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Back Analysis of Shear Strength Parameters of a Large Rock Slide in Sikkim Himalaya

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ABSTRACT

Both earthquake and rainfall induced landslides are quite common in the Eastern Himalayan state of Sikkim. Massive landslides killing tens of thousands of people with catastrophic damages have occurred in Sikkim, which shares common borders with Tibet, Nepal, and Bhutan. Under a joint research co-operation programme between India and Norway (INDNOR), landslide investigations were performed in Northern Sikkim where a massive rock slide called the 'Dzongu landslide' was investigated near the town of Mangan. This massive landslide occurred on the 13th of August 2016 when several million cubic meters of rock mass failed and blocked a tributary of the river Teesta and caused damage to infrastructures in a nearby village. In this paper a back-analysis of the shear strength parameters of this large rock slide is performed to gain a better understanding of its behaviour which led to its failure. Although some early signs of instability could be seen through satellite images in 2006, it is believed that the Sikkim earthquake of magnitude M_w 6.9 on the 18th of September 2011 aggravated the situation which over a period of time reduced the shear strength of the rock mass due to increase in pore water pressure in the slope. Such instability assessments of vulnerable slopes are warranted so that mitigation strategies, such as tunnelling, can be planned to bypass major landslides along some critical highways in the Himalaya.

Keywords:Rock slide; Landslide; Vulnerable slopes; Tunnel; Bypass; Shear strength parameters; Rock mass; Back analysis; Sikkim; Himalaya

1. INTRODUCTION

The Himalayan state of Sikkim in the North-East of India is characterised by steep slopes, lofty hills, and complex geological and tectonic settings. Sikkim covers an area of about 7300 km^2 and measures approximately 100 km from north to south and 60 km from east to west (Fig. 1). The elevation in the region ranges from 244 to 8534 m, encompassing the third highest mountain (Mount Kanchenjunga) in the world. Landslide occurrences are quite common in the Sikkim Himalaya, and the magnitude of damages caused every year in various parts of the state is quite large.

Both earthquake induced and rainfall triggered landslides are quite common in the area. In September 2011, over 1000 landslides were triggered by the 6.9 M_w earthquake in Sikkim causing devastating damages to lives and properties in the region. These landslides were subsequently mapped through remote sensing techniques with verifications on the ground (Martha et al., 2015). It was found that the areas of Mangan and Chungthang in North Sikkim were severely affected due to landsliding as these areas were close to the epicentre of the earthquake. Prior to September 2011, the region experienced another major earthquake (M_w 5.7) on 14 February 2006 which also caused a number of landslides wherein two Indian army soldiers died (Kaushik et al., 2006). This region has experienced relatively moderate and frequent seismicity in the past, with 18 earthquakes of magnitude 5 or greater being experienced over the previous 35 years within 100 km of the epicentre of the September 2011 event.

