LESSONS LEARNED FROM THE FAILURE OF A REINFORCED EARTH RETAINING STRUCTURE RESTED IN A LANDFILL

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ABSTRACT

This paper presents an investigation on failure of a reinforced earth structure for retaining residual waste in a landfill site. The site is located in a hillslope. Noticeable lateral deformations are observed on the front face of the reinforced earth retaining structure after operation of the landfill for about 6 years, and considerable subsidence takes place in the reinforced earth retaining structure itself. Investigation on the causes for the failure of the reinforced earth retaining structure is carried out in terms of analysis of monitoring data on groundwater, geophysical explorations, and design aspects. A number of reasons are blamed for the failure of the reinforced earth retaining structure: (1) improper design and maintenance in the drainage system in the landfill; (2) neglect of the topography effect and subsurface flow induced by rainfall; and (3) lack of drainage measures on the back of the reinforced earth retaining structure.

Key words: Reinforced earth retaining structure, subsurface flow, failure, rainfall-induced infiltration, topography.

1. INTRODUCTION

Reinforced earth structures are commonly used for retaining waste in a landfill site. To increase the capacity of a landfill, reinforced earth retaining structures are usually built in a hillslope. The topography in the landfill site affects the flow pattern of the runoff during rainfall. The hydrological behavior in the waste materials in the landfill during rainfall can be a critical factor in the long-term stability of reinforced earth retaining structures if the underground drainage system is not properly designed and maintained during the period of operation. In addition, a possibly larger lateral force on the back of the reinforced earth retaining structures may exist, and they may be induced by the topography effect and the water pressure in the backfill. These factors need to be taken into account in the design of the reinforced earth structure located in a hillslope or ravine.

A number of failure cases for reinforced earth structures built in slopes have been reported by Lee et al. (1994) and Fan and Chou (2002). Lee et al. (1994) reported a failure case of four reinforced soil walls built as the embankments of a highway. One of the failed reinforced soil walls was rested in the center of a ravine at its deepest part and contained a convex corner. The pronounced three-dimensional geometry produced non-uniform displacements in the wall and was believed to be one of the reasons causing failure. Fan and Chou (2002) investigated two failed reinforced earth retaining structures in the landfill site at Wugu and Sanzhi, Taipei county in Taiwan. The landfill at Wugu was used to retain residual wastes that remain after the waste treatment process in an incinerator. The landfill site was located in a ravine. The reinforced earth retaining structure was designed at the lower elevation of the landfill site. The landfill site was in operation in 1994, and the reinforced earth retaining structure collapsed three days after a torrential rainfall induced by Typhoon Zeb on October 14, 1998. Collapse of the reinforced soil structure was primarily induced by unexpected water pressure and infiltration of runoff into the bottom of the retaining structure according to the site investigation. In addition, the reinforced earth retaining structure located at the lower elevation of the landfill at Sanzhi also collapsed twelve days after the rainfall induced by Typhoon Zeb. The Sanzhi landfill was located in a slope. The inadequate drainage in the landfill was the main cause for the failure of the retaining structure. In addition, Wu and Ketchart (2008) reported a failure case of an 11-m high rock faced Geosynthetic-Reinforced Soil (GRS) wall. The wall was found to suffer from subsidence of 10 cm on the crest about 18 months after construction. The subsidence of the wall continued to increase to 25 cm associated with significant lateral bulging in ensuing 3 months. The backfill consisted of gravelly silt mixed with sands. In addition to poor compaction in the backfill, the discharge of water through an abandoned pipe behind the reinforced fill resulted in wetting of the fill on the side of wall and was considered the main cause of the failure. In addition, Koerner and Koerner (2011) summarized failure cases of eighty-two geosynthetic reinforced earth walls (Koerner and Koerner 2009) and indicated that 68% of them were caused by the improper drainage control. The failures from improper drainage may result from either internal or external sources. Leaks from drainage facilities within the reinforced soil zone are main problems for internal drainage failures. Back drains behind the reinforced soil zone are important for intercepting the external water from entering the reinforced soil zone. Base drains beneath the reinforced soil zones are for cases where high water levels are anticipated.

This paper aims to demonstrate the role of hydrology in the performance of the reinforced earth structure for retaining residual wastes in a landfill rested in a hillslope. The failure mechanism of the reinforced earth retaining structure in the landfill is investigated based on the soil moisture condition and the water level in the reinforced earth retaining structure and in the landfill. Geophysical explorations were used to investigate the soil moisture condition in the landfill. The reinforced earth retaining structure was first identified to undergo a subsidence in...
The findings obtained in the investigation can be helpful in the design and construction of the landfill in a hillslope.

