New horizon of earth reinforcement technique - current and future -

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SYNOPSIS: Earth reinforcement techniques are used worldwide and offer proven solutions to a wide range of geotechnical engineering problems. Here in this paper, recent developments of three major reinforced soil retaining wall methods in Japan were introduced in order to show how the current situation of this technique in Japan is. And the statistical data for the volume of the use was also shown, such as the total volume of the use, the scales of the structures, layout of the earth reinforcement, fill materials, and foundation conditions. Some of the case histories were also introduced with photographs and figures. And then, as one of recent research activity by the author, the study on the application of X-ray CT for the problem of earth reinforcement method combined with other method such as piling and soil improvement was introduced. In this study, a series of model test for several reinforced ground with geogrids was conducted using a newly developed test apparatus. Then, the behavior in the soil box was scanned after settlement using X-ray CT scanner. Based on these test results, the reinforcing effect by the geogrids and the soil arching effect over the pile heads was discussed precisely and those are done in 3-D with nondestructive condition. Finally, the effectiveness of the use of X-ray CT scanner in geotechnical engineering was promised.

Key words: Earth reinforcement, Geosynthetics, Steel materials, Case history, Model test, X-ray CT

1. Introduction

Earth reinforcement technique has been a powerful and economical solution to various geotechnical problems and the use of this technique has been drastically increased for this three decades starting from the beginning of 1980's in Japan. And it is important to summarize all the case histories of this technique from the beginning to up to now. The combined technique with other methods such as soil improvement, piling and others has also been used in order to apply this technique more widely. As one of examples of the combined techniques, deep mixing method of soil stabilization with earth reinforcement techniques are used in order to reduce differential settlement due to embankment loads on soft ground as shown in Fig. 1. This combined method offers the low improvement rate of soil stabilization by using the geogrids, because the embankment load is transferred to the geogrids and the pile elements. This transfer mechanism is caused by an arching effect in the reinforced soil over the heads of the pile elements and a membrane effect of geogrids. And it is considered that a search for the load transfer mechanism in nondestructive condition in three dimensions is important in order to quantify the design calculation. However, a characterization of interaction behavior between geogrids and soils over the pile heads is ongoing issue and its real behavior has not been observed precisely. Besides this behavior itself appears in the ground so that it is difficult to evaluate such behavior.

Recently, an industrial X-ray CT (Computed Tomography) scanner which is one of the nondestructive testing method has been developed and the inside behavior of material could investigate without any destructions. Author has conducted a series of studies on the application of industrial X-ray CT scanner to geotechnical engineering such as characterization of soil failure (Otani et al.,2000), visualization of the failure in mixed soil with air foams (Otani et al.,2002), evaluation of crushing soil particles in sand (Otani et al., 2005) and investigation of the failure patterns due to laterally loaded piles (Otani et al., 2006).

The objective of this paper is to introduce the current situation of the earth reinforcement techniques in Japan and here the reinforced soil retaining wall is taken into consideration. And as one of recent research activity by the author, the study on the application of X-ray CT for the problem of earth reinforcement method combined with other method such as piling and soil improvement is introduced. In this study, a series of model test for several reinforced ground with geogrids are conducted using a newly developed test apparatus. Then, the behavior in the soil box is scanned after settlement using X-ray CT scanner. Based on these test results, the reinforcing effect by the geogrids and the soil arching effect over the pile heads are discussed precisely and those are done in 3-D with nondestructive condition. Finally, the effectiveness of the use of X-ray CT scanner in geotechnical engineering is promised.

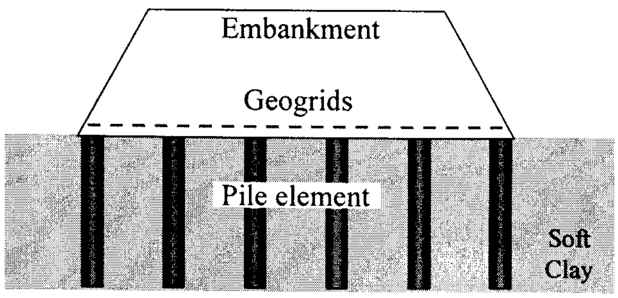


Fig.1 The outline of combined method.

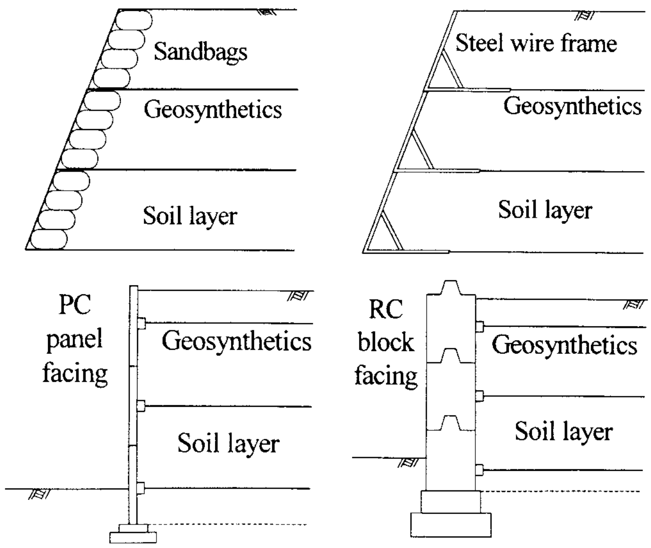


Fig.2 Schematic view of Geogrid method.

2. Reinforced soil retaining walls in Japan

Although there are different types of reinforced soil wall techniques in Japan, these are categorized by following three types:

1) Geogrid reinforced soil wall method (Geogrid method),
2) Multi-anchored reinforced wall method (Multi-anchor method), and
3) Metallic strip reinforced soil wall method (Metallic strip method).

Public Works Research Institute (PWRI) in Japan has investigated 20 construction companies in the period of 1985 to 1991 for Geogrid method and its design manual was established in 1992 by Public Work Research Center (PWRC). Fig. 2 shows schematic view of geogrid reinforced soil walls. As shown in this figure, there are different types of facings which can be used for this technique and those are sandbag type, steel wire frame type, PC panel type and PC concrete block type. Not only sandy soil but also low compressive clayey soil can be used for back fill materials.

Multi-anchor method was developed by PWRI in 1973. The design and construction manual for this technique was published in 1994 by PWRC. Schematic view of Multi-anchor method is shown in Fig. 3. This method mainly consists of backfill soil, tie bar with anchor plates and pre-cast concrete facing. Sandy soil is used for the backfill materials and cohesive soils as well. A most interesting to note is that the cohesive soils such as volcanic soil (w_L<50%) can be also applied.

