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Theory and practice on reinforced slopes with steel bars

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ABSTRACT: This paper summarizes a part of a report entitled "Study on Reinforcing Slopes with Steel Bars", which has been carried out mainly by the Laboratory of the Japan Highway Public Corporation (Nihon Doro Kodan) during the last five years.

The relation between the theory and the practice of this work is studied through: (1) large scale (full-size) in-situ model test to confirm the effect of the steel bars, (2) survey of actual results of existing facilities and (3) follow-up survey after construction. The purpose of this study is to propose a design guide for reinforcing slopes with steel bars.

1 INTRODUCTION

The purpose of the method is to stabilize the whole natural ground (slope) by installing reinforcing materials into soil which is essentially weak in tension. With this method, slopes which do not need such protection works as anchor works or pile works, can be reinforced inexpensively, safely and easily. It has been applied in the cases shown in Figure 1.

i) Prevention of small scale failure of slopes

ii) Steeper slope with reinforcement

iii) Temporary reinforcement of an excavated slope

iv) Reinforcement of slope above tunnel entrance

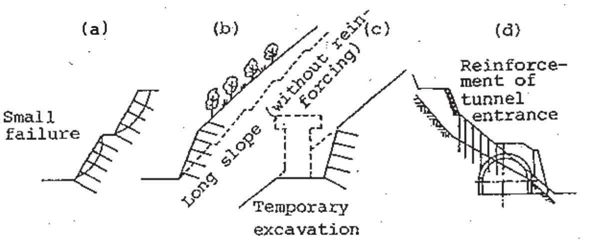

Figure 1. Simplified drawing of applications of reinforcing earthwork with steel bars

2 THEORETICAL REINFORCEMENT EFFECTS

The three kinds of effects shown in Figure 2 are considered.

i) Anchoring effect

ii) Shearing effect

iii) Effect like gravity retaining wall

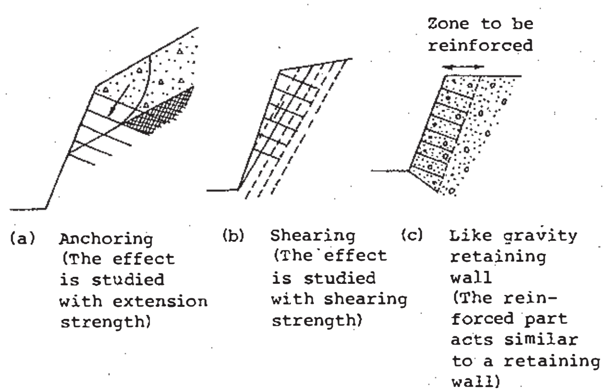

Figure 2. Types of reinforcing effects

3 IN-SITU MODEL TEST

In this paper, we report on an in-situ model test, which was conducted with a model of full size on the diluvial terrace sand and gravel, and on the Kanto loam (cohesive soil like volcanic ash) formation plateau.

(1) Test equipment and methods

The outline of specimen is shown in Figure 3. In the case of a full size load test, the equipment consists of loading frames, twelve 50-ton jacks, a cast-insitu reinforced concrete loading plate 30cm thick and four earth anchors, both in front and behind the specimen as reaction points. The load was applied through a load-controlled system in steps of 3∿5 tf/m^2 depending on the reinforcement in the specimen until failure. At each load increment the load was usually held for fifteen minutes.

The ground where the test was performed consists of a homogeneous sandy soil mixed with silt; and a typical cohesionless soil. The other ground is a typical cohesive soil.

The basic experiment with a middle-size model, which was tested before the full size test, was performed in a manner similar to that of the full-size specimen; The specimen was scaled down to 1/4 size from 3m to 75cm, the drilling diameter was scaled down to 15mm; the aluminum pipe was scaled down to an external diameter of 8mm and to a wall thickness of 1mm; and the perforated plate was scaled down to 50mm x 50mm.

The amount of vertical settlement of both ground surface and loading plate, horizontal displacement of the slope, axial tension of the reinforcing materials, and the subgrade displacements were measured.

