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Algorithm for automated design of homogeneous slopes in open pit mines using limit equilibrium method

In recent years, accidents due to slope failures in openpit/surface mines have shown an upward trend. The major factor causing such failures is the lack of scientific design of the pit and the dump slopes in mines and therefore, an optimum design of slope angle vis-à-vis slope height is of paramount importance. The slope design process is an iterative one involving large amount of computation and voluminous data, making the process a tedious and time consuming one. However, application of computer can effectively minimize these difficulties provided that a suitable computer package is available for the purpose. A good number of software are available nowadays for slope stability analysis and/or design. However, most of these software are not suitable for automated design of new slopes. In this paper, a simplified algorithm for automated design of homogeneous slopes in open pit/surface mines using limit equilibrium method (LEM) has been proposed.

Keywords: *Surface mine, algorithm, automated design, homogeneous slope, LEM.*

Introduction

In mining sector, there are two different type of slopes – one in open pit/surface mine itself (highwall slopes) and the other one in the waste dump (dump slopes). In India, rapid increase in production of various minerals has intensified surface mining activities and this has resulted in the surface mines operating at stripping ratio up to 1:15 (coal/mineral : overburden) and depth of about 500 m (Kumar and Villuri, 2015). As a direct consequence, this will increase the risks of highwall slope and dump failures tremendously, which can give rise to a significant economic losses and safety impact.

The Spokane Research Laboratory of NIOSH reported that slope failure accounts for approximately 15% of all surface mine fatalities (Girard, 2001). An analysis of the accidents in opencast mines in India revealed that slope and dump failure have started assuming an upward trend in the recent times (DGMS, 2010). A few of the recent fatal accidents/dangerous occurrences in surface mines involving slope and dump failures are given in Table 1.

The analysis also converged on one common but a major factor causing the accidents that of the lack of scientific design of the pit and the dump slopes in mines. In such a scenario slope stability analysis becomes an integral part of the life cycle of the opencast mining projects (Kumar and Prakash, 2015).

In designing a slope, it becomes necessary that the maximum economy is achieved while ensuring the safety. Hoek and Bray (1981) mentioned that slope should be steep enough to be economically acceptable and flat enough to be safe. The effect of slope angle on the economics of open pit operation becomes more pronounced with the increase in depth of mine workings (Sen, 1994). For example, a change of slope angle from 30p to 35p for a 100 m deep pit will reduce the volume (in-situ) of rock to be handled by 1519.5m^3 per meter length of slope, whereas for the same change in pit slope for a 400m deep pit, the reduction in volume of rock to be handled will be 24312m^3 per m length of slope. The economic impact of slope failure that can be measured by quantifying the effect of this event on the value of mine as measured by net present value method is also to be taken into consideration (Contreras, 2015). Slope failure may result in disruption of planned production because of loss of time required to restore the site, and additional material handling and rescheduling of equipment required to restore the site affected by the failure at additional costs (Contreras, 2015).

In the backdrop of increasing risk of failure of highwall and waste dump in surface mine, slope design assumes great importance in surface mining operation. A qualitative assessment is also important in the judgement of stability of a slope (Khajehzadeh et al., 2011), which necessitates proper design of new slope. This is possible with the determination of the acceptable slope angle that can balance optimally between additional economic benefits gained from steeper slopes, and the additional risks as a result of reduced stability of the slopes (Steffen et al., 2008).

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Table 1: Accident due to slope failure in opencast mines
(adapted from DGMS (Tech) (S&T) Circular no. 2 Dhanbad, dated 6th July, 2010)

Mine	Slope failed	Date	Consequence
Kawadi opencast coal mine	31 m high overburden bench.	24.06.2000	Ten persons were trapped and killed
Tollem iron ore mine in Goa	30 to 46 m high dump and benches.	09.12.2006	Six persons were trapped and killed under the debris
Jayant ppencast project	70 m high along the side of the slope and 6 to 19 m high across the slope.	17.12.2008	Five persons were trapped and killed; a shovel was buried.
Sasti opencast coal mine	73 m high overburden dump	04.06.2009	Two persons were killed and two excavators were buried.
Hamsa minerals and export granite mine	35 to 45 m high slope.	25.02.2010	Eighteen persons were killed and fourteen were injured bodily.
A private soapstone mine	17 m high bench failed, which was followed by 7 m high slope failure during rescue operations.	-	Three persons were fatally injured and five persons of rescue team were trapped subsequently
A coal mine	10 to 12 m high dump of waste material.	-	There was no casualty.
A coal mine	62 m high overburden dump.	-	Caused severe upheaval to an adjacent arterial road and damage to a 400 kV overhead line.