In the mean time, Metallic strip method was originally developed by H. Vidal in 1966 in France. This method was introduced to Japan in 1972. The design manual for this technique for the condition of practice in Japan was published in 1982 by PWRC. Schematic view of this Metallic strip method is shown in Fig. 4. This method mainly consists of back-fill soils, metallic strips and pre-cast concrete skin or pre-cast metallic skin. It is expected that the wall displacement is highly controlled for this technique, so that the backfill material is restricted to only sandy soil. Especially, in the case that the fine fraction content of backfill soils is over 25% or its maximum grain size is over 300mm, it is requested to cover metallic strip with high quality sandy soil.

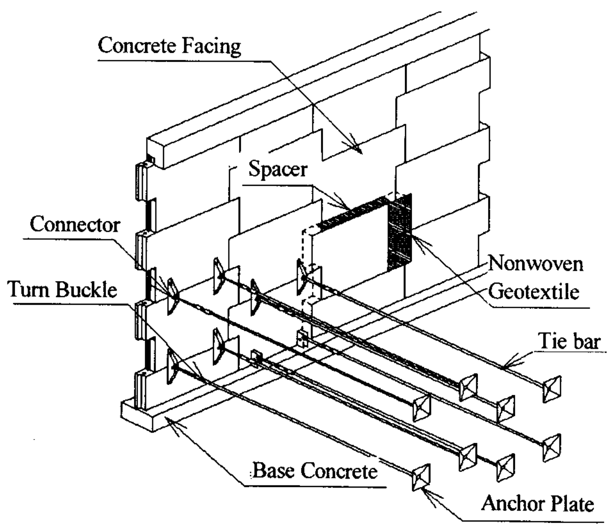


Fig.3 Schematic view of Multi-Anchor method.

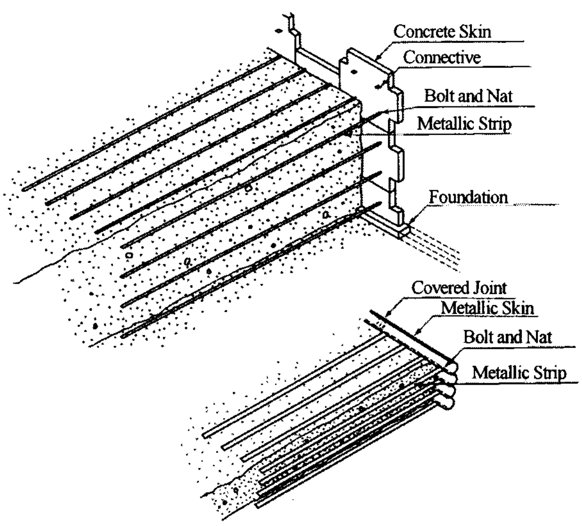


Fig.4 Schematic view of Metallic strip method.

3. Statistical data of performance

3.1 Volume of the use

In this chapter, trend of the above three reinforced soil wall methods is analyzed based on statistical data from 1980 to 2000. Fig. 5 shows the change of the number of applications for the reinforced soil walls in Japan in the two decades. The application of Metallic strip reinforced soil wall method was started to use before 1980. And Geogrid method has been applied since 1984 while that of Multi-anchor method was started since 1985. The total number of applications for all three methods has monotonically increased since each method was started to use. It is noted that the increase of the number of applications is closely related to the publication of each design manual. At the year of 2000, about 2,200 cases of reinforced retaining walls were executed by the Metallic strip method and the Multi-anchor method and 1,100 cases were constructed by the Geogrid method. Fig. 6 shows the percentage of the application fields of all the three methods. As realized from this figure, most of the applications have been done for any kinds of road constructions, which are over 80% of total number of applications. The construction for the expressway road, the national road, and the railway road were performed since it needs to be maintained eternally. These five types of applications shown in Fig.6 hold the majority of the purpose.

3.2 Scale and reinforcement layout

The total area of the wall in each application can be realized as one of the most useful ways to evaluate the scale of the structures. Fig. 7 shows the quantitative discussion on the application of this method, in which the area of the wall is compared. The volume of the applications, which are the area of smaller than 1,000 m^2, is more than 90%. Moreover the construction works are most frequently performed by the scales from $100m^2$ to $400m^2$. However, the walls which are larger than 1,000 m^2 have been constructed in recent years. Fig. 8 shows the comparison on the height of reinforced soil walls. As far as the height of the wall is concerned, those of 5 to 9m have been most commonly constructed for all the three methods. The percentage of the scales from 5 to 15m is over 60%. Geogrid method is most frequently used in the three methods to build the structures those heights are lower than 5m. And the percentage of the structures over 15m is only 1 to 5%. Fig. 9 shows the comparison of the reinforcement length. The reinforcement which is the length of shorter than 15m is commonly used. Metal strips which are 5 to 10m lengths are mostly used for the Metallic strip method and its percentage is over 75% for all the applications. For the Geogrid method, the reinforcement which is shorter than the length of 5m is mostly used.

3.3 Fill Material and Foundation

Fig. 10 shows the comparison on the filling materials used for three types of the methods. It should be referred that sand and gravel are most commonly used as the fill materials. Cohesive soil is used for both of the Multi-anchor method and the Geogrid method. Materials of rocks are acceptable for the Multi-anchor method and the Metallic strip method but are rarely used for the Geogrid method. Fig. 11 shows the comparison of materials for the foundation under the earth reinforcement structures.

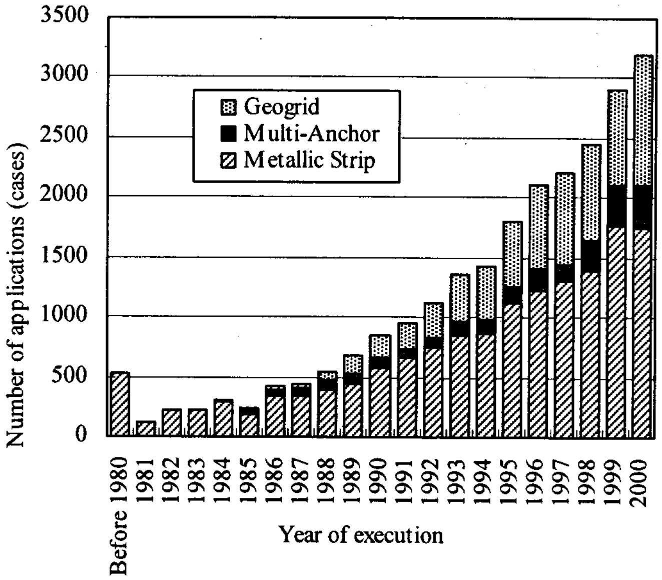


Fig.5 Number of applications of reinforced soil wall and steep slope embankment.

