Earth Reinforcement, Ochiai, Yasufuku & Omine (eds) © 1997 Balkema, Rotterdam, ISBN 9054108339

Current state on numerical analysis of reinforced soil structures

J.Otani – *Department of Civil and Environmental Engineering, Kumamoto University, Japan*
A.Yamamoto – *Technical Research Institute, Obayashi Corporation, Kiyose, Japan*
T.Kodaka – *Institute of Industrial Science, University of Tokyo, Japan*
N.Yasufuku – *Department of Civil Engineering, Kyushu University, Fukuoka, Japan*
A.Yashima – *Department of Civil Engineering, Gifu University, Japan*

ABSTRACT: In recent years, considerable interest in the earth reinforcement techniques has promoted both fundamental and practical studies as well as the development of various types of reinforcing materials. It follows that new techniques for this earth reinforcement and their applications to geotechnical engineering practice have been also running around the whole area of Asia. In this paper, the purposes are : 1) to investigate what kind of numerical analysis is conducted for this decade; 2) to investigate what kinds of models including soil, reinforcing material, and the interaction have been used; to clarify what is indispensable modeling at least; and 4) to clarify the task of numerical analysis to the design method. It is noted that this paper was prepared by the working group of Japanese Supporting Committee for Asian TC.

1 INTRODUCTION

Earth reinforcement technique has been used around the world in this three decades starting from the middle of 1960's. It is no doubt that many research and practice have been conducted under this development. Especially, the quick development of computer machine made the complicated numerical analysis possible. For example, finite element analysis was capable of solving the boundary value problems with complicated boundary conditions and material properties. Meanwhile, many conferences and symposia on the theme of earth reinforcement also have been held, and for instance, three consecutive IS Kyushu(International Symposium on Earth Reinforcement in Kyushu) in every four years('88, '92 and '96) have accepted many technical papers concerning the numerical analysis on earth reinforcement. Under these circumstances, it is expected to make clear what we know and what we do not know about numerical analysis for earth reinforcement at current stage.

In this paper, the objectives are

1) to investigate what kind of numerical analyses have been conducted;
2) to investigate what kinds of models including soil, reinforcing material, and its interaction have been used;
3) to clarify what is indispensable modeling; and
4) to clarify the task of numerical analysis to the design method.

In order to complete these purposes, First of all, the technical papers, which have been published so far, concerning earth reinforcement with numerical analysis are reviewed and based on this paper review, the statistical discussion about current state of numerical analysis is conducted. Then, the various modelings for reinforced soil including soil, reinforcing material, and its interaction are summarized by introducing some of the papers. And finally, the current state of the numerical analysis on earth reinforcement is summarized.

2 STATISTICS OF CURRENT STATE

Statistics on current state of numerical analysis is summarized based on the survey of technical papers for last 12 years(from 1985 to 1996). The papers with the keywords of "Earth Reinforcement" and "Numerical Analysis" were selected from following Journals and Proceedings:

1) Journal of Geotechnical Engineering, ASCE
2) Geotechnique
3) Canadian Geotechnical Journal
4) Soils and Foundations
5) Geotextiles and Geomembranes
6) Computers and Geotechnics
7) Int. J. Nume. Anal. Meth. in Geo.
8) Jour. of Geotechnical Engineering, JSCE
9) Proc. IS-Kyushu ('88, '92, and '96)

The total number of papers which was reviewed in this paper was 192. The purpose of these researches are listed as follows:

1) development of design chart;
2) proposal of new design method;
3) development of new numerical modeling and method;
4) analysis of case study;

5) search for the reinforcing mechanism;
6) application of new reinforcing materials; and
7) new feasibility of earth reinforcing technique.

These papers are classified into 13 items as shown in Table 1 and as a results of paper review, the papers in each item are classified. Here in this chapter, each item is discussed separately.

2.1 *Analysis Type*

There are two types of analysis which are deformation analysis and stability analysis. As shown in Fig.1, it is easily realized that the number of papers for each analysis is exactly the same between these two analyses. About 90% of the deformation analysis are finite element(FE) analysis and the rest of them are shared with Rigid Body Spring Model(RBSM) and explicit solutions such as elastic solution. Most of studies used FE analysis are the applications of constitutive equation or interaction model in order to simulate real behavior of reinforced soil structures. Recently, the use of limit state design is about to discuss for geotechnical engineering practice and in this design method, two different limit states which are serviceability limit and ultimate limit. As FE analysis can offer the result of deformation, it is possible for this results to be a useful information for design purposes, especially for serviceability limit on the limit state design. As far as the papers reviewed in this paper, not many papers has not been discussed on this point of view. When the reinforced soil structures are applied to more important soil structures, its deformation property will be able to be controlled strictly. In future works, the residual deformation after earthquake is also expected to be verified. Therefore, the purpose of FE analysis should be covered these design purposes.

Table 1 Results of paper review

Item				Number	
Object	Analysis Type		Deformation	90	
			Stability	91	
	Problem		Static	151	
			Dynamic	10	
	Structure		Embankment	51	
			Retaining Wall	41	
			Natural Slope	32	
			Foundation	46	
			Laboratory Testing	23	
Numerical Analysis Method	Analysis method		Explicit Solutions	10	
			FEM	84	
			BEM	0	
			RBSM	2	
			DEM	0	
			Slip Line Method	12	
			Upper / Lower Bound Method	12	
			Limit Equilibrium	40	
			Else	12	
	Dimension		2-dimentional	156	
			3-dimentional	6	
MateiialProperties	Soils		Sand	79	
			Clay	35	
			c and ϕ Material	61	
			Rock	8	
	Reinforcing Material	Geosynthetics	Geogrids	71	
			Geonet	1	137
			Non-woven	23	
			Woven	20	
			Geocell	3	
			Membrane	10	
			Else	9	
		Steel	Steel Bar	39	50
			Steel Strip	11	
			Else	0	
	Else			3	
Modeling of Interaction between Soil and Reinfocing Material			Individually tereated	81	
			Composite Material	21	
			Whitout Interaction	31	
			Pull-Out Strength is used	37	
			Else	4	
Compared with Experimental Results			Yes	73	
			No	88	
Year					
Area			Asia	89	
			EU	33	
			America	41	