Different modes of slope failure

Slope failures are essentially natural hazards that occur in many areas all over the world. Modes of slope failure are determined by the mechanisms that cause the outward or downward movement of slope-forming materials. The failure modes of slopes may be classified into following four basic categories.

1. Plane failure
2. Wedge failure
3. Toppling failure
4. Circular/rotational failure/non-linear failure

In case of hard rock slopes, the failure mode (plane, wedge or toppling) is generally controlled by geological features (weakness planes) and the failure surface is predetermined. In such slopes the failure mode depends on the presence and spatial distribution of weakness planes with respect to the slope face, whereas in slopes of weak rockmass (either the rockmass is weak itself or rendered weak by presence of arbitrary joint sets) the failure surface follows the path of least resistance results in non-linear failure (Hoek and Bray, 1981; Houghton, 1983; Gupta and Singh, 1986; Zhao and Zhou, 1992).

Rotational failure

In rotational failure, material slides along a curved or non-linear surface is shown in Fig.1. In case of slopes made up of homogeneous material where the individual particle size are very small in comparison with the size of the slope and the particles are no longer interlocked as a result of their shapes, the failure surface in 2-dimensional plane may be approximated by an arc of a circle results into a circular failure. Circular failures are common in waste dumps and overburden dumps. However, a failure of this type is not uncommon in highwall slopes, especially when the material is weathered or altered rocks (Kennedy, 1970; Hoek and Bray,1981; Zhao and Zhou, 1992)

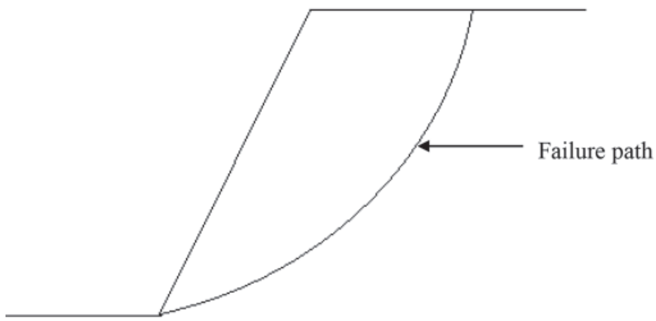

Fig.1 Circular failure in homogeneous slopes

Though there are various modes of failure that may occur depending upon the material characteristics, geo-mechanical properties and more importantly the presence of discontinuities, it has been well-established that slopes of homogeneous material generally fail in circular mode.

Circular failure analysis

In highwall slopes made up of homogeneous material and spoil dumps common mode of failure is circular one. There are various methods of circular failure analysis which can broadly be classified into two – analytical and numerical techniques. To guarantee the stability of a homogeneous slope, the circular arc method is traditionally used for stability analysis (Xiao et al., 2015). The two objectives of slope stability analysis are calculating factor of safety (FOS) for a given slip surface and determining the critical slip surface (CSS) for a given slope (Kalatehjari et al., 2014). The critical slip surface for a given slope is one which is having minimum factor of safety and therefore, circular failure analysis essentially involves optimization techniques to assess the stability of a slope.

In design process optimum slope angle is determined against desired factor of safety (ensuring stability of slope), which is an iterative one involving large amount of computation and voluminous data, making the process a tedious and time consuming one. However, application of computer can effectively minimize these difficulties provided that a suitable computer package is available for the purpose. A good number of software are available nowadays for slope stability analysis and/or design.

Software for slope stability analysis and design

In the last two decades there has been a lot of research works in application of computer for slope stability analysis based on the principle of limit equilibrium method and finite element method. Though lately, numerical techniques (FEM, FDM, DEM, etc.) caught attention of both researchers and professionals, limit equilibrium methods (LEM) are still the favourite ones of geotechnical engineers for slope stability analysis because of its simplicity, ease of use and reliability. Nowadays both LEM and FEM based software are being commonly used for slope stability analysis. There are many softwares commercially available for this purpose as shown in the Table 2.

