Seismic reinforcement method at crest of road embankment by geosynthetics

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ABSTRACT: When a road embankment fails due to earthquake, it will influence a road network by cutting off traffic at many places largely. Therefore, it is necessary to develop an effective counterplan which restrains a deformation of sliding of the road embankment due to earthquake. Based on an economical earthquake resistant method of construction, a new design technique of slip failure control is presented for evaluating the behavior of road embankment. A way to realize the design technique of slip surface control is by researching crest reinforcement structure. Based on the aspect, this paper proposes a reinforcement method of construction, in which the crest of embankment is reinforced by a geosynthetics. Applying the reinforcement method of construction we firstly carried out a full-scale model test. Secondary, we carried out a centrifuge model test to verify an effect of reinforcement by same method of construction against earthquake. As a result, it was confirmed that the embankment reinforced by the geosynthetics has a high deformation control and earthquake-resistance.

1 INTRODUCTION

In the Chuetsu Earthquake in 2004 and the Noto Hanto Earthquake in 2007, a lot of slip failures were caused on road embankment. It is urgent to develop an aseismatic reinforcement method of construction of road embankment for safe and highly reliable road network maintenance.

This paper presents a new design technique of slip failure control based on an aseismatic reinforcement method of construction for evaluating the behavior of road embankment.

In the paper, a reinforcement method of construction is proposed to prevent the devastating failure of road embankment in earthquake in which the crest of embankment is reinforced by a geosynthetics to achieve the design principle of slip failure control.

A full-scale model test in fields and a centrifuge model test are carried out based on the same method of construction to verify the effect of the reinforcement and to understand the behavior of slip failure control.

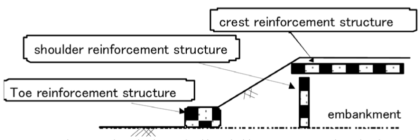


Figure 1. Design principle of slip failure control reinforcement structure

2 OUTLINE OF THE CREST REINFORCEMENT METHOD OF CONSTRUCTION

The proposed design technique of slip failure control is based on the development of the economical aseismatic construction for reinforcement method. As shown in Figure 1, three design schemes are presented: the crest reinforcement structure, the shoulder reinforcement structure and the toe reinforcement structure.

The object of the paper is to research the crest reinforcement structure and to propose a crest reinforcement method of construction in which the crest of embankment is reinforced by the geosynthetics. Figure 2 shows the crest reinforcement method of construction. According to the range of placement of geosynthetics, the method of construction is assumed to be of the earthquake-resistant reinforcement on existing and newly built embankment. For instance, as shown in Figure 2, for the case of geosynthetics installing in the surface of crest of embankment, this method of construction is applied to

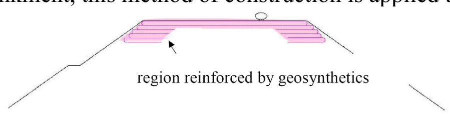


Figure 2. Outline of crest reinforcement method of construction

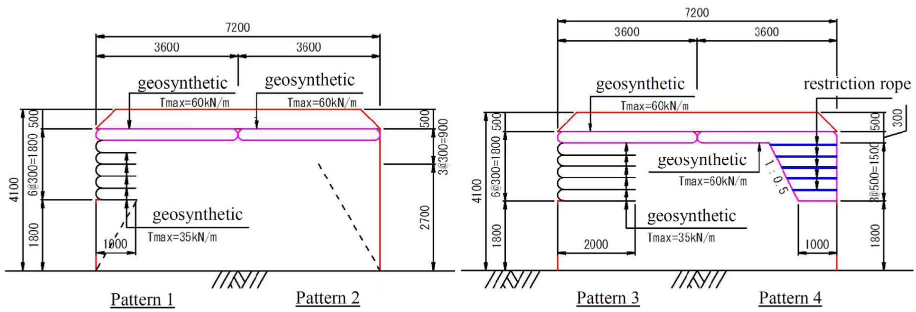


Figure 3. Reinforcement structure of embankment (cross section)

the newly built embankment as well as the existing embankment with a re-pavement. And for the case of geosynthetics installing in the sidewalk and shoulder of road embankment, it is also applied to the existing and newly built embankments. Here, it is possible to hold traffic control to a minimum limit according to the construction by the lane line regulation or partial construction of the shoulder of road when we re-pavement.

