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Research Article

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Failure Risk Analysis of Motorways Twin Tunnels: A Case Study

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ABSTRACT

Twin motorways tunnels are constructed in Aravalli Mountains of western India, for providing the smooth transport facility for man and material. These tunnels are located on four lane national highways number 76. The twin tunnel road passage connects the Kandla Port on Arabian Sea to shipment dimensional stones from Rajasthan and adjoining states from western part of the sub-continent, ultimately to the north-central India. It is constructed for fast delivery and in future it will be a catalytic development as economic driven activity. Frequently occurring landslide failure on both ends of tunnels, present study has been planned for failure-risk analysis. Tunnel failure-risk analysis carried out by back and probability analysis. The Multiple Back Analysis approach has been used, where different factor of safety (FoS) curves have been derived by numerical analysis. The back analysis shows that for both, tunnel-1 and tunnel-2, the ideal conditions calculated for minimizing failure risk has been achieved by maintaining the cohesion values 148.41 and 168.33 or more than that respectively. Probability analysis also depicting 0.66 to 2.30 factor of safety and the places of less than 1.00 are unsafe. Frequency percentage vs. factor of safety and probability percentage vs. factor of safety plot shows that there is a risk of failure of the tunnels from the cut hill slopes of corners. There are various reasons of triggering of failures in addition to transmitted vibrations from vehicular movement.

Key words: Failure-risk, back analysis, probability analysis

INTRODUCTION

Motorway twin tunnels have been made in Aravalli Mountain, along four lane road National Highway Number 76. Twin tunnels both sides are sloppy due to cutting of hills. These slopes showing failures time to time and the present study has been undertaken for finding proper solutions to stabilize the slopes in the hill cuts adjoining the twin tunnels. The slope failures phenomenon and related studies shows that on a slope, the force of gravity can be resolved into two components i.e. a component acting perpendicular to the slope and component acting tangential to the slope. The perpendicular component of gravity helps to hold the object in place on the slope. The tangential component of gravity causes a shear stress parallel to the slope that pulls the object in the down-slope direction parallel to the slope. On a steeper slope, the shear stress or tangential component of gravity increases and the perpendicular component of gravity decreases. The forces resisting movement down the slope are grouped under the term shear strength which includes frictional resistance and cohesion among the particles that make up the object. When the sheer stress becomes greater than the combination of forces holding the object on the slope, the object will move down-slope. Alternatively, if the object consists of a collection of materials like soil, clay, sand, etc., if the shear stress becomes greater than the cohesional forces holding the particles together, the particles will separate and move or flow down-slope. Thus, down-slope movement is favoured by steeper slope angles which increase the shear stress, and anything that reduces the shear strength, such as lowering the cohesion among the particles or lowering the frictional resistance. This is often expressed as the safety factor, F_s, the ratio of shear strength to shear stress.

$$F_s = \text{Shear Strength/Shear Stress} \quad (1)$$

Shear strength consists of the forces holding the material on the slope and could include friction, and the cohesional forces that hold the rock or soil together. If the safety factor becomes less than 1.0, slope failure is expected.

Triggering Events, a mass movement event can occur any time a slope becomes unstable. Sometimes, as in the case of creep or solifluction, the slope is unstable all of the time and the process is continuous. But other times, triggering events can occur that cause a sudden instability to occur. If a slope is very close to instability, only a minor event may be necessary to cause a failure and disaster. A sudden shock, such as an earthquake may trigger slope instability. Minor shocks like heavy trucks rambling down the road, trees blowing in the wind, or human made explosions can also trigger mass movement events (Stephen A. Nelson, 2013). The power of wireless sensor network technology has provided the capability of real time monitoring of landslide on highways road side and the feasibility of above study is conducted in highs of the Aravalli Mountain, where the region is known for frequently falling of stones in hilly area four lanes national highway-76 across the NE trending mountain chain (G.S. Bhardwaj et al. 2012). Similarly the national highways -8, along the mountains, connecting the Udaipur city to Ahemdabad metro of India was constructed as a four lane under infrastructure strengthening national project. A number of hills were partly cut to construct the road and as studied, several road side hill cuts measured & assessed under unsafe category located between milestones 5 km to 160 km and the geological, geotechnical and slope stability analysis shows factor of Safety (FoS) less than one. The stress concentration pattern obtained by finite elemental analysis quantifies the toe areas in terms of criticalness from failure aspect (Bhardwaj G.S.and Salvi B.L., 2012). Present study have been undertaken looking to the landslide sensitivity and frequently occurring incidents causing road blockage, fatal accidents and traffic jams in the region.

