Slope stability analysis of slides at Sonapur using strength reduction method

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SLOPE STABILITY ANALYSIS OF SLIDES AT SONAPUR USING STRENGTH REDUCTION METHOD

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ABSTRACT: Sonapur is an intense hilly region lying in the state of Meghalaya in North East India and is very near to an active seismic fault, named as Dauki Fault. Sonapur is also important because of presence of many slide prone areas along NH 6, an important highway connecting southern part of Assam, Mizoram and Tripura to rest of India. The frequent land-slides usually block the highway during monsoon or after an earthquake. Based on this issue the present study includes static and dynamic slope stability analyses of the hilly terrains at Sonapur using MIDAS GTS NX program. The slope being highly unreachable due to undulated terrain and thick vegetation, in-situ tests were not feasible, hence disturbed soil sample was collected from the site for determination of strength parameters. The slopes were analyzed considering plane strain condition for three slope heights like 5 m, 10 m and 20 m and five possible slope angles of 30°, 40°, 50°, 60° and 70° using Strength Reduction Method (SRM). For static analysis the FOS was seen to be decreasing while horizontal deformation was increasing with both increase in inclination and height of slope, based on which limiting inclination criteria was proposed for the region. Besides this, the variation of stress in the slope and shear stress at toe was studied. Also the behavior of slope during fully saturated condition showed the high vulnerability of the slopes to fail during rainy season. It is further observed that the slopes found to be safe in the static analysis under both dry and fully saturated conditions, become unstable under dynamic load.

KEYWORDS: Slope Stability, Factor of Safety, Strength Reduction Method

1 INTRODUCTION

Slope stability analysis is used for ascertaining stability of both natural and artificial slopes like hills, cuts, embankments, back-fills, etc. David Petley, a geographer at the International Landslide Centre at Durham University, United Kingdom has compiled his own database regarding landslide fatality using government statics, aid-agency reports and research papers. He reports that between 2004 and 2010, 2620 fatal landslides killed a total of 32,322 people excluding landslides triggered by earthquakes (Petley, 2012). This marks the importance of slope stability analysis to prevent landslides. With increase in construction activitiesdue to widening of hill roads, connecting remote areas, etc. the hills are being cut unscientifically leading to frequent slope failures during rainy season. Several remedial measures like soil nails (Babu, 2009), retaining wall (Loupasakis et al., 2010), anchors (Yeh et al., 2013) and geo-fabrics (Choudhury and Sanyal, 2010) are used. Sonapur is a highly landslide prone area situated in Meghalaya state along NH 6. Landslides in Sonapur disrupt the road connectivity between Indian mainland and southern part of Assam, Mizoram and Tripura. This paper discusses the stability of slope at Sonapur under static and dynamic conditions using strength reduction method.

2 METHODOLOGY

Strength Reduction Method (SRM) is a finite element based method of analysis. It is also known as SSRM which is abbreviation of Shear Strength Reduction Method. Stability by strength reduction technique is achieved by weakening the soil in an elastic plastic finite element analysis until the slope fails. The Factor of Safety (FOS) is deemed to be the factor by which the soil strength is to be reduced to reach failure. Its main concept is the systematic reduction of the shear strength envelope of a material by a factor of safety and then performing the finite element analysis of the slope until the deformation are unacceptably large or the solutions do not converge.

Mathematically the factored strength parameters formulation is shown below:

$$\frac{\tau}{F} = \frac{c\prime}{F} + \sigma \frac{\tan \varphi\prime}{F} \quad (1)$$

$$\frac{\tau}{F} = c^* + \sigma \tan \varphi^* \quad (2)$$

Where, $c^* = \frac{c\prime}{F}$ and φ^* = arc tan $(\sigma \frac{\tan \varphi\prime}{F})$ are the factored strength parameters, c is cohesion in kPa, φ is angle of friction and σ is normal stress.

3 SLOPE STABILITY ANALYSIS OF SONAPUR

3.1 Study Area

The area concerned with the present study lies in the East Jaintia Hills district of Meghalaya. Sonapur is situated approximately at a distance of 142 km south of Shillong, the capital of Meghalaya and 94 km north of Silchar, the

District Head Quarter of Cachar, Assam. Sonapur lies along NH 6 which connects the state of Meghalaya to Manipur, Mizoram, Tripura and some parts of Assam. The area is very much prone to landslide activities along a 2 km stretch between 25°06'30.09" N - 92°21'42.05"E and 25°05'35.36" N - 92°21'18.16" E onNH 6. Landslides become very frequent during rainy season leading to road blockage and causality. In 2001 one super deluxe bus skidded in the slush and fell into the Luva river, killing 7 persons.

