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Present state and perspective of design methods of reinforced soil structures

H. Miki – *Public Works Research Institute, Ministry of Construction, Tsukuba, Japan*
N. Fukuda – *Fukken Co., Ltd, Consulting Engineers, Hiroshima, Japan*
O. Murata – *Railway Technical Research Institute of Japan Railway Group, Tokyo, Japan*
S. Tayama – *Research Institute, Japan Highway Public Corporation, Tokyo, Japan*
A. Yamamoto – *Technical Research Institute, Obayashi Corporation, Tokyo, Japan*
Y. Otani – *Hirose Co., Ltd, Tokyo, Japan*
Y. Yokota – *Maeda Kosen Co. Ltd, Fukui, Japan*

ABSTRACT: The soil-reinforcing construction method has a history of over 30 years. The recent 10 years or so have seen great progress in researches and in the application of the method to soil structures in the field. Besides, various design and construction manuals have been made available, generalizing the method. The reinforcing mechanism in such soil structures, including that many such structures demonstrated their capability of withstanding severe ground motions in recent great earthquakes, has not yet elucidated entirely, and still a number of problems await solutions.

Under the circumstances, the working group of Design Method , one of the working groups of Japanese Supporting Committee of the Asian Technical Committee for Earth Reinforcement, compiled this paper mainly based on cases of reinforced soil structures in Japan to report the current situation and perspective of design methods, in particular, of geosynthetic-reinforced soil structures and soil nailing.

1 INTRODUCTION

There have been proposed many reinforced-soil construction methods for the construction or reinforcement of embankments, retaining walls, foundation grounds, etc. and for slope cutting, excavation, etc. Their history is now over 30 years. Available as reinforcing materials are steel, plastic, and other new materials, and they take various forms such as sheet, grid, strip, and bar. Besides, in case of wall-facing structures, their rigidity and weight effect vary depending on their types, structures, and materials, and hence their reinforcing effect upon walls varies.

Regarding the design methods of such reinforced-soil structures, although they are commonly based on the limit equilibrium method, various design concepts are proposed for each type of structure, and for one and the same type of structure, individual design methods concerned propose their own concepts. However, they are not necessarily reflecting such reinforcing mechanisms adequately.

This report is compiled to summarize the present state and perspective of the design methods mainly for geosynthetic-reinforced soil structures and soil nailing for natural-ground.

2 GEOSYNTHETIC-REINFORCED STRUCTURES

2.1 *General remarks*

Geosynthetic-reinforced soil construction methods are applied to embankments, retaining walls, foundations of structures, soft grounds, etc. and enable us to construct soil structures as effective as the conventional concrete structures, by reinforcing soil and giving it ductility and flexibility against deformation. However, their design methods are based on the limit equilibrium method, and do not necessarily make the most of the properties of reinforced soil, though the construction records of such reinforced soil structures are abundant.

Expected of engineers in this scientific field is to develop "more rational" and "more economical" design methods under "more unified design concept and construct a "concept of combining simple design methods and detailed design methods," as well as to elucidate the reinforcing mechanisms.

Besides, new reinforced soil structures are being developed, and new applications, tried.

Discussed in this chapter are the present state and perspective of geosynthetic-reinforced soil structures, of which the points are as follows:

(i) Subjects of the current design methods based on the limit equilibrium method
(ii) Evaluation of seismic stability and its effect
(iii) Subjects in designing reinforced soil structures as permanent structures
(iv) Design methods under special conditions
(v) Utilization of low-quality surplus soil from construction sites
(vi) Reinforcing method of surface layers of soft grounds

2.2 *Subjects of current design methods based on limit equilibrium method*

The last decade has seen concentrated technical development of geosynthetic-reinforced soil structures, and data from follow-up inspections and surveys in the field have been building up. However, the reinforcing mechanisms have not yet elucidated fully, the design methods for such construction methods reflecting them inadequately.

Left outside the consideration of the current design methods are reinforcing effects not yet elucidated adequately such as the effect of slope-facing structures, the integration effect of reinforcements and soil into one body, and the effect of exclusion of seepage water. From this point of view, it can be said that the current design methods stand on the safe side, leaving a margin in the factor of safety. This margin was demonstrated by reinforced-soil structures which withstood the severe ground motion during the Hyogo-ken southern earthquake far exceeding their design seismic forces. Although such practical design methods have been made available as mentioned above, the design method is, by its very nature, a realm of symplasm. Calculation is made possible by reducing an actual phenomenon into a simple model. Accordingly, there remains many subjects such as going one step farther in pursuit of "veiled reinforcing mechanisms" and improving the technique for the prediction of behavior, typically of deformation (numerical analysis).

Principal technical subjects of the current design methods based on the limit equilibrium method are as follows:

(1) *Effect of Slope-facing structures*
The effects of slope-facing structures are classified by Tatsuoka (1993) as follows: (i) local rigidities, (ii) overall longitudinal rigidity, (iii) overall shearing rigidity, (iv) overall bending rigidity, and (v) gravity resistance, and slope-facing structures of concrete are highly appreciated for their contribution toward the stability of slopes. However, in case that geosynthetic reinforcements 1 m long or so are arranged densely in the area adjacent to the slope face, or in case that sandbags are piled up, each layer of sandbags wrapped in geosynthetic reinforcements and sandbags and reinforcements forming a multi-decker sandwich, such a flexible slope-facing structure can be regarded as a integrated structure, which contributes to the stability of embankments considerably. But we can cite few case examples of which the design took such effect into account. To address this subject, the following two approach would be worthwhile:

(i) Assuming that some anisotropic apparent cohesion is exerted in a integrated zone, to consider c and ϕ of the integrated zone in the circular slip analysis (PWRI 1988, Kutara et al. 1991).
(ii) In case that a integrated zone has relatively high rigidity, to reckon it to exert an retaining effect as a lean-to type retaining wall (Miki et al. 1991, Miki et al. 1992).