2. BACKGROUND

2.1 Landfill Site

The landfill site, located in Kaohsiung, Taiwan, was built in 2006. The landfill is mainly used for retaining residual wastes that remain after the waste treatment process in an incinerator. The area of the landfill is 9.17 hectares. The landfill site is rested in a hillslope. To increase the capacity of the landfill, the hillslope was excavated to an elevation of 65 m. The depth of the excavation ranges from 2.5 m to 27 m. The capacity of the landfill is 676,504 m³, and the maximum design thickness of the waste is 25 m. Figure 1 shows the landfill site in February, 2013. The waste materials have been dumped to the elevation of the top surface of the reinforced earth retaining wall in 2012.

The landfill site prior to construction is mostly covered by top soils underlain by sandstones embedded with thin-layer mudstones. The thickness of the top soil is 2 to 4 meters.

2.2 Topography

Figure 2 shows the contour map of the area of the landfill before the construction. The elevation at the southwest side of the landfill is E.L. +55 m, the lowest in the landfill site, and it is E.L. +125 m at the northeast side, the highest in the landfill site. The catchment area of the landfill site is 8.14 hectares.

2.3 Reinforced Earth Retaining Structure

An 11-m-high reinforced earth retaining wall was built at the lowest elevation of the landfill site to retain the residual wastes. The reinforced earth retaining structure was first identified to undergo a subsidence on the crest of the wall at about the middle of the retaining structure in 2010. Figure 3 shows the location of the reinforced earth retaining structure and the excavated area. The vertical spacing of reinforcements is 0.7 m. The reinforcement lengths at the bottom and top of the retaining structure are 32 m and 13 m, respectively. The length of the reinforced earth retaining structure at the lower elevation of the landfill is 150 m. Impermeable geomembranes are placed on the back of the reinforced earth retaining structure. Typical design cross-section (Profile A-A in Fig. 3) of the reinforced earth retaining structure and the landfill is shown in Fig. 4. The backfill in the reinforced earth retaining structure is silty sand mixed with clayey materials.
2.4 Drainage System

Figure 5 shows the layout of the drainage system on top of the impermeable liner at the bottom of the landfill. The drainage system consists of a number of 30-cm-diameter perforated HDPE (High-density polyethylene) pipes arranging in an interlacing pattern at the bottom of the landfill to collect leachate and percolating water induced by rainfall. The drainage pipes flow into a RC collection well where is located at the lowest elevation of the landfill. Nevertheless, the collection well is located within the reinforced earth retaining structure. The collected liquids in the collection well are pumped out to the downstream through a water pump.

Fig. 5 Layout of the drainage system in the landfill (Adapted from Kaohsiung county government 2006)

3. INVESTIGATION AT THE FAILURE SITE

3.1 Deformation of the Reinforced Earth Retaining Structure

The reinforced earth retaining structure suffers from a noticeable subsidence on the crest and deformation on the wall face, as shown in Fig. 6. The top of the RC collection well was at the same elevation with the top of the backfill. The bottom of the collection well experienced limited settlement. The settlement at the top of the wall was about 0.6 m as dumping of residual wastes in the landfill reached the top of the reinforced earth retaining structure. In addition, the reinforced earth retaining structure shows a noticeable lateral bulging deformation on the wall face as well as severe brown stains induced by the subsurface flow in the residual waste on its front face, as shown in Figs. 7 and 8, respectively. The moist condition of the soil at some parts of the reinforced earth retaining structure is considerably high on its front face through the inspection in the field.

Fig. 6 Subsidence on the top the reinforced earth retaining structure (photo taken in Feb., 2013)

Fig. 7 The brown stains on the front face of the reinforced earth retaining structure

Fig. 8 Close view of the brown stains on the front face of the reinforced earth retaining structure
3.2 Groundwater in the Residual Waste

The groundwater level in the residual waste at the landfill site is monitored through the water level at the RC collection well at the lower elevation of the landfill site. The variation of the groundwater level with time from July, 2015 thru May, 2016 is shown in Fig. 9. The variation of the groundwater level with time from July, 2015 thru May, 2016 is shown in Fig. 9. The elevation of the ground surface is the same as the top of the reinforced earth retaining structure. The water level is noticeably high and varies with intensive rainfall. It indicates that the residual wastes may be highly moist at a depth greater than 5 m at some parts of the wastes during the period of operation.

