Stability of Slope During Rainfall: A Finite Element Approach

J. Sharailin Gidon and **Smurtirekha Sahoo**

Abstract The effects of different environmental factors, i.e., rainfall intensities, hydrological conditions and geological formation are inevitable while studying the stability of any slope. In this paper, these factors are taken into consideration, which consists of three different water levels, three different soil properties and five different rainfall intensities for analyzing a particular slope located in Meghalaya (i.e., one of the North Eastern states of India). A numerical analysis based on finite element method has been carried out on a slope formation found in Nongstoin, Meghalaya, India. The contribution of these parameters to the stability of the given slope is analyzed using finite element-based software (i.e., MIDAS GTX NX 2016). The variation of factor of safety with respect to time for different rainfall intensities are reported. Parametric studies based on different soil parameters are also being done. The results in terms of pore water pressure variation throughout the slope, lateral deformation of the slope have also been reported to have an insight into the response of the given slope due to various rainfall intensities and site characteristics.

Keywords Slope stability · Numerical analysis · Factor of safety · Finite element method

1 Introduction

The study of the effect of various environmental factors on the stability of slope is very common in the field of geotechnical engineering. These factors occur in different forms for, e.g., rainfall, melting of snow, earthquakes, geological factors, etc. Their impact directly or indirectly gives rise to instability to the surrounding slopes, which leads to the importance of study of slope stability. Equations and numerical models have been derived and developed to study the stability of saturated and unsaturated slopes [1]. One of the latest is the use of finite element method (FEM) [2] which can be used to virtually analyze complex slopes in two and three dimensions. FEM along

J. Sharailin Gidon (✉) · S. Sahoo
NIT Meghalaya, Shillong, India

with an elasto-plastic (Mohr–Coulomb) strain–stress technique has been shown to be a reliable and sturdy method for studying the factor of safety of slopes [2]. In unsaturated slopes matric suction or negative pore water pressure plays an important role when it is exposed to rain [3]. In an unsaturated soil, when rainfall is infiltrated, the ground water level is increased and subsequently water pressure is increased or matric suction is decreased. The decrease in matric suction leads to the decrease in shear strength of soil, this in turn, possibly leads to the occurrence of slope failures [4].

In a state like Meghalaya, which holds the record for the wettest place on earth, rain is an important factor to be studied for slope stability. Under the present investigation, a two dimensional (2D) finite element analysis has been done on a slope situated in Nongstoin, Meghalaya, India. The objective of this paper is to study the effect of soil properties, different rainfall intensities and ground water table (GWT) position on the unsaturated hill slope of Meghalaya using finite element method for a period of 48 h. The unsaturated slope under study is subjected to five different rainfall intensities (16.4, 25.5, 196.1, 212.0 and 983.0 mm) and comparative studies were made to see the response of the slope. A parametric study was done and the results of the factor of safety (FOS), displacement and pore water pressure were compared for different GWT, rainfall intensities and soil properties.

2 Numerical Modeling of Slope

2.1 Geometry and Location of Slope

The slope under study is situated in Nongstoin, West Khasi Hills District, Meghalaya, situated in the Northeast part of India. It is located at 25° 10′ N to 25° 51′ N latitude and 90° 44′ E to 91° 49′ E longitude with an elevation of 1200 m [5]. The monsoon season starts from the month of April onwards and ends around the month of October. June and July receive the maximum average rainfall. The average rainfall for the whole year is given in Table 1. It can be seen from Table 1 that heavy rainfall occurs during the month of April to October whereas less rainfall occurs during the month of November to March.

2.2 Geometry and Location of Slope

Samples were collected from the site and the properties of soil were obtained through laboratory tests. The different shear strength parameters and unit weight are given in Table 3. For the analysis, slope angle of 27° and 15 m slope height were considered. A homogeneous slope was prepared in 2D using FEM (MIDAS GTX NX 2016) and analysis was carried out using strength reduction method (SRM). The principle

