CHAPTER 2

Literature Review

2.1 General

Opencast mines are the highest production mining methods and generate huge amounts of overburden waste material, which has to be dumped either inside the mining area in the form of internal dump or outside the mining area as an external dump. The dragline machine with dumper-shovel combination is used more effectively in the removal of overburden material. The shovel-dumper combination is commonly used to remove the upper layers of overburden strata and dragline side-cast the overburden which is close to the coal seam. Dragline is used in very large open cast coal mine where coal seam is at lower depth along with relatively flat dipping and the ground surface should be horizontal (Westcott, 2004).

The dragline primarily side cast the overburden material inside the pit and forms an internal dragline dump. Internal dumping methods are the most economic waste dump management method adopted in the major opencast coal projects in India (Rai et al., 2012; Mitra and Saydam, 2012). The dragline can at max excavates 50 to 80m depth and for more overburden thickness dumper-shovel combination can be used, but with increasing thickness of overburden contrarily affects its cost effectiveness and removal of the waste material becomes expensive due to the increase in the material rehandling (Mitra and Saydam, 2012). Figure 2.1 shows the operation of dragline in an opencast coal mines. Dragline is restricted to certain limitations which are subjected to its physical capabilities and geological conditions of the mine such as;

1. It requires large deposits to ascertain enough strip length and huge reserve because of high capital requirement.

2. Dipping of strata should be gentle.

3. Shallow deposits preferably,

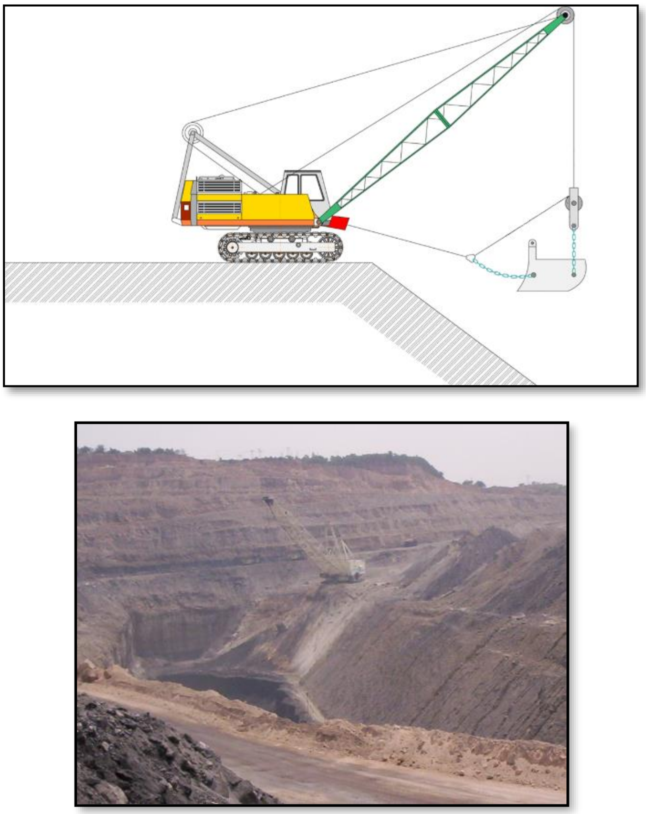


Figure 2. 1 Working of dragline in opencast coal mines.

2.2 Internal dragline Overburden Dumps

2.2.1 Introduction of dragline dump

In India, the draglines are best suited to flat deposits that consist of relatively flat-lying coal seams and overburden. The optimum positioning and operating sequence are relatively simple for a single-seam deposit for multiple-seam deposits. The relative thicknesses of inter burdens and seams result in a more complex operating sequence where dragline cuts may be supplemented by other stripping methods. There are various parameters that govern the selection of the best digging method, such as the combination of geological conditions, size, and characteristics of the dragline and management of the planning targets. The geological conditions, such as the characteristics of the coal deposit, the number of coal seams, the thickness of inter-burden, overburden, and coal seams, are the most crucial factors that are kept under consideration while choosing the appropriate digging methods. Apart from these, other factors such as blasting techniques, material strength, dump stability, engineering, and operator experience also play a significant role in selecting the desired digging method. The presence of various factors has resulted in a wide variety of strip-mining methods. The standard stripping methods are:

1. Simple side cast
2. Extended bench
3. Split bench
4. Chop-cut in-pit bench
5. Extended key cut
6. A variety of multi-pass techniques. (H. Mirabediny and E. Baafi, 1998)

In India, dragline mining was introduced in the early sixties in the former NCDC coal mines. The first walking dragline was introduced in the Kurasia mine of the SECL in 1961. Apart from this, in 1961, two P&H model crawler dragline machines of similar capacity were commissioned, each at South Balanda of the MCL and Kurasia of the SECL. Later, two draglines of similar capacity were introduced in the Bisrampur of SECL and one in Umrer of the WCL in 1965. Thereafter, dragline mining became very popular in India because of its efficiency and higher production rate without using other hauling machines.

The dragline has gained much more popularity in the past few decades in India for handling the overburden waste material in opencast mines. Currently, almost 43 draglines are working in the Indian coal mines, which handle approximately 22% of the total overburden waste material, and the dragline buckets range from 5 to 30 m^3 (Balamadeswaran et al., 2004). The dragline is one of the most expensive heavy machineries deployed in any opencast coal mine. Therefore, it is mandatory to monitor the dragline machine's proper operation under operable conditions (Rai et al., 2011).

Desirable geo-mining conditions are –

1. Large coal reserves
2. Flat gradient of the coal seam
3. Higher thickness of the overburden and coal seam
4. Large strike length
5. The coal reserve free from the significant geological/structural disturbances
6. High production requirement

A generalized dragline mining method has been shown in Figure 2.2, which describes that the dragline is sitting at the top of the overburden bench and side-cast the overburden material in a proper sequence to expose the coal seam. Dragline removes the overburden in a sequence of key-cut, main-cut, and re-handling areas mentioned in the Figure2.2. The dragline side-cast the key-cut material first, after that, removes the main cut and re-handling area, which is dumped into the narrow and long de-coaled area from where the coal has already been extracted. It is clearly shown in Figure 2.2, how the removed cross-sectional geometry of key-cut, main-cut, and re-handling material has been placed on the dragline dump side. A similar operation of removal and deposition of overburden dump is being carried out parallelly to the pit to expose the coal seam (Mohammadi et al., 2016).

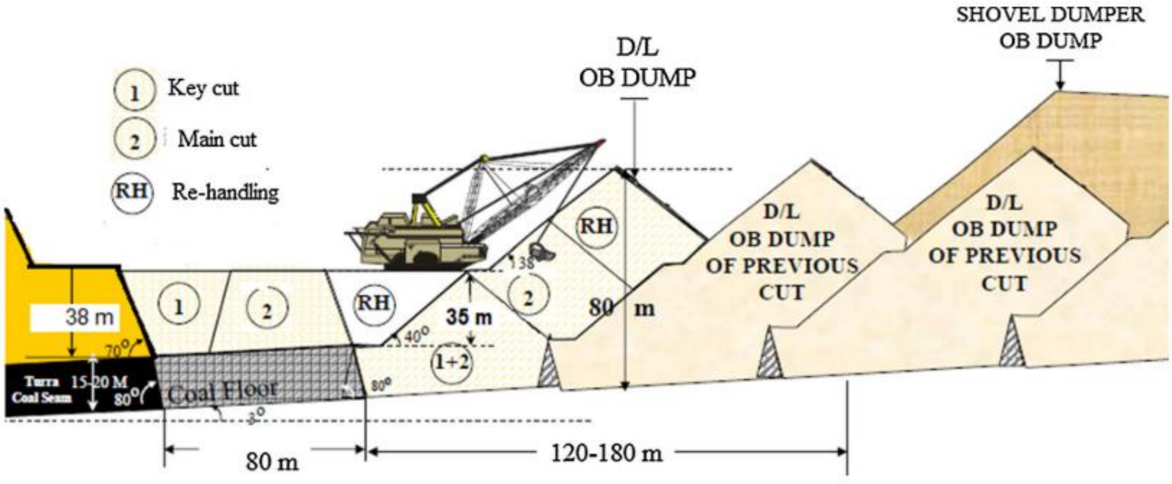


Figure 2. 2 Generalized dragline mining method.

2.2.2 Types of failure in dragline dump slope

There are many types of failure in slope. It can be divided into two types of failure, i.e., slope failure in rock slope and failure in dump slope or soil slope. The stability of rock slopes is mainly governed by rock characteristics and geological discontinuities. Various failure modes that have been described in literature (Pernichele and Kahle, 1971; CANMET, 1977; Caldwell and Moss, 1981; Blight, 1981; McCarter, 1985). Major Failure modes in dragline dumps can be divided into two types. One is the failure of the dragline dump slope, and the other is the failure of the Coal rib.

Further, the failure in dragline dump slope is classified into edge slumping, plane failure, wedge failure, flow failure, rotational failure, and composite failure. Generally, deepseated failure cannot be observed in the dragline dump slope due to the presence of a hard layer underneath the coal seam. Coal rib provides extra support to hold the dump slope; therefore, coal rib failure also ultimately leads to the failure of the dragline dump slope. The Figure 2.3 shows the failure of the dragline dump slope. The failure in dragline dump slope also involves complexity that includes both types of failure simultaneously.

