Effect of blast damage zones on the stability of a Himalayan highway cut-slope – continuum modelling approach

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ABSTRACT: Hoek & Brown introduced the disturbance factor, "D," to their failure criteria in order to account for the critical effect of blast-induced damage zone in the assessment of the rock mass parameters. Considering the vital effect of blast damage extent on the surficial stability of jointed cut slopes, the present study examines the stability behavior of a jointed cut slope that had been excavated through rough blasting practice along NH-5 in dynamic Himalayan conditions in Himachal Pradesh, India. The effect of the blast damage zone on the stability behavior has been investigated through continuum-based Finite Element modeling. A parametric study has been done by assigning different damage factor 'D' to the damage zone of the rock slope. The results demonstrate the variability in safety factors of jointed cut-slopes in relation to the extent and degree of blast-induced rock mass damage of the disturbance zones.

Keywords: Blast-induced damage zone, Highway slopes, Safety factor, Continuum modelling, Himalaya.

1 INTRODUCTION

In recent decades, the demand for constructing road networks in remote mountainous areas has been steadily increasing. However, the construction of roads in inaccessible hilly areas poses many challenges, such as geological conditions, limited equipment access, and lack of technological advancements. Drilling and blasting methods (DBM) are typically the only suitable excavation techniques for such critical conditions, as they are flexible and economical in nature (Murthy & Dey 2003, Verma et al. 2015, Ghosh et al. 2022). However, the excavation of rock slopes using DBM creates blast-induced damage zones, which leads to deterioration of the physical and mechanical properties of the rock masses (Saiang & Nordlund 2009 and Verma et al. 2018). The stability of high rock slopes along the roads is a significant concern to be dealt by engineering geology specialist, especially when using DBM for excavation. The stability issue is justified by road blockage, loss of human life, and hindrance to communication and trade. Therefore, the estimation of the stability of rock-cut slopes, constructed using DBM, has major challenges in considering the Excavation Damage Zones (EDZ) in highway cut slopes. The rock slope is considered to be nonlinear due to its inconstant nature, caused by the occurrence of joints and their varied conditions, faults, other natural discontinuities and anisotropy. Nonlinear failure criteria are widely used for the assessment of rock mass strength proposed by Hoek & Brown (1980) and Hoek et al. (2002) and their applicability, and restrictions are discussed by Marions et al. (2005).

The present paper aims to study the stability and failure characteristics of a vulnerable rock-cut slope along National Highway (NH)-05 by considering the EDZ in slope mass as parallel layers of damaged rock mass in Himachal Himalaya. The primary purpose of this work is to investigate the impact of blast-induced disturbance on the rock slope by considering the equivalent EDZ thickness based on field investigations, as well as recent literature on the thickness of EDZ.

2 GEOLOGICAL INVESTIGATION

The study area is located in the Himalayan region of Himachal Pradesh, India along NH-05 near Rampur Bushar which is known for its complex geology. The Rampur group, an assemblage of rocks with a Paleoproterozoic age, is the predominant geological feature in this area. The main rock types observed in the study area include quartzite with bands of metabasalt, slate, phyllite, and purple quartz arenite. During field visits, it became evident that the drilling and blasting practices employed for road network construction and widening were carried out in a crude manner. Field observations of several roads cut slope profiles revealed examples of poor blasting practices (Fig. 1). The blast-induced fractures along with blast-holes can be clearly seen in Figure 1 with inherent joints. These rock slopes are highly prone to varying degree of block instability caused by joints and induced fractures.