Table 1 Average monthly rainfall and rainy days at Nongstoin, Meghalaya

Month	Rainfall (mm)	No. of rainy days
January	16.4	1.2
February	25.5	2.3
March	76.1	4.8
April	196.1	10.4
May	350.4	15.3
June	641.4	18.9
July	983.4	20.9
August	570.7	18.4
September	409.2	15.3
October	212.0	7.3
November	31.0	1.7
December	17.1	1.3

behind strength reduction method (SRM) is the reduction of the shear strength parameters until the slope starts to fail [6]. SRM is chosen since it gives a systematic stress analysis of the slope and thereby providing an ordered factor of safety values [7]. The meshing of the slope model has been done considering a higher order element during meshing; this is done in order to lessen the convergence error usually encountered while analyzing the model. A transient seepage analysis of 48 h has been carried out, which was divided into two-time intervals, in the first interval (i.e., 0–24 h) rainfall was provided and in the second interval (i.e., 24–48 h) rainfall was not provided.

Three parametric studies were carried out: (i) with different GWT positions, (ii) with different rainfall intensities and (iii) with different soil properties. The different GWT positions considered for this analysis are given in Table 2, where $h_c = $ distance of the crest of slope from the GWT and $h_t = $ distance of the toe of slope from the GWT. The GWT1 position was nearest to the ground surface and the farthest was for GWT3. The rainfall intensities of 16.4, 25.5, 196.1, 212.0 and 983.0 mm were applied to surface ground level to study how the slope responds to different intensities. The different soil proper ties used for parametric study are given in Table 3. Observations were made on the response of the slope 24 h after rainfall and this was done with all the three parametric studies.

Table 2 Different ground water table positions

Name of different GWT positions	GWT1	GWT2	GWT3
h_c (m)	10.5	12.75	15
h_t (m)	4	5	6

Table 3 Different soil properties

Soil properties Sample number	Cohesion (c) kN/m^2	Angle of internal friction (ϕ)°	Unit weight (γ) kN/m^3
Sample 1	6.5	42	16.5
Sample 2	7.2	42	16
Sample 3	7.3	43	16.8

3   Results and Discussion

3.1   Parametric Studies with GWT Variation

Variations in factor of safety for different GWT positions are shown in Fig. 1. The variation shows that the factor of safety was highest for GWT3 throughout the period of 48 h and lowest for GWT1. It was observed from Fig. 1 that the initial value of FOS was 3.25 for GWT3 and initial FOS was 2.8 for GWT1. This is mainly due to the different ground water table positions. The increase in water pressure along the phreatic line led to the decrease in the shear strength of soil. The ground water level had less impact on the pattern of slope failure as observed in Fig. 1. The factor of safety values rapidly decreased in all the three positions; this is due to the high matric suction of the soil. From the figure, it was also observed that the FOS was minimum at 15 h and after the rain stopped the FOS was observed to increase gradually. In case of GWT2 and GWT1 the increase is almost constant which shows that even 24 h after the rain stopped, the slope fails to regain its original strength in the next 24 h,
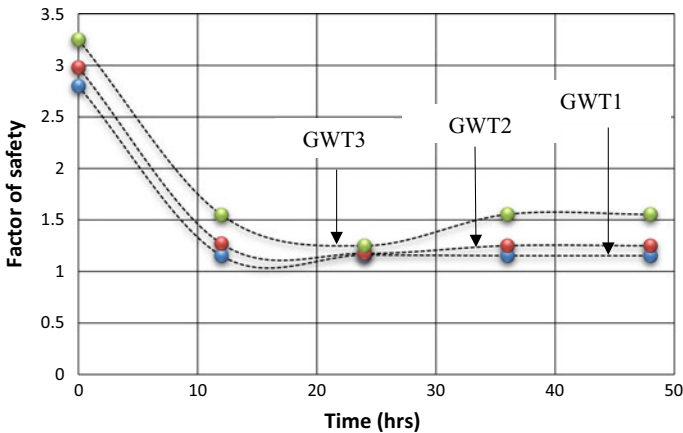

