Software Design for Direct Determination of the Required Support system for Prevention of Planar Failure; Case Study: Lead and Zinc Mine of Angoran, Zanjan

Mohammad Darbor, Hossein Jalalifar, Parviz Moarefvand

Abstract: Considerable attention must be paid to protection and maintenance of engineering structures such as dams, due to their vital role in provision of the necessary water for drinking and agriculture, and mines for the supply of industrial materials. The various software designed for the study of static stability of such structures, up to now, are not featured to determine the required support for prevention of planar failure. In such software, the necessary reinforcement to avoid slope failure is selected through trial and error, and examination of different supports. Herein, the provided software package, entitled “Slope Stability Analysis” software, is the first package capable of direct determination of the necessary support for unstable zones, using the presented equations. To make verifications, the studies on the northern slope of Angoran mine showed that the values obtained from Slope Stability Analysis software are in very good agreement with numerical results of UDEC and 3DEC software.

Keywords: Planar fracture; Angoran mine, 3DEC, anchor.

INTRODUCTION

Protection and maintenance of engineering structures are of considerable significance; herein, dams, due to their vital role in provision of the necessary water for drinking and agriculture, and mines, owing to their supply of industrial materials, demand special care. The main goal for conducting stabilization on the dams is prevention from sliding soil and rock into the reservoir which affects the reservoir capacity. The main objective behind the stabilization of surface and underground mines is avoidance from slippage of soil and rock which leads to the undesirable mixture of minerals and waste materials and consequently, the loss of the initial extraction plan; moreover, prevention from possible injuries to the people and facilities is another purpose supporting the stabilization of mines (Darbor, 2009).

Determination of a trench slope stability is possible through different methods. Herein, limit equilibrium methods can be applied to reach to a fast assessment of the stability condition of the zone. The leading advantages of these methods are their simplicity in application and the substantial experience gained through their long history, such that the reliability of limit equilibrium methods has increased throughout time (Chen, 2007; Radoslaw, 2010; Wyllie and Mah, 2004; Yu, et al., 1998).

Today, there are miscellaneous slope stability software worldwide, exploiting limit equilibrium methods. However, none of them are featured to determine the demanded support for unstable regions tending to slide, directly. In other words, determination of the necessary support in such software is indirect and recursive.

Slope Stability Analysis software package, which is coded using Delphi7 programming language, allows for obtaining a quick estimate about the static stability of the region against failure, particularly planar failure. Inclusion of all parameters contributing to planar failure such as sliding plane roughness, the underground water condition, and location and condition of tension cracks is another features of the designed package. This software contains the quality for precise determination of weight, area, normal and shear stresses exerted on the failure plane and exact properties of the tension crack, in planar failure analysis. Making use of the
software results, it is possible to focus on the critical points and obtain more accurate results for them through
numerical analyses and study of their behavior.

On the other hand, Slope Stability Analysis software package, taking into account all geometric,
geomechanical, hydrological and dynamic factors along with the present anchor properties and the required
safety factor, is capable of direct determination of the demanded support to prevent planar failure in unstable
regions.

In this work, in order to conduct a case study and the corresponding verifications, the northern slope of
the lead and zinc mine of Angoran, Zanjan, before the slide of October 2006, is studied. The results showed
that the values obtained from Slope Stability Analysis software are in very good agreement with those of
numerical analyses achieved from UDEC and 3DEC software.

Previous Studies:
The slope stability of rocks is an important problem in geotechnical engineering. This holds for both the
design and construction stages Gurocak et al., (2008). At the global level, slope stability is controlled by both
the rock mass properties and large geological features (Grenon and Hadjigeorgiou, 2010). Currently, a number
of methods are being used for the assessment of slope stability. Kinematical, limit equilibrium and numerical
analyses are generally preferred for the evaluation of rock. Kinematical analysis refers to the motion of bodies
without reference to the forces that cause them to move. Equilibrium analyses consider the shear strength along
the failure surface, the effects of pore water pressure and the influence of external forces such as reinforcing
elements or seismic accelerations. On the other hand, numerical analyses such as finite element and distinct
element methods are performed to confirm results occurred from kinematical and equilibrium analysis Gurocak

A kinematic stability analysis requires further information on the structural regime. This is possible if there
are quality data from oriented drill cores. The use of oriented drill core data permits the construction of
stereonets for different areas of the site. This can be used, in connection with the lithology, to identify regions
of similar structural characteristics. This information can then be used for slope stability analysis (Grenon and
Hadjigeorgiou, 2010).

