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Analysis of non-uniform reinforcement distribution in reinforced soil wall

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ABSTRACT: The results of three series of small-scale experiments on RS structures with non-uniform: triangular, trapezoidal and uniform - rectangular reinforcement distributions are presented. Each model wall has the same height and is reinforced with the same amount of reinforcement. Non-uniform reinforcement distribution is prepared by varied width of reinforcing strips. All walls are loaded at their crests using the smooth rigid strip footing. It is shown that the reinforcement distribution strongly influences the height of failure zones. It is presented that triangular reinforcement distribution is optimal; the least value of bearing capacity is derived for the uniformly reinforced structure; the experimental results have coincided with those predicted theoretically.

1 INTRODUCTION

In the most of RS (Reinforced Soil) retaining structures the reinforcement is distributed uniformly. However, such layouts of reinforcement in construction need not to be considered as optimal. According to Jewell et al.(1985) design method, amount of reinforcement should increase in construction with the depth below the crest of slope. This proposal is also found in some of the guidelines for the design of reinforced soil retaining wall (Tensar 1991 and Polyfelt 1997). For economical reasons, these design methods suggest to place the reinforcement in two or three zones in the structure, each characterised by different spacing or strength of reinforcement.

There is a scarce of information on influence of reinforcement distribution on a bearing capacity and failure mechanism of RS structures. Michalowski et al. (1994) and Michalowski (1998a,b) presented the results of stability calculation of reinforced soil slopes. It was found that the distribution of reinforcement with variable spacing is more economical, than a uniform spacing. A few publications on that subject, presented by Sawicki & Kulczykowski (1995) and Sawicki (2000) described the RS structure with reinforcement placed in two zones, each characterised by different spacing of reinforcement. It was showed that reinforcement distribution strongly affected the bearing capacity and the orientation of failure surface.

The purpose of this paper is to analyse the influence of non-uniform, linear distribution of reinforcement on the bearing capacity and the orientation of failure surface of RS retaining wall. The theoretical analysis based on the limit states techniques is shortly described and the results of small-scale experiments are presented and compared with theoretical prediction.

2 NON-UNIFORM REINFORCEMENT DISTRIBUTION

Linear distribution can be done using the different technical methods (Fig.1). The first one is to design the reinforcement layers with different spacing, which decreases linearly with depth. The second one is to design equal spacing, but with the strength or amount of reinforcement increasing linearly with the depth.

The reinforcement distribution in construction can be described by so called distributed strength σ_0, which represents strength behaviour of reinforcement.

For reinforcing bar or strips, σ_0 can be taken as

$$\sigma_0 = \frac{T_B}{\Delta L \cdot \Delta H}, \qquad (1)$$

where T_B = tensile limit force of a single bar or strip and ΔL and ΔH denote horizontal and vertical spacing between reinforcement elements, respectively.

For sheets of geotextile or geogrid σ_0 can be defined as

$$\sigma_0 = \frac{T_G}{\Delta H}, \qquad (2)$$

where T_G = limit force per unit length of reinforcement and ΔH = the vertical spacing.

In the paper the simple linear reinforcement distribution is analysed. For such case the distributed strength σ_0 varies linearly with the depth y (Fig.2) and can be defined as

$$\sigma_0 = n + my , \qquad (3)$$

where n and m are the coefficients of distribution.

The reinforcement could be placed in construction in three different kinds of linear distribution (Fig.3):

-triangular:

$$\sigma_0 = my , \qquad (4)$$

-trapezoidal:

$$\sigma_0 = n + my , \qquad (5)$$

and uniform – rectangular:

$$\sigma_0 = n . \qquad (6)$$

For given amount of reinforcement A the coefficients of distribution n and m could not be taken arbitrary, but should satisfy the following condition:

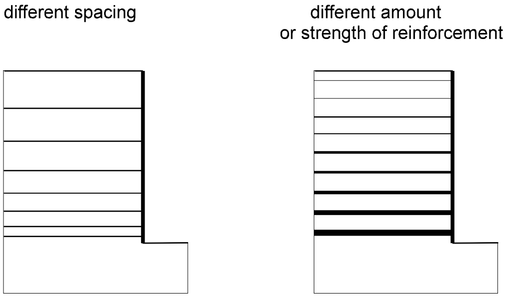

Figure 1. Examples of different methods of reinforcement distribution in construction.

