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HYDRAULIC AND STRUCTURAL STABILITY OF OVERTOPPING PROTECTION OF EMBANKMENT DAMS USING GABION MATTRESSES

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ABSTRACT: Embankment overtopping protection is a practical measure to release large and infrequent floods with no or extremely diminished soil erosion failure due to flowing water over the embankment. The overtopping protection using gabion mattresses, an assembly of a wire mesh frame packed with rock particles, and placed over the embankment crest and downstream slope, is proposed, and its protective ability against soil erosion, structural stability during overtopping and construction performance are investigated. Hydraulics of the overtopping flow is calculated by a nonlinear seepage analysis of flow through the gabion combined with a numerical integration of spatially varied flow over the gabion, then hydraulic shear stress is quantitatively determined to evaluate the soil erosion potential, resulting that it can be prevented safely by placing the gabion underlain by a non-woven geotextile. The structural stability of the gabion mattresses against the sliding failure due to the overtopping flow is assessed by sloping water flume tests and stress-deformation analysis. Embankment slope failure which may be caused by loading of the gabion on the embankment surface is also assessed by circular slip surface calculation. Both assessments show no instability of the gabion sliding along the embankment slope and no degradation in the slope stability. Selecting the farm pond embankment constructed in the early 1900s, the trial test is conducted to construct the gabion mattresses about 200 m^2 in the placement area, and completed successfully in a very short period and cost-effectively.

Keywords: Overtopping protection, Soil embankment, Gabion mattresses, Hydraulic and structural stability, Trial construction

1. INTRODUCTION

Larger floods are causing overtopping failures of farm pond embankments due to insufficient storage and/ or release capacity provided for the existing reservoirs. Among traditional modification and innovative designs for resolving this problem, overtopping protection systems for embankment dams are promising to be most applicable because they reduce construction costs and still provide a reliable level of safety [1-3]. Overtopping protection systems for embankment dams have been constructed using various types of construction materials such as roller-compacted or conventional mass concrete, precast concrete blocks, gabions, vegetative cover, riprap, and geosynthetic materials. The Federal Emergency Management Agency [3] reviewed many documents of extensive test projects conducted on these types of protection materials and provides a summary of design limits for various overtopping protection systems for embankment dams. According to this summary of design limits, it can be seen that the gabion mattress system is most preferable for the overtopping protection of farm pond embankments, usually old, low in height, and constructed using erodible soils.

The gabion mattress system is an assembly of a wire mesh frame compartment packed with rock particles. As shown in Fig. 1, the wire mesh frames are placed on non-woven fabric both along the crest and downstream slope of the embankment and tightly linked with others, then coarse gravels and/ or cobbles are packed into the frame compartments. To properly design and construct the overtopping protection system, the hydraulic and mechanical effects of

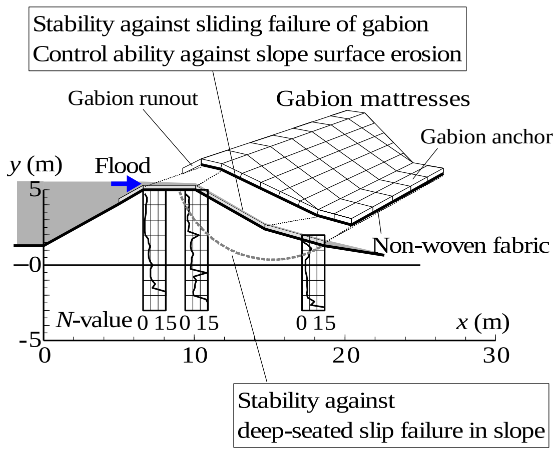


Fig. 1 Schematic layout of overtopping protection system using gabion mattresses

overtopping flow on the behavior and stability of the embankment as well as the gabion mattresses, should be well evaluated. Both the stability against sliding failure of the gabion mattresses along the embankment slope and the protective ability against soil erosion due to the overtopping flow are requirements to be evaluated and solved as indicated in Fig. 1. Loading due to placement of the gabion mattresses may cause a deep-seated slip failure in the downstream slope as shown in Fig. 1 and undesirable settlement in the crest of the embankment. This is another requirement to be solved for properly designing the gabion mattresses over the embankment.