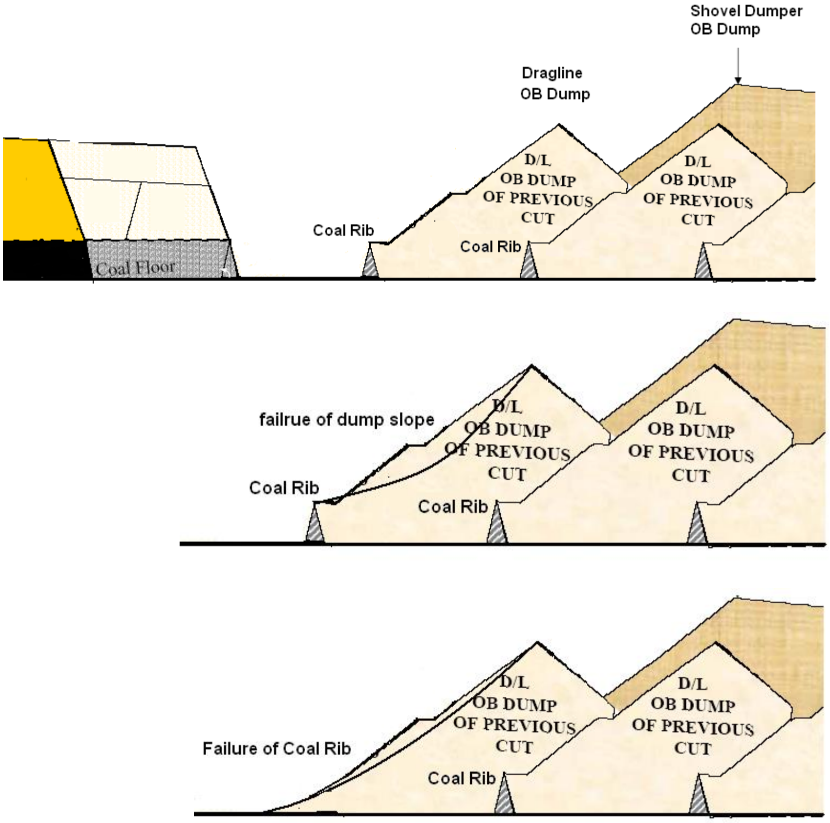


Figure 2. 3 Profile of the dump after (a) failure of dump slope and (b) failure of coal rib

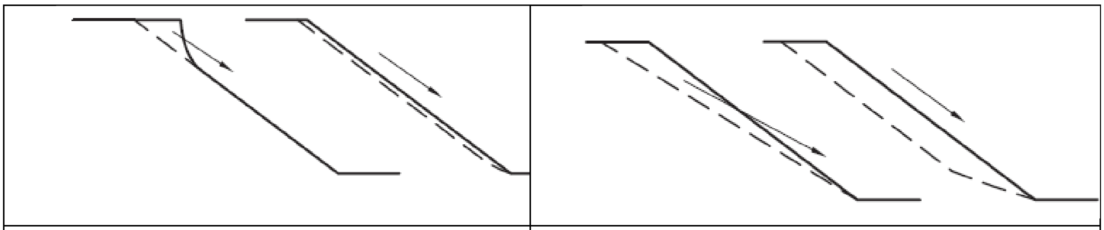
Edge slumping, also referred to as crest slumping or sliver failure is probably the most commonly observed mode of failure in large waste dumps and stockpiles (Figure 2.4(a)). All dumps formed at their angle of repose are potentially subject to the development of small failures. This failure mode involves sliding a thin wedge of material, usually originating at or near the crest, parallel to the dump or stockpile face. This type of failure generally results from over-steepening the dump face at the crest.

Over-steepening may be due to the presence of fines or cohesive waste materials or due to moisture. Failure commonly occurs when heavy precipitation relieves negative pore pressure in the fines, resulting in a loss of apparent cohesion. Edge slumping may also occur where slaking of dump materials creates a low permeability layer on the dump face, permitting the development of high pore pressures at a shallow depth. Heavy precipitation may also trigger failure in this case. Over-steepening of the dump/stockpile crest may also occur in coarse rockfill slopes. The interlocking of rock blocks may result in over-steep repose angle slopes at low confining stress. Subsequent slope creeps, dynamic disturbances, or stress changes may result in the failure of the interlock, resulting in edge slumping. Edge slumping commonly results in loss of the dump crest area and is most likely to occur in dumps constructed by end dumping in thick lifts. Push dumping, where dozers are used to push material over the crest rather than end dumping directly over the crest, and rapid rates of crest advancement also tend to promote the over-steeping of the crest. Analysis of this mechanism is typically not beneficial, as the factor of safety of the angle of repose slopes is unity by definition. These failures usually mobilize relatively small volumes of material and are managed by operational procedures and monitoring.

Plane failure involves sliding along a single plane of weakness within the waste dump and is a common mode of failure of dragline spoils. Where the plane of weakness does not daylight on the waste dump face or at the toe, some shearing through the dump or stockpile material at the toe may occur in a bi-planar failure mode. Weakness planes may be created parallel to the waste dump face if fines of waste or overburden material are dumped over the crest and form a weak zone or layer parallel to the face Failure (Figure 2.4(b)). Weakness planes may also be created where dump material slakes or degrades due to exposure or shear strain within the dump. High pore pressures within the waste dump may also contribute to plane failure. The plane of weakness parallel to the waste dump face tends to be deeper within the waste dump; therefore, failure can result more substantially.

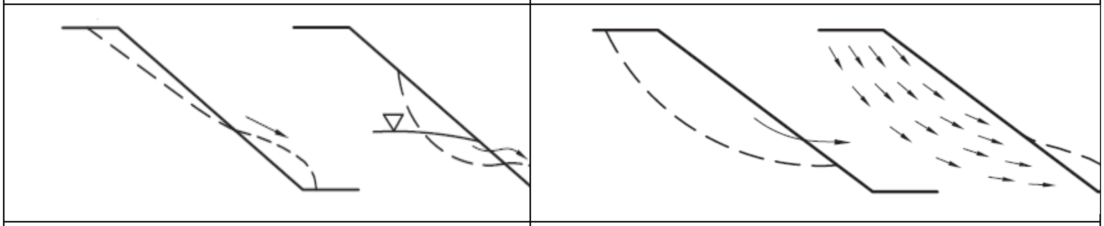
Flow failures from the waste dump face can typically be shallow and can be characterized as debris flows, mud flows, or flows slides. These failures generally involve shallow slumping and subsequent fluidization of saturated or partially saturated material. The flow's volume and velocity may increase downslope due to lateral confinement, increasing momentum, with erosion and entrainment of the underlying material (Figure 2.4(c)). Flows may develop in response to saturation of the dump due to high precipitation and infiltration, development of perched water tables, or concentration of runoff on the dump. Generally, the potential for flow type failures is higher for low-density, loose fills composed of fine-grained materials and lower for very dense, consolidated fills with few fines. Infinite slope analysis, considering seepage forces, is the traditional approach for assessing flow failures.

Circular failure: Circular failures generally occur in weak rock or soil slopes. While failures of this type do not necessarily occur along a purely circular arc, some form of curved failure surface is usually apparent. Circular shear failures are influenced by the size and mechanical properties of the particles in the soil or rock mass. Figure 2.4(d) illustrates the circular shear failure mode. Circular shear failures are closely related to step path failures. This failure mode can occur in rock structures that exhibit no planes of weakness and may not be associated with any underlying critical discontinuity.



(a) Edge slumping

(b) Plane failure



(c) Flow failure

(d) Circular failure

Figure 2. 4 Profile of the dump after failure (a) Edge slumping (b) Plane failure (c) Flow failure (d) Circular failure

2.2.3 Factor affecting dragline dump slope

The factor affecting slope stability depends on the type of slope failure and rock mass conditions. Slope failure occurs due to the downward movements of overburden material or shear stress exceeding the frictional resistance or shear strength. Therefore, factors that increase the shear stress or decrease the shear strength increase the chances of failure. The factor affecting Dragline dumps can be classified into, i.e. geotechnical properties, water, the geometry of the dump slope, erosion, and blasting.

2.2.3.1 Geotechnical properties

The geotechnical properties affecting the slope stability are particle size distribution, shear strength of dump material, density, permeability, moisture content, plasticity, etc. Materials that are coarse or have a rough texture have greater opposing frictional forces, and shear strength resists the movement. Unconsolidated material, such as sediment and soil, with no strong cementing property or interlocking crystal structure, is far less stable than hard rock. Unconsolidated materials, therefore, naturally assume gentler slopes.

Shear strength depends upon many factors, such as material type, loading rate, degree of compaction, and moisture content. The dragline dump slope's stability also depends on the shear strength of the interface between the coal Rib & and base and between dump material & foundation.

The presence of clay minerals gives more plasticity to the soil, which is one of the most important causes of slope failure. The presence of clay minerals results in a rapid decrease in cohesion during rainfall, as loss of surface frictional contact between the grains is due to high water absorption (Behera et al., 2016). Mineralogical tests indicate the presence of significant quantities of medium-order dispersive and swelling clays, including montmorillonite. Their presence is responsible for the high degree of slaking and swelling shown by much of the spoil material. The spoil material is characterized by considerable variability, and this results from lithological variations along the strike of the mine, vertical stratification in the overburden, and the rolling and depositional structure formed during the construction of the spoil pile (Richards et al., 1981)

2.2.3.2 Groundwater and Rainfall

In terms of rainwater or groundwater, the water can modify the shear strength of the dump material and create pore water pressure if water is not drained out from the dump material. Many works have been done on the rope of water in slope stability; however, the effect of water on dump stability is limited. The pore water pressure can also be generated due to the accumulation of water table within the dump mass behind the coal rib. Hence the accumulation of water strata within the dragline dump mass is one of the major causes of the accident. Richards et al., (1981) discussed water transportation and percolation through dump mass out-of-the-toe areas, and large quantities of water may seep down through discrete zones in the spoil to the base. There is also a possibility of water flow from the floor below the spoil due to loosening and cracking of the floor and base of the spoil during the construction (Richards et al., 1981).

