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Forensic Investigation of the Failure of a Marginally Stable Hill Slope

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ABSTRACT

This paper presents the forensic study of the failure of an existing naturally stable stratified hill-slope, destabilized by seepage and sequential anthropogenic construction activities. The slope, located in the Umrangso region in the Dima Hasao district in the state of Assam, India, was initially in a stable state before any human intervention. However, the site had been chosen to establish various industrial manufacturing units which resulted in a massive mass movement of the slope where deformations were observed nearly approaching the toe of the slope with the progressive stages of construction. Concrete retaining walls constructed to arrest the mass movement did not serve the purpose of protecting the slope, rather added more weight leading to further destabilization of the slope. A forensic geotechnical investigation has been carried with the aid of field and laboratory investigations and subsequently aided by the development of a finite-element based numerical model. Field visits indicated multiple reasons related to the triggering event of the slide, namely (i) absence of any stability check prior to the construction accompanied by no post-construction consequential stability analysis, (ii) heavy monsoon with torrential downpour leading to heavy infiltration, seepage and surface runoff leading to the softening the slope material, and (iii) Adopting stabilization and mitigation techniques without any sound engineering basis. The primary objective of the forensic investigation has been to precisely identify the triggering events and the mechanisms of subsequent destabilization which occurred at the site. This paper illustrates the development of a FE model to simulate the real-field scenario of the progressive construction and slope failure. The analysis had been carried out for both dry and saturated conditions of the slope. Each stage of the numerical model has been validated with the field observation and based on a vivid investigation of the outcome of the analyses the triggering mechanisms for the slope failure have been successfully identified.

KEYWORDS: Forensic investigation, Hill-slope instability, Triggering mechanism, Deformation-based failure, Finite element analysis

INTRODUCTION

Natural hill slopes are subjected to varied conditions of criticality, which are the consequences of either some natural or various human activities. Slope disasters induced by harsh natural conditions such as steep topography, fragile geology, heavy rainfall, river flood and earthquakes inducing mass movements in the form of creep, landslide, subsidence, etc. are a common phenomenon in all natural hill slopes. Amongst all, rain water infiltration or fluctuations in the level of ground water can affect and initiate the disturbance by seepage related activities which is one of the prime concerns. In addition to this, the hill slopes are being used today, in a large scale for the set up of various industries and factories and this results in a lot of construction activities in these slopes. These loading and unloading activities can create a lot of instability problems in hill slopes. Stabilization of unstable slopes can present many challenges to the engineer. To reduce some of the uncertainty, it is critical that the engineer have a clear understanding of the problem prior to the development of a design for the slope stabilization.

Studies have been carried out to find out the relationship between the triggering mechanisms, which initiates the slope instability and the causal factors which are the long term triggers, that finally results in slope failure. Sultan *et al.* (2004) had analyzed different slope failures events from different parts of the Costa target areas, which reflect diverse triggering mechanisms. The study was aimed at identifying the geotechnical response of the sediment to different external mechanisms (earthquake, rapid sedimentation and gas hydrate melting) and to establish the relation between these external mechanisms and the consequent changes in the in-situ stress state and the physical, mechanical, and elastic properties of the sediment. Saxena (2008) reviewed an extensive distress settlement of an office building resulting in visible cracks in the interior of the building in west central Florida as a first case history. In the second one, a forensic geotechnical investigation was undertaken to identify the causative factors of the slope failure and to address its extent of damage. Ering *et al.* (2015) conducted a forensic analysis of Malin landslide in India which resulted in the burial of a village of about 40 houses in western India. The investigation showed that slope failure occurred due to loss of suction between the rock and soil interface; however, heavy rainfall was identified as the triggering mechanism for the mass movement. The slope stability issues related with rainfall induced slope failures were investigated by Collins *et al.* (2004) highlighting the negative and positive pore water pressures coupled with infinite slope analysis method to present a predictive formulation of slope failure that occurred as a result of rainfall. The effects of hydraulic characteristics, initial relative degree of saturation, methods to consider boundary condition, rainfall intensity and duration of water pressure in slopes were investigated by finite element analysis with shear strength reduction technique proposed by Cai *et al.* (2004).

