Evaluation of the Stability of Various Types of Coastal Dyke Against Over-Flowing Tsunami Current

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ABSTRACT

During the 2011 Great East Japan Earthquake, fill-type coastal dykes fully collapsed by over-flowing tsunami current and totally lost their function as a tsunami barrier at many places. The collapse took place by the following two major mechanisms. That is, the subsoil in front of the toe of the downstream slope was scoured by over-flowing tsunami current, by which the concrete facing panels on the downstream slope was destabilized then flowed away (Mechanism A). The concrete panels on the crest and the top part of the downstream slope, where the velocity of the over-flowing tsunami current was increasing, were lifted up and flowed away (Mechanism B). Then, the backfill, which was un-reinforced sandy soil, therefore, having low resistance against erosion, was exposed to the overflowing tsunami current and quickly eroded. The conventional fill-type coastal dykes have not been designed to survive such deep over-flowing tsunami current as experienced during this earthquake. To make the coastal dykes stable enough against deep over-flowing tsunami current, as well as high seismic load, it is proposed to: a) make the subsoil in front of the toe of the downstream slope strong enough against scouring; and b) reinforce the backfill with a number of planar geosynthetic reinforcement layers; and c) cover the slopes and crest with concrete panels that are connected to each other and also to the reinforcement layers. In the present study, Mechanism B was simulated by small-scale model tests in the laboratory. The test results showed that these measured b) and c) are very effective to prevent the failure by Mechanism B.

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INTRODUCTION

The serious damage by the 2011 Great East Japan Earthquake includes: 1) damage to a great number of old soil structures due to strong shaking in a very wide area; 2) soil liquefaction, in particular in young reclaimed lands; and 3) damage by great tsunami. The tsunami run-up height reached 40 m in some coastal areas (Tohoku tsunami survey 2011). A great number of wooden residential houses and reinforced concrete buildings were washed away. More than 340 bridges lost their girders or approach fills or both (Kosa 2012). The number of dead and missing is 18,600, most by tsunami. The tragedy by tsunami was due to delayed evacuation in some areas and/or full-collapse of coastal tsunami barrier dykes, most of which were fill-type, by deep over-flow of tsunami current. Yet, at several places, the tsunami barrier dykes could protect towns. Typically, in Fudai in Iwate Prefecture, a huge coastal dyke (15.5 m-high and 155 m-long) successfully protected the residential area with only one dead/missing (Yomiuri Shinbun 2011).

It is obvious that the most effective means to reduce the number of dead and missing is swift evacuation of the residents in tsunami-affected areas. At the same time, coastal dykes that can survive great tsunamis are necessary to protect the hinterland by fully stopping the tsunami current lower than the dykes or by decreasing the velocity and amount of over-flowing tsunami current so that the damage by tsunami is greatly reduced. To this end, tsunami barrier dykes, in particular fill-type, should survive deep over-flowing tsunami current.

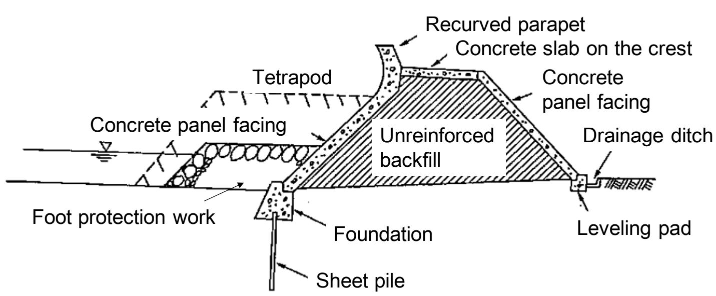


Figure 1. Typical conventional fill-type coastal dyke.