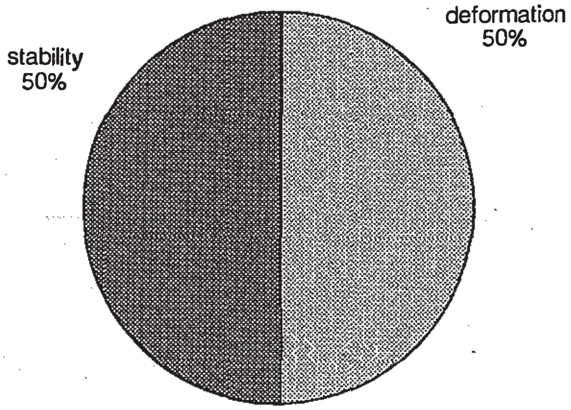


Fig.1 Analysis type

Meanwhile, for the stability analysis, about 36% of the papers concerning the stability analysis are limit equilibrium method following FE analysis(32%) and the others(27%) including slip line method and limit analysis with upper and lower bound methods. It is noted that most of limit equilibrium method are the purpose of design calculation, so that it seems somehow different from other numerical analysis.

Figure 2 shows the change of number of papers during the period of 1985 to 1994. It is easily realized that the number of papers concerning numerical analysis is increased after 1992.

2.2 *Problem Type*

Figure 3 shows the percentage of whether the problem conducted is static or dynamic. More than 90% of the papers have solved static problem. Most of papers are from Japan and U.S.A. for dynamic problem and the method of analysis are mostly FE analysis.

2.3 *Applications*

Figure 4 shows the applications of structures. In the earth reinforcement method, there are four typical applications which are embankment, wall structures, foundations, and natural slopes. Although there are a little difference in its percentage, those are almost the same percentage except the papers solving laboratory testing.

2.4 *Analysis Methods*

Figure 5 shows the variation of the methods on numerical analysis. About half number of total papers conducts FE analysis. The limit equilibrium method is the second which percentage is 23% following slip line method(7%), upper/lower method(7%), explicit solution(6%) and RBSM (1%). In the FE analysis, the ground (soil) is modeled with linear elastic, nonlinear elastic, elasto-plastic, or elasto-viscoplastic materials, and reinforcing material is modeled by truss, beam, or thin layer element. The friction property is mostly considered in the interaction model.

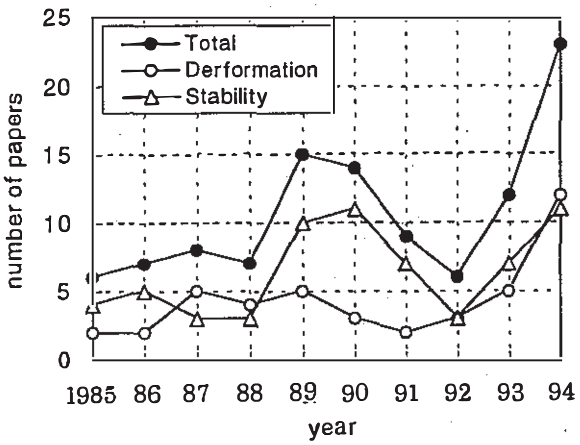


Fig.2 Change of number of papers

2.5 *Dimension*

As shown in Fig.6, 96% of numerical analyses are 2-dimensional analysis. 3-dimensional analysis is a rare case(4%). The structures of 3-dimensional analysis is the case of natural slopes. Here, the method of analysis used is FE analysis and the reinforcing material is steel bars. Although the case of using geosynthetics can be simulated in plane strain condition, for the case of natural slopes with steel bars, its dimension should be 3-dimension and its behavior deeply depends on the deformation and the axial stress acting steel bars in 3-dimension.

2.6 *Soils*

Figure 7 shows the soils which have been solved in the numerical analysis. The sandy ground is major object because the major applications such as embankment and retaining wall are used sandy materials, It is noted that the soil has been modeled with c-ϕ material(33%) because of its generality.

2.7 *Reinforcing Materials*

(1) Geosynthetics

As shown in Fig.8, the major geosynthetics solved in the numerical analysis is geogrid(51%) following nonwoven(17%) and woven(15%) geotextiles, respectively. It is noted that some of the papers deal with not special materials but any types of material. Thus the percentage of this category might be unreliable.

