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Discussion leader's report: Foundations

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ABSTRACT: This work summarizes and discusses the papers presented to the session on Reinforced Foundations at the IS Kyushu'96. These papers gave a important contribution to the state-of-the-art on the subject and also emphasized that further research is needed in order to a better understanding on the mechanisms involved in foundation reinforcement.

1 INTRODUCTION

The use of soil reinforcement in geotechnical engineering has increased markedly in the last decades. Reinforced slopes, embankments and retaining structures are now common solutions for designers for most of the routine works in the profession. Despite the large amount of research and construction experiences already gained there is still the need for additional research on several topics to a better understanding on failure mechanisms and, in particular, deformation mechanisms and long term performance of reinforced soil structures. The use of reinforcement inclusions to improve foundation conditions is certanly one of these topics. Because of the scale of the problems and consequences of potential failures, the general approach towards the reinforcement of foundations has been the use of conservative solutions in most of the cases. The papers presented to this conference show that researchers and engineers are concerned with a wide range of problems where reinforcement can increase the strength of the foundation soil and reduce its compressibility.

Depending on the main subject studied the works presented at this symposium can be divided in the following categories, as schematically shown in Figures 1 (a) to (h):

- Buried pipes in reinforced ground;
- Reinforced embankments on poor foundation soils;
- Bearing capacity of reinforced granular layers on weak soils;
- Bearing capacity of footings on reinforced slopes;
- Bearing capacity of reinforced foundation soil;
- Reinforced deep and shallow fondation elements.

The types of studies and investigations conducted in these topics were analytical studies, numerical analysis, case histories, field tests and physical modelling. The results obtained show a significant contribution to the state of the art and will be discussed later in this work.

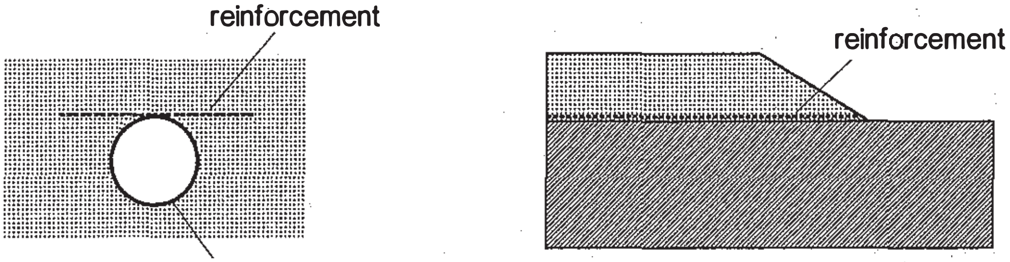
The distribution of papers on each subject is presented in Figure 2. A total of 27 papers were presented in this session. This represents a 23% increase on the number of papers presented in the same session at the last Kyushu conference (IS Kyushu'92), in 1992. Seventy four percent of the present papers dealt with bearing capacity of reinforced granular layers, reinforced foundations or reinforced embankments on poor soil. Compared to the subject of papers presented at the last IS Kyushu'92, it can be observed that there was a substancial reduction on the number of papers on bearing capacity of reinforced foundation and significant increases of papers on bearing capacity of granular layers on weak soils and reinforced embankments on soft subgrade.

The works presented and their results are summarised and discussed in the next sections for each of the subjects listed above.

2 BURIED PIPES IN REINFORCED GROUND

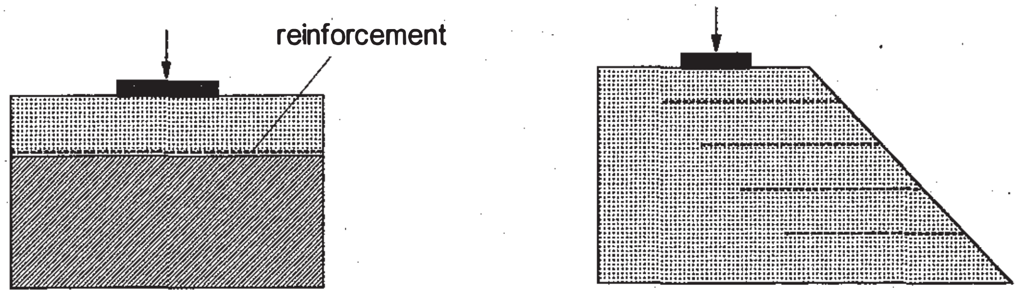
Two papers were presented on this subject and the problems approached are presented schematically in Figure 1(a). These papers involved field and laboratory model tests of pipes subjected to pull-out and vibration with different reinforcement arrangements.