To solve these problems and prove the superiority of the gabion mattress system against overtopping failure, in the paper, the protective ability against soil erosion, the structural stability against sliding failure, and the soil stability against circular slip failure of the embankment slope are investigated through the hydraulic analysis of the overtopping flow, the stress-deformation analysis of the gabion mattresses, and the circular slip surface calculation of the soil embankment. All the calculations are verified by a series of large water flume tests. Construction performance is also required to be evaluated to show that the gabion mattress system is a practical and cost-effective one. For this, selecting the farm pond embankment constructed in the early 1900s, the trial test is conducted to construct the gabion mattresses.

The design aspects of the gabion mattresses mentioned above are discussed in Chapter 3, in which it is found that soil erosion can be prevented safely by placing the gabion underlain by a no-woven geotextile and that no instability of the gabion sliding along the embankment surface and no degradation in the slope stability arise during overtopping. In Chapter 4 the trial construction test shows that the gabion mattress system 0.3 m thick and 200 m^2 in placement area is completed successfully in a very short period and cost-effectively. There may be no experience in constructing the overtopping protection system using the gabion mattresses for soil embankment dams in the country. Thus, as concluded in Chapter 5, the hydraulic and structural design method and the construction procedure discussed and developed in the study could provide a leading guideline to improve the safety level of soil embankment dams against overtopping failure.

2. RESEARCH SIGNIFICANCE

The risk of overtopping of soil embankment is increasing due to increasing floods. Traditional modification alternatives for resolving the overtopping problem, such as providing additional reservoir storage and increased spillway capacity, are often very costly. The overtopping protection systems for dams and embankments reduce costs and still provide a reliable level of safety. If many useful findings described in the paper were better known, owners of dams and/or embankments may be more inclined to improve the level of protection, leading to sustainable conservation of infrastructures for the water and soil environment.

3. PERFORMANCE EVALUATION OF GABION MATTRESSES

3.1 Hydraulics of Overtopping Flow

A part of flood water approaching the upstream end of the embankment crest enters into the gabion mattress to become a through-flow, and the rest, but much volume of the flood discharge, flows over the gabion mattress to become an over-flow as shown in Fig. 2(c). The through-flow is a seepage flow confined with a pressure head of the over-flow depth along the top surface of the gabion mattress, and governed by a nonlinear head loss equation such as Forchheimer's equation [4]:

$$i=av+bv^2 \tag{1}$$

where i is a hydraulic gradient and v is a discharge velocity of seepage flow. Coefficients a and b are coefficients dependent on rock particle size and shape, rockfill void, and water temperature or kinematic viscosity. Seepage analysis for Darcy flow, formulated by using the finite element method (FEM) [5, 6], can be easily modified to solve this nonlinear confined seepage by employing the method of successive approximations [7]. On the other hand, the over-flow is a spatially varied flow as the discharge increases or decreases along the flow direction due to local water mass exchange through the top surface of the gabion mattress [8, 9]. A method of numerical integration [10] can be well applied to solve the spatially varied flow computation. Generally, there are two control sections in this computation. One appears near a downstream end (brink) of the horizontal part of the gabion mattress on the embankment crest, and another at the beginning of the embankment slope from which supercritical over-flow is calculated along the top surface of the gabion mattress. In calculating hydraulic conditions of the overtopping flow consisting of the through- and over-flows, an iterative computation combining the FEM nonlinear seepage analysis with the spatially varied flow calculation (hereafter, referred to as the combined hydraulic analysis) should proceed until some reasonable convergence in calculated values of the local water mass movement through the top surface of the gabion mattress is achieved [9].

A farm pond embankment 30 degrees in downstream slope with a catchment area of 1 to 2 km^2 is selected. A possible maximum unit overtopping discharge of 0.35 m^3/s/m is determined based on the records of 101 fill-type dams and farm pond