Though both the above methods are yet in a study stage, we expect that more rational design concepts with due regard to such effects of slope-facing structures will be proposed in near future.

Regarding, in particular, the reinforced embankment construction method, expected is the establishment of an evaluation method of apparent cohesion in a pseudo retaining wall consisting of densely arranged sandbags and geosynthetics. If such an evaluation method is made available, its evaluation results can easily be reflected in the design of embankments through the circular slip analysis. In addition, as for the reinforcing effect of low-rigidity, nonwoven-fabric-type geosynthetics laid closely which is difficult for the conventional stability analysis methods to explain, a more rational interpretation will become available.

Besides, it is necessary for a slope-facing structure to function as a pseudo rigid body that geosynthetic reinforcements be laid closely enough to make the reinforced zone integrated and make it, as if it were a mass of stabilized soil, exert apparent, anisotropic cohesion. In this regard, a large-sized triaxial compression test was conducted with different densities of reinforcement arrangement (Kutara et al. 1991). As the results of this test, it was confirmed that apparent, anisotropic cohesion was exerted in accordance with the tensile strength of, and the spacing between, reinforcements, and the propriety of the following equation was verified:

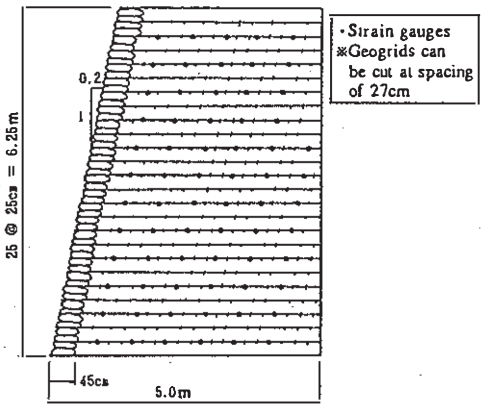
$$c_R = \beta \, T_f \sqrt{K_p}/2 \, \Delta H \qquad (1)$$

where c_R: apparent cohesion;
β: coefficient of correction;
T_f: tensile strength of geosynthetic reinforcements;
K_p: coefficient of passive earth pressure; and
ΔH: spacing between reinforcements.

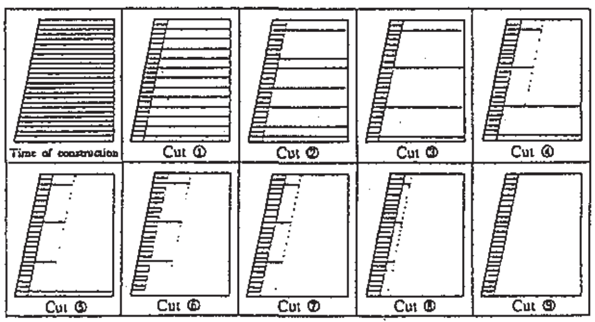
Though β is usually set at 1.0, the value of 0.43 was found in the above test.

In another study (Miki 1996a), sandbags and geosynthetic reinforcements were piled closely and alternately to construct a full-size slope-face structure (Fig. 1), the critical condition of the slope at the verge of failure was determined by cutting the geosynthetic reinforcements (cutting at 9) the circular slip analysis of the slope was performed to evaluate the effect of the slope-facing structure. As the results of this study, the safety factor of this embankment at failure appeared to be near 1.0 in case that the anisotropic, apparent cohesion in the zone of the virtual retaining wall, 45 cm thick, of piled sandbags was taken into account based on the result of large-sized triaxial compression tests with sandbags (c = 51 kN/m^2), whereas the safety factor was found to be 0.62 in case that the anisotropic, apparent cohesion was not taken into account (c = 2.0 kN/m^2), thus the former case being well consistent with the actual event.

Therefore, if a method is made available in future to



(a) Cross sectional view of steep slope embankment



(b) Cutting stages of geogrids

Fig.1 Full-scale failure test of geogrid reinforced steep embankment by cutting the reinforcements (Miki et al. 1992).

evaluate properly the anisotropic, apparent cohesion in the zone of a virtual retaining wall consisting of sandbags and geosynthetic closely arranged, the effect of such slope-facing structures can easily be reflected in design through the circular slip analysis.

(2) *Drainage effect of geosynthetics*
If geosynthetic with a drainage function is used to reinforced embankments, the effect of excluding seepage water can be expected when raining, in addition to the tensile reinforcing effect and the above-mentioned apparent cohesion effect (Kutara et al. 1990, Tatsuoka et al. 1983, Sato et al. 1984). If seepage water can be excluded even to a certain degree, it contributes considerably to the stability of embankments because the decrease in soil strength due to seepage can be delayed and restrained. At present, however, the seepage water exclusion effect is treated merely as an allowance outside the calculation of the safety factor, and we need more studies before we will be able to give it due treatment in design. If in future our study progresses to such an extent as we can take the seepage water exclusion effect into consideration in design, the usage of geosynthetic with a drainage function in top layers of embankments may begin to gain wide acceptance in reinforced embankment construction methods, too.