Figure 2. A typical coast fill-type dyke (Figure 1) that fully collapsed by tsunami, Aketo, Tanohara, Iwate Prefecture (by the courtesy of Prof. Koseki, J., Univ. of Tokyo)

The typical conventional fill-type coastal dyke has a gentle slope (typically 1.0:2.0 in V:H) covered by concrete facing panels on the up- and down-stream slopes and crest (Figure 1). During this earthquake, this fill-type of coastal dyke collapsed having fully disappeared at many places (Figure 2). It seems that many of them collapsed by the first deep over-flowing tsunami current and largely or totally lost its function against several subsequent tsunamis. The following two collapse mechanisms have been identified:

1) *Mechanism A*: the ground in front of the toe of the downstream slope was deeply scoured by the over-flowing tsunami current. Then, the concrete facing panels on the downstream slope were destabilized from the bottom and washed away, which resulted in very fast erosion of the unreinforced backfill from the downstream slope and crest, and ultimately the full-section was lost (Figure 3a).
2) *Mechanism B*: the concrete panels on the crest and the top of the downstream slope were lifted up and washed away by the over-flowing tsunami current of which the velocity increased when rushing down the downstream slope, leading to the progressive destabilization of the other facing panels on the downstream slope. Then, the backfill was quickly eroded from the down steam slope and crest (Figure 3b).

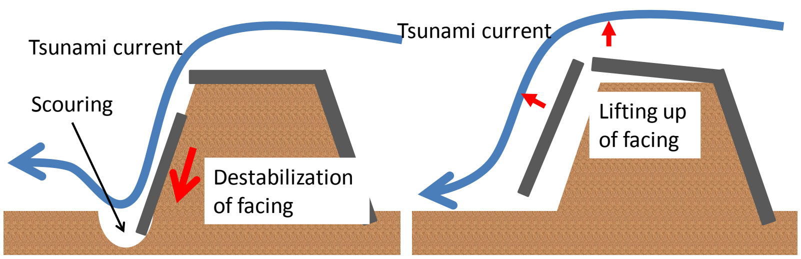


Figure 3. Collapse mechanisms of conventional embankment-type coastal dyke triggered by: a) scouring in the downstream ground; and b) lift up of facing panels

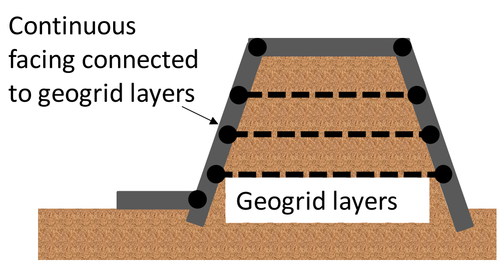


Figure 4 Proposed geosynthetic-reinforced soil coastal dyke

Based on these lessons, the authors propose a new type coastal fill-type dyke, named Geosynthetic-Reinforced Soil (GRS) coastal dyke (Figure 4). This composes continuous concrete facing connected to the geogrid layers reinforcing the backfill. The advantageous features of this type are as follows:

1) A very high seismic stability of GRS retaining walls (RWs) having full-height rigid facing has been validated by their very high performance during the 1995 Kobe Earthquake and the 2011 Great East Japan Earthquake (e.g., Tatsuoka et al. 1998, 2012). With slopes more gentle than the near vertical wall face of

these GRS RWs, this type of GRS coastal dyke should have a very high seismic stability, definitely much higher than the conventional type shown in Fig. 1.

2) With the proposed GRS coastal dyke, the ground in front of the toe of the downstream slope should be protected against scouring with a concrete slab or another relevant means. Even if some amount of scouring takes place, the facing on the downstream slope can maintain its stability much better than the conventional type. Besides, the facing has a high resistance against lift up by over-flowing tsunami current. Even if the facing is lost, the resistance of the reinforced backfill against erosion is higher than the unreinforced backfill of conventional type coastal dykes.

A series of model tests were performed to evaluate the stability of the proposed GRS coastal dyke (Figure 4) against the collapse by Mechanism B in comparison with the conventional type (Figure 1).