In this paper, a real field study of a naturally marginally stable stratified hill slope destabilized by seepage and sequential anthropogenic construction activities has been carried out. The main objective of this paper is to understand the triggering processes and the subsequent failure mechanism that led to the deformation collapse of the slope. This knowledge would further help in developing the stabilization technique to be adopted for the site.

SITE CONDITIONS

The failure mechanism of the hill slope investigated in this study is located at 25^0 31'04" (N) and $92^0$47'19.3" (E) in Umrangso region in the Dima Hasao district of Assam, India. The terrain in the area is hilly with a maximum temperature of 39.9^0C and minimum temperature of 6.0^0C, with a relative humidity ranging between 60% and 85%. The average annual rainfall of the area is 1672.0 mm and it lies in seismic zone V. The location map of the study area and the specific site in the area used in this study are shown in Fig.1 and Fig.2 respectively.

Figure 1. Location of the study area (http://www.mapsofindia.com/)

Figure 2. Location of the site (http://www.mapcoordinates.net/)

Site characteristics

The field investigation of the area under study approximately presents an idea about the soil stratification present at the site. The top 5 to 6 meters of soil layer is covered by thick stiff to very stiff, silty clay/clayey silt (CI-SC) soil, followed by 1 to 2 meters of thick hard, silty clay/ clayey silt soil beneath it. At the bottom, below the top soil layers, moderately weathered fine grained rock is present. Umrangso is a water scarce region. However, the standing water level was observed to be at a depth of 4m to 6m from the site investigations.

SEQUENCE OF DISTRESS

The site had been chosen to establish various industrial manufacturing units. All the units of the establishment are located on hill-slope with or without any benching. In the vicinity of one of the industrial units, the site (comprising of a slope of height ~55m and lateral extent ~220m) experienced a massive mass movement of soil as a result of the various stages of construction. Significant deformations of large lateral extent were observed which nearly approached the toe of the hill slope.

The sequence of distress was observed based on the site visits and preliminary enquiry at the site. The first slip was observed during July 2015. The foundation columns of the workshop building constructed on the hill slope were exposed due to the erosion of soil mass, resulting from the rainfall and subsequent landslide. The exposed columns of the workshop building were observed to be in distress condition as evident from the cracks in the walls of the building as shown in Fig. 3 and Fig. 4. As a preliminary preventive measure, rubble masonry retaining wall-I was constructed with subsequent backfilling during July-August 2015.

Figure 3. Cracks in the walls of the workshop building

Figure 4. Exposed building columns due to soil movement

Figure 5. Cracks in the floors of the colony building

Figure 6. Cracking in retaining wall-I

Further, during the period of September-October 2015, due to the continued land movement, moderate-to-severe distress was recorded in the buildings of a nearby colony area as shown in Fig. 5. This movement also resulted in the distortions, cracking, and disintegration of the retaining wall-I shown below in Fig. 6. In order to prevent further distress, rubble masonry retaining wall-II was constructed adjacent to the colony area during the month of September-October 2015. However, even with the above preventive measures, the soil movement continued, as a consequence of which retaining walls-III and IV was constructed during October 2015.

FINITE ELEMENT MODELING

Finite element modeling of the slope had been carried out to simulate the real field scenario, as closely as possible, to comprehend the failure triggering mechanisms. The critical slope geometry had been modeled in Geostudio 2007. A scaled-down model has been used wherein the actual horizontal field dimensions have been downscaled by 5, while the vertical dimensions are kept the same as that of the field scenario. Such scaling helps to generate the model stresses and strains at par with that developed in the field while the extent of the deformations in the horizontal directions as obtained from the simulation needs to be multiplied by 5 for obtaining the field extents. The entire soil depth had been classified into four layers among which the top three layers consists of soil varying in stiffness and the bottommost layer consists of impenetrable bedrock. The model of the slope for the present study along with its relevant dimensions is presented in Fig.7.

