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A debris flow induced by the collapse of a reinforced earth wall

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ABSTRACT: A reinforced earth wall (MSEW) was constructed at the edge of a tableland to establish a site for dumping abandoned soil. The site was also located on the top of a valley that has a mean slope of 18° and a length of approximate 400 m. The wall was 14.5 m high, 50 m long, and with a slope face of 70°. In the fall of 1998, a heavy storm caused the wall collapsed suddenly. Then the water blended with soil mass rushed down along the valley and formed into a debris flow that ruined a two-story house downstream and buried two people in the house. To investigate the cause of this disaster and the mechanism of the failure, a series of tests and stability analysis were conducted. The results of the analysis show that there are three factors that possibly triggered or resulted in the failure of the wall: poor compaction during construction, the heavy storm dropped more than 590 mm of rainfall in 48 hours, and the adverse effect of dumped soil piled up on the top of the wall. Hence, even the wall could maintain its stability from the design point of view, the failure still occurred because adverse conditions were not carefully considered, and good management during operation was not carefully maintained.

1 INTRODUCTION

The reinforced earth walls (or mechanically stabilized earth walls, MSEW) were characterized by their flexibility of tolerating deformations due to poor subsoil conditions under the foundation. They have also demonstrated a higher resistance to seismic loading than rigid concrete structures. Therefore, *MSEWs* have been applied worldwide for various functions. In general, the walls are quite stable under ordinary condition. However, failures may occur due to inappropriate design, poor construction, maintenance and usage. In recent years, there have been some failures that caused casualties as a result of these shortcomings. The failures have raised concerns about the safety of reinforced earth walls. The causes of failure need to be examined to clear doubts about safety.

A 3-tier reinforced earth wall 14.5 m high, 50 m long, and with a slope face of 70°, located at the edge of a tableland at Sanchin Village in Taipei County in northern Taiwan (Figure 1), collapsed suddenly under the heavy storm carried by Typhoon Babs at about 8 P.M., Oct. 26, 1998 (Figure 2). The water mixed with the collapsed soil mass, rushed down along a narrow valley and formed into a debris flow that destroyed a two-story house 400 m downstream and buried two people.

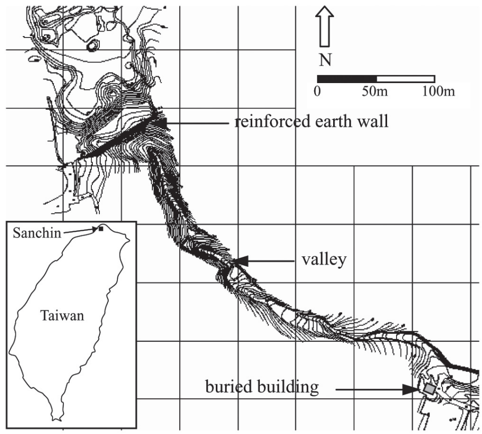

Figure 1. The topography map of the site.

According to the records from the nearest weather station, the storm induced by typhoon Babs had lasted for more than 48 hours with about 590 mm of rainfall before the wall failed.

Figure 2. The failure of the reinforced earth wall.

To investigate the cause of this disaster and the mechanism of the failure, a series of tests and stability analysis of the wall were conducted. The tests include field and laboratory soil tests, geosynthetics tests, and soil-reinforcement interface tests, etc. The stability analysis includes external and internal stability analyses on the wall under ordinary and heavy rainfall conditions.

2 SITE CONDITION

The site is located at a hill on the northwest side of Tatun volcanic mountains in northern Taiwan. The area usually has plentiful rainfall from October to March when the northeast monsoon prevails. The reinforced earth wall situated at the edge of a tableland was constructed to establish a site for dumping soil from nearby excavations. From the topographic map, it shows that the thickness of the fill on the top of the wall was about 9 m when the wall failed. There was little vegetation on the fill, this would result in high quantity of runoff at the site. The site was also near the top of a narrow valley that has a mean slope of 18° and a length of approximately 400 m (Figure 1).

In summary, the field situation had adverse environmental conditions which resulted in the debris flow:

(1) Considerable amount of rainwater-the storm gave about 590 mm of rainfall in 48 hours;
(2) Large volumes of soil - 9 m high dumped soil on the top of the wall and the backfill of the wall;
(3) The gradient of the valley - the valley had a mean slope of 18°.

3 FIELD INVESTIGATIONS AND LABORATORY TESTS

Field investigations, sampling, and testing were conducted to examine the field condition after failure and also to obtain soil and geogrids samples for laboratory tests. The profiles of the wall before and after failure, as well as the original ground surface are shown in Figure 3. It can be seen that the failure zone was within the upper half of the wall and the fill.

