

STATE OF THE ART, RECONSTRUCTION OF DAMAGED ZONES: TRANSITORY STRESSES EFFECT AND FACTORS CONTROLLING ROCK MASS STABILITY

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ABSTRACT: For the last three decades, many countries in the Middle East have been bombarded by wars. In these damaged zones, removing of destruction debris and the effect of the direct impact of blasts might trigger rock mass instabilities. This paper discusses the influence of explosives on factors controlling stability of rock masses and shows the available methods to back-analyze, investigate, and/or design near-surface rocks. Explosion waves and the resulted debris may jeopardize the geomaterial stability through different factors such as; introducing new fractures inside rocks and/or soils, temporary increasing water pressure, and dynamic loading-unloading cycles. Upon unloading as a result of removing destruction debris, the stress changes and consequently destabilize soil/rock masses. These effects become of great concern in many civil engineering projects such as, road cuts, foundations, and retaining walls. Rock slopes susceptible to instability could be divided into two categories; the structurally controlled slopes, and the complex rock slopes. One mechanism, to form a continuous rupture surface in complex slopes, is by introducing new fractures through explosions and/or high rate of loading and/or unloading as transitory stresses. The modes of instabilities that have been documented are summarized to introduce the factors affecting the geomaterial slope movement in damaged zones. Hybrid modeling approaches might be the best choice to examine a rock mass vulnerability to movement by simulating the explosive stresses. Modeling the entire reconstruction process and the effect of explosions would help to reduce or to eliminate risks in the construction of new structures in after war region.

Keywords: Transitory stress, explosion, geology, dynamic loading, modeling

1. INTRODUCTION

The stability of rock slopes is of great concern in many projects such as mining, roadway cuts, foundations, and dam excavation. According to [1], rock masses susceptible to instability can be divided into two main categories, the structurally controlled and the complex masses. Kinematics of a landslide or the type of movement is a key characteristic of the landslide itself and one of the principal criteria for classifying any landslide [2], and [3].

Five distinct modes of landslide movement can be identified, fall, slide, topple, flow and spread, [4]. Table 1 shows landslide classification system based on the slope kinematics and the type of the material involved in the instability. These landslide movements can be triggered by the effect of explosion wave's dynamic loading, water table changes, and initiating new cracks along the pre-existing joints due to high-stress concentration. This paper shows that failure due to dynamic loading, as a result of high impact explosions, may occur even in a dry slope with a non-persistent joint set. The factor affecting soil/rock slopes in the presence of explosion loading is discussed thoroughly to highlight their relative importance.

The effect of explosion stresses on geology, time, dynamic loading, the orientation of slope, water level, and rock strength need to be highlighted to understand the requirement for reconstruction of former war zones. The methods adopted to analyze such slopes need to model coupled problems that allows for fracturing. A dry rock slope adapted from [5] is presented to investigate the effect of repeated high impact explosive loading on the slope behavior.

This paper presents the available methods to investigate rock mass behavior. Explosion impact can defragment rock and soil slopes and changes their geometry and/or alter their physical circumstances. These changes due to explosion waves and the resulted debris movement can alter a rock mass behavior permanently through introducing new fractures inside rocks and/or soils.

2. ROCK SLOPES AND PROCESSES

Slope movement usually is attributed to many causes and in rare cases movement of a slope can be credited to one single reason. According to [3], the slope movement process involves a continuous series of events from cause to effect. To take a decision about a particular slope, the risk

associated with that landslide should be taken into consideration mainly in reconstructing of war zones.

Table 1: Landslides Classification System, after [2], [6], and [7].

Type of Movement	Type of material		
	Bedrock	Engineering soils	
Falls	Rockfall	Predominantly Fine Earthfall	Predominantly coarse Debris fall
Topples	Rock Topple	Earth Topple	Debris fall
Slides	Rotational Rock slump	Earth slump	Debris slump
	Translational Rock Slide	Earth Slide	Debris Slide
Lateral Spreads	Rock spread	Earth spread	Debris spread
Flows	Rock flow	Earthflow	Debris flow
	Rock avalanche		Debris avalanche
	Deep Creep	Soil Creep	
Complex and compound	Combination in time and/or space of two or more principal types of movement		

