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Design Method of the Soil Nailing Retaining Structures

1. Preamble

Reinforced earth, with its popularity in the western countries, is rather unknown in Poland and therefore has not been used in Polish building corporations. However in middle of eighties, Polish Building Company "Hydrobudowa" has been applied one of the form of reinforced earth techniques, called soil nailing. In this method, especially applied for stabilising slopes and excavations, the reinforcement, in shape of steel rodes-nails, is placed in the natural soil or in existing structures.

"Hydrobudowa" has performed a full scale experiment to test the bearing capacity of steep slope excavation protected with above mentioned technique. Following this experience, the company started to realize in practice soil nailing engineering constructions. Therefore a need is arised to establish the proper design method.

Such soil nailing construction design method was worked out in team: prof. A. Sawicki, dr. M. Kulczykowski and dr. D. Leśniewska from Soil Mechanics Department of Institute of Hydroengineering PAN. The design method, presented in the paper, is based on the solutions of elasto- and rigid plastic theory of the reinforced earth.

2. Introduction

The soil nailing technique used in constructing excavation on the Fig. 1 is shortly presented. The construction sequence of this method is:

- excavation subseqent layer of the soil (1 to 2 m deep),

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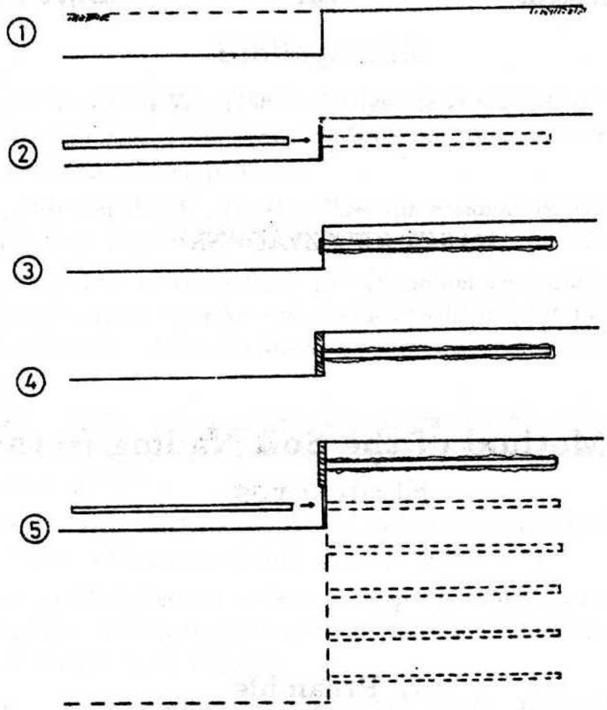

Fig. 1.

- protect steep face of excavation (apply shotcrete or silica),
- drill row of boreholes,
- place nails in the holes and inject them inside with the concrete,
- place steel wire mesh and spray another shotcreate,
- continue the excavating and the another above mentioned steeps until the full construction is ready.

To realize such construction, it is necessary to know the total amount of required reinforcement and the diameter and length of the nails. According to above method the following rules have been applied:

- the lenght of reinforcement is determined from the slope stability analysis;
- the amount and the diameter of the nails is determined from the internal stability analysis based on the rigid plastic theory of reinforced soil;
- the correctness of nails distribution in the designing construction and the other above mentioned parameters, are verified with elastic theory of reinforced earth.