Fig. 1 Variation of factor of safety with respect to a period of 48 h for different GWT
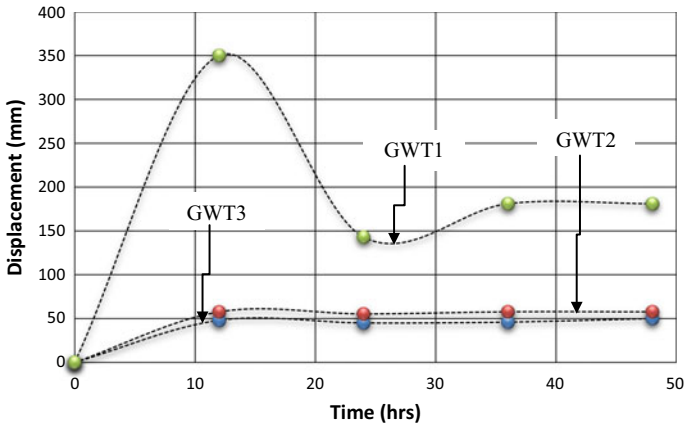
Fig. 2 Variation of displacement with respect to a period of 48 h for different GWT

this was due to the high suction capacity of the soil and the high rainfall intensity (196.1 mm).

The transient seepage analysis performed in MIDAS GTX NX also provided the displacement of slopes for different GWT positions as shown in Fig. 2. The initial displacement was nil and with increasing time the displacement increased. For GWT2 and GWT3, the displacement along *x*-direction was comparatively low to that of GWT1. This is a result of the position of GWT with respect to the ground surface. In GWT1, the maximum displacement of the slope after 12 h of rainfall was 350 mm and after which displacement decreased suddenly to 140 mm at 26 h. This shows that at 12 h of rain the slope reached a level where it cannot be displaced anymore when the GWT is very near to the ground surface. In GWT3, when the GWT position was further away from the ground surface, the displacement was very less and remained constant throughout. This was the same case for GWT2. This can be due to the compaction of soil in after 12 h of rainfall. Since the rain was constant throughout the 24 h period the displacement of soil remained same even after the rain stopped. The position of GWT in these two cases did not have much effect to the displacements.

Negative pore water pressure was highest for GWT3 and lowest for GWT1. This is a direct result of the position of GWT. For the first 12 h of rainfall the pore water pressure decreases rapidly after which the negative pore pressure remained constant.

3.2 Parametric Studies with GWT Variation

Figure 3 shows the variation of FOS for different rainfall intensities for a total period of 48 h and the total duration of rainfall was 24 h. The rainfall intensities considered were 16.4, 25.5, 196.1, 212.0 and 983.0 mm. From the figure, it can be observed that
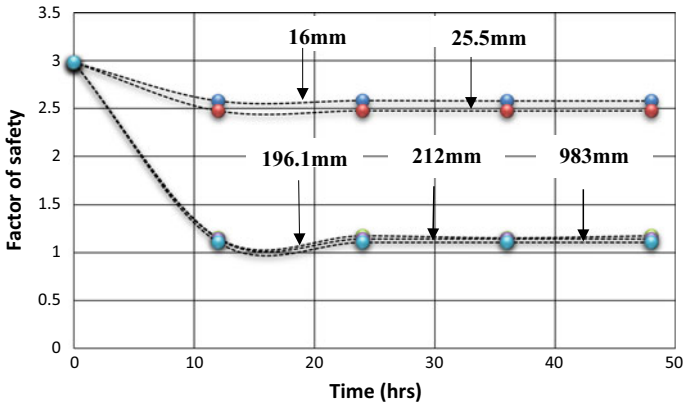
Fig. 3 Variation of factor of safety with respect to a period of 48 h for different rainfall intensities

the initial values of the factor of safety were same, because at this point rainfall has not occurred yet and all the slope properties were same. When rain started, the value of FOS for 16.4 and 25.5 mm rainfall intensities gradually decreased (as shown in Fig. 3) and achieved a minimum value of 2.6 and 2.4, respectively at 15 h. After 15 h the FOS value remained constant throughout. This shows that low intensity rainfall, did not has a substantial effect on the stability of the slope. For the rainfall intensities of 196.1, 212.0 and 983.0 mm the FOS suddenly decreased and the slope ultimately failed. The minimum value of FOS was observed at a time period of 14–18 h of rainfall and after the rain stopped, the FOS was constant and even during this period the slope failed to regain its original strength.