3 FULL SCALE MODEL TEST IN FIELDS

3.1 *Outline of model test*

A vertical embankment is constructed in extension of 3.6m, depth of 1.8m and height of 4.1m, which is surrounded by some large sandbags.

As shown in Figure 3, the model is divided into 4 reinforcement patterns. In reinforcement pattern 1, only one layer of geosynthetics is installed to reinforce the crest of embankment. In reinforcement pattern2 and 3, 5-step of geosynthetics respectively in length of 1m and 2m are placed on the position lower than the geosynthetics settled in reinforcement pattern 1, which are connected with metal fittings.

Reinforcement pattern 4 involves the geosynthetics in the ladle type, in which the geosynthetics between the face of wall and mountainside is restricted by rope. The material properties are shown in Table 1.

In the embankment we use the fine aggregate without fine-grained fraction at wet density γ_t=18 kN/m^3 which tends to occur a collapse easily. Removing the large sandbags surrounding the embankment, a collapse is caused. The changes of embankment until collapse are verified in the test. And some transducers are pasted into the geosynthetics to measure its strain until collapse.

Table 1. Properties of material

geosynthetics	tensile strength 35(kN/m), 60 (kN/m) elongation 5.0(%)	core:aramid fiber covering:polyethylene
metal fittings	ϕ 3mm, 6mm	ordinary iron wire
restriction rope	tensile strength 22(kN) elongation 40%	Polyester spinning rope ϕ 12mm
embankment	γ =18kN/m^3, c=0kN/m^2, ϕ =40°	

3.2 *Test results*

The sketch of collapse mode of reinforcement embankment is illustrated in Figure 4. Figure 5 shows the settlement of the edge of embankment slope for each of reinforcement patter.

In the reinforcement pattern1, a large failure is caused in the part lower than the reinforced part so that the overburden layer slipped.

In the reinforcement pattern2 and 3, both collapse and deformation on the crest part are small.

Moreover, the settlement on the edge of embankment in the pattern3 with a longer reinforcement became smaller.

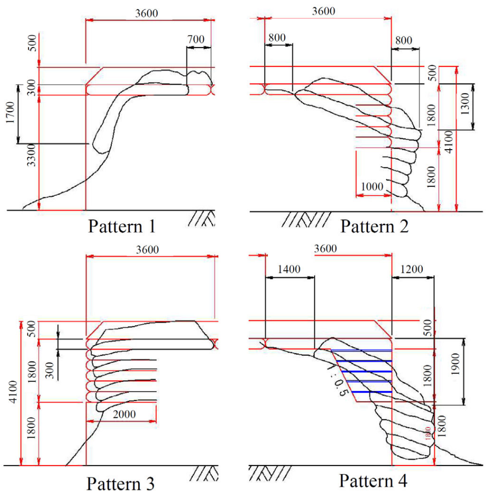


Figure 4. Cross section of collapse mode

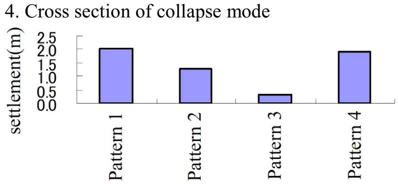


Figure 5. Settlement of edge of slope

In the reinforcement pattern4, the reinforced part with the lower part in a body slipped forward along with the collapse of lower part.

The distribution of strain for the reinforcement pattern3 with the smallest deformation is shown in Figure 7. Here, Event1 involves the time removing the sandbag in the upper part, and Event2 refers the time removing the sandbag in the lower part (refer to Fig.6). Near the crest of embankment, the strains are mainly distributed in the rear of the reinforced region and on the lower part of reinforced region the peak of strain occurred in the side of failure surface. In the reinforcement patterns1, 2 and 4, the reinforced region slipped caused by its own weight. Fixing the edge of the reinforced crest region by geosynthetics, on which one layer of embankment with height of 500mm is constructed, but it is insufficient to consider this edge as a fixed end.

