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CORRELATION OF RISK ANALYSIS METHOD RESULTS WITH NUMERICAL AND LIMIT EQUILIBRIUM METHODS IN OVERALL SLOPE STABILITY ANALYSIS OF SOUTHERN WALL OF CHADORMALU IRON OPEN PIT MINE-IRAN

KORELACJA WYNIKÓW ANALIZY RYZYKA Z WYNIKAMI OBLICZEŃ NUMERYCZNYCH ORAZ WYNIKAMI UZYSKANYMI W OPARCIU O METODĘ RÓWNOWAGI GRANICZNEJ ZASTOSOWANYCH DO BADANIA STABILNOŚCI WYROBISKA POCHYŁEGO NA POŁUDNIOWEJ ŚCIANIE ODKRYWKOWEJ KOPALNI RUD ŻELAZA W CHADORMALU W IRANIE

Slope stability analysis is one of the most important factors in designing open pit mines. Therefore an optimal slope design that supports both aspects of economy and safety is very significant. There are many different methods in slope stability analysis including empirical, limit equilibrium, block theory, numerical, and probabilistic methods. In this study, to analyze the overall slope stability of southern wall of Chadormalu iron open pit mine three numerical, limit equilibrium and probabilistic methods have been used. Software and methods that is used for analytical investigation in this study are FLAC software for numerical analysis, SLIDE software and circuit failure chart for limit equilibrium analysis and qualitative fault tree and semi-quantitative risk matrix for probabilistic analysis. The results of all above mentioned methods, was a circular failure occurrence in Metasomatite rock zone between 1405 to 1525 m levels. The main factors of failure occurrence in this range were heavily jointing and existing of faults. Safety factors resulted from numerical method; Circular chart method and SLIDE software are 1.16, 1.25 and 1.27 respectively. Regarding instability and safety factors in Metasomatite rock zone, in order to stabilize the given zone, some considerations such as bench angle and height reduction should be planned. In results of risk matrix method this zone was mentioned too as a high risk zone that numerical and limit equilibrium methods confirmed this.

Keywords: slope stability; chadormalu southern wall; FLAC; SLIDE software; risk

Badanie stabilności wyrobiska pochyłego jest jednym z najważniejszych czynników uwzględnianych przy projektowaniu kopalni odkrywkowych. Optymalne zaprojektowanie wyrobiska pochyłego z uwzględnieniem czynników ekonomicznych oraz bezpieczeństwa jest niezmiernie ważne. Istnieje wiele metod badania stabilności wyrobiska pochyłego, między innymi metody empiryczne, metoda równowagi granicznej, teoria bloków oraz metody numeryczne i probabilistyczne. W pracy tej omówiono zastosowanie trzech spośród tych metod: metody numerycznej, równowagi granicznej oraz metody probabilistycznej,

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do analizy stabilności wyrobiska pochyłego na południowej ścianie kopalni rud żelaza w Chadormalu w Iranie. Oprogramowanie wykorzystane w badaniach analitycznych to pakiet FLAK przy metodzie numerycznej, oprogramowanie SLIDE oraz wykresy kołowe przy metodzie równowagi granicznej oraz jakościowe drzewa określające występowanie uskoków i pół-jakościowe macierze ryzyka przy metodzie probabilistycznej. Wyniki uzyskane w oparciu o trzy wyżej wymienione metody wykazały wystąpienie zawalenia się skał metasomatycznych na poziomie od 1405 do 1525 m. Głównymi czynnikami warunkującymi zawalenie się skał w tym regionie była obecność licznych pęknięć oraz uskoków. Wskaźniki bezpieczeństwa uzyskane przy pomocy metod numerycznych, wykresu kołowego oraz oprogramowanie SLIDE wyniosły kolejno: 1.16, 1.25, 1.27. W odniesieniu do niestabilności w rejonie skał metasomatycznych, aby uczynić tę strefę bardziej stabilną należy uwzględnić takie czynniki jak kąt nachylenia ławy oraz obniżenie wysokości. Analiza przeprowadzona w oparciu o macierze ryzyka wykazała, że strefa ta jest strefą wysokiego ryzyka, zaś wyniki analizy numerycznej oraz wyników uzyskanych przy pomocy metody równowagi granicznej w pełni ten wniosek potwierdziły.

Słowa kluczowe: stabilność wyrobiska pochyłego, ściana południowa kopalni odkrywkowej, FLAC, oprogramowanie SLIDE, ryzyko

1. Introduction

Nowadays, most of mining resources are extracting by open pit method. Slope stability is one of the most important factors in economy and safety of open pit mines. Chadormalu iron open pit mine placed in 120 kilometer western of Yazd in Iran and 65 kilometer North West of Choghart Iron ore mine and geographical characteristics 32 degree and 17 minutes northern latitude and 55 degree and 30 minutes western longitude (Figure 1). This ore has more than 200 million tons of extractable resource and 400 million tons of explored resource (350 million tons in northern anomaly and 50 million tons in southern anomaly) (Itook, 2006).