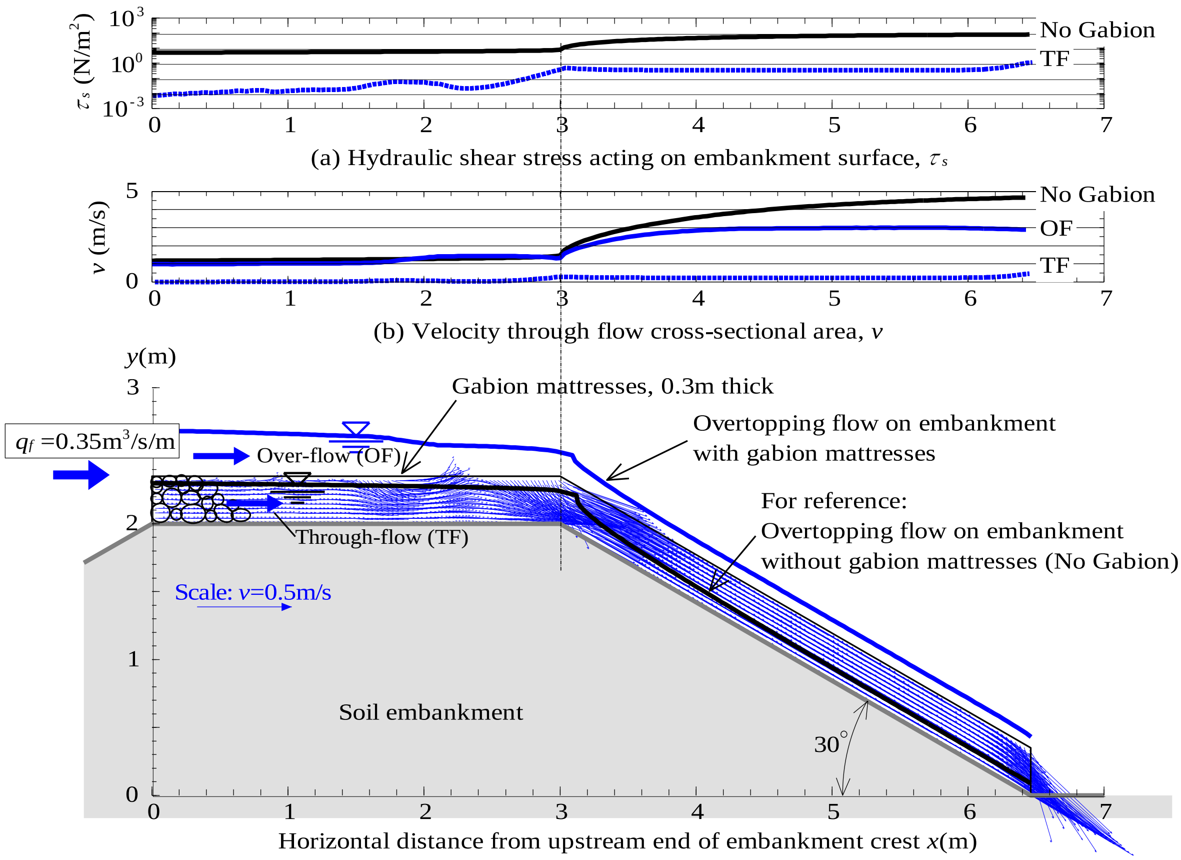


Fig. 2 Hydraulics of the through-flow (TF) and over-flow (OF) consisting of the overtopping flow on the embankment calculated by the combined hydraulic analysis, where the overtopping flow on the embankment naked (No Gabion) is given for reference

embankments recently constructed in the country. Fig. 2 shows the hydraulics of the overtopping flow on the soil embankment calculated by the combined hydraulic analysis: (c) water profile of the overtopping flow and velocity vectors within the gabion mattresses, (b) velocity v through flow cross-sectional area, and (a) hydraulic shear stress τ_s acting on the embankment surface, where τ_s is calculated by Eqs. (2a) and (2b):

$$\tau_s=\rho_w \cdot C_f \cdot v^2 \quad (2a)$$

$$C_f=n^2 g/R^{1/3} \quad (2b)$$

where ρ_w is the water density, C_f is the dimensionless friction factor, v is the average velocity of the overtopping flow just above the embankment surface, n is Manning's roughness and estimated to be 0.02 on the embankment soil surface, g is the gravitational acceleration and R is the hydraulic radius. The gabion mattress is 0.3 m in thickness and packed with round rock particles 100 to 200 mm in diameter. The coefficients a and b in Eq. (1) are 0.024 s/m and 6.13 s^2/m^2, respectively, which are determined by optimizing the seepage flow through the rockfill gabion measured in the laboratory water flume tests. The roughness coefficient of the top surface of the gabion mattresses, which is required in calculating the over-flow hydraulics, is also determined by this laboratory test to be 0.049.