LOCATION OF THE TUNNELS

Present paper deals with the tunnels constructed on the four lane road traversing across the Aravalli Mountain of Western Rajasthan. Tunnel site is almost in the mid of the Aravalli Mountain chain. Mountain chain comprises of rocks of Aravalli Super group, suffered several tectonic deformation phases resulted folded, faulted and well jointed meta-sedimentary rocks. Material properties and its behavior found typical and frequently failing from the cut hill portions, intimate part & adjoining the constructed structure. The location of tunnel and photograph of representative hill cut portion & triggering of failures are given in figure 1.

Fig. 1 Tunnel location and photograph showing failure at the crown portion

MATERIALS AND METHODOLOGY

Slope stability analysis software GALENA Ver. 4.0 used for data analysis, twin tunnels either end hill cuts analysis done for estimating the landslide failure risk by calculating stability status of tunnels and finally finding solutions for maintaining the slope designs. Portable Sound Level Meter YF-20 by using 'A' weighted response, with compressed scale switching feature, 9 volts battery, Range Lo (40-80dBA SPL) , Hi (80-120dBa SPL), Current 5mA (Operating), to measure the vehicular transmitted noise to the hill cuts, for finding its role in landslide triggering.

Back Analysis

The back analysis really gives us a full appreciation of the tunnel failure sensitivity modeling. It saves time, better and easier rapid analysis function takes the trial and error out of determining the status of failure sensitivity of different portions of the tunnels. Tunnels are modeled for the design of existing structures adjoining portions of the hill cut slopes. It clearly shows about parameters required for maintaining its strength. Different curves generated by numerical analysis are obtained through multiple approaches and derived curves for each factor of safety shows status of remedial measures in accordance with the geo-mechanical properties of the tunnel rock mass and failure sensitiveness of the hill cut slopes at entry-exit side of the crown of the tunnels. Cohesion of 4.88 calculated for Minimum Phi Value of 1.0 (Figure 2, 3).

Plot of Tunnel-1 shows decrease in phi value ranges from 2.8 to 1.0 and increase in cohesion ranges from 0.00 to 4.33 and Tunnel-2 Cohesion of 15.53 calculated for minimum Phi Value of 1.0 where decrease in phi ranges from 8.3 to 1.0 and increase in cohesion (Table 1).