Stacey [8] summarized the factors affecting rock mass instability as; groundwater conditions, the rock mass geological units, in situ and induced stress state, rock mass strength, rock mass structures and orientations, the geometry of the rock slope, the seismic environment, in the case of the open pit mine, the time frame of the mine operation may influence the mine. These factors, and literally the stability of a rock mass might be affected if it was subjected to a high amount of explosions over an extended period of time. Rock mass movement in the mining environment, roadway cut, and/or natural rock slopes can be connected through cause and effect relation. Eberhardt [9] presented instability of rock slopes processes as a cause and effect (Figure 1). However, he did not discuss explosive stresses in after war zones. In this paper, the factors influencing the rock slope instability are discussed and the influence of explosions on each factor was highlighted. To show the important effect of explosive stresses on a rock mass, a numerical model was first verified and then used to simulate failure under repetitive dynamic loading.

2.1 Groundwater

The water table location in any geomaterial mass might influence its behavior and eventually might cause movement. In addition, the stress state inside a slope depends on groundwater conditions among other factors. Moreover, water flow inside a rock mass affects the joints' behavior; this flow might cause erosion of fine material and increase the aperture of the joints with time. When explosive gasses present, water pressure increases and the gasses might react with some minerals of the filling materials which results in destroying or reducing any apparent cohesion of the infillings [10], [11], [12], and [13]. The water table location

during transitory stresses loading varies at much higher rate than the usual variation from rain or snow melting. High impact explosion waves travel deep into the ground and cause the water table to fluctuate in very short period of time. If the pore water pressure exceeds the acceptable limit, the movement might be triggered even at small scale. These type of small movements can initiate cracks that may coalesce to form a rupture surface. The effect of explosion stresses on the water table in mining or civil application is small compared to war zones; in terms of the magnitude and the power of the explosives which can't be underestimated. Hybrid methods can be utilized to model explosions and assess if permanent damage occurred due to the water table high rate of fluctuation.

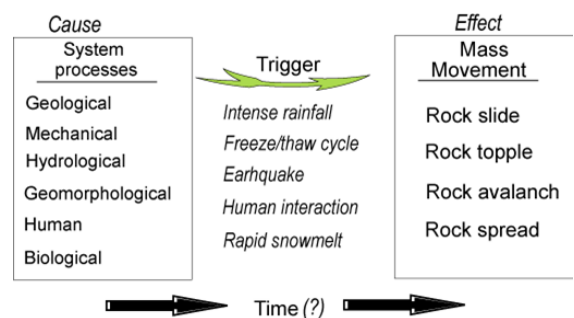


Fig. 1 Relationship between the rock mass processes and slope movement, after [9]

The principle of effective stress has been presented by [14]. As the water pressure increase as a result of explosions, the effective stress inside the rock mass below the water table will drop and cause the shear strength to decrease which might cause instantaneous instability. Above water table, saturation as a result of dynamic loading destroys capillary tension; destruction of capillary tension

in soil slopes has been studied and presented by [15]. In an area that was subjected to a high amount of explosives, the dynamic loading might destroy the capillary forces and render a stable slope into a marginally stable one or even failure.

For example, in 1960, upon the end of construction of the Vaiont Dam in northern Italy, the height of the arch dam was at over 290 meters. In October of 1963, a massive landslide occurred on the left valley wall of the Vaiont reservoir, 400 million tons of rock was involved in the landslide. The rock mass entered the reservoir at a high speed generating a wave over 230 meters high, this wave overtops the dam and traveled downstream through the river valley, destroying many villages and killing 2050 people, [16]. According to [16] the increase in pore water pressure due to filling the reservoir was the reason behind reducing the effective stress and caused the catastrophic failure. One possible explanation for this case is destroying the capillary forces due to transitory stresses produced by explosions used to excavate the ground. The high amount of explosive of the same magnitude that had been used in Iraq for an instant can cause similar dams to fail.

$$\tau = (\sigma_n - u) * \tan \phi' + c' \quad (1)$$

where: τ = shear strength, σ_n is normal stress, u is water pressure, ϕ' is the effective angle of friction and c' is the effective cohesion.

A slope that is stable at limit equilibrium may become unstable when water pressures are increased by explosions. These coupling processes are only available in numerical modeling approaches that can handle water flow through the rock mass during dynamic loading along with high computational power.