The field tests were carried out at several locations to determine the field density and water content of soils at various parts of the site. In generally, the soils had high void ratios and a high degree of saturation as shown in Table 1. The high values are because the soil is a weathered tuff originating from volcanic ashes and contains large voids. Also the soil was loose and soft due to poor compaction.

The laboratory tests of soils included index tests, permeability, and shear strength. The tests on the geogrids included tensile strength and geogrid-soil interface shear strength (pull-out and direct shear) (ASTM 1991). The test results shown in Table 1 are used in the stability analysis.

4 STABILITY ANALYSIS

The stability analysis of the wall includes external stability (check for base sliding, circular sliding,

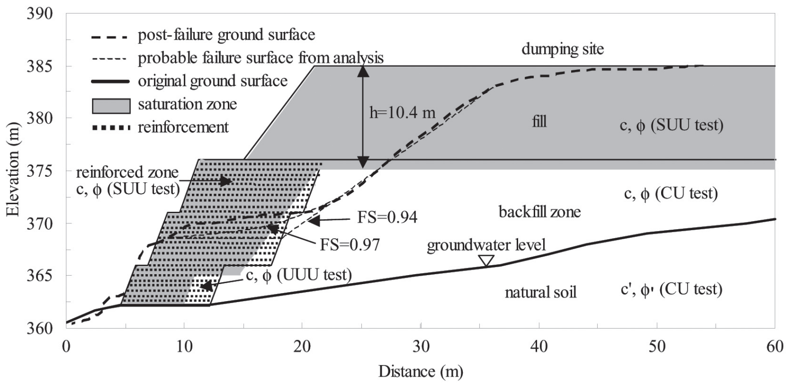

Figure 3. The cross section of the reinforced earth wall.

Table 1. The tests results.

(a) Soil tests

Tests	Property	Reinforced zone	Backfill zone
Index test	USCS soil classification	MH	MH
	Specific gravity	2.67	2.70
	Void ratio	1.65~1.95	1.45~1.56
	Degree of saturation (%)	72.6~82.3	87.8~96.3
Permeability test	Coefficient of permeability (cm/sec)	$2.5\sim19.5 \times 10^{-4}$	$1.4\sim3.3 \times 10^{-4}$
CU test	Cohesion, c (kPa)	0	39.2
	Friction angle, ϕ (°)	28	24
	Cohesion, c' (kPa)	0	0
	Friction angle, ϕ' (°)	38	37
SUU test	Undrained shear strength, c_u (kPa)	8.8	52.0
UUU test	Cohesion, c (kPa)	13.7	34.3
	Friction angle, ϕ (°)	17.6	22

(1) SUU test = saturated unconsolidated-undrained triaxial test; UUU test = unsaturated unconsolidated-undrained triaxial test.
(2) c, ϕ = total stress parameters; c', ϕ' = effective strength parameters

(b) Geogrid tests

	Property	Geogrid-1	Geogrid-2
Tensile test	Tensile strength, T_{ult} (kN/m)	60.2	90.7
	Strain at failure, ε_f (%)	10.5	14.5
Pull-out test	Interface cohesion, c_a (kPa)	4.5	3.5
	Interface friction angle, δ (°)	13.3	18.8
Direct shear test	Interface cohesion, c_a (kPa)	19.1	21.6
	Interface friction angle, δ (°)	9.1	17.5

overturning, and bearing capacity. Figure 4 is the free body diagram used in these analyses) and internal stability (check for tensile and pull-out failure of the reinforcement, soil-geogrid interface sliding, and internal circular sliding) under ordinary and heavy rainfall conditions with a surcharge from the dumped soil. PCSTABL (version 6H), a computer program developed by Purdue University, which was written in FORTRAN and uses limiting equilibrium methods for the general solution of two-dimensional slope stability problems, was used for the circular sliding and interface sliding analyses of the wall.

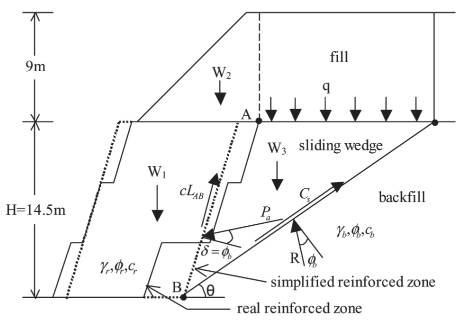

Figure 4. The free body diagram used for external stability analysis.

