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Stability Assessment of a Hill Slope-An Analytical and Numerical Approach

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Abstract: Slope failure is a very common phenomenon and critical issue in North-East India. Various types of slope failure have affected most parts of slopes and road sections in an around Sonapur area along NH-44 within Jaintia Hills district, Meghalaya, India. This area has always been prone to numerous rock slides, hazardous rock falls and deleterious debris flows as the rocks are highly jointed. These failures bring about considerable loss of life, property and also serious disruption of traffic along the highway. Again poorly designed excavations of rock slopes for road widening or construction purposes lower the stability of the slopes. The present study includes numerical solutions for the stability assessment of a jointed rock slope in hilly areas which will assist in designing proper support systems to minimize the risk of frequent failure every year especially during rainy season.

***Keywords:** Slope stability, Kinematic analysis, Finite Element Method*

1. Introduction

Slope instability has always been a major problem along engineered slopes for highways and railways in mountainous terrain. National Highway 44 is such a road in India running through hilly region of Himalaya. This is the busiest road as it is the only route to connect major parts of North East India from the rest of the country. The road encompasses continuous cut slopes along its way which are exposed to rockslide, rock fall and debris slides. It is essential in this area to have the best possible understanding of rock properties, slope geometry, structural and mineralogical properties to determine the particular problem and construct suitable protection systems near vulnerable zones. Keeping an eye to the pressing solution of the dire problem, an analysis has been carried out for the stability assessment and protection measures in this section. This paper presents analysis of a hazardous slope in the road cut section along NH-44 which is mainly susceptible to rain water. Here kinematic analysis has been carried out to know the structural instability and further Finite Element Analysis (FEA) has been done to simulate the failure mechanism followed by a suggestion for remedial measures.

2. Geology of the Area

The area is characterized by undulating topography and the presence of alternating hills and valleys. It is truncated by crisscrossed streams and a network of their tributaries. The drainage pattern in the district represent extra ordinary straight course of rivers and streams along master joints and faults which are a reflection of major geological movement in the area [1]. Soil varies from sandy to fine silty clays in the northern and western part of the district. The exposed rocks are highly jointed sandstone and shale of Oligocene age and of variable strength [1]. These rocks of the area are of sedimentary type and contain sedimentary structures such as cross beddings, load casts and ripple marks. The study is confined between Sonapur tunnel (92°21.363E'-25°06.405N') to Malidor bridge (92°27.067E'- 25°2.039N'), whose slope map with the investigated location is given in Figure 1. It has been incorporated in the Survey of India toposheet no. 83C/8.

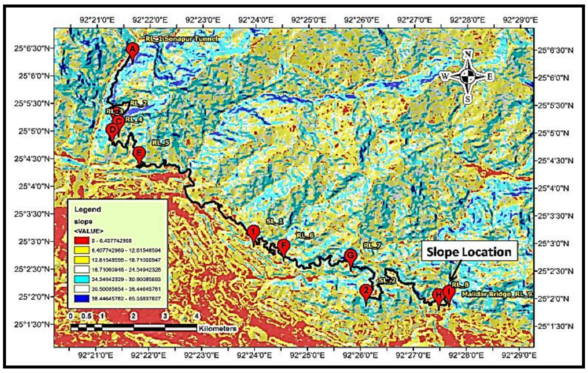

***Fig. 1:** Slope map of the study area with investigated slope location (Source ASTER DEM)*

3. Field and Geotechnical Investigation

The area between Malidor and Sonapur has been investigated for a stretch of 30 kilometers along NH-44 to gather field data and to collect samples for laboratory analysis. The rocks are sandstone and shale, highly jointed and folded in many places. The representative rock samples are cored in laboratory using diamond drilling and tested to determine the geomechanical parameters according to ISRM [9] specifications.

4. Kinematic Analysis

Kinematic refers to the geometrically possible motion of body without any force involved. It is the most simplified failure analysis to determine the probable mode of failure [8]. Unfavorably oriented discontinuities, slope face attitude and friction angle determine the rock slope failure mode such as planar, wedge and toppling with potential failure direction. In order to analyze discontinuity data and to find out modes of failure, a stereonet analysis program DIPS 6.0 [3] has been used. The input parameters were obtained from field investigation are given in Table 1. Joint friction angle of 19° is taken in the analysis.

