A distinct element modeling approach towards rock fall analysis

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Abstract

Rock slope stability problems along cut slopes are detrimental for the traffic movement and the overall economic health of the area. Rockfall and other slope failure activities have caused large devastation mainly along cut slopes. Such activities are quite rampant and poses a challenge to the rock engineering community. This study focusses on such critical issues of slope failure activities along cut slopes. Detailed field investigation was complemented with high end numerical simulation for the overall stability analysis. Distinct element method was used for studying the initiation of block detachment and rockfall behavior. Modelling was done for two different cases by varying excavation height with simultaneous variation in joint cohesion. Several parameters were obtained from the analysis which highlights the deformational attributes of jointed rock mass and conditions leading to rockfall.

Keyword: Rockfall; slope stability; DEM; Jointed rock; cut slope

1. Introduction:

Slope failures are witnessed not only in India but around the world and over the years the instances of landslides have increased manifold due to anthropogenic activities and climate change phenomenon (Singh et al. 2013a & b; Kainthola et al. 2012; Sarkar et al. 2010). Unscientific construction, inefficiency in conducting detailed geological and geotechnical investigations can be attributed as a major cause of loss of life and property along transportation lines (Singh et al. 2013). The excavation technique in different geologic material can vary significantly and a situation might arise where unplanned excavation may expose the daylighting discontinuities on the free faces, enabling kinematic destabilization of rock blocks. Depending on the height, orientation of discontinuities, volume of dislodged mass and steepness of slope face, a typical rockfall activity may transform to a large scale landslide (Singh et al. 2013c). Rockfall phenomenon is very common and a threat along the transportation lines particularly in the mountainous areas (Ahmad et al. 2013; Ansari et al. 2014; Singh et al. 2014). Rockfall activities have now being studied by engineering geologists as a different failure mechanism that can cause substantial damage, if the volume of falling mass is very large. The process of rockfall is mainly attributed to various geo-environmental conditions that can modify the geomechanical properties of rock mass to an extent that can lead to block detachment. Rainfall, glaciers, freezing and thawing and seismicity can lead to opening of joints, weakening of rock mass strength and are generally considered as the major rockfall promoters (Ansari et al. 2015).

Several approaches have been developed and improvised to understand rock fall behavior. Widely used numerical methods like finite element method (FEM) and finite difference method (FDM) cannot be used for rockfall simulation because of the several constraints in the modelling methods itself. Therefore, in the past few years, numerous softwares have been primarily developed to study rockfall. Rockfall, a type of landslide, is quite common in jointed and weathered rock masses. In order to completely understand the behavior of falling blocks from the slope face, shear stress available along the joint planes and shear strain developed as a result of sliding or deformation in general, has to be studied meticulously. These deformational attributes can be very easily simulated in a distinct element code (DEM), a method which specializes in modelling of discontinuous media like that of a jointed rock mass. One of the advantages of this method is that it can simulate large strain along the discontinuities and even rotation of the blocks is allowed.

A similar condition is encountered along roadways in Himachal Himalayas, 120km north of Shimla. The entire stretch along the banks of river Sutlej nearby Luhri area sees such activities throughout the year and therefore, an attempt has been made in this study to investigate the kinematic feasibility of the area and the mechanism of failure leading to initiation of a typical rockfall activity (Sarkar and Singh 2008a, b & c; Sarkar et al. 2009 & 2010). Detailed geological and geotechnical data along with the samples were collected from the concerned areas. Finally, with the help of high end numerical simulation, an understanding has been developed on the initiation and propagation of rockfall.

2. Study area:

The study area is a part of Kullu district in Himachal Pradesh. All along the banks of river Sutlej, cut slopes are exposed in the variable lithology of this area. Along the right bank, gneisses belonging to Kullu formation are mostly encountered whereas, schists, quartzite and dolomites belonging to Larji formation are only visible in patches (Fig. 1). The Kullu formation is the oldest suit of rocks thrusted over the youngest Larji formation in this region (Srikantia and Bhargava 1998). The rocks are highly jointed having at least three regular sets observed in the exposed surfaces and the slope face is sub-vertical ranging from 65^o to 78^o.

