, and a good agreement between the estimated global failure surface and failure surface obtained from the slope stability analysis has been found. The propagated extension cracks within the rock mass are considered to be ground water flow paths which is the second reason for the in-situ rock mass strength reduction due to the developed high pore water pressures in the toe rock mass of the overall slope. An in-situ rock mass strength reduction envelope in stability analysis to assess the rock mass strength of the Qajaran open-pit overall slope in low confinement geomechanical environment taking into account the high pore water pressures of the rock mass due to propagated extension cracks has been used. It has been found that there is nearly 20% difference when taking into account the extension crack interaction zones within a near-surface rock mass in low confinement conditions.

Keywords: open-pit slope in on unloaded (stress relaxation) condition, rock mass strength, global failure surface, lower bound of extension stresses, upper bounds of crack interaction.

Introduction. The rock mass undergoes various geological procedures such as tectonic movements, weathering, seismic impacts and so forth. Regarding these procedures, a geo-stress equilibrium state has been formed in the rock mass [1]. Any excavation process will break the previous equilibrium stress state and lead to the development of an unloading geomechanical environment near the excavation boundary. In other words, after the removal of the rock support, the 3D stress state

will almost become a 2D stress state in which the confining stress has a lower value near the excavation boundary [1]. In this redistributed stress field, the low confining stress, acting either normal or tangential to the exposed mining slope, has a major impact on the in-situ rock mass strength [1-3]. Today, there are few studies which take into consideration the effect of low confining stress on the rock mass strength in excavation-induced unloading conditions [2, 4].

The extension crack theory in unloading geomechanical environment has been developed since the 1970's. It is commonly known that the origins of the rock yield failures are the tension in nature due to extension strains acting parallel to major principle stress [3]. So far, most of the previous studies have referred to the design problems in underground excavations such as stress-strain zone observations, support design purposes, and other geotechnical engineering problems [2-4].

T. Stacey demonstrated a theory so-called extension strain criterion, which takes into account the intermediate component of the 3D stress state (e.g. σ_2) in the rock mass and is widely used to assess the extension strain zones in underground excavations. The extension strain (τ_3), acting normal to the minor principal stress (σ_3), is defined from the 3D elasticity theory by the following equation [2, 3]:

$$\tau_3 = \frac{(\sigma_3 - \nu(\sigma_2 + \sigma_1))}{E}, \quad (1)$$

where τ_3 is the extension strain; σ_1 , σ_2 and σ_3 are the major, intermediate and minor principal stresses, respectively; ν and E are the deformation characteristics of the rock, e.g. Poisson's ratio and Young's Modulus, respectively.

Based on Stacey's extension strain criterion, the extension cracks will initiate into the rock mass when satisfied the following condition:

$$\tau_3 \geq \tau_{critical}, \quad (2)$$

where $\tau_{critical}$ is the limiting tensile strength of the rock sample and defined by laboratory testing.

Furthermore, Stacey proposed to estimate the extension cracks initiation threshold in the axisymmetric condition by the following equation [3]:

$$\sigma_1 = \frac{E}{\nu} \tau_{critical} + \frac{1 - \nu}{\nu} \sigma_3, \quad (3)$$

where σ_1 is the extension crack initiation lower bound in the axisymmetric condition.

Although Stacey's empirical criterion has a number of advantages in underground excavations, after publishing, it was criticized by several researchers.

The main limitation of Stacey's criterion is that it considers the rock mass as an isotropic and linearly elastic medium, and definitely is not a true representation of the actual rock mass properties. In this regard, M. Diederich pointed out that it would be well more conservative to estimate the extension crack initiation lower bound in the rock mass based on Stacey's criterion and it should be considered as an extension cracks interaction upper bound [5]. In his doctoral thesis, Diederich demonstrated that the extension crack initiation mechanism is not sensitive to low confinement condition, and conversely, the extension crack propagation mechanism is much more sensitive to low confinement condition, since, as Hoek pointed out in 1981 [5]. Diederich proposed the in-situ rock mass reduction criterion which represents the lower bound of the extension crack initiation threshold and is based on the results gained from field and/or laboratory testing. He demonstrated an equation, completely assembled from many complicated laboratory tests and is defined as follows [5]:

$$\sigma_{1Initiation} \approx A * UCS + B * \sigma_3, \quad (4)$$

where A and B are the coefficients in the range of 0,35...0,45 and are 1,0...1,5, respectively; UCS is the uniaxial compressive strength of the rock sample.