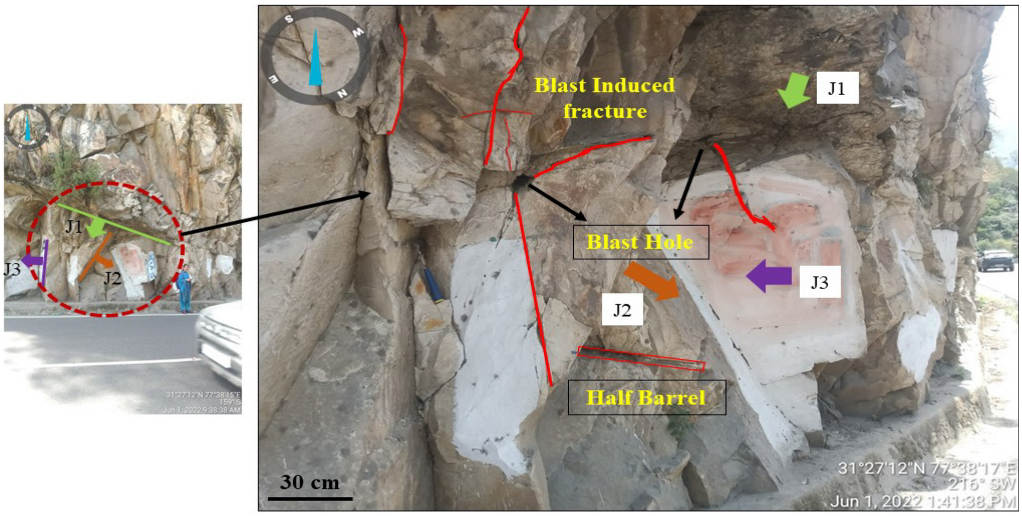

Figure 1. Blast-induced rock mass damage characteristics of a slope in the study area.

The slope mass demonstrates how the rock masses were damaged to varying degrees by the blasting activity with the properties of the rock mass being a contributing factor. Loose rock blocks persuaded by blast-induced fractures clearly indicate the extent of the damage caused by the poor blasting practices employed. For present study, a 60-meter high near vertical to negative highway slope located near Rampur Court Complex was selected, which exhibited an uneven profile brought by poor blasting (Fig. 2). The slope mass consists of well-developed three set of joints (J1, J2 and J3) susceptible for wedge and topple planar type of block failures which are highly vulnerable to the transportation as well as parking zone (Fig. 2). A detailed geological investigation was conducted to collection the important data related to slope profile, rock and joint parameters along with blast impact signatures. Geological strength Index (GSI) were used to characterize the studied slope mass details on which are given in Nath et al. (2021).

3 METHODOLOGY

Finite Element Method (FEM) is a popular continuum tool for slope stability analysis studies. It has powerful ability to provide complete solution for a model considering the application of stress and strain with given boundary conditions. The Factor of safety is calculated by applying shear strength reduction technique by reducing or increasing the material shear strength by a factor to reach the limit equilibrium state of the slope model (Griffith & Lane 1999 and Hammah et al. 2004). To analyze the stability of the rock slope, rock mass failure criterion suggested by Hoek & Brown (1980) were used, which was derived from the laboratory results of the brittle failure of intact rock by Hoek (1968), modelled by Brown (1970) and was later adapted for rock mass properties with the characteristics of rock mass joints. Due to the addition of geological parameters and the lack of suitable alternative criteria, the Hoek & Brown failure criterion gained popularity in research communities and is commonly used in modeling purposes.

To account the impact of blast damage and stress relaxation on the stability of the rock masses, the Hoek & Brown criterion includes a factor called "D," which is dependent on the amount of disturbance to which the rock mass has been exposed. This factor is particularly relevant in the present study since the studied rock slope has been subject to blasting damage in the past. Therefore, the Generalized Hoek & Brown (GHB) criterion (Hoek et al. 2002) helps to account for the impact of blasting damage and stress relaxation on the stability of the slope mass and provides valuable input for modeling and management purposes. In present study, GHB failure criterion has been used which incorporates geological observations, such as the Geological Strength Index (GSI), and a disturbance factor 'D' (varies 1 to 0) to account for the reduction in strength parameters due to blasting. GSI and D are essential input parameters to calculate the rock mass constants (mb, s, and a) in GHB criterion. To quantify the impact of blast-induced disturbance on the rock mass properties, the field collected data were used to assess the GHB rock mass parameters with increasing D values at an interval of 0.1. The GHB failure criteria assisted by the laboratory and field data are expressed in terms of effective stresses as:

$$\sigma_1 = \sigma_3 + \sigma_{ci}\left(m_b \frac{\sigma_3}{\sigma_{ci}} + s\right)^a \tag{1}$$

Where σ_1 and σ_3 are the major and minor principal stresses at failure, σ_{ci} is the UCS of intact rock.