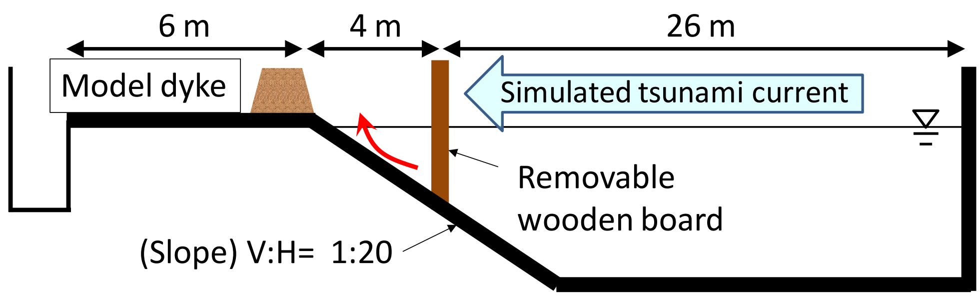


Figure 5. Model test configuration (the width of the cannel is 100 cm).

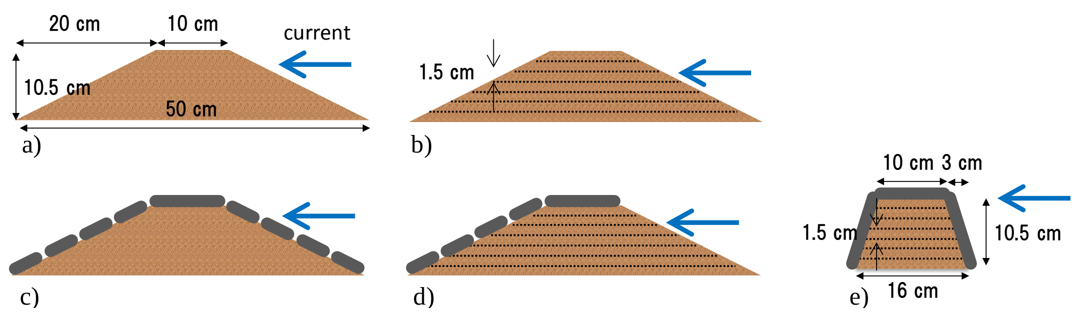


Figure 6. Coastal dyke models: a) model 1; b) model 2; c) model 3; d) model 4; and e) model 5 (the arrow denotes the simulated tsunami current).

EXPERIMENT

Figure 5 shows the model test configuration (Yamaguchi et al. 2012). To produce as much as long-period waves, a long open channel was used. The tsunami current was produced by quickly removing a wooden board behind which a mass of water had been stored. The initial difference in the water height Δh between the front and the back of the board was 15 cm and 20 cm. The simulated tsunami was continued for a period of 20 seconds. Five models shown in Figure 6 and explained below were tested. The considered model scale in length is 1:100: i.e., the simulated prototype dyke is 10.5 m-high and the initial height of the simulated tsunami is 15 m and 20 m. The model dykes were produced by compacting layer by layer moist Toyoura sand at the optimum water content (15.2 %) to a degree of compaction D_c

= 90% by the standard Proctor.

Model 1 (Figures 6a and 7): This is a model of the conventional fill-type dyke without concrete facing and reinforcement layers. This model completed collapsed by the first tsunami of Δh= 15 cm.

Model 2 (Figure 6b): The backfill of the same fill-type as model 1 was reinforced with six layers of a polypropylene geogrid with an aperture of 1.3 mm. Although this model survived the tsunami better than model 1 due to a higher resistance against erosion, it collapsed eventually by the first tsunami of Δh= 15 cm.