(3) *Prediction of deformation*
To predict the deformation of embankments and the tensile force acting on geosynthetic by using continuum FEM analysis, etc. which make up for the shortcomings of limit equilibrium models, essential is an analytical model which well represents the nonlinear deformation property and the dilatancy property of soil and the interaction property (frictional property) between soil and geosynthetic. In case of reinforced embankments, a very complex model is needed, and hence no verifiable method of such prediction has not yet established. Under the circumstances, one of the most important subjects in future is the development of a numerical simulation method which enable us to predict at a practical level of precision not only the deformation behavior of embankments during their construction, but also their post-construction behavior during rainfall or an earthquake.

2.3 *Evaluation of seismic stability and its effect*

(1) *Present state*
In regions of frequent earthquakes, armoring structures with seismic design is an important subject. As for reinforced embankments and retaining walls, seismic design methods have been established based on the concept of limit equilibrium-seismic forces are substituted with static loads by performing various laboratory and field experiments.

The seismic forces are handled by the method of determining the distribution of earth pressure acting on wall-surfacing structures during earthquakes based on experimental results (Terre Armee), or the seismic coefficient method of substituting horizontal accelerations with seismic coefficients. In design, on the other hand, an extra amount of reinforcements is provided, or the pull-out resistance between reinforcements and soil is calculated on the safe side, or the design safety factor in the stability analysis is set high, as the measures against earthquakes.

Although the current design methods do not necessarily reflect adequately the reinforcing mechanisms ascertained by experiments and tests, the recent severe earthquakes, Loma Prieta earthquake 1989 (Collin et al. 1992), Northridge earthquake 1994 (White & Holz 1996), Kushiro Offshore earthquake 1993 (Fukuda et al. 1994), and Hyogo-ken Southern earthquake 1995 (Tatsuoka et al. 1996a), revealed the high performances of reinforced soil structures (Photo 1). Some of them had been designed under ordinary conditions, which further testifies to the high performances of reinforced soil structures. This, on the other hand, suggests that the current design methods under ordinary conditions contain some allowance.

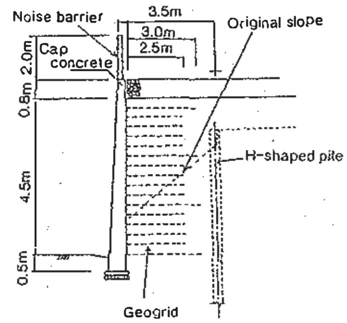


Photo 1 Scene in front of the RRR-walls in Tanata (Tatsuoka et al. 1996a).

(2) *Future problems*

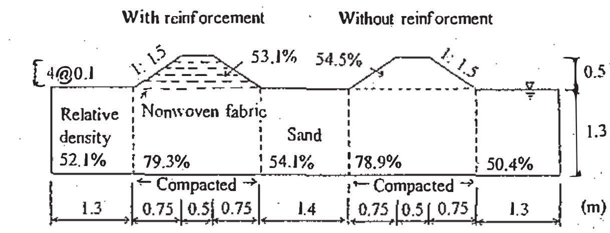
In order to reflect the seismic performance of reinforced soil structures in design, the following problems have to be solved:

(i) Setting of seismic forces: The incidence of earthquakes such as the Hyogo-ken Southern earthquake, a near field earthquake, is once in a thousand years in magnitude and type, and the maximum acceleration of the Hyogo-ken Southern earthquake recorded in the area hit most severely (magnitude VII) was over 600 gals. However, the design seismic coefficient for reinforced soil structures is 0.2 or so at the highest. The interpretation of this difference is one problem, and another is how to establish the concept of equivalent acceleration which reflects the ductility of reinforced soil structures.

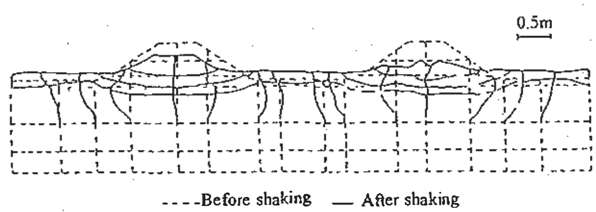
(ii) Handling of deformation: The limit equilibrium method gives no consideration to the deformation of reinforced soil structures. A certain degree of deformation of a structure, though far from causing its total destruction, can occasion it functional disorders and give it an unstable appearance. Thus, we need some measures in design to contain such deformation within an allowable extent in which the necessity of repair does not occur. An approach to such measures would be to review the concept of the factor of safety of the limit equilibrium method.

(iii) Numerical analysis methods: Seismic response analysis would be an effective means to interpret the behavior of structures during earthquakes and reflect the results in design. It is necessary to study how to make proper analytical models and how to reflect the analytical results in design.

(iv) Measures against liquefaction: Reinforcing an embankment on a soft sandy ground has no effect of restraining its subsidence if liquefaction occurs in the ground during an earthquake and it subsides, but such effect can be expected as prevention of the failure of, or cracks in, the embankment (PWRI 1989). Besides, with damage so restrained, we can relatively easily secure the means of transportation to cope with a state of emergency immediately after an earthquake, and can restore damaged structures with relatively small cost and in relatively short period of time (Matsuo et al. 1995). Such a design concept we need to build (Fig. 2).



(a) Initial condition before tests



(b) Final condition after tests at 240 gal

Fig.2 Shaking table tests on geosynthetic reinforced embankment on a liqufactive ground (PWRI 1989)

2.4 *Subjects in designing reinforced soil structures as permanent structures*

The number of reinforced embankments and soil walls constructed as permanent structures for roads, railways, housing sites, etc. has recently been increasing. In these applications, required are not only the economy but also the performance, and hence the following matters are important:

(i) Durability: The anticorrosiveness in case of metal reinforcing materials and the durability of wall surfaces in case of reinforced soil walls should be secured.