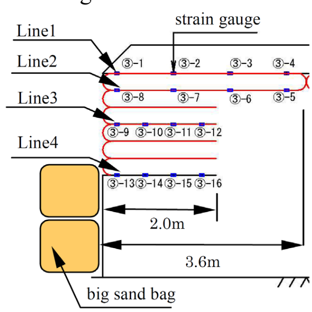


Figure 6. Configuration of strain gauge of Pattern3

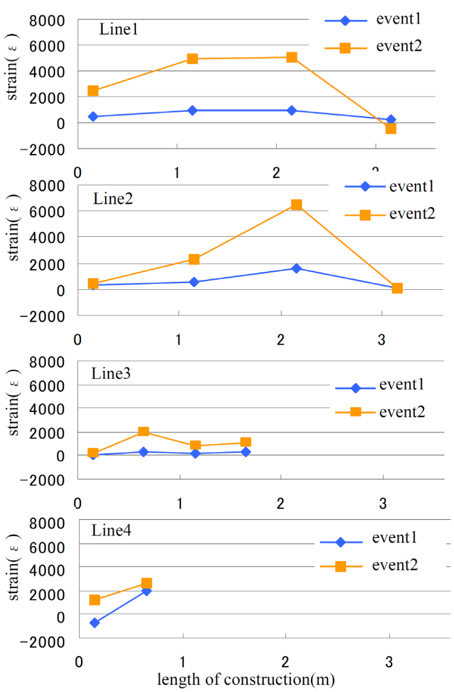


Figure 7. Distribution of strain

When a reinforcement structure is determined in the future it is necessary to examine the fixing method on the edge of reinforced region. Again, since the settlements of edge of slope in reinforcement pattern2 and 3 are restricted to a small result, the reinforcing effect on the slip below the embankment is verified.

4 CENTRIFUGE MODEL TEST

4.1 *Model test on the slip failure mechanism in the embankment without reinforcement*

4.1.1 *Procedure of model test*

Applying the steel soil container which is 900mm wide, 300mm thick and 280mm high, a centrifuge test is carried out and which contains a centrifuge acceleration of 30g. A half embankment is constructed in the height of 290mm (the height of real thing is 8.7m in 1g) and a slope is constructed in the gradient of 1:1.2 and by sufficiently mixture of the materials, using the DL clay and silicon oil to adjust the water content to 5%. In the lateral boundary of crest of embankment of soil container, a hard EPS in thickness of 15mm was installed to absorb the vibration transmitted from the soil container, and a double-stick tape by silica of Number3 is pasted on the bottom of soil container to enhance the friction between the bottom of soil container and soil material. We also use a thin rubber membrane smeared with a thin layer of grease on the surface of sidewalls of soil container to decrease the friction between soil container and soil stratum.

The embankment model is constructed in the method of hardening the soil layer by every layer thickness 30mm until the density of total fill was 1.45g/cm^3. However, the average density of 6 block samples was 1.52g/cm^3 when the test model is taken apart after test. This value is about similar with the density of the sample used to reinforcement case mentioned later. The shear wave velocity of embankment model is measured by bender element, 158m/sec in 1g and 185m/sec in 30g.

As shown in Figure 8, the horizontal and vertical accelerometers are installed in three sites to measure the input acceleration and response acceleration of embankment model. Figure 8 shows the accelerometers in the three sites: on the bottom of soil container (AH1, AV1), near the toe of slope in height of 90mm from bottom (AH2, AV2) and directly under the edge of slope in height of 230mm from the bottom. And the laser displacement sensors are installed in the surface of slope alone the direction of slope (DH1, DH2) and near the crest of edge of slope in vertical and horizontal direction (DV3 and DH3). To realize the final residual deformation of model, some color sands are dropped into the central cross section of model like a straight line in an interval of 60mm in accompanied by some markers located in the surface of earth ground in an interval of 50mm.

We try to estimate the failure mechanism of embankment as well as to master the response behavior and residual deformation. Concretely, as shown in Figure 8, two plates in 0.3mm thick are placed on the upper and central part of embankment, on the both sides of which some strain gauges passed to study the failure mechanism. There, we discussed the development of slope failure by the response time history of strain gauges.

