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Computational Analysis for the Stability of Black Cotton Soil Bench in an Open Cast Coal Mine in Wardha Valley Coal Field, Maharashtra, India

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Abstract. Coal is a prime source of energy in India and its demand is increasing every day due to faster rate of development and consumption of energy per capita. To bridge the gap between demand and supply of energy sector, there is a need for huge quantity of coal. The open cast mines are helpful to fulfill the demand to a large extent because of their higher productivity rate. Large quantity of overburden material is required to be removed to reach the underlying coal seams. Higher stripping ratio and increased depth of mines pose serious problem to the stability of mine slope due to variation in rock mass as well as mining method adopted. These problems are more chronic, where soft layers of black cotton soil occur in the slope, which behaves erratically in different environments. The bench slopes in Wardha Coal Field, face such kind of conditions, which are delicate when it comes to the safe mining activity. In this paper, an attempt has been made to simulate the condition of a black cotton soil bench imbedded in mine slope using two dimensional numerical tools. The study mainly focuses on the numerical examination of a failed Black Cotton Soil (BCS) bench, from Sasti Coal mine of Wardha valley coal held, which has translated forward by 5m on the berm. The 15m thick BCS bed is underlain by Kamthi Sandstone (KS). The numerical analysis was done under both saturated and dry conditions. This study also deals with the understanding on the effect of water on the stability of the bench slopes as the BCS usually fail during the rainy season. The numerical investigation after the exhaustive geotechnical examination found a 35% rise in factor of safety from saturated to dry condition.

Introduction

The surface mining activities are associated with a number of problems like bench slope stability, management of dump and environmental issues like land, air and water. India has an ever increasing requirement for coal and to keep pace with the rising demand, open cast mines are very helpful for increasing production (WCL, 2011). The increased demand of coal in India has lead to deeper and larger excavations. Stability of cut slope benches of these mines has become concern of utmost priority. The slope stability in open pit mines is of considerable economic importance to the mine owner and a question of life and death to the mine workers. Slope failures may also lead to loss of lives and delay in mining operations. The slope stability and the design of slopes is one of the major challenges at every stage of planning and operation which play a significant role in the safety of open pit mine slopes. The mining engineers are concerned with the designing of such a slope which will be capable of balancing two important parameters like safety and economy. It is, therefore, necessary to achieve the balance between these two conflicting requirements. The level slopes are suggested to provide the desired safety and stability, whereas steep slope results in avoiding surplus excavation of waste rock (Singh *et al.*, 1990; Singh and Singh, 1992). It requires the knowledge of geology, which provides the information about structure and/or alteration and material properties. It also needs to understand the practical aspects of design implication. Therefore, the main aim of slope stability analysis is to design a slope that is stable, economical and has minimum chance of failure (Monjezi and Singh, 2000). A number of methods are being used for the assessment of slope stability and excavability (Hoek and Bray, 1981; Goodman, 1989; Singh and Singh, 1992; Khandelwal and Singh, 2004; Sarkar *et al.*, 2009). The excavability of material depends on the geotechnical behavior of the material on the method of working and on the type and size of excavation equipment used (Zulfu *et al.*, 2008).

Slope design is of primary concern for the mine to be economical and safe in operations. The economics and safety of operations depend upon slope angle adopted for the open pits slope. Safety for the men and material in the slope requires that angle should be relatively flat, even though steeper slope angle is positive from the point of view of stripping ratio.

Our present study focuses on study of a failed Black Cotton Soil (BCS) bench, from a Sasti Coal mine of Wardha valley coal field, Nagpur, India, which has moved forward by 5m on the berm. The 15m thick BCS bed is underlain by Kamthi Sandstone (KS). The study mainly focuses on the effect of water on the stability of the bench as the BCS usually fails during the rainy season.