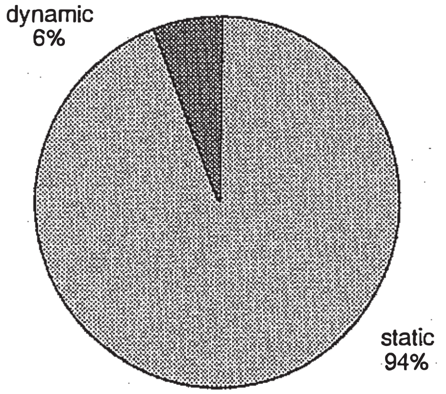


Fig.3 Problem type

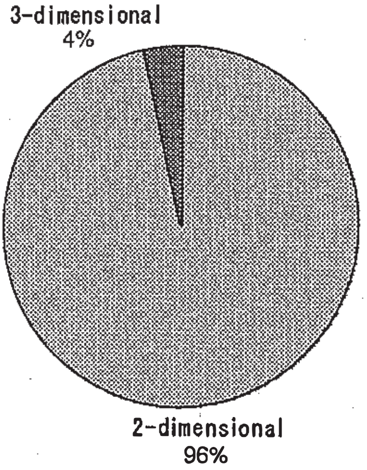


Fig.6 Dimension of analysis

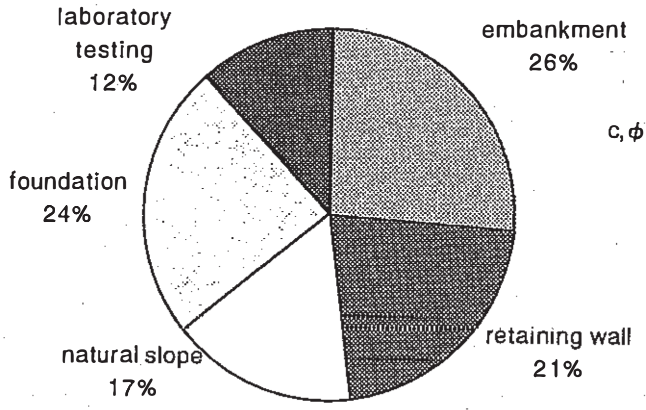


Fig.4 Applications

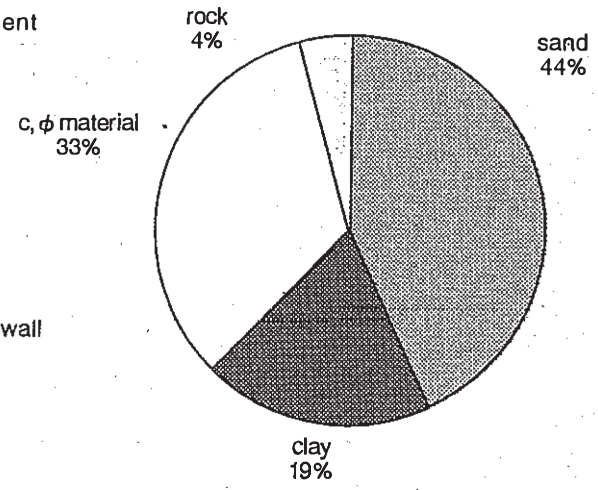


Fig.7 Soil type

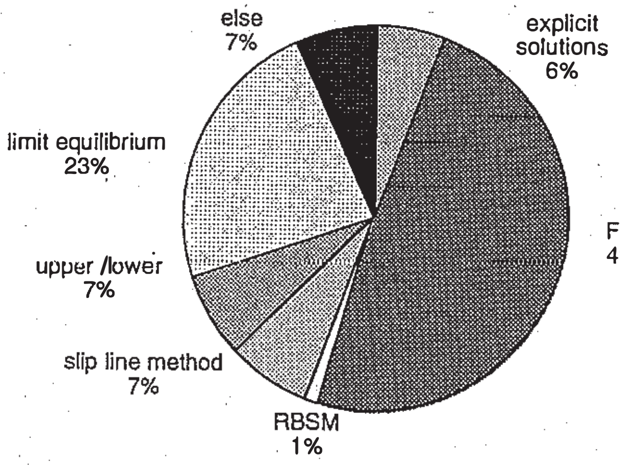


Fig.5 Analysis methods

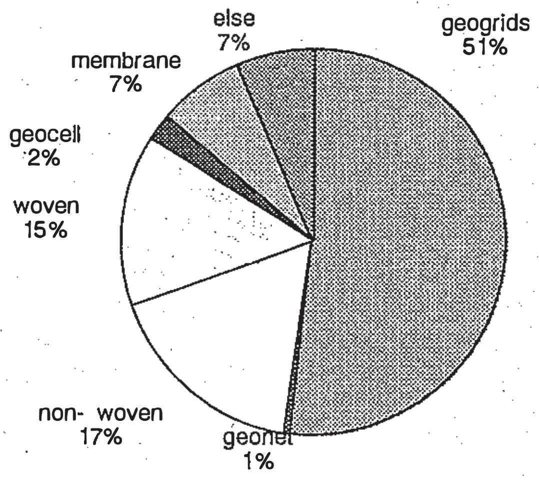


Fig.8 Reinforcing material (geosynthetics)

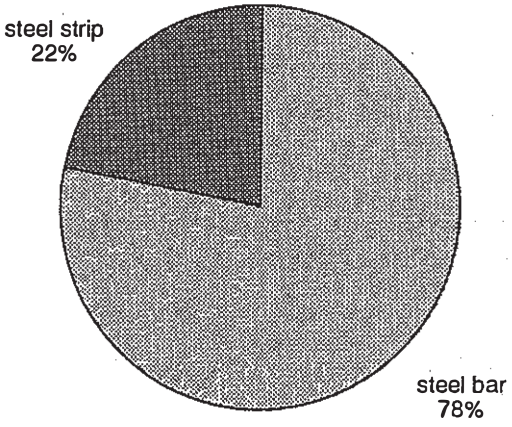


Fig.9 Reinforcing material (steel)

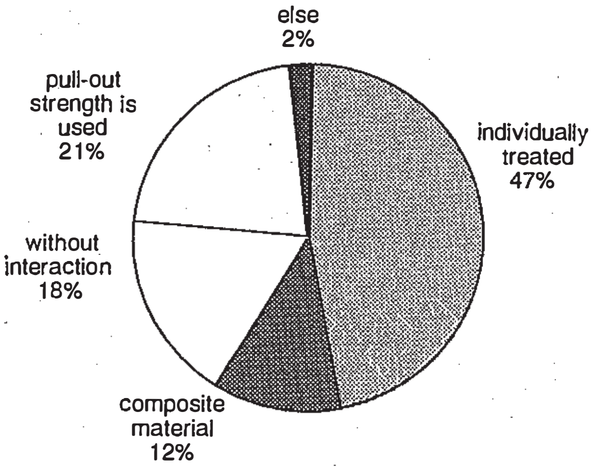


Fig.10 Model of interaction behavior

(2) Steel

As shown in Fig.9, 78% of the analyses deal with steel bars for soil nailing. In most cases, the structures used the steel bar are natural slopes and in some cases, it is applied to embankment, retaining wall and foundation. The structure used steel strip is retaining wall only (e.g. Terre Armee method).

2.8 *Interaction*

As shown in Fig.10, 47% of numerical analyses for reinforced soil structures consider interaction between soil and reinforcing material. The importance of these interaction models in numerical analysis of reinforced soil structure will be understood strongly and widely. 12% of interaction modeling in numerical analysis have been used composite material to the zone reinforced with reinforcement materials. Especially, the number of published paper related to composite material is increased after 1991. 21% of interaction is pull out testing. The results of laboratory pull-out test have been used for numerical analysis with fairy large number of percentage (21 %), especially in Japan.