Fig. 1. Geographical location of Chadormalu iron open pit mine (Attaei & Bodaghabadi, 2008)

The first phase of stability studies in Chadormalu iron open pit mine has done by SRK (English Company) and Kani Kavan Shargh engineering co. in 2008. These studies conducted due to preliminary recognition of mine geological condition and characteristic, collecting required data and complementing and determining regions of high potential failure. In this level of studies, overall angle of walls is estimated and geotechnical studies for the next phase are offered (Kani Kavan Shargh, 2008)

Due to the heavily joints and existing faults and low strength of rock mass, the southern wall of Chadormalu iron open pit mine is the most critical wall of this mine. Therefore this wall was selected to be analyzed. This selected geotechnical section of this wall is the most critical section (Figure 2.). Because of heavily joints, this rock mass zone assumed as a continuous zone. Thus FLAC software was used for numerical analysis of this section. The other software to analyze the slope stability is SLIDE. This software uses limit equilibrium method to analyze the slope stability. The analysis performed with some different hypothesis and methods such as modified Bishops, modified Janbu and Fellenius methods and etc. (Rocscience, 2010). Finally, risk assessment methods used as probabilistic methods. Risk analysis and assessment could be used in design, implementation and operation stages of a system (Haimes, 2009). In this study we have used fault tree qualitative method and risk matrix semi-quantitative method.

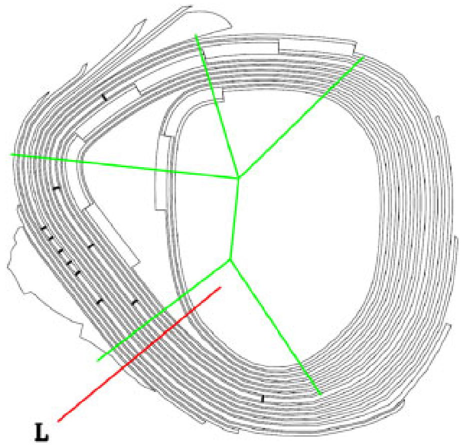


Fig. 2. Geotechnical sections in Chadormalu iron open pit mine and studied cross-section in southern wall (Kani Kavan, 2008)

2. Stability analysis by using numerical method

Several numerical softwares have been developed for rock slope analysis. Few types of software are able to model a rock mass using Mohr-Coulomb and Hook–Brown criterion. FLAC software is one of them. In this method the analyzed zone should be assumed as continues media. But it must be noted that continues modeling methods are appropriate for slope analysis consisted of dense, integrated and weak rocks, soil-like rocks or heavily jointed rocks. Nowadays, finite element method and finite difference method are used in rock slope analysis (Itasca, 2004).

Regarding to intense fragmentation of rock mass in southern wall of Chadormalu iron open pit mine and due to the fact that these continuous modeling are using where rock mass is very fragmented and has a lot of joints, so in this study we apply continuous modeling and finite difference methods.

Table 1 presents the geomechanical parameters of rock mass in southern wall of Chadormalu iron open pit mine.

TABLE 1

Geomechanical parameters of rock mass in southern wall of Chadormalu iron open pit mine

Lithology	Deformation modulus (MPa)	Specific Weight (kN/m^3)	Cohesion (kPa)	Friction Angel (Deg)	Tension Strength (MPa)
Granite	1454	24	203	56	0.019
Iron ore	2122	37	321	57	0.028
Faulted Albitite	900	25	166	52	0.016
Metasomatite	466	27	90	40	0.003

Length and width of model is two and half times of final bench height, respectively (Duncan & Christopher, 2007). In order to meshing the presented model the square-like meshes in dimension 1.5×1.5 have been used. This region of mine is dry and no ground water has been observed. Figures 3 and 4 show the results of FLAC modeling. The results indicate probability of a circular failure between 1405 to 1525 m levels. In this method the calculated results of safety factor is equal to 1.16.