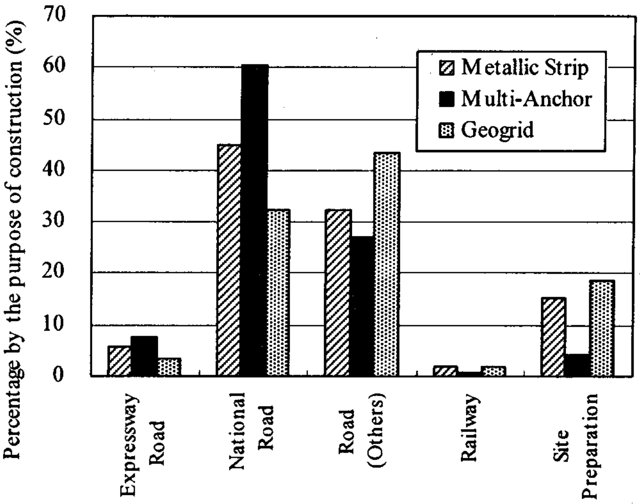


Fig.6 Percentage of the purpose of construction.

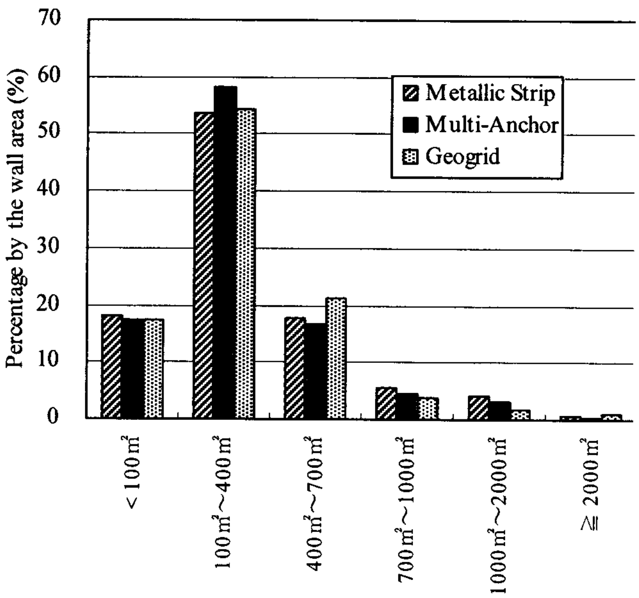


Fig.7 Percentage of the wall area.

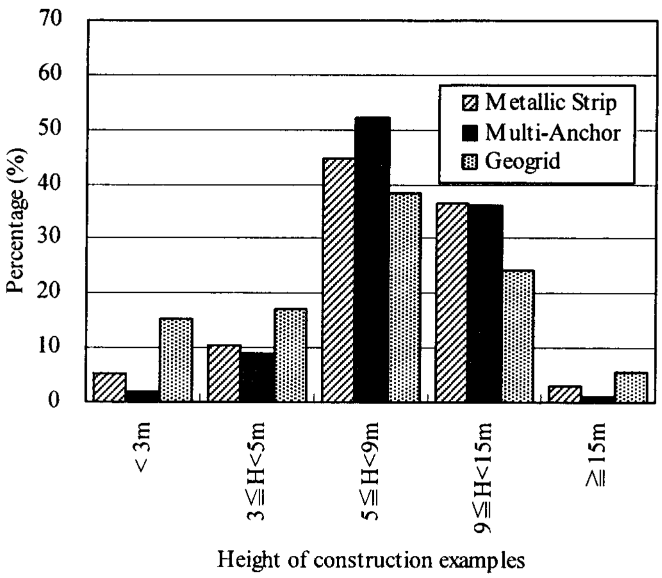


Fig.8 Wall height of construction examples.

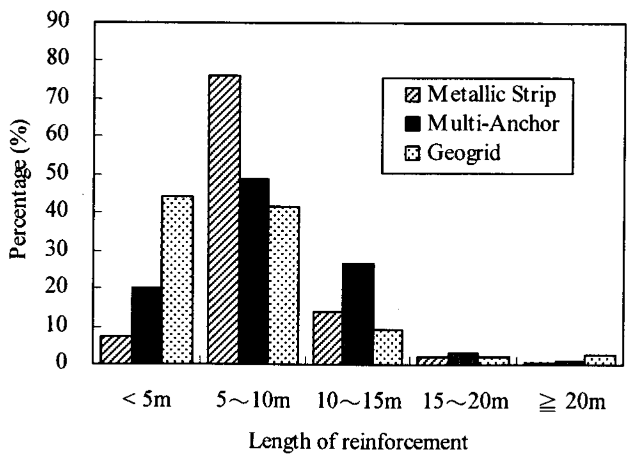


Fig.9 Length of reinforcement of construction examples.

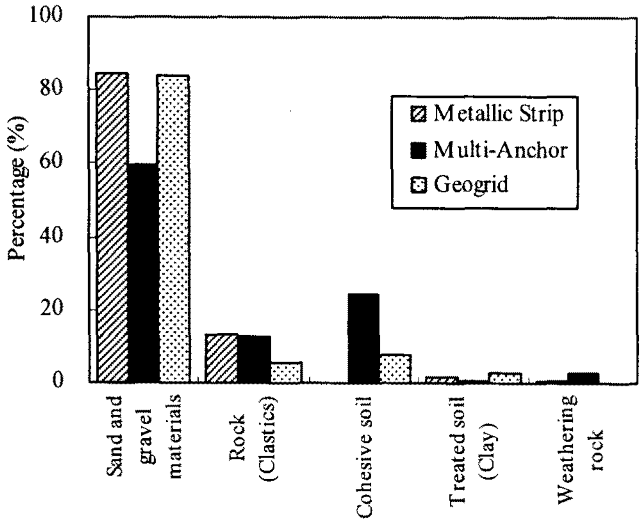


Fig.10 Fill material of construction examples.

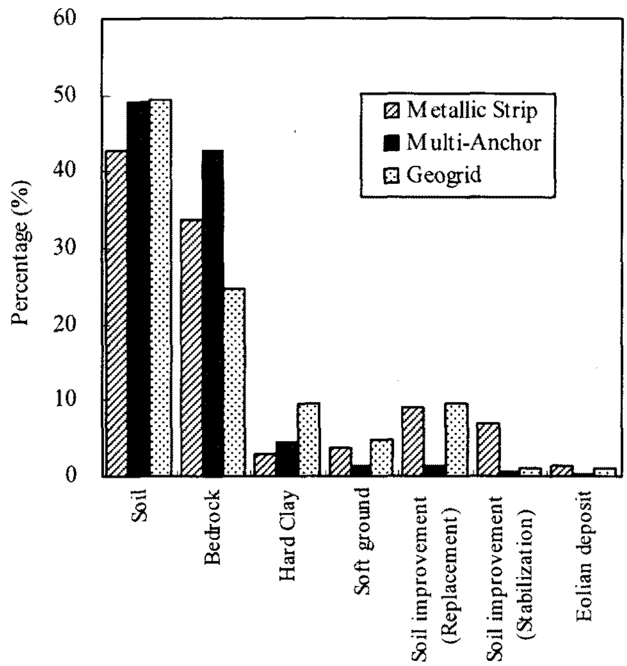


Fig.11 Foundation condition of construction examples.