Different researchers have emphasized on various factors which play key role in overall behavior of slopes (Coates, 1964; Brawner *et al.,* 1975 and 1978; Gupta and Singh 1985). These factors can be grouped as geological factor, hydrological factor, nature of material, slope geometry, physico-mechanical properties, drainage of slope, erosion, temperature, state of stress, effect of blasting and dynamic loading and time factor. A worldwide research has been done on rainfall induced slope failures and has shown that precipitation is the main contributing factor of slope failures (Brand, 1984; Tan *et al.*, 1987; Chatterjea, 1989; Lim *et al.*, 1996; Toll *et al.*, 1999). Numerical analyses of rainfall-induced slope failures have been carried out to study the controlling parameters (Cheng, 1997; Gasmo *et al.*, 2000; Tsaparas *et al.*, 2002; Rahardjo *et al.*, 2005 and 2007a,b) and the effects of antecedent rainfall on rainfall-induced slope failures (Rahardjo *et al.*, 2001 and 2008). Cho and Lee (2002) indicated that most shallow slope failures were caused by the advancement of a wetting front into the slope, Ng *et al.,* (2001) conducted three dimensional numerical analyses of groundwater response to rainfall and found that rainfall pattern, duration, and its return period have major influences on the changes in pore-water pressures in unsaturated cut slopes. Tohari *et al.*, (2007) conducted a laboratory study of slopes under rainfalls and observed that shallow noncircular slip was the dominant mode for rainfall-induced slope failures. The slope monitoring has also been carried out at Wardha Valley Coal Field (WVC) with the help of level and electronic distance measuring (EDM) instrument for the measurements of vertical and horizontal displacements, respectively (Jhanwar *et al.*, 1996; Jhanwar *et al.*, 2008).

Assessment of stability of slopes in open pit mines at different stages of mining is important for the safe and economic mining operations (Sarkar *et al.*, 2007). Slopes are generally designed based on the geo-technical data and physico-mechanical properties of geo-material. Using the rock mass properties, stability of the slopes is evaluated by empirical, analytical and numerical techniques (Singh *et al.*, 2007).

Geologic Setting

The Wardha Valley coalfield comes under the Toposheet no. 56M and covers an area of about 1440 km^2 between latitudes ~19°28 ' and 20°27 ' and longitudes ~78°50 ' and 79°45 ', located in the Chandrapur and Yeotmal district of Maharashtra state and extending over a length of 150 km from NW to SE in an almost straight line. Sasti mine comes under the Ballarpur area lies 5 km south of Ballarpur and SW from the Wardha river (Fig. 1). Sasti mine has an extension of 800 m along NNE-SSW direction. The Sasti open cast mine lies exactly south of the Wardha river. At present the depth of mine is around 80-90m. The coal seams are sub merged in the water near the basal part of the mine. It is due to the juncture of Kamthi sandstone, which is acting as an unconfined aquifer and major source of groundwater in the area (Jhanwar and Thote, 2011). Presence of water at the area is due to the fact that the mining is going on at approximately the same depth as of the local base level of the Wardha river.

The geology of Sasti mine is a part of lower Gondwana group which includes sandstone, shale, clay, coal seam and black cotton soil as an overburden. The black cotton soil (BSS) has a little red and brown color variation and varies in thickness from 8-16m (Fig. 1). BCS is underlain by a16-20m bed of friable yellow color sandstone. The friable yellow sandstone is interlayered by a 1-1.5 m thick compact sandstone seam and a 0.5m thick clay layer. The yellow friable sandstone is underlain by 2-3m thick carbonaceous shale which in turn is deposited over white sandstone having a thickness of 40-42m and a 3-4m thick layer of shale. At present the mining activity is confined on the coal seam whose thickness is 17- 19m which is present below the shale bed. The broad stratigraphic sequence of the area is given in Table1. Failure is mainly associated with black cotton soil bench due to its high water absorption and retention capacity.

