FAILURE ANALYSIS OF A REINFORCED SOIL SLOPE

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Abstract: Failures of geosynthetic reinforced soil slope (RSS) initiated by intense rainfall have been often reported recently. These incidents were likely to be the effect of strength reduction upon wetting for unsaturated fill. This paper adopts a practical approach to evaluate the probable errors in analysis that are responsible for such failures. A case study for a collapsed highway RSS was conducted to verify the developed protocol. The results were consistent with those observed in the field. The rational procedures found in this research offer a quick and simple way to estimate the stability of RSS upon wetting.

Keywords: failure, geogrid reinforcement, reinforced slope

INTRODUCTION

The applications of geosynthetic reinforced soil slope (RSS) technology have been increasing rapidly in Taiwan for the past decade. However, the frequency of structure failure has also increased as well. Based on a comprehensive forensic survey, most of the RSS failures were initiated by intense rainfall or poor dissipation of seepage (Wu & Tang 2006). It appears to be anomalous as these structures all had shown sufficient safety factor under severe rainstorm conditions based on their safety analyses. Thus, studies of wetting-induced failures and back analyses are essential to substantiate the accuracy used in the design.

Conventional safety design of RSS under rainstorm condition is based on the limit equilibrium approach, which generally assumes a condition of rising groundwater level. However, the accuracy of the analysis depends on whether or not the assumed mode of failure adequately represents the conditions actually leading to collapse. Studies for slope stability have indicated that the failure mechanism upon wetting involves moisture infiltration into the slope surface that leads to decreases in suction and soil strength (Chen et al. 2004, Collins & Znidarcic 2004, Crosta 2004, Sako et al. 2006). Although many researches have been conducted on the effect of wetting-induced slope instability, practically standard procedures have not been established to predict the corresponding slope safety. Available research for RSS also seldom addresses the effect of wetting on stability. The sophisticated failure mechanisms and time-consuming analyses for unsaturated soils also make it difficult for most engineers to integrate theory into practice.

This paper presents a case study and adopts a practical approach to the problem in which a geosynthetic reinforced slope collapsed after it was attacked by a typhoon. A modified direct simple shear test was derived to observe the strength loss of compacted fill upon wetting. Computer limit equilibrium analyses were then performed using the observed strength parameters for rainstorm conditions. The accuracy and the practicability of the procedures were verified in comparison to the actual case of failure.

BACKGROUND

The site consisted of typical cut and fill construction for a 15-m wide highway winding through a mountainous area originally built in 2003. A 19-m in height, 3-tiered reinforced slope was used to support the widening of the highway as shown in Figure 1. The ultimate strength of the geogrid used was 200 kN/m. The geological formation observed at the site was predominantly yellowish fine-grained sandstone with thinly interbedded grey shale (Figure 2). Groundwater level was found at about 1m below the ground surface. The fill material for the RSS was yellowish sandy material. The sand was classified as poorly graded sand with silty clay (SP-SC) according to the Unified Soil Classification System (ASTM D2487). Table 1 presents its detailed physical properties. In 2004, typhoon Aere attacked Taiwan accompanied by enormous rainfalls. The reinforced slope totally collapsed during the storm and caused serious traffic interruption of the highway (Figure 3).

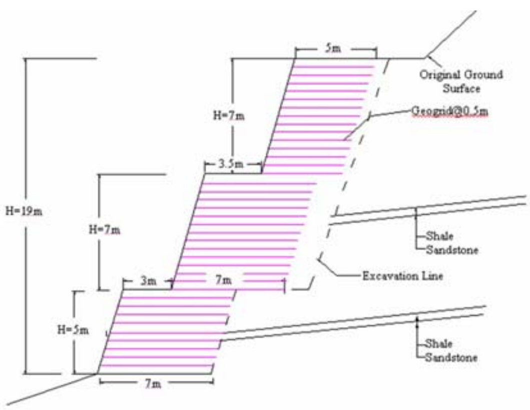

Figure 1. Original configuration of the collapsed reinforced soil slope

Figure 2. Geological formations at the site

Table 1. Physical properties of tested soil.

Property	Value
Specific gravity	2.6
Coefficient of curvature, C_c	0.76
Coefficient of uniformity, C_u	9.1
% of fines (%)	8.24
Liquid limit (%)	26
Plastic limit (%)	12
USCS soil classification	SP-SC
Maximum dry density (kN/m^3)	17.6
Optimum moisture content (%)	17

Figure 3. RSS totally collapsed during an attack of typhoon.