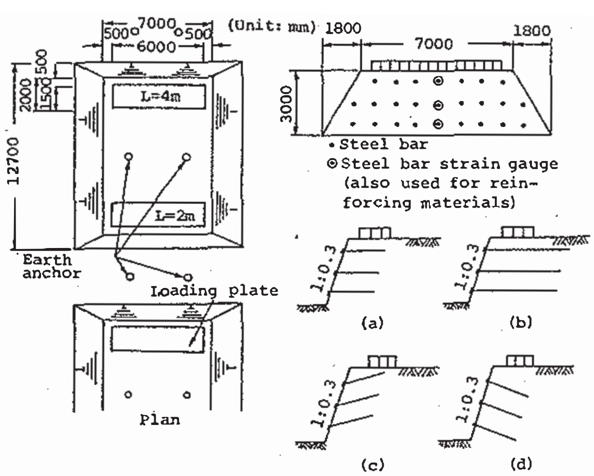

Figure 3. Schematic drawing of specimen

(2) Results of the experiment

The results of the loading experiment showed a tendency for the yield load to increase as the length of reinforcement was increased. In addition, from the curves of load and settlement after yield load, it was found that the longer the reinforcing materials were, the longer the time required for the slope to fail.

The factors affecting the reinforcement of natural ground include angle and density of reinforcement. In order to compare these factors, the following parameters were set up.

Length ratio of reinforcement

$$LR = \frac{\text{length of reinforcing steel bar } L}{\text{width of loading plate } B}$$

Density of reinforcement

$$D = \frac{\text{the number of reinforcing steel bars } n}{\text{area of slope } A}$$

Ratio of yield load

$$SR = \frac{\text{yield load of reinforcement ground } q}{\text{yield load of ground without reinforcement } q_0}$$

Figure 4 shows the relation between the length ratio of reinforcement and the reinforcing effect.

In figure 4, results are plotted for test specimen in which the reinforcement is horizontal and the spacing of reinforcement is kept constant (full size: 1m, scale model: 25cm). However, it is understood that the ratio of the yield load, between 1.0 and 3.0 of the length ratio of reinforcement, changes greatly, and, the yield load does not change much when the length ratio of reinforcement exceeds 2.0 (when the reinforcement length equals 1.5 times the distance from the top of slope to the end of the loading plate).

Figure 5 shows the relation between the angles of the reinforcement and the reinforcing effect. The results show that the angle of reinforcement in which the ratio of yield load is maximum depends upon the type of soil tested; it seems that the most effective angle of reinforcement is horizontal or downward (σ = 60° or 90°) for sand, and horizontal or upward (σ = 90° ∿ 110°) for cohesive soil.

Figure 6 shows the relation between the density of reinforcement and the reinforcing effect. It is understood that there is an upper limit, even though the ratio of yield load increases when the density of the reinforcement of the reinforcing steel bars is increased.

4 PERFORMANCE OF THE TECHNIQUE IN REAL APPLICATIONS

The results of a survey conducted in 1985 of 73 applications of reinforced slope

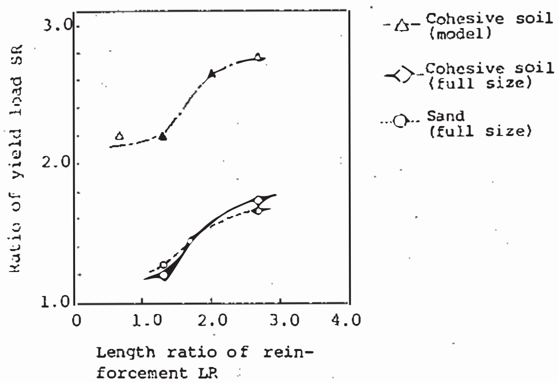

Figure 4. Relation between the length ratio of reinforcement and the ratio of yield load

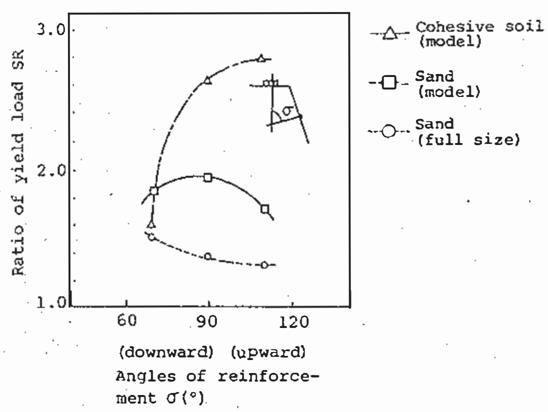

Figure 5. Relation between the angle of reinforcement and the ratio of yield load