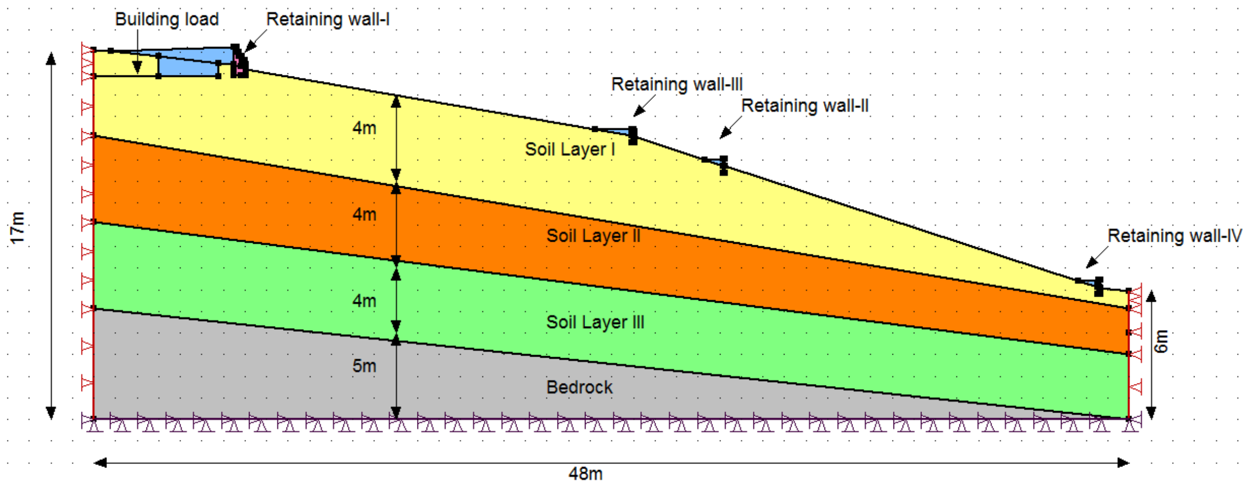

Figure 7. Model slope for the present study

Analyses Methodologies

The entire construction process had been incorporated in this model by considering the various stages of construction, in the same sequence as it was executed in the field. This sequential construction activity was simulated using SIGMA/W module to understand their effects on the progressive destabilization of the slope, and then the corresponding displacement of the slope face and its extent had been studied. In the SIGMA/W analysis after generating the initial stress conditions in the stable slope, the sequential loading and unloading process carried out on the slope in the form of excavation and addition of structures have been modeled stage wise using the load-deformation analysis method. A stress based stability analysis had been performed after every stage of construction with the aid of the SLOPE/W module in GEOSTUDIO 2007 to obtain the corresponding stability values after every stage of construction. The Mohr-Coulomb material model had been assigned for the soil layers in the stability analysis and an impenetrable bed rock had been assigned to the bedrock layer. The entry exit specification had been used to define the slip surfaces in the downstream sections of the slope. The analysis had been carried out for both dry and saturated conditions. The dry state has been analyzed using the total stress parameters and, for the saturated state, effective drained parameters material model had been used. The effect of water had been established at three different levels of the soil by conducting a steady seepage analysis with the SEEP/W module. In the seepage analysis, the fluctuation of water level had been established by using a constant head boundary condition and a 'saturated only' material model had been used for all the soil layers in the slope. The seepage analysis had been assigned as a parent to all other subsequent analysis to incorporate the pore water conditions.

Table 1. Material properties for Case I for Slope/W and Sigma/W analyses

Layer	Material model in Sigma/W	Material model in Slope/W	Cohesion (kPa) c_u	Friction angle φ_u	Cohesion (kPa) c'	Friction angle φ'	E (MPa)	E' (MPa)	Unit weight (kN/m^3)
Soil layer I	Elastic plastic	Mohr Coulomb	18.5	4	12.33	4	4.7	4.2	19
Soil layer II	Elastic plastic	Mohr Coulomb	18.5	4	12.33	4	47.6	42.5	19
Soil layer III	Elastic plastic	Mohr Coulomb	94	4	62.66	4	90.65	81	19