For different rainfall intensities, the maximum displacement was plotted as shown in Fig. 4. It was observed that for rainfall of less intensities, i.e., 16 and 25.5 mm, the resulting displacement was nil throughout the 48 h analysis. When rainfall intensities
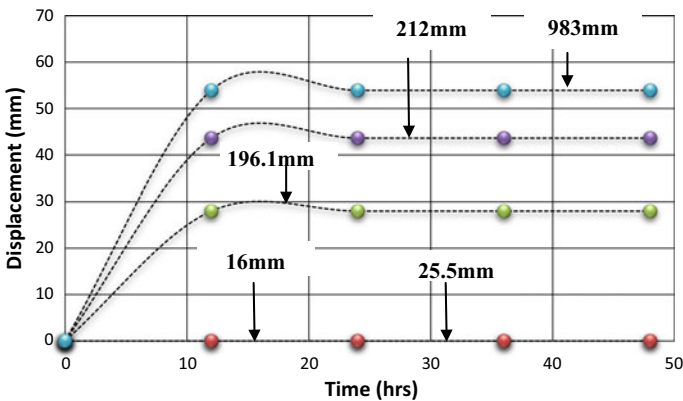
Fig. 4 Variation of displacement, with respect to a period of 48 h for different rainfall intensities

increase, the maximum displacement along x-direction keep on increasing and this increase was observed at the toe of the slope. The higher the rainfall intensity the more the pressure and ultimately the displacement will increase. The displacement along x-direction for rainfall intensity of 983, 212 and 196.1 mm was highest at 15 h of rainfall. From 15 to 24 h, the displacement decreases gradually and after 24 h the displacement remained constant. The red patch at the toe of the slope (Fig. 5) shows the occurrence of maximum displacement.

The pore water pressure was highest for the lowest rainfall intensity and as the intensity keep on increasing the pore water pressure decreased. This shows that, the higher the rainfall intensity, the lower the negative pore water pressure and this affected the shear strength of the soil. The pore water pressure variation is given in Fig. 6. The negative pore water pressure was lowest at the crest of the slope.
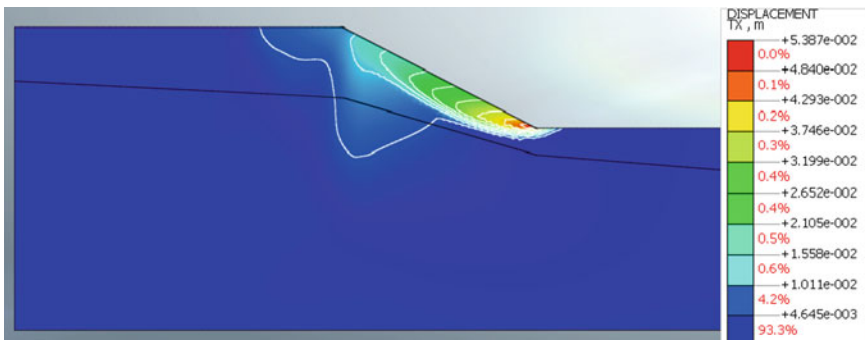

Fig. 5 Displacement contours diagram for 983 mm rainfall (highest intensity) at 48 h
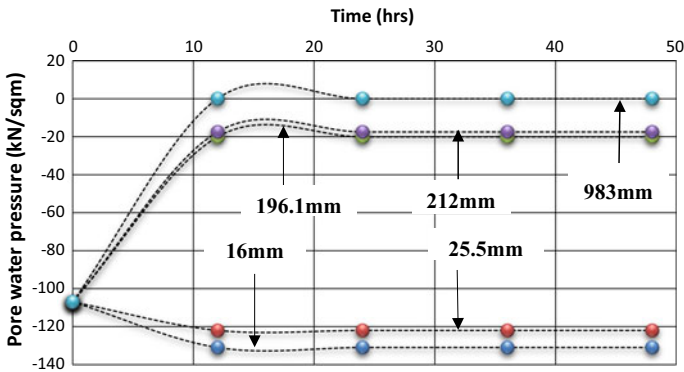

Fig. 6 Variation of pore water pressure with respect to a period of 48 h for different rainfall intensities

3.3 Parametric Studies with GWT Variation

The variation of FOS for different soil properties (as given in Table 2) is shown in Fig. 7 and the rainfall intensity in this case was 983 mm. The failure pattern is the same for all the three soil properties and sample 3 having the highest cohesion (7.3 kN/m^2) and angle of internal friction (43°) have the highest factor of safety values. Since the samples were taken from the same site location, the shear strength parameters had very little difference; because of this the factor of safety values did not show much variation.