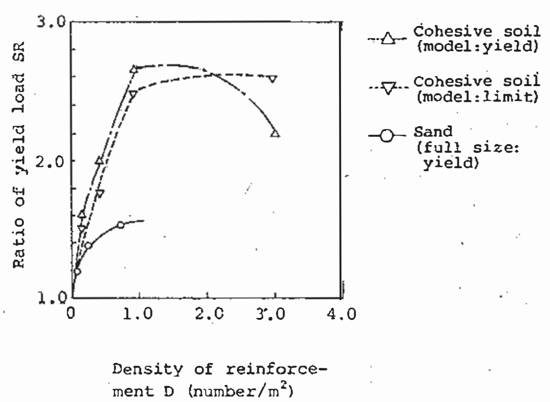

Figure 6. Relation between the density of reinforcement and the ratio of yield load

constructed by the Japan Highway Public Corporation and others are presented.

Figure 7 (a) shows the geological conditions of the reinforced natural ground. This shows that the method was used for equal numbers of soil and soft rock applications. Figure 7 (b) shows the frequency of steel bar length. This shows the frequency of use of bars over 2m but under 3.5m long is high. Figure 7 (c) shows the frequency of use of steel bars installed at an angle. Most of them are installed perpendicularly to the side-slope or horizontally. Figure 7 (d) shows frequency of spacings between steel bars. The interval is concentrated between 1m and 1.75m.

5 THEORY AND PRACTICE

5.1 Theory and experimental results

By comparing the results of the full-size loading experiment with the value calculated by the simplified Bishop's method, the ultimate equilibrium stability was analyzed. The simplified Bishop's method can be applied to the stability analysis of reinforced slope with steel bars. The simplified Bishop's method, with tensile force T affecting the slip plane, was combined and expanded is as follows;

Fs = resistance/sliding force

$$\frac{\Sigma\left\{\dfrac{c\cdot li\cdot \cos\alpha i+(Wi+Qi\cdot di)\cdot\tan\phi+Ti\cdot\sin\theta i\cdot\tan\phi}{\cos\alpha i+\tan\phi\cdot\sin\alpha i/Fs}\right\}}{\Sigma Wi\cdot\sin\alpha i+\Sigma Qi\cdot\sin\alpha i\cdot di-\Sigma Ti\cdot\cos(\alpha i+\theta i)}$$

where,

- Fs: safety factor
- ϕ : internal friction angle of the soil
- Wi: dead load of the slice
- di: width of the slice
- Qi: applied load
- li: length of the sliding face of the slice
- Ti: tensile force of the reinforcing materials affecting the base of the slice
- αi: slope of the slip plane of the slice
- c : cohesion of the soil
- θi: angle of the reinforcement

The tensile force T used in the calculation is obtained from the distribution of the tension force (axial tension) in steel plate at the yield load during the full scale load test. Soil properties were derived from the results of the tests on unreinforced specimens. The value of cohesion c and the internal friction angle ϕ were selected so that the safety factor Fs_0 becomes 1.0 at yield, as in the triaxial compression test.

The load at yield (when safety factor Fs=1.0), was found from the tension force of the steel bars T, cohesion c and the internal friction angle ϕ of the soil. Figure 8 shows a comparison between the experimental value of the yield load and its calculated value. The alphabetic characters in Figure 8 show each of the reinforcing patterns (a) to (d) in Figure