3. HIGHLIGHTS OF SOME OF THE RESEARCHES

As realized from Fig.5, most of the numerical analyses have been conducted with finite element method, so that some of papers concerning finite element analysis are summarized with their prominent points of view. Here, the analyses are divided into two categories which are deformation analysis and stability analysis. It is noted that slip line method is also discussed on the stability analysis.

3.1 *Deformation Analysis*

In order to show its modeling and purpose of the analysis, some of the technical papers are introduced.

(1) One of the pioneer works (Ohta et al., 1980)

Transverse surface reinforcements at the bottom of embankments placed on very soft foundations were found to reduce the amount of deformation of the foundations and to improve the bearing capacities through the elasto-plastic finite element analysis on an idealized model of soft foundation as well as on a field trial embankments. The constitutive equation employed is an infinitesimal elasto-plastic stress-strain relation which is reduced to the Original Cam Clay model under conditions of isotropic initial stress state and which is able to describe the anisotropic behavior of clay including the complicated responses to the rotation of principal stress direction, so called Sekiguchi-Ohta Model. The computed program used is the one originally written by Akai and Tamura (1976) which employs the backward finite difference scheme so as to ensure better stability in computations.

A trial embankment was placed on a very soft layer of peat and clay. The trial embankment, 386.3m long was divided into 4 sections; natural ground section, surface reinforcement section with sand drain treatment, sand compaction pile section and chemical pile section, each of which was about 50m. The cross sectional views of natural ground section and surface reinforced section are shown in Fig.11. All experimental parameters needed to analyze are easily determined from a few empirical and experimental considerations. The sand layer were treated as if they were overconsolidated with an overconsolidation ratio of 10. The surface steel strips reinforcement was replaced by a 1.2m thick elastic band. The performance of a field trial embankment demonstrating the effectiveness of surface reinforcement was back-analyzed, with

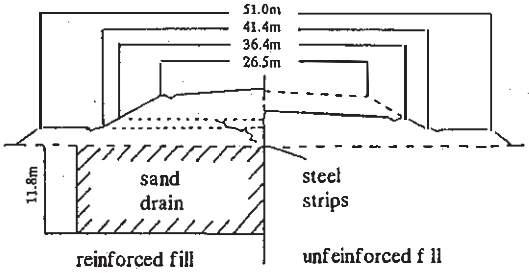


Fig.11 Cross sectional views of trial embankment (Ohta et al, 1980)

reasonable agreement, by means of the presented finite element technique. As the results of the investigations, it is concluded that the transverse surface reinforcement is one possibility technique to improve the undesirable characteristics of soft foundations.

(2) Deformation Analysis with Design Purposes (Rowe, 1984)

A numerical technique for the analysis of geotextile reinforced embankments has been outlined. This technique permits consideration of soil-reinforcement interaction slip at the soil-fabric interface, plastic failure within the soil and long deformation. The application of the approach was illustrated by reference to an embankment constructed on a soft peat deposit.

The results were obtained using a plane strain, nonlinear elasto-plastic soil structure interaction analysis to allow for large deformation. An incremental finite element technique was used in the analysis, in which the soil is assumed to be nonlinear elastic-plastic material. In the plastic state, the soil was assumed to have a non-associated flow rule of the form proposed by Davis with a dilatancy angle ψ. The model used will not permit tensile stresses for a purely friction material. Large deformation were taken into account by updating the nodal coordinates. This approach is only approximated since it neglects rotational effects. The geotextile was treated as a structural membrane with axial stiffness but negligible flexural rigidity. The soil and fabric were examined separately but were related by conditions of compatibility and equilibrium and the soil-fabric interface, the displacement of the soil and fabric were assumed to be compatible until the shear stress reached a limiting shear stress defined by a Mohr-Coulomb failure criterion. Once this shear stress was attained, slip occurred at this point. As the results, the suggested approach does provide a reasonable means of modeling the construction and performance of geotextile reinforced embankments on soft organic deposits.

(3) Deformation Analysis with interaction model (Kutara et al., 1986)

This paper introduces a no-tension FEM analysis of the deformation of geotextile-reinforced embankments. The influence of the discontinuous plane between the geotextile and the soil must be taken into consideration in such an analysis. To do so, the joint elements with a thickness of 't' were introduced between the geogrid and the soil. The geotextile was converted to plane truss elements which would resist tensile stress but not flexural stress for purposes of analyzing the deformation behavior of the composite body uniting the geotextile and the soil. Fig.12 shows the geotextile and the soil replaced with joint elements and plane truss elements. In this analysis, joint elements are provided for the upper and lower surfaces of the discontinuous plane between geotextile and the soil (see Fig.12). No-tension analysis was conducted with a model prepared by regarding joint elements with a thickness of 't' as the domain where the friction resistance between the geotextile and the soil was mobilized. The plane truss elements were connected by pins, because the geotextile is resistant