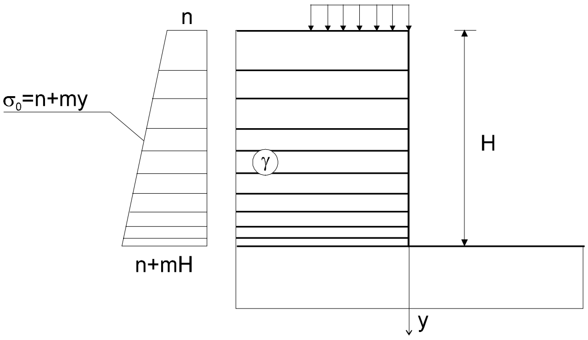

Figure 2. Non-uniform, linear reinforcement distribution in construction.

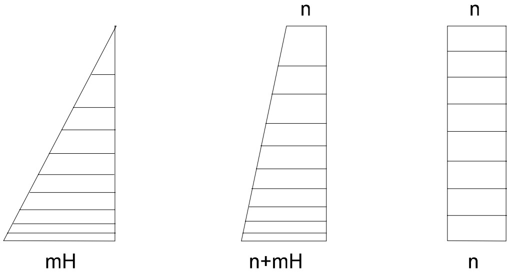

Figure 3. Triangular, trapezoidal and uniform - rectangular reinforcement distribution.

$$n+\frac{1}{2}mH=\frac{AR}{H\Delta L}\,, \tag{7}$$

where H = height of construction, A = amount of reinforcement [m^2], R = tensile strength of reinforcement [kN/m^2] and ΔL = horizontal spacing between reinforcement.

For given coefficients of distribution n, m and for the layers with equal vertical spacing ΔH, the amount of reinforcement in single layer A_L can be calculated using following expression:

$$A_L=\frac{\Delta L\cdot\Delta H}{R}\left(n+m\cdot H_L\right), \tag{8}$$

where H_L is the distance from the crest of construction to the analysed layer level.

3 UPPER-BOUND ESTIMATE OF CRITICAL LOAD

In this paper the influence of reinforcement's distribution on bearing capacity of RS retaining structures is analysed using limit states techniques. The homogenised rigid-plastic theory of RS proposed by Sawicki (1983) is applied. It is assumed that the reinforced soil consists of the soil matrix and unidirectional reinforcement, and that the perfect bonding between these constituents exists.

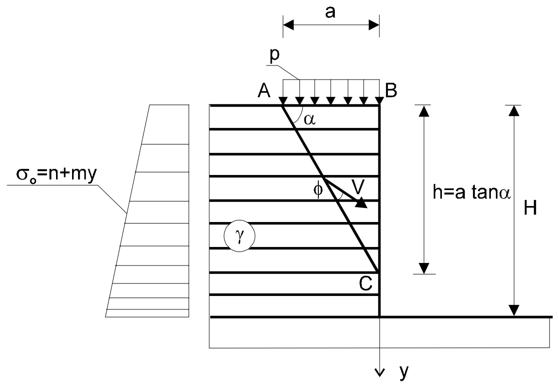

Figure 4. Kinematically admissible mechanism of failure.

The limit states theorems enable estimating so called upper-bounds of critical load of RS retaining wall. The estimate of the critical load can be obtained from the analysis of the kinematically admissible mechanism of failure, shown in Figure 4.