It is found in Fig. 2(c) that the flood water flows in waves along the embankment crest, then, after passing the brink, moves downward parallel to the embankment slope with increasing velocity of flow. The flow in waves along the embankment crest is thought to be caused by the exchange of water mass between the through-flow and the over-flow through the top surface of the gabion mattresses. v in the over-flow is much larger than that in the through-flow as shown in Fig. 2(b). This difference in v mobilizes a tractive force along the top surface of the gabion mattresses, and it may slide the gabion mattresses along the embankment slope. This stability against the sliding is discussed in the next chapter. The combined hydraulic analysis calculates the Froude number F_r of the over-flow along the slope to be 1 near the brink to about 3 near the downstream end. This large value of F_r requires an energy dissipator such as a gabion apron constructed along the downstream ground surface beginning at the end of the gabion mattress on the embankment slope. The horizontal length of the gabion apron can be determined by a conjugate relationship of the initial depth and the F_r at the end of the gabion slope [10].

3.2 Protective Safety against Soil Erosion

The hydraulic conditions of the overtopping flow on the embankment without any surface protection are calculated by using a standard step method for a gradually varied flow on a large slope [10], and shown with the notation "No Gabion" in Fig. 2. It's found that the v of the through-flow (denoted by "TF") greatly decreases to about one-fifteenth of the "No Gabion" velocity, and thus the τ_s of the "TF" to one-hundredth to -two hundredth of that of the "No Gabion" as shown in Fig. 2(b) and (a), respectively. These decreases in v and τ_s are brought by the placement of the gabion mattresses and are beneficial to the soil erosion protection of the soil embankment.

According to the excess shear stress model [11, 12] commonly used in the streambank erosion prediction, once the τ_s exerted by the water flow exceeds the critical shear stress of soil, τ_c, soil erosion begins. The critical shear stress of soil usually varies widely and should be determined by a site-specific measurement. However, in some literature published elsewhere [11-13], it can be found the τ_c may range from about 1 to 10 N/m^2. In Fig. 2(a), the τ_s exerted by the through-flow along the embankment crest is sufficiently smaller than the τ_c and there may be no soil erosion. However, along the embankment slope, the τ_s is almost equal to the τ_c estimated above and some or not-small soil erosion may begin. To protect against this erosion of the embankment soil, it was determined to place a non-woven geotextile sheet between the gabion mattresses and the embankment soil surface because it can largely reduce v as well as τ_s exerting on the embankment surface soil. As the thickness and the permeability of the non-woven geotextile sheet commercially available in the country are 0.01 m and 1×10^{-2} to 10^{-3} m/s, respectively, and as the hydraulic gradient of seepage through the non-woven geotextile approximates a tangent of embankment slope, then τ_s is estimated by Eq. (2) to be 4.5×10^{-4} to 10^{-6} N/m^2 along the embankment slope 30 degrees. These values of τ_s are sufficiently less than τ_c found above, and there may be no risk of soil erosion due to the overtopping flow.

3.3 Stability against Sliding Failure of Gabion Mattresses

During the flood overtopping, buoyancy, seepage force caused by the through-flow, and tractive force along the top surface of gabion mattresses caused by the over-flow attack the gabion mattresses and may slide it downward along the embankment slope. The stability against the sliding failure of the gabion mattresses is evaluated by using a FEM elastic stress-deformation analysis [14] in Fig. 3.