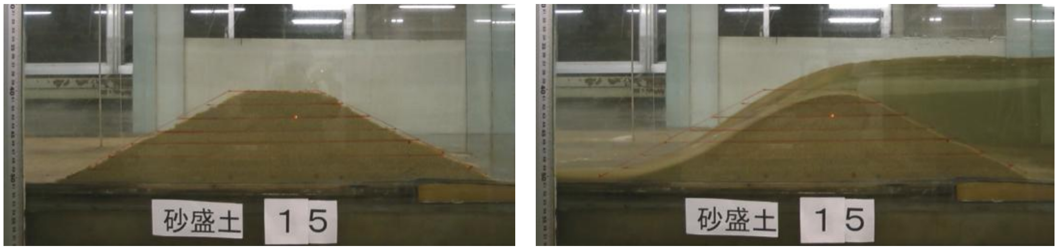
Model 3 (Figures 6c and 8): This is a model of the conventional fill-type dyke with concrete panel facing (Figure 1). The unreinforced backfill is the same as model 1. The model facing comprises unreinforced concrete panels that are 0.5 cm-thick and 5 cm times 25 cm on the up- and downstream slopes and 0.5 cm-thick and 10 cm times 25 cm on the crest. The panels are not connected to each other. This model survived the first tsunami of Δh= 15 cm but eventually fully collapsed by the second one of Δh= 20 cm.

Model 4 (Figures 6d and 9): The backfill was reinforced as model 2 and the downstream slope and crest were covered with such concrete panels as used with model 3. The concrete panels were not connected to each other, but connected with strong instant glue to the geogrid layers reinforcing the backfill. The connections did not rupture until the full collapse of the model. The upstream slope was not covered with concrete panels. The first reason for the above is that vegetation is preferred from an environmental point of view in some cases. The second reason is that the unprotected upstream slope of the reinforced backfill of model 2 was eroded only slightly. Although this model was more stable than model 3 and survived the first tsunami of Δh= 15 cm, it eventually collapsed by the second one of Δh= 20 cm.

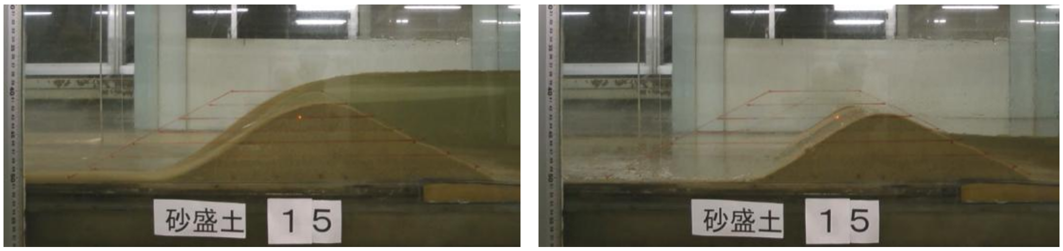
Model 5 (Figures 6e and 10): This is a model of GRS coastal dyke that we are proposing (Figure 4). The slope of the faces on both sides of this model are much steeper than the other models (i.e., about 1.0:0.3 in V:H). The faces are covered with concrete panels as used with models 3 and 4 that are connected to each other with a plastic tape (i.e., red strips seen in Figure 10a) and to the geogrid layers with strong instant glue. This model was designed not to collapse by the two mechanisms shown in Figure 3, while reducing the volume of the backfill and increasing the stability against seismic loads. The model survived the first and second tsunamis of Δh= 15 cm and 20 cm.

TEST RESULTS

Figures 7 – 10 show the behaviours of models 1, 3, 4 and 5 during the tsunami tests. By the attack of the tsunami of Δh= 15 cm, model 1 fully collapsed by very fast erosion of the backfill starting from the downstream slope (Figure 7). Model 2 also fully collapsed by the tsunami of Δh= 15 cm due to the same mechanism as model 1. However, the collapse took place more slowly by some better resistance of the reinforced backfill against erosion. It was reconfirmed that with both models 1 and 2, the erosion in the upstream slope is much slower than in the downstream slope under otherwise the same conditions.