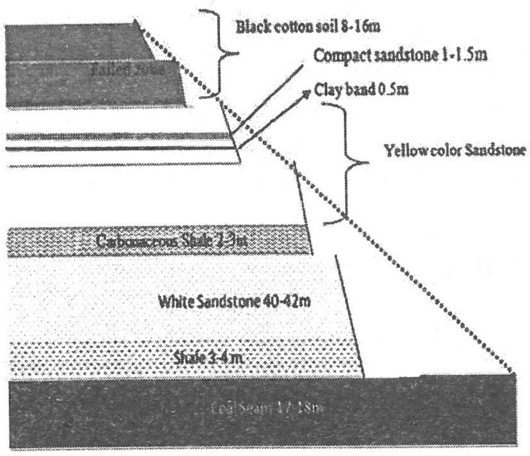

Fig 1. Generalized bench geometry of Sasti open cast mine of coal (not to scale).

Black cotton soils are always problematic in the case of open cast mining, because of their unpredictable behavior leading to substantial distress to the bench in mining and structures that are built over these soils. These soils show large volumetric changes with respect to variation of moisture contents. These soils when subjected to loading due to heavy vehicular traffic movement develop crack due to high level variation in stresses and its frequent release. These soils are derived from two types of rocks, the Deccan and the Rajmahal trap. A failed view of the black cotton soil benching shown in Fig. 2.

During the rainy season, water ingress into the soil by penetration and some of the part evaporates back into the atmosphere, some is drawn down below the root zone by gravity, where it may enter into the water table, whereas some particles were held in the root zone by the soil particles. The amount retained in the root zone is dependent upon the soil consistency and structure. The amount of the water in the root zone enters the roots of the plants and is released back into the atmosphere from the leaves of the plants by transpiration. Water in the soil

Table 1. Stratigraphy of Lower Gondwana (Source WCL, 2011)

Formation	**Lithology**	**Thickness (Avg. in m)**	**Remarks**
Detrital mantle	Clayey soil/ Black cotton and residual soil	4-5m	Color variation
Kamthis	Sandstone with intercalation of clay, Carbonaceous shale, coal	20-80m	layer of compact SSt. and clay found
Barakar	Sandstone shale, coal seam	20-140m	Economic coal seam
Talchir	Sandstone fine grained and greenish needle shale	5-15m	

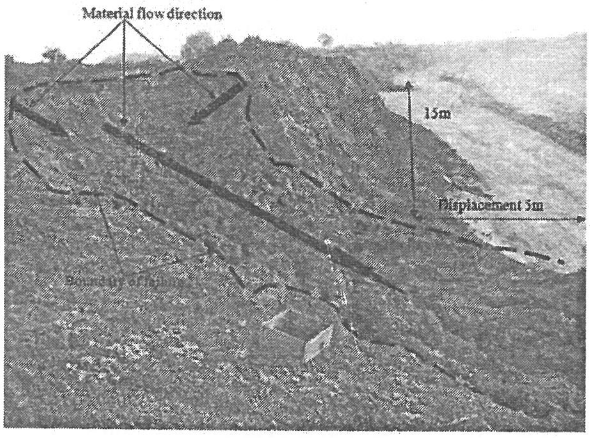

Fig 2. A view of failed bench in Sasti open coal cast mine of coal.

occupies the space between the voids that would otherwise be open. As the volume of water in the soil increases, it exerts additional pressure on the soil particles that pushes them apart. On slopes, this may lead to slope failure or mass wasting. As the soil particles are separated from the rock contact surface, thus, the friction that holds them in place against gravity is reduced and may lead to slide.