2.2 In situ and Induced Stresses

In geotechnical engineering, the factor of safety defined by the ratio of the strength of the stress of a particular material, this applies to both underground and ground structures in both soil and rocks. If the stress exceeds the strength of a material, failure initiates and might propagate in a progressive manner. Note that impact of explosions in war zones may cause stress to increase in a short period of time and eventually results in failure as we will see in the numerical model presented at the end of this paper. The stress state within a rock mass, wither it is in situ or induced by explosions may have a direct impact on slope's stability.

The stresses exerted on a rock mass can be increased or reduced by many processes, such as imposition or deposition of a surcharge load on that rock mass. This can be due to the removal of

debris resulted from destruction in war zones. High-velocity waves from intense explosions may also alter the state of stress and cause movement.

The in-situ stresses play an important role in determining the failure mode; for instance, if blocks contained within the rock slope are subject to relatively high lateral compressional forces, the confining pressure will reduce the likelihood of rocks rotating out of the slope. Note that usually explosions occur near rock surface and can cause large stress changes. This may cause reduction of confinement and rock blocks may rotate and fail. In addition, [17] argued that the in-situ stress state can influence the distribution of stresses inside a rock mass, explosions might change this distribution.

The components of stress existed in slopes are the gravitational stresses due to the mass of the rock, the tectonic stresses which may cause uplifting of a ground surface, surcharge loading, and transitory stresses, [2]. The vertical stress at a point is assumed to be solely due to the mass of the overlying rock column and any additional surcharge loading. The horizontal stress field is way more difficult to determine due to the locked in tectonic stresses involved and the transitory stresses.

Tectonic stresses are developed when movement of crustal plates forces the contact and displacement of large units of rock and cause bending, folding, and faulting of the rock units, stress concentrations might result in fracturing. In open pit environment, for example, the pit excavation by blasting results in distressing the slope surface and stress concentration at the toe, the vertical stress decreases while horizontal stresses still the same. Moreover, transitory stresses resulting from high impact explosions can cause high-stress concentration and lead to failure initiation inside a particular rock mass.

The joint distribution, orientation, and degrees of persistence also have an impact on the stress state of a rock mass [18], and [19]. Goodman [20] discussed the effect the geology on the stress concentration; he showed that changes in lithology account for large deviations from elastic stress distributions. As the stiffness of the rock increase, the ability to carry stress will increase and cause stress concentrations; repetitive explosions might also have the same effect on stress concentration.

In summary, the stress distribution is very complicated and in order to take it into account, the lithology, structures, the degree of persistence of the rock discontinuities, explosion stress, and in situ stress state should be incorporated in the analysis. Numerical methods capable of this merging all of these factors should be used to simulate the effect of stresses in the slope as shown later in this paper.

2.3 Geology

Rock formations and characteristics can affect rock mass stability. Specific types of rock can be described by certain rock mass characteristics. For example, sedimentary rocks are generally characterized by parallel bedding at which sliding might occur. Cruden and Hu [21] examined modes of failure observed in thinly bedded, sedimentary rock slopes with cross joints and found examples of buckling and toppling. Stead and Eberhardt [22] examined the numerically complex mode of failure occurred in sedimentary rock formations, tensile and/or shear failure accompanied with sliding were the reasons for those failures.

Although the rock type may give an indication of a possible failure mode, understanding of other factors such as rock weathering, stress state, water table, structures, and rock mass strength are vital in any instability assessment. Note that, altering a geology of a site requires millions of years along with many factors such as pressure and weathering. However, explosion stresses are very short lived and they will not affect the geology of a site in after war zone unless nuclear weapons capable of causing large fault's movement occurred.

2.4 Rock Mass Strength

A rock mass is a composite material consisting of different discontinuities and intact material. This composite formation adds to the complexity of the rock mass strength determination. Figure 2 demonstrate the problem; notice that, rock masses usually consist of a network of discontinuities that have a different degree of persistence and not only continuous discontinuities. The strength of the rock mass, which controls the stability, is a function of the size of the slope or underground structure under study.