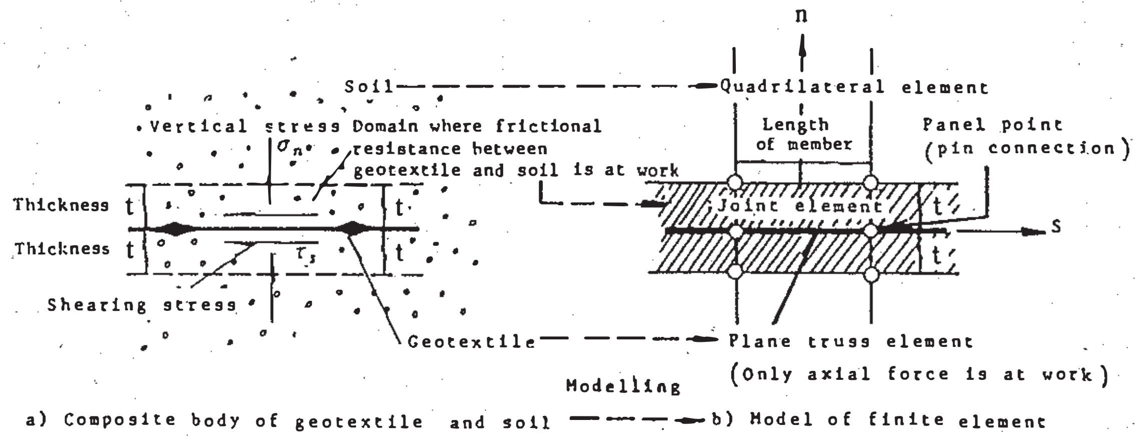
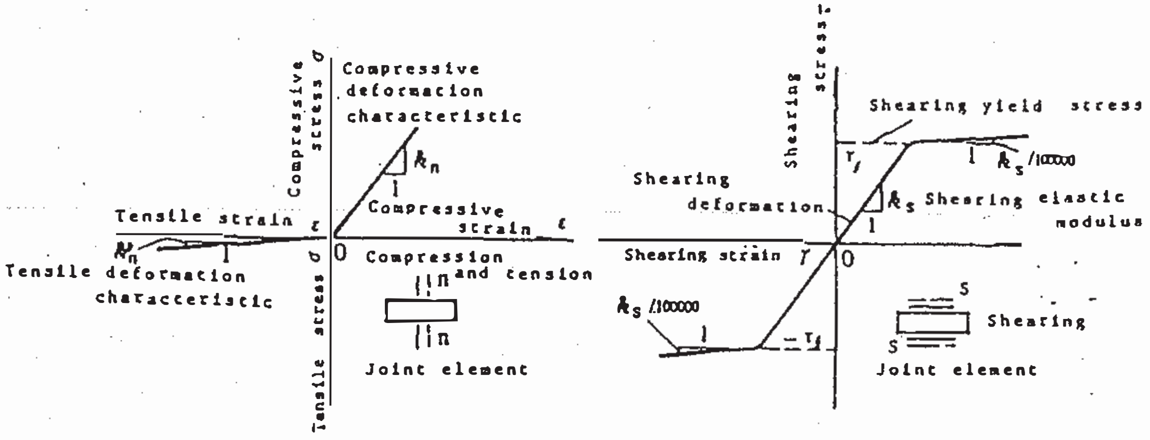


Fig.12 Modeling of geotextile and soil (Kutara et al., 1986)



(a) (b)

Fig.13 Deformation characteristics of joint element (Kutara et al., 1986)

to tensile stress in the axial direction, but has no resistance to bending stress. It was assumed that joint elements have no resistance to tensile stress of geotextile in the vertical direction, but transmit the compressive strength to the soil elements. Further, the joint element is assumed to behave as a nonlinear deformation against the shearing stress in the horizontal direction for the geotextile. Deformation characteristics of joint elements are shown in Fig.13. The results of the analysis were compared with not only those from pull-out tests for polymer grids but also with large model tests. The analytical results for the strain distribution of the geotextile in the soil and the deformation of the fill were in good agreement not only with those of the pull-out tests for geotextiles in soils but also with those of large model tests.

(4) Development of Design Charts Based on Deformation Analysis (Ogisako & Ochiai, 1990)

Finite element analysis for geogrid reinforced-soil retaining walls were conducted using the method which is capable of taking into account the displacement dependence property of the pull-out resistance of the geogrid in soils. A modeling of the geogrid reinforced soil presented here was a combination of the joint element expressing the property of discontinuous plane with the truss element transmitting the axial force only. This truss element whose ends were connected by the pin joint was used for modeling of geogrid. This interaction property was evaluated based on laboratory pull-out test in which the mobilizing process of the interaction behavior was modeled. The wall was modeled by beam element which has a stiffness for bending moment. In the analysis, Duncan-Chang model was used as a soil model. Based on the analysis results with changing height of the wall, and the spacing and length of the reinforcement, the design chart was developed.

3.2 *Stability Analysis*

There are several methods for stability analysis such as upper bound method, lower bound method, slip line method, finite element method(displacement method), and limit equilibrium method. The purpose of stability analysis is to obtain the limit load. Table 2(Otani et al.(1994)) shows the necessary conditions for obtaining the true limit load and the meaning of the solution in each method. As shown in this table, there are five conditions which should be satisfied in order to obtain true limit load. Although the limit equilibrium analysis is conducted quite a few cases, it should be noticed that the results from this analysis is unreliable without any theoretical considerations.

(1) Limit Equilibrium Method

As shown in Table 2, all necessary conditions are unknown for limit equilibrium method. But when the real failure mechanism is taken into account, the

Table 2 Necessary conditions for limit load (Otani et al., 1994)

	upper bound	lower bound	slip line	FEM (disp.)	limit equilibrium
equilibrium	unknown	satisfy	satisfy	partially satisfy	unknown
compatibility	satisfy	unknown	unknown	satisfy	unknown
constitutive equation	satisfy	satisfy	satisfy	satisfy	satisfy
force boundary	unknown	satisfy	satisfy	partially satisfy	unknown
displacement boundary	satisfy	unknown	unknown	satisfy	unknown
relation with limit load	upper bound	lower bound	lower bound	upper bound	unknown

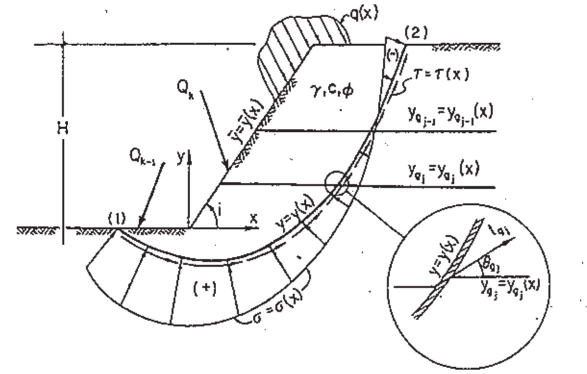


Fig.14 Basic definitions and conventions (Leshchinsky and Reinschmidt, 1985)

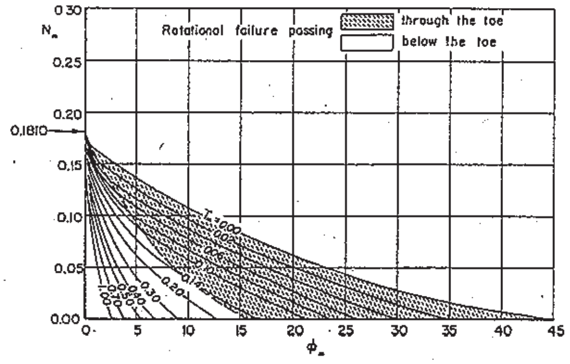


Fig.15 Stability chart for Case i = 45° and γ_g=0.50 (Leshchinsky and Reinschmidt, 1985)

obtained result should be upper bound or true. The limit equilibrium method (LEM) has been widely used in stability analysis because of its simplicity and also is used for design calculation directly.