3. Design Method of Soil Nailing Construction

3.1. Determination of Nails Lenght in Construction

The reinforcement elements must have a sufficient lenght to protect the construction against such collapse as shown in Fig. 2. In this case the reinforced zone is located inside

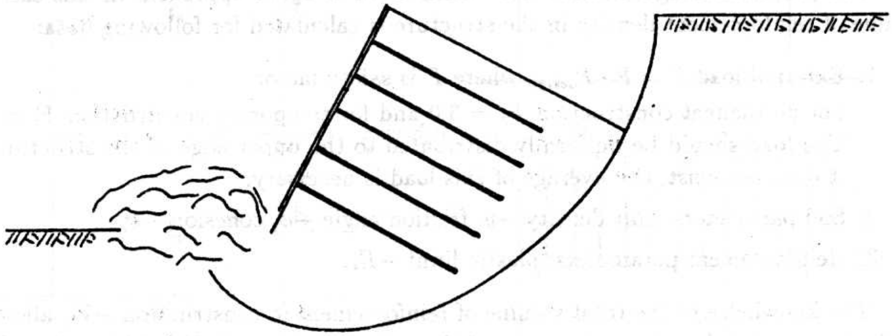

Fig. 2.

of the failure area. Therefore, the required lenght of the nails – L, should be equal to the crest's degradation zone range, estimated numerically with the proper safety factor (see Fig. 3.). Such calculation can be performed with the classical slope stability analysis, for example – Bishop method.

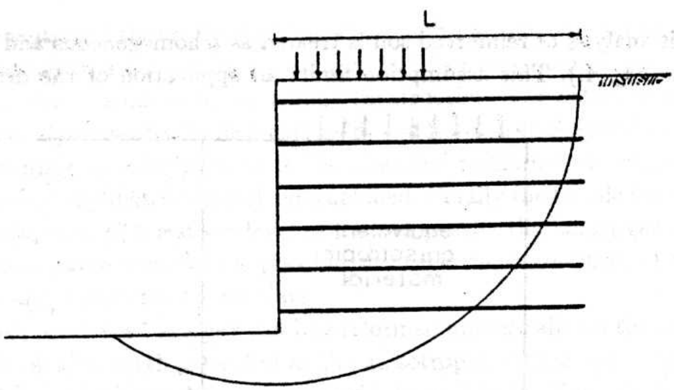

Fig. 3.

It is assumed, that the required safety factor of slip surface is equal $F_p = 1.5$ for permanent construction, and $F_t = 1.3$ for temporary construction.

3.2. Determination of the Required Density of Reinforcement

To determine the required density of insitu reinforcement the plastic limit analysis of reinforced soil slopes is applied. The details of such limit plasticity approach can be found elsewhere Sawicki (1983), Sawicki et al. (1988 a). According to these papers, the solution of bearing capacity of reinforced slope for the weighty soil, can be obtained numerically, with help of method of characteristics. This method allows to calculate the value of external load P (uniformly applied on the upper edge of the structure) for the well-known plastic parameter of soil and reinforcement. It is also possible to determine desolation zone in analized construction.

The proposed design method is a modification of upper approach. In this case the value of reinforcement density in the structure is calculated for following data:

1. External load $P = F \cdot P_{design}$ where F is safety factor.
   For permanent construction $F_p = 3.0$ and for temporary construction $F_t = 2.5$. The load should be uniformly distributed to the upper edge of the structure. In it does not exist, the average of this load is necessary;
2. Soil parameters: unit density $-y$, friction angle $-\phi$, cohesion $-c$;
3. Reinforcement parameters: plastic limit $-R_r$.

The knowledge of the total volume of reinforcement in construction $-V_r$, allows to calculate the total cross-section area of the nails $-A_r(A_r = V_r/L)$. This value allows to take diameter of the nails, and design the reinforcement distribution in construction following the mentioned below western designing principles (see Bruce et al. 1986):

- the density of instalated nails should be 1 per 0.5 to 2 m^2;
- for soil nailing the steel rodes should be taken with the diameter from ϕ 16mm to ϕ 30 mm.