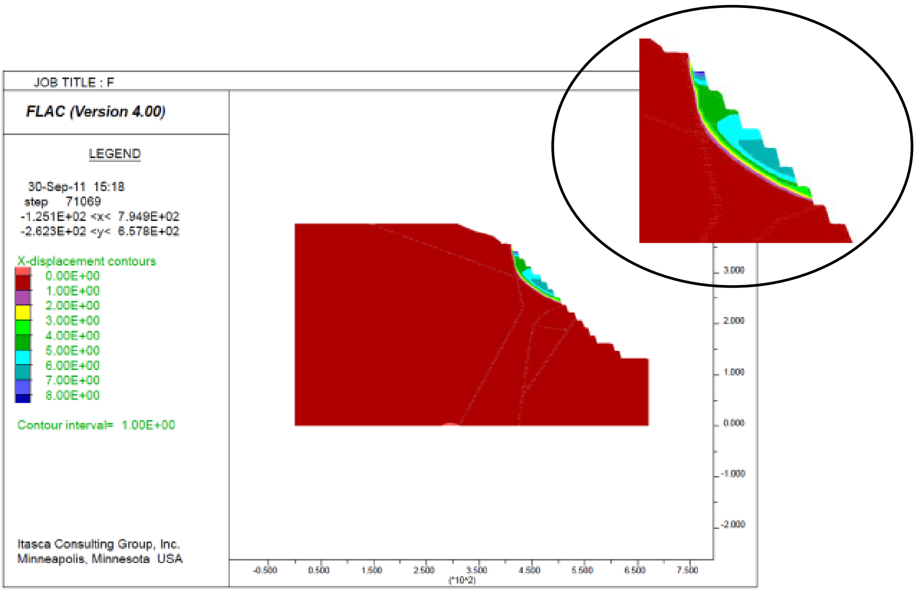


Fig. 3. X-displacement contours in studied section by FLAC software

3. Stability analysis using limit equilibrium method

In this part of the study it has been tried to validate, the model and result analysis obtained from numerical analysis, using limit equilibrium method. In order to use limit equilibrium method, SLIDE software and circular failure chart have been applied. This analysis conducted

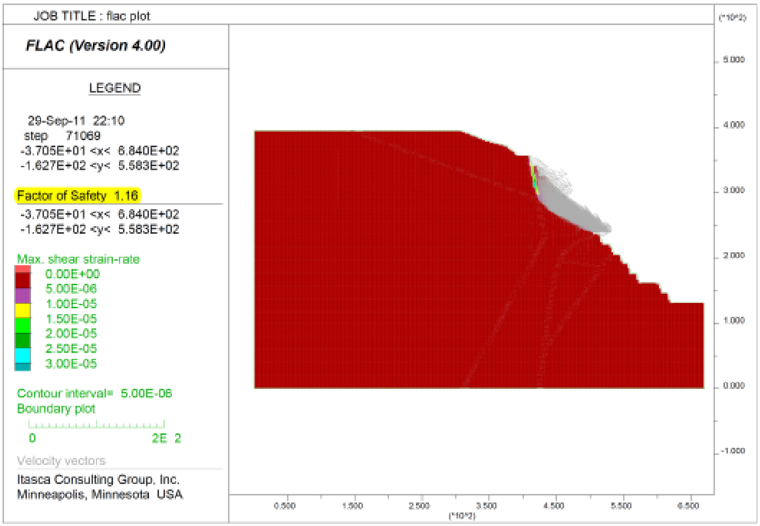


Fig. 4. Calculated safety factor by FLAC software

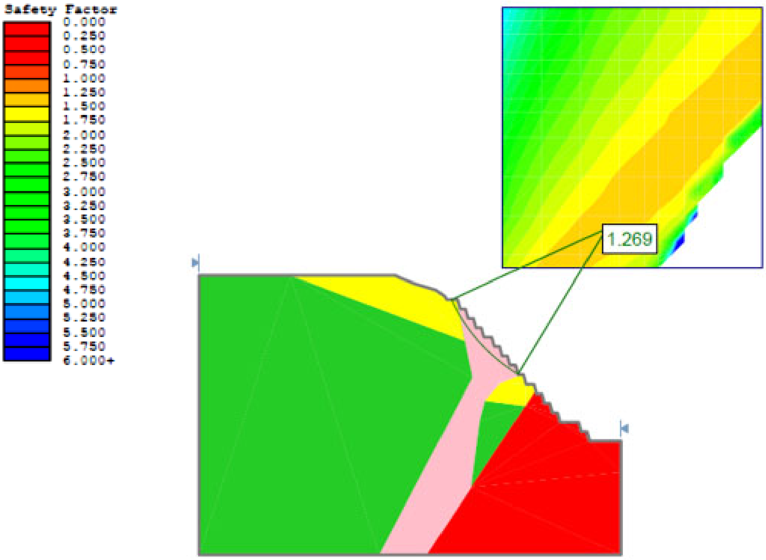


Fig. 5. Safety factor calculated by SLIDE software

with different hypothesis of modified methods such as Bishop, Janbu and Fellenius (Rocscience, 2010). In this study, modified Janbu and Bishops methods have been used in order to modeling and calculating safety factors. Figure 5 shows safety factor resulted from SLIDE software. As we can see in Figure 5, obtained safety factor equals 1.27.

By the help of Figure 6, safety factor could also be estimated. Because of the dryness of this region, this circular failure chart has been applied. Calculated safety factor obtained from circular failure chart equals 1.25.