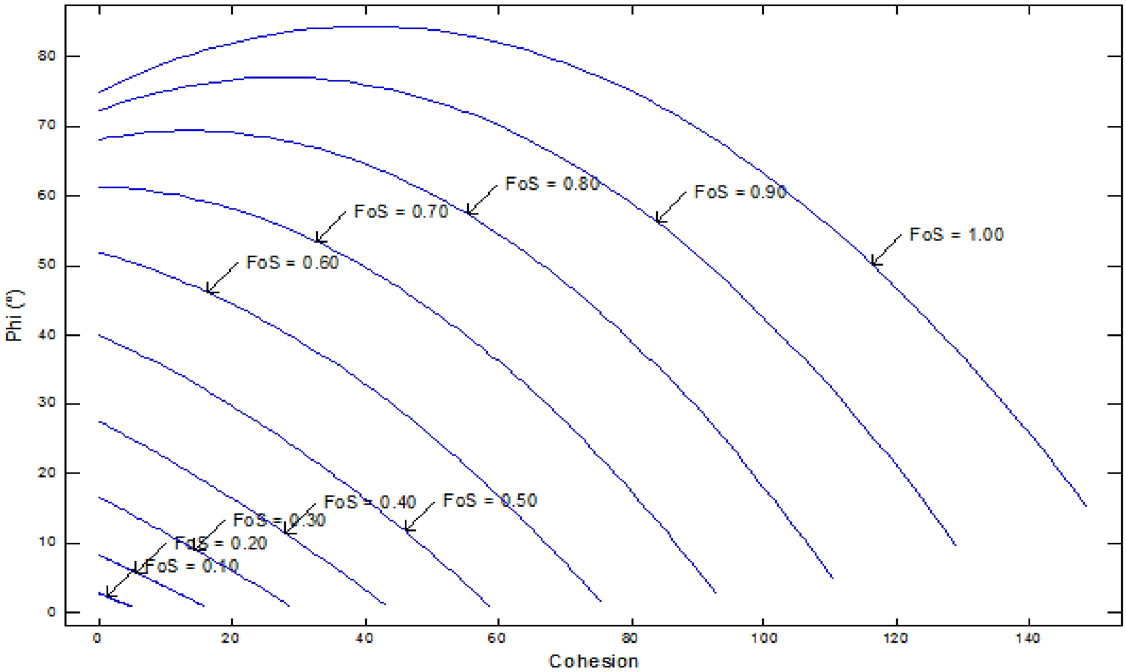

Fig. 2 Multiple back analysis-bishop simplified method of analysis of Ukhaliyat tunnel-1 SSW cut face

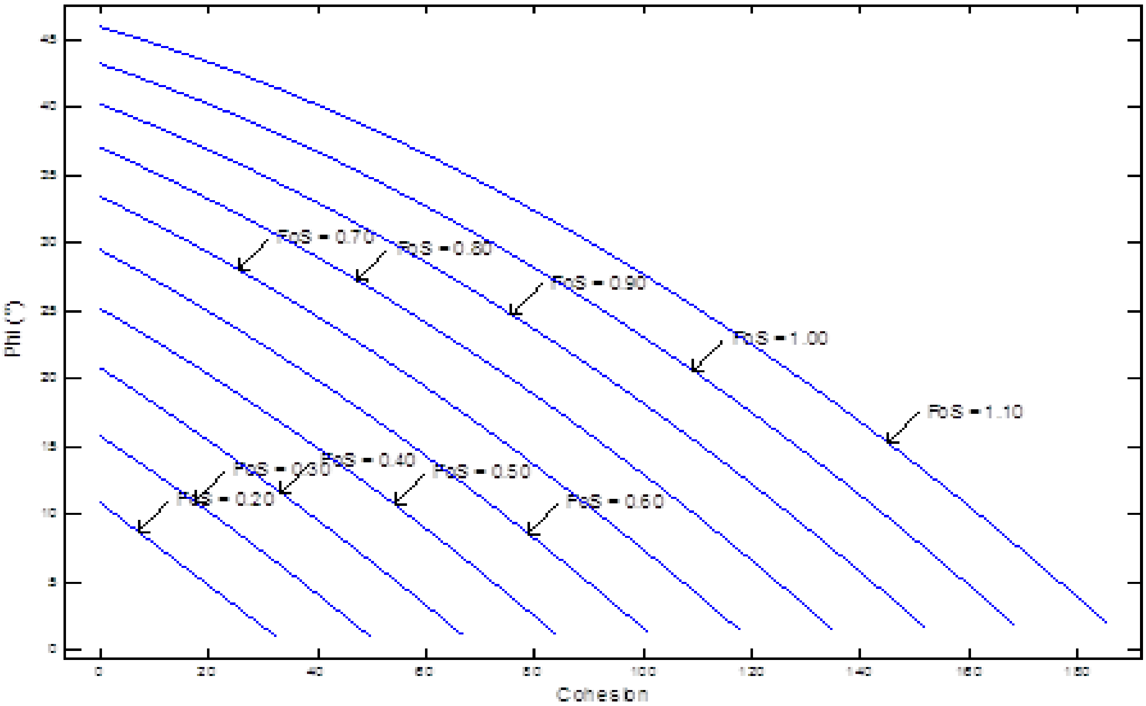

Fig.3 Multiple back analysis-bishop simplified method of analysis of Khokhariyanal tunnel-2 SSE cut face