3.3 Geophysical Explorations

Electrical sounding explorations were carried out at the landfill site to investigate the moist level in the residual wastes and in the reinforced earth retaining structure. Figure 10 illustrates the locations for performing the explorations. There are five rows of explorations, namely L3, L4, L5, L6, and L7, crossing the reinforced earth retaining structure and two explorations, L1 and L2, parallel the retaining structure. Figures 11 and 12 show the distribution of the electrical resistivity in the profile along the reinforced earth retaining structure at about the front and the back of the retaining structure, respectively. For backfill materials full of water, the electrical resistivity is about a few to 10 ȍ-m. The symbols “m” and “d” in the figures denote moist and dry, respectively, in the backfill of the reinforced earth retaining structure. In the front of the reinforced earth retaining structure, the backfill is moist up to a depth about 11 ~ 13 m, i.e., most of the backfill in the two-third part of the retaining structure are in moist conditions. The area with moist condition covers a length of approximately 15 to 40 m in the reinforced earth retaining structure.
Figures 13 to 17 show the distribution of the electrical resistivity in the residual waste in five different profiles crossing the reinforced earth retaining structure. The data cover a length of approximately 50 m away from the reinforced earth retaining structure. Amongst the five profiles, the profile L5 is located at about the central of the landfill and runs close to the RC collection well, as shown in Fig. 15. The symbols “Lm” and “Ld” denote moist and dry, respectively, in the residual waste. Residual wastes with low values of electrical resistivity cover a large area as well as up to a depth of about 15 m in profile L3 (Fig. 13), and the backfill in the reinforced earth retaining structure is moist in the lower half of the structure. In profile L5 (Fig. 15), the backfill in the reinforced earth retaining structure is moist at the upper half of the retaining structure. It shows the possibility that the RC collection well may have cracks or dislocation and result in water leakage in the backfill. Residual wastes with high moisture in the landfill reach up to about 20 ~ 30 m away from the retaining structure and up to a depth of 10 ~ 15 m, as shown in Figs. 13 to 17. A large portion of the residual wastes in the landfill are in moist conditions.
3.4 Reinforced Earth Retaining Structure after Excavation

A rehabilitation work for the reinforced earth retaining structure in the landfill site was executed in 2014. A moist condition in the backfill of the reinforced earth retaining structure was observed after excavation for about 2 m, as shown in Figs. 18 and 19. The RC structure in the photo is the collection well with location shown in Fig. 5. The moist soil condition in the backfill of the reinforced earth retaining structure after excavation agrees well with the results from the geophysical exploration.

Fig. 18 A moist condition in the backfill of the reinforced earth retaining structure after excavation for about 2 m (view from southeast)

Fig. 19 A moist condition in the backfill of the reinforced earth retaining structure after excavation for about 2 m (view from northwest)

4. REASONS FOR THE FAILURE OF THE REINFORCED EARTH RETAINING STRUCTURE

The landfill was built in a hillslope. Rainfall results in infiltration in the landfill during summer season each year and accumulates at the area of the collection well. A considerably high groundwater level was observed in the collection well, as shown in Fig. 9, due to a long-time infiltration induced by rainfall. The groundwater table is located at about 5 to 9 m above the bottom of the reinforced earth retaining structure based on the data from July, 2015 thru May, 2016. In addition, the distribution of the electrical resistivity in the backfill crossing the reinforced earth retaining structure indicates that a moist condition in the residual waste covers a distance of approximately 20 to 30 m from the reinforced earth retaining structure. The geophysical exploration also shows that the subsurface flow may seep into the backfill in the reinforced earth retaining structure, as shown in Figs. 11 and 12. Some of the areas in the backfill are moist. It implies that the geomembrane on the back of the reinforced earth retaining structure may undergo breakage or dislocation at its overlapping parts. In addition, the front face of the reinforced earth retaining structure shows noticeable water stains. The water pressure on back of the reinforced earth retaining structure and soil softening in the backfill due to high moist condition result in the subsidence in the retaining structure and in the area behind it.

The malfunction in the drainage system in the landfill is considered the main cause blamed for the subsidence and deformation in the reinforced earth retaining structure. The subsurface flow accumulating in the RC collection well was designed to be pumped out to the downstream ditch through a water pump. However, it did not work in this way. The success of the drainage system in a landfill is dependent on a number of factors: (1) proper design; (2) good quality in the construction (especially the junctions between the drainage pipe and the collection well); and (3) reliable pipe materials. The performance of these issues plays an important role in the stability of the reinforced earth retaining structure located at the downstream of the landfill.

Reasons for the failure of the reinforced earth retaining structure investigated are summarized as follows:

1. The landfill site in a hillslope collects more runoff during rainfall and results in more subsurface flow than that in a flat ground.
2. Rainfall-induced runoff flows through the cover soil and gathers on the impermeable liner at the bottom of the landfill. The percolating water is not appropriately drained out.
3. The intersection between the RC collection well and the HDPE drainage pipe may undergo split or dislocation due to the subsidence and deformation in the reinforced earth retaining structure. This results in a moist condition and high water level in the residual waste.
4. The high water pressure imposing on the back of the reinforced earth retaining structure results in outward deformations in the retaining structure.
5. Moist backfill in the reinforced earth retaining structure is induced by the infiltration of the sewage and percolating water in the landfill.
6. Softening and water pressure in the backfill of the reinforced earth retaining structure result in subsidence in the reinforced earth retaining structure.