4. Case histories

4.1 Typical reinforced wall methods

Some of the representative case histories of the three methods in Japan are introduced with figures and photographs.

Case 1: Geogrid method (Fig. 12)

- This was constructed for the abutment of bridge pier with its height of 10.3m and the fill material was cohesive soil. Drainage geotextile was also used.

Case 2: Multi anchor method (Fig. 13)

- This was constructed for agricultural road with its height of 17.0m and the fill material was cohesive soil. Geogrid reinforced soil embankment was also constructed on the top part of the wall.

Case 3: Metallic strip method (Fig. 14)

- This was constructed for local road with its height of 7.5m and the fill material was sandy soil.

These three methods have adaptability for permanent and important public structure. In these cases, construction cost was less than that of traditional solution such as reinforced concrete structure. But the reinforced soil wall method is relatively new and its long term performance has not been clarified yet.

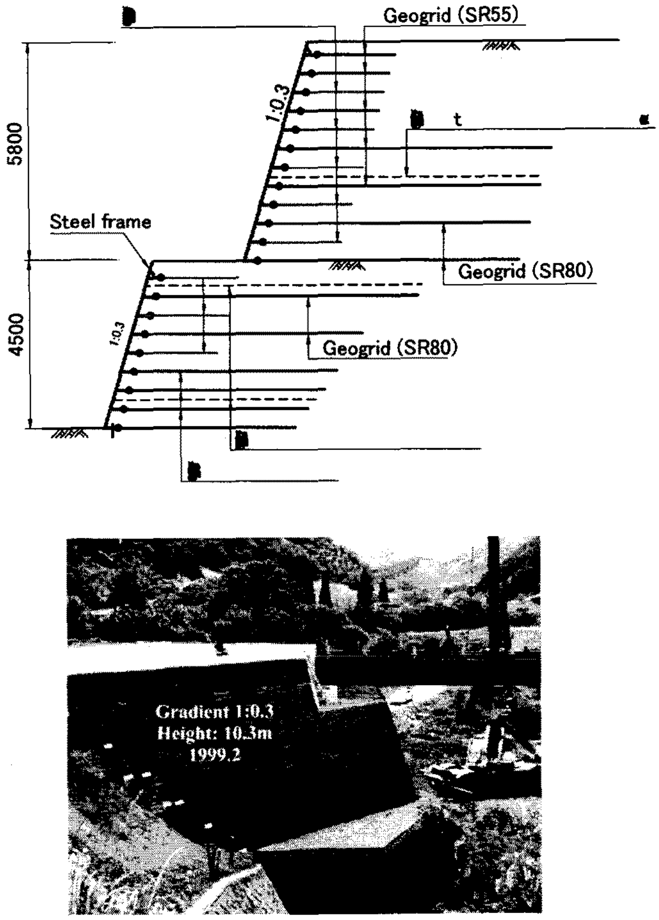


Fig.12 Case1: Geogrid method.

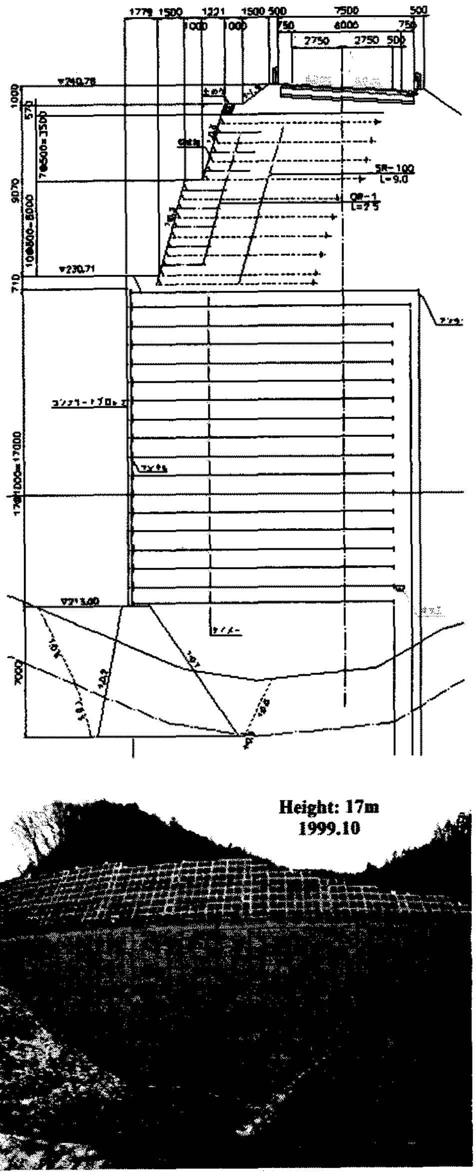


Fig.13 Case2: Multi-Anchor method.

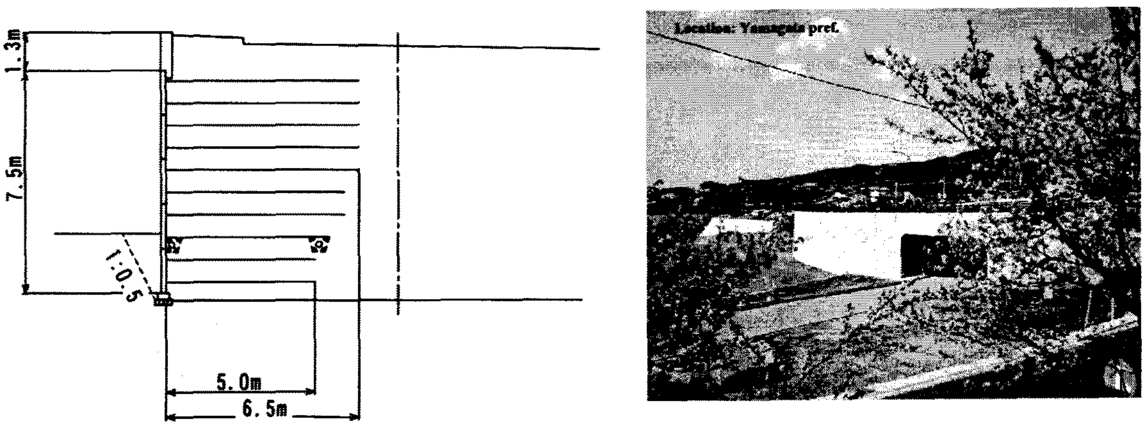


Fig.14 Case3: Metallic strip method.

4.2 Combined Method with other methods

Reinforced soil wall technique has been widely used up to now and it has been used for the case of more severe ground conditions. Recently, the combination with other methods such as soil improvement or piling is a new trend of this technique. This combined method can achieve higher performance and less cost. Here, five case histories are introduced with figures and photographs.

Case 4: Geogrid method combined with soil improvement (Fig. 15)

- Soil improvement was combined in order to increase its stability at neighboring of facing. Combined soil improvement was mixing method using cement and short fiber.