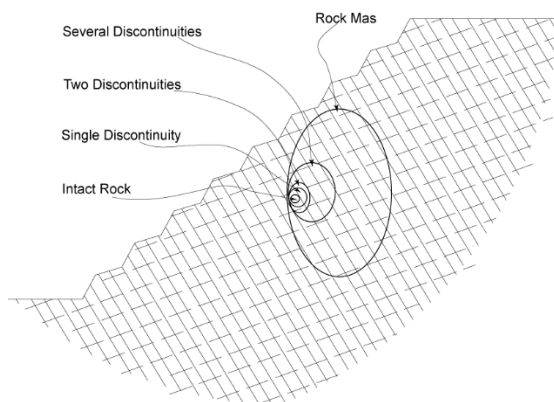


Fig. 2 Complexity of a rock mass and effect of sample size, after [23]

If the structure is in the order of 50-100 m, the instability is most likely to be controlled by discontinuities that might be continuous or discontinuous. Otherwise, Small volumes of rock tend to be stronger than larger volumes of the same rock type. As the size of the rock mass under investigation increases the discontinuities such as, joints, fractures and/or faults increase and that reduces the rock mass strength. Figure 4 shows the volume effect on the strength of the rock mass.

To determine intact rock strength, the uniaxial compressive strength of the intact rock pieces can be determined in the laboratory by using the uniaxial testing, tri-axial testing and/or in the field using the point load test. The intact rock has no pre-existing failure plane; therefore, the intact rock strength becomes a function of the crystalline structure of the rock which is an upper bound of the material strength.

If a large mass is subjected to repeated explosions, the waves will travel deeper and amount of cracks involved will increase. So, the deeper the explosion waves travel the weaker the rock mass will be. As a result, small cracks will grow to form larger ones and eventually reduce the rock strength. The suggested numerical method at the end of this paper, allows modeling of explosions and deep traveling waves.

2.4.1 Discontinuity Strength

The strength of the rock discontinuities is a critical factor controlling the rock mass stability. The geometry, continuity, orientation relative to the loading conditions, the degree of continuity and distribution affect the physical and mechanical properties of the rock discontinuities and as a result, this will affect the total strength of the rock mass. The discontinuity shear strength is dependent on the adhesive bonding of the rock, the surface asperities, and the stress that is required to shear through these features, and/or the stress required to over-riding these asperities [24]. The infilling material strength, if present, may affect the strength of the discontinuity. Moreover, gasses resulting from explosion might seep inside the rock mass and react with the water to dissolve these infilling materials. The strength of a planar failure with no infilling nor asperities described by Mohr-Coulomb failure criterion, Eq. 1.

However, for rock discontinuities with asperities (rough surface), Patton [25] introduced the term "i" as a result of experiments in which he carried out shear tests on 'saw-tooth' specimens, Figure 3. The results indicated a bi-planar failure criterion that depends on the normal stress effect. In an after war zone, the many explosions in that specific area might cause ground shaking and shear these asperities which reduce dramatically

the strength of the joint. The shear strength of Patton's saw-tooth specimens can be represented by:

$$\tau_f = \sigma_n \tan(\phi_b + i) \quad (2)$$

where ϕ_b is the basic friction angle of the surface and i is the angle of the saw-tooth face.

Although Patton's approach is very simple, it does not reflect the reality that changes in shear strength with increasing normal stress is gradual rather than abrupt. Barton and Bandis [26] studied joints behavior and proposed a more realistic rock joints behavior:

$$\tau_f = \sigma'_n \tan[JRC \log_{10} \left(\frac{JCS}{\sigma'_n} \right) + \phi_b] \quad (3)$$

where: τ_f =shear strength, σ'_n =effective normal stress, JRC = joint roughness coefficient JCS = joint wall strength, ϕ_b =base angle of friction.

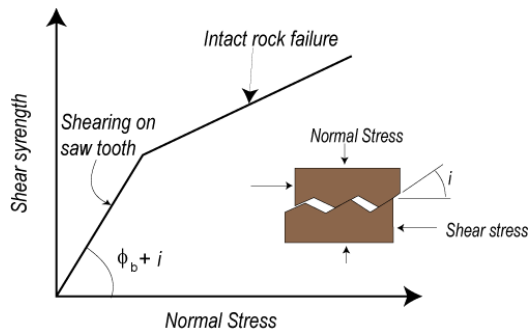


Fig 3 Schematic illustration of Patton's experiment

Note that, the JRC will be highly affected by explosive loading, especially in near-surface rock slopes. The JRC and the infilling of the rock joints might play an important role in determining the strength of the rock joints and samples should be taken and sent to the laboratory to determine the strength of these infillings and joints after transitory stresses. If the joint is non-persistent one, as we will see in the numerical model, fracturing through the intact material would form an admissible rupture surface as a result of transitory stresses.