In the limit analysis of reinforced soil is treated as a homogeneous and anisotropic composite (see Fig. 4.). This assumption limits an application of the described me-

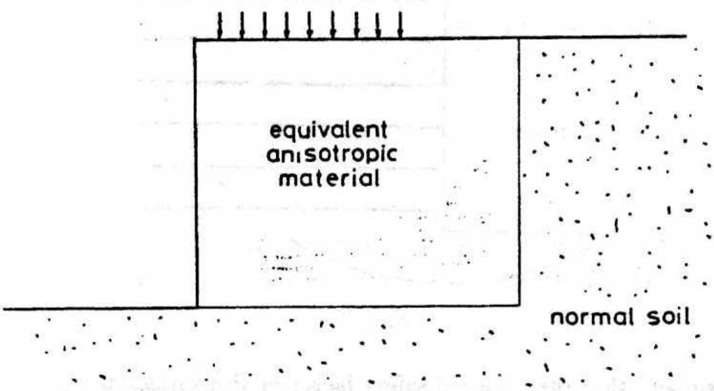

Fig. 4.

thod to uniform soils. Therefore, it is necessary to perform independent calculations of reinforcement density in each layer for the stratified slope, with the different soil parameters. In this case the additional load of weight of upper layers of soil should be taken into account (see Fig. 5.).

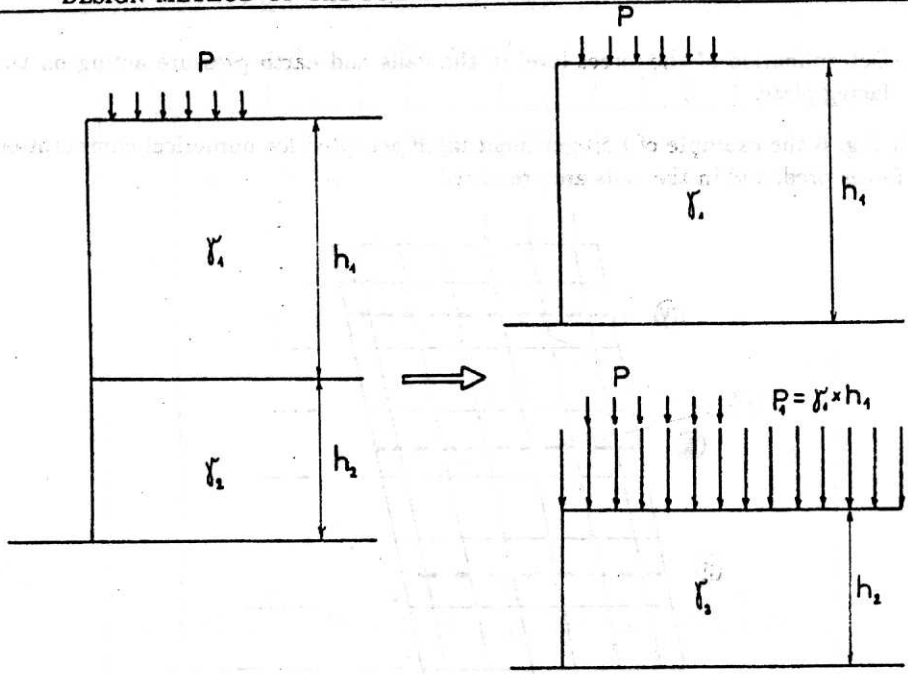

Fig. 5.

3.3. Determination of the Forces Distribution in the Nails

As it is mentioned above, for the layer slope with uneven external load distribution only the rough estimate is possible to obtain. In this case it is necessary to performed an additional elastic analysis of soil nailing construction. The details of such approach have been already presented by Sawicki (1978) and Sawicki et al. (1988 b). This analysis allows to determine the stress state in the stratified reinforced structure with uneven nails density and any distribution of external load. Finally the tensile forces in each nail can be calculated, and the stress level in the soil nearby the facing can be estimated. On the base of these results it is possible to check the correctness of reinforcement distribution and design the facing plate.