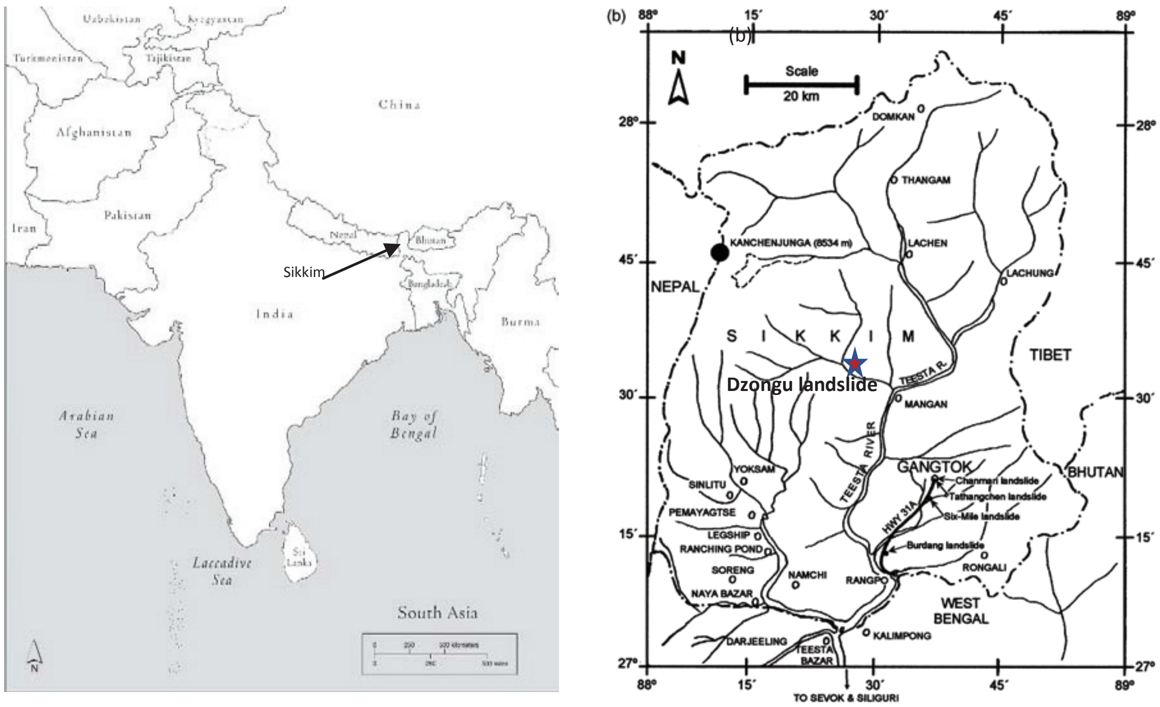

Fig. 1 - (a) Map of India showing location of Sikkim (b) Map of Sikkim showing the Dzongu landslide near Mangan

In the monsoon of 2019, rainfall induced landslides have caused a havoc in the region wherein Sikkim was cut-off from the rest of India due to multiple landslides on the National Highway NH31. These alarming facts about landslides in Sikkim have prompted the Indian Ministry of Earth Sciences and the Norwegian Research Council to initiate technical research on studying the behaviour of landslides triggered due to seismicity and meteorological conditions in the region.

In analysing a landslide, it is important to determine what factors have controlled the formation of the rupture surface and the movement on that surface. This requires an engineering analysis of the stability of the landslide mass and analysis of the changes in geologic and meteorological conditions that are correlated with landslide activity. This paper describes the above investigations for the case of large rock slide which occurred in the North of Sikkim near Mangan on the 13th of August 2016. The landslide which was approximately 900 m high and 500 m wide generated a huge cloud of dust as it failed and blocked a tributary of the river Teesta which is a 315 km long river that rises in the eastern Himalaya.

2. GEOLOGY OF SIKKIM

The Indian state of Sikkim is mainly located in the watershed of the Teesta River (Fig. 1). Through the foothills of the Himalaya, the Teesta and its tributaries have deeply eroded the terrain. As mentioned above, landslide occurrences are quite common in Sikkim Himalaya; the main reasons for this phenomenon are attributed to the geology of the area and the high intensity of rainfall in addition to seismic activity. Apart from these reasons, recent development, particularly road and housing construction have aggravated the incidence of landslides and subsidence problems (Mehrotra et al., 1996).