Table -1 Showing Results of Back Analysis

Tunnel-1			
Back analysis Curve 1-10	Cohesion calculated	Phi value	Factor of Safety FoS
Curve1	4.88	1.00	0.10
Curve2	15.53	1.00	0.20
Curve3	28.51	1.00	0.30
Curve4	42.97	1.00	0.40
Curve5	58.54	1.00	0.50
Curve6	75.16	1.00	0.60
Curve7	92.59	1.00	0.70
Curve8	110.52	1.00	0.80
Curve9	129.01	1.00	0.90
Curve10	148.41	1.00	1.00
Tunnel-2			
Back analysis Curve 1-10	Cohesion calculated	Phi value	Factor of Safety FoS
Curve1	32.16	1.00	0.20
Curve2	49.46	1.00	0.30
Curve3	66.48	1.00	0.40
Curve4	83.51	1.00	0.50
Curve5	100.53	1.00	0.60
Curve6	117.55	1.00	0.70
Curve7	134.58	1.00	0.80
Curve8	151.49	1.00	0.90
Curve9	168.33	1.00	1.00
Curve10	185.16	1.00	1.10

Probability Analysis

Out of ten counts of cohesion mean (M) and standard deviation (SD) calculated by using standard deviation calculator. Frequency percentage vs. factor of safety and probability percentage vs. factor of safety plot shows that there is a risk of failure of the tunnels from the cut hill slopes of corners (Fig.4). For tunnel- 1, total number of 500 numerical simulations of trial circles, results minimum factor of safety 0.66, maximum factor of safety 2.30,mean factor of safety 1.24.sample standard deviation 0.252 and true standard deviation 0.252 obtained by using variable parameters with the Bishop simplified method of analysis. The relationship between factor of safety and cohesion has been explained by the probability analysis. Factor of Safety for initial failure circle approximation 0.47, 500 successful analyses from a total of 500 simulations (trial circles) has been carried out by the software. Probability is 45% of the factor of safety 0.48.

For tunnel-2, probability analysis (Fig.5) estimates minimum factor of safety 0.41, maximum factor of safety 0.63, mean factor of safety 0.54, sample standard deviation 0.061, true Standard deviation 0.061, and factor of safety for initial failure circle approximation 0.89. There were 500 successful analyses from a total of 500 simulations (trial circles).