The above mentioned analysis can be performed numerically on the microcomputer IBM PC. Reinforced earth is treated as the anisotropic, elastic composite, in the case of stratified slope, with the different properties in each layer. The calculation sequence of this method is:

1. Assuming the finite element mesh of analized nailed slope.
2. Determination of the elastic properties of anisotropic composite on the base of elastic modulus of soil and reinforcement.
3. Determination of the stress state in composite with the help of finite element method.
4. Determination of the stresses in reinforcement and soil.

5. Determination of the forces level in the nails and earth pressure acting on the facing plate.

In Fig. 6 the example of finite element mesh accepted for numerical computation and forces predicted in the nails are presented.

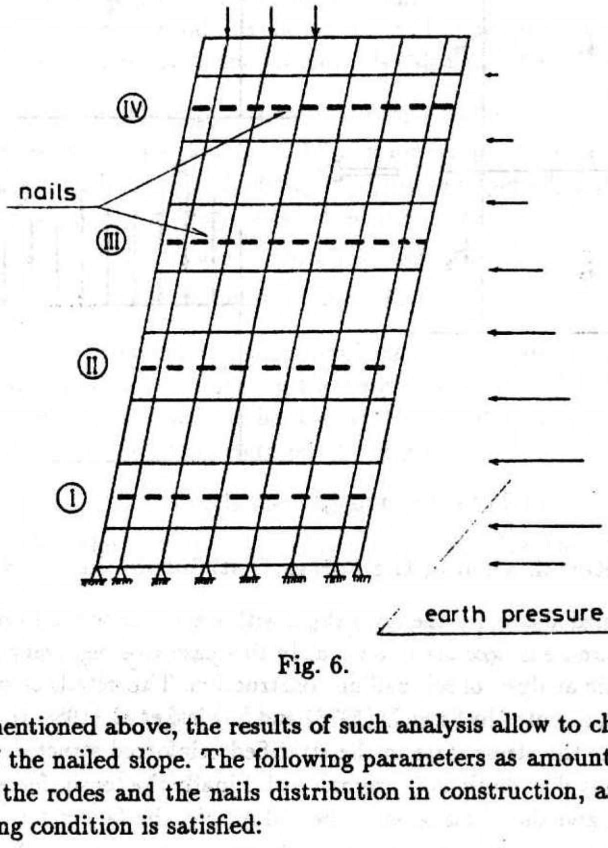

Fig. 6.

As it is mentioned above, the results of such analysis allow to check correctness of the design of the nailed slope. The following parameters as amount of reinforcement, diameters of the rodes and the nails distribution in construction, are taken correctly, if the following condition is satisfied:

$$k \cdot F_{max} \leq F_{pl}$$

where:
F_{max} – maximum force in the nails;
k – safety factor ($k_t = 2.5$ for temporary construction and $k_p = 3.0$ for permanent construction);
$F_{pl} = A_r \cdot R_r$ (A_r – cross section of nail, R_r – reinforcement plastic limit in tension).

3.4. Appendix – Experimental Data Against Theoretical Prediction

The present section is devoted to the comparison of experimental data against the calculated results (see also Sawicki et al. 1988 b). The full scale experiment was performed by Building Company "Hydrobudowa" in 1986 in Koronowo (Poland). In such experiment the bearing capacity of nailed slope was tested. The final dimensions