Rainfall infiltration affects pore-water pressure distribution within the slope and also reduces the frictional strength of the slope material (Verma et al., 2013). The decrease in shear strength may initiate movement in the dump slope along the weak plane. The migration of rainwater may enhance the discharge, leading to the development of tension cracks at various places of the dump slopes. Tension cracks are also generated due to shocks and ground vibration caused by poor blasting (Verma et al., 2013; Behera et al., 2016).

The water pressure is one of the main causes of the dump slope failure in NCL mines (Singh, 2010; Roy and Sengupta, 2014). There was water pressure due to the accumulation of the water table because of seepage within the dump mass in the western section of the mine. Hence the accumulation of water strata within the dragline dump became the cause of the accident. It is crucial to mention that during the mine operation at Jayant opencast mine, a slushy layer of 1-2m crushed rock and coal dust mixed with water accumulated on the mine floor, over which the dragline dump was formed. This slushy layer reduced the strength of the interface material, which acted as slippery material at the base of the dump. Accumulating a thick slushy layer on the dump floor became another cause of the accident.

2.2.3.3 Geometry of slope

The most important parameters that affect slope stability are the height of the dump, slope angle, and angle of repose of the overburden material. The critical slope height depends on the foundation's cohesion, density, and bearing capacity. Slope stability generally decreases with the increase in the height of the dump. As the slope height increases, the shear stress around the toe of the dump slope increases due to added weight of the dump. Shear stress is related to the mass of the material and the slope angle. The steeper the slope, the greater the tangential or shear stress component. The geometry of the dump is generally considered in 2D for simulation. However, real dump slope failures are usually three-dimensional. The geometry of spoil piles is also fairly uniform along the pit, so a two-dimensional plane strain approximation is reasonable for the analysis of such failures. A two-dimensional model is less accurate for the observation of highwall failures. However, the material distributions and failure characteristics suggest that it would still provide a valid first approximation in this case (Richards et al., 1981).

One of the major dump failures that occur at Jayant opencast mine is dragline-cum-shovel dumper combination with two draglines each in the eastern and western wings of the mine. The dragline excavates the rock parting between the bottom most coal seam, i.e., turra coal seam, and the intermediate coal seam, i.e., purewa bottom seam.

Coal rib is left as a barrier with a full height of 18 m of bottom most seam throughout the strike length of the mine. At the pre-failure stage, rib dimensions were 10m at the top and 17m at the bottom. The bigger dimension of the coal rib holding the dump mass was also one major reason for forming a steep dump slope of 45 degrees and a height of 85m (Roy and Sengupta, 2014).

From January 2008, there was a sudden increase in the volume of waste rock removal due to the presence of a hill in the dip side of the mine. As a result, the extra volume of waste rock excavated by shovel was dumped by the dumpers above the dragline dump, which acted as an additional surcharge load. This made the dragline dump profile angle steeper and reduced the berm width at the dragline sitting level. Therefore, the overall slope of the dragline dump was 45 degrees with the horizontal plane for an overall dump height of 85m before failure took place at the accident site. Hence, the steep slope of the dragline dump profile was one of the major causes of the accident (Roy and Sengupta, 2014).

2.2.3.4 Erosion

Two aspects of erosion need to be considered. The first is large-scale erosion that could erode the base of a dragline dump or below the dragline dump. The second is relatively localized erosion caused by groundwater or surface runoff. In the first type, erosion changes the geometry of the potentially unstable dump. The removal of material at the toe of a dump may create a potential sliding surface and reduce the restraining force that may stabilize the slope. The resulting decrease in shear strength may allow a previously stable dump mass to move. In addition, localized erosion may also result in increased permeability and groundwater inflow.

2.2.3.5 Blasting and Earthquake

Seismic waves pass through rock mass /dump slope and add stress which could cause fracturing in rock mass or dump slope. Friction is reduced in unconsolidated masses as they are jarred apart and liquefaction may be induced because of the vibration caused by the blasting. In a blasting event, typically, 7–25% of energy is estimated to be used in fragmentation and throw i.e. useful work (Sanchidrian et al., 2007). The rest is wasted in the form of blast-induced ground vibration, air-blast, fly-rocks, heat, light, and noise, as shown in (Bhagade et al., 2021). This blast vibration also passes through dump mass and reduces the friction between dump material for a very short duration.

2.2.4 Stability analysis of dragline dump slope

The stability of the dragline dump is important for the smooth running of the dragline. Many researchers have used limit equilibrium, finite element, finite difference, and distinct element methods for stability analysis of dragline dumps.

2.2.4.1 Limit equilibrium method

Singh (2010) has conducted geotechnical studies to know the possible reasons for the 17m high coal rib failure and the associated dragline dump failure at Jayant Project of Northern Coalfields Ltd., Singrauli, Madhya Pradesh, India. The samples of dump material were tested in the soil and rock mechanics laboratory of CIMFR. The slope stability analyses were done under different geo-mining conditions to understand the effect of the variability of the various parameters of the dump profile on dump slope stability. The factor of safety of the dump slope with its most likely profile was 0.98. The saturation of the dump base due to the presence of coal rib (it holds waterflow as a barrier), cross-cut, and dumbbell, non-existence of planned corridor width at dragline sitting level, and dumping of overburden rehandled from dumb-bell by dragline over the dragline dump would have most likely caused the dump failure. The saturation of dump base due to presence of coal rib, mid-entry and dump bell, non-existence of bench at dragline sitting level and extra dead weight of the re-handled dump bell material over the dump would have most likely caused the dump failure.

Rajkovic et al., (2010) carried out a stability analysis of the Internal waste dump “Kutlovaca” of the coal open pit mine “Potrlica“– Pljevlja using the GEOSTUDIO software using SLOPE/W based on the Limit equilibrium method. The calculation was made using Morgenstern – Price, Bishop, and Janbu methods. The impact of groundwater on stability was modelled by the pore water coefficient.

Roy and Sengupta, (2014) have proposed the guidelines for a safe dragline dump profile under the geo-engineering conditions of coal mines in Coal India using various case studies and simulations by the limit equilibrium method. They have also considered the dynamic effect of blasting on slope stability. The interface material on an inclined floor of the quarry may act as a plane of weakness at the foundation of the dump, which is one of the major causes of the failure. Geotechnical parameters (Moisture contents, Grain Size Distribution, Atterberg Limits, Cohesion, Angle of internal friction, and Bulk density) play an essential role in dump stability.

Poulsen et al., (2014) have performed a back analysis of dump slope failure in the open cast coal mine and investigated the probable mechanism of the overburden dump failure. They used both limiting equilibrium and continuum numerical methods to understand and identify the failure kinematics of the dump failure. It has been found that the residual friction angle of the material comprising the dump structural unit dominates the stability.

Rai et al., (2012) performed a stability analysis of an internal dragline dump of an opencast coal mine. Stability analysis of the dragline dump has been done using the limit equilibrium method (LEM). The sensitivity analysis has also been conducted by considering various geotechnical parameters, namely, the number of dragline cut, the thickness of coal rib, the height and slope of dragline dump, cohesion, and friction angle of dump material. The sensitivity indices of the above geotechnical parameters have been calculated. The results concluded that the friction angle of dump material has the highest sensitivity value, followed by the slope angle, the height of dump, cohesion of dump material, number of dragline cuts, width of coal rib, and gradient of the seam.

Sharma et al., (2015) have performed the identification of failure surfaces in dragline dumps of opencast coal mines of Northern Coalfields Limited (NCL), Singrauli, India. They have also identified the different failure patterns and modes within the overburden dragline dump masses fail, along with the derived failure path. The geotechnical properties of six mines of NCL have been determined using a large-size shear box testing machine. All the simulations have been done by limit equilibrium methods.

Behera et al., (2016) carried out the stability analysis of dump slope of an opencast coal mine at Talcher coalfield, Angul district, Odisha, utilizing different geotechnical parameters and mineralogical composition affecting the dump slope. The area has received prolonged rainfall, leading to dump failure and loss of valuable life and properties. The stability of the waste dump was investigated using the Bishop method and Janbu method (limit equilibrium method) to suggest an economical, sustainable, and safe disposal of the dump in the study area.

Golder and Roy, (2017) have done a geotechnical investigation of the dragline dump of Jayant open-cast mines and designed graphs and tables to cover a wide range of each parameter for mine planners and engineers to select the optimum slope geometry of waste internal dragline dumps. They collected overburden samples from mines and performed a large shear box test in the laboratory to calculate dump material's cohesion and friction angle. The average cohesion is 30.065 kPa, and the friction angle is 22.7 degrees. Fellenius Method based on the Limit equilibrium method has been used to calculate the safety factor.

Kumar and Roy, (2022) have taken a case study of Rajrappa Mines, Ramgarh district, Jharkhand, for stability analysis of the internal dump. They analyzed various

Geotechnical aspects of dumps and the mineralogy of the slope. They have used Fellenious Method to determine the factor of safety.

2.2.4.2 Finite Element and finite difference Method

Verma et al., (2013) used the finite element method for stability analysis of the internal dump slope in the Wardha valley coalfield, India Maharashtra. Plaxis2D V8 has been used to simulate the dump slope, understand the failure mechanism, and determine the effect of bench height and the number of benches on the factor of safety.

Kainthola et al., (2011) used a failed dump slope case study in western coalfield limited and evaluated the failure condition using the finite element method. The sample has been collected for testing from dump material consisting of loose fragments and lumps of friable sandstone, shale, clay, and carbonaceous shale. The factor of safety was found to increase logarithmically with a reduction in dump slope angle while keeping the dump height constant at 75 m. The numerical study comprehensively explains the slope failure mechanism in weak materials.