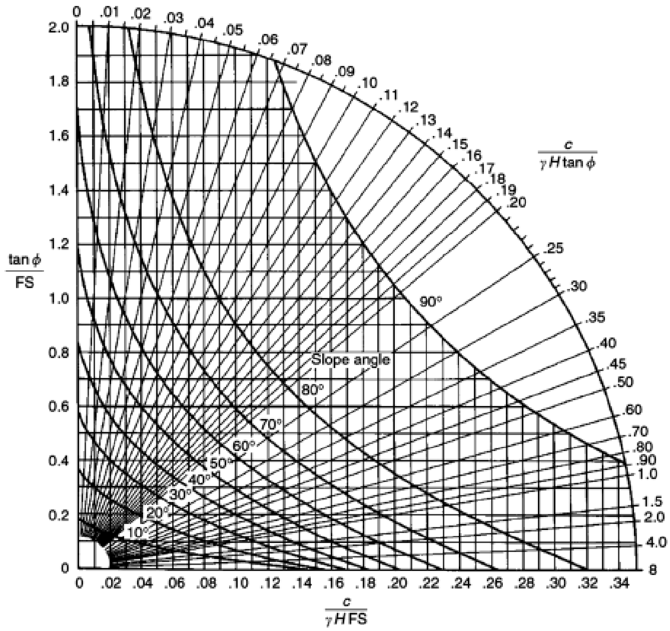


Fig. 6. Circular failure chart [8]

4. Risk assessment

Assessment could be considered as a mechanism to decrease the costs by utilizing logical methods in applying natural and human resources (Shariat & Monnavari, 1996). Final purpose of the risk assessment is, to find the best possible methods in contact with evaluated risks, which defined as risk management term. Risk management is a systematic process in identifying, analyzing and responds to the project's risks (Padash & Jozi, 2007).

Risk management includes documentation process of final decision making, recognition and application of criteria to reach into an acceptable risk level (www.ieir-riskmgt.Persianblog.ir). In definition of risk term it could be defined as "a derivation in possible events in future" (Setorg et al., 2005). Risk term also defined as "potential events which will cause future loss" (Eghtesad Novin Bank, 2008). Finally risk management term could be defined as an optimize method which an organization or investor utilizes it to encounter the risks (Hashemi & Rouzbahan, 2008).

Risk assessment divides into two major parts: qualitative and quantitative. Structured qualitative assessment has an intellectual state and happens through personal judgments (Padash & Jozi, 2007). PHA, WHAT IF, HAZOP, matrix and fault tree could be implied as qualitative methods. Two latter methods (matrix and fault tree) have been used in this study. Although the risk matrix method have been used in semi- quantitative form. Numbers have used in order to comparison and classification of risk.

We use multi-criteria decision making method in order to convert qualitative extant to quantitative. Multi-objective decision making methods especially ideal decision-making models widely apply in risk improvement studies (Gharachorlou, 2005).

Risk assessment could be used for analyzing various activities in mining engineering. For example the published researches by Duzgun (2005), Terbrugge et al. (2006), Atkins et al. (2008), Wegrzyn (2008), Ghasemi et al. (2010), Sulivan (2005) and Contreras et al. (2005) in recent years could be mentioned.

In this research, risk analysis technique has been used for slope stability analysis in an open pit mine.

4.1. Fault tree analyses (FTA)

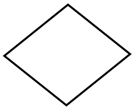
Fault tree analysis was developed in 1961 and considered as a comparative method to analyze a group of system events. In this method, to represent the effects of a hazard status, the relations between occurrences of system events will create by logical symbols (Rezazadeh, 2007). In fault tree method, at first an event has been considered, then some branches derived downward which lists extant faults in the system that relates to main event. By this method, an expert objectively lists all events in parallel, following or mixed by both cases, which has been caused by main event occurrence (Lama, 1987).

Fault tree method has four advantages in system analysis tools (Rezazadeh, 2007):

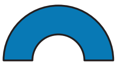
1 – Leads analyzer directly to related events to hazards and occurrence.
2 – Decreasing risk of system by indication of system operation.
3 – Helps to select the options in qualitative and quantitative analysis.
4 – Helps the analyzer in reaching organizational standard.

Signs and logic of drawn fault tree in the study will be as follows:

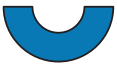
: Mediator event – a fault event occurred due to one or several previous factors which effects during logical signs.



: Undeveloped event – due to lack of information or more analysis requirement hasn't developed more.



: *And* – indicate that all input faults to *and* part must happen until output faults occurred. In algebra law it could be subscribed.



: *Or* – it is against *and*, each of input events which occurred could cause fault events.