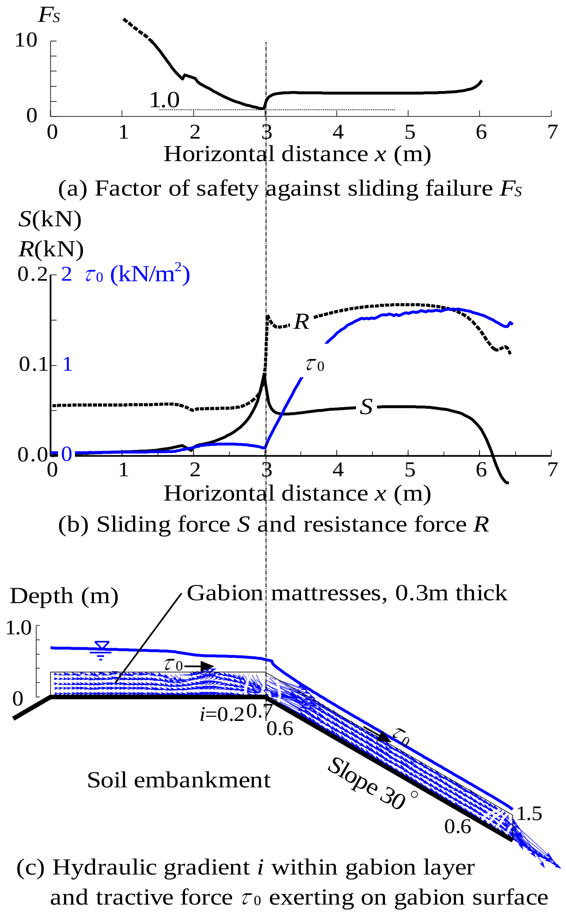


Fig. 3 Stability against sliding failure of the gabion mattresses under the overtopping flow, calculated by the FEM elastic stress-deformation analysis

The hydraulic gradient within the gabion mattresses is calculated by the combined hydraulic analysis described in 3.1 and given in Fig. 3(c). The tractive force along the top surface of gabion mattresses, τ_0, is calculated by Eq. (2) in which the difference in velocity between the through-flow and the over-flow is employed instead of v_s, and given in Fig. 3(b). In the FEM mesh model shown in Fig. 3(c), both the upstream and downstream end faces are boundaries constrained by no horizontal deformation. The bottom face of the gabion mattresses is constrained horizontally and vertically by no deformation so that the analysis can calculate the element shear stresses mobilizing the sliding force S given in Fig. 3(b).

Resistance force R in Fig. 3(b) is calculated by multiplying the force normal to the embankment surface mobilized by the element vertical stresses and, along the slope section, the vertical component of the element horizontal stresses as well as the element shear stresses, by the shear friction μ between the non-woven geotextile overlaid by the gabion mattresses and the soil surface. As there may be scarcely any data published in the country, a series of the shear tests in the field was conducted to determine μ as below: The gabion mattress 0.3 m thick and 1 m square of cross section was placed on the non-woven geotextile overlaying the soil surface, then dragged parallel to the soil surface by the backhoe machine until the gabion mattress began to slide. Sandy fine-grained soil (FS) and silt soil (MH-S) typically employed in the farm pond embankments in the country are compacted in the soil, with the result that the unconfined compression strength of the soil was 10 to 100 kN/m^2. Fig. 4 shows the relationships between the normal stress and the shear strength measured in the field shear tests. The values of μ, the slope of the linear relationship, show the normal distribution with a 95% lower confidence limit of 0.6.

It can be seen in Fig. 3(b) that the R slightly decreases at the section in front of the brink due to the through-flow in waves as shown in Figs. 2(c) and 3(c), and then increases in the slope section. The vertically downward component of the tractive forces τ_0 in the slope section may contribute to this increment in R. The factor of safety F_s against the sliding failure of the gabion mattresses, determined by dividing R by S, is given in Fig. 3(a). Although the F_s decreases along the embankment crest to the lowest value of 1.02 near the brink, the stability against the sliding failure of the gabion mattresses is evaluated to be satisfied overall. It should be noted that this is right provided that the constraint condition of no horizontal deformation given to the upstream and downstream end faces of the FEM mesh model in Fig. 3(c) is well mobilized by placing the gabion runout on the upstream slope of the embankment and the gabion anchor on the downstream end of embankment slope (see Fig. 1).

The τ_0 exerted by the over-flow may potentially cause the rock particles packed in the wire mesh compartment to move or roll downstream, failing the gabion mattresses. However, no such risk should be included in the gabion mattresses because they are connected tightly by the wire mesh. To examine the stability against the rock particle movement, a series of overtopping tests was conducted in the sloping laboratory water flume as shown in Fig. 5. The wire mesh frame 0.3 m thick was placed in a 0.5m-wide and 4m-long steel water flume, rounded rock particles 100 to 200 mm in diameter were packed into the wire mesh frame, and the end of the water flume was lifted to make an inclination of 30 degrees (Fig. 5(a)). Then unit overtopping discharge of 0.35 m^3/s/m was supplied at the upper end of the water flume for three hours (Fig. 5(b)). Configuration of rock particles on the top surface of the gabion frame was photographed before the overtopping test, and compared with one after the completion of the 3-hour overtopping test. Any movement of rock particles was not found. This confirms that the wire mesh frame employed can restrict strictly any movement of rock particles under the rapid and strong overtopping flow.