Water surface or groundwater plays an important role in stability of soil slope. Water pressure reduces the effective normal stress in a material and the resistance to shear drops. The main reason for this behavior is that water changes the property of the material filling of the discontinuities/gaps (Laubscher, 1977). This change leads to a decrease in the frictional and cohesive parameters. The pressure generated by the water is one of the most important factors leading to the slope failure (Youtain *et al.*, 1997). Most of the slope failure occurs in rainy seasons due to reduction in shear strength (Zhuping and Zhuhuan, 1997; Singh *et al.*, 1999; Sharma *et al.*, 2006). Shear strength of the soil is dependent on the normal stress on the slip surface, cohesion of soil particles, and the internal angle of friction (Sidle *et al.*, 1985). The internal angle of friction or degree of interlocking of soil particles and aggregates is dependent on the shape, size, and packing arrangement of the soil particles. Physical and chemical weathering of primary minerals, such as biotite and pyroxenes, results in production of clay particles influencing the stability of the slope (Sidle *etal.*, 1985). The effect of water pressure, u on the shear strength can be incorporated into the shear strength equation as follows:

$$\tau = c + (\sigma - u) \tan \varphi$$

Where τ is the peak cohesive strength. These equations assume that the cohesion and friction angle are not changed by the presence of water on the surface. In most hard rock and in many sandy soils and gravels, the strength properties are not significantly altered by water. However, many clays, shales and mudstones, and similar materials will exhibit significant reduction in strength with changes in moisture content.

Materials and Methods

The slope forming materials in the mine mainly consists of soil and sandstone as overburden followed by a composite coal seam of 17–19 m thickness. The soil consists of black cotton soil and silty/clayey sand and is classified mainly as clay of high plasticity (Jhanwar and Thote, 2011). The BCS and Kamthi sandstone samples were brought to the laboratory, where they were tested for both dry and saturated conditions with an aim to measure their cohesion, angle of internal friction and unit weight. The modal values were used for the computational analysis of the BCS bench slope (Table 2). The slope stability problems in this coalfield are predominantly restricted to soil and very weak sandstone benches. The slope failures occur mainly during or after the rainy season, which run from the months of June –September. Besides, external loading, on slopes by overburden dumps, also contributes to the slope instability in some cases. The average annual rainfall in this coalfield is 1250 mm (Jhanwar and Thote, 2011).

The slope stability state in WVC is typically governed by several factors like the thickness of soil formation, behaviour of sandstone rock mass, presence of faults, infiltration of precipitation into slope, presence of external

Table 2. Geo-mechanical properties of BCS and KS.

Litho type	Unit weight (kN/m^3)		Cohesion (KPa)		Angle of Internal friction (Degree)	
	Dry	Wet	Dry	Wet	Dry	Wet
Black Cotton Soil (BCS)	15-18	15.5-20	28-44	15-30	13-16	14-18
Modal Value	17	19	38	26	15.5	16
Kamthi Sandstone	21-22.4	22-24	80-160	50-110	24-28	26-31.5
Modal Value	21.7	23	110	80	25	28

loads on slopes in the form of overburden dump (Jhanwar and Thote, 2010). The slope failures were normally restricted to soil benches and underlying sandstone benches. The slope height of bench, where failure occurred is 15 m and slope angle is 72 degree, whereas the displacement of failed zone is about 5m. The preliminary analysis of failure indicated that rain was the triggering factor.

To study the influence of rainwater on the stability of BCS bench slope a finite element code was used. The finite element code is a continuum model which can be used for analysis of complex geometries, stress modelling and material behaviour. Here, the rock mass is considered as a continuum and divided into a finite number of elements with intersecting nodes. In the FEM, the structural system is modelled by a set of appropriate finite elements interconnected at points called nodes. Elements may have physical properties such as thickness and density, Young's modulus, shear modulus and Poisson's ratio. The elements are interconnected only at the exterior nodes, and altogether they should cover the entire domain as accurately as possible. Nodes have nodal (vector) displacements or degrees of freedom which may include translations, rotations, and for special applications, higher order derivatives of displacements. When the nodes displace, they will drag the elements along in a certain manner dictated by the element formulation. In other words, displacements at any points in the element will be interpolated from the nodal displacements, and this is the main reason for the approximate nature of the solution. A major advantage of the finite element- SSR method is that it does not entail any earlier assumptions on the nature of failure mechanisms. The Shear Strength Reduction technique in the finite element method involves successive reduction (by some factors) in the shear strengths of the slope forming material until it fails, which is indicated by the non convergence to a solution of the finite element model (Griffiths and Lane, 1999).