Rock	Linear elastic	Impenetra-ble	-	-	-	-	683	610.4	24.1
Retaining wall	Linear elastic	Impenetra-ble	-	-	-	-	17000	15194	29

Table 2. Material properties for Case II for Slope/W and Sigma/W analyses

Layer	Material model in Sigma/W	Material model (in Slope/W)	Cohesion (kPa) c_u	Friction angle φ_u	Cohesion (kPa) c'	Friction angle φ'	E (MPa)	E' (MPa)	Unit weight (kN/m^3)
Soil layer I	Elastic plastic	Mohr Coulomb	18.5	4	12.33	4	4.7	4.2	19
Soil layer II	Elastic plastic	Mohr Coulomb	94	4	62.66	4	47.6	42.5	19
Soil layer III	Elastic plastic	Mohr Coulomb	94	4	62.66	4	90.65	81	19
Rock	Linear elastic	Impenetra-ble	-	-	-	-	683	610.4	24.116
Retainin g wall	Linear elastic	Impenetra-ble	-	-	-	-	17000	15194	29

Table3: Model parameters for Case I and Case II for SEEP/W analysis

Layer	Material model (in SEEP/W)	Saturated Conductivity (m/sec)	Saturated Volumetric water content (m^3 /m^3)
Soil layer I	Saturated Only	3 x 10^{-8}	0.425
Soil layer II	Saturated Only	3 x 10^{-8}	0.425
Soil layer III	Saturated Only	3 x 10^{-8}	0.425
Rock	Saturated Only	2 x 10^{-10}	0.087
Retaining wall	Saturated Only	3 x 10^{-13}	0.33

Material Properties

The various properties pertaining to the real field slope used in the modeling had been collected based on the different field and laboratory geotechnical investigations. To account for the possible soil stratification, two different cases had been analyzed and studied by varying the strength parameters of the soil layers, aptly by varying the cohesion values that prevail in the real field. The material properties used in the modeling for analyzing both the cases had been presented in Table 1 and Table 2. The model parameters used in SEEP/W for conducting the saturated analysis for both the cases had been shown in Table 3.

RESULTS AND DISCUSSIONS

Stability Analysis using FE method

The static analysis using the FE formulation enables to conduct a stage-wise stability analysis using SIGMA/W. After generating the stress conditions in SIGMA/W, it is incorporated in SLOPE/W to obtain FE based stability values. The finite element based FoS values for all the different stages of construction during dry and saturated conditions are presented in Table 4 for Case I and in Table 5 for Case II. Any complete set of analysis comprises of the various stages of analysis involved in the sequential anthropogenic constructions in the site, namely: (1) In-situ analysis to assess the stability of the virgin slope before human intervention (2) Excavation of foundation of building (3) Imposition of building load at the site due to the construction of the building (4) Filling back and embedment of the shallow footings (Stages 3 and 4 are simultaneously done in the field) (5) Excavation of the foundation of the retaining wall R1 (6) Construction of R1 and simultaneous back-filing (7) Excavation of the foundation of the retaining wall R2 (8) Construction of R2 and simultaneous back-filing (9) Excavation of the foundation of the retaining wall R3 (10) Construction of R3 and simultaneous back-filing.

Stability analysis of the two different slope geometries (as defined by Case I and Case II) has been carried out for both dry and saturated conditions. Analysis of dry slope represented the hill-slope stability in the dry seasons, while the analyses with saturated slopes has been carried out with varying locations of the water table depicting the effect of varying intensities of rainfall during the monsoon periods. For any individual analyses under saturated conditions, the water table is considered at the top surface of any individual soil layer, defined by a constant head boundary condition during the seepage analysis. These analyses aids in understanding the stability of the hill-slope under different conditions, and forensically help to develop the idea whether the slope failure was triggered by the percolating or seeping water due to monsoon rainfall. Simulations with various heights of water table, when validated with the field observations, help in understanding the possible location of the in-situ water table.