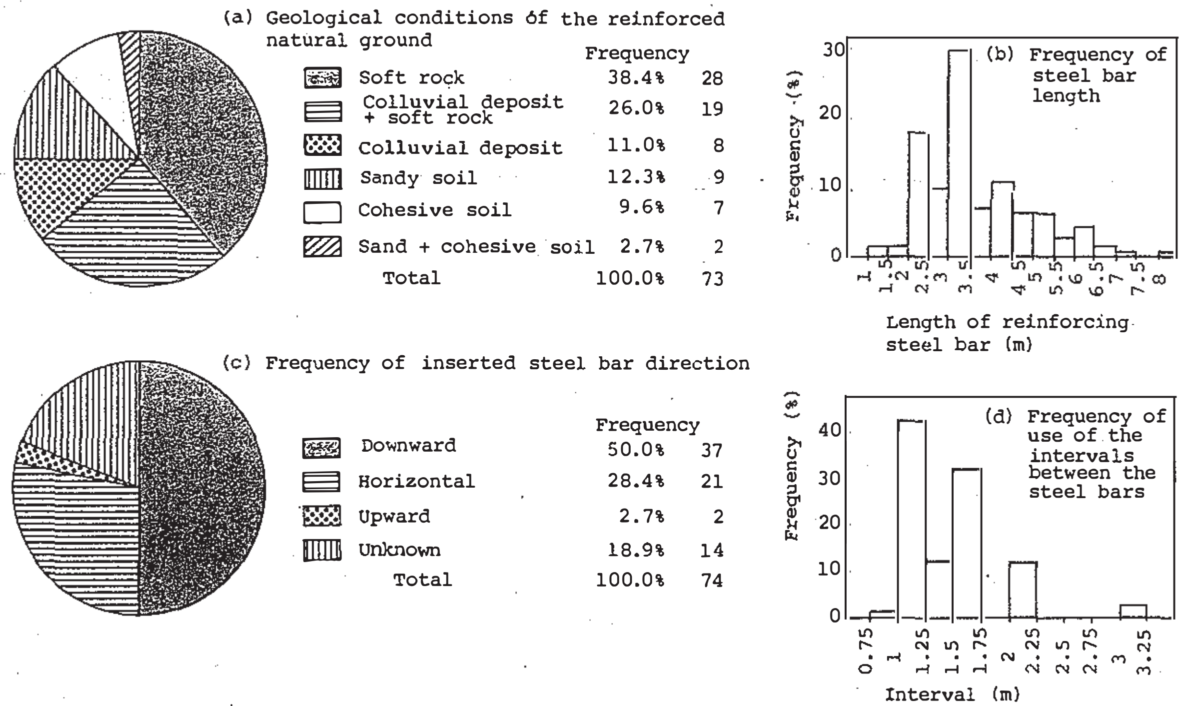

Figure 7. Actual conditions of execution at the job sites

3. Generally the experimental and calculated values of the yield load are the same; the experimental value tending to be slightly smaller than the calculated one.

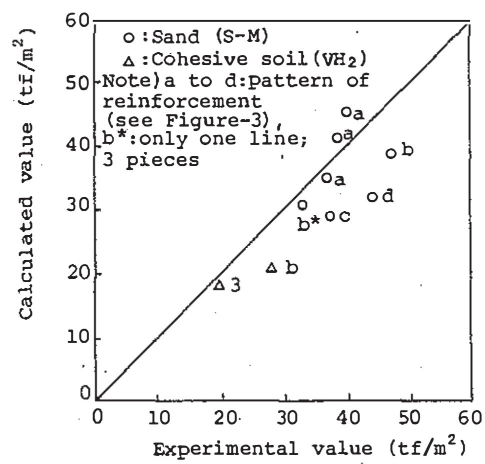

Figure 8. Comparison between the calculated value and the experimental value of the yield load

5.2 Theory and results of in-situ survey

If conditions are constant, it is expected that, theoretically, more steel bars are used in soil than in soft rock.

In Figure 9, the density of reinforcement and the gradient of slope β are plotted on the two axes, vertical and horizontal, and the actual results are plotted by actual safety conditions. The density of reinforcement was found by dividing the total length of the steel bar used on the slope by the slope area. The hatched vertical lines in the two figures refer to average standard slopes (Sectional Committee of Slope Works and Slope Stability 1986). It can be seen that the slopes remain stable even though they were steeper than the standard one.

The solid and broken lines in Figure 9 (a) and (b) are lower limits at which the slopes remain stable. The difference between soil and soft rock is slight. It seems that reinforcement of soil is more effective than reinforcement of rock. We cannot conclude that the method has been over-designed when used for soft rock, because it may have been adopted to cope with other geological requirements (such as fissures).

On soft rock, Mesozoic and palaeozoic strata (sand stone, slate, schist) have many fissures, such as bedding, joint and schistosity, and their fissures are the main cause of slope failure. In this case, the number of fissures and the direction of fissures become a problem. It is thought that the number of fissures greatly affects the shearing strength, and that the direction of fissures affects the angle of slip surface, i.e. the sliding force.