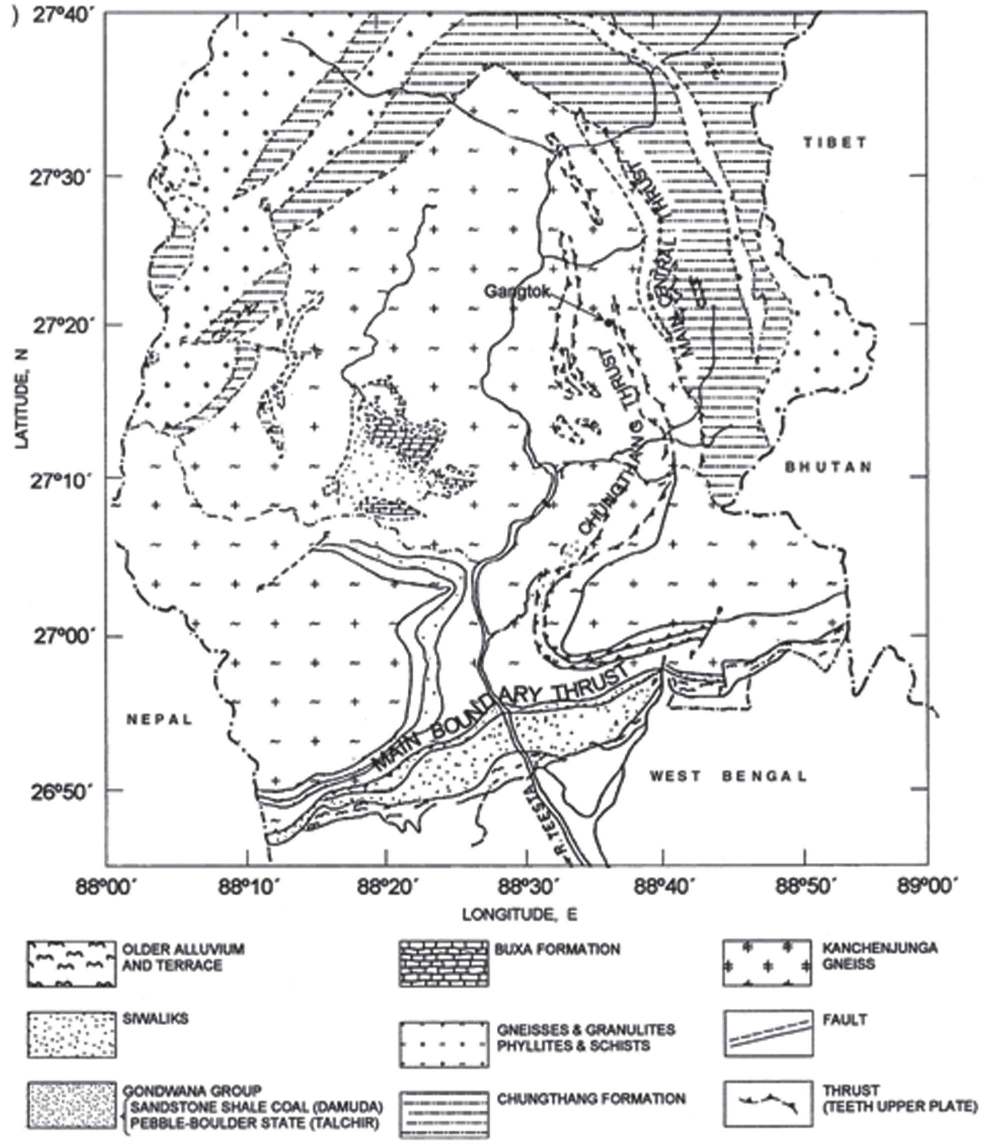

Fig. 2 - Geologic map of southern Sikkim (compiled and modified from Raina and Srivastava, 1981)

Geologically, Precambrian rocks cover a major portion of the Sikkim Himalaya and are represented by the four major rock formations, namely the Everest Pelitic Formation, Sikkim Group, Chungthang Formation and Kanchenjunga Gneiss Group (Raina and Srivastava, 1981). The Sikkim

Group of rocks consists of schists and gneisses (Fig. 2). East Sikkim is mainly dominated by rocks of the lower metamorphic grades, mainly chlorite schist, sericite schist and quartz schist. These rocks have a phyllitic appearance.

The region of central and eastern Himalaya near the Teesta River is characterised by large-scale thrust movements from the northwest towards the southeast. The East Sikkim Himalaya is mainly traversed by two thrusts called the Chungthang Thrust and the Main Central Thrust (MCT), both trending in a NW–SE direction (Mehrotra et al., 1996). The MCT is a well-known tectonic boundary between sedimentary and crystalline rocks, separating the Lesser and Greater Himalaya. It is characterised by crushed rock and fracture zones. The Chungthang Thrust involves gneissic rocks of the Chungthang Formation and schistose rocks of the Sikkim Group. These schistose rocks are present in the Gangtok region and are of interest in this paper. The Nepal-Sikkim Himalaya and adjacent foredeep area are dominated by conjugate strike-slip faults that face the wedges of the Indian shield. Rocks of this terrain are characterised by intense folding, metamorphism and thrusting in a number of tectono-stratigraphic units, which exhibit inversion in stratigraphic succession as well as in metamorphic grading.

3. SEISMICITY AND METEOROLOGY

Sikkim Himalaya is a seismically active area where the occurrence of earthquakes and landslides is frequent (Ghosh et al., 2012). Historical data on earthquakes show that the Sikkim and adjoining area lies in a region prone to be affected by moderate to great earthquakes in the past. The entire area of Sikkim lies in Zone IV of the Seismic Zonation Map of India (IS1893: 2002). The Sikkim with its adjoining region is known to be part of the seismically active region of the Alpine-Himalayan seismic belt, with four great earthquakes of the world of magnitude 8.0 and above occurring in this region. Earthquakes in this region are broadly associated with strain accumulation associated with the northward tectonic movement of the Indian Plate and its subsequent abrupt release. The strain is generally released by activity along Himalayan faults and thrusts of regional dimensions of which Main Boundary Thrust (MBT) and Main Central Thrust (MCT) are particularly important (DMCC, 2012). Figure 3 shows the MBT and MCT in Sikkim (Sharma et al., 2012) near Mangan where a huge rockslide occurred in 2016. The cause of this huge rockslide is attributed to the seismicity and meteorology of the area as discussed later during the back-analysis of the rockslide. A disastrous earthquake of magnitude M_w 6.9 (www.usgs.gov) occurred in Sikkim at 6:11 PM (IST) on September 18, 2011. This earthquake left behind a trail of death and devastation, killing about 112, injuring more than a thousand, and rendering more than twenty thousand people homeless (Sharma et al., 2012). The earthquake triggered more than 1000 landslides in Sikkim and played a role in initiating cracks on the ground and on slopes (Martha et al., 2015). These landslides were systematically mapped using very high resolution data from 8 different satellites. The results indicated that several parts of north Sikkim, particularly in Mangan close to the epicentre was severely affected by the 2011 earthquake. Morken et al. (2020) show through satellite pictures the temporal evolution of Dzongu landslide area from 2006-2015. It was concluded that the failure of the Dzongu landslide in August 2016 was preceded by ten years of slope deformation, as crack development were evident on satellite images since 2006 along the eastern flank of the failure. Over the years due to percolation of water in the tension crack and in the existing joints, the shear strength of the discontinuities reduced causing a failure of the slope.