2.5 Slope Orientation

In the case of open-pit mines, the relative pit geometry and orientation of the slopes forming the pit can also affect the stability. Note that, explosions, at normal scale, will hardly change the slope orientation but large-scale explosions might change the surface of a rock slope. Raveling, fragmentation, falls might occur and change the slope geometry. Moreover, the orientation of the structural discontinuities with respect to loading direction is also critical, and influences the rock

mass strength. Usually, failure follows the easiest path as long as the loading condition is favorable [23].

2.6 Dynamic Loading

The dynamic loadings involve both the seismic environment (explosions) and the earthquakes. Blasting of a rock slope directly affects rock mass quality of the near surface rock by inducing damage. Hoek-Brown criterion discusses this damage in controlled and uncontrolled environments such as in the mining industry. However, more research needs to be made on uncontrolled ones in war zones. Most rock engineers are aware of this over-break, but usually, this is only quantified on a visible scale with little regard to war areas.

Dynamic loading resulted from explosions play an important role in the rock mass stability due to the gravity acceleration driving force. This driving force should be incorporated in the numerical model by determining the gravity acceleration from explosions in case the slope might be subjected to further explosions of the same or higher magnitude.

In war zones, where blasting is the order of magnitudes higher than in mining or civil work, blasting effect can travel deeper into the ground and there is no tools or techniques to minimize their effect. Note that, the release of load after blasting can also cause additional damage to the rock mass, [27]. Numerical methods and limit equilibrium methods can handle the gravity acceleration but direct blasting due to war activities can only be simulated by using numerical methods such as hybrid techniques in fully coupled manner, this is introduced in section 3.

2.7 Time Effect and Temperature

In mining Environment, usually, rocks only need to be stable as long as personnel and machinery are working in the mine. As a result, rock mass failure may be acceptable and even stimulated from an economic perspective; indicating that the rock mass was not too conservatively designed. In the case of the civil engineering applications, rock masses must remain stable for long period of time. Examples include slopes designed next to highways.

Time effect on rocks also occurs through weathering under cycles of thermal expansion and contraction or freezing and thawing, [2]. Explosives in war zones might cause high-temperature fluctuation in short period of time. This sudden change of temperature might cause extra stresses inside the rock mass. Moreover, explosives in war zones usually occur over an

extended period of time; for example, the war in Iraq started in 1980's and still going. Over time the amount of damage will accumulate and failure might occur as shown in the numerical model in this paper. To study this effect, laboratory tests need to be executed to understand the effect of blasting, heat, and gasses.

3. APPLICATION

To illustrate the effect of blasts on surface rock slopes, the UDEC-DM [5] was used to model fracture initiation and propagation due to high impact explosives. I used Voronoi tessellation to generate randomly sized blocks that represent the rock mass, the flaws represent joints, cracks, or smaller discontinuities.

3.1 Model validation

To use the UDEC-DM, I validated the model by using the direct shear test results of Lajtai [28], the model after failure is shown in Figure 4. Lajtai conducted the direct shear test on an artificial rock that contained non-persistent rock joints, Table 1 shows the model properties. The artificial rocks were used by Lajtai to understand the rock mass behavior under direct shear loading. The ratio of the edge length to the size of the model was the kept constant in both the model and in the slope.

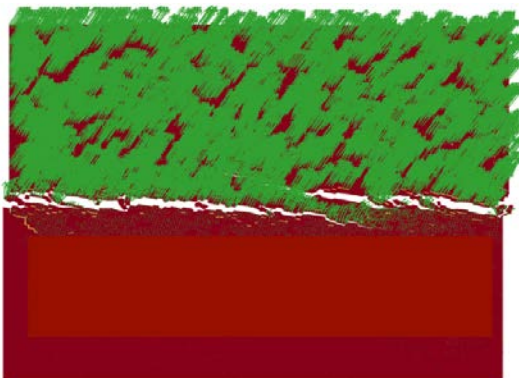


Fig. 4: The direct shear tests used to validate the modeling approach with displacement vectors

