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Impact of Rain Water Infiltration on the Stability of Earth Slopes

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Abstract: Slope failure occurs very often in natural and man-made slopes which are subjected to frequent changes in ground water level, rapid drawdown, rainfall and earthquakes. The current study discusses the significance of water infiltration, pore water pressure and degree of saturation that affect the stability of earth slopes. Rainwater infiltration not only mechanically reduces the shear strength of a slope material, but also chemically alters the mineral composition of the soil matrix. It results in the alteration of macro structures which in turn decreases the factor of safety. A few case studies are discussed in this paper to quantitatively observe the variation in factor of safety (FOS) of various earth slopes by changing the degree of saturation. The results showed that most of the earth slopes get failed or become critical when the degree of saturation approaches to 50 % or more.

Keywords: Seepage, slope failure, infiltration, factor of safety, unsaturated soil.

Introduction

For a given geology and geo-environmental condition, there are two basic groups of factors that affect the stability of a natural slope. The first category (internal factors) is about the properties of the soil mass which includes the soil grain size distribution, components, pre-existing structured planes such as pore voids, fissures and cracks inside soil mass and adjacent tectonic zones (Terzaghi, 1950). The second group (external factors) is the outside helpers, such as ground water seepage pressure, earthquake, anthropogenic activities and rainfall precipitation (Rogers, 1992; Collins and Znidarcic, 2004; Stegmenn et al., 2011). Many studies have been conducted on the slope failures and revealed that rainfall infiltration and subsequently the degree of saturation are one of the most recognized triggering factors of landslide (Brand, 1984; Anderson and Sitar, 1995; Toll, 2001; Chen et al., 2004; Orense et al., 2004; Zhang et al., 2005; Rahardjo et al., 2007; Berrones et al., 2011; Farooq et al., 2015). Generally speaking, the external factors act as a dominate part and are mostly considered by the stability analysis. However, in some of the cases, the internal factors are more critical than the external agents. Therefore, it is utmost important to consider both of these factors, while carrying out the slope stability analysis.

The natural earth slope stability is solely governed by those aforementioned factors. However; the degree of saturation is more critical and plays a dominant role among all these factors (Rogers, 1992; Ahmed et al., 2012). The infiltrating water through the soil also interacts with the soil particles (where chemical and mechanical reaction happens) which in turn changes the internal structure of the slope and makes the stability analysis more complicated.

This study critically investigates the role of the degree of saturation and rainfall precipitation in the stability of earth slope and their influences to understand the landslide failure mechanism in the slopes and the relationship between shear strength and the degree of saturation.

Factors affecting the Earth Slope Stability

Chemical and mechanical influence

Water can both mechanically and chemically interact with soils. In natural slope, water can easily infiltrate through the discontinuities and small pre-existing fissures. While penetrating through the earth, small particles such as clay minerals will dissolve into the water where hydration might take place that could result the water and soil molecule’s polarization. This situation will increase the thickness of the absorbed water around small particles and thus increases the double diffused layer (DDL). The increased DDL can weaken the bond between the adjacent soil particles, which in turn reduces the shear strength of the soil. At this stage, the slope will obviously face potential instability issues.

Since, the clay and organic soils have a very high liquid limit and expansive potential, they will swell many times larger than their original volume and the swell pressure will cause tension in the soil, which will result in expansion and extending the existed cracks (Brackley, 1973). This situation within the natural slopes can greatly reduce the FOS especially during the rainy seasons (Orense et al., 2004). On the other hand, in sandy soils, the rain water infiltration can erode the loose matrix soil near the toe of the slope that will reduce the FOS, to natural soil slopes.

Seepage pressure and seepage impediment influence

As mentioned above, water is the core factor that affects the slope stability. However, all those factors are hard to account and should be quantitatively analyzed. Generally, when carrying out the stability analysis, only the pore water pressure (PWP) is considered as most significant trigger factor (Rogers, 1992). Based on Terzagi's effective stress theory, PWP decreases the effective stress and changes the stress state in the soil that eventually leads to slope failure. Hoek and Bray (1981) studied the stability of saturated and unsaturated slopes and found that the FOS reduced from 0.5″ to 0.8″ as the slope becomes fully saturated, especially when there are tension cracks developed on the crust.

The effects of seepage pressure on slope stability could be analyzed by considering: the soil is fully saturated, the water inundates along the potential failure plane, and the potential failure plane extends infinitely through the soil (Berrones et al., 2011). Figure 1a shows schematic diagram of an embankment slope divided into small slices. The stress states of a soil slice is shown in Figure 1b.