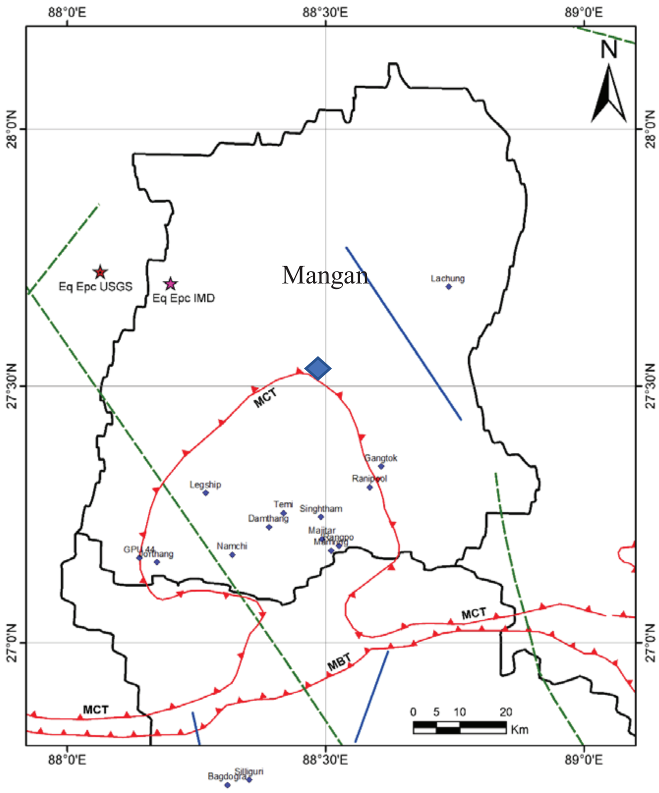

Fig. 3 - Tectonics of the region showing the location of the Main Central Thrust (MCT) and the Main Boundary Thrust (MBT) (Sharma et al., 2012)

Sikkim is located on the south-facing slopes of the Himalayan mountain range. The area is exposed to high variations of precipitation during the year. The monsoon period, which has high precipitation, extends from April to September, while a dry season exists in mid-winter. During the monsoon season, a very high-intensity rainfall in the order of 150 mm to 300 mm in 24 hours is not very uncommon in this part of the Himalaya (Koley et al., 2019). The annual average rainfall (2011 – 2018) in Mangan is around 3000 mm. Figures 4 and 5 show respectively the annual and average monthly precipitation in Mangan near the vicinity to the Dzongu landslide. It may be seen from Fig. 5 that the monsoon period which can last from May to September contributes to more than 75% of the total annual rainfall.

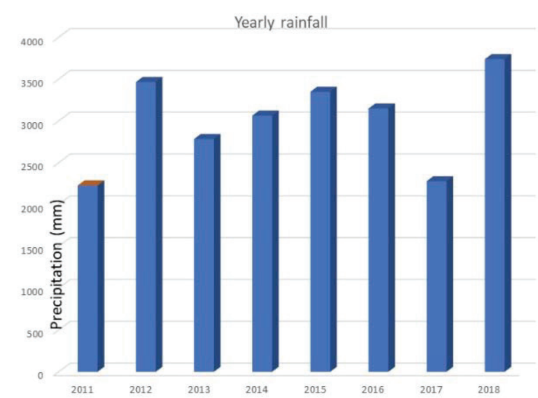

Fig. 4 - The annual precipitation in Mangan near the vicinity to the Dzongu landslide