Sharma et al., (2011) simulated an Internal dragline dump by numerical simulation considering the stability of coal rib. The shear strength reduction technique was used to determine the factor of safety of the internal dump slope. The analysis indicated that the shear stresses on coal rib increase as the dump height increases.

Rai et al., (2011) carried out the sensitivity analysis of internal dragline dump stability using finite element analysis. Sensitivity analysis has been carried out for geometrical and geotechnical parameters of the dump slope. It has been concluded from the results that friction angle is a more sensitive parameter as compared to the cohesion of dump material. The geometrical parameters of slope angle and dragline dump height are classified as highly sensitive. The height of the main dump could be classified as least sensitive, whereas the gradient of the seam and thickness of the coal rib are medium-sensitive parameters. The Figure 2.5 shows the discretized model of the internal dump slope. They have concluded that very high sensitive parameters are the most critical parameters, and great care should be taken in the use and measurement of these parameters. Minor deviations of these parameters will have more impact on the stability of the dump; therefore, care should be taken to minimize the error in determining this parameter. Error in determining very less sensitive parameters will not significantly affect the stability of the dragline dump slope. Therefore, some errors can be tolerated during the measurement of these parameters.

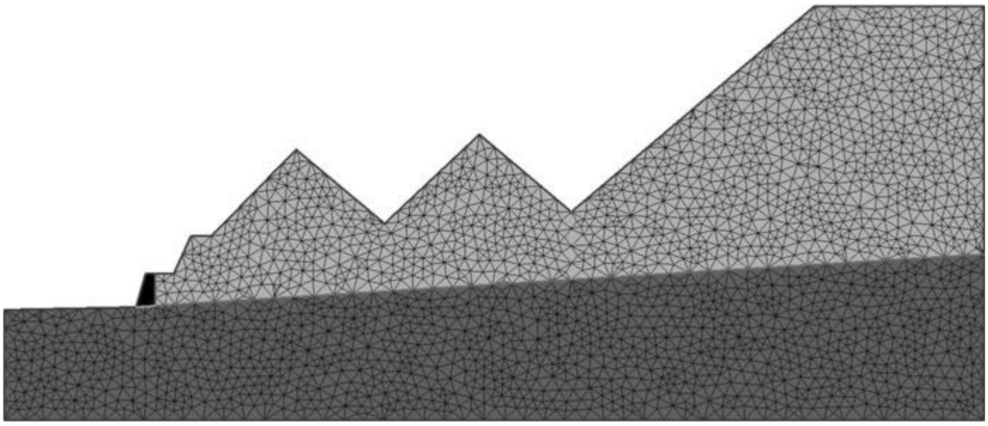


Figure 2. 5 Discretization view of internal mine waste dump

By finite element modelling, Gupta et al., (2014) conducted a sensitivity analysis of coal rib for an internal dump in an opencast mine. They focus more on coal rib stability and determine the effect of dump and coal parameters on the stability of coal rib. The sensitivity index has been calculated based on Lenhart et al., (2002). The factor of safety is more influenced by highly significant parameters. The height, the slope angle of the dragline dump, and the thickness of the coal rib are highly important parameters for the stability of the coal rib. The gradient of the seam is a medium significant parameter. In contrast, the height of the main dump and the number of draglines cut are low significant parameters for the stability of coal rib.

Patel et al., (2018) analyzed the effect of coal rib on dragline dump stability. The parameter of the coal rib is very important for the stability of the dragline dump. The coal rib is a critical parameter for the stability of the internal dragline dump. The base width and top width of the coal rib, the width of the first bench on the coal rib, frictional angle of the coal and dump interface varied to calculate the effect of the stability of the coal rib on internal dragline stability. The dump slope stability increases with an increase in the base width of the coal rib. The factor of safety remained constant after the 10m width of the coal rib at the bottom. The safety factor increases with the bench width at the coal rib top. The optimum bench width is 12m for the present case. The factor of safety is constant after 12.5^0 friction angle of interfaces (i.e., between dump and foundation). The internal dump slope fails if the friction angle of the interface is less than 7.5^0

Rai et al., (2019) investigated the failure of the internal dragline dump slope using the NCL area using the finite element method. The failed dragline overburden dump was found to displace the coal rib and overburden material approximately 80m from the original location of the toe of the coal rib. The location of the failure plane has been determined and found to be through the base of the coal rib left adjacent to the dragline dump during the extraction of coal. The data have been collected from the literature (Golder and Roy, 2017, Singh, 2010; Sharma et al., 2015). The study of overburden dump stability indicated that the interface strength and water were fully mobilized and provided a slip surface for the overlying dump material and coal rib.

2.2.4.3 Distinct element methods

Distinct element is also used to simulate the behavior of overburden. Koner and Chakravarty (2010) have used the PFC software based on the distinct element method and determined stress and strain histories, displacement, failures, etc., at any point at the dump mass, producing a better understanding of the stability of the dump masses. The properties for simulation have been determined by triaxial test in PFC. The distinct modeling has been used to determine the natural frequency of the overburden dumps, damping fraction, and the phase difference at two sides of the dump mass. The results obtained match well with the fundamental concept of the vibration theory. The distinct element modeling simulates the overburden dumps' fragmented and loose soil behaviour. This is one of the novel approaches for the stability study characteristics of overburden dump slopes. This method predicts well the sliding, failure surface, and a particular place of failure initiation with its visualization tools. Interpreting the sliding location will guide the field engineer to take reinforcing and remedial measures to stop failure at its initial stage (Koner and Chakravarty, 2010).

Koner and Chakravarty, (2010) have simulated the earthquake response of external mine overburden dumps using a distinct modeling approach. They characterized the overburden dump geometry and the associated physical behaviour of the dump mass for seismic loads. The study discussed the earthquake vibration responses and assessed the internal dynamics of the dump mass system.

Kumar et al., (2015) simulated the dragline dump and coal rib using distinct modeling using PFC software. They have varied the thickness of the coal rib and amassed its effect on crack propagation. It is concluded that the dump is unstable at a slope angle of 38^0 and stable at a slope angle of 340 (height of 83 m) as shown in Figure 2.6. The flow characteristics of the internal dump are analyzed by varying rib pillar thickness (i.e., pillar thickness of 5m,10m, and 15m). The stable width of the coal rib for the present case is 10 m. It is found that the load-bearing capacity of rib pillar increases with the increase in the thickness of the coal rib.

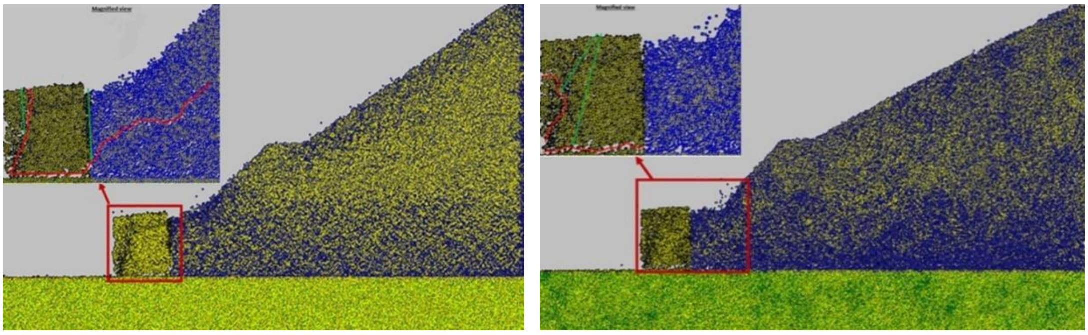


Figure 2. 6 Dump (38^0 angle) and (36^0 angle) after the simulation of models

2.2.5 Risk chart and classification for dump slope stability

2.2.5.1 General

A risk chart or a set of designed charts for homogeneous slopes of simple and typical conditions can be used to predict slope conditions quickly. The chart parameters such as surcharge load, pore water pressure, and seismic loading are produced by the analysis of substantial data along with the factor of safety, which can eliminate the necessity for iterations when calculating the safety factor. These stability charts are presented in a convenient manner to determine the comprehensive safety factors and corresponding failure patterns under different typical conditions, which engineers might prefer for performing the preliminary evaluations of slope safety.

Various classifications have been developed and proposed to assess the engineering behaviour of rock mass. Rock mass classification has been applied successfully in tunnelling and underground mining. Some rock mass classification systems developed originally for underground excavations, have been used for dump slopes or modified for slopes. The major slope stability classifications for rock slopes are slope mass rating (SMR), Chinese slope mass rating system (CSMR), Slope Stability Rating (SSR), rock slope rating (RSR), and Q-slope system for slope stability probability classification.

Researchers have developed three major types of dump slope classifications. Dump stability rating (DSR) System, waste dump and stockpile stability rating (WSR) system, and dump stability classification rating (DSCR) (Hawley and Cunning, 2017).

2.2.5.2 Risk Chart

Various researchers have developed the risk chart for stability dump slope to estimate the factor of safety of slopes with isotropic, homogeneous soil properties and simple geometry. Taylor, (1937) published a design chart to calculate the factor of safety for simple homogeneous slopes in clays with single-value undrained shear strength. Huat et al. (2006) have developed a stability chart for unsaturated residual soil slopes considering rainfall. Michalowski, (2002) used a kinematic approach of limit analysis with a log-spiral failure mechanism, while Baker, (2003) and Steward et al., (2011) used conventional limit equilibrium circular slip analyses to produce their charts. All of these methods are deterministic, and the resulting charts can be shown to give the same factor of safety for the same slope and soil properties. The advantage of the work by Steward et al., (2011) is that they produced a single chart for c- soils that do not require an iterative approach to calculate the factor of safety.