FAILURE INVESTIGATIONS

Pre-construction Stability Analysis

As shown in Figure 4, pre-construction stability analysis based on the traditional groundwater rising procedures indicated that the slope presented a safety factor of 1.63 for intense rainfall conditions. However, the RSS collapsed during an attack of typhoon with an enormous rainfall. Forensic study based on Wu and Tang (2006) showed that previous stability analysis was probably erroneous due to the ignorance of strength reduction for the unsaturated fill material.

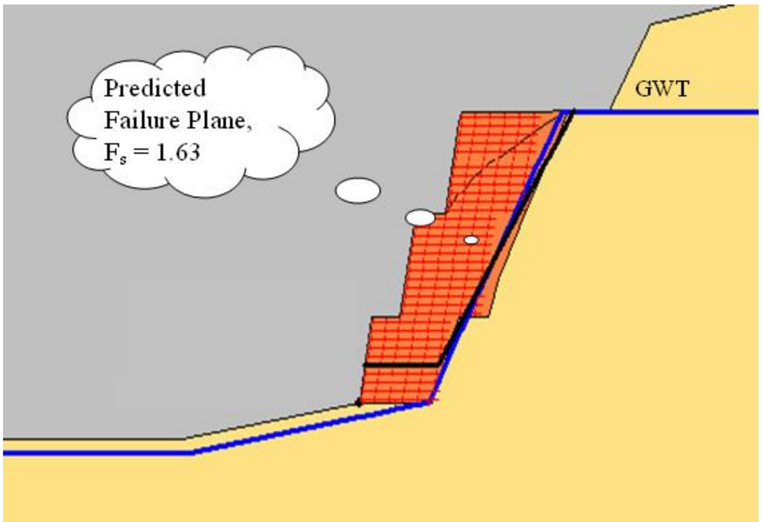

Figure 4. Result of pre-construction storm stability analysis based on the traditional groundwater rising.

Experimental Evaluations

To simulate the fill conditions of the collapsed RSS, soil specimens collected from the site were compacted to 90% of maximum density with three moisture contents, namely OMC-2%, OMC, and OMC+2%. These compacted samples were then subjected to shearing to observe the effect of infiltration on their strength variations.

Determining the shear strength parameters of an unsaturated soil involves a sophisticated and time-consuming testing program (Cabarkapa and Cuccovillo 2005). For most of the geotechnical engineering firms in practice, their testing laboratories usually do not have the capability to measure the shear strength of unsaturated soils. There is a general lack of familiarity as regards equipment, procedures, and results (Abramson et al. 2002). The experiment in this research was therefore designed specifically to develop a simple protocol using current available equipment for practicing engineers. Considering the influences of cost, time, and simplicity of the test, the simple direct shear test (ASTM D 3080) was used to observe the effect of infiltration on the variations of shear strength for sandy material compacted with different values of moisture content.

To examine the effect of infiltration on the strength reduction of compacted sand, the sample was vertically loaded without inundation to simulate the fill construction. Each sample was then soaked for 4, 12, or 24 hours to observe the effect of different time of soaking on the strength variations. Hydrocollapse due to wetting was recorded with time. The sample then was sheared to failure. Test procedures were similar to those described by Melinda et al. (2004) except shearing was not initiated until soaking of the sample was completed for the specified time. This was to simulate a rainfall-induced landslide of a fill slope under its self-weight. The primary object of the test was to observe the reduction of strength upon wetting and also keep simplicity of the testing protocol; suction was therefore not monitored throughout the test. Such arrangements were easy to perform yet able to acquire reasonable test results in relevant to the effect of wetting on unsaturated soils.

RESULTS AND DISCUSSIONS

Strength Parameters

Strength parameters are the crucial input in order to analyze the safety of a slope. The determination of these parameters in a manner truly corresponding to those conditions at the site is thus vital to an accurate prediction for the slope safety. Abramson et al. (2002) stated that the shear strength of unsaturated soils can be readily accommodated within conventional slope analyses by using a concept of total cohesion. With this approach a modified value of total cohesion is used to include the effect of matric suction within the slope.

Figure 5 summarizes all strength parameters tested for samples compacted to 90% of maximum density with varying moisture contents. In general, the infiltration caused the total cohesion to decrease with the increase of soaking times. The cohesion had totally vanished after 24 hours of infiltration for samples compacted with less moisture contents (OMC and OMC-2%). The reduction was up to 100% in comparison with to its initial value before wetting.