The stability of selected slopes in the different domains is determined for potential instability associated
with planar, wedge and toppling failure modes. The usual design procedure is to use kinematic analysis to
identify potentially unstable blocks. the designer’s ability in the recognition of the potential risks during initial
phases of the project is foremost. However, while analysis of the stereonet gives a good indication of stability
conditions, it does not account for external forces such as water pressures or reinforcement comprising
tensioned rock bolts, which can have a significant effect on stability Wyllie and Mah, (2004). However, if the
stereonet results reveal the potential risk of planar failure in the slope, after verification of the slide possibility
through determination of the safety factor using numerical and limit equilibrium methods, the possible
stabilization techniques must be applied, considering the discontinuity patterns besides hydraulic and dynamic
situations of the region. In this case, limit equilibrium analysis can be exploited for a wide range of situations,
with the shortest time, in order to make subsequent numerical analyses with special focus on unstable zones
(Chen, 2007; Yu et al., 1998).

Use of anchor in Stabilization of Slopes:
Among all stabilization methods, flattening the slope and building safety bench along with surface
drainage are often the first methods that would to be tried. Among other methods, retaining structures can be
used to improve slope stability by applying stabilizing forces to slopes. There structures reducing the shear
stresses on potential slip surfaces. In this case, prestressed anchors and anchors walls have the advantage that
they do not require slope movement before they impose restraining forces (Abramson et al., 2002; Darbor,
2009; Duncan and Wright, 2005) (Fig.1).

In order to find the net tensile force (T) of the required anchors in each slope, the following equation
(obtained from planar failure analysis relations) could be used (Table 1):

\[ U = F [W (a \sin \psi_p + a \cos \psi_p) + F_y \cos \psi_p] + W (a \sin \psi_p - \cos \psi_p) + F_y + F_y \cdot \sin \psi_p \tan \varphi - C \cdot A \]  

(1)

\[ R = F \cos (\psi_p + \Delta) + \sin (\psi_p + \Delta) \tan \varphi \]  

(2)

\[ T = \frac{U}{R} \]  

(3)
Taking advantages of the above equations and other relations presented in limit equilibrium method, Slope Stability Analysis software is designed to conduct planar failure analysis and determine the required support characteristics for unstable slopes directly. In the following sections, different features of the software are demonstrated along with a case study.

### Lead and Zinc Mine of Angoran, Zanjan and Instability Occurrence in the Northern Slope:

Lead and zinc mine of Angoran, an open pit mine, is located in the territory of Zanjan province, in the western south of Zanjan city, with the average altitude of 2950 meters above the sea level (Fig.2). Having the production capacity of 800 thousand tons of minerals per year and the reservoir supply of over 12 million tons, with the average grade of 25-30 percent for zinc and 3-6 percent for lead, Angoran mine is counted as one of the largest mines throughout Iran. The final dip of the mine is 45 degrees in waste rock and 35 degrees in minerals. The height of the benches is 10 meters (except for the highest horizon which is 15 meters high), with the dip of 74 degrees in waste and 60 degrees in minerals Ghazizadeh, (2008).

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**Table 1**: Definition of the symbols used in the above equations.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fu</td>
<td>in-block water force</td>
<td>F</td>
<td>safety factor against slide</td>
</tr>
<tr>
<td>(\Phi)</td>
<td>friction angle</td>
<td>W</td>
<td>weight of zone inclined to failure</td>
</tr>
<tr>
<td>C</td>
<td>cohesion</td>
<td>(\gamma_f)</td>
<td>failure plane slope</td>
</tr>
<tr>
<td>A</td>
<td>area of failure plane base</td>
<td>A</td>
<td>main gravitational acceleration</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>installation angle of anchor</td>
<td>(F_v)</td>
<td>in-crack water force</td>
</tr>
</tbody>
</table>

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**Fig. 2**: The location map of the study area.
Orebody Geology:

Regarding the mineral deposits, only two main schistose metamorphic and semi-metamorphic limestone masses are considerable. The lower division of the mineral deposit waistline consists of a metamorphic schistose with an approximate thickness of 1000 meters, named “Angoran Schist”. The main extension of this mass is presented along the western section of the mine, and in the east, there exists the semi-metamorphic limestone. The upper division of the mineral deposit waistline includes a semi-metamorphic crystalline gray-colored limestone with no fossil. The thickness of the rock mass is almost 200 meters and contains major and minor fractures and pores. In most regions, these fractures are filled with calcite and aragonite.

To determine the structural properties of the northern slope of the mine, the investigation team studied the fractures through a couple of scan lines in the zone, as presented in Fig.3-a. Through an extensive site investigations, two main joint sets could be distinguished (Fig.3-b, Table 2).