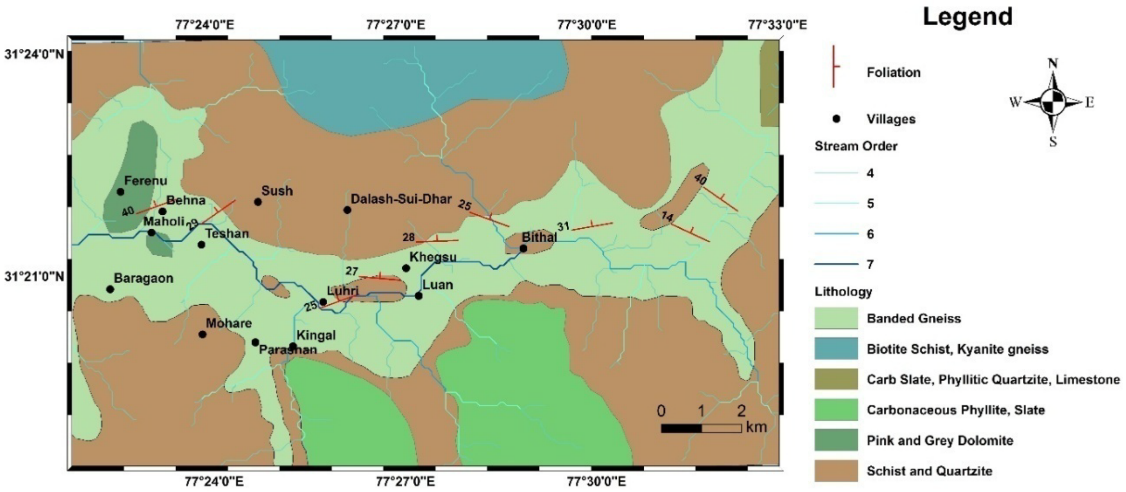

Figure 1 Geology map of the study area showing drainage pattern and variation in the trend of foliation along the right bank of river Sutlej

Bedding joints are highly persistent in nature throughout the area while the other joints are around 1 to 3m in length. The spacing between bedding joints and other joints are quite random ranging from less than one to about 2m. While the bedding joints are tight, others are filled with clay/sandy matrix. Kinematic analysis was done based on structural data obtained from field visit in the lower hemisphere equal area projection (Fig. 2). J1 and J2 joints are very critical in forming the wedges in this area and the bedding parallel joint acts as release surface and constitutes the main source of rockfall promoter. It has also been reported in the past that planar and wedge failure contributes to most of the rockfall activity around cut slopes around this area (Singh et al. 2013a & b, 2014).

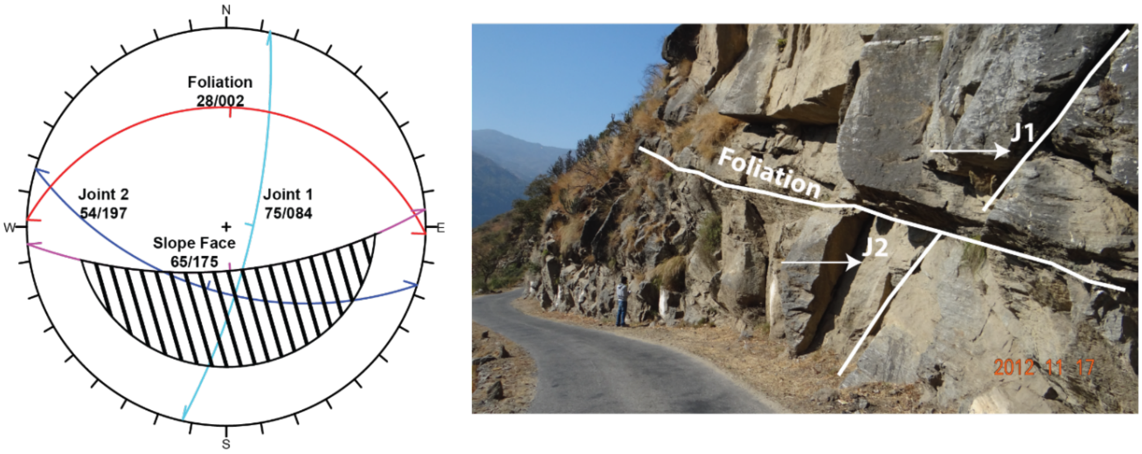

Figure 2 Lower hemisphere equal area projection of joint condition in the study area