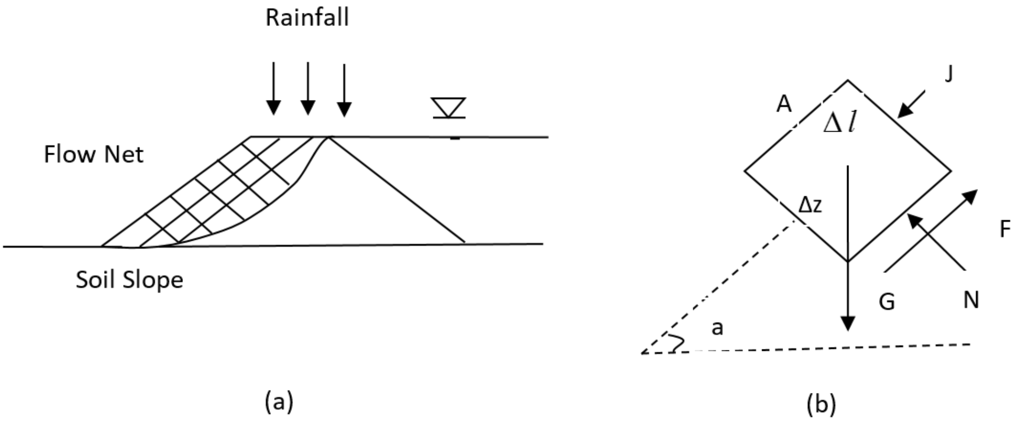

Fig. 1 Sketch of soil slope and stress state.

Lee et al. (2008) performed a series of centrifuge tests and simulated the results using numerical analysis on a layered fill slope. They found that the slope instability could be initiated by confined ground water flow in the earth slopes irrespective of fill density. The prolonged impeded seepage can lead to a localized pore water pressure build up in the slopes, sufficient enough to

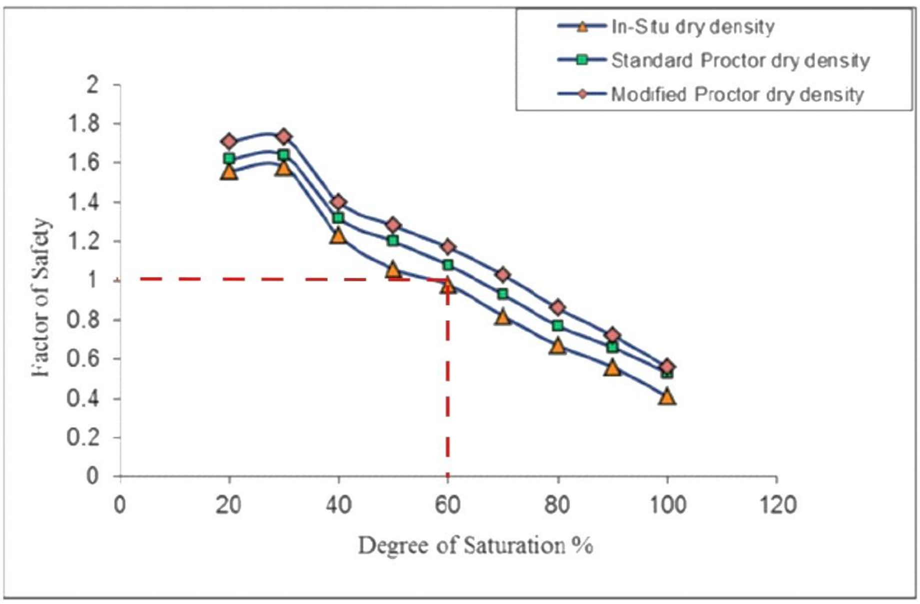

Fig. 2 The variation of FOS with degree of saturation (%) at different density, simulated in Slope W (modified after Ahmed et al., 2012).

cause failure.

Rainfall infiltration effects

Rainfall is a common trigger factor in inducing surficial slope failures. However, most of the slope failures are closely related to the rainfall infiltration pattern, not the rainfall itself (Chen et al., 2009). In order to study the rainfall infiltration procedure, many infiltration models were developed in the past. Usually, one dimensional infiltration numerical models are commonly used in evaluating the effect of rainfall infiltration. These numerical models are based on the standard concepts of soil mechanic and recognized among many researchers. Hydraulic properties also have significant influence on the slope stability. Rahimi et al. (2010) concluded that the slopes with good permeability ($k_s \geq 10^{-4}$ m/s) could be affected more by intense rainfall. The FOS of these type of earth slopes drops to the lowest minimum in high rainfall events. In other words the stability of slopes with poor drainage (i.e. $k_s < 10^{-6}$ m/s) are more affected by low rainfall intensity events.