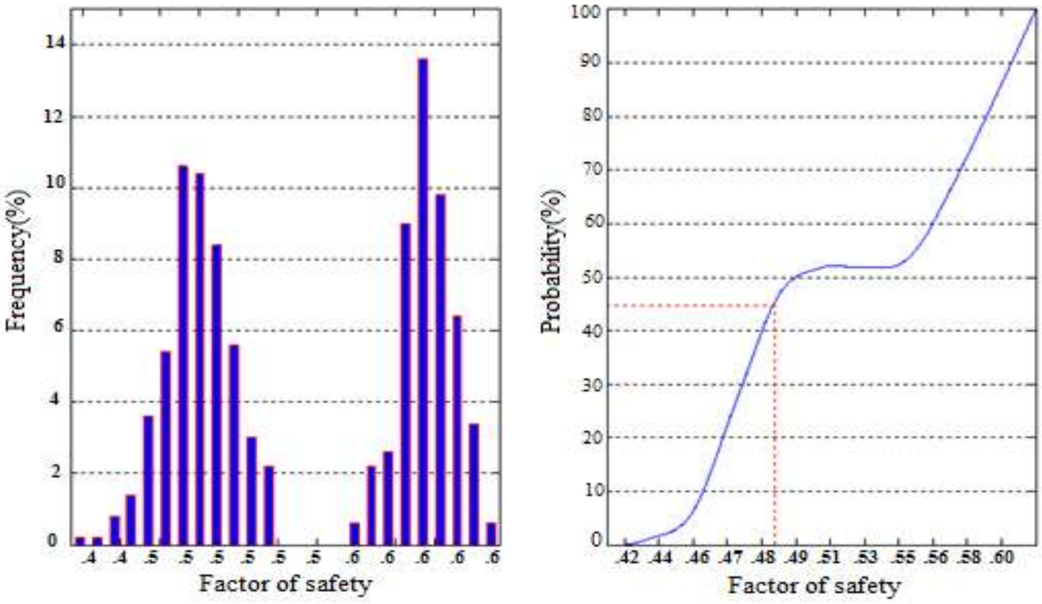

Fig. 4 Probability analysis plots of tunnel-1

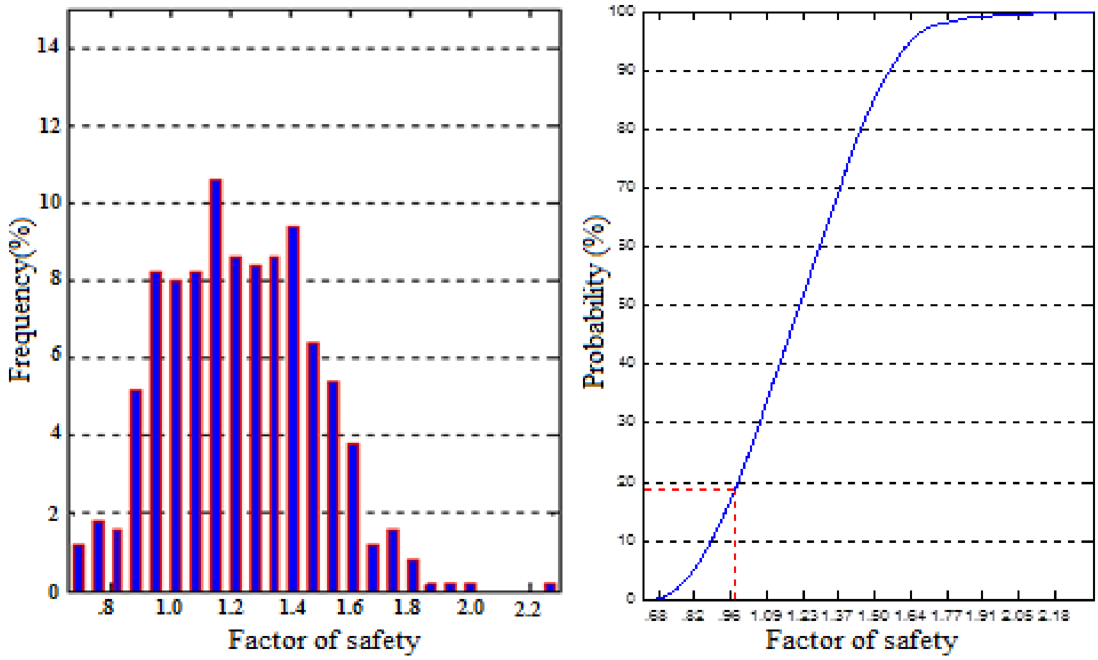

Fig. 5 Probability analysis plots of tunnel-2

RESULT & DISCUSSION

To understand tunnel failure risk, both probability and back analysis is required. It is a kind of three dimensional risks. Present study is related to these aspects and by realizing its significance that the tunnels constructed in Aravalli Mountain region needs careful, precise and systematic study about regular monitoring to avoid the landslide consequences. Back and probability analysis optimizes the designs of hills excavations' at tunnel and assessing the failure risks at the open hill cuts portion of the tunnels (David A. H. and David T. H. 2004).

Tunnel side landslides are potentially serious events that bring along human and economic losses. Different studies conclude that in general there are main causes of landslides like geological, geomorphologic, geotechnical, climatologically, hydrological conditions and anthropic intervention. Landslides detonated by rain, is caused by changes on the pore pressure produced by a decrease in the suction when a humid front enters, as a consequence of the infiltration initiated by rain and ruled by the hydraulic characteristics of the soil. Failure occurs when this front reaches a critical depth and the shear strength of the soil in not enough to guarantee the stability of the mass. Critical rainfall thresholds in combination with a slope stability model are widely used for assessing landslide probability (Robin G. McInnes et al., 2002).

It is very true that the reliable estimates of slope stability are essential for safe design and planning of road cut hill slopes which accommodate a number of tourist destinations around the world. The failure of cut slopes along these hills puts human life in grave danger and it is also disastrous for the economy. According to Kainthola, A. et al. (2012), a section of 100 m high jointed basalt hill slope was analyzed numerically in a distinct element code, which is apt for simulating the behaviour for jointed rock. The analysis was carried out for both the dry and saturated conditions. The distinct element analysis of the hill slope demonstrates it to be marginally stable under dry condition, while for the saturated condition, the hill slope fails along well defined joint planes.