Case 5:Multi-anchor method combined with EPS (Fig. 16)

- EPS was combined in order to reduce the overburden pressure which was applied at the top of the wall. Unit weight of EPS was 0.1-0.3 kN/m^3.

Case 6: Multi-Anchor method combined with soil improvement (Fig. 17)

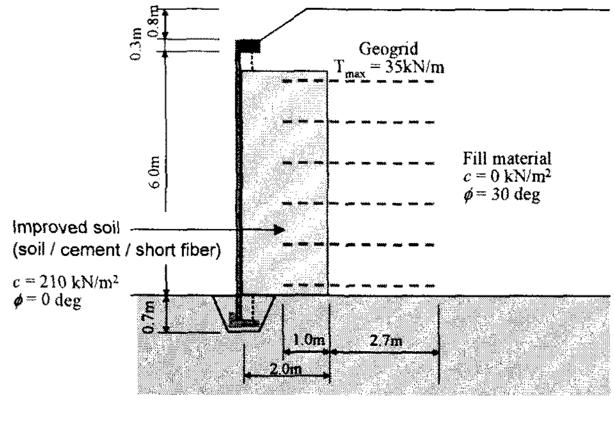
- Soil improvement was combined in order to reduce the self weight of the wall. This was the countermeasure for reducing bearing capacity of the foundation. Soil improvement was combined using recycled foam glass.

Case 7: Geogrid method combined with preloading and prestressing (Fig. 18)

- Preloading and prestressing were combined in order to increase vertical stiffness of the wall and stability against earthquake.

Case 8: Geogrid method combined with deep mixing and jet grouting (Fig. 19)

- Deep mixing and jet grouting were conducted in order to reduce the deformation of the foundation.



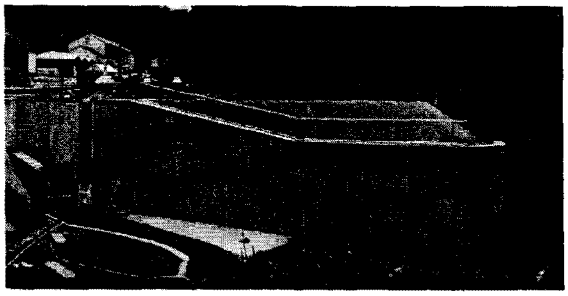
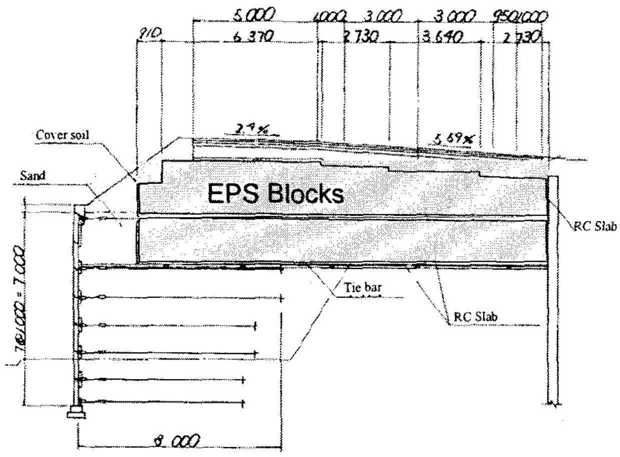


Fig.15 Case4: Geogrid method combined with Soil Improvement.



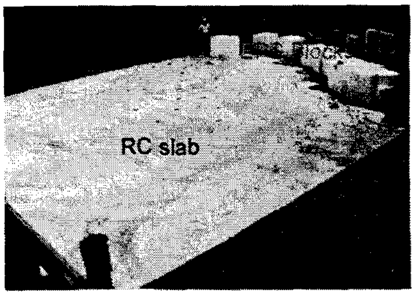
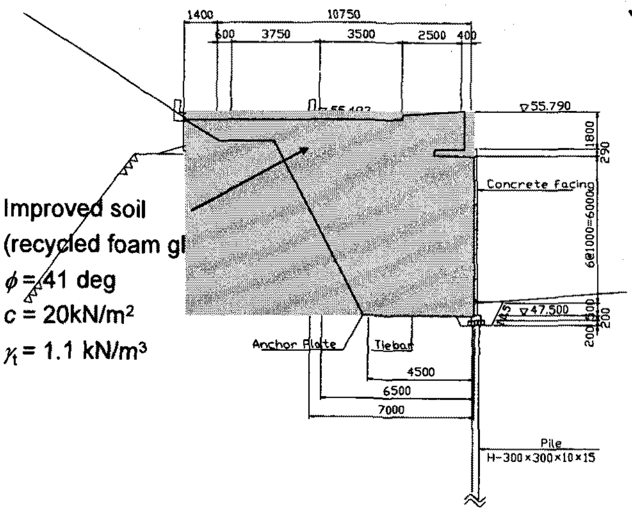
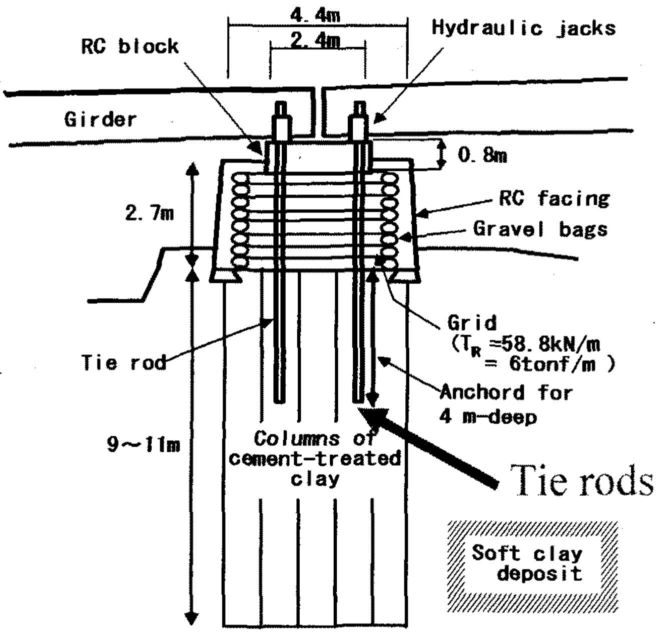
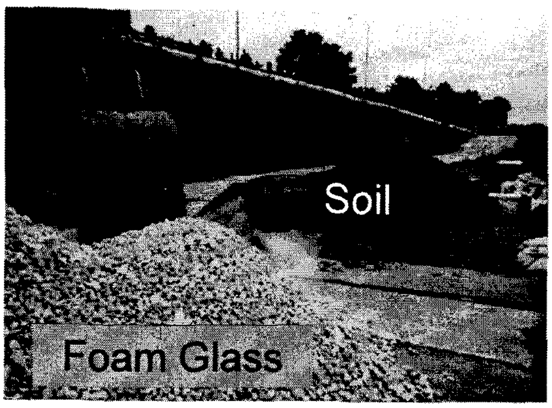


Fig.16 Case5: Multi-Anchor method combined with EPS.