3. Numerical simulation:

The application of numerical simulation in the field of rock engineering has increased very rapidly since last 20 years. With the development of several numerical codes especially for slope stability analysis, the work of researchers or any engineering professionals has become much easier. Some of the most commonly used methods in slope studies are finite element method (FEM), finite difference method (FDM), distinct element method (DEM) and of course the limit equilibrium method (LEM). Although, LEM, FEM and FDM have been greatly used in stability analysis of slopes, but because of some inherent weakness in each method, DEM is mostly preferred in jointed rock slopes. UDEC (a distinct element code), developed by Cundall, is very efficient tool in simulating the behavior of jointed rock mass and successive block detachment leading to rockfall (Cundall and Hart 1992; Cundall 1980). Previously, several researchers have used DEM for the stability analysis of highly jointed rock mass along cut slopes and other areas in rock engineering (Kainthola et al. 2012 & 2014; Rathod et al. 2011 & 2012; Bhasin and Kaynia 2004). One of the important reasons for the selection of DEM in complex rock mass is that they are able to simulate even high strain conditions with the added benefit of block detachment (Jing 2003; Jing and Hudson 2002).

Slope geometry

The slope geometry was kept very simple mainly because of the near vertical surface topography of the studied section (Fig. 3). The 10X20m rock section was dissected into distinct rocks block. The two critical joint sets were added to the model with the purpose of developing different block sizes. The idea was to generate the overhangs with a dimension of block size generally encountered in the field and simulate block detachment leading to rockfall due to road widening activities.

Material Properties

The material properties were determined in the laboratory from the samples collected during field visit. Bulk and shear modulus were obtained from young's modulus and poisson's ratio and shear strength parameters were estimated from triaxial tests (Table 1). The rock and discontinuities were simulated as linear Mohr-Coulomb material in the UDEC model.

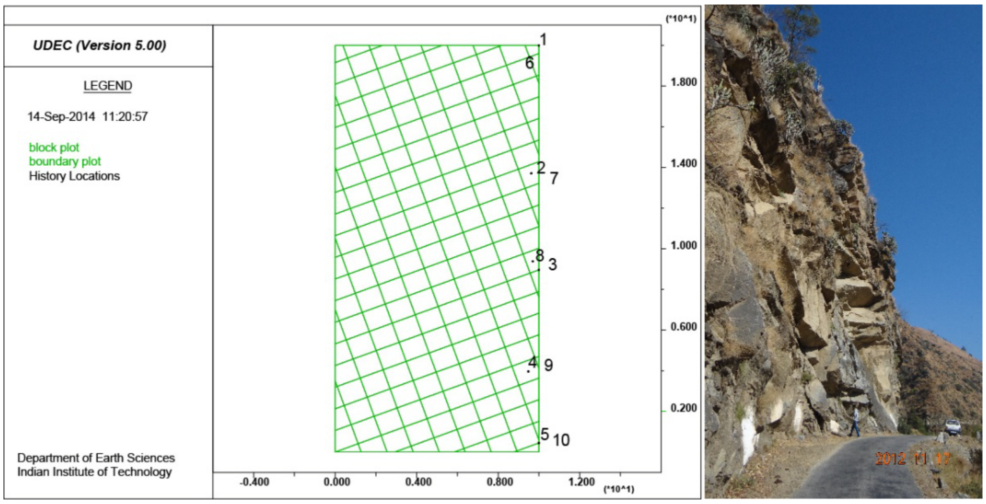

Figure 3 Block geometry created in a DEM for a cut slope on the right bank of river Sutlej

Table 1
Material properties used in the simulation for intact rock and joints

Parameters	Cohesion (MPa)	Angle of internal friction (^{o})	Bulk Modulus/ Normal Stiffness (GPa)	Shear Modulus/ Shear Stiffness (GPa)	Density (kg/m^3)
Intact rock	9.8	41	26	7	2700
Joint	0.01	30	10	1	-

The joint strength parameters were evaluated from Schmidt hammer tests and other laboratory experiments. The given values represent the mean of all the values measured. The numerical model in the present paper aims at measuring the progressive displacement in a 20m high jointed rock wall against excavation and also to shed some light on the problem of overhangs in the region. Several scenarios have been considered with an excavation width of 5m and 8m. For each excavation scenario, two conditions were modeled, one with 0.1MPa joint cohesion and another with 0.01 MPa joint cohesion.