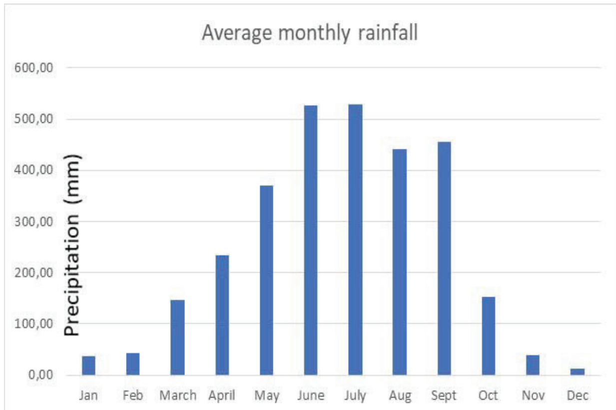

Fig. 5 - Average monthly precipitation from 2011-2018 in Mangan

4. DZONGU LANDSLIDE INVESTIGATION

Under a joint research co-operation programme between India and Norway (INDNOR), landslide investigations were performed in Northern Sikkim where Dzongu landslide was investigated. This is a massive landslide which occurred near the village of Mangan around 13:30 h (IST) on 13 August 2016. Figure 6 shows the photos of the landslide taken from the top and from the bottom of the landslide which is basically in gneissic schistose rock. The landslide is around 900 m long and 500 m wide. Several million cubic meter material of the rock mass failed which blocked the river Kanaka and TholungChhu which are tributaries of the Teesta river. The lake washed away about 300 m stretch of the road and submerged five houses in Mangan village (Martha et al., 2017). According to eye witnesses the rock slide generated a huge cloud of dust due to its rapid downward movement resulting in an air-blast. The thickness of the debris varied between 30-50 m and the size of some of the boulders observed on the debris were about 50 cubic meters. The landslide was rectangular in shape as can be seen in Fig. 6. Three sets of joints dipping towards, East, West and North-East could be identified. The exposed landslide suggested a translational type of failure in the main body with the possibility of a wedge type failure on the top. As mentioned earlier this area suffered a severe earthquake in 2011 where several large landslides occurred on the upstream side and crack developments were evident in areas near the epicentre of the earthquake including the Dzongu slide area. Figure 7 shows a recent google image of the area in which one can see the Dzongu landslide that occurred in 2016 while another landslide called the Bay Tholung landslide on the upstream side occurred during the 2011 earthquake. The major cause of failure of the Dzongu landslide may be attributed to the ground water seepages in cracks over the years resulting in reduced shear strength of the rock mass.

Fig. 6 - Picture of the Dzongu landslide taken from the top (left) and from the bottom

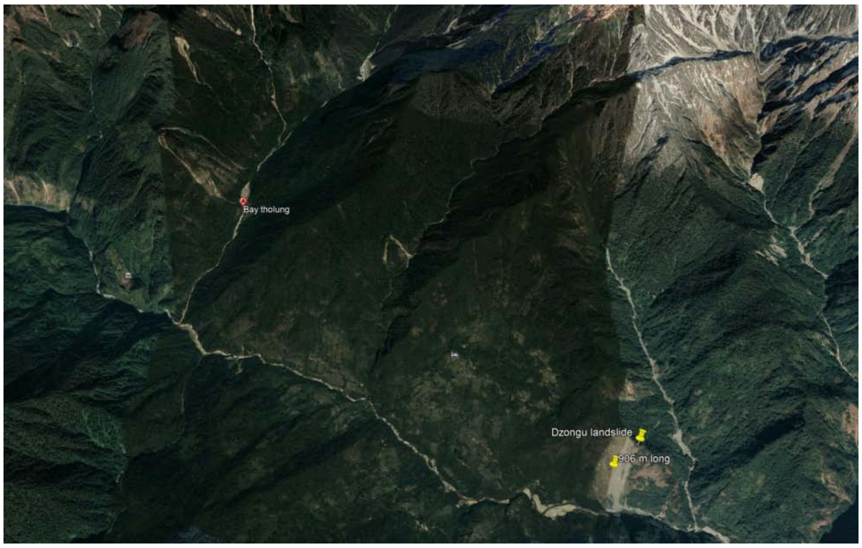

Fig. 7 - Google image of the Dzongu landslide that occurred in 2016 and the Bay tholung landslide which occurred during the 2011 earthquake

Ground water seepages from the exposed joint planes were identified through satellite images by Martha et al.(2017) (Fig. 8). A back-analysis of the joint shear strength parameters of this landslide is performed to gain a better understanding of the mechanics and behaviour of the landslide.

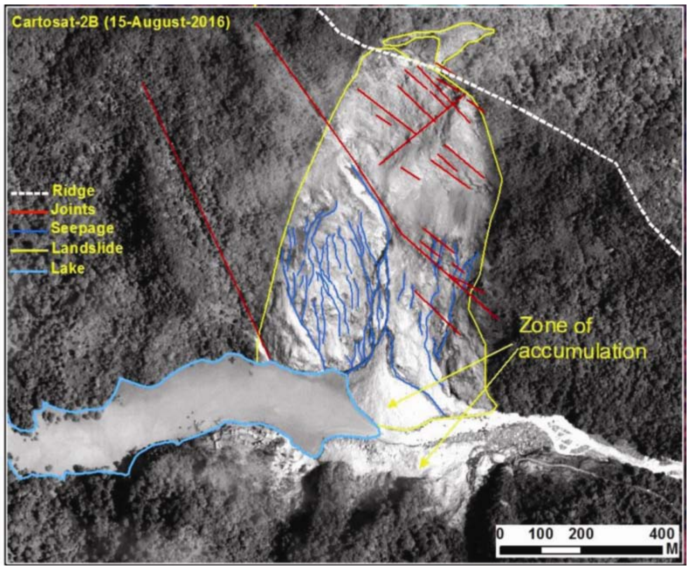

Fig. 8 - Cartosat image of Dzongu landslide showing the water seepage through joints after its failure (Martha et al., 2017)