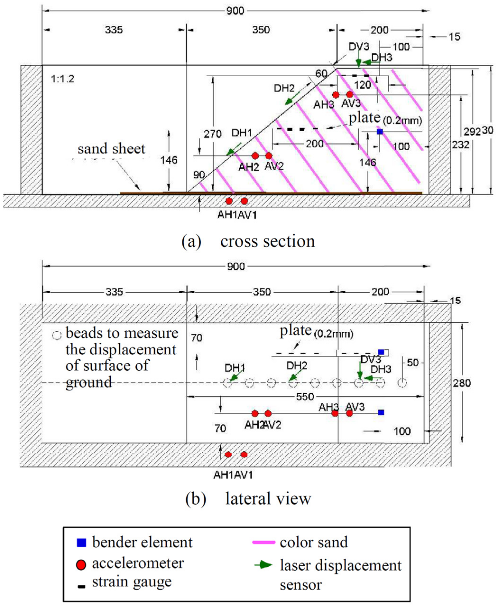


Figure 8. Centrifuge model without reinforcement

4.1.2 *Situation of residual deformation of embankment*

Figure 9 shows the cross section cut from model, the residual condition of color sands and the position of the markers installed on the surface of earth ground before and after vibration. As shown in the figure, the slip surface is assumed as the estimated line formed by connecting the broken parts of color sand together. It is shown from the results that it is possible to reappear the failure mechanism of embankment in the laboratory model tests with the conditions of the constructed model and vibration.

Moreover, more than one of slip surface in the model test can be identified, as shown in Figure 9, formed in a shallow depth of 40~50mm normal to the surface of slope and in a deep one of 80mm.A potential slip surface is also observed slightly in the depth of 130mm. Comparing these three slip surfaces, it is seen that the middle one is the biggest, after that the shallower one and then the deeper one.

It suggests that the failure surface of embankment cannot be assumed as the critical circular slip surface simply and that it is necessary to estimate the cumulative slippage by more than one slip surface when we calculate the slippage.

It is seen from the trace in Figure 9 that the clods of earth near the edge of slope disturbed by a slip and the displacements of markers in the edge and central part are almost same respectively 89mm and 87mm along the direction of slope. And it also shows the settlement on the edge of slope is 65mm.

The middle slip surface is occurred near the central of crest at a distance of 97mm from the edge of slope.

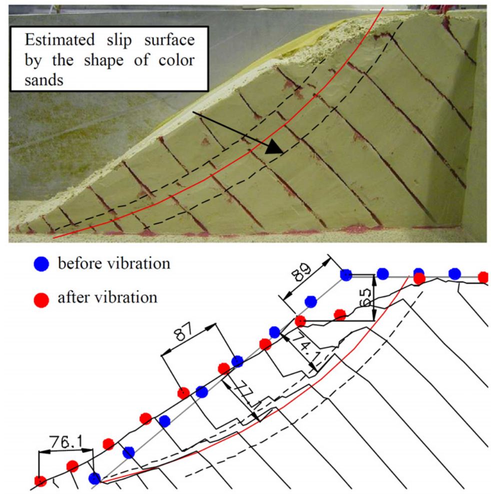


Figure 9. Residual deformation inside embankment

When cutting the soil from the locations of plates applied to measure strain, Figure 10 shows the situation of residual deformations of the plates placed on the upper and central part of slope. It is evident from the figure that in the state of residual deformation when the plate is dragged along the slip surface a large deformation convexly toward the bottom of embankment. Furthermore, as assumed that the plate can be installed in the position where crossing the slip surface.

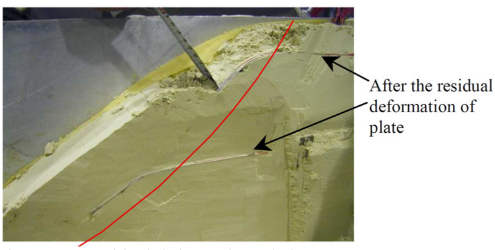


Figure 10. Residual deformation of plate

Among the strain gauges in pairs stuck on the front and back of plate, the time history of flexural strain, which calculated from the two strain gauges connected to the upper plate (εM3 and εM4) and the two strain gauges connected to the central plate (εM1 and εM2), is shown in Figure 11.Averaging the strain on the front and back of plate, note that deformation is positive convexly toward the upper of plate here and that the deformation is negative concavely toward the upper of plate.