Case 1

Initially, a 5m high quarry with 1m width was carried out at the right bottom fringe of the section by removal of blocks (Fig. 4). Both translational and rotational movements were observed in the excavated region. At 0.1 cohesion, the maximum displacement observed was 0.142m, slightly increasing to 0.144 when joint cohesion was decreased to 0.01MPa (Fig. 5). The velocity vectors also showed a slight increase from 0.35 to 0.36m/sec (Fig. 6). This high magnitude was attained by some of the block in the vicinity of the excavation while the other blocks were in equilibrium or showed no noticeable disturbance (Figs. 5 & 6). An interesting observation noticed from the plot of block rotation was disturbance at the rear end of the excavation at 0.1 cohesion. This may be from the fact that the high joint cohesion inhibited block movement and small openings created as a result of block removal came to equilibrium with time. But for the other case, low joint cohesion allowed progressive displacement and rotation along the persistent daylighting joints (Fig. 6).

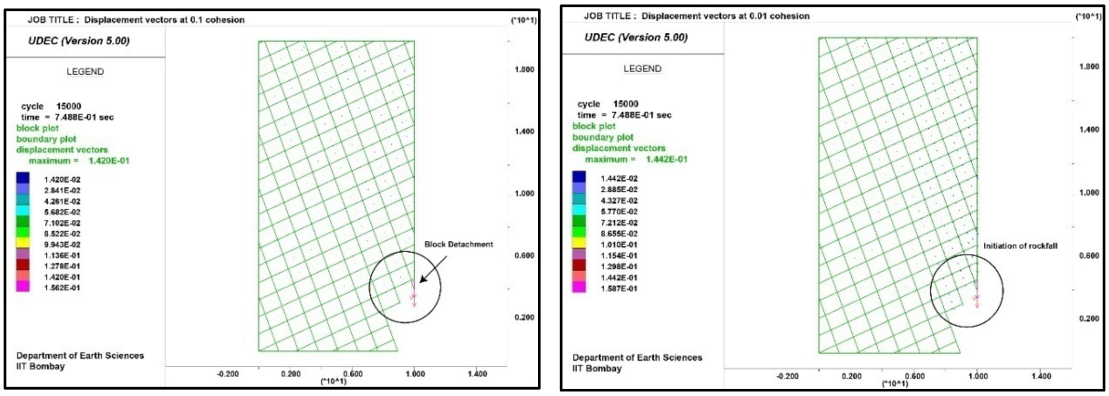

Figure 4 Displacement vectors at 0.1 and 0.01 MPa joint cohesion

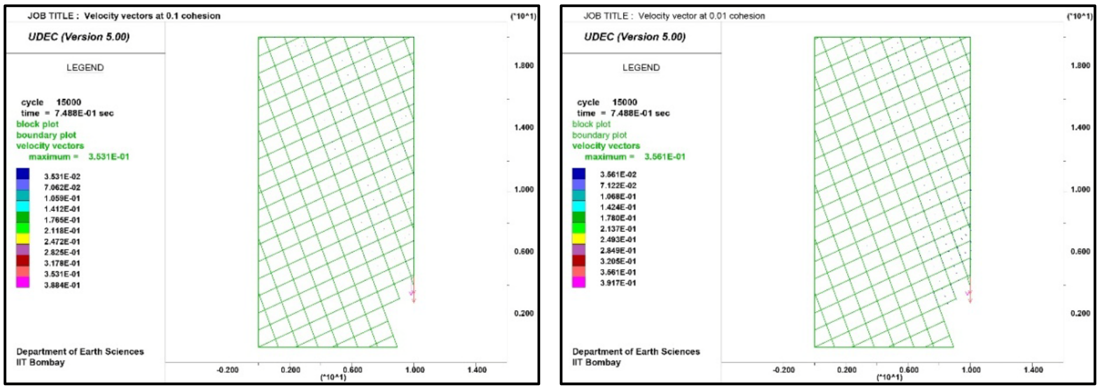

Figure 5 Velocity vectors at 0.1 and 0.01 MPa joint cohesion

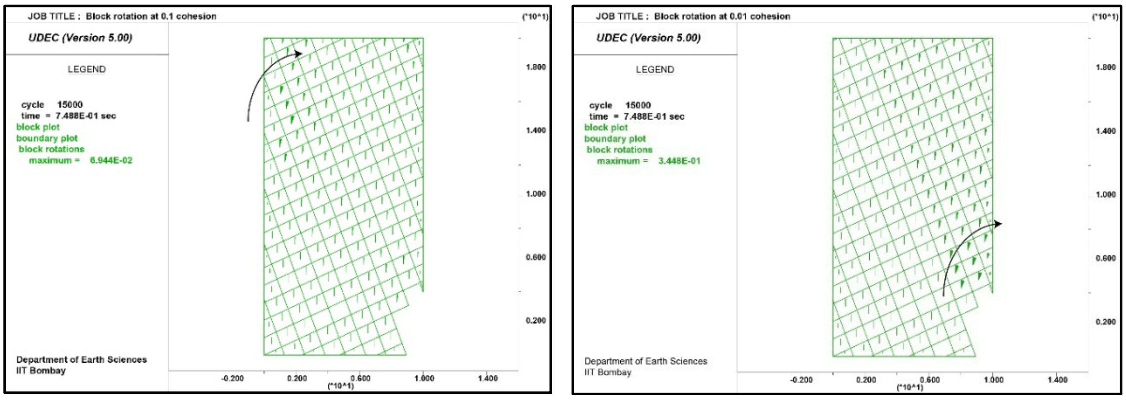

Figure 6 Block rotation at 0.1 and 0.01 MPa joint cohesion

Case 2