From the stability values enumerated in Table 4, it is observed that the considered slope geometry is marginally stable under dry conditions, and does not manifest massive slope failure. When saturated, the stability reduces substantially due to the incorporation of the water table at different locations. However, the stability value tends to increase, as obvious, when the water table is considered at deeper locations. From the low stability values illustrated in Table 4, it can be stated that Case I slope geometry tended to be unstable right from the in-situ stage when water table was considered into the analyses. This signifies that the slope would have failed during the intense rainfall season even without any anthropogenic activities. This observation is in contrary to the site observation which shows no record of slope failure before any construction activity. Hence, it was concluded that consideration of all soil layers to have low in-situ strength parameters proved to be an exaggeration and is not possibly representing the field scenario.

Table 4. Stability values for Case I for both dry and saturated conditions

Sl. No.	Stage of construction	Dry	Water level at a ht. of 17m (W_1)	Water level at a ht. of 13m (W_2)	Water level at a ht. of 9m (W_3)
		FoS Values	FoS Values	FoS Values	FoS Values
1	In-situ	1.416	0.920	1.029	1.054
2	Building foundation excavation	1.388	0.952	1.025	1.053
3	Imposition of building load	1.038	0.489	0.609	0.854
4	Filling back of foundation	1.078	0.975	0.976	0.88
5	Excavation for R1	1.076	0.989	0.975	0.875
6	Construction and backfilling of R1	1.064	1.038	1.038	0.919
7	Excavation for R2	1.087	1.146	1.077	0.935
8	Construction and backfilling of R2	1.083	1.151	1.097	0.936
9	Excavation for R3	1.071	1.080	1.083	0.931
10	Construction and backfilling of R3	1.081	1.066	1.060	0.924

Table 5: Stability values for Case II for both dry and saturated conditions

Sl. No.	Stage of construction	Dry	Water level at a ht. of 17m (W_1)	Water level at a ht. of 13m (W_2)	Water level at a ht. of 9m (W_3)
		FoS Values	FoS Values	FoS Values	FoS Values

1	In-situ	2.112	1.411	1.588	1.511
2	Building foundation excavation	2.1	1.373	1.577	1.513
3	Imposition of building load	0.976	0.821	0.793	0.769
4	Filling back of foundation	0.967	0.850	0.802	0.774
5	Excavation for R1	1.015	0.875	0.825	0.805
6	Construction and backfilling of R1	0.985	0.838	0.798	0.785
7	Excavation for R2	1.373	0.817	1.065	1.025
8	Construction and backfilling of R2	1.344	0.752	0.967	1.007
9	Excavation for R3	1.288	1.029	1.035	0.975
10	Construction and backfilling of R3	1.294	1.024	0.984	0.959

Table 5 illustrates the FoS values as obtained from the analyses of Case II slope geometry. It is observed that under dry conditions, the slope geometry is stable until the building is constructed. Taking evasive measures by constructing retaining walls R1 an R2 would have sufficiently stabilized the slope. However, such scenario was not observed in the field, as construction of retaining walls R1, R2 and R3 did not have significant stabilization effects. When analyzed for saturated conditions, it is clearly observed that slope illustrated significant failure. Moreover, as observed in the field, construction of R1, R2 and R3 had no effect on the improvement of stability of the slope. Hence, it can be clearly stated that the Case II slope geometry is a very good idealization of the stratification existing in the field. The results of the stability analyses also gets cross validated by the field observation that the major mass movement in the site was observed after the monsoon season and after the construction of the building. The sequence of distress as mentioned earlier in the paper was also observed to be simulated by the analysis. Most importantly, analyses of Case II slope geometry revealed that the construction of the sequence of retaining walls did not improve the stability issues of the moving slope, as observed in the field as well. This suggests that Case II slope geometry is apt in representing the in-situ site characteristics.