3.2 Numerical Modeling

Due to undulations and thick forestation, undisturbed samples could not be collected from the site. However, disturbed samples were collected from the site and strength parameters at different relative densities, viz. 50%, 60% and 70% and water contents, viz. 5%, 10% and 15% were determined through direct shear tests for the numerical modeling. It is assumed that the field conditions will fall in this range and thus the analysis will give a fair idea on stability of slope. Following range of soil properties were obtained from the laboratory tests:

Maximum and Minimum Unit Weight: γ_{max} = 16.83 kN/m^3 and γ_{min} = 12.81 kN/m^3

Maximum and Minimum Cohesion: c_{max} = 22.3 kPa and c_{min} = 17.9 kPa

Maximum and Minimum Angle of Friction: φ_{max} = 33° and φ_{min} = 23.2°

Present analysis is carried out with the following range of parameters:

Cohesion: c1 = 18 kPa; c2 = 20 kPa; c3 = 22 kPa

Angle of friction: φ1 = 22°; φ2 = 29°; φ3 = 33°

Unit weights 17 kN/m^3, 15 kN/m^3 and 13 kN/m^3

The height of slope was taken as 5m, 19m and 20m based on the failure reports submitted by BRO (Border Roads Organization).

For the present study a plane strain condition was considered. Higher order elements were considered during meshing in order to increase the efficiency of FEM analysis. MIDAS GTS NX which is a Finite Element based platform where we can perform slope stability analysis, dynamic analysis besides other types of analysis has been used for this study.

3.3 Slope Stability Evaluation Results

Initially slope stability evaluation of Sonapur was carried out for dry static condition. Firstly, the FOS was seen decreasing with an increase in the angle of inclination of the slope reflecting the vulnerability of such slopes to failure with greater inclinations. Figure 1 shows the variation of FOS against the angle of inclination ranging from 30° to 70°for soil unit weight 17 kN/m^3, cohesion 18 kPa and angle of internal friction 23° for different heights of the slope. Besides, from the figure it is also seen that the FOS is considerably decreased with an increase in the height of the slope from 5 m to 20 m.Table 1 gives the limiting inclination condition as per the dry static analysis considering an additional FOS of 20 %. Thus, for a slope which has already undergone some deformation in the previous monsoon and become steep,chances of failure are quite high even during the dry season.

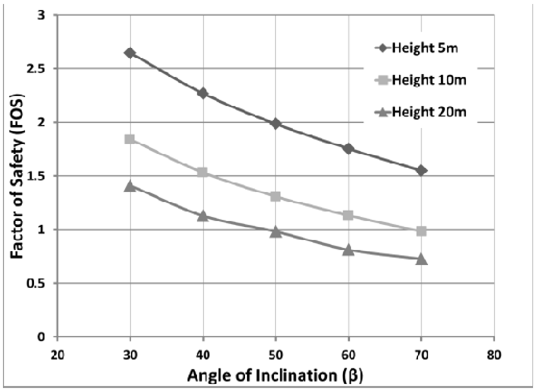

Fig. 1 Variation of FOS with inclination

Most of the Sonapur hills are very steep and Figure 1 shows that the critical angle of inclination for a 20m high slope is 50^0. This analysis confirms vulnerability of Sonapur hills to slide down even during dry season. However, an undisturbed hill is observed to be quite stable even during monsoon period.

Table 1 Limiting inclination criteria for Sonapur for dry season

Height in m	Limiting Inclination for dry season (Considering 20% additional FOS)
5	Slopes of all category were found to be safe from steep to mild
10	Slopes of inclination above 50° were found to be vulnerable so 50° is the limiting inclination
20	Slopes of inclination above 30° were found to be unsafe even during dry season, so 30° can be set as the limiting inclination

Apart from the FOS, SRM of analysis provides detailed information about the deformation behavior of the slope. It has been seen that the deformation increases with an increase in the angle of inclination which shows that the FOS is not the only governing factor for the stability of a slope. From Figure 2 it is seen that the amount of horizontal deformation increases with an increase in angle of inclination of slope and also with an increase in the height of the slope. The deformation was seen to be more prominent as the height of the slope increased. Thus, a slope may have a FOS greater than 1, but may undergo a high deformation greater than the tolerable limit. Figure 3 shows the deformation along x-axis for the particular condition. The region near the toe which is highlighted with dark patch showed the maximum displacement along x-axis i.e. is the maximum horizontal displacement as 31.85 cm. Figure 4 shows the total displacement of the slope i.e. about 32.18 cm. From these two figures the probable failure surface can be inferred though SRM does not provide a critical slip surface as it does not assume any failure surface unlike LEM. Based on that necessary remediation measures can be taken to protect the slope.