Leshchinsky and Reinschmidt (1985) proposed a method of stability analysis based on LEM for geomembrane(geotextile) reinforced soil structures. The main purpose of their study was to prepare design charts. Figure 14 shows the analytical domain and boundary conditions for the analysis. Theoretical framework for the study was based on a kind of LEM developed for unreinforced plain slope(Baker and Barber, 1978). The slip surface and the normal stress along the slip surface were expressed in terms of unknown functions y = y(x) and τ = τ(x), respectively. The failure mechanism y(x) and the internal stress τ(x) were solved simultaneously using a variational limiting equilibrium approach. When the conventional LEM are concerned (e.g. Jambu, Bishop, Fellenius methods, etc), they are implied by the assumption regarding direction or line of action of the interslice force, and hence the obtained solutions are lacking a complete physical interpretation. However, the solution by this method is verified as an upper bound solution in plasticity. They incorporated the reinforcing forces as external forces into the above LEM.

Figure 15 illustrates the typical stability charts based on their proposed methodology. Nm, ϕm and Tm in the figure denote the cohesion of soil, the internal friction and assumed tensile strength of reinforcement, respectively. These values are normalized by the unit weight and the slope height and are further mobilized by the factor of safety Fs (e.g. Fs=1.5 for the chart in Fig.15). This figure shows that stronger the membrane the deeper the failure. The required reinforcing force in a design can be determined under arbitrary c and ϕ and the assumed Fs. Since several assumptions are introduced at the stage of incorporating the reinforcing force, it can not be avoided that the solution always deviate from the absolute solution.

(2) Finite Element Method(FEM)

There are two main methodologies in stability analysis using FEM. One is the elasto-plastic deformation analysis following the stress history from initial condition to the limit state. The other is the limit analysis based on the upper or lower bound theorems on plasticity. The former is an extension of the deformation analysis mentioned in 3.1. However, the large deformation and strain localization are required to be considered in the case of failure problem, this type of analysis should be more complicated.

Elasto-Plastic Finite Element Method

Kotake et al.(1997) simulated the results from small plane strain compression tests on sand reinforced by planar material. The soil and reinforcement were modeled by Mohr-Coulomb and the ordinary truss element, respectively. The softening type of constitutive model was applied to the shear band area to explain not only the post-peak behavior but also the occurrence of shear band formation passing through the reinforcement.

It should be regretted for the very few applications of the promising elasto-plastic deformation analysis method based on the large deformation theory in the analysis of the reinforced soil structures.

Rigid Plastic Finite Element Method(RPFEM)

In this method, the stress history until arriving at limit state can not be presented, however, the arbitrary failure mechanism, the loading system, and the stress distribution can be simultaneously obtained as the upper bound solution without any additional assumptions which are essential for LEM. Furthermore, it has been proved that the solution obtained by the minimization process is the

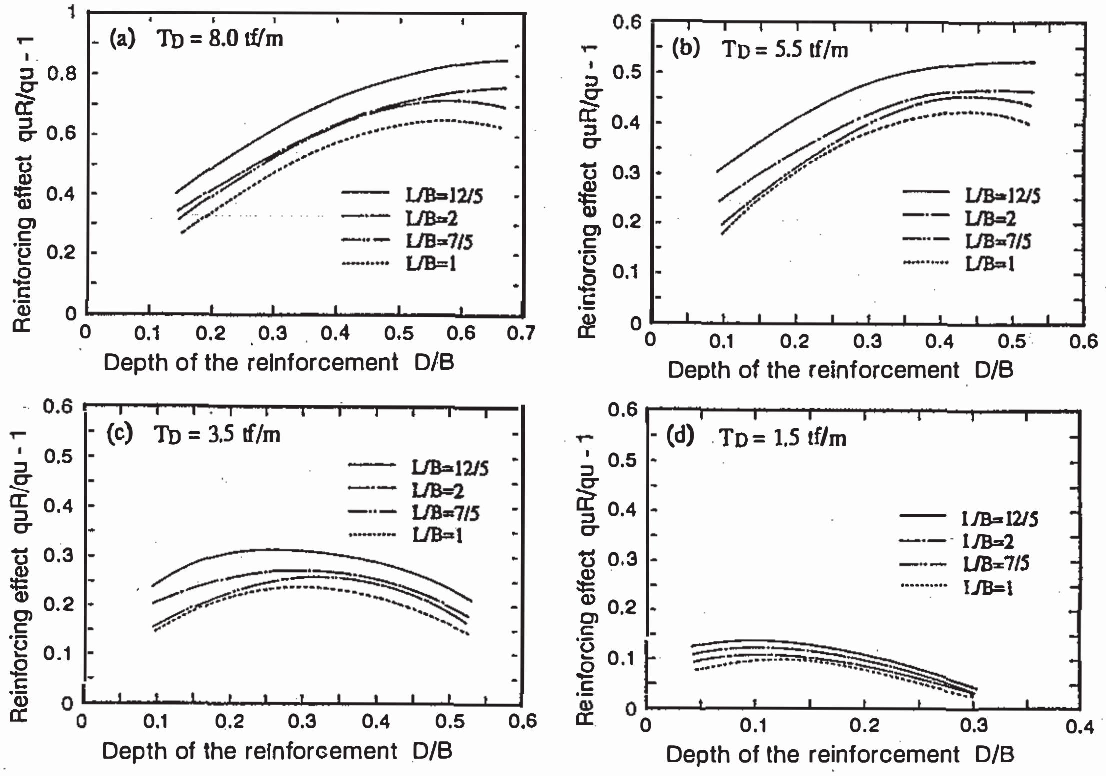
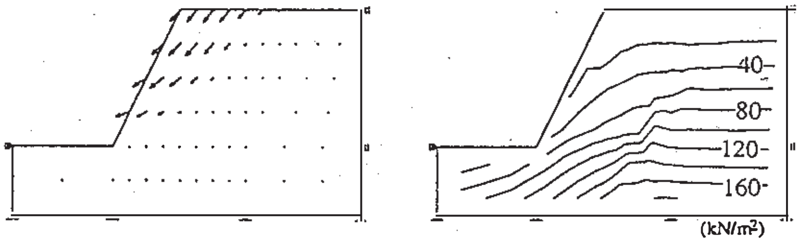