Table 1: *Orientation data of the cut slope used for kinematic analysis*

Discontinuity	Dip (°)	Dip Direction (°)
Joint Set (J1)	85	205
Joint Set (J2)	82	290
Bedding (J3)	30	60
Slope Face	83	240

5. Numerical Analysis

Various numerical tools such as Limit Equilibrium Method (LEM), Finite Difference Method (FDM), and Finite Element Method (FEM) have been used by researchers for analysis of slope stability problems [2], [4], [6], [11], [16], [18]. Recently the Finite Element Method has gained its popularity due to its robustness in arbitrary boundary and interface condition, complex problem solving capacity, free from presumption of critical slip surface and elimination of assumptions regarding the inclinations and locations of interslice forces [7]. The equivalent factor of safety in finite element program is calculated through Shear Strength Reduction (SSR) technique [12], [17]. The SSR technique involves reducing Mohr-Coulomb strength parameters C (cohesion) and Φ (angle of friction) by a strength reduction factor (SRF) until non-convergence occurs within a specified number of iterations and tolerance [5], [6]. Non-convergence occurs when there is unsolved force and displacement induced at each node of a finite element model [10]. The SRF that corresponds to the last convergence state is equivalent to the safety factor. The reduced strength parameters Cr and Φr are defined as

$$\mathrm{Cr} = C/F \quad (1)$$

$$\tan(\Phi r) = (\tan\Phi)/F \quad (2)$$

Where F is the shear strength reduction factor.

The present paper analyses a cut slope in a jointed rock mass using the geotechnical software RS2, which is based on finite element code for rock and soil application [15]. The Finite Element (FE) analysis has been done in conjunction with Mohr-Coulomb stress-strain method which proves to be a reliable method for accessing factor of safety of slopes [6]. The FE code determines the overall deformation behavior of a jointed rock mass using the method for modeling the visco-plastic multilaminate framework [14]. The assumptions required in the formulation of multilaminate framework are: all joints in a set should be parallel, continuous and unfilled and the volume occupied by the joint sets must be small compared to the total volume of the rock mass [13].

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Table 2: *material parameters used in FE Model*

Material Parameters	Value
Unit Weight (MN/m3)	0.027
Peak cohesion (MPa)	0.08
Peak friction angle (Degree)	24
Residual cohesion (MPa)	0.06
Residual friction angle (Degree)	21
Dilation angle (Degree)	0
Young’s modulus (GPa)	3.5
Poisson’s ratio	0.28
Joint Parameters	**Value**
Peak cohesion (MPa)	0.01
Peak friction angle (Degree)	19
Dilation angle (Degree)	0

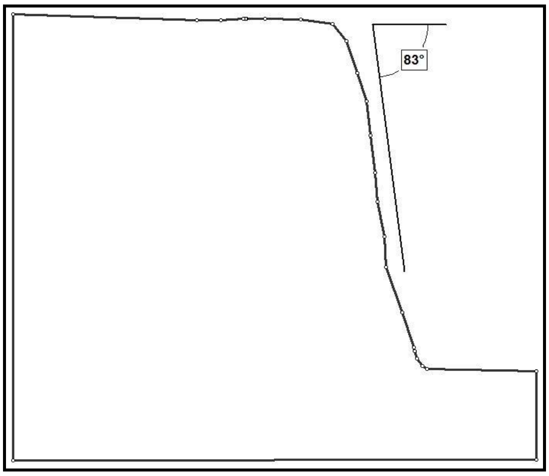

Fig. 2: *Geometry of the investigated road cut slope used in finite element*

6. Results and Discussions

Analysis of discontinuity data and their relation to the slope face indicates that the cut face is structurally unstable. Two modes of failure have been recognized which include wedge failure (Fig. 3) and flexural topple (Fig. 4) with potential failure direction towards 261° and 241° respectively.