Fault tree is drawn due to an event occurrence. In drawing fault tree it has been tried to list all important factors which could cause instability of each slope. In order to have an analysis of southern wall of Chadormalu iron open pit mine, before an accident occurrence, we have explained some guidance colors which indicate amount of every factor effects in mine and given wall (Figure 7).

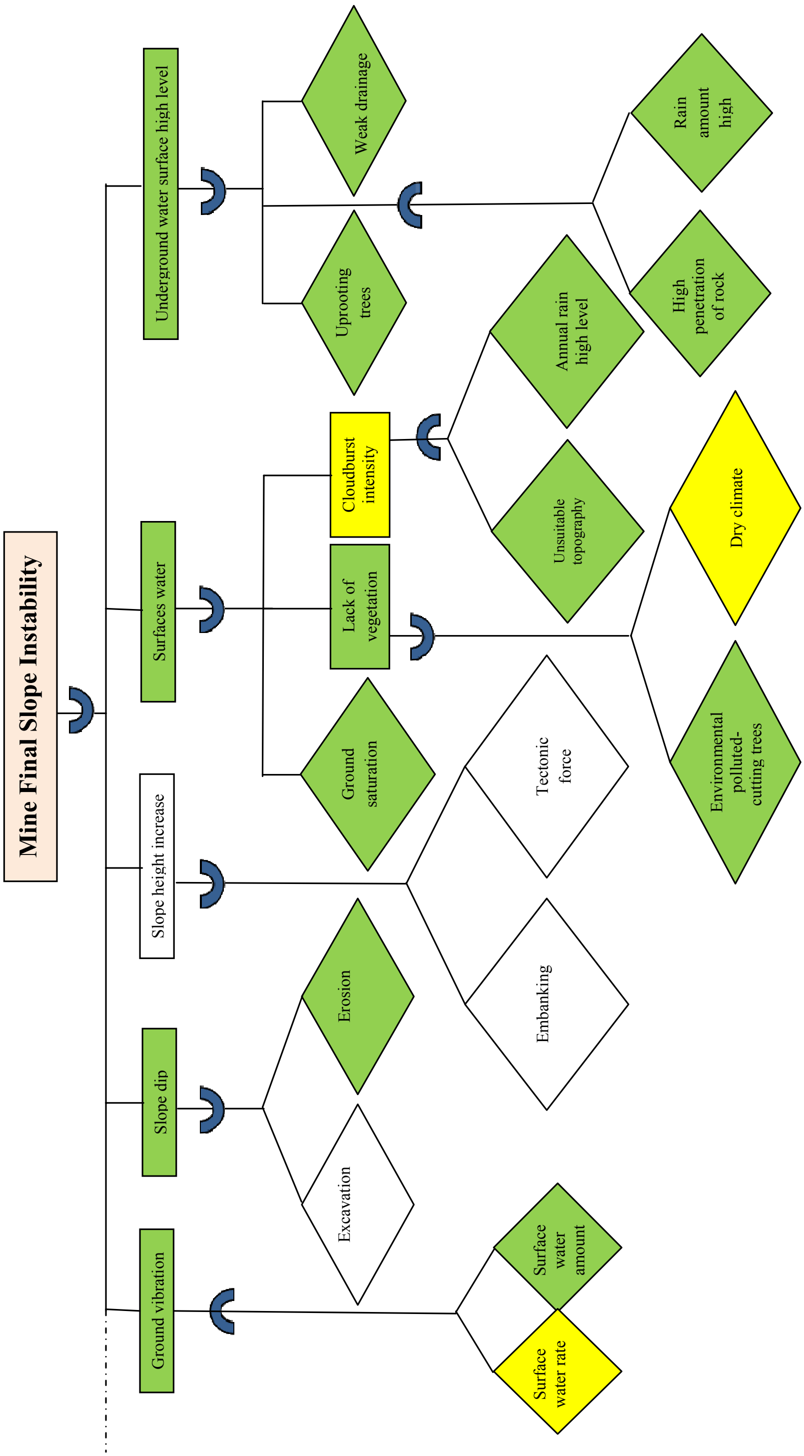
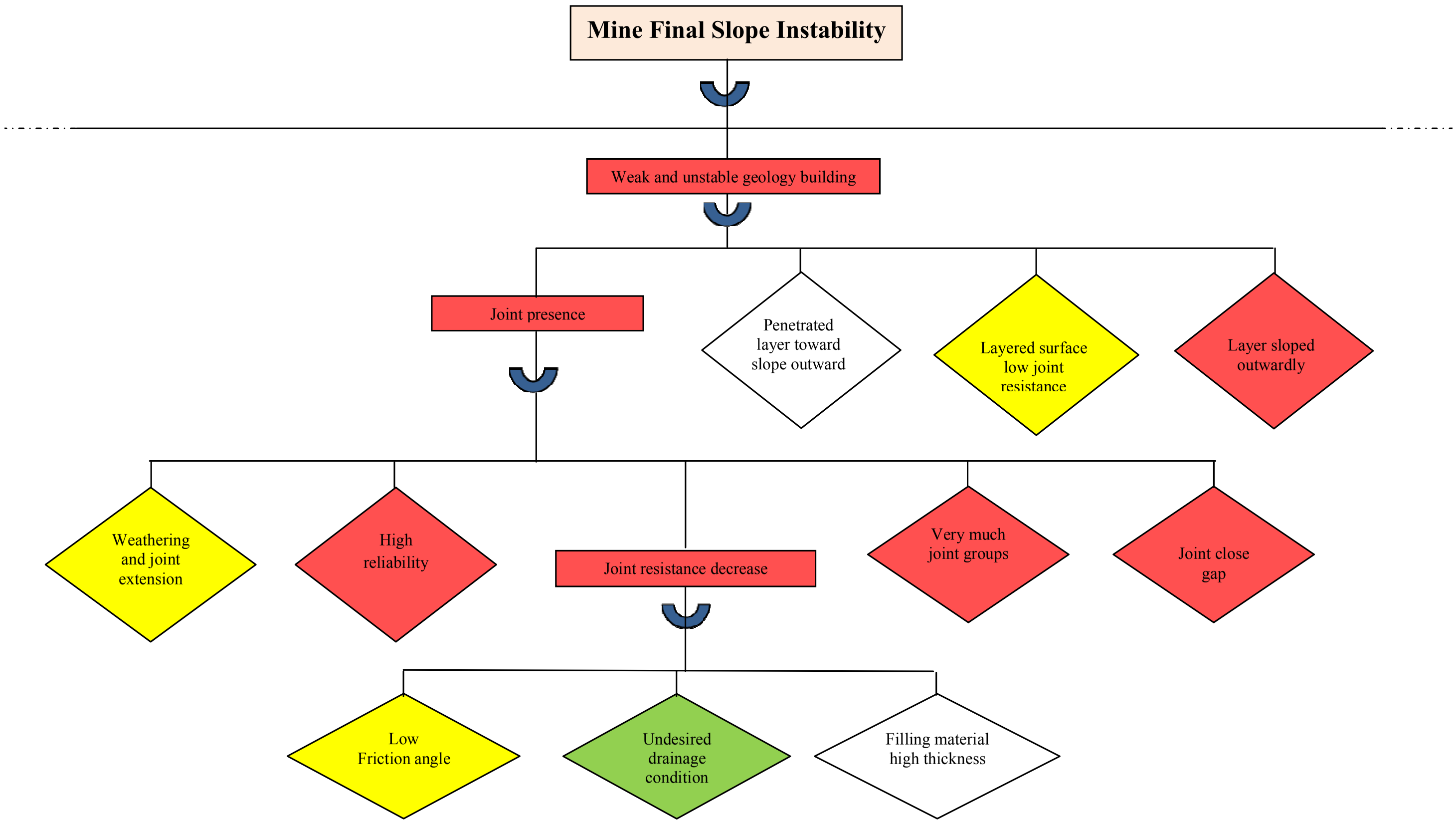
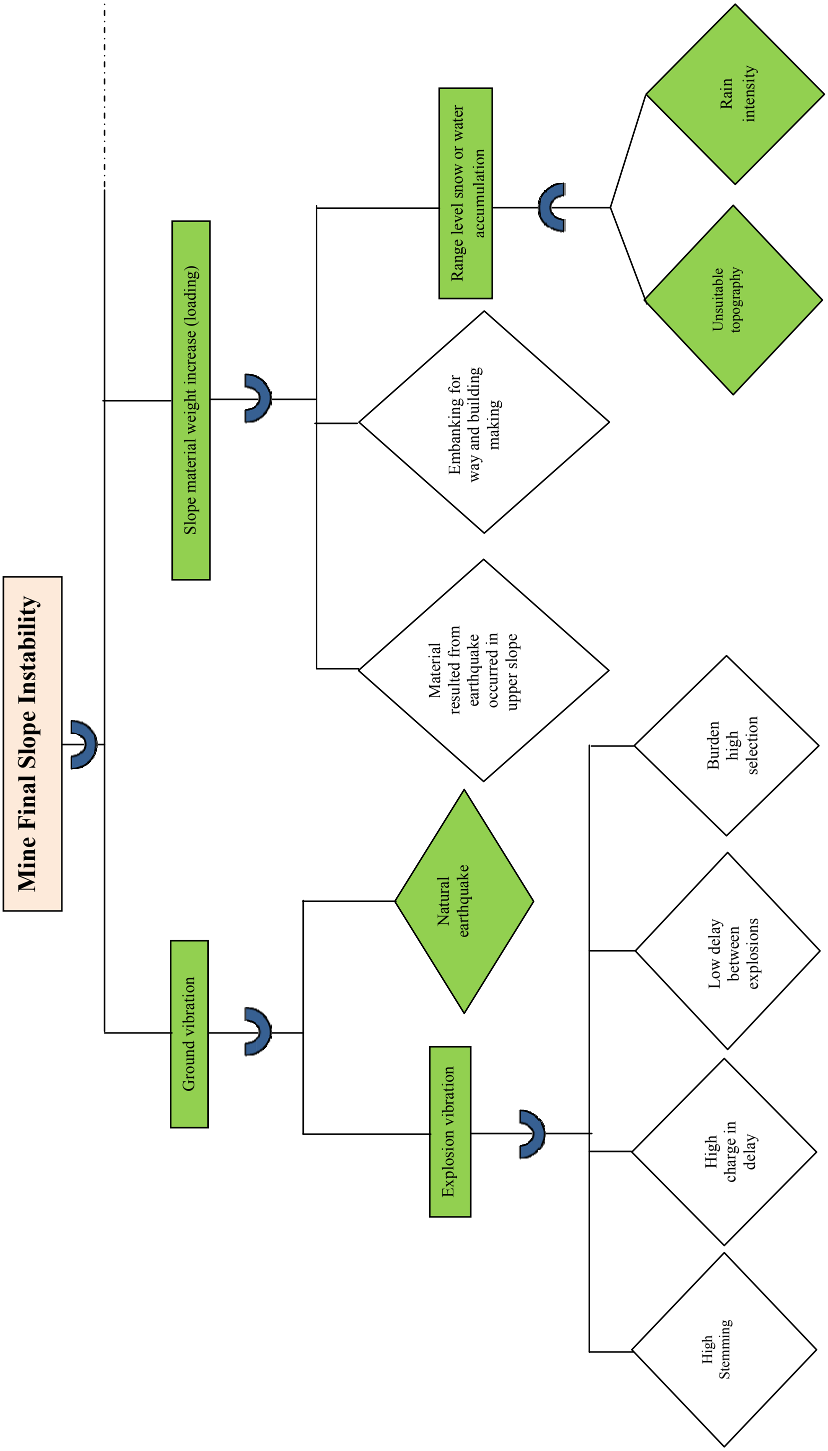


