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Model loading tests of reinforced slope with steel bars

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ABSTRACT : To investigate the behavior of steel reinforced slope and verify adequacy of the design that employs the limit equilibrium method two series of model tests, vertical loading plate tests and centrifugal loading tests, are conducted. Reinforcement effect that depends upon the length of reinforcing member is confirmed and the behavior of a slope reinforced by short members, such as a gravity earth retaining wall, is examined.

1 INTRODUCTION

To achieve stabilization of the cut slopes the steel-reinforced earth method, the reinforcing of cut slopes with steel bars, is widely practised and becoming popular now-a-days in Japan. Up to the present time the steel-reinforced earth method has been occasionally brought under scrutiny to clarify its effectiveness and mechanism by conducting model tests and in situ tests. In the present research two kinds of model tests are conducted with an objective of establishing a design procedure together with the clarification of the reinforcing mechanism. One is the model loading test where the shoulder of a sandy model slope is loaded by a loading plate and the other is a centrifugal loading test where a similar sandy model slope is exerted by the centrifugal load. This report presents the test results and especially the reinforcement effects that vary with the lengths of reinforcing members.

2 MODEL LOADING TESTS

2.1 The outline of tests

The apparatus for the model loading test is set up as shown in Fig.1. A model slope is made up in the soil container and the shoulder portion of the slope is vertically loaded by means of a loading plate. And a series of tests were conducted on the model for two purposes; one is to find the effect of reinforcing length and the other is to conduct comparative tests on the effects of quasi-retaining wall.

The quality adjusted mountain sand that is obtained from Tama New Town is used for making the model slope. The physical properties of the adjusted sand samples are as shown in Table 1. The model slope is made up by compacting the sand and its unit weight is managed to become γ_t = 1.620 gf/cm^3 at every 10cm thickness of sand. And in the case of retaining wall the model wall is made up by mortar.

As reinforcement the phosphorus bronze strip with a thickness of t=0.5mm and width b=5mm is used. Epoxy resin is used as an adhesive to affix sand to the reinforcing strips. At the outer tips of the reinforcements a plate is attached to give a slight restraining effect to the slope.

The loading is achieved by means of an

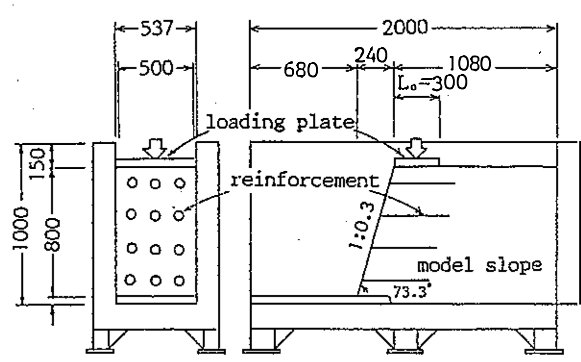

Fig.1 Schematic diagram of model loading test

Table 1. Physical properties of test soil

Items	Physical properties
Water content ratio w	15.3%
Specific gravity Gs	2.66
Maxmum grain size	4.76 mm
Cohesion c	0.1 kgf/cm^2 *
Angle of internal friction ϕ	39.0° *

*:Results of plane shear tests

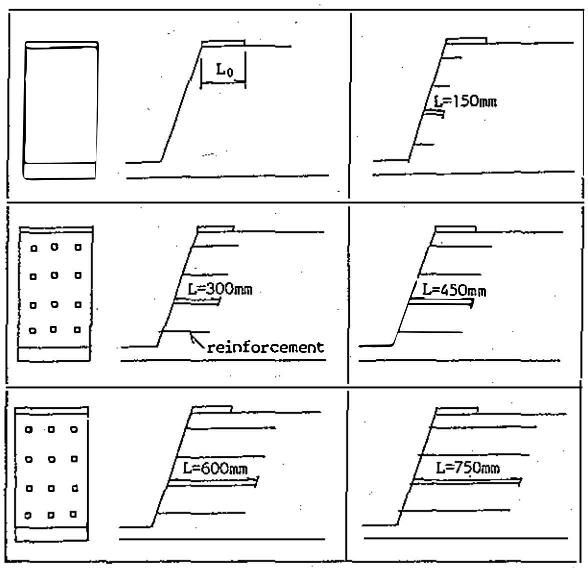

Fig.2 Models for observing reinforcing Machanisum(Test Series I)