Jiang et al., (2017) have done a quantitative risk assessment of slope failure in 2-D spatially variable soils by limit equilibrium method and developed an empirical approach to identify representative slip surfaces. Javankhoshdel and Bathursthave, (2014) used Simplified probabilistic slope stability design charts for cohesive and cohesive-frictional soils. The data for the design of the chart was produced using conventional probabilistic and Monte Carlo simulation in combination with conventional limit equilibrium-based circular slip analyses using the SVSlope program. Ray et al., (2020) developed a risk chart for the identification of potential landslides due to the presence of residual soil. They have used three critical parameters to predict the stability of residual soil slope in the natural landslide areas. They have concluded that the overall stability of a slope depends on the critical combination of slope inclination, slope height, and depth of the residual soil layer.

Baker and Tanaka, (1999) and Baker et al., (2006) presented complete design charts for slope stability analysis under static and seismic conditions based on the limit equilibrium method (LEM). Michalowski, (2002, 2010) provided a series of design charts considering pore water pressure and seismic forces based on the limit analysis method (LAM). Steward et al., (2011) proposed two design charts for computing soil slope safety factors under five failure mechanisms using the SLOPE/W software. Sun and Zhao, (2013) extended the work of Klar et al., (2011), in which a new graphical approach was presented to obtain convenient charts to estimate the slope safety factor and identify the failure mode.

A set of stability design charts for homogeneous slopes under different conditions (simple condition, surcharge load, pore water pressure, and seismic loading) is presented based on substantial data. These stability charts help in obtaining the comprehensive safety factor rapidly, without any iterative procedures. Furthermore, the type of failure mode can be determined at the same time.

The risk chart will help in accurately evaluating the risk of slope failure with less effort. The only value of importance is required for the evaluation of slope condition. It will also help in the quick identification of the vulnerability of various slope profiles. The risk chart can be used during preliminary investigation in the study area to assist engineers, researchers, and policymakers. However, no risk chart has been proposed for the dragline dump slope.

2.2.5.3 Classification for dump slope

Rock mass classification is an altogether different approach to assess the engineering behaviour of a rock mass. In a classification system, empirical relations between rock mass properties and the behavior of the rock mass concerning a particular engineering application are combined to give a method of designing engineering structures in or on a rock mass. Rock mass classification has been applied successfully in tunneling and underground mining for some years. Some rock mass classification systems developed originally for underground excavations, have been used for slopes or modified for slopes. The significant types of the classification system used for rock slope stability are slope mass rating (SMR), for Chinese condition Chinese slope mass rating system (CSMR), Analytic hierarchy process (AHP), and the Fuzzy delphi method (FDM), Slope stability rating (SSR).

Slope mass rating (SMR) is a classification system developed by Romana, (1993) as an extension of Bieniawski's, (1993) rock mass rating approach for applying to rock slopes.

To assess the slope instability, some parameters are introduced including the attitude of discontinuities, the slope failure modes, and slope excavation methods.

Romana proposed ‘Slope Mass Rating’ (SMR), which was obtained from RMR by subtracting a factorial adjustment factor depending on the joint-slope relationship and adding a factor depending on the excavation method.

$$SMR = RMR + (F1 \,.\, F2 \,.\, F3) + F4$$

The RMR is computed according to Bieniawski’s 1979 proposal, adding rating values for five parameters:

(i) Strength of intact rock;

(ii) RQD (measured or estimated);

(iii) Spacing of discontinuities;

(iv) Condition of discontinuities; and

(v) Water inflow through discontinuities

Romana and Zuyu developed a Chinese slope mass rating system (CSMR). They introduced two coefficients ξ and λ and modified the slope mass rating (SMR) formula.

$$CSMR = (\xi * RMR) + [\lambda * F1*F2*F3 + F4]$$

Here ξ, represents the slope height factor, and λ represents the discontinuity factor. These factors are included in the system because several failures have occurred, but SMR indicates these are stable slopes.

A rock slope rating (RSR) system has been developed to use in evaluating rock slope stability under various geological conditions and engineering requirements. The proposed method, hereafter called the rock slope rating (RSR) system, is intended to be more comprehensive than the slope mass rating system previously proposed.

RSR system evaluates the probability of failure for plane and wedge sliding, toppling, and circular failures. The probability of each mode of failure is determined individually. The main categories for input parameters are geological features, safety requirements, groundwater conditions, slope geometry, joint characteristics, and geomechanical parameters.

The analytical hierarchy process (AHP) and fuzzy Delphi method (FDM) combined for the assessment of slope rock mass quality. This research treats rock classification as a group decision problem and applies the fuzzy logic theory to the criterion of weighting calculations.

The proposed procedure was applied to determine the rating of rock slopes with the hierarchy and weighting factors modified for rock slopes. After determining the slope rock mass quality for each case, the Linear Discriminant Analysis (LDA) model was used to classify whether they are stable or not, and the LDA procedure carried out the discriminant functions, which can determine the failure probability of rock slopes. The main advantages of FDM are that it can reduce the number of surveys to save time and cost and includes the individual attributes of all experts. Thus that can effectively determine the weighting of each parameter with the variation of geological conditions based on only required two rounds of investigations and comprehensive discussions by a group of experts.

Slope stability rating (SSR) considered five additional parameters whose relative effects on the stability of fractured rock slopes were precisely examined based on data retrieved from different rock slope sites. An overall rating for the rock mass is obtained from the summation of the individual ratings of each parameter. Among the number of parameters that may influence the stability of jointed rock masses, besides the discontinuities condition (reflected by the GSI value), the following five parameters were retained in the present study:

1. Uniaxial Compressive Strength (UCS) of intact rock
2. Rock type (Lithology)
3. Slope excavation method
4. Saturation of slope
5. Horizontal earthquake acceleration

The sensitivity analysis was then performed based on the values of the parameters mentioned above. The SSR value is obtained by summation of the individual rating of each parameter, whose relative weight was calibrated based on a number of case studies. The system was additionally reviewed and subsequently modified on those case studies.

2.2.5.3.1 Dump Stability Rating (DSR)

DSR system considers 11 factors and the factors are: dump height, dump volume, dump slope, the foundation of the dump, degree of confinement, foundation type, dump material property, method of construction, piezometric and climatic conditions, dumping rate, and seismicity. Point ratings are assigned to each factor, weighted as per their overall importance, and the sum of the individual point ratings gives the dump stability rating. Point ratings are assigned to each factor, weighted as per their overall importance, and the sum of the individual point ratings gives the dump stability rating or DSR. Greater DSR values inferred lower relative stability and vice versa. As per the range of DSR values (maximum value of 1800), four dump stability classes (DSCs) are classified, and each DSC is assigned a relative ‘failure’ or instability hazard descriptor. For instance, dumps with DSR ratings of less than 200 are set to DSC I (‘negligible’ instability hazard), while dumps with DSR values of more than 1200 are assigned to DSC IV (‘high’ instability hazard).

2.2.5.3.2 Waste Dump and Stockpile Stability Rating (WSR) System

This system incorporates some of the concepts used in the DSR system but with a different structure. It requires calculations of 22 key factors that are thought to affect stability (double that of the DSR system). These 22 factors have been further organized into seven groups, namely regional setting, foundation conditions, material property, geometry and mass, stability analysis, construction, and performance. Each factor is assigned a numerical rating. The sum of these ratings gives the waste dump and stockpile stability rating (WSR).

The maximum WSR is 100, with a higher rating signifying a more stable configuration. WSR values are subdivided into five waste dump and stockpile hazard classes (WHCs). Waste dumps or stockpiles with a very high WSR rating (more than 80) are assigned to WHC I and are characterized as presenting a relatively very low potential for instability (i.e., a very low instability hazard). Conversely, waste dumps or stockpiles with a very low WSR rating (less than 20) are assigned to WHC V. They are characterized as presenting a relatively very high potential for instability.