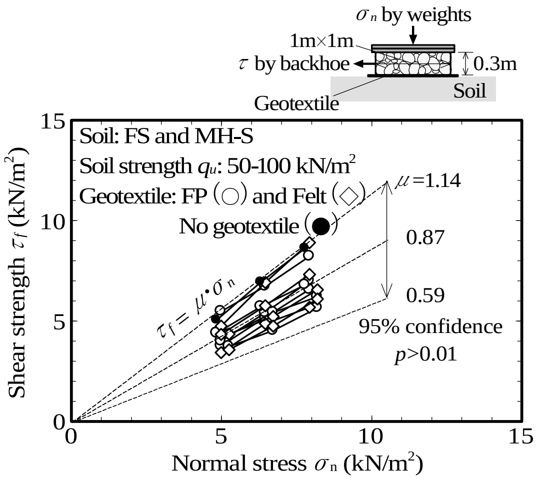


Fig. 4 Determination of the shear friction μ between the non-woven geotextile overlaid by the gabion mattresses and the soil surface

(a) Top surface of gabion packed with rock particles (b) Overtopping flow in 0.5m-wide sloping water flume

Fig. 5 Overtopping test in laboratory water flume 30 degrees in slope

3.4 Stability Against Deep-seated Slip Failure in Embankment Slope

It may be thought that the effect of surface loads exerted by placing the gabion mattresses on the embankment slope stability becomes larger in the embankment lower in height such as the farm pond embankment. Selecting the embankment 3.75 m high as shown in Fig. 1, the circular slip surface analysis (the simplified Bishop method of slices) combined with the seismic coefficient method was conducted to calculate the factor of safety F_s along critical slip surface in the embankment slope under HWL seepage condition as shown in Fig. 6. The embankment has three layers of clayey soil, whose coefficients of shear strength, c and φ, are estimated from the N-values given in Fig. 1 and tabulated in Fig. 6. The calculations in the case of no seismicity and the case of seismic coefficient 0.15 are given, and, in each

Soil	N-value	c (kN/m^2)	ϕ (deg.)	E (kN/m^2)	Poisson's ratio ν
1	3	25	0	2,100	0.3
2	5	41	0	3,500	0.3
3	7	0	32	4,900	0.3

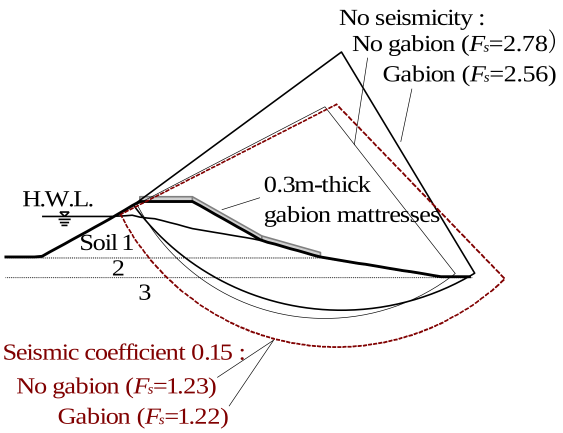


Fig. 6 Factors of safety along critical circular slip surface in embankment slope

case, the F_s and the critical circular slip surface for the embankment protected by the gabion mattresses are compared with those for the embankment without the protection (denoted by "Gabion" and "No gabion," respectively). It is found in Fig. 6 that, both in the case of no seismicity and the case of seismicity, decreases in the F_s due to the placement of the gabion mattresses are small and the positions of the critical circular slip surface do not show any large changes. All mentioned above demonstrate that the placement of the gabion mattresses does not degrade the slope stability of the embankment.

Fig. 7 shows the vertical deformation (settlement) around the embankment crest calculated by the FEM elastic stress-deformation analysis to discuss the effect of the surface loads of the gabion mattresses on the deformation behavior of the embankment. Deformation moduli are estimated from the N-values measured in Fig. 1, and tabulated in Fig. 7. Poisson's ratio is assumed to be 0.3. Maximum settlement found near the crest brink is about 0.03 m and 0.85 % in a ratio to the embankment height and is evaluated to be sufficiently allowable in construction.