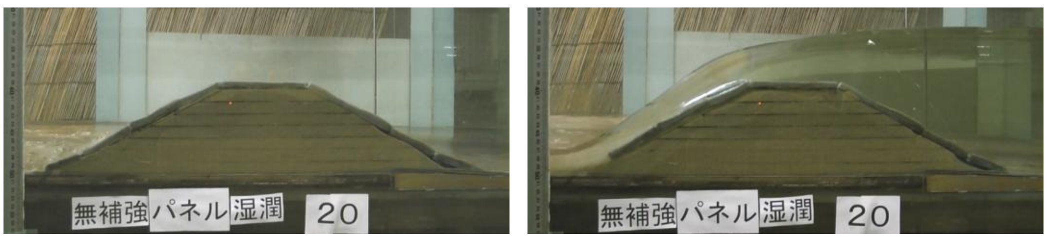


a) t= 0 seconds since the start of test b) t= 7 seconds

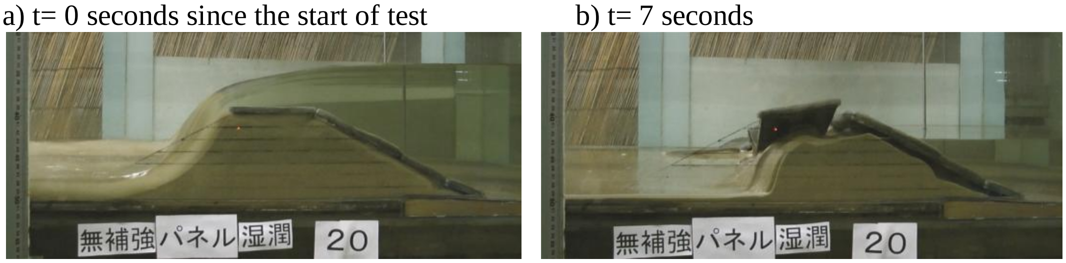


c) t= 14 seconds d) t = 24 seconds

Figure 7. Model 1 subjected to tsunami of of Δh= 15 cm

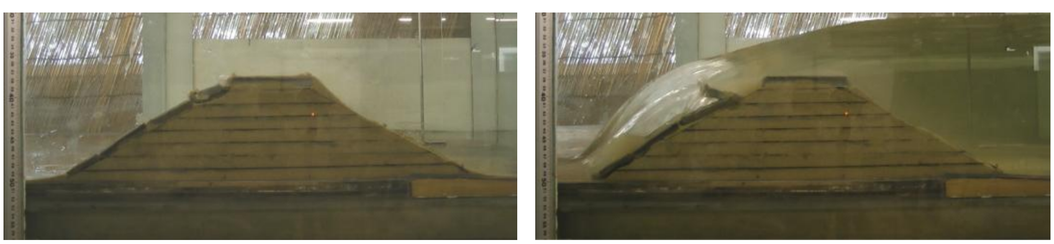


a) t= 0 seconds since the start of test b) t= 7 seconds

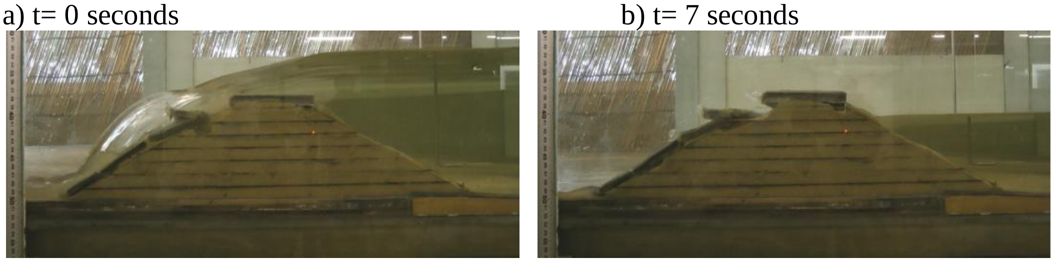


c) t= 14 seconds d) t= 26 seconds

Figure 8. Model 3 subjected to tsunami of of Δh= 20 cm



a) t= 0 seconds b) t= 7 seconds



c) t= 14 seconds d) t = 23 seconds

Figure 9. Model 4 subjected to tsunami of of Δh= 20 cm

a) When tsunami just arrived.