(ii) High stability and rigidity: It is necessary for the deformation of structures not to become excessive under various load conditions such as traffic load, rainfall, earthquake, etc. This is especially true of important structures such as bridge abutments.

(iii) Checkup of seismic stability and systematization of seismic design: To design reinforced soil structures as permanent structures, their seismic design methods have to be systematized as those for reinforced concrete or steel structures are done. This subject has taken up in 2.3 *Evaluation of seismic stability design method*.

(iv) Environment: Permanent reinforced soil structures have to be designed so that they can be in harmony with their environment including sceneries. Wall-facing structures, or wall facings, harmonious with various environment are also needed. Vegetative facings are friendly with environment.

Regarding the subject (ii), the deformation of a reinforced soil structure after being put in service can be minimized by providing, for example, a rigid wall-facing stucture. This is applicable to bridge abutments which, as shown in Fig. 3, support girders and hence are allowed only small deformation (Tateyama et al. 1994). For the same purpose of minimizing the deformation of structures after being put in service, a prestress, pre-load, reinforced soil wall construction method as shown in Fig. 4 is also devised (Tatsuoka et al. 1996b), and would be applied to abutments to support girders of longer spans.

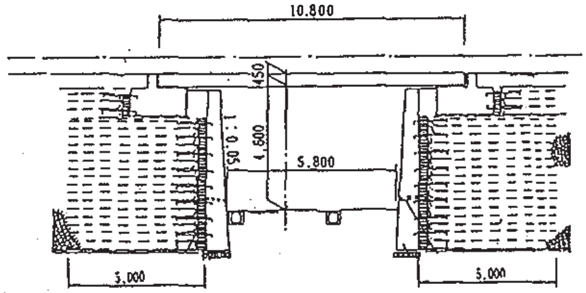


Fig.3 Cross section of geosynthetic-reinforced soil bridge abutments at Shinkansen Yard, Nagoya (Tateyama, et al., 1994).

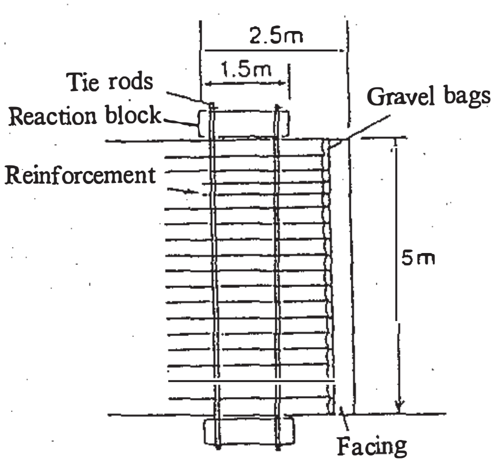


Fig.4 Typical PL/PS GRS retaining wall (Tatsuoka, et al., 1996b.)

The subject (iv) is also of considerable importance, since in order for reinforced soil structures to exist for a long period of time, they have to be compatible with their environment including sceneries. Requests for vegetation have been increasing recently, and accordingly the development of methods of vegetation and, at the same time, of providing high durability of paragraph (i) is a subject.

2.5 *Design methods under special conditions*

As far as the height of embankments, external forces, ground conditions, etc. are normal, the limit equilibrium method would continue to be practiced most commonly in future. Under special conditions, however, such as very large scale, existence of an important structure nearby, use as bridge abutments to support girders, soft ground, etc., it may become necessary to perform deformation prediction by a numerical analysis method, etc., in addition to the checkup of stability by the limit equilibrium analysis method.

Fig. 3 show an example of the application of such design method to an abutment supporting girders. Against the large local load acting from a girder-supporting foundation onto the top of the abutment, or embankment, the closely arranged geosynthetic reinforcements and the rigid wall-facing structure minimize the deformation of the abutment. The specifications of such a wall-facing structure such as required strength of, vertical spacing between, and length of, reinforcements, and configuration of the wall-facing structure (thickness, arrangement of reinforcements, etc.), necessary to secure a given factor of safety, can be determined by the limit equilibrium analysis. However, because this was the first application of the geosynthetic-reinforced soil structure to such abutments, and also because it was a railway bridge which requires strict limitation on allowable deformation, the deformation was predicted by numerical analysis, and the calculated results were compared with the measured data obtained by conducting static loading tests. Besides, the measurement was continued after the bridge had been put in service to confirm the safety of the bridge (Tateyama & Murata 1994). It was confirmed through these analysis, test, and measurement that in case of the bridge structure, or configuration, shown in Fig. 3, the deformation of abutments supporting girders of spans of 10 m or so fell within an allowable extent if the safety factors of such abutments had been secured by the limit equilibrium analysis. Thereafter to date, more than 10 bridges have been constructed by using the above technique.

In the case of a large-scale reinforced soil wall constructed on a very soft ground (Kojima et al. 1994), numerical analysis was performed in advance to predict the consolidation settlement of the ground and the deformation of the embankment, and the height of the pre-loading embankment, the leave-it-alone period, the time of construction of the wall-facing structure, and so on were determined by using the predicted values as reference data.

Thus, under the special conditions, numerical analysis is needed in our practical affairs. To predict the deformation of reinforced embankments and tensile forces acting on geosynthetic by using continuum FEM analysis, etc. which make up for the shortcomings of the limit equilibrium analysis method, essential is an analytical model which well represents the nonlinear deformation property and the dilatancy property of soil and the frictional property between soil and geosynthetic. In case of reinforced embankments, a very complex model is needed, and hence no verifiable method of such prediction has not yet been established. Under the circumstances, one of the most important subjects in future is the development of a numerical analysis method which enable us to predict the deformation behavior of embankments at a practical level of precision, and the precision can be improved by practicing comparative study with data of laboratory tests and field measurement. Besides, the improvement of precision of the numerical method leads to the rationalization of the limit equilibrium method.