The variation in the degree of saturation greatly affects the shear strength of earth materials and plays a vital role in the stability of slopes (Orense et al., 2004; Lade, 2010; Ahmed et al., 2012; Farooq et al., 2015).

The unsaturated condition should also be incorporated in order to investigate the nature of a partially saturated slope where the water is not evenly distributed in void spaces of the soil. Fredlund et al. (1978) introduced modified Mohr Coulomb failure criterion to investigate behavior of unsaturated soils that was successfully adopted by Gui and Yu (2008) in evaluating some unsaturated lateritic soils and concluded that the matric suction plays significant part to contribute in the shear strength in unsaturated conditions.

The effect of rainfall infiltration could be investigated by conducting geotechnical investigation of the matrix material of the failed earth slopes to find out the shear strength parameters (cohesion 'c' and angle of internal friction 'phi') of the material at in-situ dry density. Later those shear strength values could be utilized in the slope stability analysis using different software to find out the FOS of those slopes under different conditions. The current study is focused to discuss the effect of degree of saturation on natural slopes under varying degree of saturation. A few case studies are presented in the next section to elaborate this important scenario.

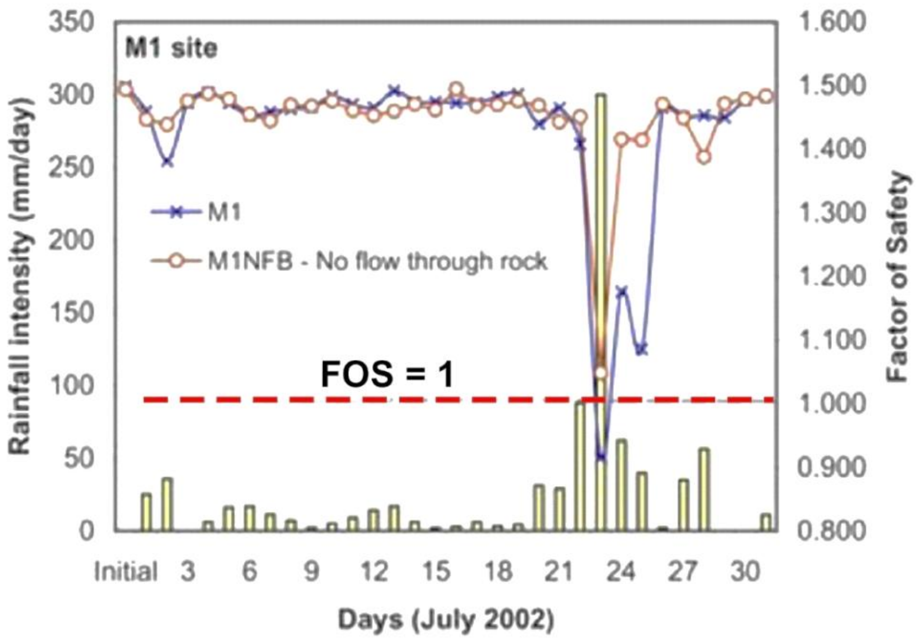

Fig. 3 Change of FOS with the intensity of rainfall in July 2002 of a landslide in Lesser Himalaya Nepal (modified after Ranjan et al., 2009).

Slope Failure Case Studies

Simbal landslide was triggered along Lahore Islamabad M2 Motorway due to intense rainfall in October 2005 (Ahmed et al., 2012). A comprehensive study was executed to investigate the effect of degree of saturation on the shear strength of landslide matrix material. Basic engineering properties and classification of the matrix material were determined on samples collected from the field. The shear strength parameters were computed by performing direct shear test at different degree of saturation. The results were later incorporated in slope/W software to determine the variation in FOS with the shear strength parameters (c and phi) at varying degree of saturation. Figure 2 shows that the slope became critical at 50% saturation, where the FOS reached to 1.

Northern Pakistan is known for significant landslide activities during the monsoon rainfall season every year (Ahmed and Rogers, 2014; Ahmed et al., 2014). According to the studies performed using the geomatics techniques by Mustafa et al. (2015) the majority of landslides triggered in Murree region of Punjab are caused by the prevailing anomalous drainage pattern. The large number of small tributary streams is passing through the study area and intersecting the road cut slopes at various locations. This situation makes the slopes more unstable due to the increased degree of saturation, excessive pore water pressure and uplift in the rainy season (Ahmed et al., 2012) and caused local significant life and property damages.

