CHAPTER 1

INTRODUCTION

1.0 General

Recent increase in the demand of energy consumption has led to increased opencast mining operations. Easy access to the shallow depth coal seams through opencast mining is becoming a popular excavation method. The locations of the coal seams at greater depths lead to higher stripping ratio. Thus deep and large opencast mining operations result in removal of huge quantities of waste overburden material and subsequently dumping it outside the quarry areas or back-filling in the excavated areas as the case may be. The waste piles called overburden dumps are mainly composed of mixture of fragmented rocks and loose soil. In recent years the unprecedented increase in the rate of accumulation of waste overburden dumps has been a great geo-environmental concern mainly because of frequent dump slope failures. General increase in the awareness of hazards has led to more focussed attention towards the safe and economic design of both internal and external waste overburden dump slopes. But due to the complex site conditions and many other techno-economic reasons, the external dumping has been practised in Indian mining conditions instead of internal dumping.

Presently, the optimum stable dump slopes dimensions during and after mining operations are the industry requirements worldwide. On the one hand, stable slope is essential for the safety of men and machinery, on the other hand vast amount of land and resource may be conserved by optimising the geometry of the dumps and their mode of dump generation. Increasing the dump slope angle allows to accommodate more volume of the waste overburden material in a particular dump with the same base area while making it more prone to failure. It is therefore, a great techno-economic and operational challenge to go for the most efficient design, in the light of these two conflicting requirement by optimising the dump slope angle that is steep enough to be economically acceptable and flat enough to be safe (Koner and Chakravarty, 2010a); which gets accommodated well within the leasehold area of the mine. Field conditions govern the design of overburden dump geometry and also the stabilisation steps. The interactions between fragmented rocks and loose soil particles, and their size distribution in overburden dumps (Koner and Chakravarty, 2009a, 2010c) are very important components of the know-how from the engineering perspective. The design and remedial measures for overburden dumps (Witcher, 2007) necessarily depends on how well the granular interaction mechanism is known to the field engineers. It has become the greatest point of interest for the researchers in this area in the world today. A lot of new approaches and tools have been developed and are in the process of developing for proper numerical analysis of the stability keeping the macro- and micro-level interactions of the dump materials into considerations.

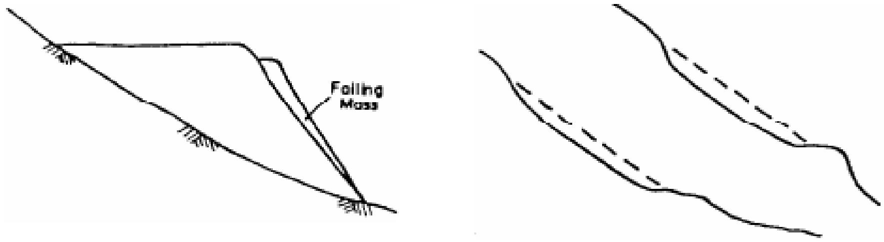
1.1 Overburden Dump Stability Concept

Considering the weight or volume or height aspects, the waste overburden dumps are some of the largest structures built by man. Compared to other engineered structures little investigation, analysis, design or control has been used in planning and operation these dumps. This relative lack of attention is often attributed to the small economic value of dumps. But recent unprecedented rise of open pit mining with higher stripping ratio and subsequent building of large external dumps along with their failures have attracted the attention of the field mining engineers and managers. Monitoring and understanding the mode of potential failure, thus detecting the impending failures can avoid undesirable consequence of failure (Caldwell and Moss, 1981) leading to loss of production, machinery, skilled man power, time and other associated geo-hazards. Adequate simultaneous field and numerical investigations, and design are needed to obtain a clear understanding of the potential modes and consequences of failure. Only if dump movement and failure be accommodated, could the dump construction proceed safely. Based on the material characteristics and the state of stress in external dumps, certain failure modes appear to be more likely than others in dump slopes. Generaly, low stress state in dump slopes influences the modes of failure. There is a chance that more plausible failure modes for dump slopes are yet to be discovered through rigorous analyses. Such a discovery is not unlikely, however, considering that today’s high stripping ratio at open pits and subsequent dumping at the surface will be superseded by higher dumps in the future, particularly for the coal mines of India.

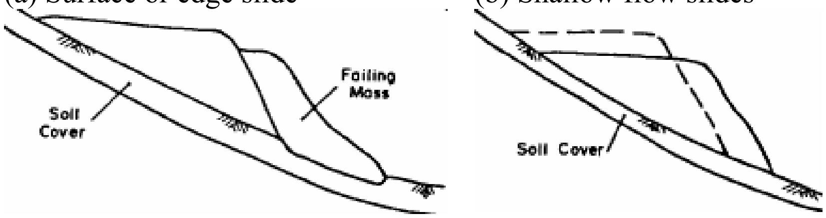
Some other factors, like vibrations due to blasting etc. are also very important for the stability of the dump slopes. Vibrations from blasting could potentially trigger a failure. Furthermore, the relative high frequency of the blast acceleration waves prohibits them from displacing large dump mass uniformly. Seismic events (i.e., low frequency vibrations) could be more dangerous for large scale dumps (Roberto et al., 2008), and there have also been several seismic induced failures of natural slopes observed (Roberto et al., 2008). Stability of dump slopes has been analysed using numerical methods of various types. MacLaughlin et al. (2001) illustrated the distinction between limit equilibrium methods and discontinuum based numerical approach in slope stability analysis; to mention one, the limit equilibrium methods cannot account for changes in the driving and resisting forces which are possible in numerical methods. The issue of the knowledge of the modes of failure at a particular dump slope is important and the above mentioned analysis tools are used to predict the same in full details. Here some of the observed failure modes in dump slopes are described below.

1.1.1 Observed Failure Modes and Failure Mechanism

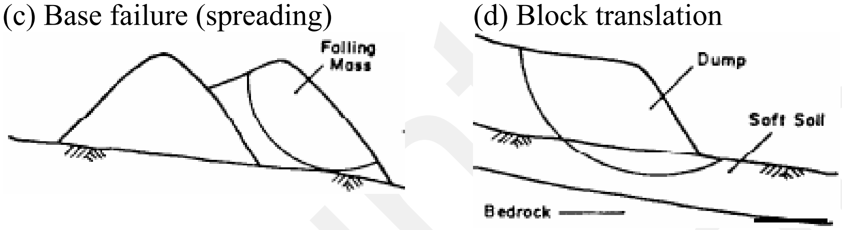
The various failure modes that occur in mine waste dump have been summarised by Caldwell and Moss (1981) along with a review of the methods of analysis and illustrated in Figure 1.1. The failure due to surface or edge slides occurring as the material moves down the slope have been mostly observed in crest tipped embankments and best evaluated by the equations describing the stability of an infinite slope. If sufficient water enters the slope and flows parallel to the face, a shallow flow slide may occur. Dumps placed on flat ground of competent soil are least likely to fail. However, if the flat ground is covered by a thin layer of weak material, base failure may occur. Block translation may occur where a dump is formed on inclined ground and the soil cover is relatively thin and weak. Unusually high water tables in the embankment, earthquakes or the decay of organic material beneath the dump may initiate such a failure.