2.6 *Utilization of low-quality surplus soil from construction sites*

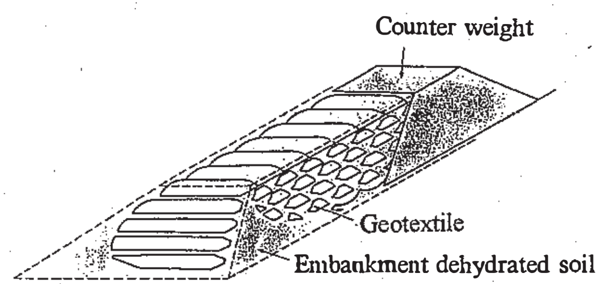
The volume of surplus soil from construction sites has recently been increasing as urban development, utilization of underground, and so on have vigorously been carried forward. Particularly in urban areas, it has become difficult to secure disposal lands of such surplus soil. Under the circumstances, utilization of such soil is hoped for so that construction of buildings and structures can smoothly be carried forward. In the Metropolitan area, of the annual total volume of surplus soil of about 120 million m^3, approx. 70% is silt, Kanto loam, cohesive soil, etc. of high water content and low quality. Accordingly, how to use these low-quality soils is the point of the promotion of the surplus-soil utilization.

As a technique to utilize such soils of high water content and low quality, the embankment construction method using geosynthetics to improve drainage and strength is very effective. An embankment being constructed with cohesive soil of high water content is apt to lose its stability due to an excessive pore water pressure, if occurred, during its construction. In this case, by using geosynthetics as horizontal drainage materials, excessive pore water pressure is dissipated and the soil strength improves through its consolidation, as the construction progresses. Thus, such use of geosynthetics make the otherwise difficult construction works simple and economical. Stabilization with cement, lime, etc. becomes unnecessary, surplus soil without any treatment can be carried from the site of its generation to the site of its utilization, and while piling up the soil, soil strength develops by the selfweight effect of piled soil and the drainage effect of the geosynthetics. In this method, it is not purported to add strength to soil by the stabilization of soil or the tensile reinforcing effect of geosynthetics, but the original strength of soil is derived. In this meaning, it is very rational and economical.

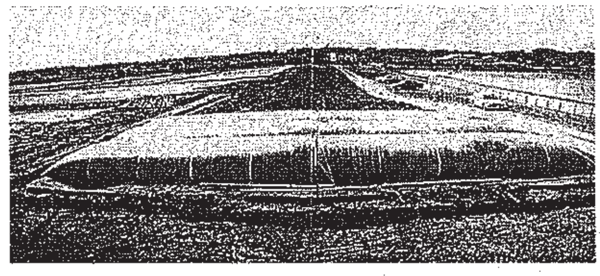
However, because the design method of the current embankment construction method using cohesive soil of high water content and geosynthetic to improve drainage and strength is proposed based on a theory applicable to saturated soils, it is applicable to only such soils. It is necessary in future to establish a theoretical method applicable to a little bit unsaturated soils, too. Besides, hoped for are not only methods applicable to embankments on land, but also methods applicable to underwater embankments as underwater lands being reclaimed from the sea.

Moreover, it is difficult with the conventional method to construct stable, steep slopes with low-quality surplus soil from construction sites, but if such construction becomes practically possible by using geosynthetics, the prospects of such construction method will be bright in the high social mood for recycling.

Regarding the geotextile-tube dehydration method (Miki et al. 1996) which is under development as one of the researches for high-grade soils, basic



(a) Schematic diagram of the use of tubes to form an embankment.



(b) Piled up geotextile tubes.

Fig.5 Tests of geotextile tube dehydration method (Miki. et al., 1996).

experiments are being conducted to apply the method to envelop-and-pour-type dikes; i.e., pouring sludge of Kasumigaura (a vast creek in the Kanto plains) into large-sized tubes of which the periphery and length are 10 m and 20 m, respectively (Fig. 5). In addition, construction works are being carried forward, deposited silt in dams utilized by this method, and construction of multi-natural revetments by this method are under way. The evolvement of the sacked dewatering method in future is expected.

2.7 *Reinforcing method of top layers of soft grounds*

In Table 1, applications of geosynthetics to embankments on soft grounds are classified into four categories.

In the soft-ground top-layer reinforcing method for cover soil, proposed are a number of design concepts which take the bearing-capacity mechanism into consideration. However, since the influence of such construction methods is significant, the tensile strength of reinforcing materials is in reality determined based on experience in the past. Accordingly, hoped for is the establishment of more rational design methods through analyses of construction cases to date.

In the soft-ground top-layer reinforcing method for embankments, it is made clear from the feasibility study made by the Public Works Research Institute that in case of a deep soft ground or a high embankment of which the given stability factor against slip can not be secured by sand drains alone, using geogrids as an auxiliary method is effective from an overall point of view. Therefore, hoped for is the development of applications unique to geosynthetics and competitive with the conventional construction methods.

Regarding the combined method of the geosynthetic reinforcing method and the CDM, proposed is a method that, with an idea similar to the pile-net method, the whole foundation ground of an embankment is improved with piles by the CDM of a low improvement rate (10-30%), and the shortage of stability against circular slip are made up for with geogrids of high strength, or geosynthetic is used as a countermeasure against the settlement differential between on the improved soil bodies and on the unimproved soil (PWRC 1993, PWRI 1992, Murata et al. 1986, RTRI 1987).. Although such method combined with the CDM of a low improvement rate has not yet established as a design method, it is expected to come into practical use as a new and economical approach to the improvement of soft grounds.