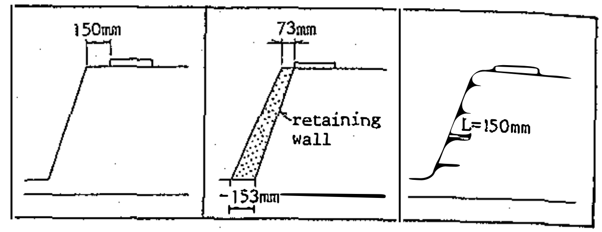

Fig.3 Models for observing effect of quasi-retaining wall (Test Series II)

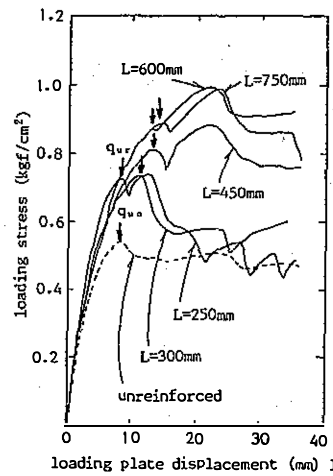

Fig.4 Results of loading test (Series I)

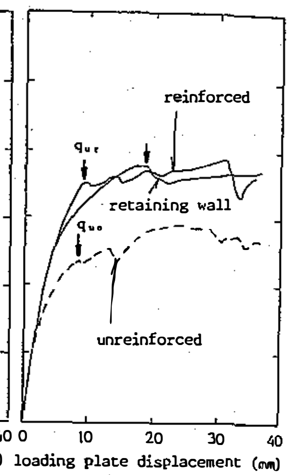

Fig.5 Results of loading test (Series II)

electric screw jack that controls the displacement of vertical loading at the rate of 0.5mm/min. At every stage of displacement the measurements are made for the displacement of loading plate by dial gauge,the loading stress by load cell and the axial stress of reinforcement by strain gauge respectively. After loading is completed the slip failure pattern of the slope is sketched.

A series of tests that are conducted for observing the effects of reinforcing length (Test Series I) contain 5 cases of sandy slopes with different reinforcement lengths and a case of sandy slope without reinforcement as shown in Fig.2. The other series of tests are also conducted to evaluate the effects of short reinforcements which are acting as quasi-retaining wall (Test Series II). These tests are concerned with loading tests of the model embankment without reinforcement and the model retaining wall.

The weight of the model retaining wall is taken equal to the weight of the soil of reinforced zone of the case with reinforcement. And the place of loading of Test Series II is different from that of Test Series I as shown in Fig. 3.

2.2 Test results

(1) The relationship between the loading plate displacement and loading stress

The relationship between the loading plate displacement and loading stress for each case of model test of Test Series I is as shown in Fig.4. Here as stated in the figure the first peak value of loading stress is considered as the limiting or ultimate condition and this value is taken to be the ultimate loading stress (q_u). The ultimate displacement of loading plate is about 8mm when the slope is without reinforce- ment and it becomes 8mm~13mm with reinforcement and the bigger the reinforcement effects the higher the ultimate displacement value will be.

Fig.5 reveals the relationship between the loading plate displacement and loading stress for each case of Test Series II. The case with reinforced slope has a similar result with the Test Series I and in the case of retaining wall the ultimate condition is reached at a higher displacement value of about 18mm.