Table 2: UDEC-DM and the properties of the rock

Property	Rocks	UDEC-DM
Φ (°)	37	35
c (MPa)	1.2	$<2\sigma_t$
kn (GPa)	-	10
ks (GPa)	-	10
σ_t (MPa)	1.1	1.1

The results of the modeling show good agreement between the laboratory results and the numerical model results see Figure 5. The numerical model predicted successfully the non-linear behavior observed by Lajtai. To check the

effect of the size of the edge on the model performance, I varied the edge length between 0.5 and 1.1 mm. Figure 6 shows no significant change occurred. To examine the effect of shear (k_s) and normal stiffness (k_n) ratio on the direct shear performance, I tested the model under various (k_s/k_n) ratios, Figure 7 presents the results. As shown in the Figure the changes in the ratio have minimal effect on the model performance.

3.2 The slope model

To examine the effect of several explosives I modeled a rock slope with non-persistent rock joints subjected to cyclic loading. Figure 8, shows the model with pre-existing non-persistent joints, Table 3 shows the properties of the rock mass. In these types of slopes, internal fracturing is essential to form a continuous rupture surface. This 100 m high slope had discontinuous pre-existing joints as shown in the figure. The slope was marginally stable when a friction angle of 38° and tensile strength of 0.9 MPa was used for the flaws properties. To simulate the effect of explosions, seismic loading-unloading of 0.1 g was introduced in 10 cycles. At failure, the intact rock bridges fractured and coalescence occurred between the pre-existing rock joints and the newly formed fractures in the intact rock to form a rupture surface, see Figure 9. This fracturing initiated next to the tip of the joints at cycle number 4.

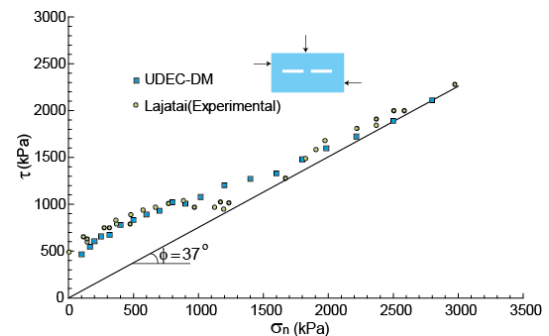


Fig. 5: Lajtai's results, and the UDEC-DM results

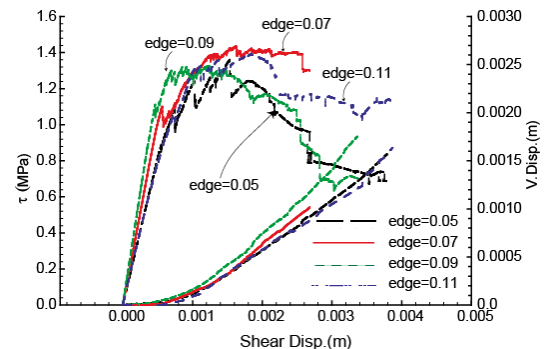


Fig. 6: The model performance due to variation of the edge lengths

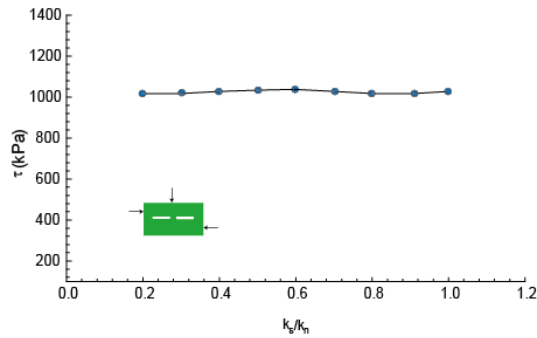


Fig. 7: Effect of (k_s/k_n) on UDEC-DM direct shear

The results of the modeling indicate that repeated dynamic loading, similar to the effect of the blast, caused fracturing in the form a wing cracks that merged with pre-existing rock joints to form an admissible rupture surface. Note that, the rock mass above the newly formed rupture surface continued to slide and form a pile of rocks at the toe of the slope as shown in Figure 10. Which shows the completed movement of the slope. This result usually observed in the field in which rock slopes rarely move as a single mass, but usually fragmented. The repetitive dynamic loading on the rock slope caused stress concentration at the tip of the joints and initiated cracks as shown in Figure 10. Further dynamic loading caused the slope to fail. I monitored the surface acceleration at the surface to validate the model and its behavior under dynamic loading, see Figure 11.