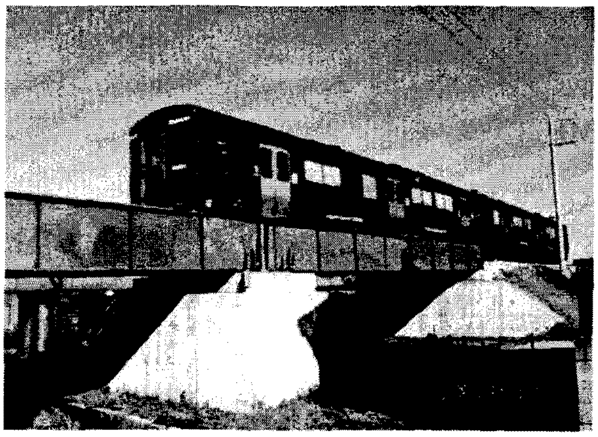


Fig.17 Case6: Multi-Anchor method combined with Soil Improvement.

Fig.18 Case7: RRR method (Modified Geogrid Method) combined with Preloading-Prestressing.

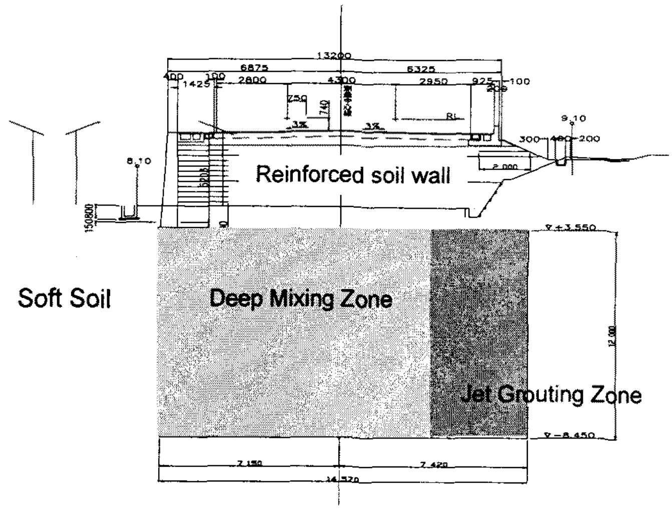


Fig.19 Case8: RRR method (Modified Geogrid Method) combined with Deep Mixing and Jet Grouting.

5. One of recent studies on earth reinforcement –use of new research tool-

5.1 X-ray CT method

The detected data are assembled and the cross sectional images are reconstructed using an image data processing device by means of the filtered back-projection method. By using all these cross sectional images around the circumference of the specimen, three dimensional (3D) image can be also reconstructed. It is noted that the scan area is 600mm height with 400mm diameter so that the specimen to be scanned on the specimen table has to be within that area. Medical CT scanners are most commonly equipped with 140 kV x-ray tubes while the industrial one used here is equipped with 300 kV x-ray tubes. Thus, it is easily realized that the capacity of scanning for the industrial use is much higher than that of medical one, so that the possibility of quantitative discussion may be expected. In the image processing analysis, the following so called "*CT-value*" is used:

$$CT-value = (\mu_t - \mu_w)\kappa / \mu_w \qquad (1)$$

where μ_t :coefficient of absorption at scanning point; μ_w: coefficient of absorption for water; and k : constant (Hounsfield value). Here, it is noted that this constant is fixed to a value of 1000. Thus, the *CT-value* of air should be –1000 because the coefficient of absorption for air is zero. Likewise, this value for water is 0 from the definition of Eq.(1). The CT images are presented with shaded gray or black color for low *CT-value* and light gray or white color for high *CT-value* in all the subsequent black and white images. The total number of levels on these colors is 256. It is well known that this *CT-value* is linearly related to the material density. Fig. 20 shows the relationship between CT-value and density of the soil. The results of Toyoura sand are plotted in this figure and this result shows a linear relation, so that the *CT-value* can be a parameter for evaluating the density change due to the compression of the soils, and the distribution of the density change in soils could be evaluated quantitatively using X-ray CT scanner. It is noted that the precise contents of X-ray CT method can be obtained in the reference by Otani et al. (2000).

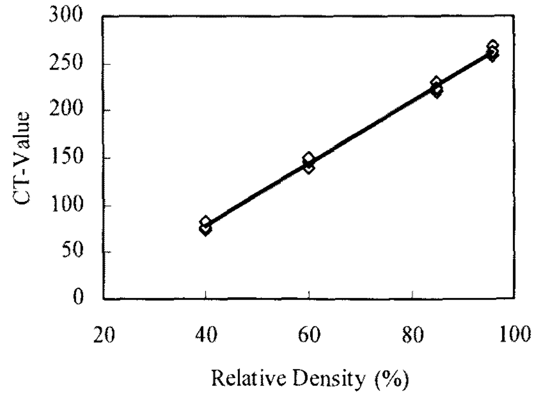


Fig.20 CT-value — Density relationship for Toyoura Sand.

5.2 Test procedure

A series of model tests for several types of geogrids was conducted using a settlement test apparatus as shown in Fig. 21. It is noted that the soil box in the apparatus made by an acrylic molding, which is the size of 200mm height with 126mm diameter, was set in the CT room. The model pile, which was the size of 15mm diameter, was set on the bottom of the soil box assuming end bearing pile. And, four piles were set at intervals of 45mm. The settlement plate which can penetrate through the piles using a jack, was set at the bottom of the soil. The method of pulling down this settlement plate at constant speed was assumed as a consolidation settlement of soft ground under embankment. Soil used in this test was dry Toyoura sand. In this test, the dry density was fixed to the relative density of 80% and the overburden pressure of 3.2kPa was applied by dead-load in order to conduct relatively large confining pressure as the condition under embankment. The settlement plate was pulled down under displacement control and the test was stopped at the settlement of 5mm. For the CT scanning, initial and the stage at after 5mm settlement were scanned with 1mm thickness for maximum height of 40mm above the settlement plate. Fig. 22 shows geogrids used in this test. Fig. 23 shows tensile force-strain relationship for Grid-A and Grid-B. Grid-A is a geogrid with horizontal and vertical rib intervals of 2mm. Grid-B is a geogrid with horizontal and vertical rib intervals of 9mm. These geogrids were installed above 5mm height from the pile head into the soil. The test cases are three, in which CASE1 is the basic condition without geogrids, CASE2 is the condition of installing Grid-A, and CASE3 is the condition of installing Grid-B.