b) t= 14 seconds

Figure 10. Model 5 subjected to tsunami of Δh= 20 cm

Model 3 (Figure 6c; a model of the conventional fill-type coastal dyke shown in Figure 1) survived the first attack of the tsunami of Δh= 15 cm. This was due to the effects of concrete panel facing covering the backfill. As seen from Figure 8, however, this model could not survive the tsunami of Δh= 20 cm ultimately having fully collapsed by the following process: 1) As seen from Figure 8a, the bottom panel of the downstream slope was first washed away triggered by erosion of the backfill immediately behind. 2) As seen from Figure 8b, when t= 10 seconds since the arrival of the tsunami, the top panel at the downstream slope was firstly lifted up and washed away, followed by the other ones on the downstream slope and the one on the crest. 3) As seen from Figure 8c, fast erosion of the backfill started from the downstream slope. 4) As seen from Figure 8d, the full-section of the dyke was finally lost.

Model 4 (Figure 6d) survived the tsunami of Δh= 20 cm. Figure 9 shows the behaviour of this model during the attack of the tsunami of Δh= 20 cm. The top panel on the downstream slope rotated toward outside about its bottom but was not washed away immediately due to a connection with the geogrid layer behind (Figure 9a). The upstream slope was eroded only slightly in spite of no facing. Ultimately, the model lost the upper part of the backfill triggered by erosion starting from the top part of the downstream slope (Figure 9c).

Figure 10 shows the behaviour of model 5 (Figure 6e: a model of the proposed GRS coastal dyke, Figure 4). The model survived very well the attack of the tsunami of Δh= 20 cm without exhibiting any significant erosion of the backfill and any decrease in the crest height, despite noticeable shear deformation by the thrust force of the tsunami.