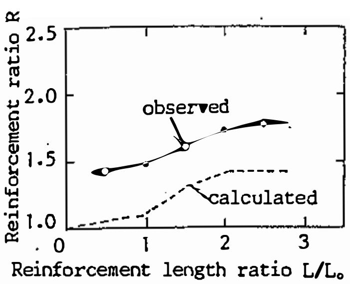

Fig.6 Relationship between R and L/L_0 (Series I)

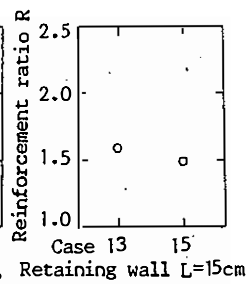

Fig.7 Comparative effects for quasi-retaining wall

(2) The evaluation of reinforcement effect by reinforcement ratio

The reinforcement effect is evaluated by using the reinforcement ratio R as given by the following equation.

$$R = q_{ur}/q_{uo} \quad ....(1)$$

where R : the reinforcement ratio
q_{ur} : ultimate loading stress at the slope with reinforcement (kgf/cm^2)
q_{uo} : ultimate loading stress at the slope without reinforcement (kgf/cm^2)

Fig.6 gives the relationship between the dimensionless reinforcement length-ratio (L/L_o) i.e. the reinforcement length L divided by loading plate width L_o=300mm and the reinforcement ratio R in the case of tests with varying reinforcement lengths. It is to be noted here that the bigger the length of the reinforcement the higher the reinforcement ratio will be in the range of reinforcement length ratio 1.0 ~2.0. When the value of reinforcement length ratio exceeds 2.0 the reinforcement ratio stops to increase. The width of the loading plate L_o is considered almost equal to the cross-sectional length (thickness) of the sliding zone. In the present loading test it is found to be the most effective when the length of the reinforcement is twice the thickness of the sliding zone. The reinforcement effect is significant even if the value of reinforcement length ratio is less than 1.0. This is considered to be due to the fact that the earth integrated and constrained by the reinforcements resists against sliding i.e. the so called behavior of the quasi-retaining wall. Fig.7 shows the reinforcement ratio of the test case which is conducted to investigate the effect of quasi-retaining wall. In case the reinforcement with length L=15 cm that corresponds to the reinforcement length ratio L/L_o =0.5 is laid in place it has a similar reinforcement effect just as much as the effect that is obtained when the earth constrained by the reinforcement is replaced by the same mass of retaining wall. From these test results it is learnt that the steel reinforced earth is as much effective as a quasi-retaining wall. And the reinforcement ratio that corresponds to the quasi-retaining effect is almost the same as that of the model retaining wall. It is deduced that the mechanism differs with the relationship between loading plate displacement and loading stress.

(3) The slip failure line and axial force on the reinforcement

The slip failure patterns observed in the Series I tests and the distribution of axial forces on the reinforcement recorded at the ultimate loading condition are as shown in Fig.8. The slip failure line generates from the rear edge of the loading plate. And a deep slip failure line is pronounced more distinctly in the case of the longer reinforcement. This is the so-called special characteristics of the loading tests under the loading plate. In the case of L = 15cm and L = 30cm which is when the reinforcement length L is less than the width Lo of the loading plate the slip failure line is generated from the rear end of the third reinforcement row from above and extends to the front end of the lowest reinforcement row. In contrast to this in the case of L = 45cm, L = 60cm and L = 75cm the slip failure line appears on the front end of the lowest reinforcement after crossing the third row from above.

The tendency that is clearly noticed is that the bigger the length of reinforcement the larger the axial force on the reinforcement will be. And the position of the maximum axial force on the reinforcement gets deeper away from the slope surface. When the differences that arise from the different laying positions of reinforcements are observed for all cases, the axial forces are somewhat high at the upper-row reinforcements. And the position where the axial force of each row of reinforcement is maximum is situated shallower in the case of lower row reinforcements and it does not directly depend on the position of the slip failure line.

(4) The verification of the ultimate equilibrium method

The test results are verified by considering the loading stresses in addition to the equation (2) of the ultimate equilibrium method that anticipates the tensional effects and also used at present by Japan Highway Public Corporation.