The mechanism depends on slippage of the rigid wedge ABC along the planar failure surface AB. The velocity V of uniform translation is inclined at angle ϕ with respect to AB. This inclination results from the assumption about the associated flow rule. The expression for the upper-bound estimate of the critical load can be derived by equating the energy dissipated along the failure surface to the work done by external forces and self-weight forces of RS structure.

The following formula represents the upper-bound estimate of critical load:

$$p=\frac{\left(n+\frac{1}{2}ma\tan\alpha\right)}{\tan\left(\alpha-\phi\right)}-\frac{1}{2}\gamma a\tan\alpha, \tag{9}$$

where ϕ= angle of internal friction, α= angle between the direction of failure surface and the horizontal direction, a= width of loading area and γ = soil density.

The value of unknown angle α can be obtained from the expression:

$$\frac{\partial p}{\partial \beta}=0\,, \tag{10}$$

which leads to the following result:

$$n\left[\sin 2\left(\alpha-\phi\right)-\sin 2\alpha\right]+ma\left[\tan\alpha\sin 2\left(\alpha-\phi\right)-\sin^2\alpha\right]+ \\ -\gamma a\sin^2\left(\alpha-\phi\right)=0. \tag{11}$$

Due to the complicated form of the expression (11) the solution of angle α can be obtained numerically for the experimental data. Knowledge of a and α enable to estimate the height h of the failure zone:

$$h=a\tan\alpha\,. \tag{12}$$

This theoretical solution is used to design the experimental models of RS retaining wall.

4 MODEL TESTS

4.1 *Experimental method*

The model walls were constructed in strong box with an inner dimension of 660 mm long, 500 mm high and 260 mm wide. To reduce the friction effect the frontage sidewall was made of glass and the opposite sidewall was covered with a smooth aluminum plate.

Each model wall was 171 mm in height and was reinforced with 9 layers of reinforcement, which were placed at equal vertical spacing of 19 mm. The configuration of the model is shown in Figure 5.

The reinforcement used in the models consisted of aluminum strips 300 mm long and 18 μm thick. In each layer three identical strips were connected to the cardboard panels used as the wall facing (see Figure 6). For non-uniform distribution the width of reinforcement in each layer was varied with the depth.

The backfill and the foundation were constructed from the sand that was rained through air by using the hopper kept at 1 m high from the sand surfaces. The models were built on a 150 mm thick foundation. A temporary support in the form of wooden plate and platform was positioned on the top of the foundation soil in front of the wall face to keep the facing in place during construction. Each of sand layer was flattened with the grader.

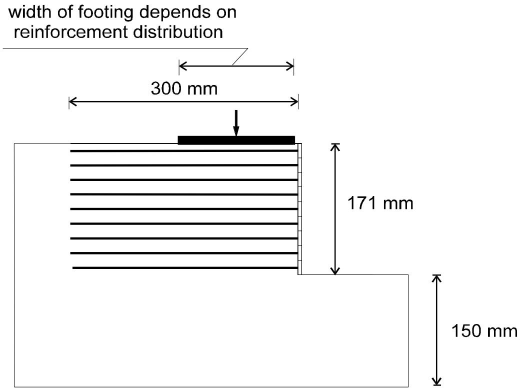

Figure 5. Configuration of the model wall.

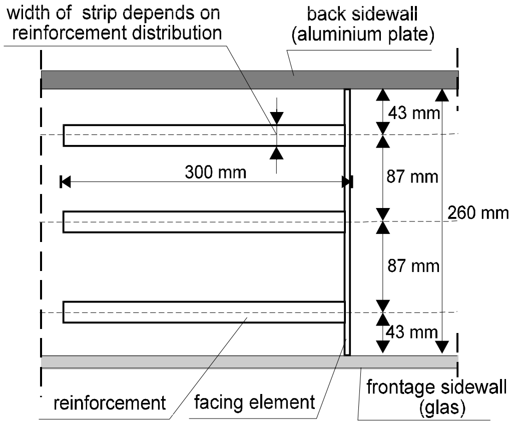

Figure 6. Arrangement of reinforcing strips in reinforcement layer.