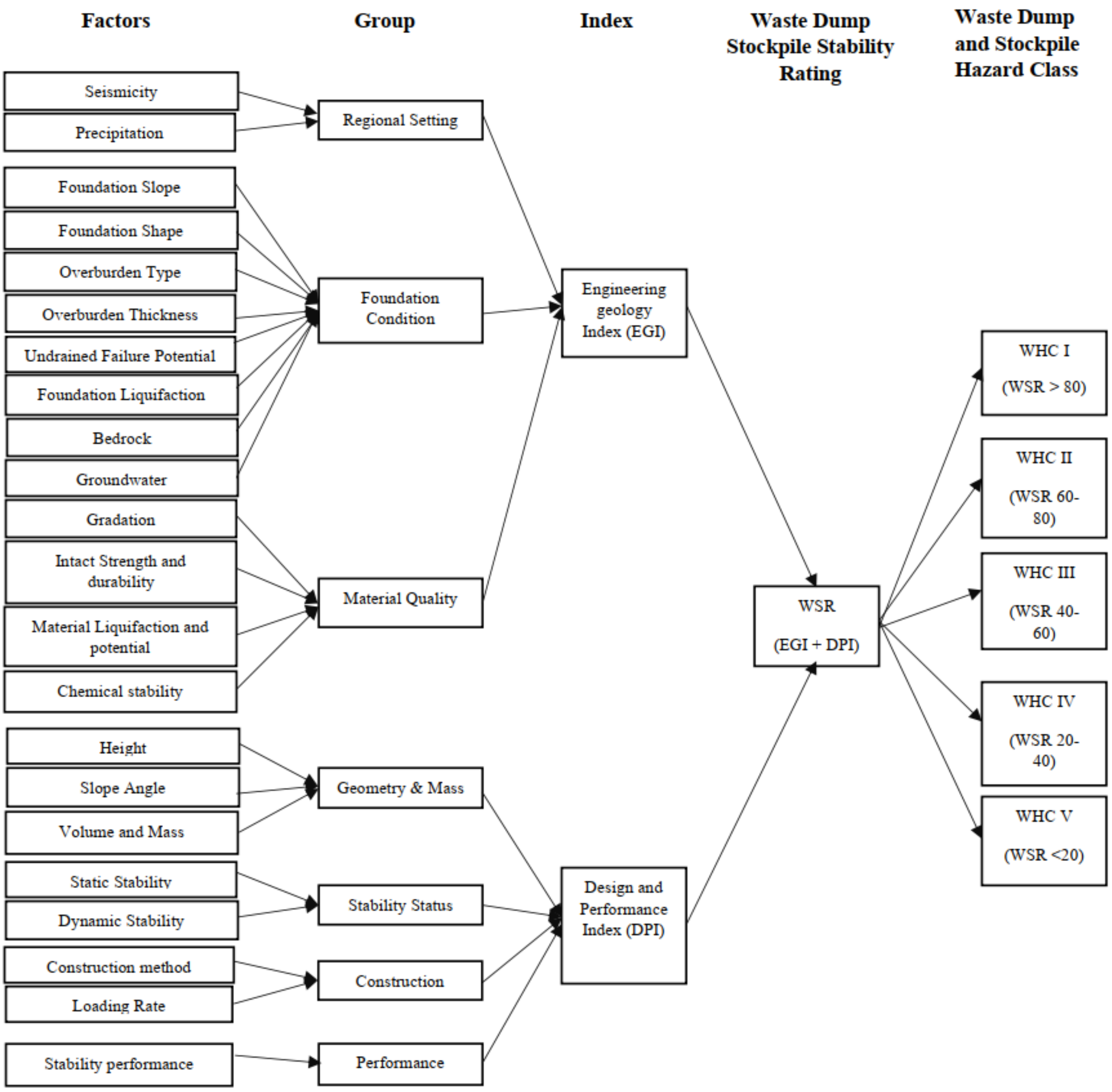


Figure 2. 7 Structure of the waste dump and stockpile stability rating and hazard classification (WSRHC) system

The structure of the new WSRHC system is illustrated in Figure 2.7. The system incorporates many of the concepts that were used in the 1991 DSR system; however, the structure is somewhat different. The new system requires the evaluation of 22 key factors or attributes that are thought to affect stability. These factors have been organized into seven groups. Numerical ratings are assigned to each factor, and the sum of these ratings defines the waste dump and stockpile stability rating (WSR). The maximum possible WSR is 100, with a higher rating indicating a more stable configuration. WSR values have been subdivided into several waste dump and stockpile hazard classes (WHCs).

Waste dumps or stockpiles with a very high WSR rating (more than 80) are assigned to WHC I and are characterized as presenting a relatively very low potential for instability (i.e. a very low instability hazard). Conversely, waste dumps or stockpiles with a very low WSR rating (less than 20) are assigned to WHC V and are characterized as presenting a relatively very high potential for instability (i.e. a very high instability hazard). Intermediate classes (WHC II, III, and IV) represent waste dumps and stockpiles with an intermediate potential for instability/intermediate instability hazard. The detailed descriptions of the various factors that compose the WSRHC system, and guidance in evaluating individual factor ratings are organized into seven groups (Figure 2.7)

Regional setting

The regional setting category includes factors that are related to the geographic location and climate of the site. The key factors in this category are seismicity and precipitation.

Foundation conditions

The Foundation Conditions group includes factors that are related to the physical attributes of the foundation or the footprint of the waste dump or stockpile. The key factors in this group that are thought to potentially affect stability and are applicable to most waste dumps and stockpiles are the topography (Foundation slope and foundation shape), the type and thickness of the foundation soils (Overburden type), the competency and structure of the underlying bedrock, and groundwater conditions.

Material quality

The Material Quality group includes factors that are related to the physical attributes of the materials used to construct the waste dump or stockpile and collectively determine the shear strength, deformational behavior, and hydrological characteristics of the structure. The key factors in this category are gradation (particle size distribution), intact strength and durability, and chemical stability. A fourth factor that could potentially have a substantial negative impact on stability, but is applicable only to a relatively small subset of waste dumps and stockpiles, is the liquefaction potential of the material.

Geometry and mass

The Geometry and Mass group includes factors that are related to the size and shape of the waste dump or stockpile. Larger, higher waste dumps and stockpiles, and those with steeper overall slopes, tend to be more susceptible to instability, and such instabilities tend to be larger and have greater runout and more adverse impacts than smaller, lower and flatter structures. Out of the 16 dumps in the 1991 survey that reported poor or very poor performance, seven (44%) had overall heights of more than 250 m, nine (56%) had overall slopes of more than 35°, and five (31%) exceeded a total mass of 2 × 108 t. The criteria chosen to characterize geometry and mass include various height and slope angle parameters and the bulk volume or mass of the waste dump or stockpile. Collectively, geometry and mass factors are weighted to account for a maximum of 10 points, or 10% of the maximum possible WSR.

Stability analysis

The stability analysis group is intended to directly capture and contrast differences in stability based on the results of objective stability analysis and the acceptability criteria upon which the design is based. As discussed earlier, a wide variety of analytical techniques may be used to analyze the stability of a waste dump or stockpile. These various techniques may be grouped into two basic categories: deterministic and probabilistic. Deterministic techniques are designed to calculate a specific index value that represents stability, such as the factor of safety (FOS) or strength reduction factor (SRF). The FOS approach is the most commonly associated with the limit equilibrium method (LEM) familiar to most practitioners. The SRF approach is more commonly associated with numerical modeling techniques, such as finite element, distinct element, and related techniques, which are becoming more popular.

Construction

The construction rating includes two roughly equally weighted factors, construction method, and loading rate, and accounts for a maximum of 15 points, or 15% of the maximum possible WSR. The construction sequence and rate of development can have a very significant impact on the waste dump and stockpile stability and performance. All other factors being equal, waste dumps and stockpiles that are constructed slowly and from the bottom up in thin lifts are much more stable and perform much better than those that are constructed rapidly using single, high lifts. In this context, performance would include both instability and settlement.

2.2.5.3.3 Dump Stability classification Rating (DSCR)

Dump slope rating has been developed for Indian coal mines using numerical modelling. Various field data have been simulated by using numerical modelling. This system incorporates six parameters, namely, the overall dump height, overall slope angle of the dump slope, number of benches, hydrological condition, the cohesion of dump material, and the internal angle of friction of dump material. Dump slopes are classified into 4 stability classes; A with negligible failure hazard, B with low failure hazard, C with moderate failure hazard, and D with high failure hazard. Based on the rating system dump slopes are divided into various dump stability classes. Dump stability classes are mainly used to recommend the level of effort for the investigation, design, and construction of dump slopes. The level of monitoring, the requirement of support, optimizing the height, and dump slope can be easily done based on the classification.

The 1991 dump stability rating (DSR) system, which is reproduced herein as Table 2.1, established a numerical index based on consideration of 11 factors. Higher DSR values inferred lower relative stability and vice versa. The range of possible DSR values (maximum possible value of 1800) was subdivided into four dump stability classes (DSCs), and each DSC was assigned a relative 'failure' or instability hazard descriptor. For example, dumps with DSR ratings of less than 200 were assigned to DSC I, which was characterized as having a 'negligible' instability hazard, and dumps with DSR values of more than 1200 were assigned to DSC IV and were characterized as having a 'high' instability hazard.

One of the key attributes of the DSR system was the recognition that many factors can impact the stability of a waste dump. The system also provided a qualitative way to assess how varying key design parameters or implementing different mitigative measures could affect stability and to compare the experience and behaviour of different waste dumps at a given site and from one site to another the table shows the details of DSR system.

Table 2. 1 Dump stability rating

Key factors affecting stability		Range of conditions or description	Point rating
Dump height	Low	<50 m	0
	Moderate	50-100 m	50
	High	100-200 m	100
	Very High	>200 m	200
Dump Volume	Small	<1 x 10^6 BCM (bank cubic meters)	0
	Medium	<1x10^6 -5x10^7 BCM	50
	Large	>5x10^7 BCM	100
Dump Slope	Flat	<26°	0
	Moderate	26°-35°	50
	Steep	>35°	100
Foundation Slope	Flat	<10°	0
	Moderate	10°-25°	50
	Steep	25°-32°	100
	Extreme	>32°	200
Degree of Confinement	Confined	Concave in plan or section; valley or cross-valley fill, toe buttressed against opposite valley wall; incised gullies that can be used to limit foundation slope during development	0

	Moderately confined	Natural benches or terraces on slope; even slopes, limited natural topographic diversity; heaped, sidehill or broad valley or cross-valley fills	50
	Unconfined	Convex slope in plan or section; sidehill or ridge crest fill with no toe confinement; no gullies or benches to assist development	100
Foundation Type	Competent	Foundation materials as strong or stronger than dump materials; not subject to adverse pore pressure; no adverse geologic structure	0
	Intermediate	Intermediate between competent and weak; soils gain strength with consolidation; adverse pore pressures dissipate if loading rate controlled	100
	Weak	Limited bearing capacity, soft soils; subject to adverse pore pressure generation upon loading; adverse groundwater conditions, springs or seeps; strength sensitive to shear strain, potentially liquefiable	200
Dump material quality	High	Strong, durable; less than ~10% fines	0
	Moderate	Moderately strong, variable durability; 10–20% fines	100
	poor	Predominantly weak rocks of low durability; greater than ~25% fines, overburden	200
Method of construction	Favourable	Thin lifts (< 25 m thick), wide platforms; dumping along contours; ascending construction; wrap-arounds or terraces	0
	Mixed	Moderately thick lifts (25–50 m); mixed construction methods	100
	Unfavourable	Thick lifts (> 50 m), narrow platforms (sliver fills); dumping down the fall line of the slope; descending construction	200
Piezometric and climatic conditions	Favourable	Low piezometric pressures, no seepage in foundation; development of phreatic surface within dump unlikely; limited precipitation; minimal infiltration into dump; no snow or ice layers in dump or foundation	0
	Intermediate	Moderate piezometric pressures, some seeps in foundation; limited development of phreatic surface within dump possible; moderate precipitation; high infiltration into dump; discontinuous snow or ice lenses in dump or foundation	100
	Unfavourable	High piezometric pressures, springs in foundation; high precipitation; significant potential for development of phreatic surface or perched water tables in dump; continuous layers of snow or ice in dump or foundation	200
Dumping rate	Slow	< 25 BCM/m of crest/d; crest advancement rate < 0.1 m/d	0
	Moderate	25–200 BCM/m of crest/d; crest advancement rate 0.1–1.0 m/d	100
	High	> 200 BCM/m of crest/d; crest advancement > 1.0 m/d	200
Seismicity	Low	Seismic Risk Zones 0 and 1	0
	Moderate	Seismic Risk Zones 2 and 3	50
	High	Seismic Risk Zones 4 or higher	100

There are some limitations due to that above mentioned classification systems could not be used properly for the classification of dragline dump slopes in Indian conditions. The above classification system did not consider the dragline dump and coal rib parameters which is important in dragline dump stability.