The presence of the reinforcement increases pull-out resistance and reduces pipe settlements, as reported by Babin et



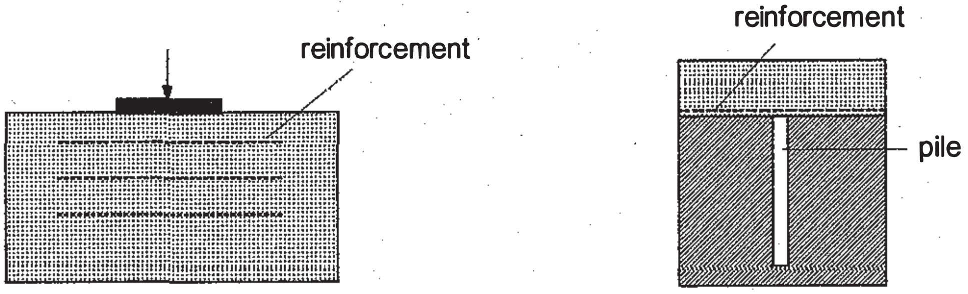
(a) Buried pipes

(b) Reinforced embankments



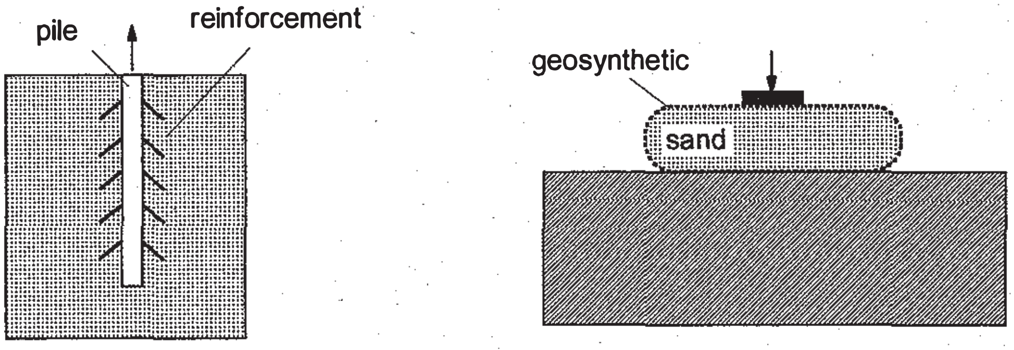
(c) Reinforced granular layers on weak soil

(d) Reinforced slopes



(e) Reinforced foundations

(f) Deep foundations and reinforcement



(g) Reinforced piles

(h) Sand mattress

Fig. 1. Types of problems studied.