(a) Surface or edge slide (b) Shallow flow slides



(c) Base failure (spreading) (d) Block translation



(e) Circular arc failure (f) Foundation circular failure

Figure 1.1: The Possible Failure Modes in Mine Waste Dumps (Caldwell and Moss, 1981)

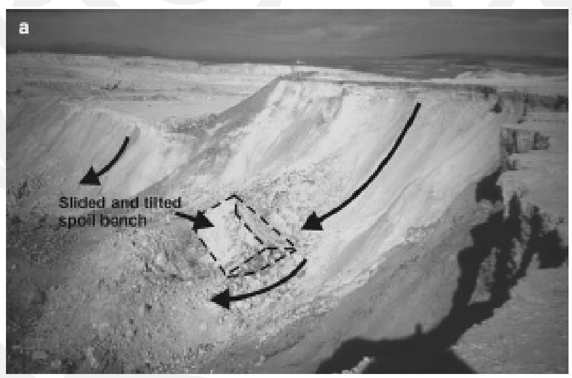


Figure 1.2: A Scarp (circular failure) of Instability INS1 at Central Anatolia (Kasmer et al., 2006)

The failure modes are associated with a mechanism that has also been extensively studied. Circular arc failure through the dump material is most common where the dump material contains a significant percentage of fine grain soil. Similarly, a circular arc failure surface may develop through a deep foundation soil deposit of fine grained soils (Caldwell and Moss, 1981). At Central Anatolia (Kasmer et al., 2006) observation showed influence of the floor inclination on the mode of failure. At the back of the failure, there was a well defined scarp feature where failed material at the base of the failure has dropped lower in elevation than the material at the front (Figure

1.2). Some backward-tilted sections of the uppermost spoil benches have moved down along this surface as seen in Figure 1.2. This suggested that circular failure (rotational movement) initiated the failure from the back of the dump where the dump height was at a maximum. Similar studies need to be carried out for the slope failures in order to increase the long term stability of the dumps (Robertson and Skermer, 1988).

1.1.2 Technical Analysis of Past Dump Failures

A complete geotechnical analysis and numerical modelling of the dump slope failures may provide interesting facts for better and safer designs of the external overburden dumps. Table 1.1 briefly summarises a few reported waste overburden dumps failure studies at coal-deposits to emphasise the importance of the investigation. In the Table 1.1, of the eight reported cases, the height for the sixth case was mentioned to be 60 m; whereas for run out distance was mentioned to be 500 m for 1st case, 600 m for 2nd case and 30- 50 m for the 7th case study reported. The failed volume was also noted to be 100,000-150,000 cm^3 for the 1st case, 108,000 cm^3 for the 2nd case and upto several millions of cm^3 for the 6th case study. Coal deposits are sedimentary deposits and the overburden typically contains relatively weak shales, siltstones, sandstones, and low-quality coal. Various terms are used to describe the overburden material remaining in the waste piles, like dumps, waste piles, coarse colliery, spoil, gob, heaps, etc.

Many uncertainties exist in understanding slope failure of waste dumps, because of their heterogeneity, complex pathways of fluid flow (both air and water), and imprecisely known characterization of the foundation etc. Triggering by static liquefaction (Dawson and Morgenstern, 1995; Dawson et al., 1998; Valenzuela et al., 2008) has also been found to cause failure of dump slopes. Liquefaction occurs when a loosely-packed material becomes saturated and denser, and then the material flows as if a liquid, typically as a result of an increased pore pressure and reduced effective stress (Neuendorf et al., 2005). However, most waste dump failures are not triggered by liquefaction. In order for liquefaction to occur, several conditions must exist (Valenzuela et al., 2008):

- The material must have enough sand and fines to sustain high pore pressure.

- The material must be loose enough to contract when a stress is applied.
- The material must be nearly or completely saturated.
- There must be presence of a triggering mechanism (heavy rainfall event, earthquake, weak foundation, etc.).

Hence, it may be observed here that proper design of the steps for the technical analyses of the dump failures is necessary for achieving the safest dump geometry.

Table 1.1: Description of Reported Slope Failures at Mine Sites

Sl. No.	Mine name and location	Description of slope failure	Date of slope failure	Comments	References
1.	Jupille coal mine, Belgium	Removal of toe of a fly ash storage facility caused a flowside	1961	11 deaths, house destroyed	Blight and Fourie (2005)
2.	Aberfan coal mine, wales, UK	Flow slide of coal waste dump, dump was place on top of a spring	October 1966	144 deaths, extensive damage to property	Dawson et al. (1998), Blight and Fourie (2005)
3.	Goonyella coal mine, Queensland, Australia	Numerous slope failures of spoil piles in 1970s.	1970	Failure occur along planar surfaces that concentrate moisture	Richards et al. (1981), Seedsman and Emerson (1985)
4.	Buffalo Creek coal mine, USA	Overtopping of coal dump	1972	118 fatalities, 4000 homeless and $50 million damage	Blight and Fourie (2005)
5.	Sulphur mine, Tarnobzeg, Poland	Toe failure caused by plastic clay in the subgrade and manner of dumping (raised in successive layers)		The principal cause of the toe-failure of the dump is the exceeding of the ultimate load-bearing capacity of the subgrade due to pressure exerted on it by the dump.	Mularz and Rybicki (1977)
6.	Niederlausitz, Eastern Germany	15 flowslide of lignite waste rock piles	1955-1988	Water level rises in rounded, fine- to medium grained sands	Witcher (2007)
7.	Valea Manastirii, Gorj, Romania	Landslide	March 2000	Total displacement of the disturbed mass was 30 to 50 m, a 800 m section of the River Motru was completely blocked, creating a high flood risk to the villages upstream.	Stanciucu (2005)

1.1.3 Failure Indicators of Dump Slope

The failure indicators provide a first hand feel about the stability of the dumps. Indicators like the shear strain rate, velocity and displacements etc. are most widely used. Deformations occur in a slope as a result of stresses and shear displacements in the mass of the material forming the dump slope. Some of these deformations, such as consolidation, are not indicative of failure while others, such as shear displacement along the failure surface are. To predict the failure it is necessary to distinguish deformations which indicate failure from those which do not. This requires an understanding of the failure mode and the deformations that accompany it (Kasmer and Ulusay, 2006).

Analytical techniques which are currently available for the analysis of dump deformations are cumbersome to use (McCarter 1981) or are not sufficiently accurate to enable pre-construction estimates to be made of the consolidation and failure deformations. Instead, failure criteria are usually based on experience gained as the dump is constructed. The rate of deformations and a change of the rate of deformation have generally been observed to be good indicators of the behavior of a slope. They may be used to establish criteria indicative of failure. Here in this study also these indicators have been incorporated for estimating the safety factor of the dump slopes.