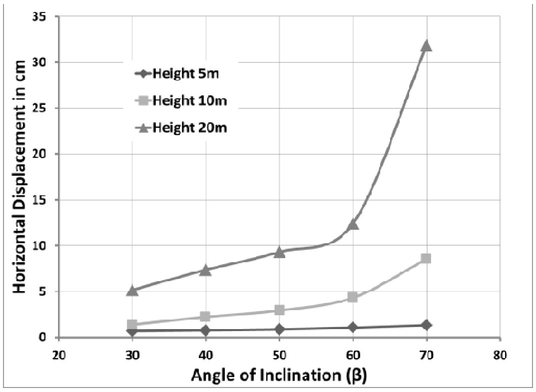

Fig. 2 Variation in horizontal displacement with inclination

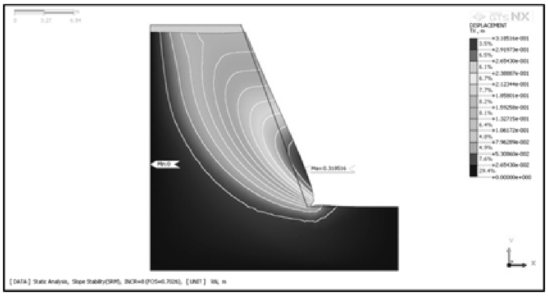

Fig. 3 Deformation along x-axis (for minimum FOS under dry static condition)

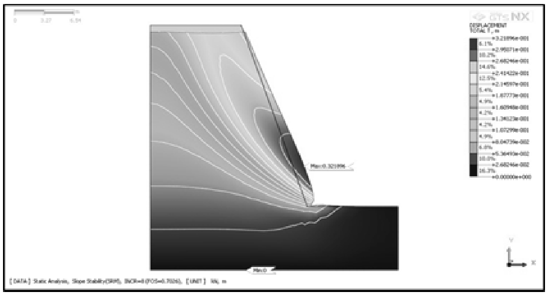

Fig. 4 Total deformation (for minimum FOS under dry static condition)

Another important advantage of using SRM over Limit Equilibrium Method (LEM) of analysis is that it provides information of how the stress strain varies for a particular slope. Figure 5 shows the variation in normal stress (σ_{xx}) against angle of inclination for slopes of height 5 m, 10 m and 20 m. In the figure σ_{xx} T5, σ_{xx} T10 and σ_{xx} T20 represent the maximum tensile stress for slope of height 5 m, 10 m and 20 m respectively, while, σ_{xx} C5, σ_{xx} C10 andσ_{xx} C20 represent the maximum compressive stress developed at the toe for slope of height 5 m, 10 m and 20 m respectively. It is seen that tensile stress is developed on the upper portion of the slope and increases both with increase in inclination and also with increase in the height of the slope.The nature of stress at the toe is compressive, which also increases with both increase in height and inclination of the slope.Tensile stress developed at the uphill portion can be attributed to the tendency of the downward movement of the soil mass due to the effect of gravity. It is observed that the compressive stress at the toe increases excessively with increase in height of slope and angle of inclination. For example, the compressive stress at the toe for a 10 m high slope with angle of inclination 70^0 is 150 kPa whereas the stress for a 20 m high slope is 400 kPa. While Figure 6 shows the increase in shear stress at toe with an increase in inclination of the slope.