Furthermore, hoped for as a countermeasure against earthquakes are studies to apply geosynthetic-reinforced soil construction methods to the restraint of subsidence of embankments, during earthquakes, constructed on soft sandy grounds which threaten liquefaction when hit by an earthquake. This subject has taken up in 2.3.

Table 1. Category of geosynsethics application for countermeasures of soft ground.

Application	Construction method (reinforcements)
Surface reinforcement for reclamation	Sheets laying method (geowovens) Nets laying method (geonets) Sheets and ropes method (geowovens etc) Sheets and bamboos method (geowovens)
Surface reinforcement for embankment	Planar reinforcements (geotextiles) Single layer type (Steel rods with anchor-plates) Multi-layer type 3-D reinforcements (Geomats, Geocells)
Piles combined with reinforcement	Piles-nets method (Steel wires, Geotextiles) Deep cement mixed piles-nets method (Geonets, Geogrids)
Subgrade reinforcement	Improve bearing capacity (Geogrids) Prevent boiling of mud in railway subgrade (Geocells, Geononwovens, Geowovens, Geomembranes)

3 GROUND REINFORCEMENT

3.1 *General remarks*

The ground reinforcement has a variety of uses such as used to construct stabilizing structures of natural slopes and cut slopes, retaining walls, excavation works and reinforcing structures of foundation grounds. In this chapter, we discuss this method, focusing on stabilizing structures of natural slopes and cut slopes.

The ground reinforcement has empirically been used in construction fields since long time ago, and laboratory experiments and test construction started in 1985 or so, the method recognized as a ground reinforcement.

The reinforcing principle of this method is: when excavation of, or change of the load on, a natural ground begins to cause its deformation, tensile, compressive, shearing, bending, and other forces act on its reinforcements. At the same time, the reinforcements exert passive resisting forces, restraining the deformation and stabilizing the natural ground. In the current design method of ground reinforcement, however, the limit equilibrium method is commonly used, and therefore it is hardly good enough to reflect the above reinforcing principle adequately (Research Committee for Ground Reinforcement, JGS 1996). In order to incorporate the design in the actual behavior of reinforced natural grounds, the following have to be made properly: (i) setting of design parameters of natural grounds, (ii) evaluation of the functions of reinforcing materials, (iii) introduction of a design method which takes account of deformation, and (iv) evaluation of the effects of slope-facing structures.

On the other hand, the following are the subjects attracting attention recently: construction works with monitoring, seismic stability and its evaluation method, durability as permanent slope , construction method taking account of the landscape, application of new materials and new construction methods, and so on.

3.2 *Stability analysis*

(1) *Setting design parameters of natural grounds*
The strength parameters of the soil and the pull-out resistance of the reinforcements used in designing a ground reinforcement are usually determined by their individual tests. However, because the strain levels, at which the pull-out resistance of the reinforcements, the shearing resistance of the soil, and the passive resistance of the soil against the reinforcements are different, it is necessary to determine such design parameters, taking account of these strain conditions. For instance, in case that the peak value is used as the pull-out resistance of the reinforcements, a strength corresponding to the same strain level in stress-strain relation of soil shall be used. Proposed in the U.K. is a method of using residual strengths as strength parameters of grounds (Department of Transport, UK 1994), which takes into account decrease in the strength parameters to be caused by deformation.

(2) *Evaluation of functions of reinforcements*
When the natural ground with reinforcement is deformed, the deformation exert tensile, compressive, shearing and bending forces on reinforcement laid in the ground. These forces vary, depending on the specifications of reinforcing materials, e.g. shape, tensile rigidity, compressive rigidity, bending rigidity, shearing strength and coefficient of friction, the properties and conditions of grounds, e.g. coefficient of deformation, strength parameters and moisture condition, and the interaction between soil and reinforcements. At present, in most cases, the reinforcing effects of reinforcements are evaluated based on their tensile resistance. There are few cases taking account of tensile, compressive, shearing and bending resistance mentioned above. In France, the multicriteria method concerning the pullout failure, failure by plastification of the soil before the nail, the tensile and shearing strengths of the bar, and reinforcement plastification caused by the bending moment (Scientific Committee of French National Project CLOUTERRE 1993).

(3) *Introduction of design method taking account of deformation*
In the current design method, stability is checked by the limit equilibrium method, but deformation is not taken into account. Accordingly, at present, as the means to reduce the deformation of natural grounds and adjacent structures, the overall safety factor against the ultimate failure condition is set high, or consideration is given to the arrangement of reinforcements. Regarding the stability of a natural ground under excavation, tried is a method of estimating the displacement from the properties of the ground and the height of wall by using empirical formulas based on measured data (Scientific Committee of French National Project CLOUTERRE 1993).

Being performed as post-analysis using numerical analysis, i.e. FEM, are the stability evaluation of ground reinforcement and the evaluation of axial forces of reinforcements, based on the strains and the distribution of local safety factors. In future, when the ground reinforcement is applied to natural grounds of important structures or adjacent to structures, such evaluation method will be needed more and more for the estimation of deformation in the design stage.