Based on Diederich's criterion, the in-situ rock mass strength will drop towards the lower bound of the extension crack initiation threshold defined by equation (3) [6]. If there are well-obtained results from laboratory triaxial tests, this very criterion will provide an accurately estimated extension crack initiation lower bound [4].

The statement of the problem and selection of the methodology. The goal of this research is to investigate the unloading effect on the in-situ near-surface rock mass by using the proposed in-situ rock mass strength reduction criterion in slope stability analysis. This is done by estimating the extension crack initiation lower and interaction upper bounds for which the strength of the in-situ rock masses will start to reduce towards the lower bounds of the extension crack initiation threshold. The main objectives to achieve these goals include numerical simulation of the unloading induced stress-strain state, the assessment of the in-situ weak rock mass strength and prediction of the global failure mechanism in Qajaran open-pit overall slope.

The rock mass strength in an unloading geotechnical environment. Large-scale open pit slope stability assessment in difficult terrain conditions is considered to be an important and relevant problem. It is crucial to give an accurate characterization to the rock mass and failure mechanism behaviors in rock slope designs.

One of the main requirements in rock slope engineering designs is considered to provide accurately quantified rock mass strength [5]. It is well known that

depending on the observed domain scale, the in-situ rock mass strength is well lower than the strength of the intact rock, which is a result of pre-existing intercepted geological discontinuities within the rock mass [5]. The rock masses are almost always under high stress conditions the strength of which is controlled by the degree of fracturing, the loading/unloading and ground water conditions [5]. The rock mass behavior also depends on large-scale mining blasting near-excavation boundaries which leads to open-up preexisting fractures in the surface, as well as initiating new extension cracks of man-made origins.

The extension crack initiation lower and interaction upper bounds for the rock mass of the South-West overall slope of the Qajaran open-pit mine, Zangezur CMC, in Armenia, have been estimated. There exists a major geological structure in the South-West overall slope, such as fault, dipping nearly parallel to the exposed slope. The fault consists of mainly clayey-crushed materials and has up to 50 m total thickness. The hydrothermally altered and weathered monzonites and granodiorites surround the fault above. There are mainly porphyry-granodiorites and slightly altered monzonites behind the major geological discontinuity.

Firstly, the extension crack initiation lower bound has been estimated based on Diederich's criterion by equation (3) and is expressed as follows:

$$\sigma_1 = A * UCS + B * \sigma_3 = 0,35 * 42,95 + 1,0 * \sigma_3 = 15,03 + \sigma_3, \quad (5)$$

where UCS is the average compressive strength of the weathered rock and equal to 42,95 MPa; A and B are coefficients for brittle rock samples and obtained equal to 0,35 and 1,0, respectively from laboratory testings [7-9].

The extension crack interaction upper bound for the rock mass surrounding the overall slope of the Qajaran open-pit mine in the current depth condition based on Stacey's extension strain criterion has been estimated. First of all, we set equation (1) in Phase 2,0 software to define the absolute value of τ_3 and the extension crack interaction zones at the toe rock mass of the overall slope of the open-pit mine based on finite element method as shown in Figure 1.