5.Lessons Learned from the Case Study

Reinforced earth retaining structures are commonly used for retaining waste materials in a landfill located in a hillslope. A proper drainage system is important in the long-time stability of the reinforced earth retaining structure located at the downstream side of the landfill. The major impact for the reinforced earth retaining structure in a landfill site located in a hillslope is the water pressure induced by the rainfall-induced subsurface flow and potential water leakage into the backfill in the retaining structure. To improve the reliability of the drainage system in a
landfill, a number of ideas in the design and construction aspects are illustrated:

1. **Use planar drainage system to collect leachate**

   The pipe system on top of the impermeable membrane at the bottom of the landfill is not considered effective in the collection and removal of leachate and percolating water induced by rainfall. Drainage geocomposites in association with pipe system can be more favorable than the pipe system in collecting and removal of landfill leachate. Geocomposites are installed on top of the impermeable membrane and creates a rapid collection and discharge of all liquids within the landfill.

2. **Design a slightly sloping ground at the bottom of the landfill**

   To effectively collect the leachate in the landfill, the bottom of the landfill is recommended to be sloping towards the downstream of the site instead of a flat ground. In addition, a number of sub-regions with independent planar drainage and pipe system can be arranged at the bottom of the landfill to enhance the efficiency for collecting the leachate (Qian et al. 2002), as shown in Fig. 20.

3. **Strengthen the connection between different drainage components**

   The leachate collected at the sump of the landfill generally is not easy to discharge by gravity flow, and it is often extracted by submersible pump. The collected leachate can be directed to a collection well through HDPE pipes. The integrity at the intersection between the collection well and the drainage pipe plays a key factor in the effectiveness of discharge in the landfill. Figure 21 shows an example of the inside view of a RC collection well as well as an inflow HDPE pipe. The intersection in the RC collection well and HDPE pipes is normally connected without a sticking process. To avoid split at the intersection between the collection well and the drainage pipe, a reliable connection between these two components needs to be examined carefully. Additionally, leakage in the drainage pipe may take place if the connection between the pipes is not properly designed or badly constructed in the field. The drainage pipes in the landfill need to reliably connect each other to maintain its function in a large area.

   In addition, an alternative solution for the design at the intersection between the collection well and the HDPE pipe is to replace RC collection wells with large-diameter HDPE pipes. The intersection between the HDPE collection well and the inflow HDPE pipe can be joined tightly by thermal heat fusion and mechanical methods to protect the connection from split or dislocation.

4. **Use multiple leachate collection sumps and monitoring the groundwater level at various locations in the landfill**

   Multiple leachate collection sumps can be used at different locations in the downstream side of the landfill to increase the efficiency in discharging the collected leachate. In addition, instrumentations for the groundwater level at different location in the landfill can be installed to ensure the effectiveness of the drainage system.

6. **SUMMARY**

   The paper investigates the failure of a reinforced earth structure for retaining residual waste in a landfill. The landfill site is located in a hillslope. The reinforced earth retaining structure undergoes significant subsidence and outward deformation on its front face after operation for 6 years. Noticeable water stains resulted from the subsurface flow in the landfill are observed on the front face of the reinforced earth retaining structure. Residual wastes in a moist condition in the landfill reach up to about 20 ~ 30 m away from the reinforced earth retaining structure and up to a depth of 10 ~ 15 m based on the results of the geophysical exploration. The drainage system, consisting of percolating pipes arranged in an interlacing pattern and a RC collection well, at the bottom of the landfill does not function as expected in design. The water pressure on the back of the reinforced earth retaining structure and soil softening induced by leaching water in the backfill result in considerable subsidence and lateral deformation in the reinforced earth retaining structure. The drainage pipe system may be dislocated at the intersection with the collection well, or the drainage pipe system at the bottom of the landfill is ineffective in collecting leachate.

   A reliable leachate collection system in the landfill is important to ensure the long-time stability of the reinforced earth retaining structure and operation of the landfill built in a hillslope. A number of issues in the design aspects are suggested: (1) use planar drainage system to collect leachate; (2) design a slightly sloping ground at the bottom of the landfill; (3) strengthen the connection between different drainage components; and (4) use multiple leachate collection sumps and monitoring the groundwater level at various locations in the landfill.

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