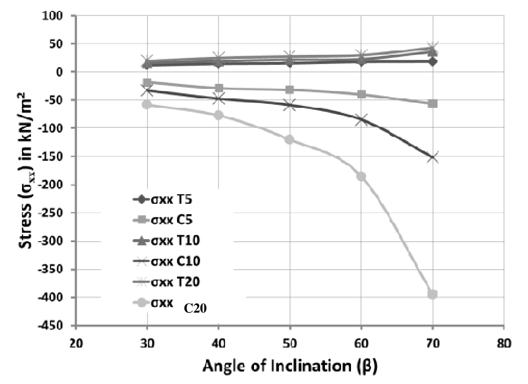

Fig. 5 Variation in stress with inclination

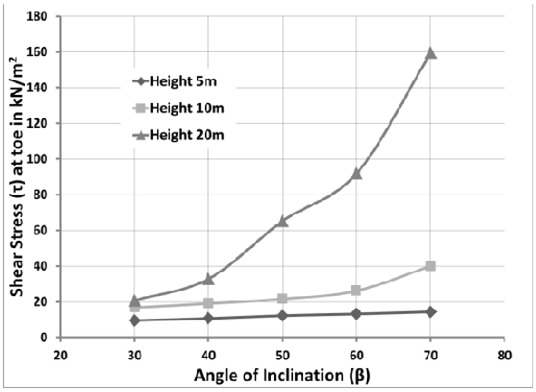

Fig. 6 Variation in maximum shear stress at toe

It has been seen that the occurrence of landslides in this region is quite common during rainy season, so after the dry static analysis another static analysis was carried out for the slope under saturated condition so that the maximum vulnerability of the slope can be studied.For a 5 m high slope the FOS under dry condition is reduced under saturated condition, numerically from 1.549 to

1.405 while the maximum horizontal deformation increases from 1.04 cm to 1.1 cm. While for a 10 m high slope the effect is more prominent; slope with 70° inclination which is already found to be unsafe during dry static condition shows a further reduction in FOS from 0.982 to 0.9. Similarly, FOS at dry condition for 60° and 50° inclination is reduced from 1.133 to 1.041 and 1.309 to 1.207 respectively at saturated condition although the increase in displacement is minimal of about 1 cm. Thus for a minimal displacement the increase in mobilization of shear force is high. Further for slopes of height 20 m having inclinations 30° and 40° the FOS is quite high and the slopes are found to be safe during dry condition.These stable slopes are found to be almost on the verge of failure under saturated condition. This pertains to the increase in vulnerability of the slopes to failure during rainy season when minor to major landslides become very common. Figure 7 shows a comparison between FOS at dry condition and FOS at saturated condition (soil properties : unit weight (γ) 17 kN/m^3, cohesion (c) 18 kPa and angle of friction (φ) 23°). The reduction in FOS is more for low height slopes. In the comparative study it is also seen that the displacement and maximum shear stress at toe during the wet season are very high in comparison to those during dry season.

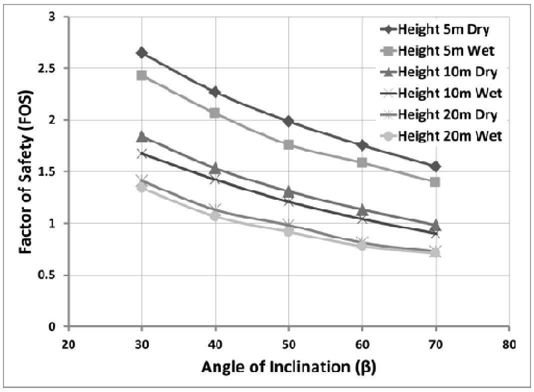

Fig. 7 Comparison of FOS between dry and wet season

The most stable slope under static analysis is subjected to El-Centro Earthquake as the ground acceleration for dynamic analysis. The El-Centro Earthquake accelero-gram data is of 53.72 sec duration which showed a peak ground acceleration of 0.3569 g at 2.14 sec. For the purpose of dynamic analysis Non-linear Time History coupled with SRM was performed. Dynamic analysis was performed for a total of three models for each of the three heights which were found to be relatively most stable under static condition. It is seen that in all the three cases the FOS comes to be much lower than 1. Table 2 gives a comparison of the FOS obtained in dry static, saturated static and finally after dynamic analysis.

Table 2 Comparison of FOS under static and dynamic condition

Height in m	Inclination (*β*)	FOS dry static	FOS saturated static	FOS dynamic dry
5	70	1.54	1.39	0.98
10	30	1.84	0.90	0.52
20	30	1.41	0.67	0.5

4 CONCLUSIONS

SRM of analysis provides additional information about displacements, stress and strain developed in the slope apart from FOS unlike LEM. This method of analysis was adopted for stability consideration of the hill section of NH 6 at Sonapur. Following conclusions are drawn from the present study:

a) With increase in inclination the FOS decreases while the displacement and stress increase. Maximum displacement occurs near the toe.
b) Slopes of height 20 m are highly vulnerable even during dry static condition
c) Both tensile and compressive stresses are developed in the slope under normal condition. Tensile stresses are developed near the top and compressive stresses near the bottom of a slope. Both the stresses increase in magnitude with increase in slope angle and height of slope. For a slope angle of 70^0 and slope height of 20 m the maximum compressive stress at the toe is around 400 kPa. The corresponding shear stress at the toe is observed to be around 160 kPa.
d) Factor of safety reduces with increase in degree of saturation.
e) A slope stable in both dry and wet analyses are found to be unsafe under a dynamic load.
f) SRM analysis shows a better understanding of slope failure

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