Then the layer of reinforcement was placed on the exposed portion of sand. Next layer of soil was placed, in turn, on it, and this process was repeated for successive layers, until the model wall reached the desired height. The temporary support was then removed.

All walls were loaded at their crests using smooth rigid strip footing. It was shown (Kulczykowski 1998, 2002) that the reinforcement distribution strongly influences the dimension of failure zones. In order to obtain the same height of failure zones for different reinforcement distribution the footings with altered width were applied (see Figure 7).

4.2 *Material properties*

The soil used as a backfill and a foundation was dry silica sand (water content w=0). Results of triaxial compression tests indicated that the soil exhibited a friction angle ϕ of 31^o at confining stresses within the range expected in the models. The sand was rained through air under controlled condition to a bulk density ρ of 1.73 Mg/m^3 (unit weight γ of 17 kN/m^3). The density index of the soil was I_D=0.96.

Results of tensile tests of reinforcing strips indicated that the plastic limit of reinforcement R was 39 x 10^3 kN/m^2 and the elongation at break was 5%. No test was performed on the interfaces between the strips and the model soil.

4.3 *Results of the model tests*

Six tests on reinforced model walls were conducted for rectangular, trapezoidal and triangular reinforcement distribution (two tests for each kind of distribution).

The theoretical solution, described above, was used to design the coefficients of distribution: n and m and the width of the footing a. The calculation were performed considering that the height h of failure zone was equal to the height H of the model. This assumption was made for better comparison the results obtained for different reinforcement distribution.

The coefficients: n and m were obtained from the Equation 7. Then the width of footing a was chosen using Equation 11 and Equation 12. Finally, the following parameters were taken to the experiments:

- for rectangular (uniform) distribution: n=12.3 kN/m^2, m=0 kN/m^3, a=0.09 m,
- for trapezoidal distribution: n=8,5 kN/m^2, m=44,7 kN/m^3, a=0.12 m,
- for triangular distribution: n=0 kN/m^2, m=144.1 kN/m^3, a=0.15 m.

The width of reinforcement strips was calculated using Equation 8. For rectangular distribution all strips had the same width: 29 mm. For trapezoidal and triangular distribution the width of strips was increasing linearly with the depth (see Table 1).

Table 1. Width of reinforcement strip

Number of reinforcement layer *	Trapezoidal distribution	Triangular distribution
	mm	mm
1	22	3
2	23	10
3	25	16
4	27	22
5	29	29
6	31	35
7	33	42
8	35	48
9	37	55

* From the crest of construction.

The footing base was loaded at a constant vertical displacement rate of 3.3 mm/min, until model failure occurs. The applied load and vertical displacement of footing were measured using data acquisition system. The deformation of the wall during loading was observed through the glass sidewall. The failure mechanism and the orientation of failure surfaces, detected by means of colored sand were recorded by photo camera.

The failure zones in model constructions are presented in Figure 7. For all tests the same failure mechanisms were observed. The failure was developed along the surface from the footing edge to the base of the wall facing. This mechanism was associated with tensile failure of the reinforcement

The average experimental results of the critical load and the inclination of the failure surface are presented in Table 2 and Table 3, respectively. These results indicate that the structure with triangular reinforcement distribution was the strongest and the least value of bearing capacity was derived for the uniformly reinforced structure. It was shown that the reinforcement distribution strongly influenced the orientation of failure surface.

5 COMPARISON BETWEEN EXPERIMENTAL RESULTS AND THEORETICAL PREDICTION

The comparison between observed and predicted results is presented in Table 2 and in Table 3.

In Table 2 the experimental results and theoretical prediction of the critical load of RS model walls with different reinforcement distribution are compared.

Table 2. Comparison between experimental results and theoretical prediction of the critical load of RS wall.