2.2.6 Slope Stability Analysis Using Numerical Simulation

Geotechnical engineers primarily use factor of safety (FOS) values, which represent the ratio of shear strength of the slope to shear stress on the slope, to determine how close or far slopes are from failure (Pradhan et al. 2014). Various techniques are available including analytical (Limit Equilibrium) and numerical (Finite Element and Finite Difference) methods which can be used to obtain the FOS of a slope under investigation. Analytical methods which include the limit equilibrium method (LEM) and the circular or non-circular failure surface method utilize the slope displacement model for locating the possible sliding surface and the corresponding FOS. Although analytical methods are computationally efficient, due to their inherent drawbacks such as simplifications of the whole study region and utilization of predefined failure surface, they fail to provide a complete understanding of the slope behavior. Thus, the use of analytical methods is mostly restricted to a limited area having simple slope geometries. In order to overcome the drawbacks of analytical methods, numerical simulation was developed as a theoretically more realistic and rigorous technique for slope stability analysis (Verma et al. 2016). The major disadvantage of numerical simulation is the prolonged solution time required to set up the computer model and perform the analysis (Abdalla et al. 2015). With the development in the field of computation and data analysis, numerical simulation can now be executed within a reasonable period and with higher accuracy. Non-linear modeling using numerical simulation offers a number of advantages over LEM (Griffiths and Lane 1999) including the elimination of a priori assumptions on the shape and location of failure surfaces, the elimination of assumptions regarding the inclinations and locations of interslice forces, the capability to model progressive failure, the calculation of deformations and the incorporation of displacement-controlled ground-structure interaction. The general approach is valid for a wide range of applications. Griffiths and Lane (1999) highlighted some key differences between traditional LEM and numerical methods and elaborated on the advantage of numerical methods over LEM. Numerical methods like the finite element method (FEM) and the finite difference method

(FDM) can model complex behaviours, such as problems that consist of several stages, large displacements, and strains, non-linear material behavior, or unstable systems.

The FOS calculations using FEM and FDM use the shear strength reduction (SSR) technique (Matsui and San, 1992; Duncan 1996; Dawson et al., 1999; Griffiths and Lane, 1999; Hammah et al., 2005). In the SSR method, shear strength parameters (cohesion and angle of internal friction) of slope-forming material are reduced until failure occurs and the critical strength reduction factor (SRF) is calculated which is equivalent to the factor of safety (Gover and Hammah, 2013). The SSR technique involves the use of factored strength parameters in a non-linear numerical method. The shear strength properties of the model material are scaled until the stability limit is reached (Dawson et al., 1999; Griffith and lane, 1999). In this technique, simulation of the slope model is performed in a series of increasing F_{trial}, and the actual shear strength properties friction angle (φ) and cohesion (c)) are decreased with each trial as per the equation shown below:

$$C_{trial} = \frac{1}{F_{trial}} C$$

$$\varphi_{trial} = tan^{-1}(\frac{1}{F_{trial}} \tan \varphi)$$

$$\tau_{trial\,strength} = C_{trial} + \sigma_n \tan \varphi_{trial}$$

$$F_{trial} = \frac{\tau_{trial\,strength}}{\tau_{stress}}$$

where C_{trial}, φ_{trial} and $\tau_{trial\,strength}$ are the reduced value of cohesion, friction angle, and shear strength on each trial, respectively, and the F_{trial} at which the slope model fails is the FOS of the model. The continuum approach to SSR considers a discretized zone in a finite element or finite difference continuum model and uses predefined displacement limits at points of interest or uses model convergence as an indicator of equilibrium. For similar element shape functions, the set of algebraic equations solved in finite element analysis is identical to the finite difference method (Dawson et al., 1999). This factoring of strength parameters allows reinforcement and other external effects to be modeled without modification to determine stability. The approach allows for the reinforcement and the rock and soil mass itself (if heterogeneous) to develop modified internal loads and stresses as a function of pre-yield displacements and strains. Most importantly, the critical failure surface develops naturally during the non-linear solution and does not need to be predefined or determined through optimization algorithms. Brittle or strain-softening behavior and dilation effects are also accommodated.

2.2.6.1 Probability analysis

Generally, tools used in geomechanics, like stress analysis (e.g., FEM and FDM), are deterministic in nature (a single set of input parameters gives single output). So, to develop a reliable design approach, the probabilistic method is used to deal with the variability of the input parameters (Vanmarcke, 1980). The application of SSR, in combination with the probabilistic analysis tool (Monte Carlo simulation), has been used by many researchers to evaluate the FOS and other deformation parameters for soil as well as rock slope (Dawson, 1999; Griffiths and Lane, 1999). It is required that the statistical distribution of all the input parameters is either known or assumed to determine the probability of failure and FOS, by assigning a statistical distribution to one or more model input parameters, this allows the user to account for the degree of uncertainty in the value of the parameters (Vanmarcke, 1980; Singh, 2019; EL Ramly, 2005). Input data samples are randomly generated, based on the user-defined statistical distributions. A given slip surface may then have many different values of safety factor calculated. This results in a distribution of safety factors, from which a probability of failure for the slope can be calculated. The ultimate goal of a probabilistic slope stability analysis is to obtain the complete distribution of factor of safety values given a set of random input variables with specified statistical properties. From the distribution of the factor of safety values, the probability of failure can be determined.

In order to carry out a Probabilistic Analysis, one must define at least one input parameter which may include material property, joint property, or field stress as a random variable. Statistical properties of the selected input random variables used for PA are acquired by statistical evaluation of available geotechnical and geological data (EL Ramly, 2002). The type of statistical distribution (generally normal or lognormal or triangular or exponential for geotechnical parameters), together with the distribution parameters (mean, standard deviation, relative minimum, and relative maximum values), define a probability density function (PDF) for a random variable. In general, the applicable statistical distribution for a particular random variable is generally obtained using curve fitting of the statistical data obtained through laboratory tests, field investigations, and literature reviews. A PDF describes the distribution of possible values that a random variable may assume, for a hypothetical, infinite set of observations of the variable.

After selecting the random variable and identifying its PDF and statistical properties, the PA is performed using various sampling methods like Monte Carlo, Latin Hypercube, or the Point Estimate method. Among all these sampling methods, the Monte Carlo Sampling Method is the most widely used and applied in this study. In general, the Monte Carlo or Latin Hypercube methods are recommended, since one can define the number of samples directly, and there is flexibility in choosing from a wide variety of statistical distributions for each variable. For Monte Carlo sampling, each input parameter that is defined as a random variable is sampled according to the statistical distribution that was selected for that particular variable, the sampling method, and the number of samples (El Ramly, 2002). This generates ‘N’ values of each random variable (where N is the number of samples). As shown in Figure 2.8, each iteration of the Probabilistic Analysis is carried out by loading a new set of random variable samples and re-running the analysis. This is repeated ‘N’ times where ‘N’ is the number of samples.