A large difference between the results of two strain points of upper plate (εM3 and εM4) and two points of central plate (εM1 and εM2) is shown in Figure11. Firstly, as shown in Figure11, the two points of εM3 and εM1 near the slope initially deform concavely, and the deformation begins to increase at 7.8sec for εM3 and 9.3sec for εM1. Then, the deformation increased to shift convexly toward the upper of plate near 8.3sec for εM3 and 11.9sec for εM1 until the deformation tends to level off on 12.6sec for εM3 and 16.1sec with the increase of deformation. Comparison of characteristics of strain between the two plates shows the deformation on the upper part of embankment exceeds the one on the central part. It means that slip failure is developed from the upper part of embankment.

On the other hand, the point of εM2 placed in the deeper position and the point of εM4 initially deform convexly to the upper of plate and obtain the same magnitude of strain on 8.1sec. Subsequently, the deformation of εM2 becomes larger than that of εM4.

It can be presumed that the two points of εM1 and εM3 are in the slip surface and the two points of εM2 and εM4 lie in the region in stable state below the slip surface.

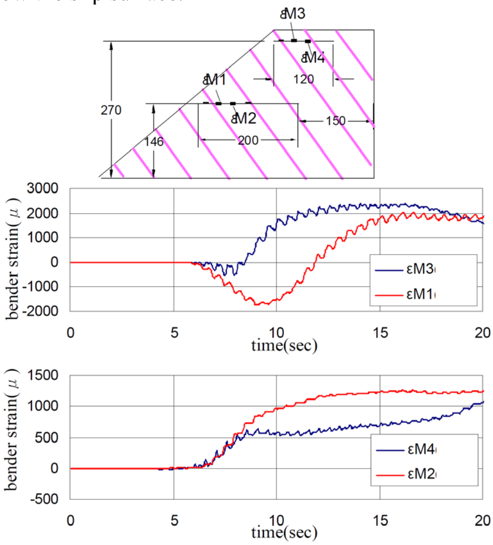


Figure 11. Time history of plate strain gauges

4.2 *Model test on the crest of embankmentreinforced by a geosynthetics*

4.2.1 *Procedure of model test*

It is shown from the model test on natural embankment as stated before that the deformation of upper part exceeds the result of central part so the slip failure was assumed to occur and develop from the upper part of embankment. Based on this collapse mechanism of embankment, it can be expected that the failure surface stopped at the position of reinforcement and sliding downwards when the reinforcement is employed on the crest of embankment. Based on the information from the model test in fields, the method of construction for reinforcing the crest of embankment is examined by the effect of reinforcement in the case with the least reinforced region.

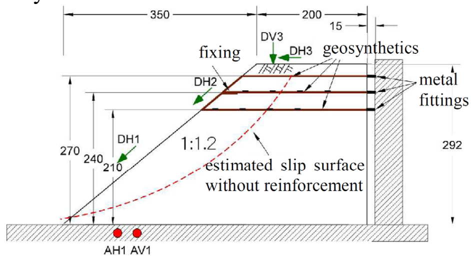
Table. 2 Condition of model test

	average density (kN/m3)	shear wave velocity (m/s)	horizontal acceleration on the bottom of soil container (gal)
without reinforcement	15.3	185	488
Case1	15.3	186	473
Case2	15.7	202	466
Case3	16.0	193	496
Case4	15.2	170	515

