New Horizons in Earth Reinforcement – Otani, Miyata & Mukunoki (eds)
© 2008 Taylor & Francis Group, London, ISBN 978-0-415-45775-0

Large-scale overflow failure tests on embankments using soil bags anchored with geosynthetic reinforcements

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ABSTRACT: Every year, a great number of dams for agricultural irrigation are seriously damaged or totally destroyed by flood overflow exceeding the drainage capacity of a spillway. To increase the stability of the downstream slope of such small earth fill dams against overflow, it is proposed to protect the downstream slope by using inclined soil bags anchored with geosynthetic reinforcement. Two tests on hydraulic overflow-induced collapse of the downstream slope were performed on full-scale models, 3.5 m high and 2.3 m wide with a downstream slope of 1V: 1.2H. The first test was conducted on an unreinforced soil slope subjected to a fixed level of overflow and the other was on the geosynthetic soil bags with extended tails (GSET) in which soil bags were placed on the downstream slope and subjected to stepwise increased levels of overflow. Results showed that the GSET model protected by using the soil bag system was stable enough against temporary flooding at overflow levels required in the field. In particular, the rate of progressive erosion of the downstream slope when subjected to high overflow levels was significantly reduced by reinforcing the slope.

1 INTRODUCTION

1.1 *Background*

Across Japan, there are approximately 210,000 reservoirs with earth dams constructed for agricultural irrigation that are lower than 15 m in height. It is reported that, among them, approximately 20,000 earth dams have deteriorated and need urgent but cost-effective repair. Every year, a great number of dams are seriously damaged or even totally destroyed by flood overflow exceeding the drainage capacity of the spillway and by earthquakes, as typically seen in Photo 1. This can cause a serious disaster in the downstream area. To substantially increase the stability of the slopes of such small earth dams against overflow and seismic loads, Mohri et al. (2005) proposed to protect the downstream slope of a small earth-fill dam by using large-scale soil bags with additional sheet for anchoring into the embankment as shown Fig. 1. Furthermore, Matsushima et al. (2005) modified this soil bag system to use inclined soil bags anchored with geosynthetic reinforcements as shown in Fig. 2. This geosynthetic soil bags with extended tails (GSET) spillway is designed to function in emergency cases of temporary flooding.

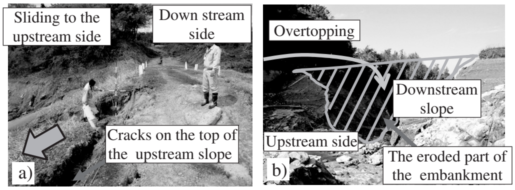


Photo 1. Failures of small earth dams: a) by the Niigata-chuetsu earthquake in 2004 in Kawaguchi town; and b) totally collapsed by heavy rainfall during Tokage typhoon No.200423 in Awaji Island.

The compressive strength of cohesionless soil that is not reinforced while located at the surface of a soil mass is essentially zero. On the other hand, soil located

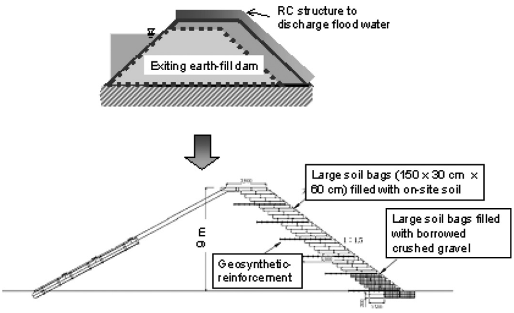


Figure 1. A new technology to rehabilitate existing old earth-fill dams to have a high flood discharge capacity and a high seismic stability (when applied to a 9 m-high typical earth-fill dam; Mohri et al., 2005).

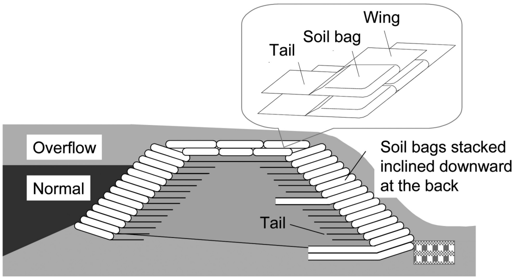


Figure 2. Basic components of geosynthetic soil bags with ex-tended tails (GSET) spillway for temporary flooding (Matsu-shima et al., 2005a&b).