Fig.16 Reinforcing effects of geogrid foundation ground (Otani and Ochiai, 1993)

absolute solution at the limit state. When the RPFEM is applied to the stability problem of reinforced soil structure, modeling of reinforced soil is delicate, since it is quite difficult to know the behavior of reinforcement and its interaction with surrounding soil at the limit state.

Otani and Ochiai(1993) firstly used rigid plastic finite element method for the problem of earth reinforcement. In their paper, the new reinforced soil model was developed using composite theory with reinforcing material and the surrounding soils. Not only the bearing capacity but also the failure mechanism for the reinforced foundation ground have been discussed based on the analysis results. One of the results are shown in Fig. 16. In this figure, L: length of reinforcing material; B:width of foundation; D:depth of placing reinforcing material, and the improved bearing capacities were evaluated quantitatively. The conclusions of this study are listed as follows: (1) The bearing capacity of geogrid reinforced foundation ground is increased as the depth and the length of the reinforcement increases, but there are an optimum depth in order to mobilized the maximum reinforcing effect; (2) There is also an optimum number of geogrids for multiple type of earth reinforcement structures.

Asaoka et al.(1994) assumed that the length between arbitrary soil elements touching the reinforcement did not change at the limit state of soil mass. Under this 'no length change' constraint condition, the reinforcement suppresses the plastic flow of soil along reinforcement by keeping the nodal distance constant. This assumption is relied upon the fact that the rigidity of reinforcement is considerably large compared to the soil, especially at limit state of soil. The 'no length change' condition was mathematically formulated as a linear constraint condition on velocity field, and was incorporated in to the RPFEM by Lagrange multiplier method. As the real reinforcing materials never appear in this computational work, artificial model, e.g. truss element, joint element, etc., are not directly used to explain the behavior of reinforcement. Such elements are generally used in most of the computational works by FEM for the reinforced soil. Therefore, the real material constants for reinforcements are not required except the soil constants to solve the reinforced soil system. This methodology is very simple and proved to be acceptable, yet essential. It should be noted that the more material constants in the analysis, the more indefinite factors affecting the result, although the modeling seems to be close to the reality. In stability analysis by LEM, the effect of reinforcement is introduced as a resisting external force. The tensile force acting on reinforcement is a typical internal force which restricts the soil deformation. Therefore, the value of this internal force can never be decided beforehand. One of the most significant advantage incorporating the constraint condition is that the tensile force distribution along a reinforcement can be computed very well along with the well defined failure mechanism, the loading system (or factor of safety)



(a) Velocity Vectors (b) Mean Stress Contours

Fig.17 Velocity vectors and mean stress distributions in the case of c-ϕ soil without reinforcing material (Asaoka et al., 1994)

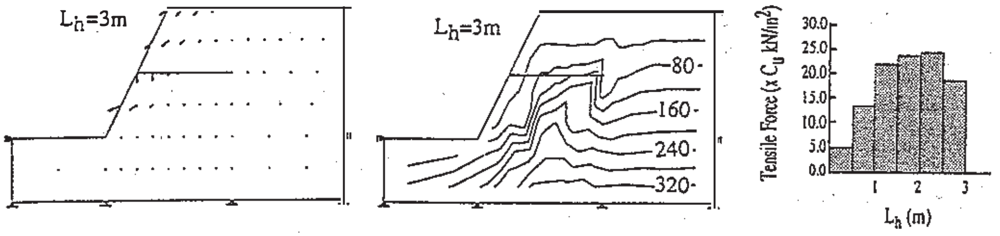
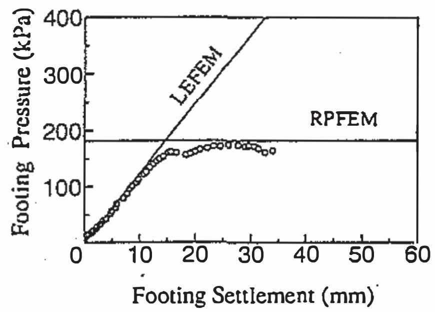
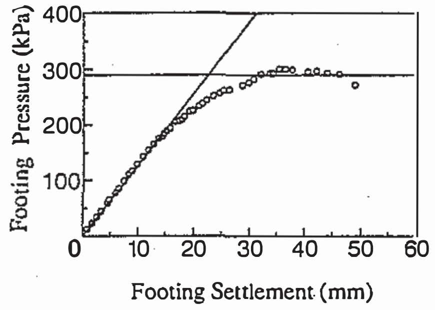


Fig.18 Velocity vectors, mean stress distributions and tensile force along reinforcements of different lengths in case of c-ϕ soil(Asaoka et al., 1994)