![Image](a.png)

![Image](b.png)

Table 2: Joint set characteristics on the northern side of Angoran mine.

<table>
<thead>
<tr>
<th>Spacing (cm)</th>
<th>Dip</th>
<th>Dip direction</th>
<th>Discontinuities</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>75</td>
<td>235</td>
<td>Joint 1</td>
</tr>
<tr>
<td>500</td>
<td>80</td>
<td>150</td>
<td>Joint 2</td>
</tr>
</tbody>
</table>

Owing to the concentration of the activities at the northern slope of the pit and the position of the tension cracks behind it, section I-J is selected for modeling, among 19 geological sections (Fig.4).

4-2. Selection of Analysis Method and Procedure:

Two dimensional (2D) analyses are employed for modeling. It is due to the fact that considering the present geological sections, the main geological structures and faults in the region intersect in small angles. On the other hand, a two-dimensional (2D) (plane strain) analysis also can be regarded as conservative in cases where 3D failure should be expected, and it is often preferred in design (Cornforth 2005).

Mohr-Coulomb elasto-plastic model has been used in the numerical analysis of the northern slope of the mine. Table 3 presents the mechanical properties of the limestone, schist and clay layers along with I-J section faults. Iso-volumetric strain contours showed that the formation and extension of the initial tension crack is similar to the position of the actual one (Fig.5-a). Drawing the displacement vectors as shown in Fig.5-b, the failure plane of the geological section of I-J is determined.

Table 3: Possible ranges for the mechanical parameters of rock mass of the northern slope of Angoran mine [5,6].

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Descrip.</th>
<th>GSI</th>
<th>RQD</th>
<th>UCS (MPa)</th>
<th>ϕ (deg)</th>
<th>ψ (deg)</th>
<th>C (kPa)</th>
<th>σ0 (kPa)</th>
<th>Em (Mpa)</th>
<th>α</th>
</tr>
</thead>
<tbody>
<tr>
<td>semi-metamorphic limestone</td>
<td>min-max</td>
<td>42-52</td>
<td>60</td>
<td>75</td>
<td>2500</td>
<td>252-867</td>
<td>23.35-33.14</td>
<td>20-86</td>
<td>3374.63-1311.39</td>
<td>0.25</td>
</tr>
<tr>
<td>chlorite schist</td>
<td>min-max</td>
<td>50</td>
<td>51</td>
<td>30-100</td>
<td>2500</td>
<td>855-880</td>
<td>25.11-32.93</td>
<td>33-122</td>
<td>833.79-7337.39</td>
<td>0.28</td>
</tr>
<tr>
<td>Clay</td>
<td>min-max</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2100</td>
<td>40180</td>
<td>10.5-16</td>
<td>0</td>
<td>40512</td>
<td>0.3</td>
</tr>
<tr>
<td>Faults</td>
<td>min-max</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>40180</td>
<td>10.5-16</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Fig. 4: Geological section of I-J, for numerical and limit equilibrium analysis.

Fig. 5: (a) volumetric strain rate of the model, formation and extension of the tension cracks, (b) displacement vectors and failure plane of the geological section of I-J (with the maximum displacement of 18.87 meters).
In this section, the failure plane floor is the bench No. 2960 with the maximum displacement of 18.87 meters. The safety factors in different parts of section I-J are displayed in Fig. 6 Itasca Consulting Group, (2003).

![Fig. 6: Safety factors in different parts of the geological section of I-J.](image)

According to the numerical analyses results, the minimum safety factor in the bench No. 2960 (slippage plane floor) is around 2 (Fig.6).

4-3. Possibility of Planar Failure in the Bench No. 2960:
Slope Stability Analysis software was designed with the aid of Iran National Science Foundation, exploiting Delphi7 programming language, with the following aims:
1- Quick assessment of static stability situation of the region against planar failure considering the extent of surface roughness.
2- Determination of dependency on support system.
3- Direct determination of the necessary support system to prevent planar failure without reference to the common methods being used in other software (such as trial and error, and risk analysis)

In order to evaluate the probability of planar failure incident, the geometric, geological and geo-mechanical properties of different benches, utilizing Table 3, are entered to the Slope Stability Analysis software, for the most critical values (geological section of I-J). According to the obtained results, the safety factor of 2.2 is achieved for the bench No. 2960 (Figs. 7 and 8). It should be mentioned that the application of depth and percentage of tension crack water has been in accordance with precise tool measurement results.

The results obtained from Slope Stability Analysis software showed that the safety factor against planar failure is 2.08 in the bench No. 2960. Moreover, the values of effective normal stress on the failure plane and shear stress in the discontinuity surface are 113.61 and 29.97 kPa, respectively.