In the second stage, $2X8m^2$ blocks were removed indicating a typical road widening process. This created further avenues for the formation of overhangs and increased chances of rockfall activities. The maximum displacement of the blocks observed at 0.1 MPa joint cohesion was around 0.504m, increasing to 0.516m at 0.01MPa joint cohesion (Fig. 7). The maximum velocity vector recorded was 1.36m/sec, increasing to 1.37m/sec (Fig. 8). Increased excavation resulted in enhancing the displacement and velocity vectors as a result of which block detachment takes place leading to the initiation of rockfall (Figs. 7 & 8).

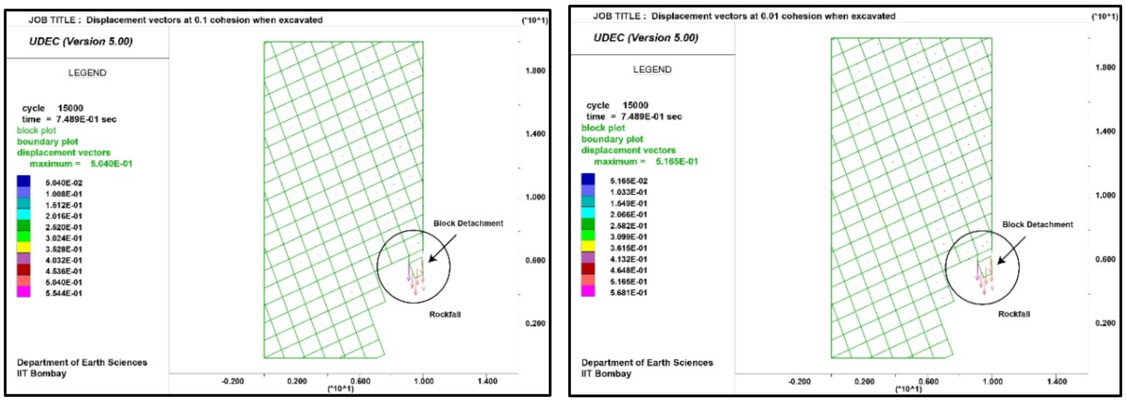

Figure 7 Displacement vectors at 0.1 and 0.01 MPa joint cohesion and increased excavation

The overall blocks show almost no signs of deformation against excavation, except near the removed blocks. This is also confirmed by plot of block rotation where the maximum rotating block (failed block) attains a value of around 1.93 for both the cases, obvious as the block initiates failing already at 0.1 MPa joint cohesion (Fig. 9). The direction of block rotation is anticlockwise (for failed blocks) in comparison to the first case where most of the blocks showed clockwise movement (Figs. 6 & 9). It would not have made much difference, had the persistent daylighting joints been cohesion less, because the release surface itself is very tight and would not allow movement, but certainly a slight increase in magnitudes is an expected outcome.