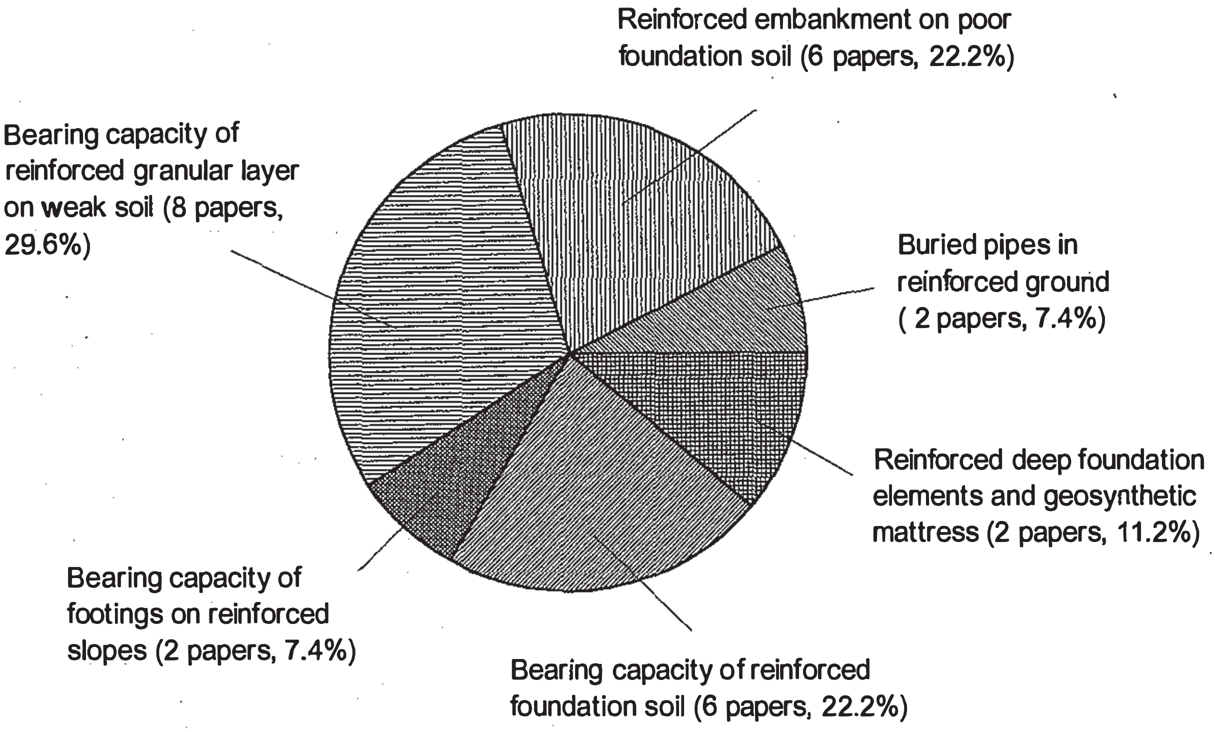


Fig. 2. Distribution of papers in the session.

al (1996). Field pull-out tests showed that pipelines in reinforced soil can resist twice as much pull-out loads than in unreinforced soil. The Authors also presented a empirical expression to estimate the ultimate pull-out load that can be applied to a pipe-line in reinforced soil. The influence of the reinforcement in reducing erosion was also investigated.

Nagase et al (1996) performed model tests of pipes buried in sand on a shaking table and showed that geotextile reinforcement reduced pipe flotation due to vibration. Appropriate reinforcement dimensions were also investigated. Differences between flotation resistance were attributed by the Authors to bending stiffness and geonet mesh opening sizes. However, it may also have been caused by tensile stiffness and/or soil-reinforcement interaction, which depends on net geometry and mesh size. Tests trying to study each factor (bending stiffness, tensile stiffness and soil-reinforcement interaction) independently should be performed to identify the role of each mechanism.

3 REINFORCED EMBANKMENTS ON POOR FOUNDATION SOILS

The geometrical aspects of the studies on reinforced embankments are presented in Figure 1(b) with the traditional arrangement for the reinforcement installed at the base of the embankment. In one of the papers the embankment rested on a reinforced layer in the foundation soil. Six papers were presented on this subject.

As its has been observed in several previous works in the literature the presence of the reinforcement reduced fill deformations and settlements.

Behbahani (1996) described case histories on the use of geosynthetic reinforcement for the stabilization of embankments on soft soils. Reductions in fill deformations and settlements due to the use of reinforcement were observed by the Authors.

Imanishi et al (1996) presented a case history of a geosynthetic reinforced road embankment on very soft soil. The Authors observed a redistribution of strains in the reinforcement during construction as the soft subgrade was partially replaced by the geonet reinforced embankment.

Klosek (1996) addressed the use of geosynthetics as reinforcement of embankments built on areas with mining activity. Theoretical and finite element method predictions showed that the reinforcement brings significant reductions on vertical and horizontal stresses in the foundation.

Poopath (1996) reported smaller pavement deflections for an embankment reinforced by a weak and extensible non woven geotextile. The question in this case is whether the geotextile layer increased the foundation strength by drainage instead of other reinforcing mechanism, because of its low tensile stiffness.

The length of the reinforced granular layer below the embankment was investigated by Shukla and Chandra (1996) assuming the foundation soil composed by Winkler springs. The stress-strain behaviour of the embankment was neglected. A limit length for the contribution of the reinforced granular layer was estabilished and the influence of pre-stressing the geosynthetic reinforcement was also investigated. It should be pointed out that soils behave in a different way, besides the difficulties in determining appropriate values for the soil reaction modulus in this case.

Tanabashi et al (1996) presented results of finite element analysis of embankments on soft soil. The analysis approached the important aspect of construction effects and how reinforcement performs under these circunstances. The results showed that the effect of the embankment weight was greater than the effect of the bulldozer weight for low embankment heights (of the order of 0.3 to 0.5m). In fact, one would expect the other way round in constructions on soft soils. Unfortunately the Authors did not comment on the magnitude of stresses transferred to the foundation and if the finite element formulation accounted for large deformations, which would be appropriate under these circunstances.