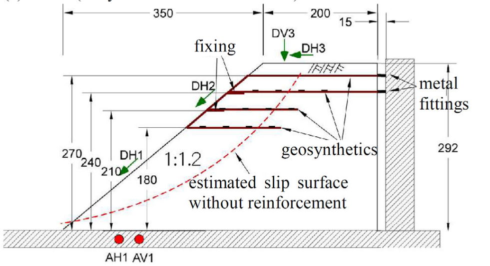
As shown in Figure 12, the model tests are performed in four cases by varying the construction method of geosynthetics. In case 1, as shown in Figure 12 a two layers of geosynthetics, viz. paving surface with 3-step structure, are installed in the whole surface of crest of embankment (named as face reinforcement). In case 2 shown in Figure 12 b, two layers of geosynthetics is cut into soil block with fixing on edge of geosynthetics (rectangle reinforcement) in combination with one layer of face reinforcement, viz. paving surface with 4-step structure. The two cases are the basic method of construction of crest reinforcement. And in the cases as shown in Figure 13 only the cases with rectangle reinforcement is discussed involving the least region for the crest reinforcement of embankment. In case 3 a 4-step structure with three layers of rectangle reinforcement is settled, and in case4 a 3-step structure with two layers of rectangle reinforcement.

In cases 1 and 2, considering the half structure, the face reinforcement is fixed on the sidewall of soil container. In cases2, 3 and 4 with rectangle reinforcement, it is necessary to determine the length of fixing. Referring to the minimum length of paving 0.1m recorded in design and construction manual (2000), in our research it is constructed as 40mm (in actual scale: 1.2m), the geosynthetics is placed in an interval of 30mm (in actual scale: 0.9m) by the model scale. To ensure the geosynthetics integrated with each other in the slope, the geosynthetics tucked up in the surface of slope is combined together with the next geosynthetics by a needle.

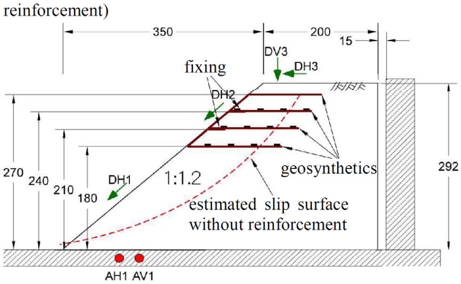
To examine the effect of reinforcement on embankment, it is necessary to establish the model tests at the same conditions, for instance, the construction of model, input data of earthquake motion and so on. The average density of 6 block samples for the model is taken apart after test is shown in Table2. The shear wave velocity of embankment model measured by bender element and the maximum of input acceleration measured in shaking table are also shown. In this way, the model test is carried out nearly at the same condition.



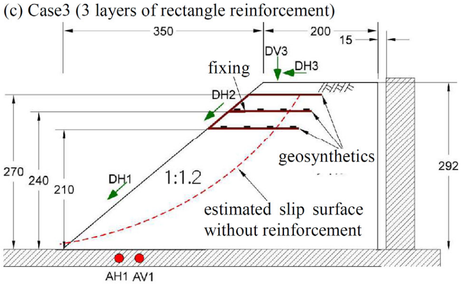
(a) Case1 (2 layers of face reinforcement)



(b) Case2 (1 layer of face reinforcement, 2 layers of rectangle reinforcement)



(c) Case3 (3 layers of rectangle reinforcement)



(d) Case4 (2 layers of rectangle reinforcement)

Figure 12. Outline of model test with geosynthetics

Compared with the test results of the case without reinforcement,the reinforcing effect of geosynthetics is discussed by different construction of crest reinforcement.

The similarity between the model and real reinforcement will be discussed as follows. According to the following equation, if we assume the stiffness of material in model is the same as the value of real thing, it can be satisfied only by adjustment of the thickness of material However, it is difficult to adjust the thickness if considers the centrifugal acceleration, the similarity should be satisfied by reducing the stiffness of material. In the model test, assuming the tensile stiffness ($E_p t_p$) of geosynthetics in real thing is 1000kN/m, we select one geosynthetics of model. The tensile stiffness ($E_m t_m$) of the selected geosynthetics is actually 24.4kN/m (conversion in real thing: 732kN/m), which is less than but mostly similar with the tensile rigidity of assumed real thing.

$$E_m t_m n = E_p t_p$$

Where E: stiffness of material; t: thickness of material and n: centrifugal acceleration, and suffixes m and p denote the model and real thing.