The middle section of the wall was chosen to be the model cross section as shown in Figure 3. It was divided into four zones of soils, the reinforced, backfill, dumped, and natural soil zones based on field investigation. Furthermore, the height of the fill on the top of the wall and the probable failure surface are determined by the post-failure topography and survey. However, the exact extent of the fill was not known, it was then regarded as a variable in the stability analysis. In ordinary condition, the extent of dumped soil is assumed to be at the edge, considering the most critical situation.

The shear strength parameters used in the zones are shown in Figure 3. In ordinary condition, the UUU test results are used in the reinforced zone due to partially saturated condition (S = 73 ~ 82%). Whilst the dumped soil has a relatively high degree of saturation (S = 88 ~ 96%), thus the shear strength parameters in this zone uses the CU test results. The total stress parameters (c, ϕ) are used for the soils above the ground water table, and the effective stress parameters (c', ϕ') are selected for the soils below the ground water table. The shear strength parameters of the soil-geogrid interface and the tensile strength of geogrids are from the geogrid test results. The values of the parameters are taken from Table 1.

The results of stability analysis under ordinary condition are shown in Table 2. In most circumstances, the factors of safety (FS) are higher than minimum

Table 2. The stability analysis results under ordinary condition.

	condition	FS	FS_{req}
External stability	Base sliding	25.7	1.3
	Circular sliding	1.2	1.3
	Overturning	32.4	1.3
	Bearing capacity	6.5	3.0
Internal stability	Tensile failure	3.9	1.5
	Pull-out failure	8.5	2.0
	Interface sliding	1.2	1.3
	Circular sliding	1.4	1.3

FS: analytic value
FS_{req}: minimum required value (Victor & Barry 1995)

required values, except for external circular sliding and internal interface sliding. Nevertheless, the wall still maintained stability even under an unexpected fill surcharge of 9 m.

Under the stormy conditions, the soil beneath the ground surface would become saturated as a result of the infiltration of rainwater. The depth of the wetting front can be calculated using the simplified equation (Lumb 1962):

$$h = \frac{kt}{n(S_f - S_i)} \tag{1}$$

where:
h = depth of wetting front (mm)
k = hydraulic conductivity of soil (mm/hr)
t = rainfall duration (hr)
n = porosity
S_f = final degree of saturation (set as 100 %)
S_i = initial degree of saturation

From equation (1), the depth of the wetting front is calculated as 10.4 m. Hence, the shear strength parameters from the SUU test are used for the saturated zone. As stated above, the exact extent of the fill was unknown, so the distance to the edge is varied to investigate its effect on the stability.

The results of the analysis under stormy condition are shown in Table 3. The results show that the factor of safety decreases as the fill is closest to the crest of the wall. The wall would fail (FS = 0.99) and sliding along the soil-geogrid interface when the distance between the edge of the fill and the crest of the wall was 6 m. If the distance is reduced to 4 m, the factor of safety of sliding along the interface between the middle and the lower tiers is 0.94. However, the factor of safety along the probable failure surface from the survey is 0.97. The two failure surfaces are very close as can be seen in Figure 3. Therefore, the wall was very likely to fail under this condition.

Table 3. The stability analysis results under stormy condition.

Condition	Distance from dumped soil to the edge of the wall	
	6 m	4 m
External circular sliding	1.22	1.16
Internal circular sliding	1.37	1.37
Interface sliding	0.99	0.94
Sliding along probable failure surface	1.02	0.97

5 DISCUSSIONS AND CONCLUSIONS

According to the stability analysis of the reinforced earth wall, there are three factors that possibly triggered or resulted in the failure of the wall: (1) the backfill material had a high void ratio of 1.51 indicating the backfill had not been compacted appropriately during construction. Thus the backfill was very permeable; (2) the heavy storm dropped more than 590 mm of rainfall in 48 hours. The rainfall intensity coupled with the high permeability of the soil would give a saturated zone of 10.4 m deep beneath the ground surface, that not only increased the weight of the soil but also decreased the shear strength of the soil;
(3) the fill placed up to 9 m high on the top of the wall had an adverse effect on the stability of the wall.

From the analysis under stormy condition, the wall would fail when the fill was placed within a distance of 4 m from the edge. It shows that the unplanned fill on the top of the wall had a critical effect on the stability. The situation was obviously beyond the designer's considerations and became the cause of this failure.

In general, reinforced earth walls are safe structures when designed and constructed correctly. However, for the wall examined in this paper, it could have been stable under ordinary conditions, but the failure occurred because of adverse weather and loading conditions which were not properly considered. Additionally poor maintenance and controls of filling resulted in critical conditions.

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