4 BEARING CAPACITY OR REINFORCED GRANULAR LAYERS ON WEAK SOILS

The bearing capacity of reinforced granular layers was investigated in 7 papers presented to the symposium. The studies involved the traditional arrangement with the reinforcement placed on the foundation surface (Figure 1(c)) as well as arrangements with multiple layers of reinforcement. In one of the cases the influence of the presence of piles under the reinforced zone was also investigated.

Significant reductions in settlements and rut depths were observed by Manjunath and Dewaikar (1996), Cancelli et al (1996) and Knapton and Austin (1996) in large scale laboratory tests. The ratio between the size of the containers used in the tests and the size of the footings may have caused some boundary effects. The Authors did not comment if this effect was somehow investigated or evaluated.

Cancelli et al (1996) observed a punching failure mechanism in large laboratory tests of unreinforced paved roads and an reduction of 30 to 50% on settlements with the use of geosynthetic reinforcement. The influence of the presence of the reinforcement on the asphalt thickness was also investigated.

Fakher et al (1996) emphasised the importance of dimensional analysis on the interpretation of model loading tests of reinforced ground. The Authors also performed model tests on extremely soft subgrades, with undrainded strength of the order of 0.06 kPa. Special techniques were employed for sample preparation and undrained strength measurements. The Authors comment on the importance of reinforcement flexural rigidity (in plane bending stiffness) as a dominant factor in constructions on super soft clays.

Hirao et al (1996) used model tests of footings on granular fill on soft subgrade and concluded on the importance of the reinforcement bending stiffness on the bearing capacity of the system. Again, it is not clear if reinforcement bending stiffness, different interaction mechanisms or modelling limitations were responsible for different responses of the system.

Knapton and Austin (1996) reported large scale tests of unpaved roads reinforced by a geogrid layer. Tests results showed that the presence of the reinforcements reduced rut depths by 50 to 70%. The Authors did not comment on the possible influence of boundary effects on the test results.

Manjunath and Dewaikar (1996) studied the behaviour of square footings on granular layers on soft soil subjected to inclined loads. The granular layer was reinforced by a non woven, needle punched, geotextile. The influence of the inclination of the load on the footing was investigated for reinforced and unreinforced cases. The bearing capacity for the reinforced case was 30 to 50% greater than for the unreinforced case. Tilting of the footing in reinforced cases was also considerably less than in unreinforced cases (20 to 40% less).

Shivashankar et al (1996) also performed model tests on footings on granular soil ovelying soft soil with and without the presence of piles in the foundation. The test results showed that the presence of piles under the reinforced mass significantly increases the stiffness of the system. Optimum reinforcement length was also investigated. Some modelling limitations due to the use of real reinforcement materials in the model tests can be identifyed.

Tanaka et al (1996) performed tests with geogrid reinforced clay-cement layers. The appropriate grid mesh size was observed to be very important in this type of application. The Authors also provide suggestions in terms of design procedures for this type of application.

5 BEARING CAPACITY OF FOOTINGS ON REINFORCED SLOPES

The bearing capacity of footings on reinforced slopes was also investigated in two papers, as presented in Figure 1(d).

Das at al (1996) investigated the optimum position for the footing on the slope, depth of reinforced zone and spacing between reinforcement layers. A procedure for estimating bearing capacity was also presented. This procedure is limited to a certain range of slope angles and model tests results are required for its use.

Ohtsuka et al (1996) observed that the reinforcement effect depends on the reinforcement stiffness and that there is a limit value of reinforcement strength beyond which the reinforcement effect is constant. This seems difficult to understand. Could it be due to reinforcement location or a different failure mechanism such as reinforcement pull-out, for instance? The same Authors also observed a limit value for the reinforcement length which, on the other hand, is reasonable and has also been observed in other works in the literature.

6 BEARING CAPACITY OF REINFORCED FOUNDATION SOIL

A total of seven papers studied the use of multi-layers of reinforcement in the foundation soil (Figure 1(e)).

Physical and numerical modelling and theoretical studies by Ju et al (1996), Nataraj et al (1996) and Zhao et al (1996) showed that the presence of the reinforcement almost doubled the foundation bearing capacity. Limiting values for the influence of reinforcement length, number of reinforcement layers and reinforced zone depth were identified. Regarding the model tests by Ju et al (1996) it can be argued on the possible influence of side friction along the in internal walls of the container used for the tests and on the limitations on the scaling of the reinforcement material in view of the other dimensions adopted.