1.1.4 Saturation Effect

The stress state in waste dump slopes has been found to be dependent upon the groundwater conditions. The water table in dump mass depends on rainfall infiltration, surface topography, and presence of nearby water bodies like rivers or lakes etc.; and the dump material characteristics (Maulem, 1976). Additionally, the actual shape and location of the water table depends on the dump slope geometry, the permeability characteristics, and recharge from surroundings. Parts in waste dumps below water table are subjected to groundwater pressure, and act to reduce the effective stress at a given point (Bishop, 1959); leading to a reduction of the available shear strength (Fredlund et al., 1978) of a failure surface (i.e., the reduced normal stress). Furthermore, existing ground water pressure can act as an additional driving force on failure surfaces for certain failure modes. A secondary effect of water present at dump mass is the weathering and subsequent reduction of material strength. The permeability or hydraulic conductivity (Leong and Rahardjo, 1997), of the dump material determines its ability to transmit a fluid. The presence of discontinuity at the dump mass may contribute towards permeability of the water. The coupled effects are difficult to quantify. In normal engineering practice, two-dimensional approximations are commonly used (Cai et al., 1998; Cai and Ugai, 2004; Koner and Chakravarty, 2008; Chakravarty et al., 2008).

1.1.5 Dynamic Loading Effect

Sudden ground motion during blast vibration and earthquake has been found to induce significant inertia forces in a dump slope. The induced inertia forces alternate in direction and magnitude a number of times. Thus, the factor of safety of a dump slope may drop below unity several times during seismic vibration. As a result, possible accumulation of displacements might exceed the limiting case and induce failures of the dump slopes (Chugh and Stark, 2006).

In a conventional engineering analysis of a dump slope failure against dynamic load of an earthquake force, the waste dump slope is usually analysed with the calculation of factor of safety under a pseudostatic inertia force, presumably generated by an earthquake induced ground motion (Baker et al., 2006). This is certainly true under static gravity loading conditions. However, under earthquake loading, the reduction in factor of safety only exists for a very short period of time for which large inertia forces are induced. All these driving forces will be rapidly removed at the end of an earthquake excitation. The overall effect of an earthquake on the dump slope is therefore the accumulation of displacement at the failed section (Kveldsvik et al., 2009). If these accumulated displacements are sufficiently large, the dump slope may normally be considered to have failed. The factor of safety of dump slope changes during earthquake all the time due to changing inertia force with time. The critical aspect in earthquake engineering is to determine the yield acceleration which has been used to estimate the overall displacement at the dump slope (Newmark, 1965).

It has been observed that the dump stability is influenced by factors of two broad categories, like the general factors of saturation, dynamic loading etc.; and the internal parameters like the slope angle, material properties, the mode of dumping, compaction etc (have been explained in section 1.3 below). Along with these parameters the approaches for analysis of the stability of the dumps have a significant role in defining the proper design and stability assessment for these dumps (Koner and Chakravarty, 2009b, 2010b). Hence, in the following two sections the available approaches and the methods of analyses have been briefly explained.

1.2 Approaches for Dump Stability Investigation

There are various approaches available for the analysis of the stability of the dumps depending on the objective of the study. Earlier researchers have observed different types of dumps including the dragline generated dumps and applied various analogies for their scientific and technical study.

Kasmer et al. (2006) studied dragline spoil dumps and suggested that a compound sliding failure mechanism would be realistic for the spoil pile failure analysis in the pit. They concluded that movement of the spoil piles was co-initiated by the softening of moisture sensitive material at the base of the spoil and the cracking of spoil material due to settlement and compaction movements. Two failures they had investigated were composed of a circular surface passing through the spoil itself and a planar surface along the weakest interface between the floor strata (bottom clay) and the dump mass. In their study both finite element and limit equilibrium methods were used.

Fernando and Nag (2003) recommended some of the safe dumping strategies for internal stacker dumping and compared the factor of safety obtained using the tools Galena and Gwedgem. Determination of dump soil characteristics has been discussed in their work.

Woźniak (2009) investigated the geotechnical characteristics of the cohesive dump soils. The nature of the dump soil substance was assumed to be very susceptible to the change of water content. It had been shown that increasing water content facilitated plastic deformation of the cohesive dump soil and did change the compressibility modulus. Steiakakis et al. (2009) pointed out that the regional groundwater conditions should be clearly defined before the start of the dump operation at any particular site. Also, the strength of the spoil material close to the base should be studied in detail because the base of the deposit plays a significant role in both the stability of the waste dump and the design of preventive measures. The mixing of overburden with fly ash, as it has been the case in the past, was expected to contribute to the improvement of the mechanical strength parameters of the materials since fly ash absorbs moisture from clay and substantially increased the strength of the resultant mixture due to the pozzolanic properties of ash. Rassam and Williams (1999) dealt with waste rock dump slope stability using 3-D numerical methods. In this work, non-linear Mohr-Coulomb failure criterion has been successfully implemented in deeply-seated failure plane of dump slope.

Roy (2006) carried out dump stability on the parametric influence of mine floor at back filled dumps and illustrated safe dump profile for the specific dumps investigated. Engineering properties of dumps soil and their influence on dump instability has been discussed in the work of Roy (2005). Tesarik and McKibbin (1999) identified the physical properties and climatic conditions affecting the stability of old stable rock dumps as well as failed rock dump slope.

Thus on the whole, it has been noticed that the dumps have been studied till date with various analogies suiting the analytical, field-based studies and numerical modelling approaches. It is assumed that the interactions of the material composing the dump materials also need to be studied at length before assessing the stability and the associated geo-hazards of these dumps.

1.2.1 Methods for Investigation of Stability of Slopes

It should be noted that dumps are characteristically different from the conventional cut and fill slope or rock slope, but they have some similarity with the geotechnical slope problems. In external overburden dumps both the ends are open, so analysis of stability in both directions is essential, unlike the internal dumps which are confined from three directions. Understanding the methods for analysis is important in both the cases. A brief summary of slope stability analysis methods that have evolved over the past years have been given below.

Over the years, numerous methods and methodologies in slope stability investigation have been developed and used through research, which have later been practiced in routine engineering works. Many different analytical methods have been developed and used in the assessment of slope stability. A comprehensive slope stability analysis involves evaluation of various design parameters such as slope angle, slope height and others.

1.2.1.1 Empirical and Analogue Methods

Empirical and analogue approaches are based on the earlier experience of dealing with a particular geological structures, material type, groundwater regimes and slope problems. Although the experience factor may often be the key component, the decision making process usually must be supported by analytical procedures such as slope stability charts, kinematic analyses or limit equilibrium methods.

The analogue approach extrapolates problems encountered in certain areas to new places of the same or similar geological and geomorphological structure, material type and human activity. It is closely related to the empirical approach in the sense that one must have enough experience, confidence and sound engineering judgment from previous work in the particular area of interest. Slope mass rating (SMR) classification, an extension of the rock mass rating (RMR) system (Bieniawski, 1989), has been found to be potentially a very useful tool in the preliminary assessment of slope stability, providing information about instability modes and required support measures. The methods of kinematic analysis, slope stability charts and limit equilibrium falling under this category have been briefly explained below followed by the other used methods.