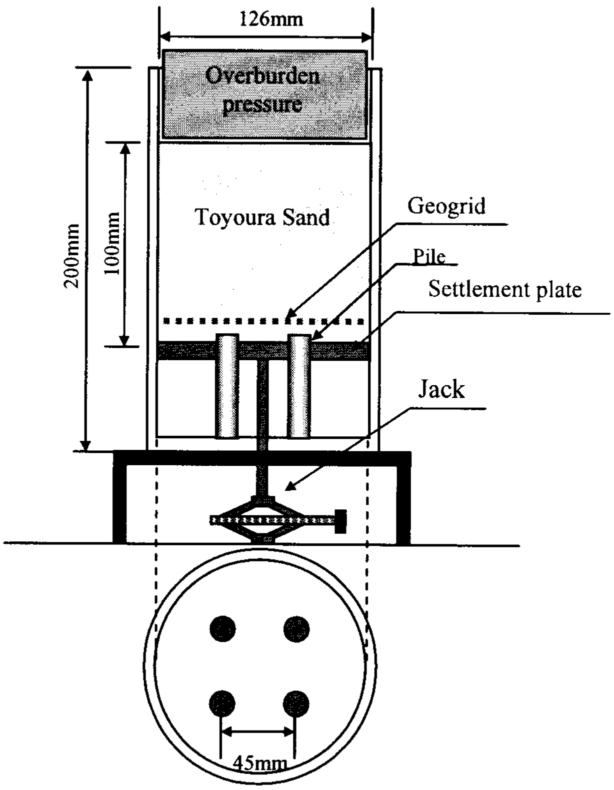


Fig.21 Settlement test apparatus.

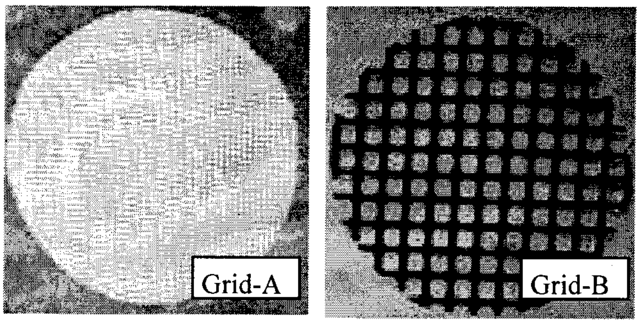


Fig.22 Geogrids.

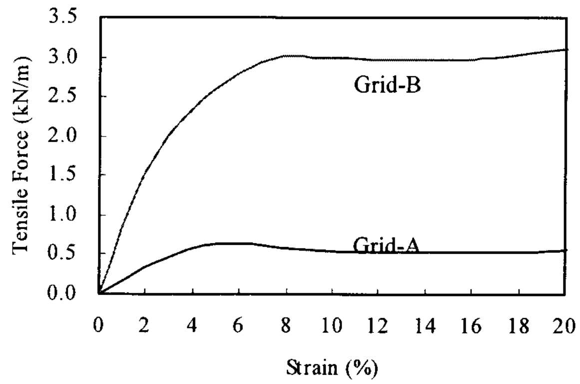


Fig.23 Tensile Force – Strain relationship.

5.3 Results and discussion

Fig. 24 shows the cross sectional images of after 5mm settlement at the height of 2mm intervals for three cases. As easily realized, the density around the circumference of the pile head is decreased as the settlement plate is pulled down, which is the appearance of the area of ring shape with black color in the image of CASE1. These low density areas are interrupted in each other at the area of within 10mm height above the settlement plate. The density change of CASE2 is similar to CASE1. But the low density area around Grid-A is quadrangle shape. This shape is caused by the effect of geogrid shape. But the change of the density in CASE3 is different from that shown in CASE2. It can be considered that this difference is caused by the stiffness and the type of the geogrids. Since a large number of cross sectional images have been obtained for all the cases, three dimensional images can be reconstructed. Fig. 25 shows the vertical reconstruction images. These images were reconstructed by the density change using different colors as shown in Fig.25. It is more clearly shown that the area of high density right above the pile head is surrounded by the banded area of low density for CASE1 and CASE2. It may be considered that those banded areas of low density are the areas of strain localization. The angle of density change due to piling is observed in CASE1. It is considered that this behavior is caused by the effect of soil arching. For CASE2, the area of density change extends to horizontally due to the existence of geogrids. Thus, the angle of density change for CASE2 is decreased due to the effect of Grid-A. For CASE3, the area of changing density is not as large as that of CASE2 and it seems that the stress concentration is rather smooth. And this area of density change is observed between the piles and the geogrids. Here, if it is assumed that the transmission of the overburden pressure due to the settlement influences the density change over the pile head, it can be considered that the smaller the angle of this density change is, the wider the load distribution in the ground is. And this can be also considered to be the effect of soil arching and at the same time, the membrane effect due to existing of geogrid. Fig. 26 shows

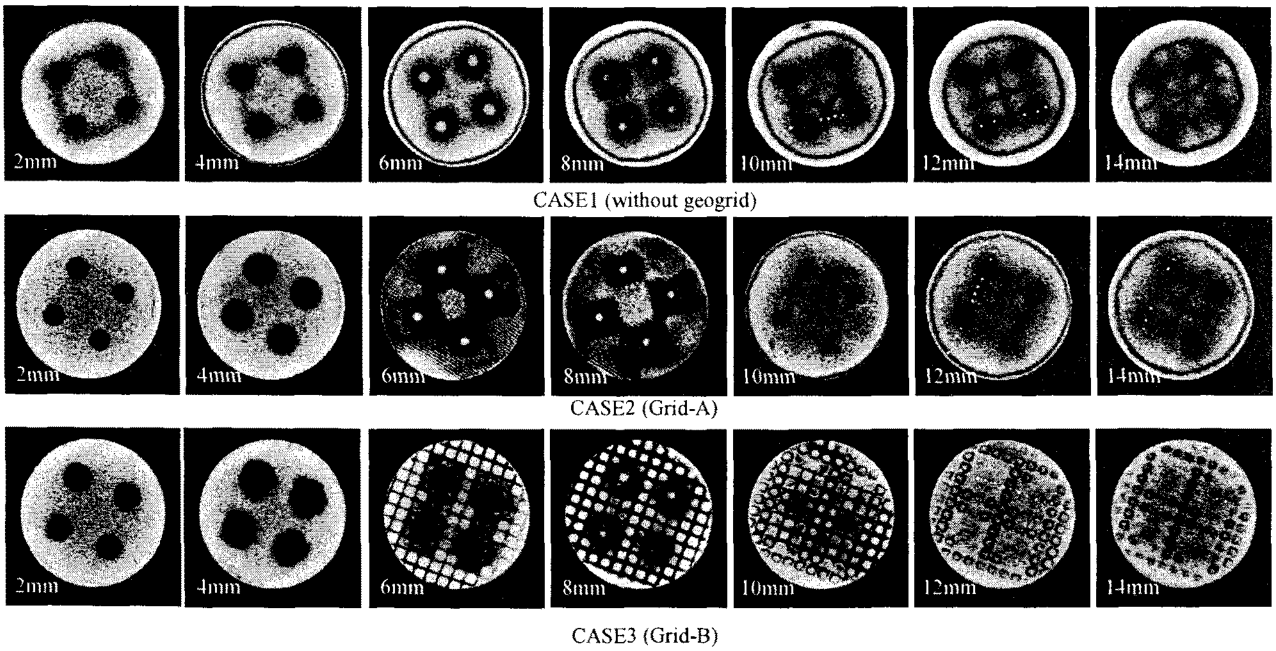


Fig.24 Horizontal cross sectional images.