According to Fredlund and Rahardjo (1993), the decrease of cohesion can be attributed to the loss of matric suction due to infiltration. Conversely, the friction angle increased with the increase of soaking time. It appears to be anomalous as research findings have indicated that friction angle is effectively independent of matric suction (Fredlund and Rahardjo 1993). Such phenomenon should be the effect of further consolidation of soil particles triggered after the hydrocollapse of soil sample. A longer consolidation promotes greater increases in the effective stress. It can be seen that samples compacted with less moisture content (OMC-2%) presented significant strength weakness upon wetting. It is logical to conclude that fill slope compacted dry-of-optimum will be more vulnerable to failure after intense rainfall. Rehardjo et al. (2003) and Chen et al. (2004) reported many landslides of man-made slopes coincided with such behaviours.

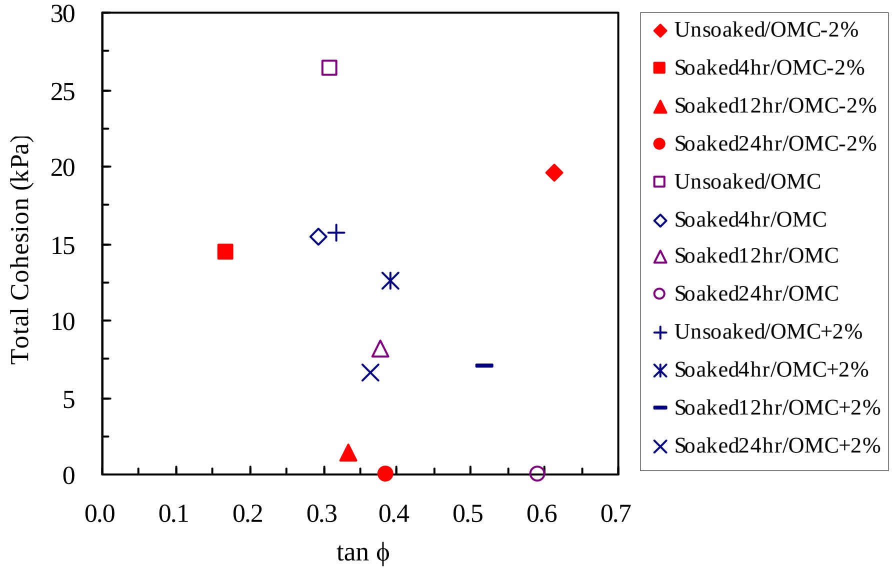

Figure 5. The effect of wetting on the reduction of strength parameters

Stability Analysis

Almost all traditional RSS stability analyses are conducted using computer programs based on limit equilibrium methods. ReSSA has been on the market recently used by practicing engineers. It is relatively easy, simple, and user-friendly for RSS analysis. To reduce the annoyance of facing unknown challenges for engineers, this paper proposes that a conventional program such as ReSSA can still be used for unsaturated slope stability analyses. However, the reduced strength parameters observed using the above modified simple direct shear test must be used to account for the effect of infiltration on strength loss. For normal and earthquake conditions, drained or undrained strength parameters applied for stability analyses of fill slope remain unchanged to those that would be used in conventional procedures. For intense rainfall conditions, boundary of infiltration should be established first and the strength parameters for soil strata within the range of wetting band should be revised using the reduced values.

High-intensity rainfall induced landslides of fill slope often occur on relatively shallow slip surfaces. The depth of the wetting front can be approximated based on soil characteristics and rainfall conditions (Abramson et al. 2002) or in terms of pore pressure (Collins & Znidarcic 2004). A more practical alternative would be to assume a reasonable depth of wetting front. The landslides in unsaturated fill slopes are generally shallow and the failure surfaces are usually parallel to the slope surface. Therefore, for a short-term intense rainfall condition, the depth of wetting front of a sandy fill typical for RSS can be assumed reasonably within a range of 2 to 6m. For long-term conditions, a worst case can be assumed that the phreatic surface rises to coincide with the slope surface and that the slope is completely saturated.

The safety of RSS was examined further using the protocols developed in this study. Strength parameters of the fill material were reduced in stages to simulate the effect of infiltration resulting from the downward movement of a wetting front. It can be seen in Figure 6 that the factor of safety (F_s) decreased with the increase of depth of wetting front. The reduction of pullout resistance of the reinforcement also presented significant negative effect on the F_s. The pullout resistance is a function of soil-geosynthetic interface shear resistance (Moraci and Recalcati 2006). FHWA (2001) recommended a pullout resistance factor (F^*) to be used as the correlation for soil and geosynthetic interaction. Based on its definition, a reduction of soil shear strength certainly causes F^* to decrease as well. The calculated factor of safety and the predicted mode of failure have shown a good agreement with what was observed in the field (Figure 7). The illustrated case study shows that sophisticated infiltration and slope stability analysis may not always be necessary for analysing rainfall induced slope failure. Rational results also can be available using traditional analysis with proper experimental simulations. Further studies are underway to verify the presented method.