5. PLANAR STABILITY ANALYSIS OF DZONGU LANDSLIDE

The Dzongu landslide was analysed using the RocPlane software (version 2) which is an interactive tool for assessing the stability of planar sliding blocks and wedges in slopes (RocScience.com). The analysis included the effect of water pressure on the slope and seismicity. Ground based Lidar was used for mapping the landslide (Morken et al., 2020). The geometry of the model was constructed based on the lidar scan and limit equilibrium analysis were performed on the sliding block. Figure 9 shows the sliding block model used for the analysis of landslide. The non-linear Barton-Bandis model was used for describing the shear strength of the discontinuities (Barton and Bandis, 1990).

The parameters JRC (joint wall roughness), JCS (joint wall compressive strength) and ϕ_r (residual friction angle) were mapped in the field in accordance with the recommendations given by Barton and Choubey (1977). The original form of this non-linear «JRC - JCS» criterion for predicting the shear strength of rock joints is written as:

$$\tau = \sigma_n \tan\left[JRC \log\left(\frac{JCS}{\sigma_n} \right) + \Phi_r \right] \tag{1}$$

where σ_n =effective normal stress and τ = shear stress.

The residual friction angle ϕ_r for unfilled joints may be determined from Schmidt hammer and tilt tests using the following equation (Barton and Choubey, 1977):

$$\Phi_r = (\Phi_b - 20^o) + 20\left(\frac{r}{R} \right) \tag{2}$$

The parameter ϕ_b is termed the basic friction angle for flat, sawn, but unpolished, weathered surfaces of the rock in question. The parameters R and r are the Schmidt rebound values on fresh, dry unweathered and weathered surfaces respectively.

A summary of the geotechnical data gathered from the site including the joint shear strength parameters used for analysing the slope are shown in Table 1.

