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Case studies of geosynthetic reinforced earth structure failures

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ABSTRACT: This paper collected eleven cases of failure for geosynthetic reinforced earth structures (RES) in northern Taiwan. Qualitative forensic studies were conducted to explore the causes of the structure failures. The results of the research indicated that intense rainfall was the primary natural influence causing the RES failure. Incorrect engineering practices also were relevant in the failure of RES. However, inadequate planning and poor construction workmanship were the most important causes. In addition, the study also showed that the RES failures were due to a lack of essential trainings on traditional slope stability analysis instead of deficient RES know-how. Lessons learned in this study can be valuable to technical development and safety improvement for engineering practices related to geosynthetic reinforced earth structures.

1 INTRODUCTION

Reinforced earth structure (RES) consists of reinforced soil slope (RSS) and mechanically stabilized earth wall (MSEW). RES has been used widely with a variety of applications in hundreds of thousands of projects implemented around the world. It presents many advantages and makes it attractive for infrastructure development and often becomes the first choice for many embankments or earth retaining projects. However, with the increased use of RES, the number of RES failures has also increased. These incidents are not only directly jeopardizing the relevant facilities around the structure, but also distressing the confidence of potential clients regarding the safety and application of RES (Scarborough 2005).

Failure plays an important role in engineering practices. Through the forensic study of failures, engineers can learn to avoid similar technical errors, allowing them to build more efficient, safer structures. For the engineer, knowledge of engineering failure is just as important as knowledge of its successes. To avoid any additional RES failure, it is necessary to conduct a forensic study to explicate the common mistakes that have caused the collapse of the RES and offer guidance for future engineering practices. A number of RES failures have occurred in the past decades, however, only a few case studies of failure have been analyzed (Mitchell and Zornberg 1995, Chou 2000, Yoo 2002, Huang et al. 2003, Scarborough 2005, Ling and Leshchinsky 2005). This research collected eleven cases of failure for RES in northern Taiwan occurring within the past three years. These live cases and eight additional cases reported by Chou (2000) were then compiled and studied. Qualitative forensic investigations were conducted and the most frequent causes of RES failure along with the evidence and mechanisms were explored and examined. The post failure studies serve as lessons for practicing engineers and engineering students concerning the difficult technical, professional, and procedural issues that may arise during engineering practices for geosynthetic reinforced earth structures.

2 CAUSES OF FAILURE

Based on site observations and engineering studies for each failed case, the causes of failure generally can be distinguished as natural influences and professional mistakes. Each category can be further classified into detailed sub-issues. The influence of each sub-issue was then rated based on the evaluation of its significance in causing the failure. Figure 1 summarizes the rated weight of all items that were related to the failures. Frequency is defined as the total occurrences of each observed cause divided by the quantity of total cases studied. Due to the limitation of this paper's length, detailed information of all the studied cases and their statistical results can be found in Tang (2005) and are not presented here.

2.1 *Natural influences*

2.1.1 *Intense rainfall*

The research indicates that about 89.47% of the failures were related to intense rainfall (rated weight ≥1). Failures significantly affected by intense rainfall were up to 63.15% (rated weight ≥4). Numerous worldwide studies have reported that intense rainfall has been the major factor responsible for many slope failures including reinforced earth structures (Huang 1994, Rahardjo et al. 2001, Pando et al. 2005). When rainfall initiates an unstable man-made slope, the mechanism is that water infiltration reduces soil suction in the unsaturated compacted soil. This causes a decrease in the effective stress on the potential failure surface reflected in a decrease in the soil strength to a point where equilibrium cannot be sustained in the slope (Abramson et al. 2002). In addition to the loss of shear strength, surface erosion, seepage force, and hydraulic gradients caused by surface run-off or groundwater also have a significant adverse effect on the slope stability.

2.1.2 *Earthquake*

There are only two cases in the study that failed during the 1999 Ji-Ji earthquake in Taiwan. Both cases collapsed due to strong seismic motion. The statistical frequency is 10.53%. Since then several significant earthquakes have occurred around the island, however, no more RES damage has been reported. In comparison with the greater amount of damages of conventional concrete walls during earthquakes, RES presents better dynamic performance. Huang et al. (2003) indicated similar findings. In their study, Ling and Leshchinsky (2003) reported that the failure of a modular-block RES was due to inadequate design in resisting compound failure during the presence of horizontal and vertical accelerations.