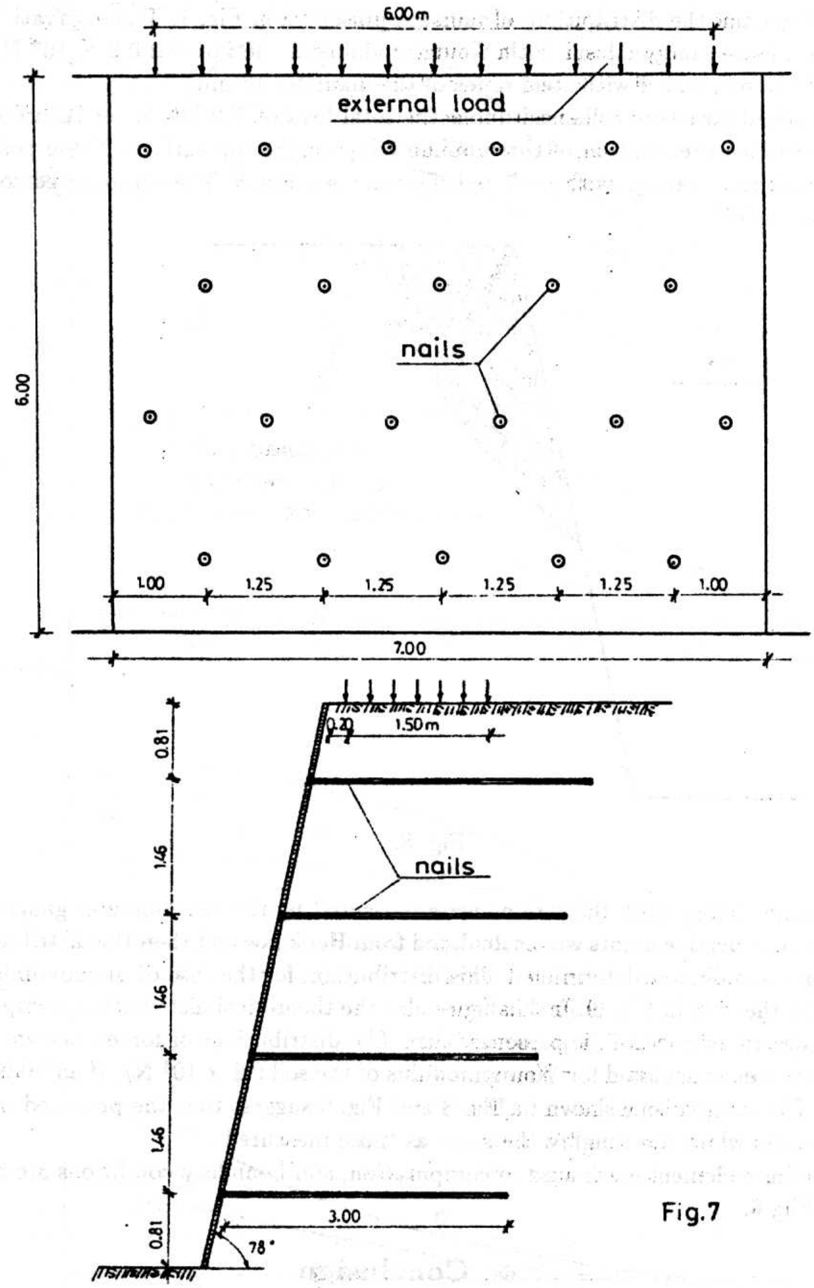
6.00 m
external load
nails
6.00
1.00
1.25
1.25
1.25
1.25
1.00
7.00
0.81
1.46
1.46
1.46
0.81
0.20
1.50 m
nails
3.00
78°
Fig.7

Fig. 7.

of this slope and the distribution of nails are presented in Fig. 7. The excavation was made in a loose sandy subsoil with Young modulus in the interval 0.2×10^8 N/m^2÷ 0.6×10^8 N/m^2, nailed with steel rodes of the diameter 16 mm.

The nailed structure collapsed under the total load of 790 kN. After failure it was possible to measure position of three points lying on the slip surface. These positions coincide, almost exactly, with predicted slip zone, see Fig. 8. The computated collapse load was 780 kN.