$$m_b = m_i \, exp\left[\frac{(GSI - 100)}{(28 - 14D)}\right] \tag{2}$$

$$s = exp\left[\frac{(GSI - 100)}{(9 - 3D)}\right] \tag{3}$$

$$a = 0.5 + \left(\frac{1}{6}\right)\left\{exp(\frac{-GSI}{15}) - exp(\frac{-20}{3})\right\} \tag{4}$$

m_i and s are material constants, where s = 1 for intact rock. The influence of the disturbance factor on excavated rock slopes was investigated with a fixed EDZ thickness parallel to the slope profile. The EDZ thickness of 4-5 m (Verma et al. 2018 and Yang et al. 2020) was considered in the FE slope with D varied from 0 (Undamaged) to 1 (Highly damage). Initially, the equivalent continuum model of the slope with three joints were created using RS2 (Rocscience Inc. 2019) and rock mass as well as joint parameters were assigned (Fig. 2). In total, 11 such FE slope models were created with EDZ layer having rock mass parameters for different D varied from 0 to 1 with interval of 0.1. To simulate the models and calculate critical Strength Reduction Factor (SRF), shear strength parameters of the intact rock and joint sets were increased to reach the equilibrium under static conditions.

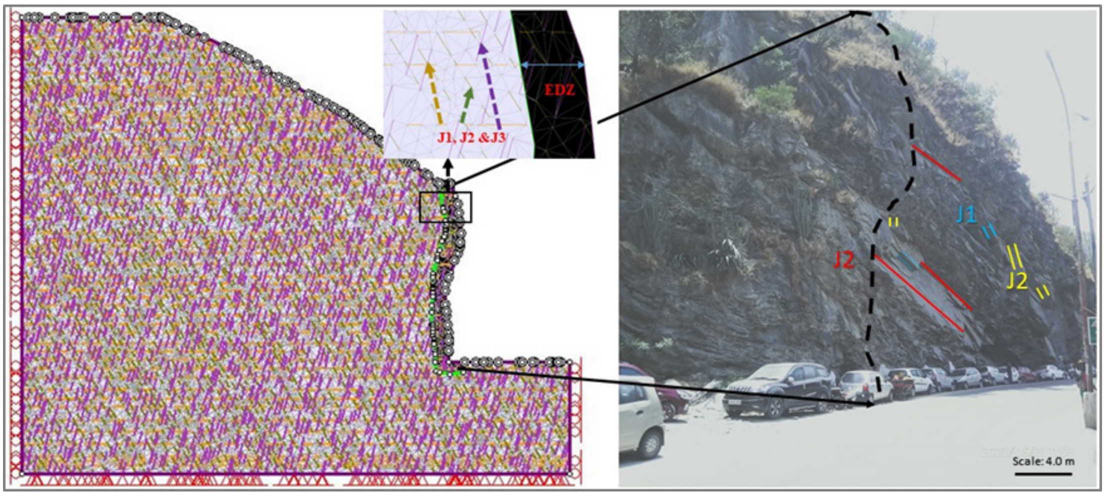

Figure 2. Discretized equivalent continuum jointed slope model of studied highway with EDZ layer.

4 RESULTS AND DISCUSSION

The computed FE results of the slope models at different damage factor (D) suggest that when the D increased from 0 to 0.6 for the EDZ layer, the safety factor (SRF) fluctuated between 0.9-0.89, followed by a constant SRF of 0.89 for D between 0.7 to 0.9. The minimum SRF of 0.88 was found at D=1 (Fig. 3). The obtained maximum displacement ranged from 0.547 - 1.43 m, with maximum shear strain ranged from 0.0591 - 0.112 for D values from 0 to 1 respectively (Fig. 3). After decreasing trend up to 0.5D, a progressive increase in total displacement and maximum shear strain are observed with increasing D, with an exceptional spike at D=0.2. It is to note that the total displacement and shear strain increase sharply after 0.5D which can be associated with the sharp decrease in the strength parameters of the slope mass. Though there is an obvious trend observed for displacement and shear strain, the change in factor of safety is rather insignificant and erratic with a value varies between 0.9 and 0.88. The simulation results exhibits scattered strain pattern in the upper slope section up to 0.5D and characterized by a thick zone of failure pattern initiated from the toe of the slope along the EDZ (Fig. 4). However, after D at 0.5 up to 0.9, the strain pattern characterized by two thick path that follows the day-lighted joint orientation prominent near the EDZ (Fig. 4). When the simulation model approaching D at1, the failure pattern is concentrated at the contact zone along the EDZ layer (Fig. 4).