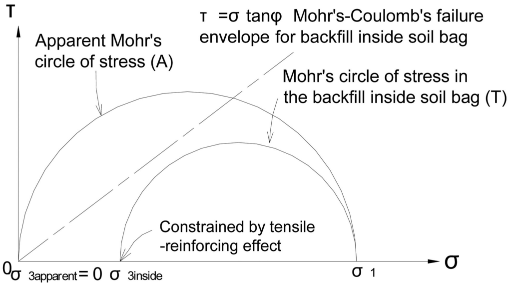


Figure 3. Stress states of soil bag located at shallow layer of slope represented by Mohr's circle of stress.

in a soil bag is subjected to additional confining pressure due to tensile reinforcing effects of the soil bag even when there exists no external confining pressure. Therefore, soil in a soil bag can exhibit compressive strength as represented by a Mohr's circle of internal stress denoted by *T* in Fig. 3 (Matsushima et al., 2006). The Mohr's circle of apparent stress denoted by *A* indicates the apparent stress condition of the soil bag. Due to the high compressive strength of the soil bag by this confining effect of the bag, not only slope stability but also washout resistance against overtopping can be increased, effectively protecting the slope face.

1.2 *Stream regimes of stepped spillways*

A GSET-spillway with stacked soil bags (Fig. 2) can be considered as one specific type of stepped spillway. Due to its high energy dissipating effect, such a stepped configuration has been widely used for concrete dams. A number of researchers have already studied the overflow characteristics of such dams (Hubert, 1994). The overflow characteristics can mainly be classified into the following three types (Fig. 4) depending on the step height, the discharge and the slope of the spillway:

1) nappe flow, characterized by the formations of a nappe and an air pocket at each step (Fig. 4a);
2) skimming flow, characterized by the formation of an eddy at each step (Fig. 4b); and
3) formation of free fall at the top of the slope (Fig. 4c).

However, no study on the influence of such regimes on the stability of GSET-spillway against overtopping has been performed. Figure 5 shows a conceptual illustration of damage mechanisms, as a function of overflow level, that may affect the stability of the GSET-spillway subjected to overtopping. The main damage mechanisms that are to be taken into account in the design of GSET-spillway against overtopping may include:

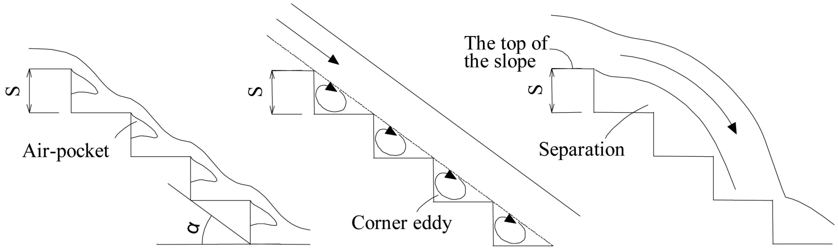
a) suction of backfill material by negative pressure; i.e., washout of soil particles from the slope through spaces between the soil bags;
b) attrition of geosynthetics by tractive force; and
c) breakage of geosynthetics by penetration force caused by free water fall.

To evaluate the stability of GSET-spillway against overtopping affected by these three damage mechanisms, a series of large-scale model hydraulic overflow failure tests was conducted. Based on observations of the tests, the damage patterns on the GSET-spillway were identified and categorized as a function of different stream regimes that depend on overflow levels.

2 OVERFLOW-INDUCED COLLAPSE TESTS

2.1 *Experiment models and materials*

Figure 6a shows a large-scale GSET-spillway model with a total of 24 soil bag steps placed on the downstream slope. The model is 3.5 m high and 2.3 m wide with a downstream slope of 1V: 1.2H. Figure 6b is a view of the completed downstream slope. Figure 6c shows a soil bag, integrated with a tail and a wing while approximately 0.2 m high, 0.6 m wide and 0.6–1.0 m long with a weight of 200 kg. The tail is



(a) Nappe flow (b) Skimming flow (c) Free fall flow

Figure 4. Stream regimes of stepped spillways (after Hubert, 1994).