The deformation analysis of ground applied of the ground reinforcement have the same subject, e.g. correct initial condition, constitutive model of ground materials, boundary condition and so forth, as deformation analysis commonly recognized in the field of the geotechnical engineering. In addition, the interaction between soil and reinforcements has attracted significant attention. Accordingly, the following specific subjects for the deformation analysis of the ground reinforcement have to be addressed:

(i) Modeling taking account of the dilatancy effect restricted by relative displacement between soil and a reinforcement or a shearing zone along the boundary caused by such relative displacement

(ii)As for the expression (composite material) of the assumptions for a pseudo-retaining wall and the unification effect of a group of piles.

(iii) Reducing the three-dimensional behavior of linear reinforcements into a two-dimensional model

(iv) Modeling of pressure-bearing grounds and facing units

In addressing the deformation problem in future, the construction works with monitoring by back analysis would be an effective means to narrow down the gap between the precision in surveys and tests to determine the parameters and the precision of analytical models on one side and the precision of actual design on the other side.

(4) *Evaluation of effectiveness of facing units*
It is ascertained by experiments, etc. that facing units have large effectiveness on restraining the deformation of the ground, provided the facing units and the reinforcements connect together tightly (Mutamatsu et al. 1995). Consequently, several design methods which take account of the effectiveness on facing units, are proposed (Japan Highway Public Corporation 1995, RRR Construction Method Association 1993).

Fig. 6 illustrates the design concept employed in the method, giving consideration to the effectiveness of the facing as well as the effectiveness of the reinforcements.

In this design method, as shown in the equation (2), the resistance force of a reinforcement, T_{pa}, is the lowest among the pull-out resistance of the reinforcement due to the sliding mass, T_{1pa}, the pull-out resistance mobilized in the resisting area, T_{2pa}, and the tensile strength of the reinforcement, T_{sa}. The earth

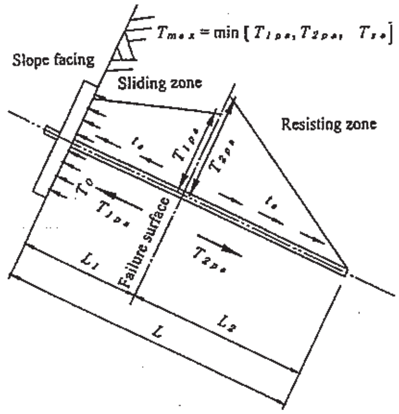


Fig.6 Schematic distributions of resisting forces on the nail (Japan Highway Public Corporation 1995).

pressures of the sliding mass acting on facing unit, To, is considered in calculating T_{1pa}.

$$T_{pa} = \min.\ \{T_{1pa},\ T_{2pa},\ T_{sa}\} \qquad (2)$$

3.3 *Construction works with monitoring*

It is difficult to grasp the soil properties of a natural ground in advance and precisely, moreover it is difficult to predict the deformation of the natural ground during the phase of its reinforcing works and set managerial criterion values. Important is, therefore, construction works with monitoring; i.e., to conduct measurement of the displacements at the top of slope, the displacements in the ground, the axial forces exerted on the reinforcements, etc. and to review the managerial criteria and the design based on the measured data.

An approach using "back analysis" has recently come into use. Fig. 7 shows such a case (Tayama et al. 1996a, Japan Highway Public Corporation) and the arrangements of measuring instruments and apparatus. Fig. 8 is the flow chart of the construction works with

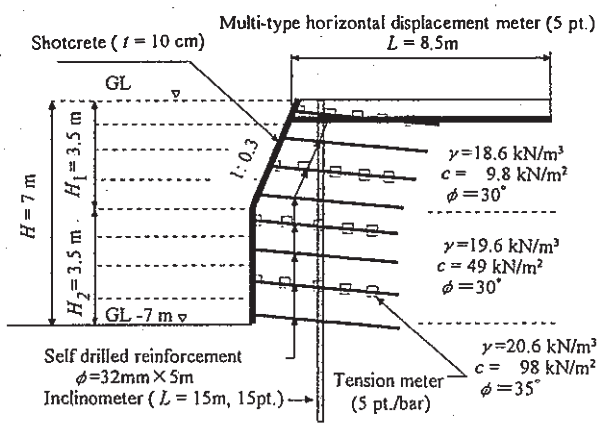


Fig.7 Cross section of test cut-slope and instrumentations (Tayama et al., 1996a).

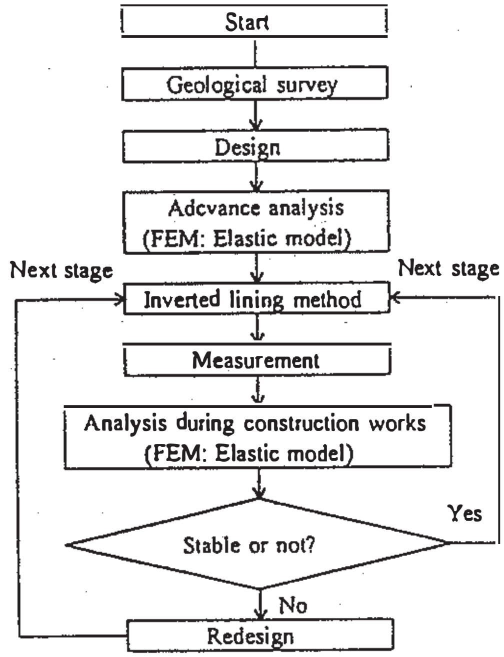


Fig.8 Flow chart of construction control system by applying backward analysis (Tayama, et al., 1996a).

monitoring regarding the case above. At the end of data each stage, FEM back analysis is conducted based on the so far obtained to review the soil parameters (mainly the modulus of elasticity), and FEM analysis is conducted again based on the soil parameters which was revised to evaluate the stability of the reinforced soil structure at the next stage or at the completion of works. This approach, however, has many problems such as the stability-evaluation method.