Figure 10 and Figure 11 show actual conditions of slopes without reinforcement on mesozoic and palaeozoic strata in

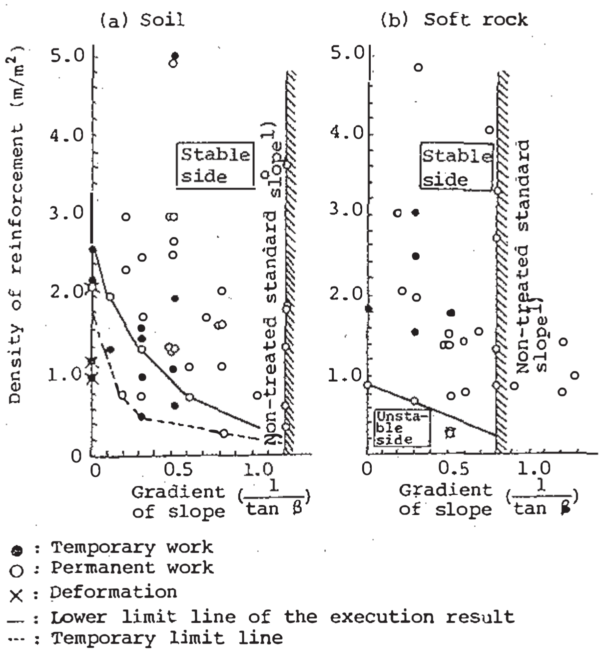

Figure 9. Comparison of the reinforcing effect of soil and soft rock

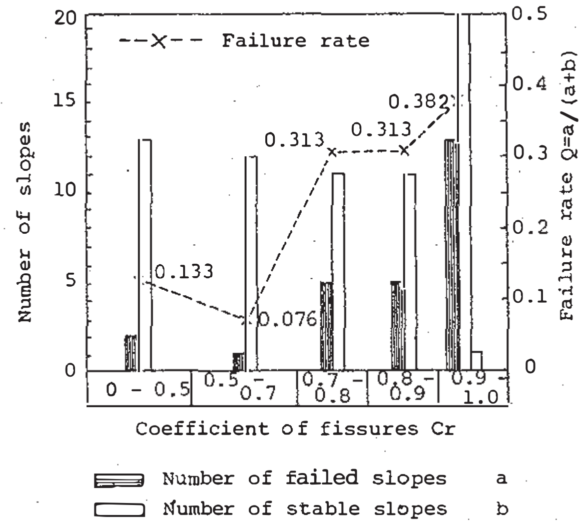

Figure 10. Slope failure rate by coefficient of fissures (Okuzono 1983)

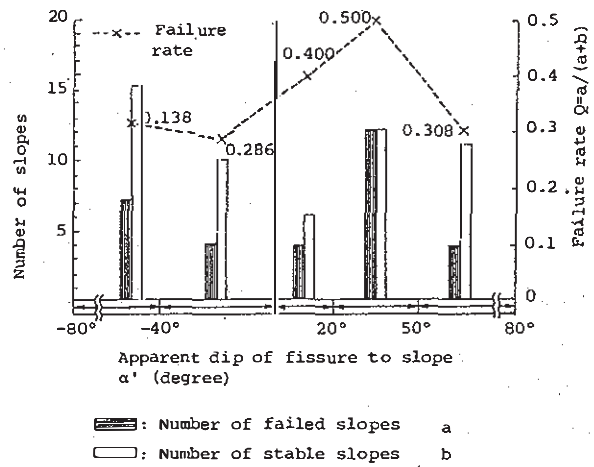

Figure 11. Slope failure rate by fissure dip (Okuzono 1983)

highways (Okuzono 1983). Figure 10 shows the coefficient of fissures Cr (see following formula) calculated from the elastic wave velocity (natural ground: V_{pl}, sample: V_{p0}) which was measured for the natural ground and samples. The figure shows the number of slope corresponding to the coefficient of fissures on bar graphs by failed and stable slope samples.

$$Cr = 1 - (V_{pl}/V_{p0})^2$$

The broken lines in the figure are a failure rate (Q). The values were obtained by dividing the number of failed slopes by the total number of slopes for that value of Cr. The value indicated an index of failure. The graph shows that Q increases as Cr increases.