For Mohr-Coulomb material shear strength reduction factor (factor of safety) F can be determined from the equation:

$$\frac{\tau}{F} = \frac{c}{F} + \frac{\tan \varphi}{F}$$

Where τ is the shear strength of the material and F is the strength reduction factor (SRF). The approach can be used for materials following both the linear Mohr-Coulomb strength criteria and non linear generalized Hoek-Brown criteria (Hammah *etal.*, 2005).

The analysis was carried out for the 15m thick BCS bench slope underlain by KS. The bench slope has an angle of 72°. Saturated condition was simulated first, under which the BCS bench has already failed. The values for the saturated BCS and KS have been given in Table 2. The BCS slope was then analyzed for dry conditions.

Results and Discussion

The numerical model for the BCS bench slope in the saturated condition gave a factor of safety of 0.81 with the development of the tension crack 9m behind the slope face (Fig. 3). In the field the failure surface has also been recorded 7 m behind the slope crown (Fig. 2). The failure has taken place in a circular manner which matches with the actual scenario. A maximum effective normal stress of 0.5 MPa, where as a maximum shear stress of 0.06 MPa was developed at the toe of the slope. The generated effective shear and normal stress at the slope face had almost become negligible around 0.9m above the toe of the slope (Fig. 4A). Across the railure plane (A-B), the maximum effective shearing stress generated gradually reaches the value of 0.068 MPa, around 4.5m behind the slope, which dies out further away from the slip surface (Fig. 4B). The effective normal stress increased gradually, away from the slope, reaching a maximum value of 0.23 MPa, 9m behind the slope (Fig. 4B). The increase in normal stress can be attributed to the increase in overburden, while moving away from the slope face.

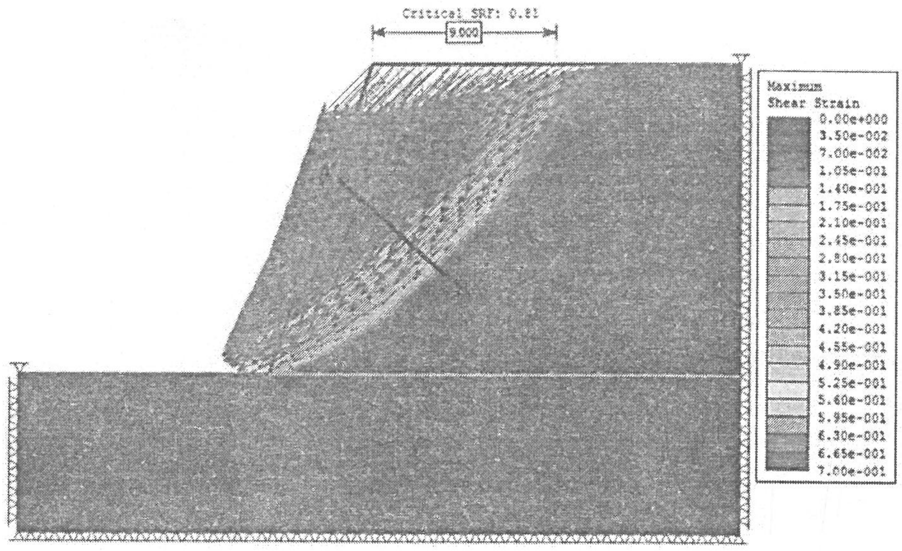

Fig 3. The failed BCS bench slope with deformed mesh and displacement vectors (saturated condition).