Fig. 7. Slope Instability Fault trees



Continue of Fig. 7. Slope Instability Fault trees



Continue of Fig. 7. Slope Instability Fault trees

White color: means that there is no available information about effects or lack of effects.
Green color: it has very low effects.
Yellow color: it has middle effects
Red color: it is very effective.

As its represented, joint existence is one the most important and main factors which threatened the slope stability. Joint existence plays an important role in deformation and shear behavior of rock mass. Jointed rock mass strength is significantly smaller than intact rock strength (Goodman, 1970). Many studies have conducted in different resources about any mentioned factors which caused slope instability. For example, various studies about joints have proved that the more filling material thickness the less joint strengths (Kaji, 1974; Eurenius & Fagrestrom, 1969). Drainage factor is another condition which controls filled joints behavior. Drained shear strength is always bigger than undrained shear strength (Memarian, 2008). Friction angle directly affect joint strength. Increasing friction angle will cause joint shear strength increase. Joints existence in rock mass, have major effects on deformation and shear strength of rock mass. In hard rocks which have joints with relatively low distance, (for example one meter) rock mass mechanical behavior is more depends on joints behavior rather than intact rock behavior (Rezazadeh, 2007).

Regarding colors allocated to fault tree and above mentioned issues following logical results could be interpreted: Rock strengths of southern wall of Chadormalu iron open pit mine is relatively suitable which could be seen Table 1. On the other hand, regarding very unfavorable joint condition and density of joint it could concluded that in this wall, mechanical behavior of rock mass is more depended to joints behavior rather than intact rock behavior.

4.2. Risk matrix

Risk matrix analysis method is a simple method for evaluation and management of risks. This method is basically qualitative but it could be stated quantitatively. In this method, risk index equals occurrence of hazardous event probability multiplied by consequence intensity. In order to evaluate, slope zone it has been divided into four parts (Figure 8). These four parts

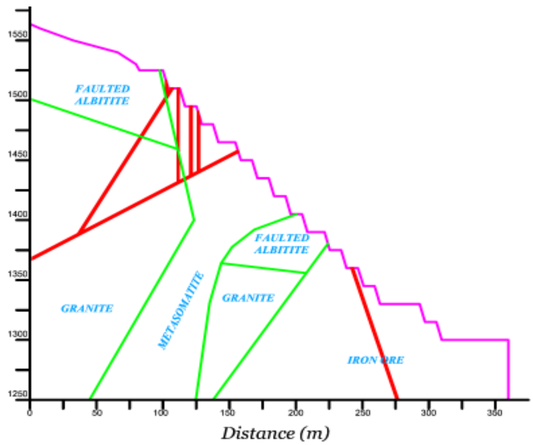


Fig. 8. Geological cross-section of Chadormalu iron open pit mine southern wall

include: Iron ore faulted, Albitite-Granite (lower), Metasomatite, faulted Albitite-Granite (upper). Regarding the existent of geomechanical parameters in every section and experts opinion, occurrence probability and consequences have been studied.