Reinforcement distribution	Experimental data	Theoretical prediction
	kN/m^2	kN/m^2
Rectangular	44.9	37.5
Trapezoidal	46.5	38.7
Triangular	50.0	42.8

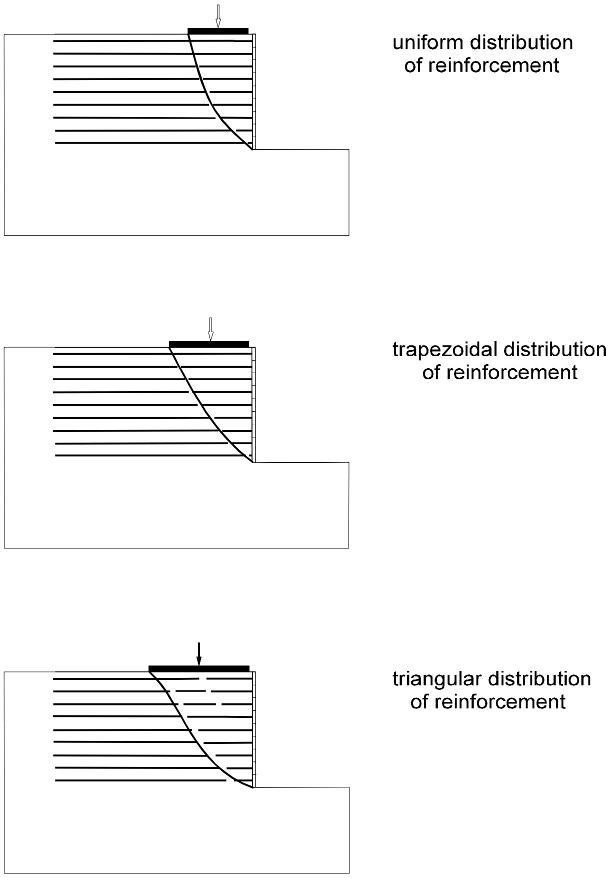

Figure 7. Failure zones in the model tests.

It was shown that the triangular distribution of reinforcement made the structure the strongest. The difference between measured and predicted critical load (of about 15 %) was probably due to boundary friction effect on the sidewall.

Table 3. Comparison between observed and predicted inclination α of the failure surface.

Reinforcement distribution	Experimental data deg	Theoretical prediction deg
Rectangular	62	61.5
Trapezoidal	55	55.0
Triangular	49	47.5

In Table 3 the experimental results and theoretical prediction of the inclination of failure surface of RS model walls with different reinforcement distribution are compared. The experimental inclination of the failure surface was approximately equal to that obtained from the theoretical prediction. It was shown that the lowest value of the failure surface inclination corresponded to the triangular reinforcement distribution.

6 CONCLUSIONS

In the paper the laboratory tests performed on the models of RS retaining walls with non-uniform: triangular, trapezoidal and uniform - rectangular reinforcement distributions are described. To design the experimental models the analysis based on the limit states theorems is used. Each model wall has the same height and is reinforced with layers of equal vertical spacing. Therefore, the non-uniform reinforcement distribution is prepared by varied width of reinforcing strips. In all cases the models contain the same amount of reinforcement. All walls are loaded at their crests using the smooth rigid strip footing. It is shown that the reinforcement distribution strongly influences the height of failure zones. In order to obtain the same height of failure zones for different reinforcement distribution the footings with altered width were applied.

With regard to the experimental and theoretical results it is interest to note that:

1. The RS retaining wall reinforced by the triangular distribution of reinforcement is the strongest.
2. The linear distribution of reinforcement strongly influences the orientation of the failure surfaces.
3. The kinematical limit approach with the failure mechanism depending on slippage of the rigid wedge along the planar failure surface gives a good estimation of the experimental results.

In conclusion: it is presented that triangular reinforcement distribution is optimal; the least value of bearing capacity is derived for the uniformly reinforced structure; the experimental results have coincided with those predicted theoretically.

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