1.2.1.1.1 Kinematic Methods

Kinematic analysis of slope stability is characteristics of rock slope containing well developed discontinuities. This analysis is based on the orientation of discontinuities defined usually in terms of dip and dip direction. The interpretation of the data uses stereographic projections, allowing for a two dimensional representation of the three dimensional data. Kinematic analysis evaluates either manually or using computer programs (Diederichs, 1990), the freedom of the discontinuity bound blocks to displace. More sophisticated kinematic analyses based on topological block theory have also been developed by Goodman (1985) to determine the keyblocks within a slope. Kinematic methods may be used only for the plane and wedge failure analysis; hence it has a little scope left to be applied in the circular failure mode that is prevalent in mine dump as observed from the literature.

1.2.1.1.2 Slope Stability Charts Method

Slope stability charts provide a fast and useful tool for a simple homogeneous slope stability assessment using past data. Therefore, in order to apply them to field conditions, it is necessary to approximate the real slope with an equivalent geometry and material. As suggested by Duncan (1996a), the most effective method of developing a simple slope profile for chart analysis is to begin with the cross-section of the slope drawn to scale. On this cross section, using judgment, the expert would draw a geometrically simple slope that approximates the real slope as closely as possible. In the next step the shear strength for chart analysis needs to be averaged. Hence, this method is limited in its application for complex site and dump conditions.

1.2.1.1.3 Limit Equilibrium Method

The two-dimensional limit equilibrium method remains the most commonly used technique for slope stability analysis in routine engineering practice. This popularity can be attributed to its relative simplicity and ease of use, as well as the many decades of experience in its application. The stability of both soil and rock slopes may be assessed using this method. In limit equilibrium methods of analysis a condition of incipient failure is postulated along a continuous slip surface of a known or assured shape. The slope stability, usually with respect to shear strength, is then defined using a factor of safety. The factor of safety is generally be defined as the ratio of the total force available to resist failure to the total force tending to induce failure (Hoek and Bray, 1981) shown in Figure 1.3. The nature of the failure surface has a direct bearing on the material type composing the slope. The circular failure plane is representative of homogeneous soils, waste rocks and heavily fractured rocks with no identified structural pattern, whereas composite failure surfaces are the most common ones observed in field conditions.

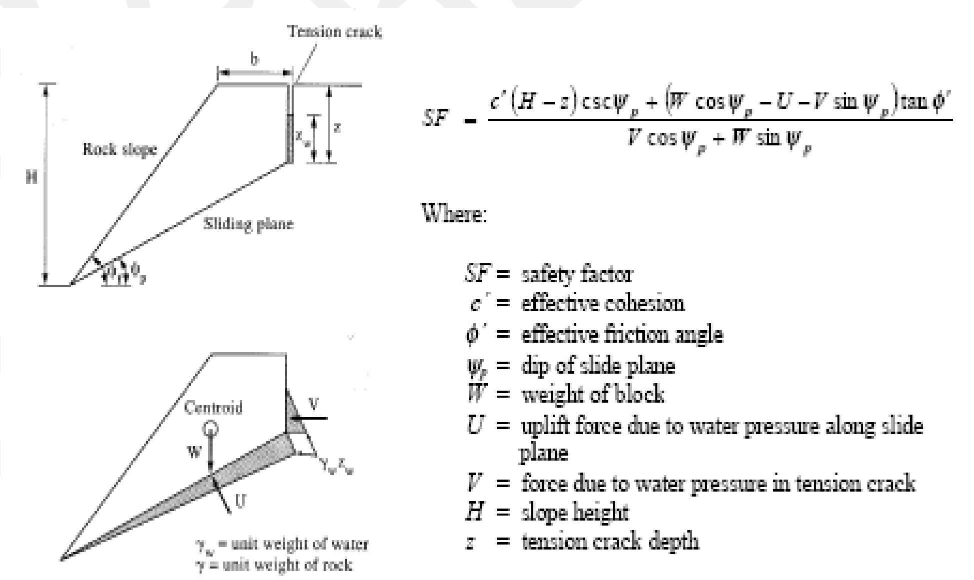


Figure 1.3: Limit Equilibrium Solution for Planar Failure (Hudson and Harrison, 1997)

For hard rock and low stress conditions the failure surfaces would be approximated by the existing discontinuities as shown in Figure 1.3. Limit equilibrium methods have been further developed for incorporating more complicated failure mechanisms, such as toppling, as shown in Figure 1.5 or wedge and stepped-path failures (Figure 1.6). In an attempt to represent the actual field conditions more realistically, three-dimensional limit equilibrium methods have also been developed (Hungr, 1987). Comparison between these two types of limit equilibrium methods (Cavounidis, 1987) show that the three-dimensional methods provide overestimated values of the factor of safety compared to the two-dimensional approach, keeping the other parameters the same. Limit equilibrium methods also allow for evaluation of various aspects, such as the dynamic loading by introducing a force representing horizontal acceleration; the role of progressive failure mechanism (Chowdhury, 1978), or the unsaturated conditions (Fredlund and Rahardjo, 1993) and others commonly found in field conditions. Misfeldt et al. (1991) coupled the limit equilibrium method with the seepage analysis to simulate a progressive valley deepening in order to understand the historical development of an unstable river bank.

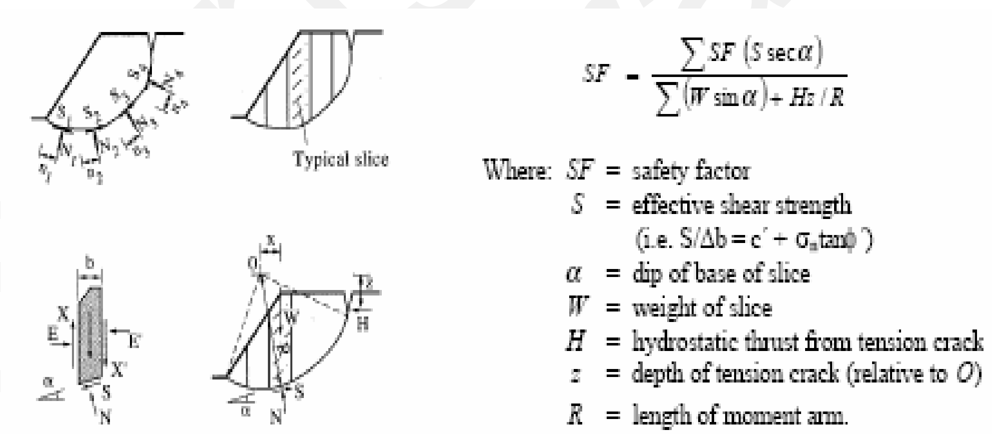


Figure 1.4: Limit Equilibrium Solution for Circular Failure (Hudson and Harrison, 1997)

Limit equilibrium methods provide reasonably good results for situations in which the failure mode is readily identifiable and involves translation or rotation (Figure 1.4). The advantages of limit equilibrium methods are in their simplicity of use and minimal requirement of computational power. The analysis can be performed relatively quickly using any commercially available slope stability program or even a standard spreadsheet program.