The absolute value of the extension strain at the toe weathered rock mass of the overall slope at the current depth defined from numerical modeling is equal to $\tau_3 = -1,2e - 06$ [8, 9]. Now, using the magnitude of τ_3 in equation (2), we can estimate the extension crack interaction upper bound above which the pre-propagated cracks will interact to each other by developing axial macroscopic spalling/splitting cracks at a low confinement condition. The extension crack interaction upper bound has a straight line equation view and is shown in Figure 2:

$$\sigma_1 = -\frac{E}{\nu} \tau_3 + \frac{1-\nu}{\nu} \sigma_3 = 17,94 + 3,76 * \sigma_3. \quad (6)$$

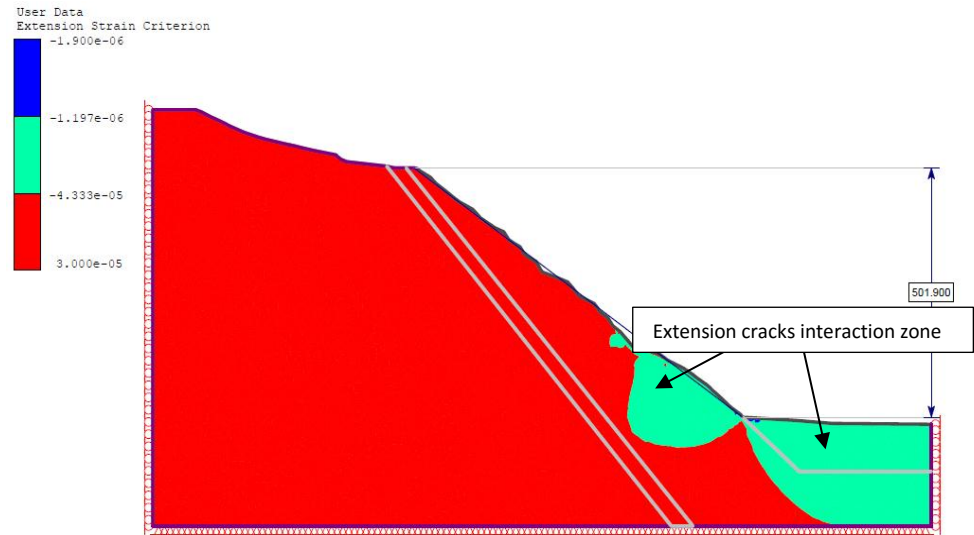


Fig. 1. The extension strain zone at the toe rock mass of the Qajaran open-pit mine overall slope based on Stacey's criterion

In Figure 2, the estimated extension crack initiation lower and interaction upper bounds based on Diederich's and Stacey's criteria are shown, respectively.

After the assessments of the lower and upper bounds of the extension crack initiation and interaction thresholds, we can sum up that the near-surface rock mass strength of the South-West overall slope of Qajaran open-pit mine will drop towards the extension crack initiation lower bound.

In Figure 2, the rock mass below the estimated extension crack initiation threshold will remain undisturbed. Above the initiation threshold, in region I in which the minimum principle stress, thus the confining stress, is near zero, the extension crack propagation mechanism is dominant which characterizes the brittle behavior of the in-situ rock mass. In this unloading geomechanical environment, the extension cracks of man-made origins will propagate parallel to maximum compressive stress, and when the maximum compressive stress exceeds the estimated upper bound, they will develop and form the axial macroscopic cracks due to which the in-situ rock yield will drop at a low confinement condition and have a non-linear strength envelope as shown in Figure 2. Therefore, it is found that the in-situ rock mass strength is a function of near-zero confining stress. Above the extension crack initiation threshold, the lower the confining pressure is, the higher the intensity of the extension cracks propagation mechanism and the lower the in-situ rock mass strength due to the fractured (brittle) behavior.