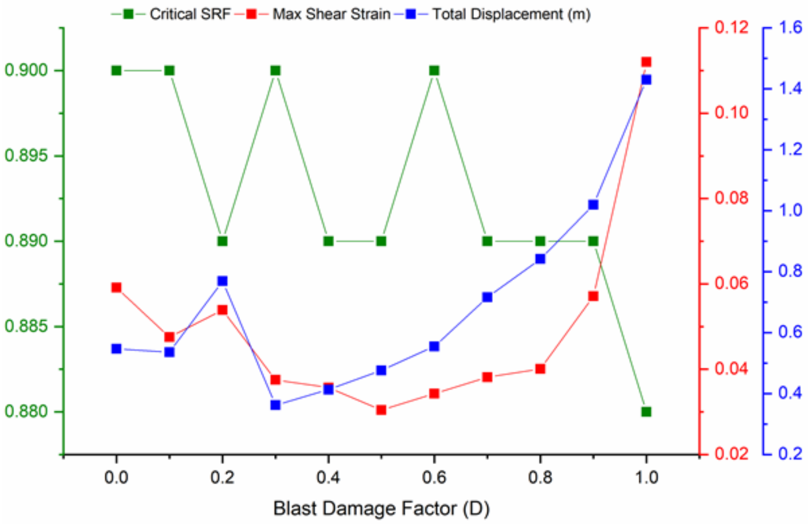

Figure 3. Variation in critical SRF, total displacement and maximum shear strain with damage factor.

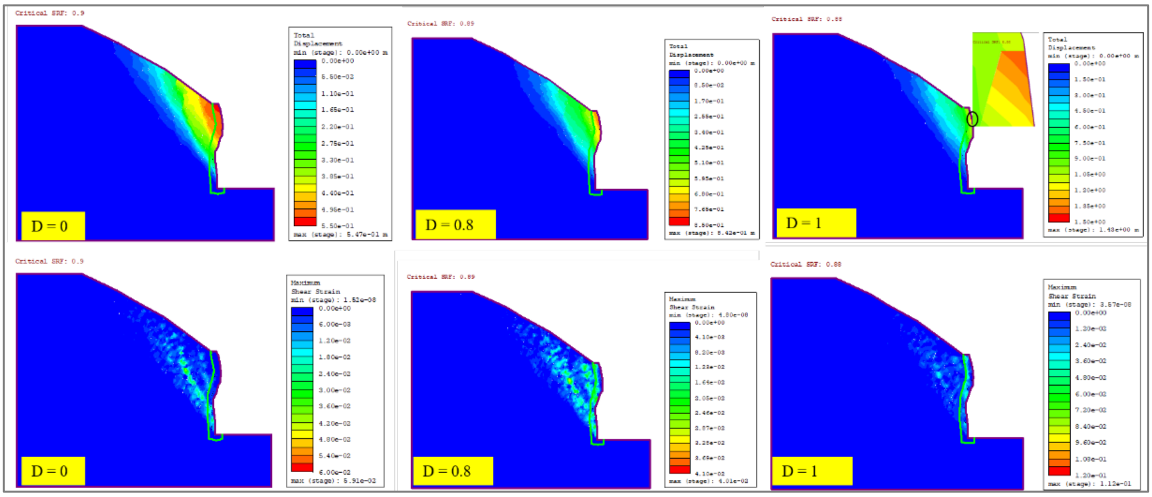

Figure 4. Total displacement and maximum shear strain contours with EDZ boundary for D at 0, 0.8 & 1.

5 CONCLUSIONS

In the present study, the effect of the blast damage factor (D) on the stability characteristics of a vulnerable highway slope has been investigated through FE modeling. Blast damage zone of 4-5 m parallel to slope profile was considered and FE models were simulated with different D from 0 to 1 assigned to the damage layer. The simulation results suggest almost similar variation in displacement and shear strain throughout with sharp increase after D of 0.5 with the maximum value achieved of 1.43 m and 0.112 respectively for D at 1. However, the change in critical SRF is rather trivial and erratic with value varies between 0.9 and 0.88. Variation in displacement and shear strain contours signify the change in deformation characteristics of the studied cut slope under varied damage factor values. Results suggest dispersed strain pattern up to D at 0.5 characterized by a thick zone of strain accumulation initiated from the toe of the slope. Whereas strain accumulation follows two thick path along the day-lighted joints near the slope face under D varies from 0.5 to 0.9. However, in the EDZ slope model with D at1, the strain is concentrated near slope surface along the EDZ contact zone.

ACKNOWLEDGMENT

Som Nath thankfully acknowledges the support by the MHRD doctoral fellowship granted by the Indian Institute of Technology, Roorkee, India.

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