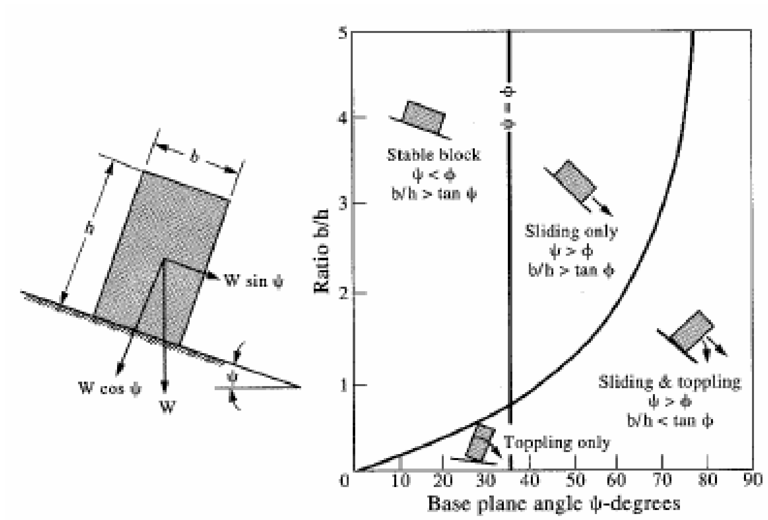


Figure 1.5: Sliding and Toppling Instability of a Block on an Inclined Plane (Hoek and Bray 1981)

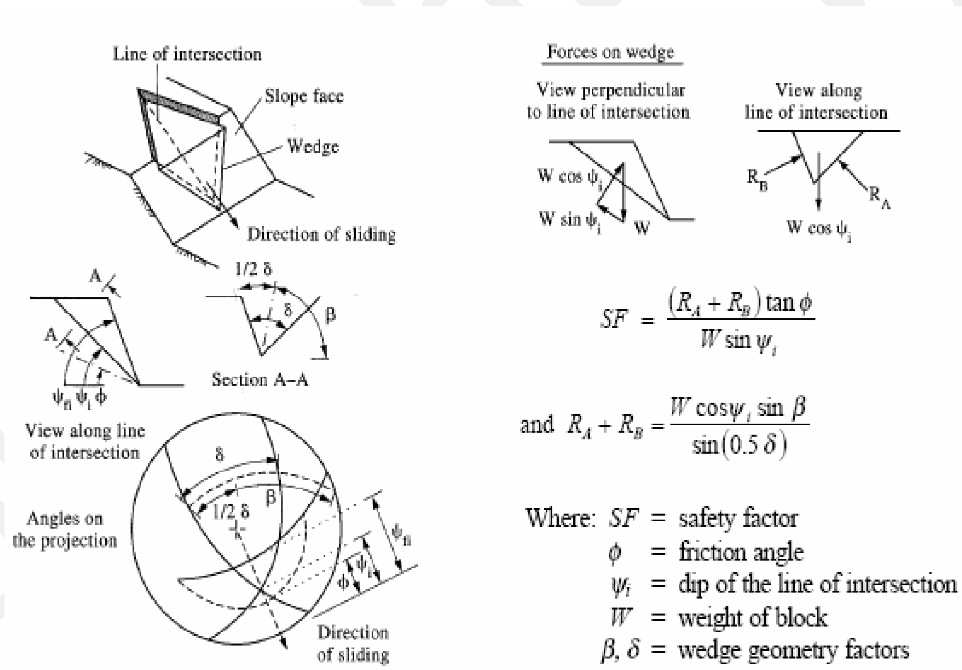


Figure 1.6: Limit Equilibrium Solution for Wedge Failure under Dry Conditions with Frictional Strength only (Hudson and Harrison, 1997)

Limit equilibrium methods have several disadvantages. The confining stresses are difficult to be incorporated; considerations for the stress-strain behaviour of the slope material and the time factor are also difficult to be incorporated into the model. Furthermore, limit equilibrium methods are difficult to be applied for complex material and site conditions; they assume that failure occurs along a failure surface according to a perfectly plastic shear force law (i.e. shear force is independent of displacement) and hence, no consideration is given to the displacements in the soil and rock mass (Cheng et al., 2007).

Each of these methods has some limitations which have further been investigated using the following methods described in short below for overcoming the limitations.

1.2.1.2 Fracture Mechanics Method

The application of fracture mechanics to rock slope stability takes into account the importance of crack-tip stress concentration and considers that the rock failure occurs as a result of crack initiation and propagation. The basic principle of this method is that the jointed rock slope stability is governed by the stress intensity factors at the joint tips rather than by the frictional resistance along joint surfaces (Whittaker et al, 1992). The concepts of fracture mechanics makes it possible to predict the formation of failure surfaces in jointed rock masses and to explain how stepped-path failure occurs. However, this method would fail for loose materials composing the dumps.

1.2.1.3 Probabilistic Method

The development and application of probabilistic risk analysis for slope stability has increased significantly in the last decades, providing a powerful tool for solving problems, implementing design and decision making. Quantification of limited or uncertain data used in analysis, and judgment based on the same may be studied (Rechitskii, 1982). Probabilistic risk analysis is used in an effort to overcome the subjective judgment of slope stability parameters and results in a single value representation namely the factor of safety (Figure 1.7). The subjectivity and uncertainties are due to the spatial variability of the material properties, as well as due to the uncertainties in reliability of the hypothesis carried out to approximate the mechanical behaviour of the rock and soil mass.

In this method each variable used in the analysis is given a probability distribution function instead of single design value. Typically a Monte Carlo simulation are used to generate random numbers from which all the variable values are assigned, using spreadsheet add-in programs, such as @RISK 5.0 (Palisade Corp.). They both require that the distribution of all input variables be either known or assumed. It is not a method in itself, but is linked and used in conjunction with other methods (namely, limit equilibrium, block theory, numerical modelling etc) for better assessment of the stability of the slopes.

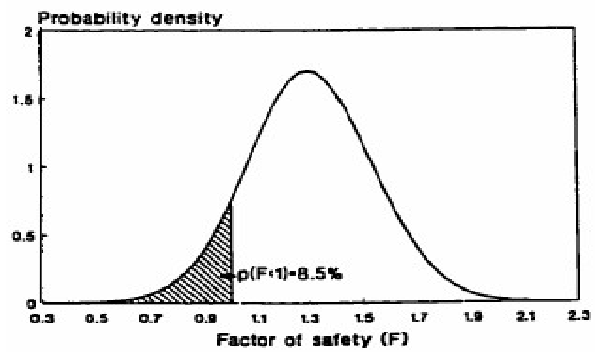


Figure 1.7: Probability Distribution of Factor of Safety (Pine, 1992)

1.2.1.4 Physical Modelling Method

The method of physical modelling has been used with success in all areas of geomechanics. It was a popular analytical tool especially in 1980s. The use of centrifuge modelling has been found to provide very good results. A wide range of materials has been used ranging from mixtures of sand, oil, plaster and water to brick models. The problem of scaling from field to the laboratory has been recognized. Centrifuge model have been found to be very capable of simulating the deformation and failure patterns in slopes to be expected under field conditions, as it is possible to simulate the geometry and stresses using a prototype model of the slope. The limitations appeared to be relatively high cost and the need for specialized equipment, as well as the problem of deriving reliable quantitative results from the experimental setups. The principles and relevant scaling laws relating to centrifuge model testing have been discussed in detail by Schofield (1980). Overcoming the limitations of this model led to the development of the various numerical methods as discussed below.