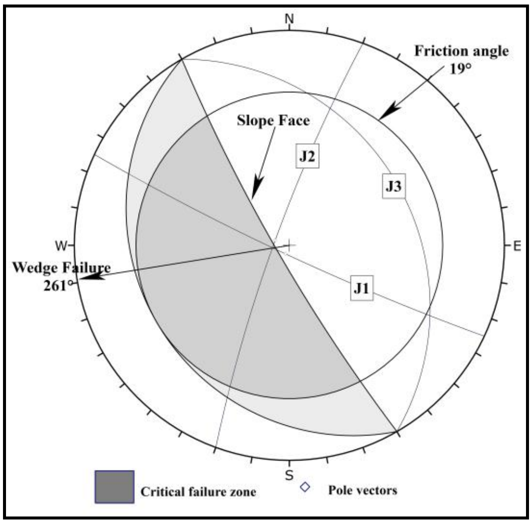

Fig. 3: *kinematic analysis for wedge failure showing potential failure direction towards 261°*

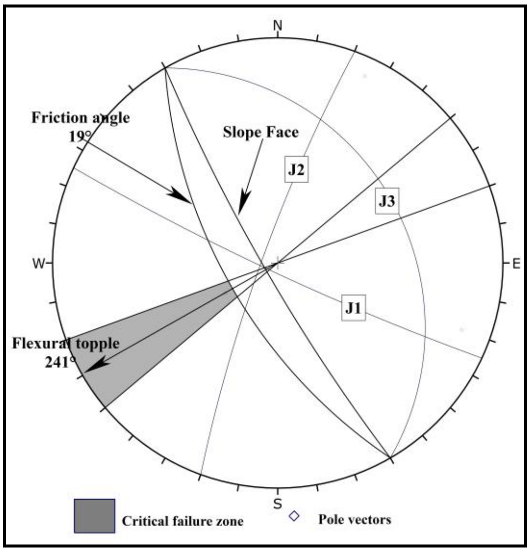

Fig. 4: *Kinematic analysis for flexural topple failure shows a potential failure direction towards 241°*

Maximum total displacement and minimum strength factor (Figs 5, 6) are observed to be 4.8mm and -1 respectively. The graph in Figure 7, shows that the displacement is increasing gradually from the toe to top of the slope which may induce rock fall at the top portion. Figure 8, suggests a maximum differential stress of 1.45 MPa at the toe where the strength factor (Fig. 9) also has a negative value representing higher induced stress than material strength. Highest shear strain of 0.003 is also observed in the toe region (Fig. 10). Maximum stress concentration along with critical safety factor presumes the possibility of toe collapse and subsequent failure of the cut slope. A factor of safety of 1.19 has been attained through the Finite Element Analysis. The slope is critically stable but any small scale disturbance will further reduce the FoS and cause failure, particularly when the area experience heavy rainfall.

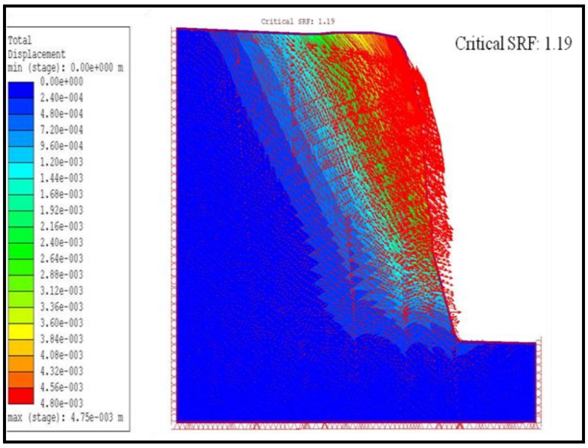

Fig. 5: *Finite element analysis for total displacement with displacement vectors. Maximum total displacement is 4.75e-3m*

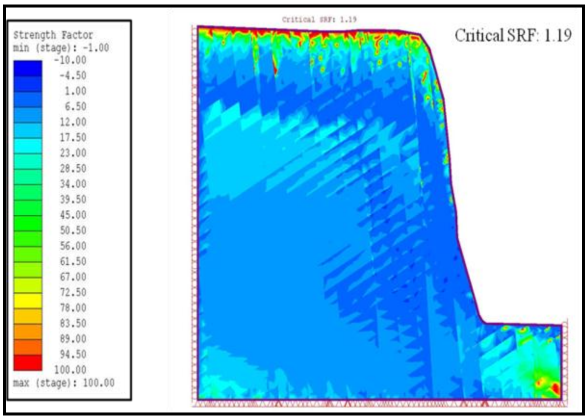

Fig. 6: *Finite element analysis for strength factor resulted a minimum strength factor -1*