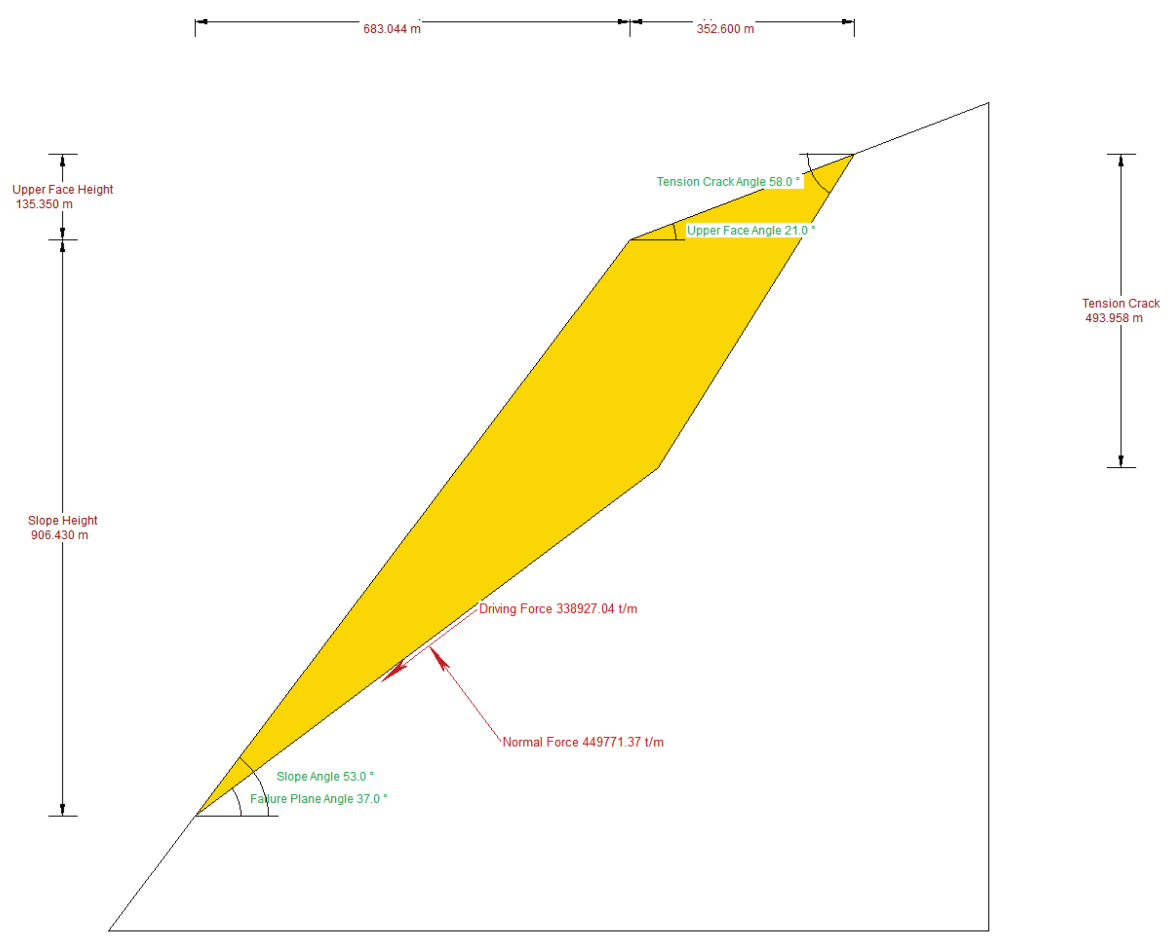

Fig. 9 - Block model used for the analysis of the landslide in RocPlane software

Table 1 - Summary of geotechnical data

Symbol	Definition	Typical range
W	Weathering Grade	I -II
RQD	Rock quality designation (%)	60-100
S	Joint spacing (m)	1-5
JRC	Joint roughness coefficient	8-12
A	Roughness amplitude per 0.5m (mm)	5-15
Φ_r	Residual friction angle (degrees)	22-28
JCS	Joint wall compressive strength (MPa)	100-200
Joint direction		
Set 1	Striking NS and dipping 45° towards the East	42-48°
Set 2	Striking NS and dipping 60° towards the West	55-65°
Set 3	Striking EW and dipping 60° towards North-East	55-65°

The area of the slide consists of gneissic rock which are foliated and at places the rock is basically micaceous schist. Three sets of joints could be identified in the field.

Applying the joint strength input parameters (JRC=10, JCS=150 MPa, Φ_r=26°) to the model shown in Figure 9 the factor of safety was computed as 1.22. This factor of safety was calculated based on the assumption that there exists no pore water pressure and seismicity.

In the next phase of analysis water pressure was included by applying peak pressure in the middle of the slope and 20% water filled relative to the height of the slope. This situation would probably have occurred over a period of time as the water started seeping into the joints as explained earlier. In this case the factor of safety was reduced from 1.22 to 1.17. It was noted that as soon as the water was filled up to 50% of the height of the slope in the model the factor of safety become less than 1.0 indicating that water has a major influence on the stability of the slope. Figure 10 shows the case when the water was filled to 50%.