4. TRIAL CONSTRUCTION OF GABION MATTRESSES

4.1 Overtopping Discharge and Design Specification of Gabion Mattresses

Selecting the farm pond embankment located in Nagaoka, Niigata, Japan, a trial construction of the gabion mattresses was carried out to know an efficient and safe way of construction, the security required for safe construction, and the days and cost required for construction. As given in Table 1, the farm pond embankment selected is an earth fill 3.75

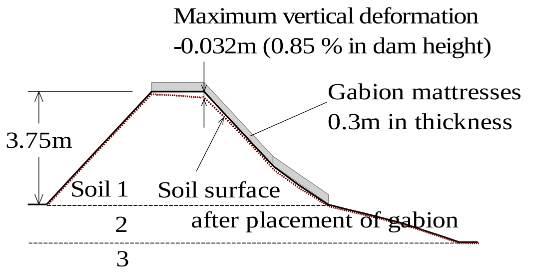


Fig. 7 Vertical deformation caused by the placement of gabion mattresses 0.3 m thick (Note that the vertical scale is two times the horizontal scale.)

m high constructed in the early 1900s, whose section is shown in Fig. 1 together with the N-values measured by the screw weight sounding test.

In Table 2, a 200-year flood is estimated to be 2.40 m^3/s by taking the catchment area and the precipitation data recorded from 1976 to 2022 into account. The design flood is determined to be 1.2 times the 200-year flood. As the release capacity of the spillway is small, it is assumed that all of the design flood discharge overtops the farm pond embankment. Then the unit overtopping discharge is calculated to be 0.094 m^3/s/m by dividing the design flood by the crest length of the embankment.

To determine the most suitable specification of rock particle size and thickness of the gabion mattress, the overtopping flow hydraulics, the stability against the sliding failure of the gabion mattresses, and the stability against the deep-seated circular slip surface in the embankment slope described in the former sections 3.1, 3.3, and 3.4, respectively, are calculated iteratively until overall stability and safety of the overtopping protection system are satisfied. 0.3 m in thickness of the gabion mattress and the rounded rock particles 100-200 mm

Table 1 Characteristic data of the farm pond embankment selected for the trial construction

Construction year	The early 1900s
Type	Earth fill embankment
Crest width	3.5 m
Height	3.75 m
Crest length	30.8 m
Downstream slope	29 degrees
Catchment area	0.1390 km^2
Reservoir area	0.0014 km^2
Spillway	Height 0.8m × width 0.7 m Release capacity 0.70 m^3/s

Table 2 Design flood and unit overtopping discharge

Flood concentration time	44.2 min
Design rainfall	62.4 mm/h
200-year flood	2.409 m^3/s
Design flood	2.891 m^3/s
Unit overtopping discharge	0.094 m^3/s/m

Table 3 Specification of the gabion mattress system

Dimension	Thickness 0.3 m Unit weight 16.624 kN/m^3
Rock particles	Rounded cobble, D100-200 mm
Depth of overtopping flow	0.3 m (through-flow) + 0.03 m (over-flow)

in diameter are determined to be employed in constructing the overtopping protection system as given in Table 3.

4.2 Trial Construction of Gabion Mattresses

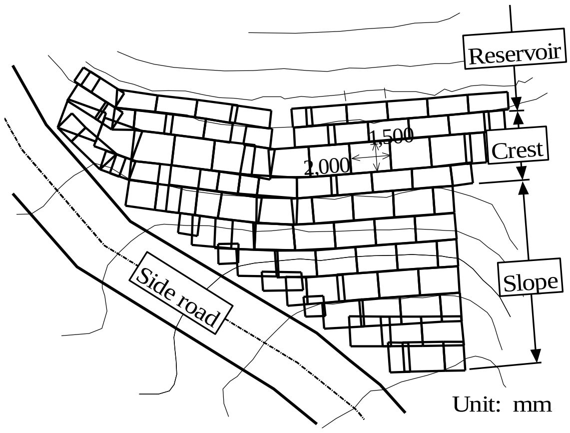
Construction of the gabion mattresses, about 200 m^2 in the area of placement, began in October just after the end of paddy irrigation, and was completed in a very short period of about one month at a reasonable cost.