In order to asses slope instability occurrence probability and consequences intensity rate, exist many different tables in various resources which is approximately similar (Lama, 1987; Kumamoto, 2007; Guglielmetti et al., 2007). Following tables has been arranged, regarding the risk definition, based on probability of an event occurrence (Table 2) in its effects (Table 3). This method has been used for ranking and risk management more than reliability indication (Tables 4 and 5).

In previous section, all factors which could cause mine slope instability, investigated in the form of fault tree. Including factors which studied in rock strength are: joints, faults, and elasticity modulus and cohesion and friction angle. Regarding mentioned issues and expert's opinions, risk rate classified as Table 5.

TABLE 2

Scores related to occurrence probability

Occurrence probability	Score	Description
Impossible	1	Occurrence is not possible or occurred by very low probability (occurrence probability is very low).
Unlikely	1.01-2	Including events which occurred by low probability (occurrence probability is low).
A little probable	2.01-3	Including events which occurred sometimes (occurrence probability is average).
Likely	3.01-4	Including events which probably happen (occurrence probability is high).
Frequently	4.01-5	Including events which happened frequently (very high probability).

TABLE 3

Scores related to occurrence intensity

Occurrence Intensity	Score	Description
Trivial	1	No problem for the system or labor
Medium	2	Event will cause damages or trivial delay
Serious	3	Event will cause damage and injury which is compensated. Maybe delays even for one week
Critical	4	Event will cause injury or considerable damage which is compensated. Maybe delays even for 2 weeks
Disastrous	5	Event will cause a non-compensable damages that are very serious

TABLE 4

Scores related to different risk level

Risk	Risk Index	Description
Low	2.01-5	Risk without any decrease is acceptable. There is need no reaction or record maintenance.
Medium	5.01-9	Risk is relatively acceptable. Must be tried to decrease the risk but cost must be limited and investigated accurately.
High	9.01-15	Risk placed on an acceptable border. To eliminate or reduction of risks considerable resource allocation is needed.
Very high	15.01-25	Risk is not acceptable. Until it is not decreased the operation must not be started. If by using all resources, Risk doesn't reduce, the work must stop.

TABLE 5

Risk Index

Unit	Occurrence probability	Consequence intensity	Risk index	Risk level
Iron ore	1.33	3	3.99	Low
FA-Gr lower	1.83	2	3.66	Low
Metasomatite	3.83	4	15.32	Very high
FA-Gr Upper	2.16	3	6.48	Medium

5. Conclusion

Inasmuch as Chadormalu iron open pit mine complexity (geologically and geo structurally) and also numerous problems which existed in southern wall, much attention has been paid to its wall stability and analysis. Among this, the section *L* which assumed as a critical section has analyzed. Regarding that, in this study three methods, numerical, limit equilibrium and risk analysis have been used, though the correlation of results could be of much importance.

Numerical analysis using FLAC software represented that the wall placed in the zone of Metasomatite rock, will have a circular failure. This zone has eight benches which placed between 1405 to 1525 m levels. Safety factor obtained in this method is 1.16. Stability in the other zones of slope is relatively acceptable. Regarding the acceptable safety factor which is 1.5 for mine overall slopes, stabilizing of the given wall is recommended. Methods such as height and slope scaling down could be effective.

In order to analyze the slope, using limit equilibrium method, SLIDE software and also existing graphs have been used. Results of SLIDE software was in accordance with numerical analysis results. Circular failures will occur in Metasomatite rock zone. Safety factor obtained from SLIDE method is 1.27 and in diagram method is 1.25.

Risk analysis performed in two forms of fault tree and semi-quantitative risk matrix. Fault tree is a logical trend which may represent instability occurrence cause in mine slopes. In this study it has been tried to investigate effects of any above factors probability of the wall instability by the help of expert's opinion. As it's clear, joints and faults are the most important factors of instability in walls which have been studied. Other factors such as surface water and ground water condition are of less importance. Finally, it has been tried to analyze the wall situation using semi – quantitative risk matrix method. Result of this matrix also indicates very high risk in the Metasomatite zone.

Since, one of the important parts of extraction operation in open pit mines is investigating the stable and instable zones and managing the risks, related to instable slopes therefore, the main part of geotechnical slope management is permanently data collecting program and geotechnical data measurement. Therefore, continuous slope monitoring and instrumentation in order to identifying instability signs is necessary.

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