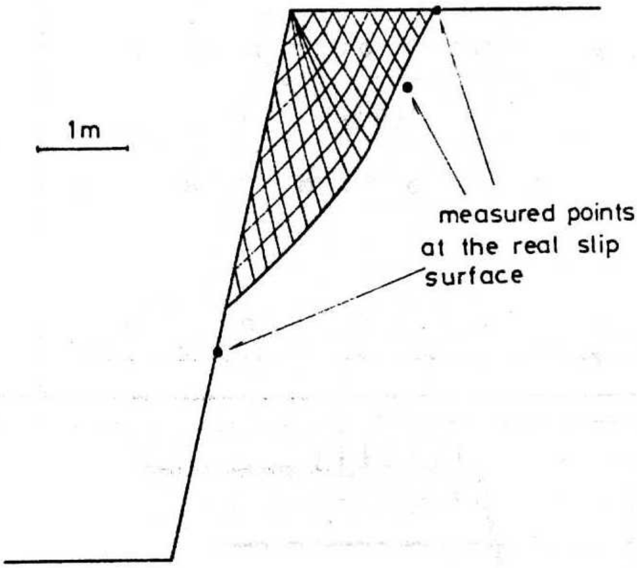

Fig. 8.

In some chosen nails the strains were measured by the tensionmeter gauges. The stresses in respective points were calculated from Hook law and then the distribution of forces in the nails was determined. This distribution, for the case of maximum load, is shown by the dots in Fig. 9. In this figure also the theoretical distribution, computated by the described method, is presented also. The distributions of forces, shown by the solid lines were calculated for Young modulus of the soil 0.2×10^8 N/m^2 and 0.6×10^8 N/m^2. The comparisons shown in Fig. 8 and Fig. 9 suggest that the proposed method gives results which are roughly the same as those measured.

The finite element mesh used in computation, and boundary conditions are presented in Fig. 6.

4. Conclusion

In the present paper the design method, based on the application of rigid plastic and elastic theory of reinforced earth, to the analysis of nailed slope, has been shown. Such method can be also easily adapted to design other structures based on the classical reinforced earth technique. In the APPENDIX the theoretical prediction has been