Ranjan et al. (2009) modeled a landslide in GeoSlope/W software to understand its failure mechanism that was triggered by Monsoon rainfall in the Lesser Himalaya, Nepal. The analysis was based on the limit equilibrium theory and the method of slices (Bishop Method). Their analysis showed that the Lesser Himalayan slopes were generally triggered by the effect of transient positive pore water pressure as a result of intense monsoon rainfall and bedrock seepage (Fig. 3). In a particular event reported by Ranjan et al. (2009), when the rainfall intensity increased to its maximum value on July 24 2002, the FOS dropped to 0.9. The failure was attributed to the antecedent rainfall, which reduced the soil suction and increased the transient pore water pressure as mentioned by Gui and Yu (2008).

The Havelian landslide was partially triggered due to an earthquake of 8.1 in October 2015 (Source: USGS) in Puna village of Havelian (a Tehsil of Abbottabad district). On November 23, 2015, a few weeks after that major event, the subject landslide was reactivated due to a heavy rainfall event and subsequently failed catastrophically. The landslide also blocked a main tributary river in the Poona village of Havelian cutting off more than 50 villages from the rest of Khyber-Pakhtunkhwa.

The investigation work for the failure analysis of Havelian landslide began with a site visit for field investigations and landslide matrix sample collection. Laboratory tests were performed on the collected samples to characterize the landslide material and to estimate its strength parameters to further incorporate them in the failure analysis of the landslide. The failure analysis of Havelian landside was performed using Slope/W software inputting shear strength parameters (c and phi) computed at varying degree of saturation using insitu dry density (Fig. 4). The results concluded that the factor of safety reduces remarkably from 1.21 to 0.19 with increasing degree of saturation (Ahmed et al., 2016). The Figure 4 reveals that the slope becomes critical, as the degree of saturation approaches 60% and becomes unstable above that value.

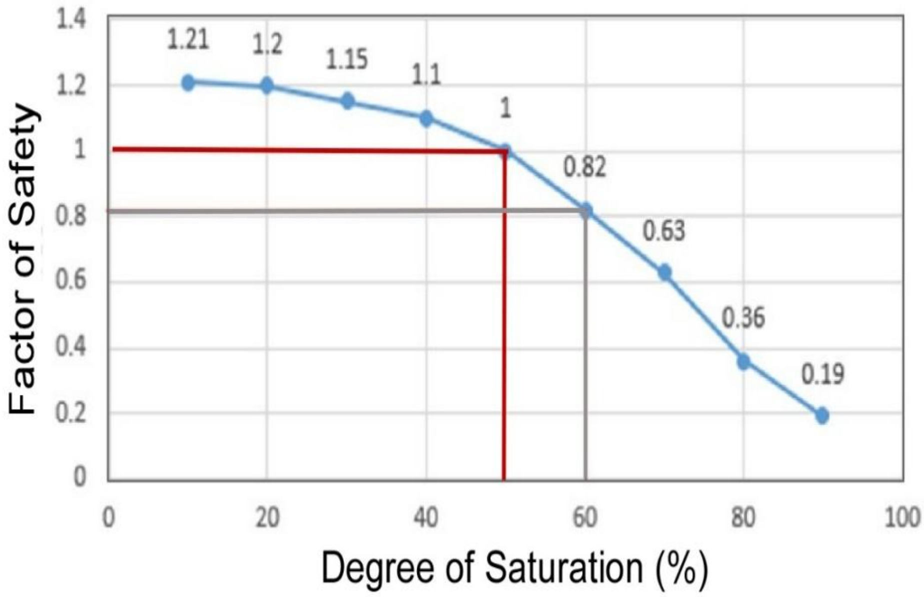

Fig. 4 the variation of FOS with degree of saturation (%) at in situ density, simulated in Slope W.

This study overall emphasizes the critical role of rainfall infiltration, pore water pressure and degree of saturation behind the failure of many landslides. These factors cause the reduction in shear strength of the landslide matrix material in the areas, where intense precipitation is frequent event in summer. The study also emphasizes on the role of providing adequate drainage in these areas in order to reduce the landslide hazards.

Conclusion

The study was carried out to discuss the role of various factors including rainfall infiltration, ground water flow, seepage, pore water pressure and degree of saturation on the stability of earth slopes. These factors greatly tend to reduce the shear strength of the landslide matrix material, which further reduces the FOS of the earth slopes. Hydraulic properties govern the penetration speed of water and thus influence the seepage process. Some of the studies show that the unsaturated soil apparently seems much stronger than saturated soil due to matric suction. However, it is difficult to determine the degree of saturation, especially under transient state. The degrees of saturation along with pore water pressure during an event of intense rainfall mainly govern the failure mechanism of various earth slopes. This situation could be modeled using various slope stability software. Few landslide failure case studies discussed in this article highlight the impact of degree of saturation on the variation of FOS of the earth slopes. The subsequent results concluded that the earth slopes generally become critically beyond the 50% degree of saturation depending upon the insitu soil type and degree of compaction of the natural slopes.

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