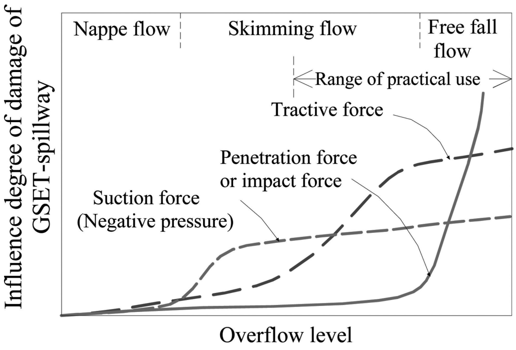


Figure 5. Damage mechanism of GSET-spillway as a function of overflow level.

designed to anchor a soil bag inside the slope while the wing connects horizontally adjacent soil bags. The bag is made of a woven polypropylene (PP) sheet. This PP geotextile is relatively cheap and widely used for agricultural-related purposes. Figure 7 shows its tensile load–strain properties. The infill material of the soil bags was a crushed concrete aggregate, having a slight inter-particle cementation due to residues of cement that had not been fully hydrated. The backfill materials in the shell and core zones of the slope, behind the soil bag, were Kasama sand and a mixture of Kasama sand and Kanto loam (proportion 1: 1 in weight). Figure 8 and Table 1 present the grading curves and physical properties of these soil bag infill materials as well as the slope backfill materials. The shell and core zones were compacted by manual tamping to degrees of compaction higher than 95% (D-value). The overflow depth (h_0 and h_1) on the upstream side and the center of the crest were measured by using water gauges. To evaluate the displacement distrbution of the downstream slope surface, a laser profiler, having a servo motor control system, was set in parallel with the downstream slope. For reference, a hydraulic test on a large-scale unreinforced embankment made using Kasama sand, 3.5 m high and 2.3 m wide having a downstream slope of 1V: 1.8H, was conducted at a discharge unit quantity flow $q = 0.050\,\mathrm{m^3/s/m}$.

2.2 *Test conditions for GSET-spillway model*

Figure 9 shows the time history of discharge unit quantity flow in the overflow-induced collapse test on the GSET-spillway model. In this figure, the ranges of flow level in which respective damage levels were observed during the test (explained in the next section) are also presented. The test consisted of the following two stages:

Stage 1: Without artificial physical damage to the soil bags; and
Stage 2: With artificial physical damage to the soil bags by cutting the surface and loosening the infill material to simulate damage by floodwood, chemical or ultraviolet degradation.

As the downstream slope was stable even when the discharge unit quantity flow became as high as $0.48\,\mathrm{m^3/s/m}$, it was decided to add the second stage. At the second stage, where the surface deformation by overtopping became noticeable, at every step increase of overflow level at selected stages denoted by a, b, c, d, e, f, g, h and i in Fig. 9, surface surveys of the downstream slope were conducted by laser profiler.

2.3 *Overflow level 1 (no or little damage)*

When the overflow depth, h_0, was less than 23.8 cm (i.e., S/d_c became 1.248–10.67, where S is step height and d_c is critical depth), a relatively steady flow in a staircase pattern was observed due to a high-energy dissipation caused by the soil bag steps. White water, which was actually rich-aerated flow, was formed while a small hydraulic jump impacted each soil bag step (Photo 2a and Fig. 10a). This stream regime was categorized into nappe or transition flow (Fig. 9). This observation is consistent with the lower limit of S/d_c at which a nappe flow is formed in stepped spillways: i.e., $S/d_c = 1.623$ at $\alpha = tan^{-1}\ (1/1.2)$, according to Yasuda et al. (1999).

Nappe flow, having nappe and air pockets, has no or little negative pressure at the corner of soil bags. Therefore, suction of the backfill material from the slope behind the soil bags might not occur. Accordingly, no