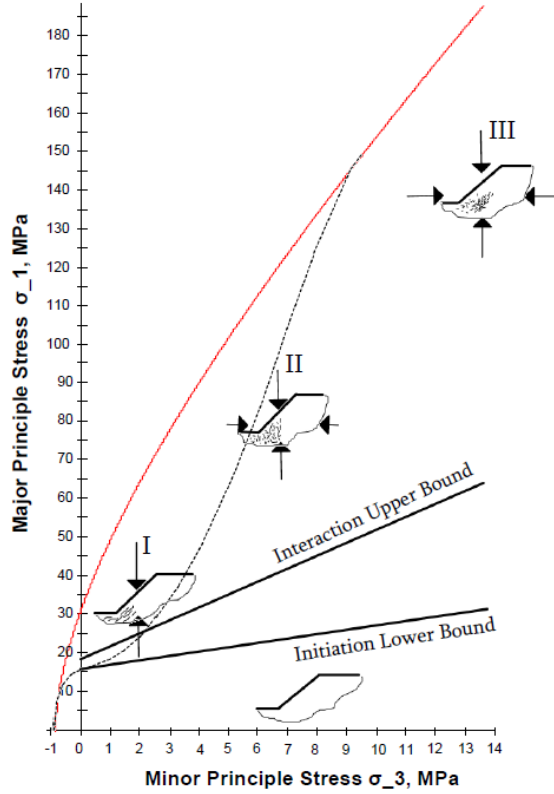


Fig. 2. The in-situ rock mass strength reduction to the lower bound of the extension crack initiation threshold in an unloading geomechanical environment

In the II region, the so called quasy-3D stress state in which the confining pressure is not zero and higher than that in region I, the extension crack initiation mechanism is dominant and in this region, a macroscopic shear rupture forms depending on the values of maximum compressive stress. In the 3D stress state (i.e., in the III region), in which the confining pressure can be half of the UCS of the intact rock, the shear failure is a function of extension crack initiation and accumulation mechanisms (Fig. 2).

Therefore, in the excavation-induced unloading condition, the in-situ rock mass strength will reduce due to propagated extension cracks. On the other hand, the propagated extension cracks will become water flow paths out-of the exposed face into the excavation area and therefore will lead to increase the permeability and porosity of the rock mass and hence the pore ware pressure of the near-surface rock mass.

According to the investigation in this article, when the maximum actual stress component ($\sigma_{1actual}$) exceeds the estimated lower bound of the extension crack

initiation threshold, the extension cracks will commence to propagate normal to the minimum principle stress resulting in the reduction of the in-situ rock mass strength. And when $\sigma_{1actual}$ exceeds the extension crack interaction upper bound, the propagated cracks will interact each other developing large-scale axial spalling or splitting failures tangential or normal to the exposed mining slope. On the other hand, the elementary rock blocks in the toe rock mass, developed by propagated extension cracks, are free to rotate and move over each other, which are precursors of a toppling failure. There is a good agreement between results obtained from field observations, in which toppling failures are observed, and the outputs from this investigation, in which unloading-induced failures are considered.

The global failure mechanism. In the fractured, brittle rock mass, the failure mechanism is progressive (unstable) and almost always occurs rapidly, with little or non-warnings. In the man-made fractured rock mass, the frequent failure mode is a toppling failure. By other researchers, it refers to unloading-induced failures [5, 10].

Where huge information about a major geological discontinuity such as tectonic fault exists, it is unacceptable to think that the failure surface will only develop along that discontinuity [11]. It is essential to have a correctly estimated failure mechanism and rock mass strength to provide a precise mining slope stability design [5]. By the way, the progressive failure mechanism consists of 2 and/or more failure mechanisms in the brittle, fractured rock mass. Undoubtedly, the global failure mechanism is 3D and there is much more conservatism in rock slope stability analysis to consider the 2Dimensionality of the rock slopes [11].

The global failure surface of the South-west overall slope of the Qajaran open-pit mine has been theoretically estimated in which there is a major geological feature dipping nearly parallel to the exposed mining slope as depicted in Figure 3.

In this research, it is expected that the damage zone, due to propagated extension cracks at the toe of the overall slope combined with a tectonic fault will develop the global failure surface which consists of two types of failure mechanisms:

1. In the crest of the overall slope where the tectonic fault is intersecting the ground surface, the planer failure surface will develop which passes through the footwall of the tectonic fault.
2. At the toe rock mass, the developed damage zone is vulnerable to failure. It is needless to say that the global failure surface will occur along the preexisting geological discontinuity and through the toe rock mass by developing a step path or a secondary failure surface (Fig. 3).