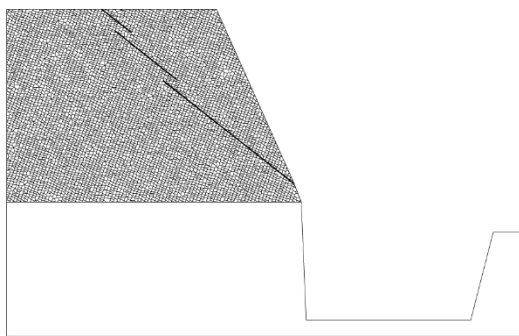


Fig. 8: Rock slope with pre-existing non-persistent rock joints with Voronoi joints.

Table 3. Properties used in dynamic modeling

Property	Planar Failure
Φ ($^{\circ}$) (basal plane)	35
c (MPa)	1.5
kn (GPa)	10
ks (GPa)	10
σ_t (MPa)	0.9
Φ ($^{\circ}$) (internal flaws)	38

4. CONCLUSION

As a result of blasting in war zones, rock masses goes under substantial changes. This paper discussed the different factors affecting rocks in after war zones to facilitate reconstruction and showed numerically the effect of explosions on the stability of a rock mass under explosive stresses. The factors affecting slope instabilities and their relationship with explosive stresses were discussed individually and followed by a hybrid numerical model that was validated by using direct shear test data. Transitory stresses increase the groundwater level temporarily, destroys the joint strength, disintegrate a rock mass, and might cause fracture initiation, propagation, and failure. The results of this paper showed numerically that explosive stresses with time caused failure of a stable rock slope due to fracture initiation, coalescence, and formation of admissible rupture surface. As loading-unloading cycles continue the rock mass - under repeated explosions- started to deteriorate and to disintegrates. It worth mentioning that the numerical model example represents brittle rocks and over-consolidated deposits may behave in the same way especially in the present of slickensides.

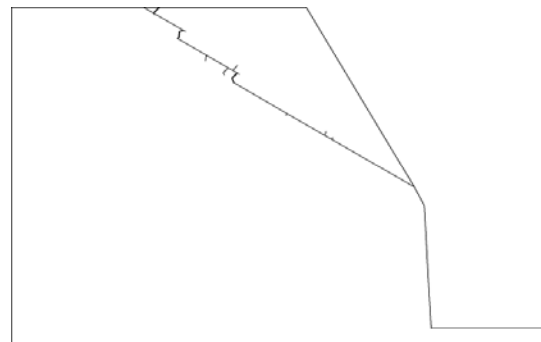


Fig. 9 The UDEC-DM, coalescence between joints

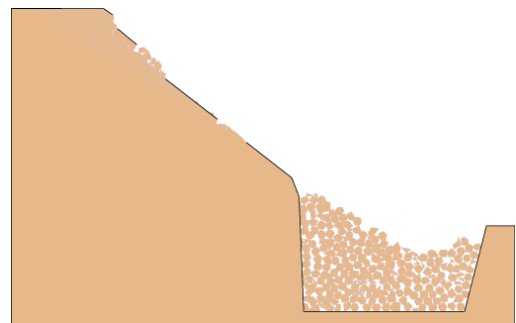


Fig.10: Failure of the rock slope as a result of 10 cycles of 0.1 g dynamic loading acceleration.

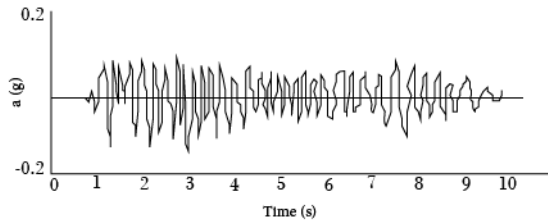


Fig.11: Surface acceleration of one cycle of 0.1 g

5. ACKNOWLEDGEMENTS

The author would like to acknowledge the financial contribution of Abu Dhabi University and the ORSP, Award number 19300215.

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