2.2 *Professional issues*

2.2.1 *Planning*

Prior to the design of the RES, the engineers should conduct necessary site investigations to identify potential problems and site compatibility and perform essential countermeasures to ensure the safety of the RES. Detailed subsurface information should be obtained to support accurate analysis and design. In addition, the engineers should also communicate with the client to clearly identify the safety requirements and avoid misuse of the structures. Based on the evaluation of this research, 52.63% of the cases failed due to improper planning. Evidence indicates that the most critical problem would be ignorance of the importance of a detailed site exploration. Without correct site information, all the following engineering practices are highly likely lead to incorrect consequences.

2.2.2 *Analysis and design*

The accuracy of analysis and design ensures the safety of the RES. The inclusion of an erroneous design or miscalculation can cause a variety of failures ranging from a simple malfunction to a total collapse. This type of cause could be the direct result of a lack of experience, negligence, a lack of education, incompetence, or the inability to communicate (Greenspan 1989). Based on the study, the frequency of this type of error was 36.85%.

The results of the evaluation indicate that the most common errors made in the analysis are using incorrect strength parameters. The common practices for RES analysis include using effective stress parameters deduced from triaxial consolidated undrained tests. However, for embankment construction, a total stress analysis using unconsolidated undrained values of shear strength would be more appropriate to access the stability of the slope during and immediately after construction (Abramson et al. 2002). In addition, the effective stress parameters also cannot truly reflect the stress condition of unsaturated soils. As described earlier, matric suction plays an important role in an unsaturated soil slope. The stability of the RES during and shortly after the construction is highly dependent on the changes in matric suction. The analysis that totally ignores the effect of matric suction is risky for the structure. Most of the observed RES failures occurred after a relatively short period following the construction. Such a phenomenon may be considered as an evidence of such an error.

The analysis for RES usually has been conducted by using computer programs developed based on the limit equilibrium theory. STEDwin is the most common one used in Taiwan. Generally, this program is easy to work with and engineers use it for typical RES analysis without difficulty. However, many reinforced earth structures are widening configurations from the existing slope. The fill structure placed on a slope presents a potential for downward movement not to mention other adverse site effects such as seepage, earthquake, and geological dip formation. The interface stability is therefore important to the RES safety. Unfortunately, STEDwin does not assess translational failure for the RES in a convenient manner. As a result, engineers rather assume failure goes through the circular slip surface and take advantage of the auto search of the program. The calculated safety factor is therefore may not be the correct minimum value of the structure. Ignorance of the importance of interface stability would be one of the key causes of RES failure in Taiwan.

As described earlier, intense rainfall has activated many a RES to fail. In a tropical area, intense rainfall frequently occurs. Therefore, it is the responsibility of the engineers to account for such unfavourable conditions in the analysis and make the structure safe.

The failures after intense rainfall indicate the negligence or incompetence of the engineers. It has become a common problem for the RES professional in Taiwan. Evidences indicate that instead of deficient RES know-how, the failures of the RES were due to a lack of essential trainings on traditional slope stability analysis.

2.2.3 *Materials*

The safety of any structure is highly dependent on its material's stability and durability. Therefore, the selection of reinforcement for RES must consider the performance, service life, and the environmental conditions of the structure. The reinforcements used in Taiwan are predominantly geogrid made of a variety of geosynthetic materials. Because of its complexity, the quality verifications of geogrid on site are always problematic. Disputations regarding the selection and the installations of a geogrid are quite common during the engineering practice for RES. However, despite the complexity of the material, failures mainly caused by a geogrid in this research are insignificant. The frequency is only 5.26%. It was also observed that those geogrid materials that caused failures were all made of fibreglass. Such material has a brittle characteristic not favourable with the flexibility of the RES. Strain compatibility between reinforcement and structure must be evaluated if this type of geogrid material is proposed for use.