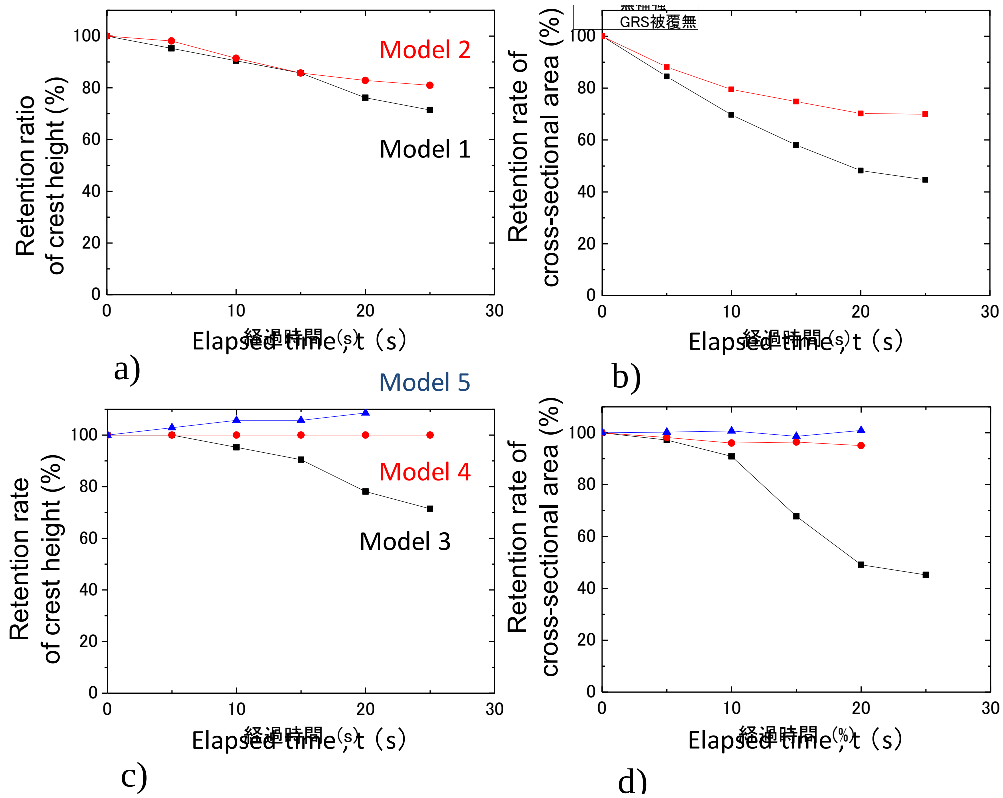


Figure 11 Retention rates of crest height and cross-sectional area after the start of tsunami attack; a) & b) models 1 and 2 when Δh= 15 cm: and c) and d) models 3, 4 and 5 when Δh= 20 cm

The stability against tsunami attack of the models was evaluated by the retention ratio of crest height and cross-sectional area seen from the side (Figure 11). For the tsunami attack of Δh= 15 cm (Figures 11a and b), model 2 exhibits a higher retention ratio of cross-sectional area than model 1. For the tsunami attack of Δh= 20 cm (Figures 11c and d), the process of fast erosion with model 3 is readily seen from a significantly decreasing rate of the retention ratio. Model 5 exhibited essentially no loss in the height and cross-section. Model 4 exhibits very good performance as model 5 by the end of the flow of tsunami current over the crest (t≈ 25 seconds). However, the loss of the cross-section continued subsequently during the tsunami that continued with a continuing decrease in the crest height and ultimately the model lost the top part (Figure 9c).

CONCLUSIONS

The following conclusions with respect to the stability of fill-type coast dyke against the over-flowing tsunami can be drawn from the test results presented above:

1. When the backfill was not reinforced and not covered with facing, very fast erosion of the backfill started from the downstream slope and the full cross-section was quickly lost.
2. The rate of backfill erosion decreased by reinforcing the backfill with geogrid layers. However, the unreinforced backfill dyke without being covered with facing ultimately was fully eroded.

3. The start of backfill erosion delayed by covering the crest and the up- and down-stream slopes. However, once the facing panels on the crest and at the top of the downstream slope were lost, the other panels on the downstream slope were subsequently lost, then very fast erosion started, resulting to the loss of the full-section.
4. By connecting the facing panels to the geogrid layers reinforcing the backfill, the facing became more stable and the backfill erosion was substantially delayed.
5. Further by connecting the facing panels to each other, the dyke became more stable even with both up- and down-stream faces being near vertical (i.e., the proposed GRS coastal dyke, Figure 4).

At three sites in a range of about 2.5 – 3.5 km south of the place shown in Fig. 2, three bridges of Sanriku Railway were washed away by tsunami during the 2011 Great East Japan Earthquake. These bridges are now under reconstruction to geosynthetic-reinforced soil integral bridges (Tatsuoka et al., 2009), scheduled to be completed by the end of 2013. With GRS integral bridges, the approach fill is reinforced with geogrid layers that are connected to the RC facing (i.e., the abutment) and the girder is integrated to the top of a pair of facings on both ends. The approach fills of these GRS integral bridges have the similar structure as the proposed GRS coastal dyke (Fig. 4). Moreover, an about 6 m-high RC frame structure for a length of about 200 m including Shimano-Koshi Station, at one of these three sites, collapsed by tsunami during that earthquake. This elevated structure is also under reconstruction to embankment having the similar structure as the proposed GRS coastal dyke, but with more gentle slopes, to function as a tsunami barrier. The details will be reported in the near future.

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