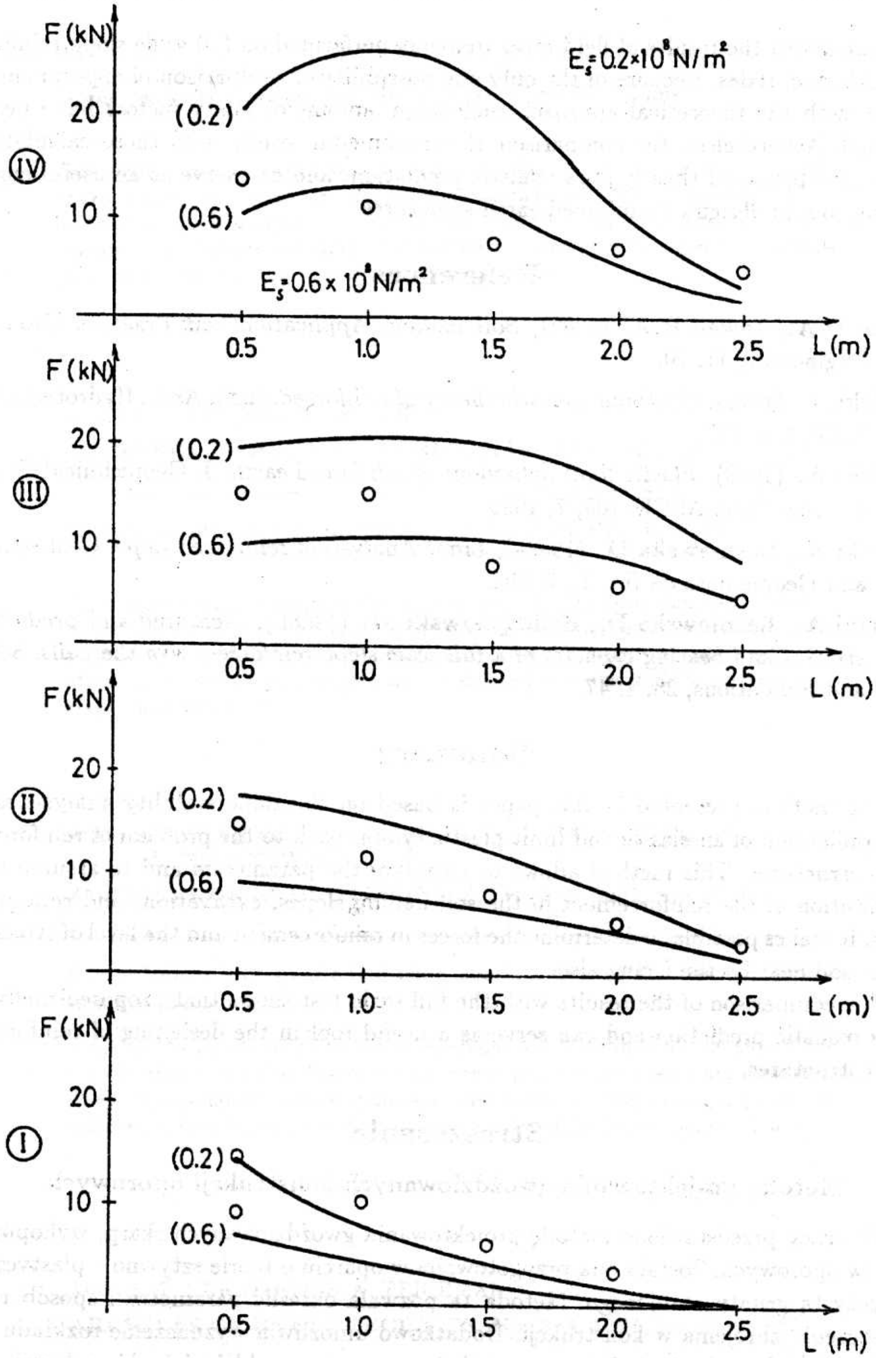
F (kN)
E_s=0.2×10^{8}N/m^2
20
(0.2)
IV
10
(0.6)
E_s=0.6×10^{8}N/m^2
0.5
1.0
1.5
2.0
2.5
L (m)
F (kN)
20
(0.2)
III
10
(0.6)
0.5
1.0
1.5
2.0
2.5
L (m)
F (kN)
20
II
(0.2)
10
(0.6)
0.5
1.0
1.5
2.0
2.5
L (m)
F (kN)
20
I
(0.2)
10
(0.6)
0.5
1.0
1.5
2.0
2.5
L (m)

Fig. 9.

compared with the results of field measurements performed on full scale slope reinforced with steel rodes. Because of the only one possibility of comparison of experimental results with the theoretical approach such large amount of safety factors have been assumed. Nevertheless, the comparison of experimental results with those calculated shows that proposed theory gives realistic predictions and can serve as an useful engineering tool in design of reinforced earth structures.

References

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Summary

The method presented in this paper is based on the slope stability analysis and the application of an elastic and limit plasticity approach to the problem of reinforced earth structures. This method allows to calculate the parameters and to assume the distribution of the reinforcement in the soil nailing slopes, excavations and retaining walls. It makes possible to determine the forces in reinforcement and the level of stresses in the soil near-by the facing also.

The comparison of the results with the full scale test shows that proposed method gives realistic prediction and can serve as a useful tool in the designing of reinforced earth structures.

Streszczenie

Metoda projektowania gwoździowanych konstrukcji oporowych

W pracy przedstawiono metodę projektowania gwoździowanych skarp, wykopów i murów oporowych. Została ona przygotowana w oparciu o teorię sztywno – plastyczną i sprężystą gruntu zbrojonego. Metoda ta pozwala określić parametry i sposób rozmieszczenia zbrojenia w konstrukcji. Dodatkowo umożliwia wyznaczenie rozkładu sił rozciągających w zbrojeniu i stanu naprężeń w gruncie w pobliżu ścianki czołowej.