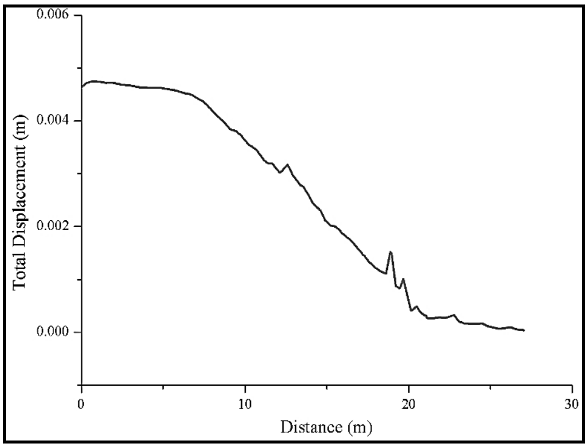

Fig. 7: *Distance from top to toe along the slope surface vs Total displacement graph, representing an increasing trend of total displacement towards top of the slope*

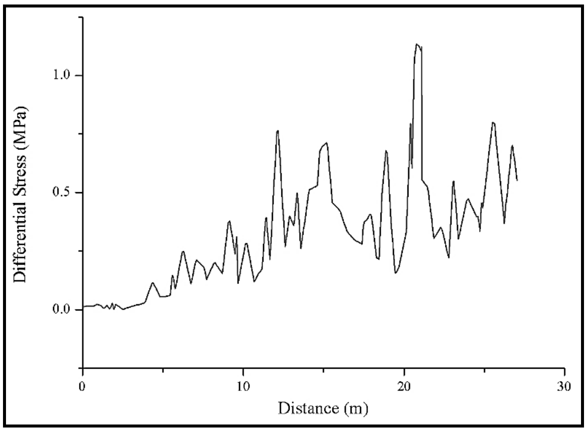

Fig. 8: *Displace from top to toe along the slope surface vs. differential stress graph which suggests a maximum differential stress of 1.45 MPa at the toe*

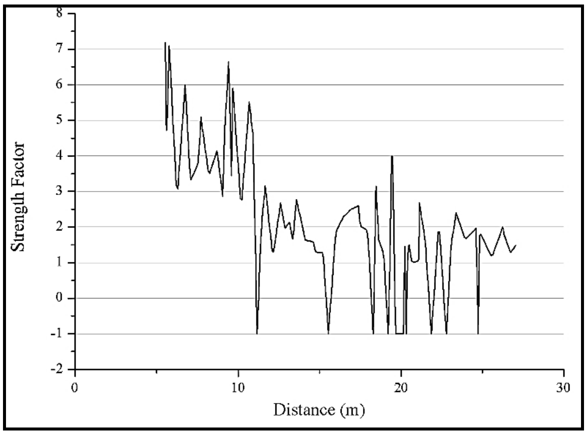

Fig. 9: *Distance from top to toe along the slope surface vs. strength factor graph which shows a value of -1 in the toe region*

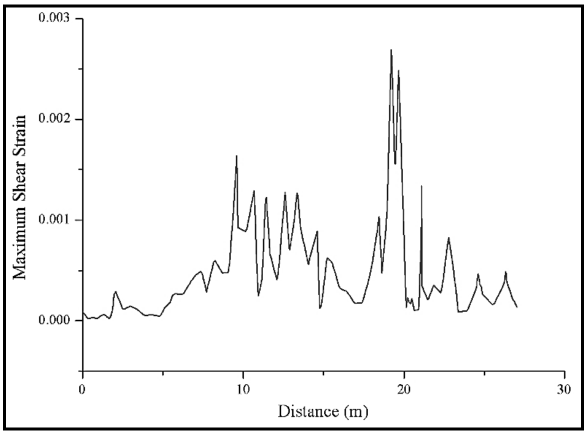

Fig. 10: *Distance from top to toe along slope surface vs. Maximum shear strain of 0.003 at the to*

7. Conclusions

The study area experiences continuous mass movement particularly in the rainy season and, needs proper attention to stabilize it. The existing slope angle is very high and hence proper dressing of the slope is necessary. The rock slope stability has been examined using both kinematics and numerical simulation. From this analysis, it can be inferred that the area is vulnerable to failure. The presence of multiple sets of joints in rock masses and intensive rainfall will further accelerate the slope failure. The jointed rock strata can be strengthened by rock bolts to reduce the rock fall. The retaining wall at slope toe will help to improve the FoS as well as long term stability of the existing slope.

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