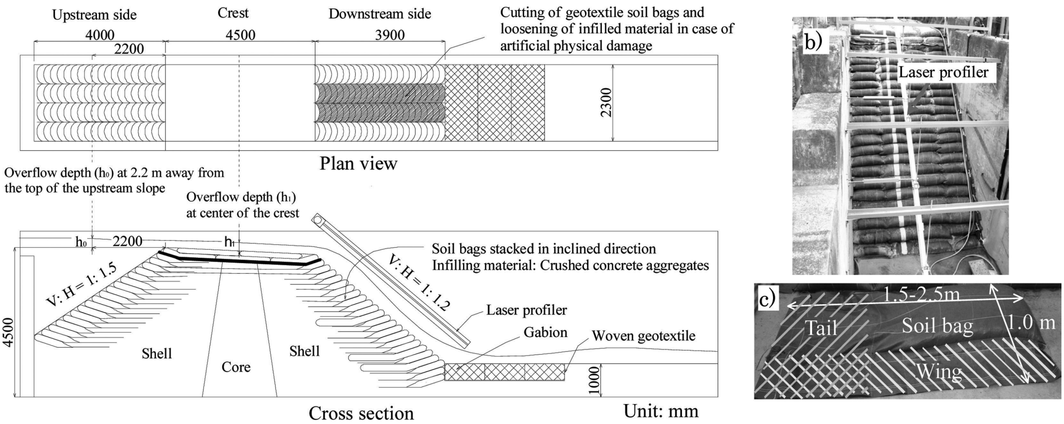


Figure 6. Large-scale overflow-induced collapse test: a) Plan view and cross section of full-scale small earth dam; b) Downstream slope of constructed GSET-spillway model; and c) Large-size soil bag integrated with wing and tail.

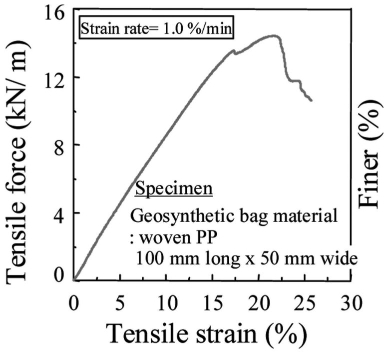


Figure 7. Tensile load-strain relationship for a tensile test performed on the PP woven type geosynthetic used for soil bag.

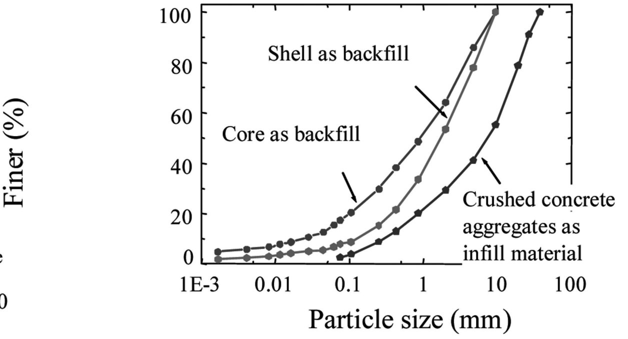


Figure 8. Distribution curves of infill material of soil bags and backfill materials of embankment.

damage on the embankment, such as deformation, suction of backfill material or breakage of soil bag, was observed.

2.4 *Overflow level 2 (minor or moderate damage)*

When the overflow depth, h_0, increased to between 23.8 cm and 32.3 cm (i.e., S/d_c became 0.649–1.248), a thick vein head flow, separated from the top of the downstream slope, started forming, which gave an impact on a limited number of soil bags. As seen from Photo 2b, a heavy flow started entraining air at some distance after having leaped over several soil bag steps below the starting point (Fig. 10b). This stream regime entraining air is basically classified into skimming flow, which is consistent with the upper limit of S/d_c for the formation of skimming flow in the case of a stepped spillway, $S/dc = 1.126$ at $\alpha = tan^{-1}(1/1.2)$, according to Yasuda et al. (1999). Skimming flow having a corner eddy creates negative pressure (i.e., suction) at the corner. Therefore, the damage observed on the slope at this stage included: i) suction of backfill materials from the slope behind the soil bags through the void area between the interfaces between the vertically and/or horizontally adjacent soil bags; ii) attrition of soil bag surfaces; and iii) perforations of soil bags by sharp edges of the crushed concrete aggregates, induced by impact and tractive force. Photo 3a shows the sucked backfill material that remained on the periphery of the void between the soil bags' interfaces after the test. Photo 3b shows the surface attrition and the punching holes at sharp edges of crushed concrete particles.

At the subsequent test stage, artificial physical damage was given to the soil bags repeatedly, four times, by cutting the surface of geotextile soil bag and loosening the infill material, as shown in Photo 4, during overflow testing for a total period of 150 min at a discharge rate of $q = 0.348\,m^3/s/m$ at respective stages between damaging operations. It was found that the

Table 1. Properties of infill material and backfill materials (JIS 1210).