When taking into account the brittle (strain-softening) behavior of the rock mass due to extension crack propagation mechanism at low confinement conditions (Fig. 2), the overall slope has a factor safety of nearly 20% below. Thus, taking into

consideration the in-situ rock mass degradation due to extension crack propagation in an unloading geomechanical environment, the mining slope will have a much more real safety factor than when we use the peak strength of the rock mass.

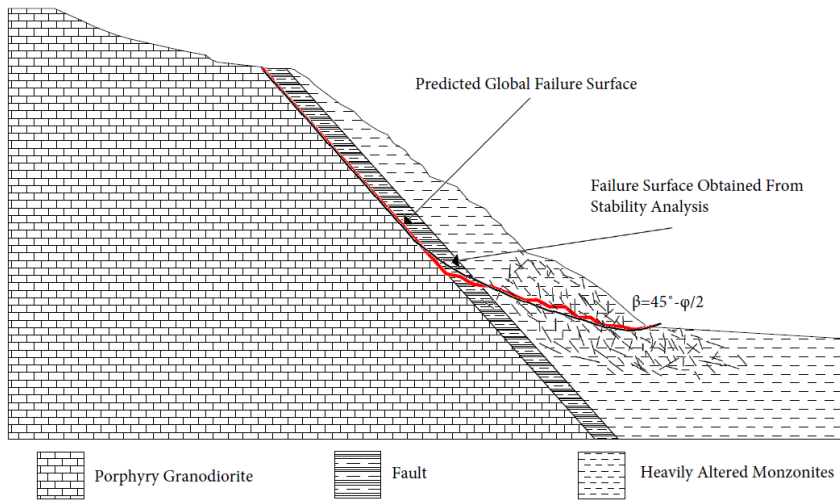


Fig. 3. The comparison between the theoretically estimated global failure surface and the failure surface obtained from the stability analysis of the overall slope of the Qajaran open-pit mine

Conclusions. In the unloading geomechanical environment, the extension crack initiation lower and interaction upper bounds for the rock mass, presented with weathered monzonite and granodiorite, in the overall slope of the Qajaran open-pit mine is estimated. It has been shown that the in-situ rock mass strength in the South-West overall slope of the Qajaran open-pit mine is a function of low confining stress. Meanwhile, the low in-situ rock mass strength is a result of the increased pore water pressure at the toe rock mass due to propagated extension cracks. Hypothetically, the global failure mechanism and location in the overall slope of the Qajaran open-pit mine are estimated. A good agreement between the theoretically estimated failure surface and the failure surface obtained from the slope stability analysis has been found. When we take into account the brittle (strain-softening) behavior of the rock mass due to the propagated extension cracks at low confinement in the South-west overall slope stability analysis, the factor safety is 20% below than that based on the conventional failure criterion. This is explained by the reduced in-situ rock mass strength due to propagated extension cracks at the toe rock mass of the mining slope in the unloading geomechanical environment and by high pore water pressure.

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**ՔԱՋԱՐԱՆԻ ԲԱՑԱՀԱՆՔԻ ՉՐԵՈՒՎԱԾ ԿՈՂԻ ԿԱՅՈՒՆՈՒԹՅԱՆ ԳՆԱՀԱՏՈՒՄԸ
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ԺԱՄԱՆԱԿԱԿԻՑ ՏԵՍՈՒԹՅՈՒՆՆԵՐՈՎ**