Otani and Yamamoto (1996) performed model tests of footings on reinforced and unreinforced foundations using aluminium rods as the foundation layer. The displacements and rotations of some rods were measured and it was observed that the latter was a function of the reinforcement position and length. The Authors attributed to reinforcement length and bending stiffness a major influence on the deformation mechanism of the reinforced foundation. However, perhaps the same conclusion could also be reached based on different mechanisms of interaction having occurred.

Simonini (1996) performed finite element analyses and model tests of circular footings on reinforced sand. A satisfactory agreement between numerical and experimental results was achieved and both studies showed a punching failure mechanism for the foundation. Triaxial tests on specimens reinforced with horizontal reinforcement layers were also conducted as part of the study. These tests were also modelled by finite elements whose predictions copared well with the test results. A similar numerical study was conducted by Sitharam et al (1996) where it was observed that the point of maximum tension in the reinforcement layer depended on the reinforcement stiffness. A similar work was presented by Yamamoto and Otani (1996).

An interesting design method for the estimate of bearing capacity of the multi-layer reinforced foundation was introduced in Zhao et al (1996). The method is based on the slip-line theory and its use is very straightforward. Design charts and a worked example are provided. The Authors observed a limiting value for the depth of the reinforced zone in the foundation beyond which the reinforcement strength has little influence. This was also observed by Ju et al (1996) in model tests. The results of the method are consistent with the results presented by Ju et al (1996) and by Simonini (1996). It would be interesting to see how the method's predictions compare with model or field test results.

7 REINFORCED DEEP AND SHALLOW FOUNDATION ELEMENTS

Figures 1(f) to (h) shows schematically the arrangements studied for the combination of reinforcement and deep foundation elements and for the use of geosynthetic mattresses for load tranference to the foundation layer.

A Finite Element study performed by Nakai and Uno (1996) predicted that the uplift capacity of a pile can increase by 70% with the use of protruded bars orientated downwards, for which case the influence of the bars bending stiffness was negligible (Figure 1(g)). The reinforcement bending stiffness was observed to be important only for horizontal bars. The Authors could have commented on the effects of some reinforcement modelling and construction difficulties.

Ohkubo et al (1996) studied the problem of reinforced embankments founded on piles on soft soil. The Authors observed that the presence of geogrids on top of the piles had a significant effect on the displacements of the pile heads using the Finite Element method. Maximum geogrid strains were observed to occur near the pile head and negative strains were predicted in between piles. That might be expected for the region below the embankment slope due to the mobilization of different horizontal pile displacements. However, the Authors also observed that for the central region of the embankment, which seems unexpected.

Yasufuku et al (1996) conducted tests with geosynthetic (geogrid) mattresses resting on a foundation composed by springs (Fig. 1(h)). The magnitude of the stresses transferred to the foundation depended on the ratio between mattress thickness and footing width. A simple design approach to determine the mattress thickness was presented. Again, it should be pointed out the simplicity of the use of springs to simulate soil and the limitation of this procedure as commented earlier in this work.

8 CONCLUSIONS

This report tried to summarize the works presented in the session on Reinforced Foundations at the IS Kyushu'96. The main conclusions are as follows:

- A significant contribution to the state-of-the-art has been given by high quality papers, which unfortunately the limited amount of space does not allow the Author of this report to elaborate more.
- A range of relevant problems were investigated and design methodologies presented which enhanced the potentials of the use of reinforced foundations.
- Some papers attributed to reinforcement bending stiffness a important influence on the behaviour of the reinforced soil. However, for polymeric and flexible metalic grids this influence is likely to be negligible. Perhaps the role of other factors, such as soil-reinforcement interaction, may have been minimised or obscured in these works.
- Some aspects of the use of reinforcement in foundations have still to be better investigated. One of these aspects is the deformability of the reinforced mass. This is a key factor for the use of reinforcement in foundations of structures. The prediction of settlements of footings on unreinforced granular media is already very complex. Efforts should be concentrated in developing accurate methodologies for this type of prediction when reinforcements are present.
- One should to bear in mind the limitations of numerical and physical modelling and should try to evaluate them. Problems such as reinforcement modelling and approach used to determine stresses along the soil-reinforcement interface in the Finite Element Method may influence the results obtained. The transformation of three dimensional problems in two dimensional equivalents is also subject to criticisms. The same applies to physical models if enough care is not given to proper scalling of materials and boundary effects.

REFERENCES

All the references presented in the text can be found in the first volume of the International Symposium on Earth Reinforcement - IS Kyushu'96.