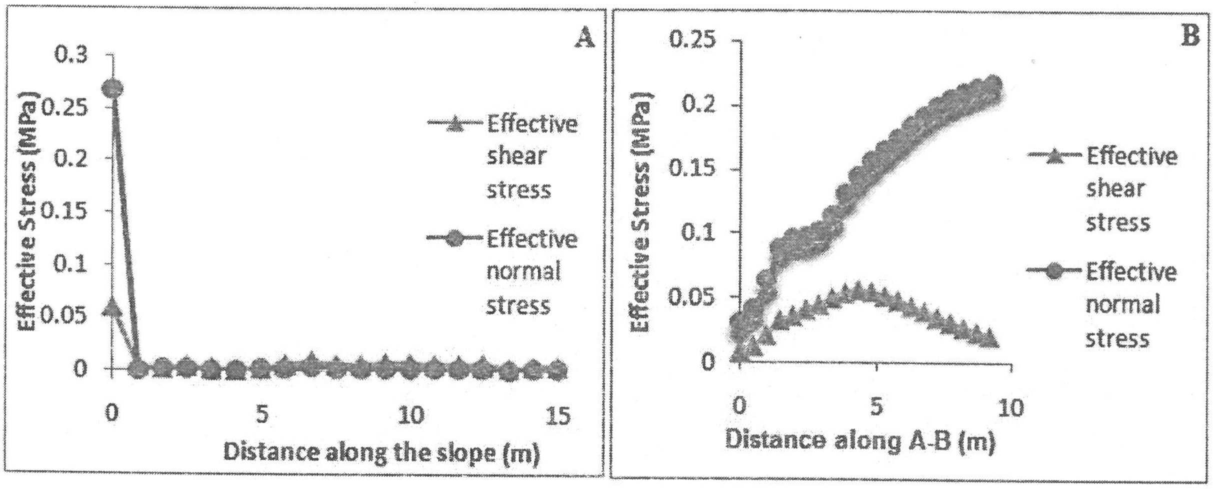

Fig 4. The variation of effective normal and shear stress (A) along toe of the slope and (B) along the distance A-B, across the slope in the saturated conditions.

The factor of safety in the dry condition was raised by 35% to reach a value of 1.09 (Fig. 5). In the dry condition, it was found that the maximum shear strain concentration zone has shifted around 7m behind the slope face at the crown. There has been an increase in the maximum effective shear stress along the slope length, reaching a maximum value of 0.23 MPa (Fig. 6A). The rise in effective shear stress along the slope may be accredited to the high value of SRF above which there will be a drastic reduction in factor of safety (Kainthola *et al.*, 2011).

The stress generation in the BCS bench slope has been affected by two different lithologies, which can be seen from the breaking, offsetting and sharp bending of stress lines along the material boundaries in the numerical model (Fig. 5).

The maximum effective normal stress generated across the slip surface has been shown to increase gradually towards the back of the slope due to increase in the overlying stress (Fig. 6B). The effective shear stress reaches a maximum value of 0.055 MPa and then starts to decrease as it crosses the zone of maximum shear stress concentration. In both the cases, the effective normal stress across the failure surface (A-B) remains almost constant at the periphery of the failure zone and increases further inwards to the slope.

Conclusion

In the present study, a failed Black Cotton Soil (BCS) bench slope in Wardha Valley Coal field was investigated numerically. The relevant geo-mechanical properties were determined in the field as well as the laboratory. The BCS bench slope that usually fails during the rainy season were affirmed using finite element method which gave a FOS of 0.81 for saturated condition while for the dry conditions the FOS attained was 1.09 which is critically stable for the progressive slope. This study also confirms the instability of slope due to high water holding capacity of BCS, however, to prevent such types of failure, it is always advisable to have a better drainage system to maintain the shear strength at the equilibrium