1.2.1.5 Numerical Modelling Method

In the last three decades, there has been great increase in the application of numerical methods in the field of geomechanics. Conventional forms of analyses are limited to simplistic problems in their scope of application, encompassing simple slope geometries and basic loading conditions, and as such, provide little insight into slope failure mechanisms. Many rock slope stability problems involve complexities relating to geometry, material anisotropy, non-linear material behaviour, in situ stresses and the presence of several coupled processes (e.g. pore pressures, seismic loading, etc.). To address these limitations, numerical modelling techniques (Zheng et al., 2005) have been enhanced to provide approximate solutions to problems, which otherwise would not have been possible to be solved using the conventional techniques. Numerical methods of analysis used for slope stability investigations may be broadly divided into three approaches: continuum, discontinuum, and hybrid modelling. However, the hybrid modelling approach has been undertaken as a part of the discontinuum method for the present study in order to understand the advantages of the hybrid method over the conventional micromechanical approach in capturing the discrete particle shape as well as the material interactions for analyzing the stability of the slopes. Hybrid codes involve the coupling of these two techniques (i.e. continuum and discontinuum) to maximize their key advantages. Table 1.2, below, summarizes the advantages and limitations inherent in these different numerical modelling approaches. A brief of the earlier work using the three approaches have been described below.

1.2.1.5.1 Continuum Based Approach

The continuum modelling approach is best suited for the analysis of slopes that are comprised of massive rocks with isotropic and homogeneous material formations. The non-linearity may be taken into considerations by varying the domain equations and the failure criteria to be evaluated for the failure analysis. This approach provides an approximate result of the stability of the slopes in terms of displacement, velocity and yielding parameters (Koner and Chakravarty, 2010a). This approach fails to model the discrete particle failure in the dump mass. Both 2D and 3D models are possible for the continuum method.

1.2.1.5.2 Discontinuum Based Approach

Although 2D and 3D continuum codes are very useful in characterizing rock slope failure mechanisms, it is important to recognise their limitations, especially with regard to whether they are representative of the dump mass under consideration.

Where a rock slope comprises of multiple joint sets, and a dump slope comprises loose soil and fragmented rock which control the mechanism of failure, then a discontinuum modelling approach may be considered more appropriate. Discontinuum methods treat the problem domain as an assemblage of distinct, interacting bodies or blocks those are subjected to external loads and are expected to undergo significant motion with time. This methodology is collectively referred to as the discrete element method (DEM). The development of discrete element procedures represents an important step in the modelling and understanding of the mechanical behaviour of discrete rock and loose soil masses (Deluzarche et al., 2002).

Although codes may be modified to accommodate discontinuities, this procedure is often difficult and time consuming. In addition, any modeled inelastic displacement is further limited to elastic orders of magnitude by the analytical principles exploited in developing the solution procedures. In contrast, discontinuum analysis permits sliding along and opening/closure between blocks or particles (Liu et al., 2003). The underlying basis of the discrete element method is that the dynamic equation of equilibrium for each block in the system is formulated and repeatedly solved until the boundary conditions, and the laws of contact and motion have been satisfied. The method thus accounts for complex non-linear interaction between blocks or even particles at micro-levels.

1.2.1.5.2.1 Hybrid Approach

Hybrid approaches are increasingly being adopted in slope analysis. This may include combined analyses using limit equilibrium stability analysis; and finite element ground water flow and stress analysis such as the one adopted in the GEO-SLOPE suite of the software (Geo-Slope 2000). Hybrid numerical models have been used for a considerable time in underground rock engineering including coupled boundary /finite element, and coupled boundary-/distinct element solutions. Advances include coupled particle flow and finite difference analyses using PFC3D and FLAC3D (Itasca, 2005). These hybrid techniques have already shown significant potential in the investigation of such phenomena as piping slope failures, and the influence of high groundwater pressures on the failure of weak rock slopes (Stead et al., 2006). In order to characterise the micro-mechanical interactions between the particles and anticipate their influence towards the stability analyses along with the continuum considerations of the dump mass for stability assessment, the hybrid approach has been followed for the present study.

Table 1.2: Salient Features of Three Different Numerical Methods

Analysis method	Critical input parameters	Advantages	Limitations
Continuum Modelling (e.g. finite element, finite difference)	Representative slope geometry; constitutive criteria (e.g. elastic, elasto-plastic, creep etc.); groundwater characteristics; shear strength of surfaces; in situ stress state.	Allows for material deformation and failure. Can model complex behaviour and mechanisms. Capability of 3-D modelling. Can model effects of groundwater and pore pressures. Able to assess effects of parameter variations on instability. Recent advances in computing hardware allow complex models to be solved on PC's with reasonable run times. Can incorporate creep deformation. Can incorporate dynamic analysis.	Users must be well trained, experienced and observe good modelling practice. Need to be aware of model / software limitations (e.g. boundary effects, mesh aspect ratios, symmetry, hardware memory restrictions). Availability of input data generally poor. Required input parameters not routinely measured. Inability to model effects of highly jointed rock. Can be difficult to perform sensitivity analysis due to run time constraints.
Discontinuum Modelling (e.g. distinct element, discrete element)	Representative slope and discontinuity geometry; intact constitutive criteria; discontinuity stiffness and shear strength; groundwater characteristics; in situ stress state.	Allows for block deformation and movement of blocks relative to each other. Can model complex behaviour and mechanisms (combined material and discontinuity behaviour coupled with hydro-mechanical and dynamic analysis). Able to assess effects of parameter variations on instability.	As above, experienced user required to observe good modelling practice. General limitations similar to those listed above. Need to be aware of scale effects. Need to simulate representative discontinuity geometry (spacing, persistence, etc.). Limited data on joint properties available (e.g. jk_n, jk_s).
Hybrid / Coupled Modelling	Combination of input parameters listed above for stand-alone models.	Coupled finite difference distinct element models able to simulate material displacement as well as deformability of the material.	Complex problems require high memory capacity. Comparatively little practical experience in use. Requires ongoing calibration and constraints.

Hence, it has been observed that the each of these numerical approaches has some limitations in terms of modelling the actual field scenario. A comprehensive study of the effects of the different modelling approaches towards the stability of the dump slopes need to be undertaken before suggesting the better methods of analyses. The influence of the micro-mechanical interactions towards the stability of the dumps needs a greater consideration. Hence, through this study the researchers have tried to come up with a model for analysing the complex behaviours observed in field conditions.