the model of the embankment load parts on the ground in between the pile elements for current design method (Public Work Research Center, 2000). Fig. 27 shows the reconstruction images in three dimensions for CASE1. This image was extracted an area alone without the density change between the piles. As easily realized, Fig. 26 and Fig. 27 are similar enough in each other. Thus, it is confirmed that the transmission of the overburden pressure according to the settlement influences the density change over the pile head. Fig. 28 shows the same three dimensional image for CASE3. The shape of the embankment load for the grounds in between all the piles is rather complicated due to the influence of the geogrids. However, the total volume decreases by placing the geogrids. Therefore, it is confirmed that the embankment load that acts on the ground between the piles decreases by installing the geogrids.

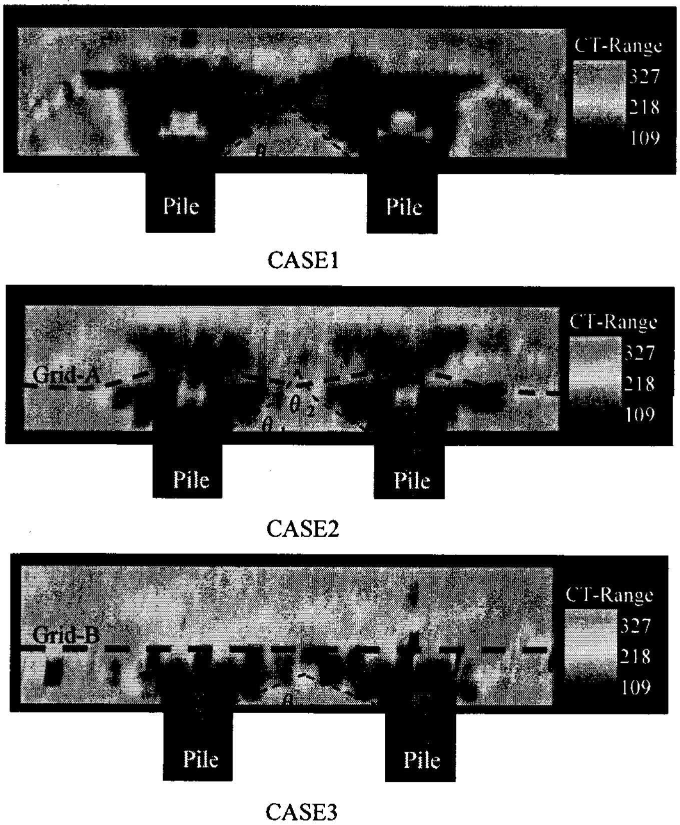


Fig.25 Vertical reconstruction images.

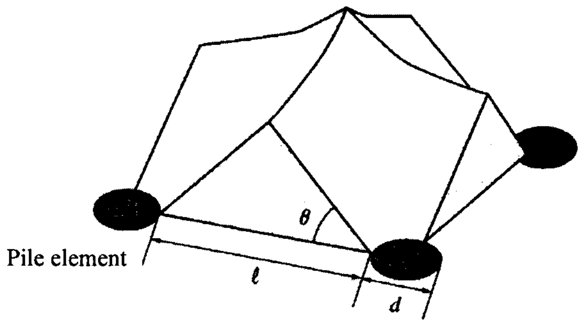


Fig.26 The proposed model of the embankment load that act on the ground between the piles at existing design method (PWRC(2000)).

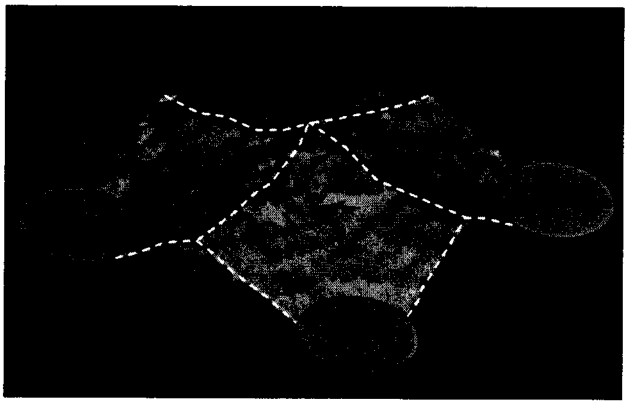


Fig.27 Three dimensional image that extracts an area alone without the density change between the piles (CASE1).

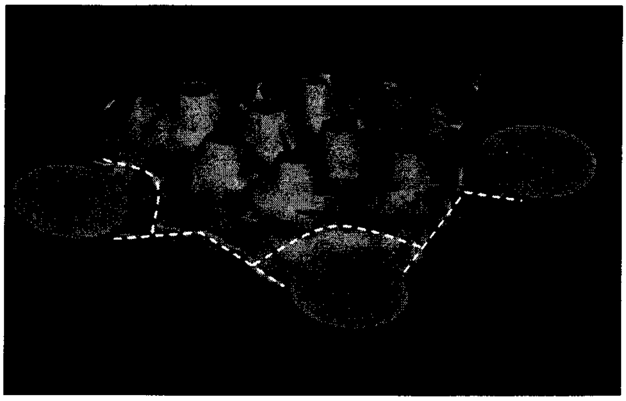


Fig.28 Three dimensional image that extracts an area alone without the density change between the piles (CASE3).

6. Conclusions

In this paper, firstly, the statistical analysis of case histories of reinforced soil wall technique in Japan was conducted and it was found out that the number of applications of reinforced soil wall in the year of 2000 was one hundred times as much as those in 1981. And the main application field was road construction and the height of the wall which is from 5 to 15m was most commonly used. It was also concluded that a reinforced soil wall method combined with the other methods such as soil improvement and others is a powerful solution for earth reinforcement technique.

And secondly, current research activity by the author on the technique of combined with other methods was also introduced. The following conclusions were drawn from this second part:

1) The transmission of the overburden pressure according to the settlement influences the angle of density change over the pile head;
2) In addition to the soil arching effect, the membrane effect is demonstrated by installing the geogrids; and
3) The membrane effect depends on the property of geogrids.

It is obvious that earth reinforcement technique is one of the best solutions for any geotechnical engineering problems, which are not only new construction site but also the remediation or countermeasure method for any kinds of natural disasters such as earthquake, heavy rain, tsunami and so on. And it is expected that the technique itself becomes more and more complicated in order to select better technique such as combined method with other methods. It is also confirmed that X-ray CT could be a new direction of testing tool of solving any geotechnical engineering problems.

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