Another study shows that the geometry of slope (height and angle) has a more effective role in rock fall as compared to the mass of the block. Most of the rock fall occurred due to nature and orientation of discontinuities in the rocks. Bounce height is more variable in case of variable geometry of slopes, whereas, in case of increasing mass of the blocks, bounce heights also increases with same paths. No similar path in case of varying geometry, bounce heights show complex behaviour with increasing height. Slope geometry is more critical parameters for the rock fall in comparison to the mass of the rock fall blocks (M. Ahmad et al 2013).

Overall the factor of safety is the ultimate gauge of measuring the sliding or likely to be landmass. It is explained by following equations, expressing angle of inclination, cohesion, coefficient of friction and mass of the hill cut part under risk of failure.

$$Factor\ of\ Safety = \frac{W cos\emptyset * \mu + c}{w sin\emptyset} \quad (2)$$

Where $\emptyset$= Angle of inclination, c = Cohesion, μ= Coefficient of friction, W= mass

In the present case similarly the relationship between cohesion calculated for minimum value of phi 1.0 for tunnel-1 and tunnel- 2, clearly establishing the failure risk analysis (Figure 6).

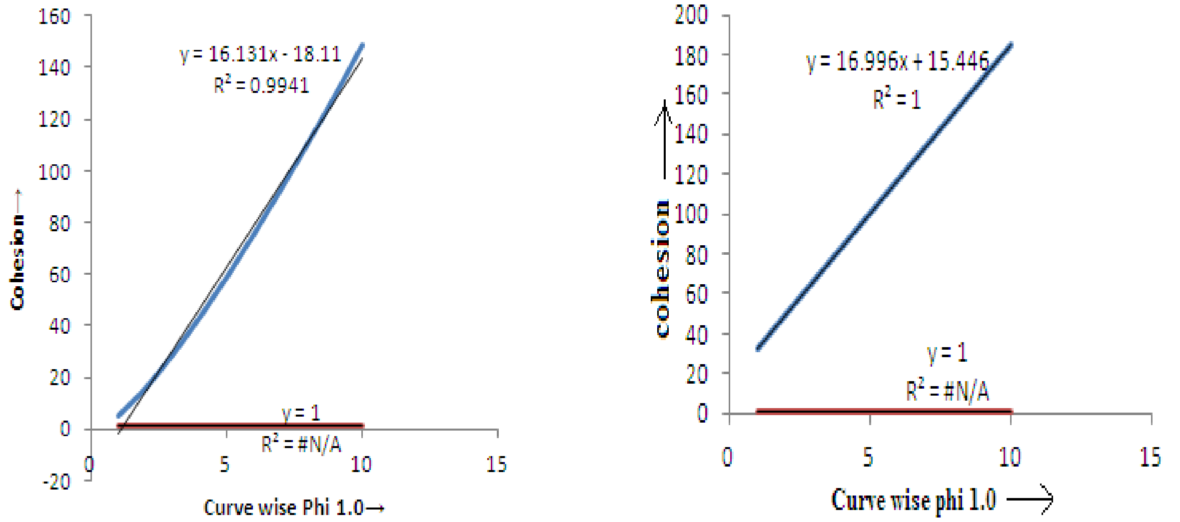

Fig. 6 Relationship between cohesion calculated for minimum value of phi 1.0 for tunnel-1 and tunnel- 2

Along NH-76, the sound levels are also measured with portable sound level meter YF-20 by using 'A' weighted response. Tunnels side noise levels are expected to increase number of times in 24 hours (Daily) about 6 dB (A) within 200 m of the carriageway, and also by about 6 dB (A) within 20 m. In general, an increase of more than 5dB (A) is considered significant, and absolute noise levels above 65 dB (A) are considered unacceptable. The predicted levels of noise measured at 20, 100 and 200 m distance from the tunnels (external force) shown in figure 7, explains the higher levels and measured levels are higher side, acting on the face of the cut slopes are contributing to the failure (NHAI, 2005).