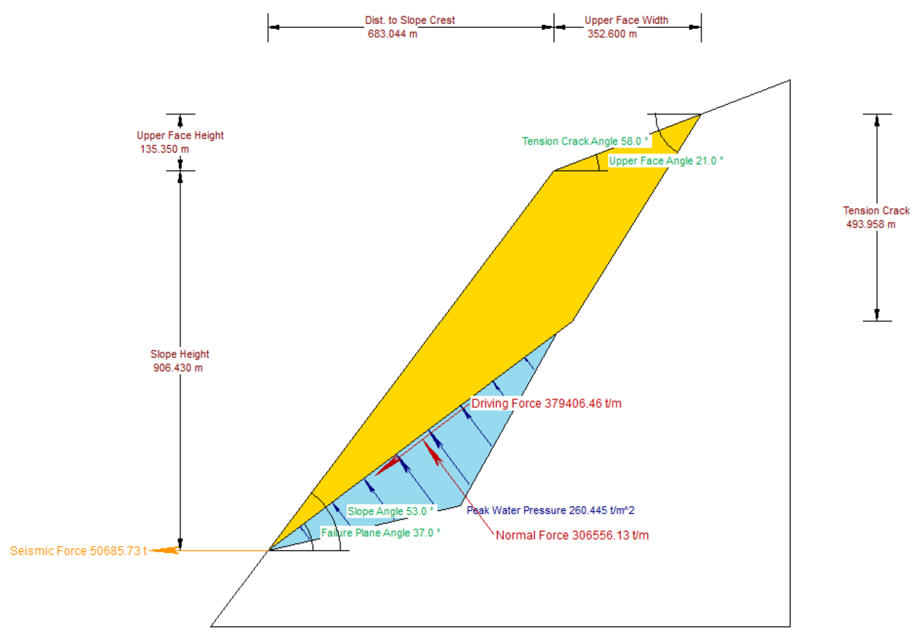

Fig. 10 - Block model with pore water pressure in the landslide

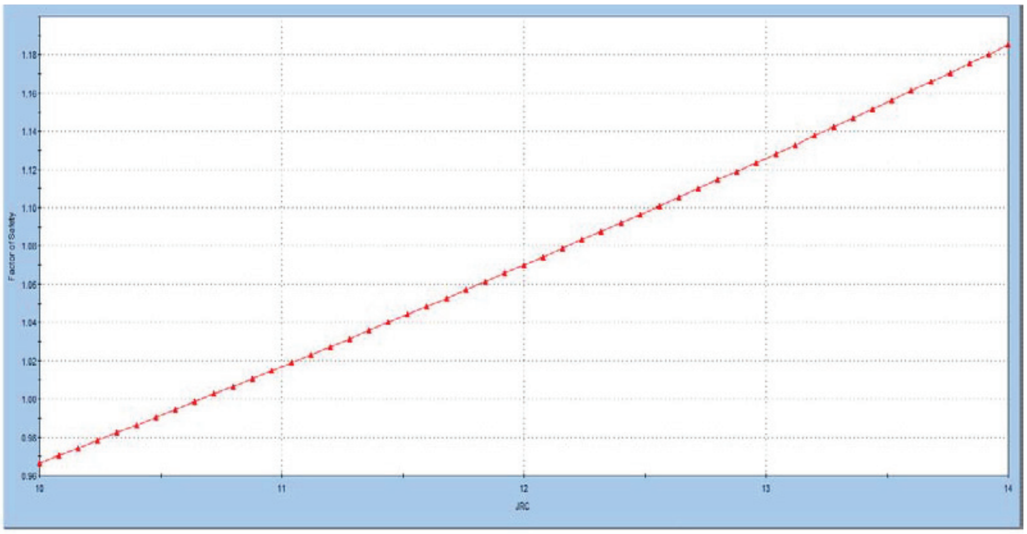

Fig. 11 - Joint roughness coefficient (JRC) versus factor of safety (FOS), below JRC 11 the slope becomes unstable

In the next phase of simulation seismic loading was considered. To simulate earthquake loading, we need to know the seismic coefficient which is a dimensionless number that defines the seismic acceleration as a fraction of the acceleration due to gravity. Typically, the coefficient might be around 01.-0.2. In the analysis, a relatively small earthquake loading using a seismic coefficient of 0.1 is applied to the model without any water pressure (dry slope). The results showed that the factor of safety was reduced from 1.22 to 1.0 indicting that a small amount of water is required to destabilize the slope. According to the hazard zonation map of the area the seismic coefficient should actually be in the range of 0.3-0.4. These relatively high seismic coefficients were obtained through large scaleseismicity analysis for seismic source zone classification and estimation of maximum credible earthquake for a deterministic or quasi-probabilistic seismic scenario generation (Pal et al, 2000). In the analysis, if the seismic coefficient is increased to 0.3 the slope fails immediately signifying the fact the slope was highly vulnerable to earthquake loading. Several sensitivity studies have been performed on the slope by changing the shear strength parameters and by varying the water pressure etc. One interesting result indicated that if the shear strength JRC is increased from 10 to 12 then the slope is still stable with a FOS of 1.07 eventhough we have water pressure (20%) and seismic coefficient of 0.1. This result is shown in Figure 11 where JRC is plotted on the horizontal axis and FOS on the vertical.

It may once again be emphasised that the 2011 earthquake initially destabilized a large area near the epicentre where this slope is located. The analysis indicate that a new earthquake would have caused the slope to fail, but since no major earthquakes were reported in the area after 2011 the slope failed due to ground water seepages over the years resulting in reduced shear strength of the rock mass. The above analysis has clearly shown how slopes in Sikkim may be vulnerable to new earthquake loadings and pore pressure changes over time. A systematic mapping and monitoring of slopes in the region are warranted to avoid catastrophic failures which may cause future damages to lives and properties in the region. Furthermore, such mapping and monitoring will help in chalking out some major mitigation strategies, such as bypassing the slope instabilities through tunnelling, to avoid disruption of major communication links (roads) along critical Himalayan roads (Goel et al., 2012).

6. CONCLUSIONS

Landslide investigations were performed in North Sikkim where a massive rock slide called the 'Dzongu landslide', which occurred in August 2016, was investigated near the town of Mangan. Although some early signs of instability could be seen through satellite images in 2006, it is believed that the Sikkim earthquake of magnitude M_w 6.9 on the 18^{th} of September 2011 aggravated the situation. A back analysis of the shear strength parameters have indicated that the slope failed due to increased pore water pressure which over a period of time reduced the shear strength of the rock mass. Pseudo-static earthquake analysis indicated that the slope was highly vulnerable to a new earthquake and would have failed but since no major earthquakes were reported in the area after 2011 the slope failed gradually as the shear strength decreased. The back-analysis strength parameters of slide are; JRC = 10, JCS = 150MPa, $\phi_r = 26°$. The by-pass tunnel shall be sufficiently deep below the rok slide surface and lined with concrete lining for long-term stability.

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