The majority of reinforced earth structure consists of compacted fill. The study indicated that about 31.58% of the failures were caused by the poor quality of the fill. Many engineers believe that reinforcement would be the major support system for the RES service loads. The stronger the reinforcement is, the more loading the RES can sustain. In reality, compacted fill offers most of the support for a service load. Reinforcement only provides additional improvement. The ignorance of the importance of the fill leads to negligence in the selection of fill materials. In addition, the site conditions or the financial burdens of the project often limit the probability of selecting suitable fill materials. As a result, virtually all kinds of fill materials such as silt, clay, or crushed shale have been used for RES in Taiwan. Although the use of fine-grained poorly draining materials in RES may not warrant damages of structure, proper safety measures must be specified to ensure the performance of the RES (Mitchell and Zornberg 1995). Good structure performance is strongly dependent on maintaining a low water content in the poorly draining fill. Therefore, an appropriate drainage system must be installed to dissipate surface run-off or seepage in a timely manner for the RES. Large movements occur in the RES when pore water pressures were generated, and failures were reported in marginal backfills reinforced with impermeable inclusions that became saturated after rainfalls (Mitchell and Zornberg 1995, Scarborough 2005). The designers or the geosynthetic material distributors who favour the use of RES must realize that the safety of the structure is highly dependent on the availability of qualified fill materials.

2.2.4 *Construction*

The performance of compaction controls the quality of fill material. Also, the placement of reinforcements has to follow certain procedures. Although contract documents clearly specify the construction procedures, acceptable construction quality may not be achieved unless reliable construction performance is exactly followed.

Poor construction workmanship certainly warrants higher probability of instability not to mention the technical difficulties inherited from the unsuitable materials. The frequent rainfalls in a tropical area further reduce the chances for a better compaction performance. As a result, failures caused by poor filling quality are as high as 44.44%. Improvement of construction workmanship becomes mandatory to ensure the safety of the RES. Independent construction surveillance should be engaged for compaction verifications to ensure fill quality.

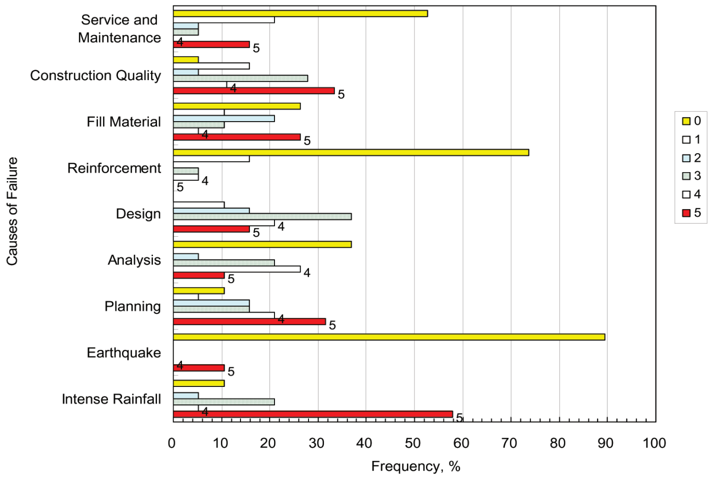
2.2.5 *Service and maintenance*

Many owners of RES ignore the importance of overuse or maintenance of a facility. A typical example is the placement of a surcharge or loading in excess of the capacity of the structure. Other problems such as neglecting routine clean-up of the drainage system, paying no attention to cracks, deformation, or settlement lead to much worse damage. The research indicates that about 15.79% of the observed cases failed due to negligence of service and maintenance.

3 CONCLUSIONS

Based on the forensic diagnosis of the observed RES failures, intense rainfall was the most important natural influence to causing the RES failures. Incorrect engineering practices also were relevant to the RES failures. However, inadequate planning and poor construction workmanship are primarily responsible for the RES failures. The study also showed that the failures of the RES were due to insufficient trainings on traditional slope stability analysis and design rather than deficiency in professional RES know-how.

The findings presented in this research provide essential lessons for RES professionals. It is beneficial to the technical development and safety improvement for engineering practices with reinforced earth structures.



Rate of Significance:
0 - negligible, 1 - extremely slight, 2 - slight, 3 - moderate, 4 - considerable, 5 - extremely considerable

Figure 1. Causes of failure and their statistical ratings for the studied geosynthetic reinforced earth structures.

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