Deformation and seepage characteristics of the slope in dry and saturated conditions

The displacement characteristics along the face of the slope for the critical stages of construction pertaining to the probable existing soil stratification in the field (Case II) is shown in Fig. 8 to Fig. 12 for dry and saturated conditions, respectively. Results from the analyses showed that for both dry and saturated conditions, the deformations in the first two stages of construction were negligible. The abrupt increase in deformations starts from the addition of the building load and its increment continues till the addition of the first retaining wall R1, after which no significant increase of deformation was observed for the rest of the stages of construction. Therefore, it can be clearly pointed out that the Stages 3-6 of the various construction sequences (as illustrated in Table 4 and Table 5) are the main triggering factors leading to the initiation and progression of deformation in the marginally stable hill-slope.

It can be noticed that saturation of the upper soil layers lead to higher degree of destabilization as illustrated from the larger values of displacement of the slope face. It can also be seen that different degrees of saturation result in different extents of deformation in the slope face. Seepage analyses conducted with varying levels of water heads yielded different phreatic surfaces and the water flux along the slope face was determined. The results of the simulations were compared with the field observation in terms of the location of water emanating out of the slope face after the monsoon period. Figure 12 shows the water flux along the slope face for Case II slope geometry fully saturated with water and the phreatic line is at its culmination in comparison to the other cases having different positions of water table. It can be observed that the Validating with the real field scenario the level of saturation with gave the maximum displacement can be adopted. A plot showing the variation of water flux along the face of the slope is shown below in Fig. 12. It can be observed that the water flux attains a negative value beyond a distance of 180 m from the crest of the slope. This signifies that water is emanating out from the slope face through this particular location, which is an outcome of the phreatic line intersecting the slope face at the said location. Visit to the distressed site also revealed water emanating out from the slope face as seeping spring at and around the said location (~ 150-200 m from the slope crest). Thus, it can be conclusively stated that the heavy monsoon season led to the saturation of the most parts of the slope and the rise of the phreatic lie towards the ground surface made the soil comparatively weakened (manifested by lower strength properties), and subsequently leading the massive mass movement of the soil. As shown in Fig. 7, retaining wall (R4) was constructed with the provision of weep-holes accompanied by an adjacent water-carrying nallah (open channel conduit) with the intention of releasing the water seeping through the slope. However, the phreatic line intersecting the slope at a much higher elevation had actually rendered R4 to be a dysfunctional one, and hence, resulted in a massive wetting of the toe of the slope, leading to the observed distress at the site.

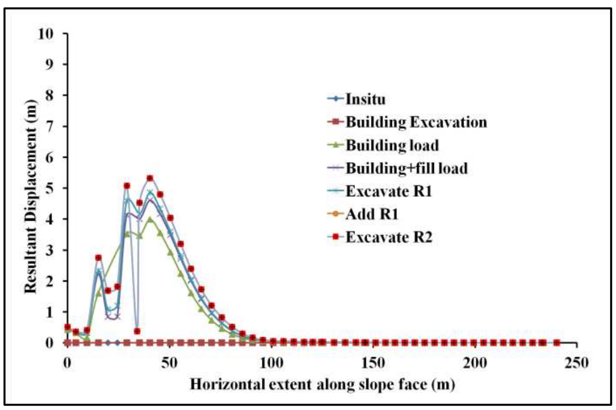

Figure 8. Displacement for the critical stages in dry condition

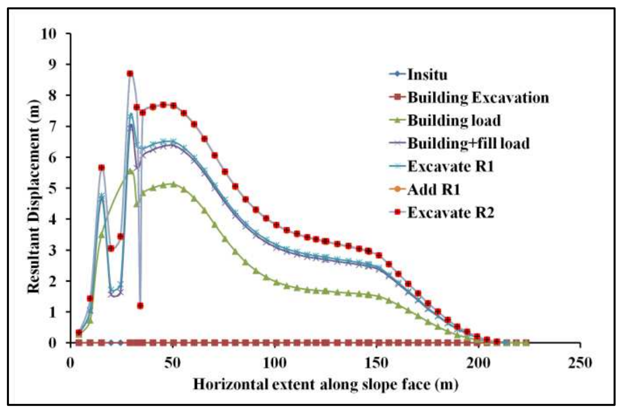

Figure 9. Displacement for the critical stages in saturated condition (W_1)