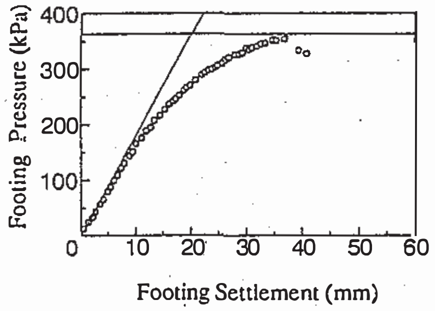
and the mean stress distribution, simultaneously. The major findings by Asaoka et al.(1994) were as follows: 1) The reinforcement is more effective in sand material, i.e. c-ϕ material compared to the reinforcement in purely cohesive soil. 2)In sand material, restraining of soil by reinforcement increases the mean confining stress distribution in soil element along the reinforcement. The increase in stability is attributed to the increase in mean confining stress. 3)In purely cohesive soil, the acting reinforcing force is not directly effective in the stability. Figures 17 and 18 show the calculation results on an unreinforced and reinforced sand slopes, respectively. Allowing the length between two consecutive nodes to keep constant, the mean stress will rise which eventually lead to an increase in the absolute strength of the frictional material. The high tensile force in the reinforcement should be attributed to this reason. Thus, the reinforcing force acts like an anchor in such deep zone with high mean stress distribution or the zones close to the slope faces if slopes have rigid panel facing providing high confinement effect to the frictional materials (Kodaka et al, 1995). Kodaka et al.(1995) introduced the 'no bending' constraint condition to the aforesaid methodology in order to explain the role of facing. The 'no bending' condition assumes that the angle formed by three nodes along the rigid facing does not change, i.e. no bending. This linear constraint condition which is similar to the 'no length change' condition mentioned above, was incorporated to the RPFEM. In their study, the propriety of the methodology was illustrated through the 1g medium scale model test on sand slope and the subsequent simulation. The ultimate load, the failure mechanism and the tensile force distributions along the reinforcement obtained by the analysis well support the result of the model tests. They also performed the deformation analysis using linear elastic finite element method (LEFEM) introducing both 'no length change' and 'no bending' constraint conditions on the deformation field in order to simulate the deformation of reinforced soil slope. Even though this simulation covered only the initial tangent of load - settlement curve, the result showed that the method was good enough in practical use. Figure 19 shows the results of both the model test and their simulation. The small circles, the horizontal line and the inclined line show the results of the model test observation, RPFEM (i.e. ultimate load) and LEFEM (i.e. initial tangent of load - settlement curve) results, respectively. The computational results well explain the model test results without any complicated modeling for reinforcement. In addition, the usefulness of the methodology as a tool for design could be seen.



(i) Type A (Plain Slope Model)



(ii) Type B (Reinforced Slope without Facing)



(iii) Type C (Reinforced Slope with Panel Facing)

a. Mild Slope (1 V:0.5H) Models

Fig.19 Results of footing pressure - settlement curve and failure load with model test observations (Kodaka et al., 1995)

CONCLUSIONS

Current state on numerical analysis in earth reinforcement was reported by conducting paper review and also summarizing some of the papers. Following conclusions have been drawn:

(a) For deformation analysis

(1) Most of the analysis are FE analysis.

(2) In the FE analysis, there are two types of modelings: (i) separately modeling with soil, reinforcing materials, and its interaction; (ii) composite modeling or the model without interaction model.

(3)Although plenty of numerical analyses have been conducted, the analysis with the purpose of discussing more details of serviceability limit on limit state design has not been done so far. This should be the future works.

(b) For stability analysis

(1) Although the limit equilibrium analysis has been conducted with large number of papers, most of them are a part of design calculation. And also, the result by this analysis only should be evaluated quantitatively because that is never followed with theoretical solution.

(2) The FE analysis has been used for the purpose on the stability of reinforced soil structures, such as elasto-plastic and rigid plastic FEMs. The result of these analyses are able to count on quantitatively and should be effective.

The numerical analysis is a power tool to solve boundary value problem with difficult material property and boundary conditions as the computer machine is improved. Therefore, it is concluded that the numerical analysis should be used in order to search real deformation property and failure mechanism of reinforced soil structures.

ACKNOWLEDGMENTS

Authors would like to express their sincere thank you to all the authors who have published the technical papers which we reviewed here in this paper. And also we would like to give our gratitude to not only the member of the Japanese Supporting Committee but also all the members in Asian Technical Committee.

REFERENCES

Asaoka, A., Kodaka, T. & Pokharel, G. 1994. Stability Analysis of Reinforced Soil Structures using Rigid Plastic Finite Element Method. Soils and Foundations, 34(1):107-118.

Kotake, N, Tanaka, T., Tatsuoka, F. & Yamauchi,H. 1997. Numerical simulation of strain localization and failure in reinforced sand. Proc. of Int. Symp. on Deformation and Progressive Failure, IS Nagoya, (to appear).

Kodaka, T., Asaoka, A., and Pokharel, G. 1995. Model Tests and Theoretical Analysis of Reinforced Soil Slopes with Facing Panels. Soils and Foundations, 35(1):133-145.

Kutara,K., Gomadou,M., and Takeuchi,T. 1986. Deformation Analysis of Geotextiles in Soils using the Finite Element Method. Geotextiles and Geomembranes 4:191-205.

Leshchinsky, D. & Reinschmidt, A.J. 1985. Stability of membrane reinforced slopes. Journal of Geotechnical Engineering Division, ASCE, 111(11):1285-1300.

Ogisako,E. and Ochiai,H. 1990. Analysis and design for geogrid reinforced-soil wall. Jour. of Construction Engineering, JSCE, Vol.421,VI-13:105-114 (in Japanese).

Ohta,H., Mochinaga,R., and Kurihara,N. 1980. Investigation of Soft Foundations with Surface Reinforcement. Proc. of 3rd Australia-New Zealand Conference on Geomechanics: 360-365.

Otani,J. and Ochiai,H. 1993. Bearing capacity of the reinforced soils by rigid plastic finite element analysis. Proc. of the 2nd Asian-Pacific Conf. on Computational Mechanics:445-460.

Otani,J., Ochiai,H., and Li,X.X. 1994. Bearing capacity analysis of reinforced foundation ground by geosynthetics. Proc. 8th Int. Conf. on Computer Methods and Advances in Geomechanics, U.S.A.:1397-1402.

Rowe,R.K. 1984. Reinforced Embankments: Analysis and Design. Jour. of Geotechnical Engineering, ASCE, Vol.110,No.2:231-246.