As same as the model test without reinforcement, the input acceleration on the bottom of soil container (AH1, AV1), the response acceleration inside embankment and on the crest, the deformation along the direction of slope and the horizontal and vertical deformation on the crest near the edge of slope are measured. To realize the final residual deformation of model, some color sands are dropped into the central cross section of model like a straight line at 60mm intervals and some markers located in the surface of earth ground in an interval of 50mm.Then to measure the distribution of strain of geosynthetics on full surface, the strain gauges are installed only at one side of geosynthetics. Since the restriction of model it is difficult to paste the strain gauges on two sides of geosynthetics so it is impossible to separate the flexural and axial strains. In the following, we will examine the behavior of embankment by the situation of residual deformation and the data obtained from the displacement sensors placed on the crest and slope of embankment.

4.2.2 *Examination of test results*

The central cross section which behaves the final form of slip surface in case2 with two layers of face reinforcement and case3 with one layer of face reinforcement in combination with two layers of rectangle reinforcement is shown in Figure 13. The test result in case1 as shown in Figure 13 a shows the deformation on the crest of embankment is small and the geosynthetics near slope tends to lower which means a large shear resistance induced. It is also shown from the trace figure of final form that the measured deformations on the crest of embankment are 13.8mm vertically by the model scale and 1mm horizontally, which are decreased in a great deal compared with the case without reinforcement.

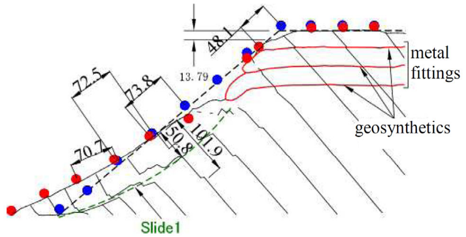
However, there are inferior regions on the boundary of geosynthetics so that a large failure surface occurred in the part lower than the region but cannot developed into the reinforcing region. The deformation normal to the lower part of slope is 72.5mm which is not reduced greatly than the case without reinforcement, but it shows that the slip surface on the lower part of slop denoted by Slide1 in Figure 13 is formed in a relatively shallow position in depth of 50.8mm.

It is shown from the trace of final form in case2 (Fig.13b) that the deformation of crest of embankment cannot be observed nearly and the scale of slip failure formed in the lower part of slope is also smaller than case1. The vertical and horizontal deformations measured by laser displacement sensors are 0.96mm and 0.3mm. In the slope the other one layer of geosynthetics used, the reinforcing region is increased so that a higher restraining effect on slip failure is represented than case1. In addition, we don’t observe the inferior region on the boundary of geosynthetics. This is because the edges of rectangle reinforcement have not been fixed to allow the movement partially. The deformation on the lower part of slope is also decreased greatly to 13.2mm. It is concluded that when the reinforcing region is increased with one layer of geosynthetics the reinforcing effect become large.

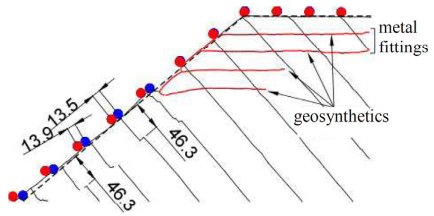
Figure 14 shows the test results for the cases only with rectangle reinforcement. From the test result in case 3 with three layers of rectangle reinforcement shown in Figure 14 a, we can observe that the slope below the reinforcing region moves forward and a slip surface formed in a shallow position of 22.2m deep normal to slope is restricted to the lower part of reinforcing region but without a general failure in embankment. The slip surface paralleled to the slope is developed to the edge of slope in the case without reinforcement. However, the slip surface on the upper region of geosynthetics is cut off and the first layer of geosynthetics is curved to the toe of slope.

It is confirmed from backside of reinforcing region on the crest of embankment that a number of small crack is caused because the whole reinforcing region in a body moves to the front. It is assumed that a provisional slip surface passes through the edge of geosynthetics may occur except that occurred in the lower part of reinforcing region. The deformation on the lower part is about 50mm to slope which is little less than the case without reinforcement, while the deformation on the upper part becomes 8.6mm which sufficiently shows the restraining effect on deformation by reinforcement.