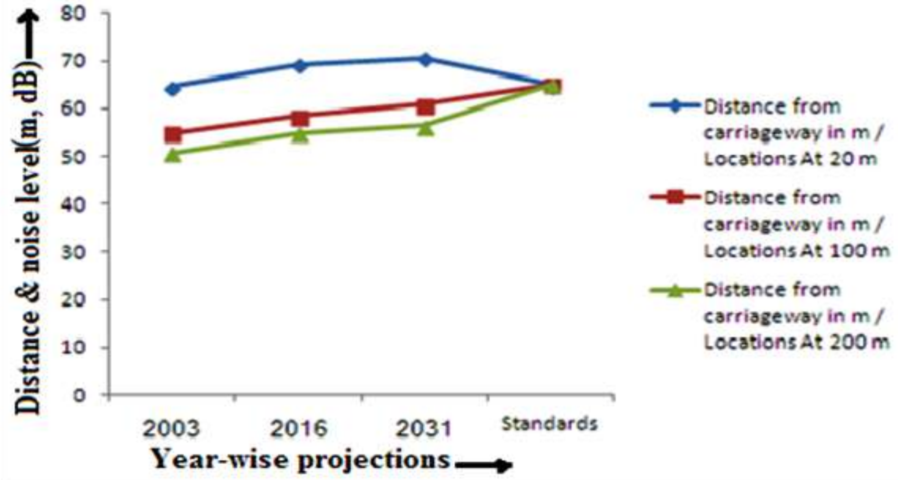

Fig.7 Plot of the predicted levels of noise (After NHAI, DPR, 2005)

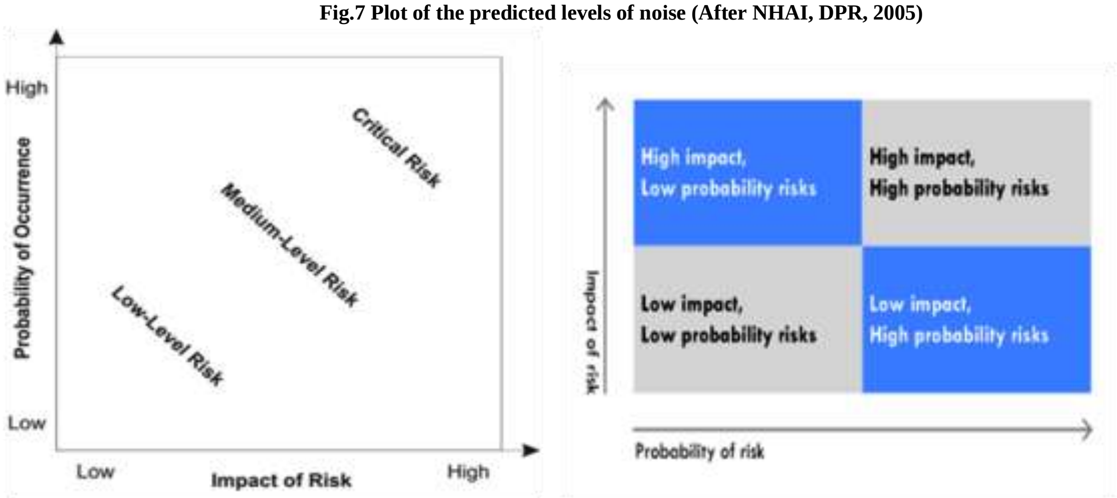

Fig. 8 Risk Impact/Probability Chart (after, www.jiscinfonet.ac.uk, 2014)

The probability of landslide occurrence and impact risk explained by schematic diagram showing importance of the study undertaken (Figure 8). When the probability of landslide occurrence is low there will be low level risk. As the probability of occurrence increases the critical risk increases.

CONCLUSION

Motorways twin tunnels constructed in Aravalli Mountains are associated with high impact & high probability of landslide failure risk from both ends and twin tunnel structure proper with high impact and low probability risk. Landslides probability of occurrence and impact of risk as well as impact of risk and probability of risk both are directly proportional. Noise levels at 20, 100 1nd 200 meters distances from the four mane motorways twin tunnel is one of the significant factor of landslides triggering. The variations in cohesion and phi value are mainly responsible for failures and the failure risk analysis undertaken i.e. probability and back analysis are identified as feasible and viable. Rock excavations and its profile or hill cut slope surface design optimization may be effective in minimize the failure risk of twin tunnel area, if their designs are optimized on the basis of results of probability and back analysis. Regular monitoring by probability and back analysis are advisable for these tunnels and similar kind of tunnels elsewhere.

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