Although it is necessary to pursue a method of construction works with monitoring required high precision like the approach above, the measurement and analyses to be performed in such an approach are costly and the merit of economy of the ground reinforcement is reduced. Accordingly, hoped for is research and development of a simpler method; for example, based on the measurement of displacement at only the top of the slope.

3.4 *Seismic stability and its evaluation*

There were many ground reinforcement structures in the area hit by the Hyogo-ken Southern earthquake, and reports have been made to confirm their high seismic stability (Matsui et al. 1995, Tsukuda et al. 1996, Fujii et al. 1996, Otani et al. 1996). Besides, the ground reinforcement has been adopted to restore damaged structures, its advantage derived well. However, the current seismic design methods do not necessarily appreciate the earthquake-resistant performance of ground reinforcement. Accordingly, to be considered in making seismic design of ground reinforcement are the following:

(1) *Necessary conditions*
Because ordinary cut slopes are not armored with seismic design, the necessary conditions for the seismic design of reinforced cut slopes have to be set.

(2) *Earthquake-resistant performance of ground reinforcement*
When a reinforced cut slope begin to deform under a seismic load, the tensile forces of the reinforcements increase and they function to maintain the shearing strength of the soil without reducing the restricting pressure and to bear the seismic load. Besides, ground reinforcement has high toughness in the meaning that its deformation at failure is larger than that of unreinforced ground. Since ground reinforcement has excellent seismic stability in both the strength and the toughness, it is not too much to say that it has larger effect in the seismic condition than in the stationary condition. The high toughness of ground reinforcement is not directly reflected in the stability analysis by the limit equilibrium design.

These features taken into account, described below are the subjects of the current design method in order to establish, in future, a seismic design system which can precisely evaluate the earthquake-resistant performance of ground reinforcement.

(1) *Setting of seismic loads*
Levels of seismic forces, failure modes of ground reinforcement, effects of vertical seismic load are to be determined and set by occurrence probability of earthquake types such as near field earthquake and great earthquake, their incidences taken into account. Therefore, the limit state design method would be an effective means.

(2) *Modification of seismic coefficient method*
There is a tendency that the higher the cut slope is, the more the horizontal acceleration of the slope face is amplified. Accordingly, the applicable range of the seismic coefficient method, the applicability of modified seismic coefficient method, and the modification method have to be studied. Model tests and seismic response analyses assuming seismic conditions are effective means, and also seismic observation of long, large slopes is hoped for.

(3) *Optimization of seismic response analysis*
Toward more detailed seismic analysis, a method of modelling reinforcements in two dimensions which is capable of taking account of three-dimensional reinforcing effect and non-linear seismic response analysis which enable us to analyze the strain area of soil and reinforcements during earthquakes of large deformations are needed.

Given the above subjects, we have to clarify the failure mechanisms and earthquake-responding properties and conditions by surveying ground reinforcement structures damaged by earthquakes and making comparative study of results of shaking-table tests and numerical analyses.

3.5 *Durability as permanent structures*

In case that a reinforced ground with steel materials like reinforcing bars applies for a permanent slope, the durability of the reinforcements has to be given careful consideration. In Europe, conceptions such as corrosion prevention with plastic sheaths, corrosion allowance, and so on, are introduced into guidelines (Scientific Committee of French National Project CLOUTERRE 1993, Gassler 1988), etc. In Japan, although some guidelines or the likes prescribe corrosion allowances, their base data seem poor. Recently Japan Highway Public Corporation extracted some reinforcing bars using over-core boring at nine permanent slopes more than 10 years old, and examined their corrosion conditions through material tests, etc (Tayama et al. 1996b). As the result, pointed out as the causes of their corrosion were shortage of grout around the top parts of the reinforcing bars, short covering of their lower parts by grout, etc. However, because their survey was limited, data have yet to be collected and accumulated.

3.6 *Landscape*

Because the ground reinforcement enables to construct steep cut slopes, which means the reduction of topographical alteration and the reduction of cut over areas of forests, it can be said to be friendly to scenery. Because the reinforcements are driven in the ground, concerned with the landscape are the surface structure, or facing, and the shape of the cut slope. At present, available as scenery-friendly surface structures, instead of the conventional sprayed mortal or plain concrete surfaces, are wall-surface vegetation (vegetation blocks or vegetated frames arranged grid-form), vegetative facings (continuous fiber-reinforced walls), and cosmetic finishes (cosmetic blocks resembling stone-masonry retaining walls, or relief wall surfaces).

Described below are the present subjects and the perspective regarding the landscape problem:
(1) Both the water retentivity for vegetation and the drainage function for its stability have to be given to a facing structure to be vegetated. Besides, structure which will be easy and economical to maintain is required.
(2) When a slope is steep and high, it give us oppressive impression. A certain proper gradient has to be found from this aspect.
(3) Demand for facing structures constructed with precast members is expected to increase due to the necessity of laborsaving execution of works. Such members have to be developed in such colors and finishes as match the various construction sites.

Besides, design of ground reinforcement shall includes landscape design which takes account of natural environment such as climate and social environment (Miki 1996b).

3.7 *Application of new materials and new construction methods*

New construction methods, for instance, of using, as core materials, materials with drainage function, or glass or vinyl fibers of high anti-corrosiveness and high strength, of expanding the tips of reinforcements have recently been developed. Also the construction method of forming soil-cement anchors of 40-50 cm diameters and place core material in the center of each anchor have been developed. For these methods, the accumulation of construction cases is awaited.

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