1.3 Factors Affecting Dump Stability

In this section the dump dimension and site specific factors affecting the stability of mine waste dumps have been discussed, with a mention of the dump stability rating scheme proposed by Piteau Associates (1991). With respect to the study conducted in this work, a number of factors, obtained through the work of earlier researchers, known to contribute to instability are compared and contrasted below:

a) Foundation conditions: Presence of soft soil layer or black cotton soil at the base needs to be considered separately for dumps stability analysis.
b) Dump configuration: Dump heights and angle of repose have been found to significantly influence the stability.
c) Construction conditions: All dumps are constructed as loose, and active dumping continues till the specified height is reached or the surface dumping lease land gets exhausted.
d) Construction materials: Materials characteristics which have been found to be closely associated with the base of the runout zone in the mine external overburden dumps should also be properly considered.
e) Climate: Rainfall has deeper impact on the failure of external mine waste dumps. Rainfall may contribute towards the liquefaction, flowslide, collapse potential, or collapse trigger, and overall progressive failure could explain the instabilities that preceded the flowslides.

Thus, for a realistic dump slope stability (1) a good understanding of the dominant failure mechanisms in the dump slopes, and (2) an analysis tool that can be used to assess the stability of a dump subjected to various failure mechanisms; must be understood before the analysis. The methods of stability analyses span a very wide range. A better analysis method can explicitly account for slope geometry, material conditions, hydrological conditions, and external loading factors.

Hence, the basis for stability study must be an understanding of the failure mechanism in external dump slopes. The failure mechanisms of dump slopes of loose soil, and fragmented rock, are generally poorly understood and/or known. This is due to the fact that wide variety of the dump configurations and material conditions prevail and provide a complex nature of failure. The most important issues to be taken into consideration are:

(1) Conditions for the occurrence of different failure mechanisms;

(2) Conditions for failure initiation (stress levels at which failure starts);

(3) Shape and location of the failure surface;

(4) Effect of dump slope geometry on the mechanism of failure.

Consequently, in order to increase the understanding, there is a need to study these aspects for the most commonly observed and assumed failure mechanism. This includes circular shear failure and crest failure, as discussed in section 1.1.1.

1.4 Scope of Work

A limited amount of failure cases is the main hindrance to quantify the issues listed in section 1.3. Furthermore, the large physical scale of the problem precludes the use of laboratory tests as means of investigating failure mechanisms. Physical model tests present a possible solution, but they suffer from the difficulties associated with down-scaling the material properties. Among the available analysis methods that can be considered, limit equilibrium methods are not suitable, as they require an assumption of failure mode. Traditional limit equilibrium methods (Duncan, 1996a) do not take into account the stress strain pattern (Duncan, 1996b) in the stability analysis of overburden dumps. Also, purely empirical methods are inadequate since they do not provide any new information about failure mechanisms. Probabilistic methods suffer from limitations in the practical applicability under limited number of failure cases.

A more appealing and suitable approach is to use numerical modelling for the study of failure mechanisms and to tune them with the available slope failure cases as observed in the field conditions. The numerical modelling approaches (i.e., finite –element, finite -difference and discrete element methods) show stress strain distribution (Hammah et al., 2004; Koner et al., 2008) for the stability analysis.

In dumps stability, it is very important to know the location of instability. The numerical models (i.e., finite –element, finite-difference and discrete element) can show the regions of probable failure with better accuracy (Shukha and Baker, 2003; Hammah et al., 2005). The particulate nature of the overburden dump materials has characteristic influence on stability. Lump sized boulders and small rock fragments slide down at the dump slope surface similar to grains of sands running down in sand piles. These phenomena do not affect the overburden dump slope stability when they occur in small scale and are localised in nature, whereas heavy rain and dynamic loads may lead to large scale instability. The effect of the presence of loose soil and fragmented rock in the slope mass, on its stability could not be analysed with accuracy with continuum based numerical modelling approach, whereas, the discontinuum based approach takes into account the granularity of the medium and the particle-to-particle interactions for analyzing the stability (Wang et al., 2003; Kim and Yang, 2005). The outputs of the discontinuum based approach could be useful for determining the amount of displacement of the dump slopes as well as the place of failure initiation.

In view of this a comparative study of the continuum and discontinuum based methods has been undertaken for the assessment of external overburden dump stability. Analyses of the effect of dynamic loading impacts at various points on the dump surface may be a precise approach to comprehend the overall stability using the numerical methods for overcoming the insufficient knowledge about the stress-strain state in the dump mass. Analyses of the saturation of effects at the dump slopes may provide useful information regarding the point of strain localisation i.e. place of instability. Coupled effect of these two external conditions may render more near to field assessment in the cases of overburden dump failures. The optimisation of dump space utilisation with site specific conditions would greatly help the on-field mining professionals in the present scenario. Assessment of failure at the tip of dump surface could be the bench mark of the present research work.

Collection of the dump samples for estimation of the geotechnical properties of the slope materials is a big challenge faced by the researchers. Thus characterization of the dump materials for subsequent analyses and assessment of the stability under the complex site conditions considering the saturation effects, the dynamic loading effects and effect of varying slope dimensional parameters with conventional analytical approach, and comparing the outputs obtained with those of the continuum based, discontinuum based and hybrid approach needs a lot of research. Under the limited resources this study has concentrated on analyzing the effect of these parameters on the stability of the external overburden dumps in the Wardha Valley Coalfields, India.

1.5 Objective

The objective of the present investigation is to apply numerical methods for

a) Optimizing the dump slope angle for maximum overburden accommodation capacity.
b) Analysing the effect of saturation and dynamic loads for dump stability.
c) Modelling the micromechanical behaviour of the overburden dump and their influence on the stability of dumps.

To achieve the above mentioned objectives, the following tasks have been undertaken for the present study:

1. Collection of field data (location of external dump, area covered for old dump, area specified for running dump, location of nearby nullah, black cotton layer thickness, borehole log of the site, present and final stripping ratios of the project etc.) and external overburden dump sections. Collection of field sample from the selected eleven mine sites following a standard sampling plan.
2. Determination of geotechnical and physical characteristics of the collected dump samples in laboratory. A total of 252 samples have been used in the present study.
3. Execution of continuum based static numerical modelling of the overburden dumps by varying dump height, dump slope angle, BCS thickness under various material characteristics obtained in the laboratory, to obtain the safe dump dimensions for the analysed cases. Depending on the availability three types of external dump have been selected from each of the 11 mine sites for the present research work. The saturation level was varied in the numerical model for the external overburden dumps to study the stability under wet condition.
4. Investigation of the safe geometries, found from the above study, under dynamic loading conditions by pseudostatic analysis and fully dynamic analysis.
5. Execution of the biaxial simulation and the angle of repose test to obtain micromechanical parameter(s) necessary for the discontinuum modelling.
6. Investigation of the micromechanical interactions using the discontinuum approach for dry conditions for the safe geometries.
7. Comparison of the micromechanical modelling results with the hybrid approach for a small number of safe geometries for understanding the slope failure

mechanism under the combined effect of particle-to-particle interactions and material deformability.

8. Collection of some of the recent dump failure data from field studies for comparison with the outputs obtained from each of the numerical models.