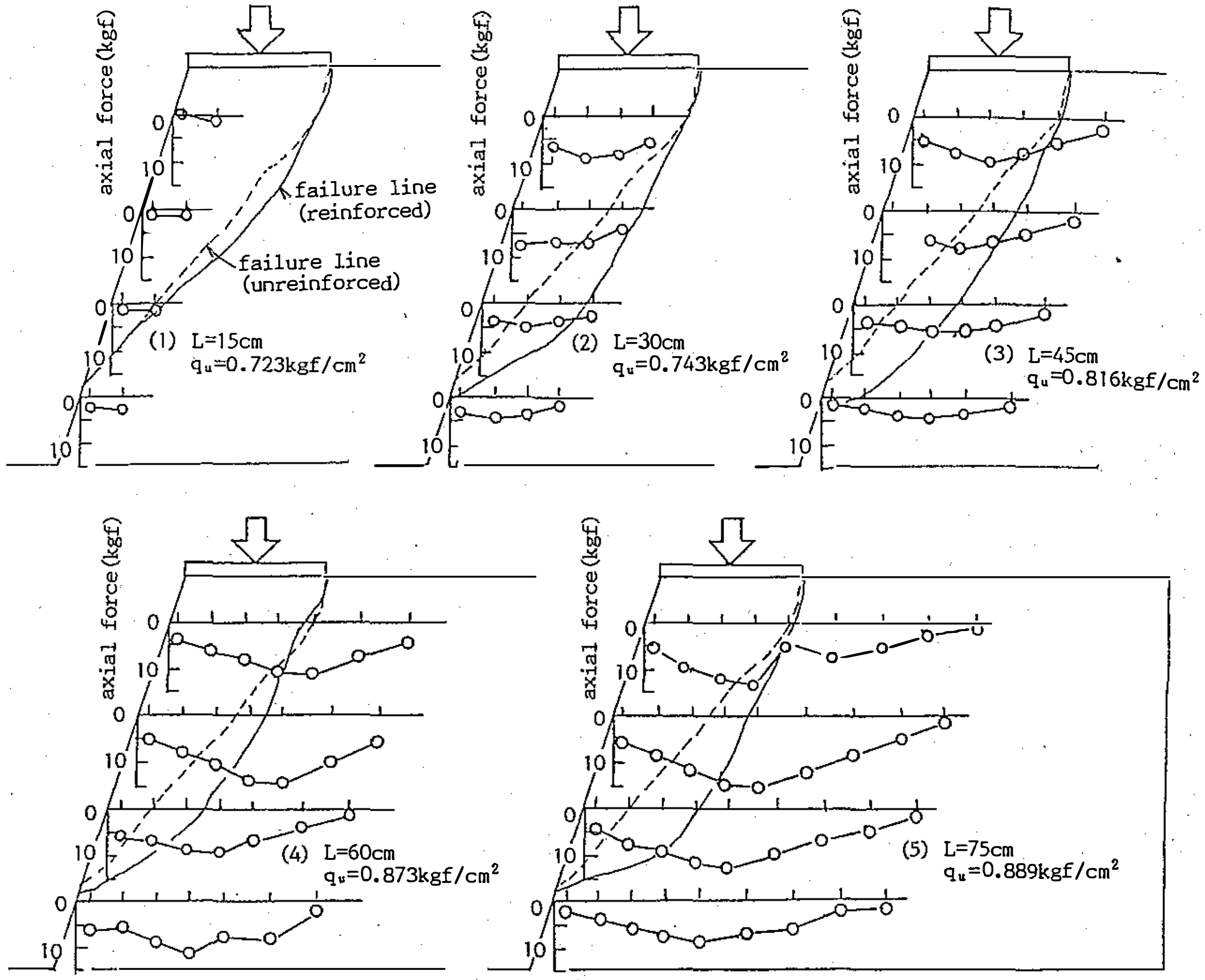

Fig.8 Slope failure line and axial force on reinforcements

$$F_s = \frac{cl + (W\cos\alpha - Ul)\tan\phi + T\cos\beta}{W\sin\alpha} \quad (2)$$

where

- F_s : safety factor
- c, ϕ : shear constants of soil
- W : weight of sliding soil
- U : pore water pressure
- T : tensional force of reinforcement
- α : the angle between the sliding surface and the horizontal
- β : the angle between reinforcement and slip failure surface