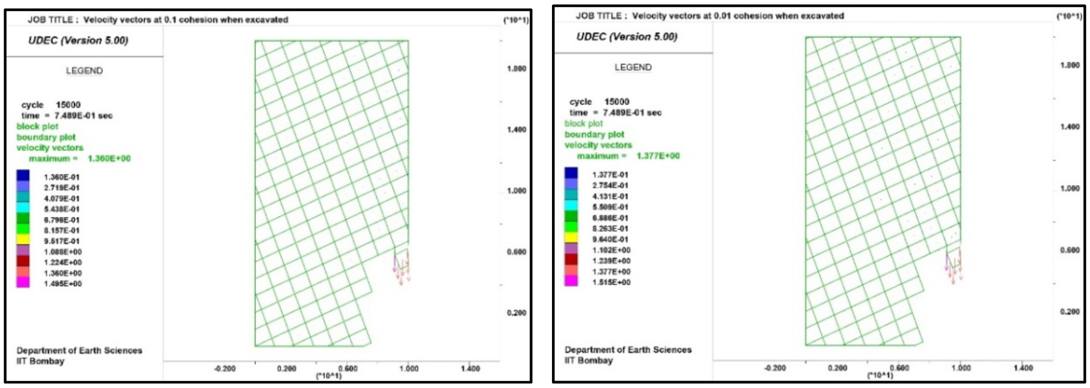

Figure 8 Velocity vectors at 0.1 and 0.01 MPa joint cohesion and increased excavation

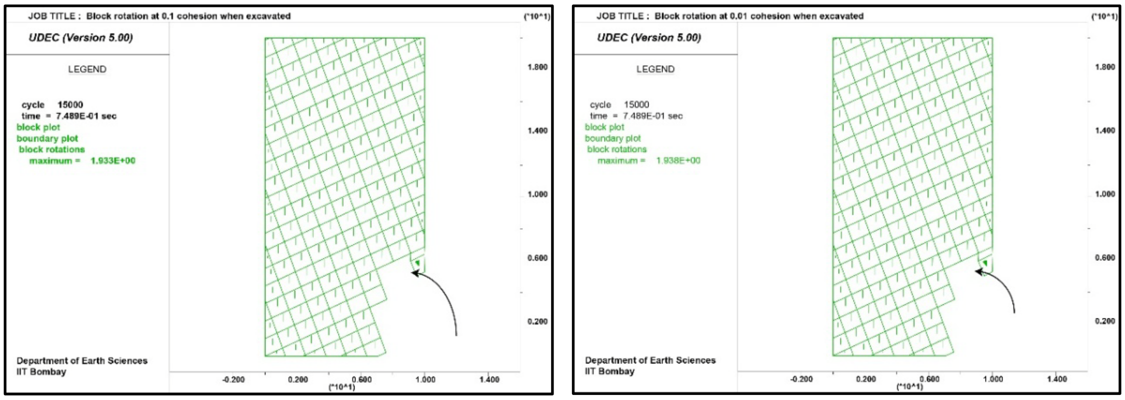

Figure 9 Block rotation at 0.1 and 0.01 MPa joint cohesion and increased excavation

4. Results and discussion:

DEM's package UDEC provides quite a useful insight into the deformation attributes of the studied highly jointed slope section. The displacement history was monitored for all the selected points in the modeled geometry (Fig. 3). As has been discussed earlier that the increase in displacement and velocity is only observed in the vicinity of the excavated zone, the displacement history plot confirms the same (Figs. 10 & 11). The plot shows that curves become almost horizontal, except for some cases where failure occurs, and the overall system tries to attain equilibrium. Displacement history for increased excavation has not reached the stable phase for 15000 cycles and it is certain that with time the curves will tend to accomplish the stable phase (Fig. 11). It may also happen that other blocks nearby starts detaching from the slope face with increased cycle.