Վ.Վ. Հովակիմյան

Քաջարանի բացահանքի հարավարևմտյան չբեռնված կողի (կողի ապարային զանգվածի սեփական քաշից ձևավորված կողային ցածր ճնշման պայման՝ չբեռնված երկրամեխանիկական միջավայր) ներկայացված ապարային հողմահարված մոնցոնիտներով և գրանադիորիտներով, միջկողային զանգվածում գնահատվել են ապարների ձգման լարումներից առաջացած ճեղքերի զարգացման ստորին սահմանը և ճեղքերի փոխհատման վերին սահմանը: Տեսականորեն գնահատվել է բացահանքի կողի ապարային զանգվածում ձգման ճեղքերով սահքի մակերևույթի տեղադիրքը, ինչը թույլատրելի սահմանային տեսության համաձայն՝ ունի զգալի համապատասխանություն բացահանքի կողի կայունության հայտնի մեթոդով գնահատման վերլուծությունից ստացված սահքի մակերևույթի հետ: Ցույց է տրվել, որ համաձայն լեռնային ապարային զանգվածի ամրության գնահատման առաջարկվող մեթոդների՝ բացահանքի չբեռնված, կողի լեռնային երկրամեխանիկական միջավայրում ձգման ճեղքերի տարածման ինտենսիվությունը ուղիղ համեմատական է ապարային զանգվածում տարածվող ցածր լարվածությանը, ինչը հանգեցնում է լեռնային ապարային զանգվածի ամրության ձևավորմանը: Հողվածում ապարային զանգվածի նվազագույն լարվածային դաշտում ճեղքերի զարգացման մեթոդը կիրառվել է Քաջարանի բացահանքի հարավարևմտյան կողի կայունության երկրամեխանիկական հիմնավորման վերլուծության ժամանակ՝ հաշվի առնելով կողի հիմքի ապարներում ձևավորված ձգման ճեղքերի տարածման գոտիները, որոնցով պայմանավորված է նաև ֆիլտրվող ջրերի բարձր ծակոտկենային ճնշումների զարգացումը: Կողի կայունության երկրամեխանիկական վերլուծությունից ստացվել է, որ չբեռնված միջկողային լեռնային ապարային զանգվածում զարգացող ձգման ճեղքերի՝ ցածր լարվածային դաշտի առաջացման պայմաններում բացահանքի կողի կայունությունը նվազում է շուրջ 20%-ով:

Առանցքային բառեր. չբեռնված կող, ապարային զանգվածի ամրություն, գլոբալ սահքի մակերևույթ, ձգման լարումների ստորին սահման և ճեղքերի փոխհատման վերին սահման:

**ОЦЕНКА УСТОЙЧИВОСТИ НЕНАГРУЖЕННОГО БОРТА
КАДЖАРАНСКОГО КАРЬЕРА С ПОМОЩЬЮ СОВРЕМЕННЫХ ТЕОРИЙ
РАСПРЕДЕЛЕНИЯ НАПРЯЖЕНИЙ В ПОРОДНОМ МАССИВЕ**

В.В. Овакимян

Выполнена оценка образованных растягивающими напряжениями нижней и верхней границ развития и пересечения трещин в прибортовом массиве горных пород

юго-западного ненагруженного (образованное низкое давление от собственного веса породного массива борта) борта Каджаранского карьера, представленного выветренными монцонитами и гранодиоритами. В массиве горных пород борта карьера теоретически оценено положение поверхности скольжения по трещинам растяжения, что имеет хорошую сходимость с положением поверхности сдвига, установленным при расчете устойчивости борта по известному методу предельного равновесия. Показано, что согласно предложенным методам оценки устойчивости массива горных пород в геомеханической среде ненагруженного борта, интенсивность распределения трещин растяжения прямо пропорциональна низкому напряжению в породном массиве, формирующему прочность массива горных пород. В статье развитие метода образования трещин в поле минимальных напряжений породного массива использовано при геомеханическом обосновании, анализе и установлении устойчивости юго-западного борта Каджаранского карьера с учетом распределения зон растягивающих трещин, сформированных в породах основания борта, чем обусловлено и развитие высокого порового давления. По результатам материалов геомеханического анализа устойчивости борта получено, что из-за развивающихся в породном массиве ненагруженного борта трещин растяжения и поля низких напряжений устойчивость борта карьера снижается на 20%.

Ключевые слова: ненагруженный борт, прочность горного массива, поверхность глобального скольжения, нижняя граница растягивающих напряжений, верхняя граница пересечения трещин.