Maximum displacement along x-direction for different soil samples are plotted in Fig. 8. Initially the displacement was zero and the displacement showed a substantial
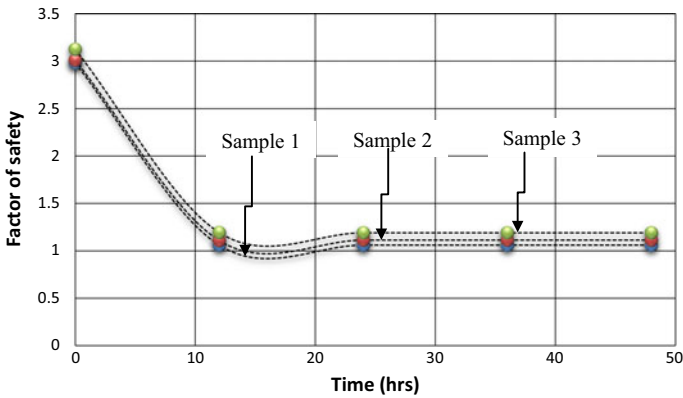

Fig. 7 Variation of factor of safety with respect to a period of 48 h for different soil properties
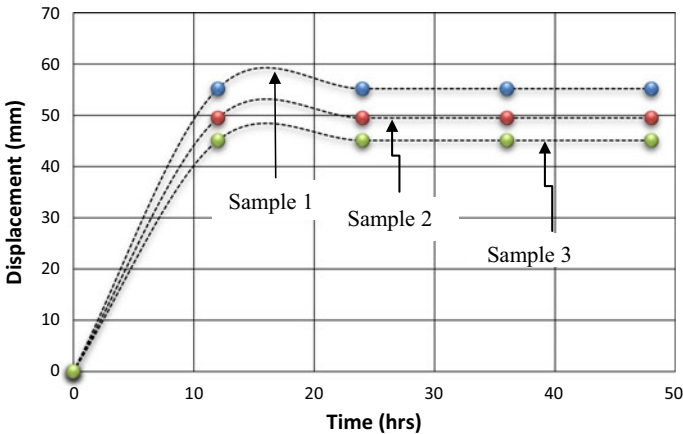

Fig. 8 Variation of displacement, with respect to a period of 48 h for different soil properties

increased during the first 12 h of rainfall. From 12 h the displacement gradually decreased till 24 h and after which it attained a constant value. Since the displacement pattern was same and the values did not vary much for all the three samples it can be concluded that the different soil properties have similar effect on the slope.

The negative pore water pressures for all the three soil parameters were the same throughout the analysis of 48 h. Initially the negative pore water pressure was -107 kN/m^2 and as the rain started, the value decreases steadily and attains a constant value of -20.1kN/m^2 after rain. In the case of pore water pressure also, the shear strength parameters did not have significant effect to the slope.

4 Conclusions

The variation of GWT and rainfall intensities showed a very significant effect to the slope at Nongstoin, Meghalaya, whereas the different soil properties did not show a noticeable effect. The overall results can be summarized below as.

1. Initial values of FOS for all analysis are quite high, hence during the dry season, the chances that the slope will fail is very low. This is due to the high value of negative pore water pressure. When rain is applied, the negative pore water pressure or matric suction decreases over the time which directly affected the slope stability. It can be observed that as the matric suction decreases, FOS also decreases and attains a minimum value around 14–18 h during heavy rainfall intensities.
2. It can also be noted that during high rainfall the FOS rapidly changed with time, which is the result of the high permeability of the soil in the area, leading to the rapid seepage of rain water when the intensity of rainfall is high. The slope under study appears to be vulnerable to the high rain intensity, hence proper remedial measures needed to be taken to the slope under consideration in order to avoid any hazards during heavy rainfall.
3. The displacement was highly affected by the high GWT position. When the rainfall intensities were high the observed displacement along x-direction was higher.
4. Since all the three soil samples were collected from the same area, the different soil parameters did not show any significant effect to the slope under consideration.

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