As shown in Figure 14 b, it shows the result in case4 with two layers of rectangle reinforcement.

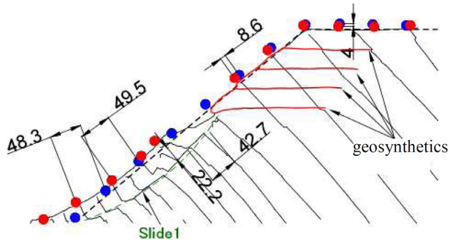


(a) residual deformation in Case1

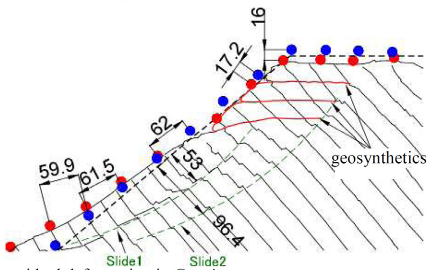


(b) residual deformation in Case2

Figure 13. Situation of residual deformation (Case1, Case2)



(a) residual deformation in Case3



(b) residual deformation in Case4

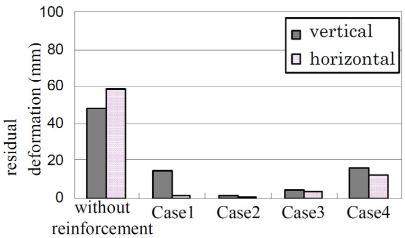
Figure 14. Situation of residual deformation (Case3, Case4)

The reinforcing region in case4 is reduced by 1 step of geosynthetics than case3. Based on this respect, the settlement of crest of embankment is 16mm in case4 which is larger than that of case3 and the scope of slip surface restricted to the part below reinforcing region is larger than case3 because the reinforcing region in this case moves more largely than case3. In addition, it is shown in case4 that a provisional slip surface (slide2) passes through the edges of geosynthetics more clearly than in case3. It is also shown from Figure 14 b that the normal deformation of slope is 60mm in the lower part, and 17.2mm in the upper part. Now it is examined that the reinforcement does have the restraining effect on deformation.

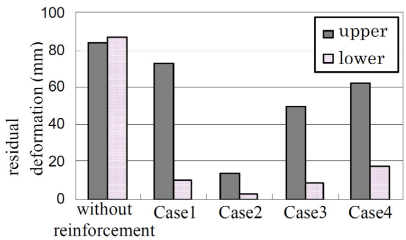
Assuming some short geosynthetics sparsely are installed into the whole slope it is possible that there is a large reinforcing effect on stability of slope and deformation control due to the crest of embankment strengthened profoundly. Based on the test result, the geosynthetics constructed on the crest of embankment can effectively restrict the deformation of crest and can transfer the developing region of slip surface downwards, which should reduce the failure of the crest of embankment.

4.2.3 *Comparison of residual deformation of slope and crest*

The deformation of embankment is shown in Figure 15. Compared with the case without reinforcement, the horizontal and vertical volume of residual deformations on the crest of embankment in reinforced cases are decreased greatly as shown in Figure 15 a. However, for the embankment slope in lower part it has not an evident restriction on residual deformation but the upper part obtains a large restrained effect on residual deformation. It means the construction on crest of embankment is available on preventing devastating failure.



(a) residual deformation on crest of embankment



(b) residual deformation on slope of embankment

Figure 15. Comparison of residual deformation

5 CONCLUSIONS

Based on the full-scale model test in fields and the centrifuge test, the reinforcing effect and the earthquake resistant capability of the crest reinforcement method of construction are examined.

It is clear that this method of construction takes on a good aseismatic effect by effectively reinforcing the crest of existing embankment.

The major purpose of this method of construction is to keep the standard road traffic which permits the urgent traffic operation by preventing the fatal failure of embankment during earthquake such as the road blocked rather than exhibit the reinforcing effect of reinforcement on the whole embankment. That is deformation in the lower part of embankment slope is permitted to a certain extent. This research presents the principle of reinforcement method of construction at collapse of embankment slope.

In the future, the reinforcement method of construction should be applied to practical embankment to establish a good design technique.

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