Fig. 8(a) shows the front view of the downstream slope partially placed by the gabion mattresses and covered with the non-woven geotextile sheet. After stripping the topsoil of the embankment slope, compacting the silt soil onto the slope surface, and leveling the surface soil by using a backhoe, the non-woven fabric was placed on the surface of the embankment followed by the wire mesh frames. Rock particles were dumped into the wire mesh frame compartment and packed moderately by hand. Fig. 8(b) shows a plane layout of the placement of the wire mesh frames designed for the trial construction. Some difficulties in laying the wire mesh frames on the slope surface as pointed out in [15] can be seen as the slope changes locally along the downstream direction as well as along the traverse direction of the embankment, and because of a fan shape of the downstream slope area in the plane.

4.3 Strength Required for Topsoil in Downstream Slope

As mentioned in the preceding section, the topsoil of the downstream slope should be stripped and replaced by a new clayey soil or silt soil so that it works as a firm foundation soil overlaid by the gabion mattresses. Before the beginning of the trial construction, the strength of the surface soil in the downstream slope was measured by the portable cone penetration test. Fig. 9 shows the unconfined compression strength q_u along the soil depth measured by the test. As no or very small strength is found near the surface soil about 0.05 to 0.1 m deep, the topsoil of the downstream slope was stripped, replaced with the silt soil, and compacted by pressing a bucket of the backhoe onto the soil surface until its strength achieved at least 100 kN/m^2 which distributes 0.1 m in the depth of soil and more. As shown in Fig. 9, q_u in the surface soil replaced and compacted almost sufficiently achieves the requirement.

(a) Front view of the downstream slope partially placed by the gabion mattresses and covered with the non-woven geotextile sheet



(b) Layout of placement of the gabion mattresses in plane

Fig. 8 Trial construction of the gabion mattresses on the low farm pond embankment

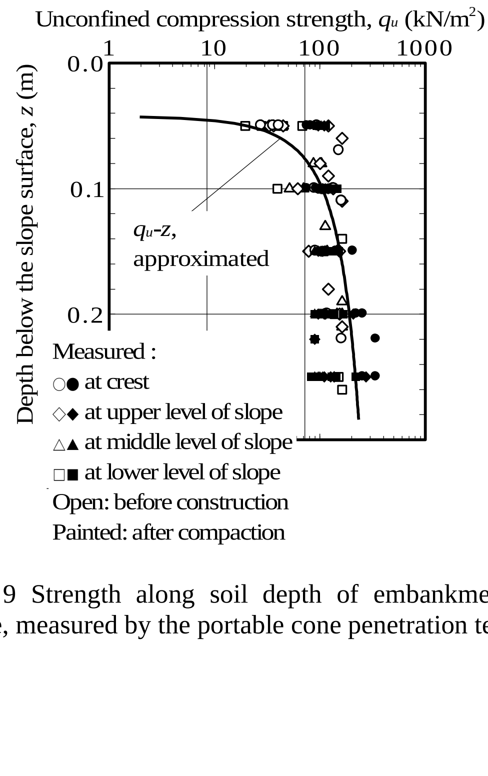


Fig. 9 Strength along soil depth of embankment slope, measured by the portable cone penetration test

5. CONCLUSIONS

The gabion mattress system, an assembly of a wire mesh frame packed with rock particles, and placed over the embankment crest and downstream slope, was proposed for the overtopping protection of embankment dams. Its protective ability against soil erosion, structural stability against the overtopping flow, and embankment slope stability due to loading of the gabion were evaluated well through a series of laboratory water flume tests, and by using the hydraulic analysis of the overtopping flow, the stress-deformation analysis of the gabion structure, and the circular slip surface calculation of the embankment slope. All the results showed that the embankment overtopping protection could be an effective and safe measure to release large and infrequent floods with no or extremely diminished soil erosion failure due to flowing water over the embankment. Following the laboratory or in-room discussions above, the trial construction test was conducted on the low and old farm pond embankment to assess the practical applicability and cost-efficiency of the gabion mattress system. The 0.3m-thick gabion mattress packed with round rock particles 100 to 200 mm in diameter was constructed successfully.

The gabion mattress system discussed has 30 to 40-year durability in the natural environment as it's designated to employ the wire mesh coated with zinc. If many useful findings described in the paper were better known, owners of embankment dams may be more inclined to improve the level of protection and can enjoy a long lifespan of the embankment dam, leading to sustainable conservation of infrastructures for the water and soil environment. It's also known that any potential environmental impact of constructing the gabion mattresses over the soil embankment on the local wildlife and vegetation should be elaborately assessed. This is a forthcoming task in the project discussed in the paper.

6. ACKNOWLEDGMENTS

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