4-4. Verification of presented code with Numerical Simulations:
Comparison of UDEC numerical analysis results and those of S.S.A limit equilibrium analyses showed that the safety factors obtained from the two methods have a little and acceptable difference, and this fact is due to the inclusion of surface roughness factor in the limit equilibrium method. Other modifications performed, in comparison to the common softwares, are:
1- Barton equations have been employed combined with Mohr-Coulomb equations for planar failure analysis, which results in more reliable results. The common software, in the base of limit equilibrium, only consider the waviness and plane angle for the failure plane, while exploiting Barton’s criterion for the failure plane is more valid and accurate.
2- Position and depth of the tension crack in the unstable zone has been included in the planar failure analysis computations (Fig.7).

4-5. Design of the Reinforcement system Using 3DEC and S.S.A Software:
As discussed, there is a tendency for slide in the northern slope of Angoran mine according to the failure plane determined from Fig.5-b. To decide the reinforcement system, if required, and to determine the restraint model (if) needed, following steps are carried out:
1- All existing benches in the northern slope of Angoran mine are defined, along with their corresponding joint shear properties besides their spillage volume and area, which is obtained through numerical analyses (Fig.9).

Fig.7: Geometric and geo-mechanical properties of bench No. 2960, and the information about the present tension crack.

Fig.8: Extra forces present in the bench No. 2960, and the planar failure analysis output in the same bench of Angoran mine, using Slope Stability Analysis software package.

Fig. 9: Geometric features and shear properties of critical joint in section I-J.
According to the numerical analyses performed in 3DEC software, the unstable block weight is 77714 MN and the slide surface area is 18881 m² (Figs. 10 and 11) (Itasca Consulting Group, 2003; Kveldsvik et al., 2008).

**Fig. 10:** Block model of the northern mass of Angoran mine before downfall, and the beneath slide surface modeled.

**Fig. 11:** Eastern north – western south section of downfall (in the downfall direction).

In the second phase, the support system characteristics and the tension crack properties are defined according to the results obtained from precise tools, as shown in Fig.12. Furthermore, gravitational acceleration of the earthquake and the situation of the existing discontinuities are defined (Fig.13-a).

Through an extensive numerical and limit equilibrium methods, it was concluded that the northern slope of Angoran mine needs 8536 anchors in 20 rows. Each row contains 427 anchors with 1.31 m spacing, and angle of -1.03 degrees with the horizon. The anchorage length was considered 26.1 m (Fig.13-b). Considering the fact that too many anchors are demanded, it is proposed to remove the unstable zone partly and reduce the weight and also apply drainage. Then, the new situation should be analyzed and the modified support system would be designed.

**Conclusion:**

Limit equilibrium analysis has been the most popular method for slope stability calculations. A major advantage of this approach is that complex soil profiles, seepage, and a variety of loading conditions can be easily dealt with.
Fig. 12: Information on the support system and the tension crack properties present in the northern slope of the mine.

Fig. 13: (a) Defining the gravitational acceleration of the earthquake and the present discontinuities’ situation, (b) the required support for stabilization of the northern slope of the lead and zinc mine of Angoran.

Slope Stability Analysis software package is the first package featuring the quality of direct determination of required support for unstable zones. Briefly, the main features of the software are as follows:

1- The planar failure analysis software which have been developed in the recent decades, making use of limit equilibrium method, only take the waviness and plane dip angle into account for the failure plane, while exploiting Barton’s equations combined with Mohr-Coulomb relations leads to more accurate results. In the Slope Stability Analysis software, the tension crack position in an unstable region has been taken into account along with Barton’s criterion, in the planar failure analysis computations. Comparison between the numerical results obtained from UDEC and 3DEC software and those achieved using the limit equilibrium method through S.S.A., for the bench No. 2960 in the lead and zinc mine of Angoran, proves acceptable accordance.

2- In the S.S.A. software, the heuristic equations of 1, 2 and 3 (extracted from planar failure analysis relations) are used for direct determination of the net tensile force of required anchors, employed to prevent planar failure. The mentioned equations cover all support system factors and geological, hydrological and geo-mechanical situations of the unstable zone. In this software, there are no limitations in the region dimensions, discontinuity surface altitude and geo-mechanical parameters, for the prediction of model behavior.

3- Taking into account all factors contributing to failure, Slope Stability Analysis software allows for better and optimum time and project management, besides reduction of the potential risks and injuries to the people engaged in the project, and is also a good means to minimize the mining variable costs.

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