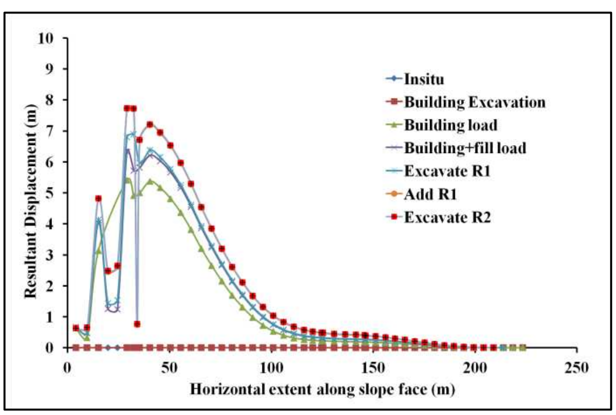

Figure 10. Displacement for the critical stages in saturated condition (W_2)

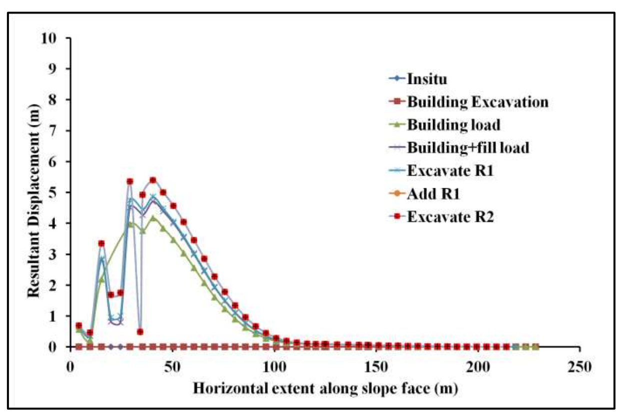

Figure 11. Displacement for the critical stages in saturated condition (W_3)

Figures 14 and 15 exhibit the deformation characteristics observed for the two most critical stages of construction (Stage 3 and Stage 6, respectively) with the identified slope geometry, soil stratification and the location of the phreatic surface and its intersection region in the slope. Supplement to Fig. 7, it can be observed from the deformation contours of Fig. 14 that a shallow slope movement with significant deformation extent has taken place at Stage 3 itself, when the building has been constructed. The deformation reached a depth of 4m below the ground surface and laterally extended up to 200 m from the building location towards the downhill of the slope. In order to arrest the movement originated due to the building construction, R1 was constructed with a foundation embedment depth of around 1 m from the ground surface.

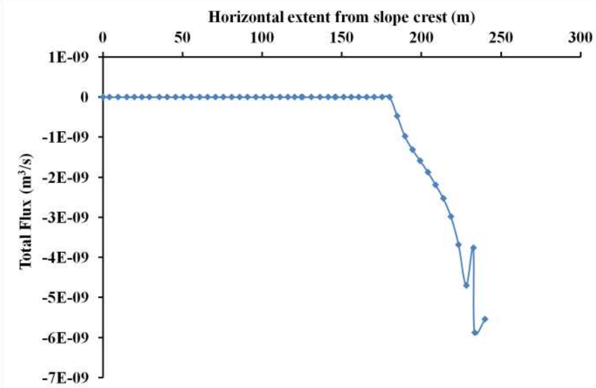

Figure 12: Variation of water flux along the slope face

Figure 13: Water emanating from slope face

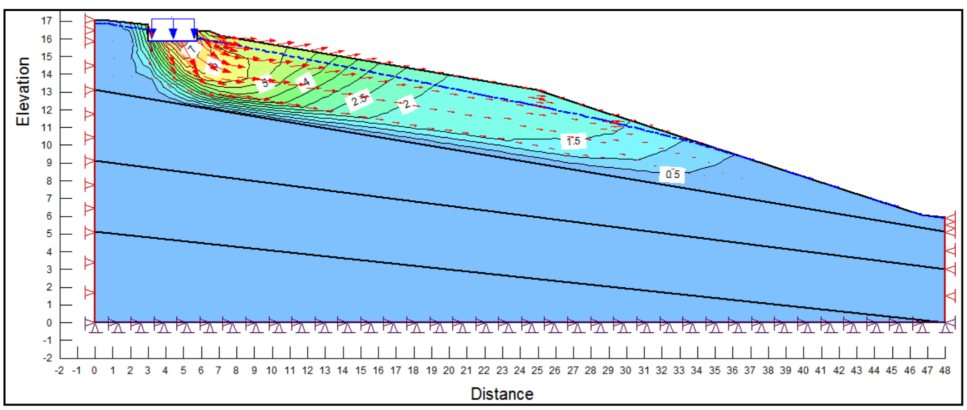

Figure 14. Deformation of the slope (Stage 3)