Type	Material	U_c	G_s	F_c(%)	k (cm/s)	Compaction method Ab (Bb in the case of infill material)	
						ρ_{dmax} (g/cm^3)	w_{opt}(%)
Infill (soil bag)	Crushed concrete aggregates	39.2	2.605	2.6	2.67E-04	1.868	12.8
Shell	Kasana sand	20.3	2.650	7.8	1.21E-04	1.935	11.6
Core	Kasama sand and Kanto loam mix	68.3	2.617	17.4	1.27E-06	1.470	24.6

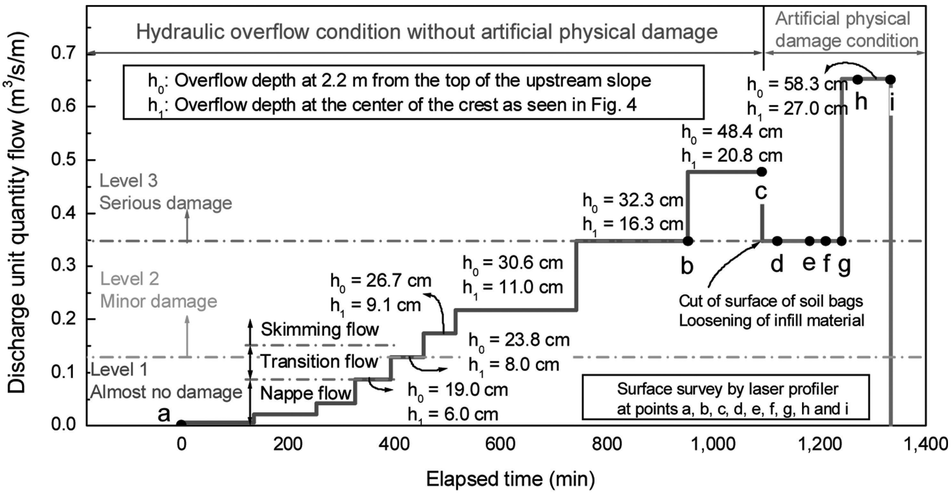


Figure 9. Time history of discharge unit quantity flow for the test per-formed on GSET-spillway model.

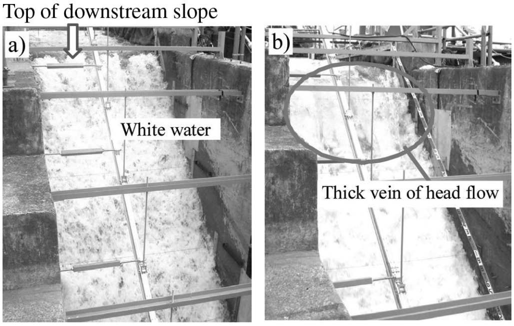
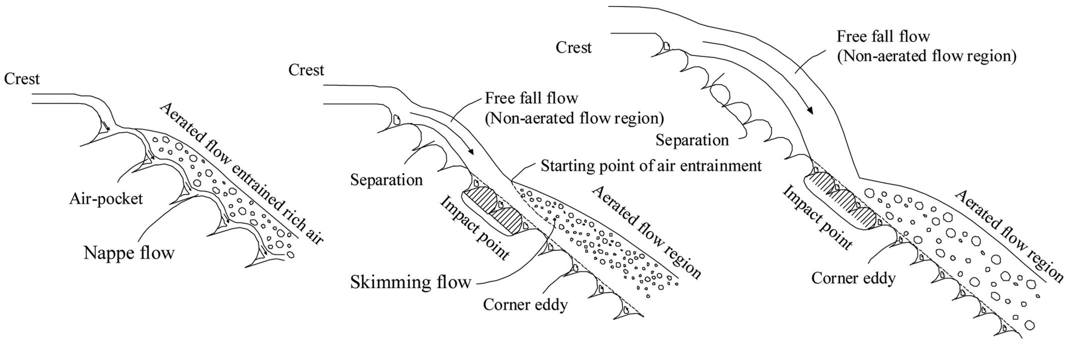


Photo 2. Stream regime on the downstream side: a) Overflow level 1 at q = 0.087 m^3/s/m; and b) Overflow level 2 at q = 0.348 m^3/s/m.

infill material (i.e., crushed concrete aggregate) had been slightly cemented by hydration of remaining cement. Figure 11a shows the profile of the deformed downstream surface at stages d, e, f and g plotted in Fig. 9. It seemed that impact and tractive forces by water flow were strong and infill material was washed out in the vicinity of the places of artificial loosening. Subsequently, as schematically shown in Fig. 12, the torn-off edge part of a geotextile sheet of soil bags became like a flange, covering and sealing the torn-off area while preventing further erosion of infill material from the inside of soil bags. Subsequently at overflow level 2, progressive erosion did not develop. Furthermore, it is likely that the combination of dense arrangement of geotextile sheet inside the slope and slight cementation of the infill material contributed significantly to the high stability and resistance of the slope surface, preventing serious damage.