The analysis is conducted in such a way that the determined ultimate loading stress yields the safety factor of 1.0 taking the slip circle, with due consideration of the test results, as the circle that passes through the rear portion of the loading plate. Moreover the strength coefficient of the slope's foundation is derived from the backward computation using the safety factor of the unreinforced slope as 1.0 and the tension of the reinforcement (T) is found out from the circumferential friction resistance that is obtained from the separate pull-out tests.

The results of the computation are as shown in Fig.6. These results are lower in value than the results of the model tests. This is considered to be attributed to the fact that the equation (2) takes into consideration only the effect of pull-out resistance ($T\cos\beta$ item) ignoring the restraining effect of foundation and bending strength of reinforcement that are difficult to evaluate. However the computation results confirm the tendency that the reinforcement efffect increases greatly within the range of reinforcement ratio 1.0 to 2.0. This fact well demonstrates the result of the model test.

3. CENTRIFUGAL LOADING TESTS

3.1 The outline of tests

The model slope is made up in the same way

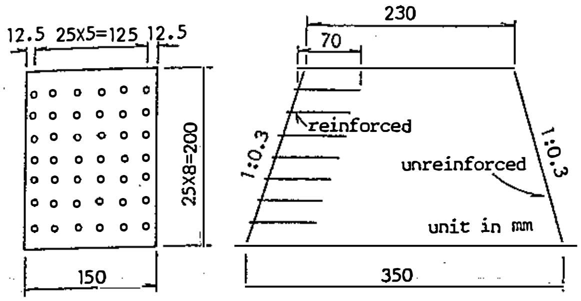

Fig.9 Model slope for centrifugal loading test

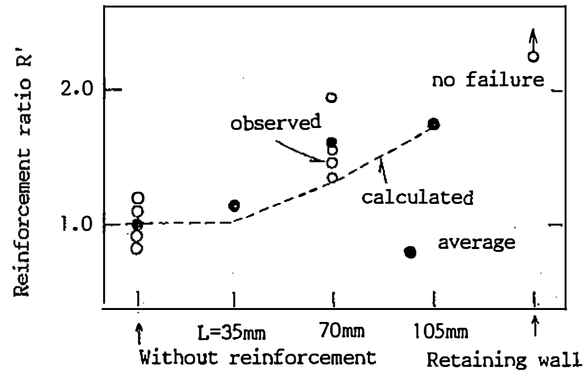

Fig.10 Reinforcement ratio in centrifugal loading test

as the model shown in Fig.9 and the centrifugal loading tests are conducted with a view to verify the reinforcement mechanism in time of self-load rapture. The test soil is the same as that of the model loading test and the reinforcement is the phosphorus bronze strip with diameter ϕ0.4mm and it is affixed with sand. The centrifugal load is increased at a rate of 1 G/min and continued to increase until the model slope fails. After the completion of the tests the slip failure pattern is sketched and the condition of the reinforcements observed.

3.2 Test results

(1) Evaluation of reinforcement effects by reinforcement ratio

The test results obtained from each case of model slope is as shown in Fig.10 and it is arranged in order by reinforcement ratio R' which is given by the following equation.

$$R' = \frac{\text{Failure acceleration for slope with reinforcement}}{\text{Failure acceleration for slope without reinforcement}} \quad (3)$$

The reinforcement effect is not so distinct with the reinforcement length 35mm, but the effect is clearly noticed when the reinforcement ratio reached the value of 1.59 to 1.69 for the length of reinforcement 70mm to 105mm. And in the case of the retaining wall the failure of slope did not take place even after the acceleration reached the maximum of the test machine. This is because of the fact that the subsidence surpasses all other behaviors of failure such as sliding, overturning, etc. in the centrifugal loading tests.