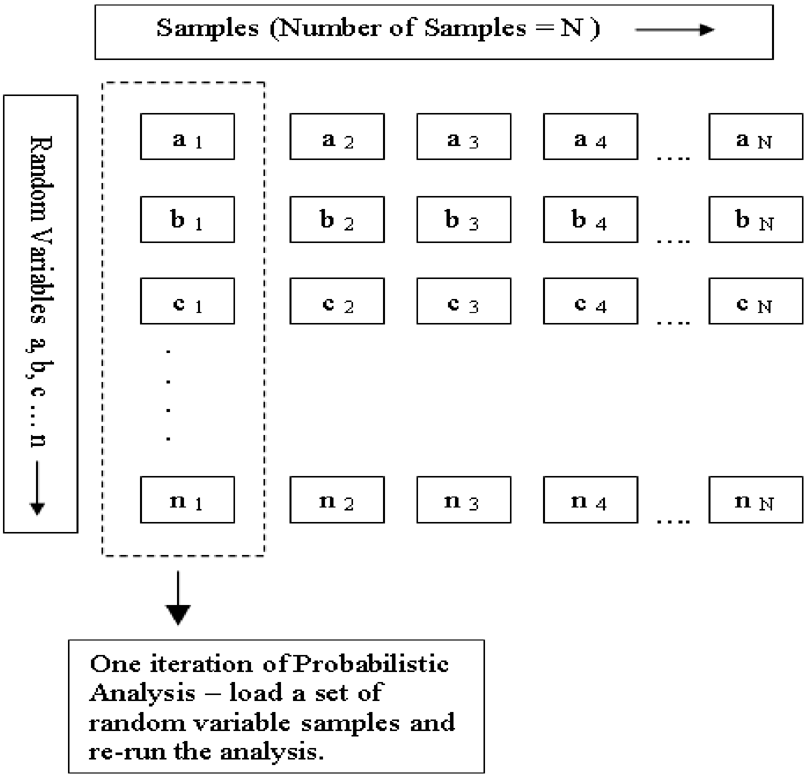


Figure 2. 8 Random Variable Samples used for Monte Carlo Probabilistic Analysis

The Monte Carlo method is very powerful and flexible and can be applied to a very wide range of problems. It is also very simple to use and can be quite accurate if enough simulations are performed. In the Monte Carlo method, samples of probabilistic input variables are generated and their random combinations are used to perform a number of deterministic computations. For the Monte Carlo or Latin Hypercube methods, the number of samples must be defined. This will determine the number of samples that will be generated for each random variable for the probabilistic analysis. For example, if the number of samples is 1000, then 1000 values of each random variable will be generated, according to the sampling method and statistical distribution for each random variable. The analysis will run 1000 times, creating 1000 sets of results from which the statistical output data will be derived. The accuracy of Monte Carlo simulation increases with the increase in the number of samples generated (Basahel and Mitri, 2019), whereas computation time also increases with the increase in the number of samples. Therefore, the selection of a number of samples depends on the level of accuracy required for a particular problem.

2.2.7 Machine learning: Artificial Neural Network

ML algorithms are powerful and flexible, statistical modeling tools used for formulating complex geotechnical problems, owing to their fruitful conduct in simulating non-linear multivariate problems (Chen et al., 2019; Das et al., 2011; Erzin and Cetin, 2013; Kim et al., 2018; Paudel et al., 2016). One of the most commonly used ML techniques is Artificial Neutral Networks (ANN) which is comparatively new in the field of slope stability analysis.

In recent years, ML techniques have been an attractive research topic for solving geotechnical problems. Currently, ML techniques are considered to be one of the most sorted analytical techniques for instability prediction (Das et al., 2011; Khandelwal et al., 2015; Kim et al., 2018; Lu and Rosenbaum, 2003; Paudel et al., 2016; Verma et al., 2016)

.

An artificial neural network is a modern computing technique that is used to simulate data in a manner the human brain analyzes and processes any information. It comprises an interconnected assembly of artificial neurons that pass on the information through the tendons, which exist in the neuron. The ANN model comprises hundreds of single units, neurons, and respective weights combinedly to form neural structures. Since it processes the information that’s why it is also called processing elements (PE). The PE is an equation that forms a relationship between independent and dependent variables (Monjezi, 2013; Agatonovic-Kustrin, 2000). Each neural network is formulated in three layers viz. the input layer, one or more hidden layers, and an output layer (Figure 2.9). The intermediate layer(s) do not interact directly with the external environment and hence are called hidden layers. All the neurons are positioned into hidden and output layers, while the input layer remains free of neurons (Pradhan and Lee, 2010a, b). ANN is a powerful tool for the simulation of data used primarily when the relationship between the independent and dependent variables is unknown. It can easily identify and learn the existing correlation between the dependent and independent variables from recorded data. The ANN method is an information-processing system simulating the structures and functions of the human brain. It attempts to imitate the way in which a human brain works in processes such as studying, memorizing, reasoning, and inducing with a complex network, which is performed by extensively connecting various processing units. It is a highly interconnected structure that consists of many simple processing elements or neurons capable of performing massively parallel computations for data processing and knowledge representation. A neural network can be considered an intelligent hub that can predict an output pattern when it recognizes a given input pattern. The neural network is first trained by processing a large number of datasets. After completion of proper training, neural networks can detect similarities when presented with a new pattern and accordingly, result in a predicted output pattern. This property gives excellent interpolation capability to the technique, especially when input data is not exact. Depending on the availability of computational capabilities, neural networks may be used as a direct substitute for auto-correlation, multivariable regression, linear regression, trigonometric, and other statistical analysis techniques. When data are analyzed using a neural network, it is possible to detect important predictive patterns that were not previously apparent to a non-expert.

At present, the ANN technique is considered to be one of the most intelligent tools for simulating complex problems. This technique has the ability to generalize a solution from the pattern presented to it during training. Once the network is trained with a sufficient number of sample datasets, for a new input of a relatively similar pattern, predictions can be done based on previous learning. Due to their multidisciplinary nature, ANNs are becoming popular among researchers, planners, designers, etc. as an effective tool for the accomplishment of their work. ANN is used for the prediction of uniaxial compressive strength, investigation of point load index, tunnel design, optimum rock support design, stability assessment of tunnel, stability of waste dump slopes, for determining mining blasts, chemical explosions, and many other activities. These applications demonstrate that neural network models are efficient in solving problems when many parameters influence the process, and when the process is not fully understood. Also, sufficient historical or experimental data must be available when applying this method.

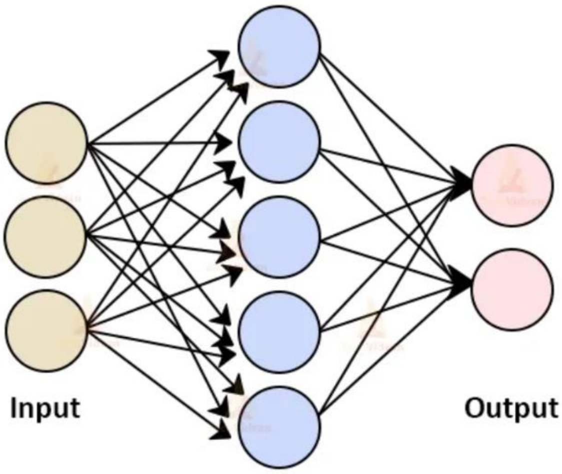


Figure 2. 9 Basic Architecture of an ANN network

Establishing a technique for dump slope stability prediction is very strenuous as a precise evaluation involves many geometric and mechanical variables Furthermore, due to the demanding nature of engineering assignments, the prediction should be made in a short computational time. These requirements have aggravated the complication in evolving a precise prediction technique for slope stability analysis. In slope stability analysis, the factor of safety (FOS) is generally used to describe the overall functioning and vulnerability of a slope toward failure. The overall performance of a slope and precise prediction of its FOS is not a simple task. This is primarily due to the complexity of the precise estimation of mechanical properties of the influencing parameters, their magnitude of impact, and the intricacy of their relationships. Therefore, various sources of uncertainties govern the evaluation of slope stability (Cho, 2009). The overall performance and the corresponding FOS of a slope, have been probed analytically, numerically, and latest by using Machine Learning (ML) by researcherslike Abdalla et al., (2015) and Rukhaiyar et al., (2018).

In the last few decades, there are several successful applications of ANN, which investigated slope stability and evaluated slope failure characteristics. Ni et al., (1996) combined fuzzy sets theory with artificial neural networks to evaluate the stability of slopes and to predict the slope failure potential. The results of the ANN were in good agreement with the analytical results. Sakellariou and Ferentinou, (2005) used a back-propagation learning algorithm to estimate the factor of safety of slopes and their stability status based on several geotechnical and geometrical input parameters. The performance of the network was measured and the results were compared to those obtained using standard analytical methods. Wang et al., (2005) used a back-propagation neural networks model with four layers and a training data set of landslide samples to predict the stability and safety factor of slopes. Ferentinou and Sakellariou, (2007) combined ANN tools with generic interaction matrix theory to estimate slope stability controlling factors. They developed an integrated method for estimating the factor of safety, and slope stability and for predicting the slope performance under static and seismic loading. They concluded that computational intelligence tools are promising and should be further exploited in tackling such complex problems. Ural and Tolon, (2008) used ANN to predict the factor of safety of saturated slopes under earthquake. They studied the importance of the seismic coefficients for slope stability, and safety and assessed the importance of the slope and dynamic input parameters in the stability of slopes in the event of an earthquake. Cho, (2009) integrated the finite difference method into a probabilistic analysis of slope stability and employed an artificial neural network-based response surface to calculate the probability of failure through the first-order and second-order reliability methods and a Monte Carlo simulation technique. He carried out a probabilistic stability assessment for a hypothetical two-layer slope for validation of the developed method. Based on the results from two examples, he indicated that the ANN-based response surface can be successfully applied to slope stability probabilistic problems. Lin et al., (2009) used a neural network-based model for assessing the failure potential of highway slopes. They explored the degrees of influence of several factors on slope stability and used the developed ANN models to investigate the slope failure characteristics before and after the earthquake. Kaunda et al., (2010) use backpropagation artificial neural network architecture to predict the slip or failure surface of active landslides, among other parameters. They concluded that the neural network models predict slip surfaces better than the limit equilibrium slip surface search using the most conservative criteria. Das et al., (2011) developed several neural network models to classify the slope as stable or unstable and for the prediction of the factor of safety. They compared their results with other models based on support vector machine and genetic programming and they observed that the ANN model is very accurate. As presented, different variations of ANN methods have been used to predict the factor of safety and they were successful with different levels of accuracy. These ANN methods were based on training data resulting from some experimental data or generated by some specific method of analysis.

In recent years, various machine learning tools have been implemented successfully in several slope stability projects, whether it was for natural or artificial slopes. The artificial neural network (ANN) being one of them, has been considerably used in solving various slope stability cases. Also, there are several documented cases of the use of multiple regression analysis (MRA) for stability analysis. Multiple regression analysis (MRA) is a statistical technique that mainly derives a relationship between the output variable and the input variables. This technique has also been found to be useful for solving slope stability problems.