2.5 *Overflow level 3 (serious damage)*

When the overflow depth, h_0, exceeded 32.3 cm, a very thick vein of head flow with a free fall for a long distance gave severe impact on a limited number of soil bags, resulting in progressive erosion toward the



(a) Level 1 ($h_0 = \sim 23.8$ cm) (b) Level 2 ($h_0 = 23.8\text{-}32.3$ cm) (c) Level 3 ($h_0 = 32.3\text{-}58.3$ cm)

Figure 10. Schematic flow regimes in overflow levels.

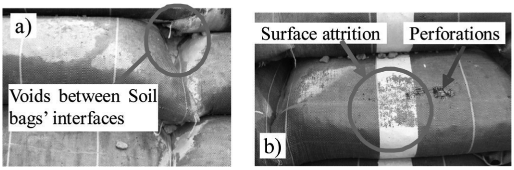


Photo 3. Minor or moderate damages: a) Evidence of sucked backfill material in cell zone behind stacked soil bags; and b) Attrition surface and perforations on soil bag surfaces.

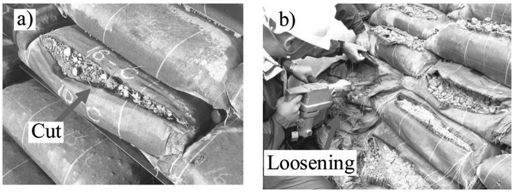


Photo 4. Artificial physical damage: a) Cut of the surface of geotextile soil bag; and b) Loosening of the infill material.

inside of the slope (Photo 5a and Fig. 10c). Fig. 11b presents the profile of the deformed downstream surface at stages b and c in Fig. 9 (before giving artificial physical damage to the soil bags). It was found that a limited number of soil bags deformed severely due to impacts by over-fall of a very thick vein.

Figure 11c shows the profile of the deformed downstream surface after periods of 30 min and 90 min since the start of flow at a rate of $q = 0.652$ m^3/s/m, at stages h and i plotted in Fig. 9, after having given artificial physical damage to the soil bags. It was found that, after 90 minutes, the erosion had reached the foundation of the slope along the axis of waterfall formation. Differently from overflow level 2, a free fall having sufficient force to penetrate the soil bags was formed, which resulted in severer progressive erosion. Photo 5b shows a trace of deep erosion that was formed by a waterfall. This erosion, which reached the foundation, is critical damage to the slope for the stability of the embankment. However, the rate of development of erosion with the reinforced slope was substantially slower than with the unreinforced slope, which collapsed at 5 min (as shown in Photo 6) at a much lower discharge of $q = 0.050$ m^3/s/m. It is to be noted that, even after this severer erosion in the slope, the settlement at the crest of the GSET-spillway was negligible due likely to reinforcement effects. This high performance of the GSET-spillway shows that this technology can alleviate serious damage to the downstream slope caused by overflowing of earth dams.

The test results showed that a long free fall creates strong penetration force, which results in severe damage on the downstream slope for a small earth dam. It is therefore important both to reduce the penetration force and to increase the resistance against such force of soil bags. To this end, it is suggested: 1) to arrange a short slope with a gentle gradient from the top corner to the impact point at the upper part of the downstream slope; and 2) to reinforce the surface of soil bags at the impact point to provide sufficient resistance against the penetration force.

3 CONCLUSIONS

The effectiveness of GSET (Geosynthetics soil bags with extended tails) spillway against temporary flooding was evaluated by overflow-induced collapse tests. The damage pattern and erosion development depend on the overflow levels:

Overflow level 1 (nappe flow regime): nearly no damage

Overflow level 2 (skimming flow regime): Some backfill material in the slope may be sucked out by suction created by corner eddies, while attrition and perforations on the soil bag surfaces may be caused by tractive and impact forces. A combination of dense arrangement of geotextile layers in the slope