(2) Slip failure lines (patterns)

The representative slip failure line for

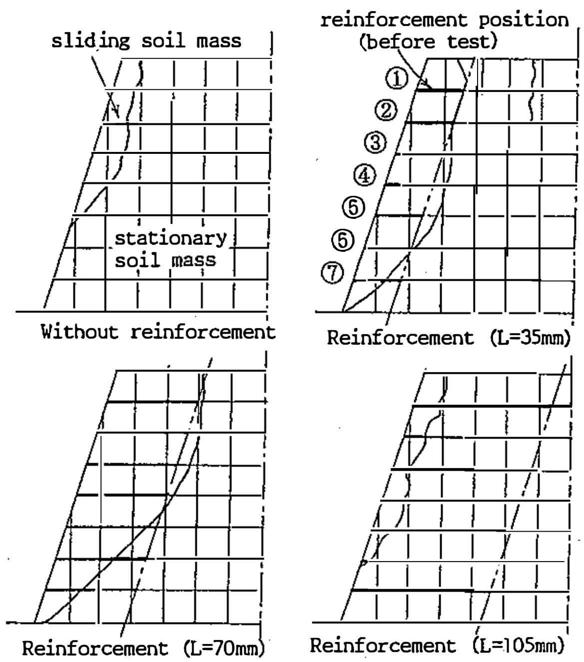

Fig.11 Sketching of slip failure lines (centrifugal loading test)

all model slopes is as shown in Fig.11. The shallow slip failure line that generates from the middle of the slope is observed in the model slope without reinforcement. Furthermore in the case of the model slopes where the 35mm and 70mm long reinforcements are laid the slip failure line that comes up to the surface passing through the rear of the reinforcement as it starts from the toe of the slope is observed and the failure takes place in the portion behind the reinforced zone. In the case of 105mm long reinforcement a shallow slip failure line generates crossing the reinforcements of the middle of the slope irrespective of the high failure acceleration. In the above mentioned loading tests the slip failure line generates from the rear part of the loading plate irrespective of the length of the reinforcement. But in the centrifugal loading tests the position of slip failure line changes since the bond of reinforcement with the stationary soil is in balance with the bond of reinforcement with sliding soil. The case with the 35mm long reinforcement gives no particular effect to the reinforcement ratio but a big effect is noticed at the slip failure line. This is considered to be the so called quasi-retaining effect. It is clearly understood that the retaining wall's slip failure mechanism is different from that of the slope with reinforcement.

(3) Verification by ultimate equilibrium method

The reinforcement effect due to the changes of reinforcement length is verified by the ultimate equilibrium method taking into consideration the increase of dead load (W) of the equation (2) that results from the centrifugal force. The method of analysis is almost the same as that of the model loading test. Since the slip failure line is taken at the least safety factor the slip failure lines for all cases are different from each other.

The value of reinforcement ratio R' obtained from the computation is as shown in Fig.10. In a similar manner with the model loading tests the computed results are on the safer side. The higher safety factors, especially in the cases of reinforcement length L = 35mm and L = 70mm where the failure lines passes through the rear portion of the reinforcement, are considered to be due to the fact that the computation does not take into account the effect of quasi-retaining wall. From these facts it is to be deduced that it is feasible to apply the limit equilibrium method to the centrifugal loading tests.

4. CONCLUSION

From the test results the followings can be concluded.

① For the sandy slope the longer the reinforcement the bigger the reinforcement effects will be. In the model loading tests the increase of reinforcement effects is flattened out when the reinforcement's length is taken twice the thickness of the sliding soil layer.

② In the model loading tests the slip failure line that passes through the rear portion of the loading plate is generated irrespective of the reinforcement's length. But in the centrifugal loading tests the slip failure line changes with the change of the reinforcement's length.

③ Even if the reinforcement is short the reinforcement effect can be thoroughly noticed as a result of the quasi-retaining wall effects but the slip failure pattern is different from that of the retaining wall.

④ The design by equation (2) that is at present used by Japan Highway Public Corporation is found to be on the safer side as judged from the results of both the loading plate test and the centrifugal test. It is to be concluded that this equation is practically applicable.

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