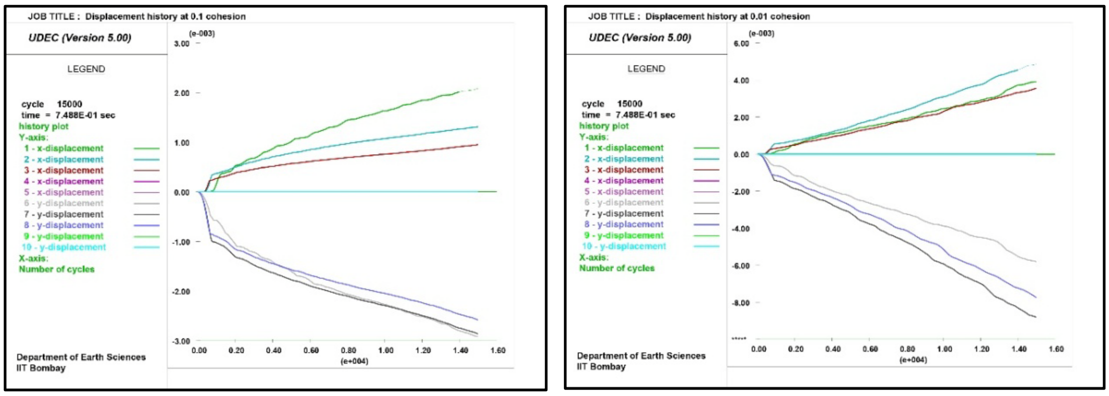

Figure 10 Displacement history for selected monitoring ponits for 0.1 and 0.01 MPa joint cohesion

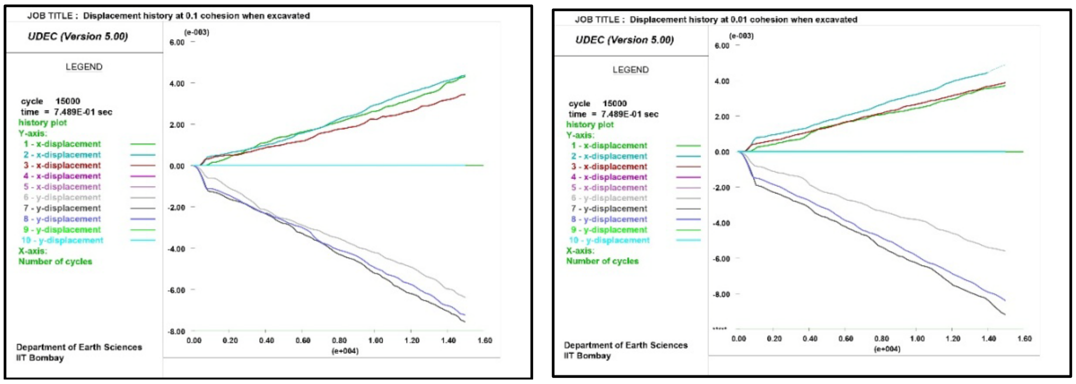

Figure 11 Displacement history for selected monitoring ponits for 0.1 and 0.01 MPa joint cohesion when excavated

The change in the deformational attributes of displacment, velocity and block rotation for the two cases is summarized in table 2. The mentioned data shows the maximum value achieved for each parameter during the analysis. There is not much difference between the values for different joint cohesions. For case 1, the maximum value reached is too low to initiate rockfall even at low cohesion but as the excavation is increased to 8m, value changes drastically and block detachemnt can be seen even at lower cohesion.

Table 2
Variation in deformational attributes corresponding to displacement, velocity and block rotation

Parameters	Case 1		Case 2	
	0.1MPa	**0.01MPa**	**0.1MPa**	**0.01MPa**
Maximum Displacement (m)	0.142	0.144	0.504	0.516
Maximum Velocity (m/sec)	0.353	0.356	1.36	1.37
Maximum block rotation	0.0694	0.344	1.933	1.938

5. Conclusion:

Rockfall analysis was carried out for a highly jointed and vulnerable cut slope along the right bank of river Sutluj, Luhri, Himachal Pradesh. The stability analysis was carried out by detailed field investigation, laboratory testing followed by application of high end numerical simulation in a DEM's package UDEC. Kinematic analysis shows that the possibility of wedge formation is quite prevalent in this location and a major cause for the initiation of rockfall. The numerical simulation provided very comprehensive results in terms of displacement, velocity and block rotation due to excavation of rock block from the slope face in a typical activity of road widening process. Two cases with two different conditions were simulated to determine the deformation parameters. Joint cohesion and excavation height was varied during this analysis. The results shows that there is a progressive increase in the displacement as the joint cohesion decreases for a 5m excavation. The displacement shoots up as more blocks are removed, as a result of which block detachment occurs from the slope face transforming to a typical rockfall activity. There is an increase in the rockfall falling velocity with increased excavation. The plot of block rotation shows that due to stress release near the vicinity of the excavated blocks some disturbance is noticed at the far end. This was interpreted to be due to restraining of blocks against downward descent because of high joint cohesion. Overall, the study suggests the use of high end numerical simulation in the stability analysis of highly jointed rock slopes.

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