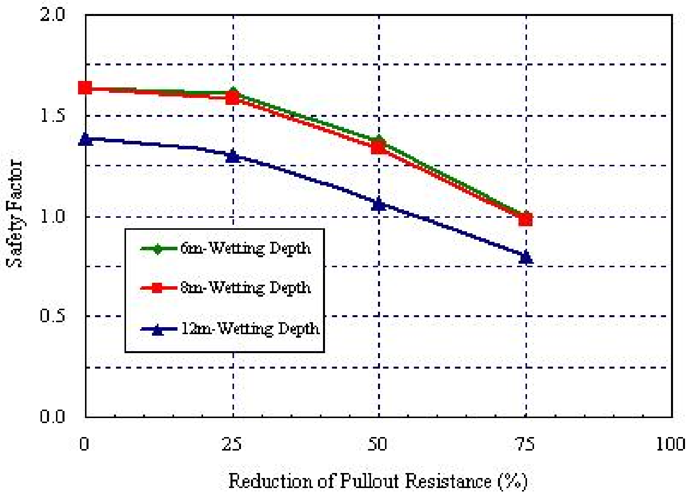

Figure 6. The variations of factor of safety with the depth of wetting front and reduction of pullout resistance.

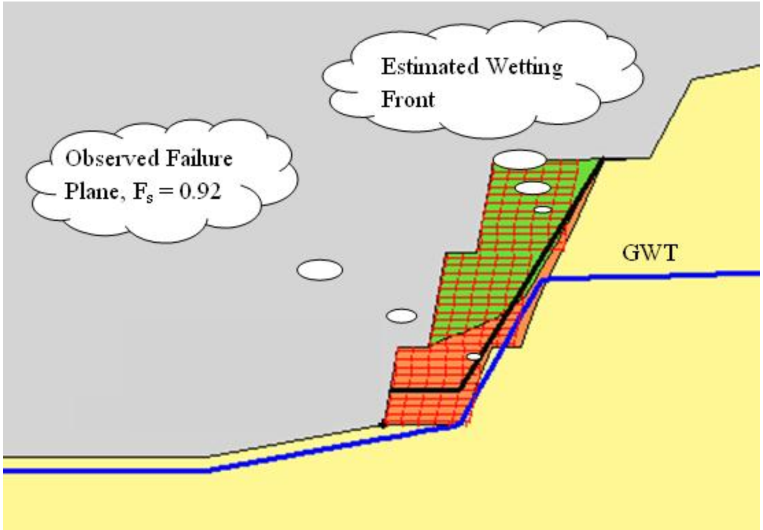

Figure 7. Result of stability analysis showing a wetting depth of 12-m caused the RSS to collapse.

CONCLUSIONS

Failures of RSS during or shortly after intense rainfall are attributed to the infiltration of wetting fronts into slopes. The slope instability of unsaturated soils has been known to be caused mainly by the reduction in shear strength due to the decrease of matric suction. Numerous studies have been conducted in an attempt to develop solutions for integrating the effect of rainfall into slope stability analyses. However, standard procedures have not been established to predict the slope safety. The modified simple direct shear tests developed in this research appropriately simulate the strength reduction upon wetting in the field. The as-compacted moisture content and the duration of infiltration presented prominent effects on the shearing behaviour and strength parameters. The infiltration not only reduced the strength of unsaturated compacted sand but also decreased the pullout resistance of geogrid reinforcement. Such effects were highly correlated with the time of inundation. In general, the infiltration caused the cohesion to decrease with the increase of soaking times. For samples compacted with less moisture contents, the cohesion could vanish completely after 24 hours of infiltration. The decreases have shown a good agreement with the loss of matric suction due to infiltration. Based on the test results, samples compacted with less moisture content presented significant strength weakness upon wetting. Common practices for RSS compacted dry-of-optimum will thus be more vulnerable to failures after intense rainfall.

The test results allow practicing engineers to use traditional simple computer programs such as ReSSA to examine the possibility of rainfall induced failure for RSS. An illustrated example based on a case study demonstrated that the calculated safety factor and the predicted mode of failure agreed reasonably well with what was observed in the field. This suggests that instead of sophisticated infiltration models and rigorous finite element approaches, rational results can be available by using traditional analysis with properly adjusted input parameters based on conventional experiments. The proposed method in this study offers a simple and practical way to evaluate the stability of RSS upon wetting. While the protocols described provide a practical solution, further studies are needed to verify the presented method.

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