The results are plotted against α' on Figure 11. α' is the apparent dip of fissure, which is the angle between the main fissure (bedding, schistosity) and a level surface on the cross section. Similarly, the failure rate for values of α' is shown by broken lines. The highest failure rate occurs particularly between 20° and 50° on the right side (dip slope) rather than the left side (receiving slope).

On the basis of the primary factors obtained and the failure rate, the evaluation marks of the two primary factors of each slope without reinforcement, which were found by the survey of actual condition, were added together. The added values are referred to as the evaluation marks of each slope (total evaluation marks).

In Figure 12, horizontal and vertical axes show the total evaluation mark and the gradient of slope, respectively. The evaluations of the actual slope, stable or unstable conditions, are plotted. As shown, the upper right side of the broken lines shows slopes (mark:•) on which failure occurred, and the lower left side of the broken lines shows the stable slopes. Consequently, in the case where slopes without reinforcement were designed, the slopes steeper than the angles of the lines were unstable. The design of such slopes was unavoidable.

On the other hand, Figure 13 shows the actual research results of slopes reinforced by the same method. As shown, most of the plotted marks are over the broken line in Figure 12, the limit line of non-reinforcement. These slopes remained

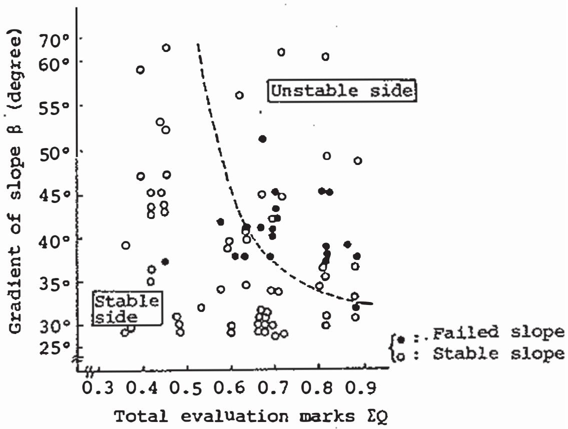

Figure 12. Total evaluation marks and limit gradient of slope of mesozoic and palaeozoic strata (non-reinforced) (Okuzono 1983)

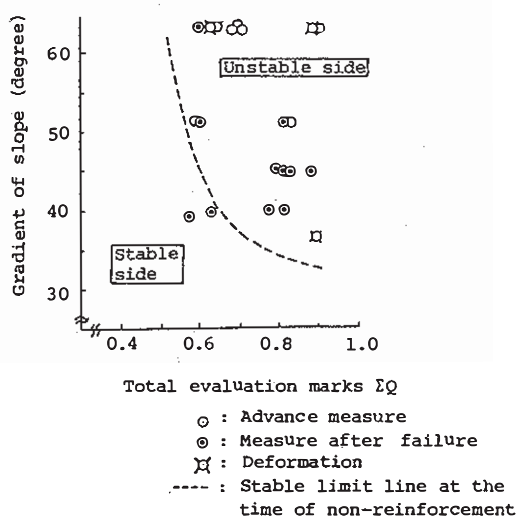

Figure 13. Relation between total evaluated marks and gradient of slope (reinforced)

stable, even though the slopes were steep. However, some plotted marks, which extend far over the limit line, have deformed (mark: ⌑). A limit line may be drawn in the vicinity of the deformation.

6 SUGGESTIONS FOR PREPARING A GUIDE

The Japan Highway Public Corporation has been preparing a draft for a reinforced earthwork design guide. We intend to introduce a design procedure.

First, consideration is given to the size of failure that would occur on an unreinforced slope. The degree of failure is classified into three types: small (several tens of m^3), medium (several hundred m^3) and large (several thousand m^3). In case of a small failure, an empirical design is adopted. In case of a medium failure, a slope is designed by stability analysis. In case of large failure, other methods, such as anchoring or recutting, is studied. The empirical design in the case of a small failure is generally according to Table 1 from the results of section 4. Stability analysis is calculated by failure types as shown in Figure 2.

Table 1. Specifications of empirical design

Parameter	Range
Drilling diameter	ϕ40mm (equivalent to leg drill)
Diameter of steel bars	D19 ∿ D25
Length of steel bars	2m ∿ 3m
Density of reinforcement	one bar/$2m^2$
Angle	from horizontal to right angle

7 ACKNOWLEDGEMENTS

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