TABLE 2: SOFTWARE FOR SLOPE STABILITY (ADOPTED FROM PARMAR AND DAVE, 2015)

Software	Method of analysis
SLIDE	Limit equilibrium method
PLAXIS	Finite element method
SLOPE/W	Limit equilibrium method
GSLOPE	Limit equilibrium method
STABLE WV	Limit equilibrium method
FLAC/Slope	Finite difference method
GALENA	Limit equilibrium method
SVSlope	Limit equilibrium method
CLARA-W	Limit equilibrium method
CRISP 2D	Finite element method
HYDRUS	Limit equilibrium method
GEO FEM	Finite element method
Phase^2	Finite element method

Algorithm for automated slope design

In case of in-situ slopes, there is no scope to design the overall slope height, and it is only slope angle which is to design in such a manner that for the given slope height and other parameters the FOS of slope is more than or equal to a desired value. The slope design methodology is shown in Fig. 2 in the form of a flowchart.

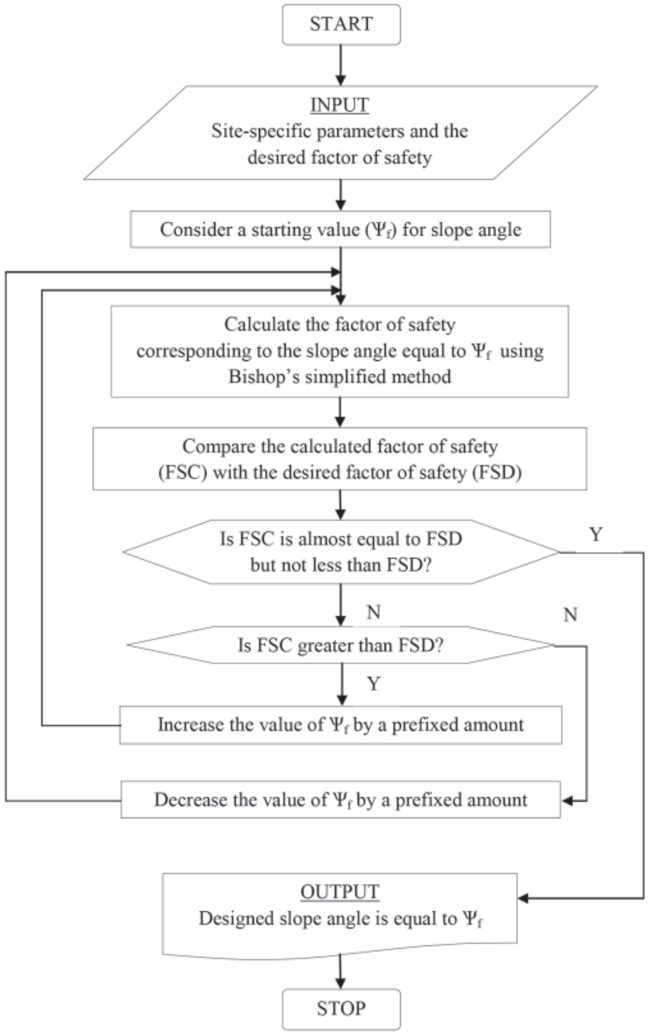

Fig.2 Slope design methodology

The design process constitutes the following steps:

1. The site-specific parameters (physico-mechanical properties of slope material including the specific weight, ground water condition and slope height) and the value of factor of safety desired (FSD) are specified.
2. A starting value (realistic) for slope angle is assumed.
3. The factor of safety corresponding to the assumed slope angle (FSC) is calculated using Bishop's simplified method.
4. The FSC is then compared to the FSD. If FSC is less than the FSD, the slope angle is reduced by a prefixed amount. The factor of safety of the new slope angle is determined and the process is continued. On the other hand, if FSC is more than the FSD, the slope angle is increased by a prefixed amount. The factor of safety for the new slope angle is determined and the process is continued.
5. The process continues till the FSC is almost equal to but not less than the FSD, and the corresponding angle may be considered as the designed slope angle.

Conclusions

Most of the software commercially available for slope stability analysis can be used for design of new slopes using trial and error approach, which are not automated ones and require more time for designing new slopes. Moreover, software developed using numerical methods require input parameters not routinely measured. The proposed simplified algorithm using limit equilibrium methods requires very few routinely measured input parameters for automated design of slopes at minimum expense of time. Reliability concept can also be incorporated in the proposed algorithm.

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SYMMETRICAL COMPONENT ANALYSIS OF AN UNBALANCED MINE POWER DISTRIBUTION SYSTEM IN B²-SPICE

(Continued from page 319)

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