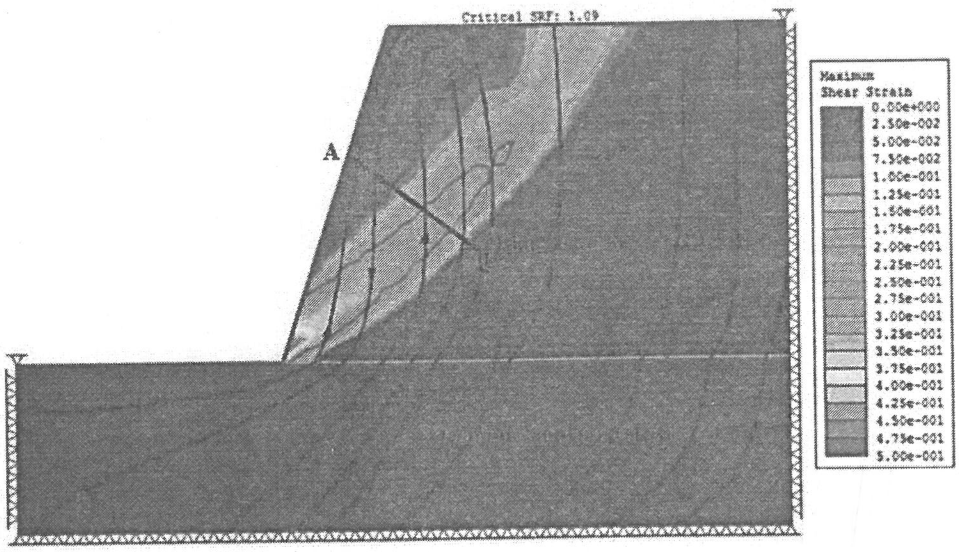

Fig 5. The failed BCS bench slope with stress (black) and iso-lines (brown) and maximum shear stress concentration (dry condition).

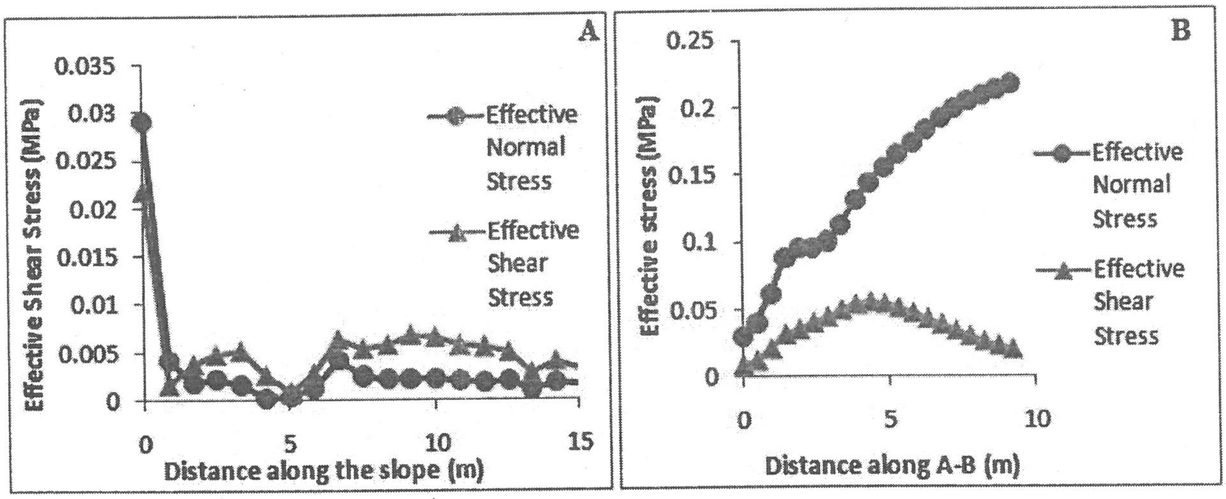

Fig 6. The variation of effective normal and shear stress along (A) along the toe of the slope and (B) along the distance A-B across the slope in the dry conditions.

level. The investigation has validated the effect of material type on the stress generation and concentration which has been observed along the material boundaries. The study authenticates the use of finite element methods for the stability analysis of the earth slopes.

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