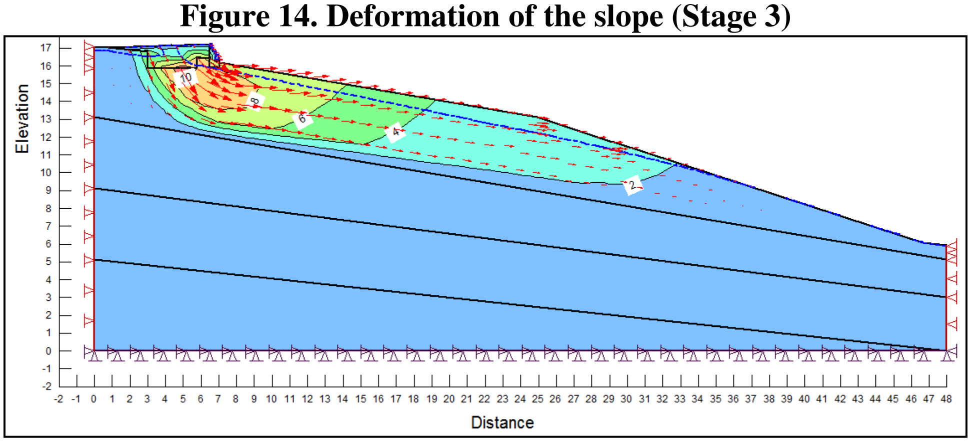

Figure 15. Deformation of the slope (Stage 6)

It can be well understood that this retaining wall, with its backfill, is actually floating on the moving soil mass, and would offer no benefit in arresting the slope movement, which is what exactly happened in the field, where no signs of the arrest of the movement was seen. Rather, after the construction of the retaining wall, large movements were seen even at a distance of 150 m from R1 in the field. Figure 15 exhibits the same in the numerical simulation. The construction of the retaining wall and its subsequent backfilling, in reality, added more load on the moving soil, thus generating additional movement as observed both in the field and in the numerical simulation. The extent of the lateral deformation encompassed the locations of R2 and R3, and hence, their construction was of no additional improvement to the stabilization of the moving slope. The extent of the deformation beyond the retaining walls R2 and R3 reached the colony area and caused a massive damage to the habitation (as shown in Fig. 5 and Fig. 6).

CONCLUSIONS

The main objective of this study was to identify the triggering mechanism of the slope failure of a marginally stable slope located in the North Eastern region of India. In order to attain the objective, with the aid of an obscure knowledge about the stratification from the boreholes in the nearby location, a finite element model of the critical soil geometry had been developed using GEOSTUDIO 2007. Each stage of modeling had been validated with the real field scenario during the subsequent field visits. The results from the analysis indicated that the external stimulus that initiated the slope instability process was the addition of the workshop building load. The seepage of rain water along the slope further aggravated the condition. To prevent the slope failure, construction of the masonary retaining wall-I at a founding depth of 1 m from the ground level, instead of founding it up to the bed rock, did not serve the purpose; rather, it added additional load to the affected slope which caused further slope movement. To prevent this, further two retaining walls were constructed at different locations of the slope, which did no good to protect the slope. The increase in the pore water pressure during the various loading conditions had reduced the strength of the slope leading to its instability. Therefore, the primary objective of this study which was to simulate a real field existing slope and to identify the triggering mechanisms leading to its instability had been achieved. This knowledge can further be used to implement appropriate stabilization techniques which will provide a permanent solution to the slope instability problem of the region.

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