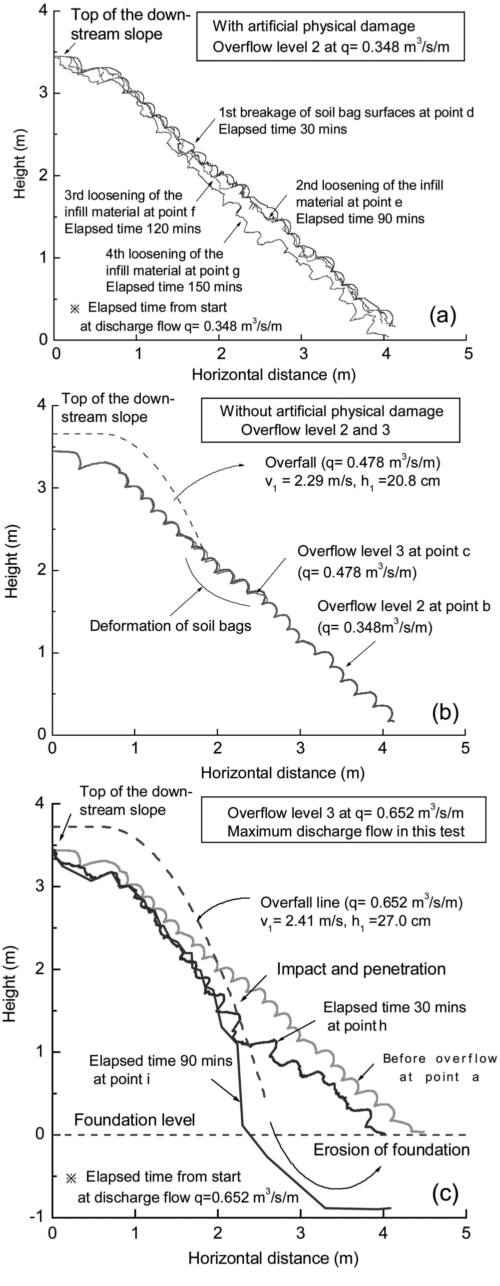


Figure 11. Distributions of displacement on downstream slope surface at: a) points d, e, f and g; b) points b and c; c) points and a, h and i.

and slight cementation of the infill material could prevent fast development of erosion. At overflow level 2, which is the design condition in practice, minor or moderate damage to the GSET-spillway can be expected.

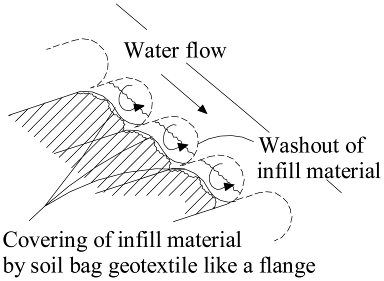


Figure 12. Schematic diagram of erosion on the down-stream slope with densely arranged geotextile layers in case of the ar-tificial physical damage at overflow level 2.

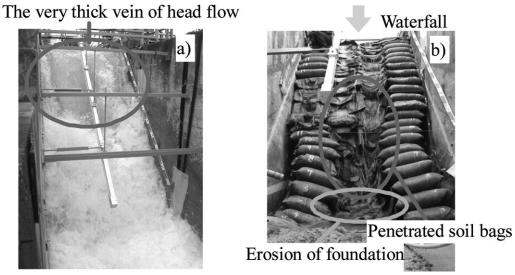


Photo 5. Overflow level 3(serious damage): a) Stream regime on the downstream side at overflow level 3 at $q = 0.652\,m^3/s/m$; and b) Erosion trace like the formation of a waterfall basin af-ter final overtopping.

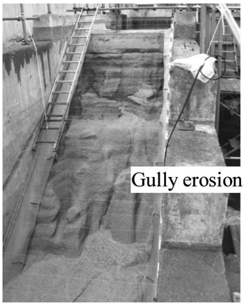


Photo 6. Erosion trace on un-reinforced soil slope after 5 min-utes at $q = 0.050\,m^3/s/m$.

Overflow level 3 (formation of a very thick vein of over-fall): A long free fall was formed, which had sufficient energy to penetrate soil bags and then cause fast development of erosion, seriously damaging the GSET-spillway. Yet, the development rate of erosion was significantly slower than with the unreinforced slope, while the settlement of the crest was negligible. Therefore, total collapse might not take place even during a very strong flood.

It is concluded that the GSET-spillway is effective technology to prevent the collapse of the downstream slope by overflowing of earth fill dams.

ACKNOWLEDGEMENTS

The authors are grateful to the National Institute for Land and Infrastructure Management (NILIM) and Public Works Research Institute (PWRI) for their cooperation, and also to Dr. Duttie and Dr. Warat for their help, discussions and advice.

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