The work flow followed for the present investigation has been presented in Figure 1.8.

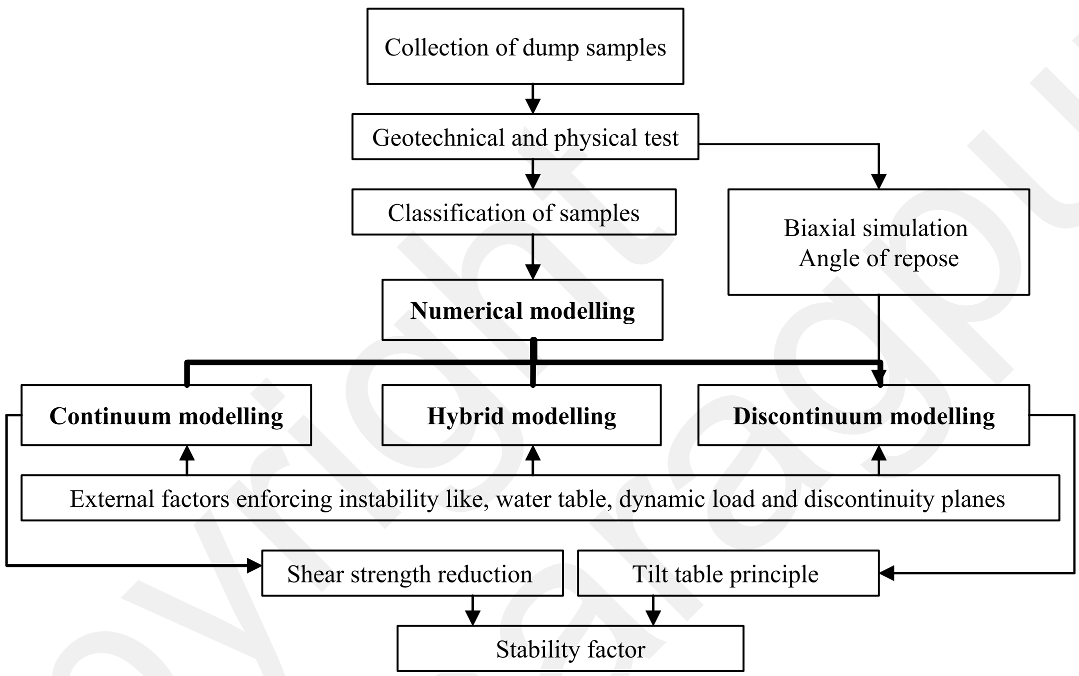


Figure 1.8: Work Flow Chart of this Study

The method followed in this study for analysing the stability of the dump slopes may be broadly subdivided into three distinct tasks: (1) geotechnical characterisation of the dump material, (2) development and establishment of the approach for numerical modelling of dump slopes; and (3) application of modelling approach to the study of dump failures including the case studies, and thus attempting to resolve the issues listed above in section 1.3.

The first task concentrated on characterization of the dump materials using the laboratory tests following the standards. This primarily consists of proper sample collection, followed by sample preparation and laboratory testing. The analyses of these outputs have been used for the next two steps to study the stability of the external overburden dumps.

Numerical modelling is not without its difficulties. Models may quickly become very complex, and there are many pitfalls for the user. Consequently, there is a need for a methodological description how to apply modelling to external overburden dump slope problems. This is the objective of the second task outlined above, which includes the selection of a suitable numerical code, as well as resolving the particular aspects of modelling dump slope stability problem.

The third task constitutes, the numerical analyses applied to study failure mechanism for some typical generic slope geometries as well as the case studies. This exercise is not intended to simulate a particular case in detail; rather it explores general characteristics of various failure cases. In this study, attention is primarily focused on circular shear failure.

1.6 Important Findings from the Present Investigation

The investigation carried out in the present study clearly demarcates the importance the numerical approaches for better understanding of the failure mechanism in the external overburden dumps. The limitations of each of the numerical modelling approach has also been studied for their suitability to (1) capture the field conditions in terms of material characterization, (2) analyse the particle-to-particle interactions leading to failure, and (3) similarity of the numerically failed surface with the field scenarios. Apart from these, the effects of the saturation and dynamic loading conditions have also been investigated.

The mode of generation of the external dumps have been analysed and the most stable dump dimensions as well as their shapes have been obtained under the existing field conditions.

Micromechanical modelling of external overburden dumps composing of loose soil and fragmented rocks helps the investigator to find the detailed displacement profiles along the dump surface as well as the location of failure arising due to loss of contact bonds at particular stress levels. These observations corroborate well with the fields observations especially in the case of crest failures.

1.7 Thesis Organization

The thesis is divided into five main chapters apart from the conclusion and references. The basics of the external overburden dump stability problems have been discussed in the introduction chapter. The failure types and stability investigation carried out in the earlier works has been mentioned in this section. Objective and tasks for the present research work have also been discussed in this chapter.

Chapter 2 presents a detailed study on the geotechnical sampling scheme and testing methods. The sample collection program for 252 samples has been discussed at length. Several parameters for physical and strength properties (specific gravity, grain size distribution, Atterberg limits, compaction characteristics, shear strengths) of the dump materials have been determined using standard techniques as per ASTM specification. The physicochemical properties have also been studied using standard methods. The dump samples have also been classified in accordance to universal soil classification system.

Chapter 3 presents the theoretical backgrounds of the used methods in this research work. The first one, the continuum based numerical approach, has been discussed with its different initial conditions, boundary conditions, and material constitutive laws at different loading conditions. And the second, the discontinuum based DEM approach, has also been discussed at length. The particle size, contact laws and bond characteristics have been discussed. The method of hybrid approach as part of DEM has been discussed in this section.

Chapter 4 presents a detailed analysis on continuum based approach. This part has been subdivided into several parts namely, parametric analysis, case study, dynamic loading conditions and the effects of saturation on dump slope stability. Single stage, double stage and triple stage dumping patterns have also been numerically analysed. The ranges of the parameters studied in this part are dump height varying from 10 m to 90 m, slope angle from 20° to 45° and berm widths from 12 m to 25 m for geometric optimisation of the dump slope configuration in the studied coalmines area. The dynamic loading conditions have been discussed using two approaches, (1) pseudostatic and (2) fully dynamic approach. The Relative displacement developed due to these dynamic loads has been compared for various cases. The last part of this chapter deals with the effects of saturation on dumps stability.

Chapter 5 presents the micromechanical approach for dump stability problems. The difficulty of determining the micromechanical parameters in laboratory is overcome by numerical simulation, first biaxial simulation and second angle of repose test. The synthetic material has been scaled to that of physical overburden dump sample by repetitive methods. In a similar way, the angle of repose test has been carried out. The micromechanical modelling has been performed for both static loading and dynamic loading conditions. The displacement profile has been compared for continuum and micromechanical approaches for similar loading conditions and other physical parameters. The chapter ends with the analysis of a limited number of cases with hybrid approach.

Chapter 6 summarises and concludes the salient points of this research work. The scope of the future work has also been outlined.