

NEW APPROACHES TO REINFORCED EARTH CONSTRUCTION

Konstantin Sh. Shadunts¹, Oleg Y. Eschenko²

ABSTRACT

The paper discusses the possibility of using the principles of bionics for designing reinforced earth embankments. Practical usage and novelty of proposed approach are shown on the example of number of patented concrete constructions. The results of model tests (method of equivalent material) and computer calculations (Finite Element Method – 2D, Limit Equilibrium Method – 3D), confirm high efficiency of proposed approach.

INTRODUCTION

Due to wide use of reinforced soil technology in recent years the problem established of effective methods for optimization of the structures and reduction of cost of construction has become real. The use of the principles of construction bionics opens wide possibilities for the solution of this problem.

To a certain extent some of these principles have been used by a number of scientists (Table 1).

TABLE 1 : WELL-KNOWN EXAMPLES OF USE OF PRINCIPLES OF BIONICS

№	Principles of bionics	Example and author
1.	Principle of heterogeneity	Maximum efficacy can be achieved if several materials with various properties are used in the construction: soil and reinforcement (Schlosser and Vidal, 1969)
2.	Principle of power lines	Arrangement of reinforcing elements along the direction of action of maximum tensile deformations allows an increase of stability of the construction by 10-20% (Milligan, 1974)
3.	Principle of uniformity of function and form	It is possible to increase efficacy of reinforcement with the use of steel bands if their surface is corrugated (Schlosser and Elias, 1978)
4.	Principle of equality of limit deformations	In order to fully mobilize the strength properties of materials, they should be chosen in such a way that the limit deformations of extension of the soil and reinforcement should be nearly equal (Gray and Al-Refeai, 1986)

As it is clear from Table 1 the principles of construction bionics should be converted into a form suitable for design in order to be used in the reinforced soil structures.

Some of the well-known principles of bionics are discussed as they are interpreted by the authors (Eschenko, 1991).

¹ Konstantin Shadunts, professor, Kuban State Agrarian University, Krasnodar, Russia

² Oleg Eschenko, ass. professor, Kuban State Agrarian University, Krasnodar, Russia

PRINCIPLE OF EQUALITY IN STRENGTH

Stressed-strained state (SSS) of the embankment is characterized by high irregularity both in longitudinal and transversal directions. In this state the strength properties of the materials in different parts of the embankment are used to various degrees.

In this case the principle of equality in strength requires to select materials (soil and reinforcement) in such a way that their spatial arrangement should provide uniform SSS and should allow full use of their strength.

In general, the solution of this problem is associated with many difficulties and it should be divided into several stages.

Improvement of equality of strength as far as the height of the embankment is concerned (plain task, cross section)

In order to work out the recommendations as far as rational distribution of reinforcement along the height of the embankment is concerned we have carried out three series of computations using “ARMDAM” program (finite element method, plain deformed state, written by the authors).

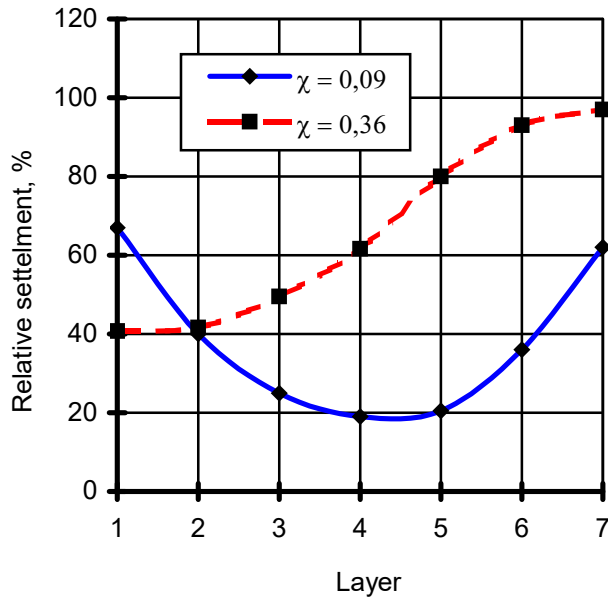


Figure 1 : Reinforcement efficacy

In the first series of computations the criteria of evaluation of reinforcement efficacy were determined. For this purpose the height position of one layer of reinforcement has been changed and the embankment SSS has been analysed. The influence of reinforcement has been evaluated according to the value of relative settlement of the embankment ridge and safety factor in the soil elements ($F_s = \tau_{max} / \tau_i$) averaged according to horizontal layers.

It is clear from Figure 1 that by near bedding of a non-compressed ($\chi = D/H = 0.09$, Figure 2b) layer there is a clearly expressed extremum by which the settlement of the ridge becomes minimal. The comparison of the height situation of reinforcement with soil margin factors field shows that the most effective position of the reinforcing layer coincides with the minimum on F_s indicator, i.e. maximal effect due to reinforcement takes place when reinforcement is introduced into the weakest parts on the embankment.

In the second series an influence of the character of reinforcement distribution according to the height of cross section on the embankment SSS was studied. Six main configurations were considered (Figure 2): uniform distribution (a); distribution due to the condition of equality of areas cut off on vertical stress profile σ_z (b); reinforced raft (c); the method being suggested – introduction of reinforcement into the soil layers with minimal safety factors F_s (d and f); check variant (e).

The analysis of the results being obtained has shown that in all cases the embankment SSS is similar as far as quality is concerned and is characterized by an increase (in comparison with non-reinforced embankment) of the safety factors of soil F_s in lower and middle parts of the slope. At the same time the reduction of safety factors took place in the upper layers. As in the case of one reinforcing layer the highest increase of F_s took place near reinforcement. From the point of view of quantitative results the diagram being suggested (d) proved to be the best one, because it provided minimal settlements of the ridge and the least irregularity of distribution of safety factors F_s . SSS improvement of soil mass is accompanied by the increase (as compared with other diagrams) of tensile stresses in reinforcing elements (there is no slip).

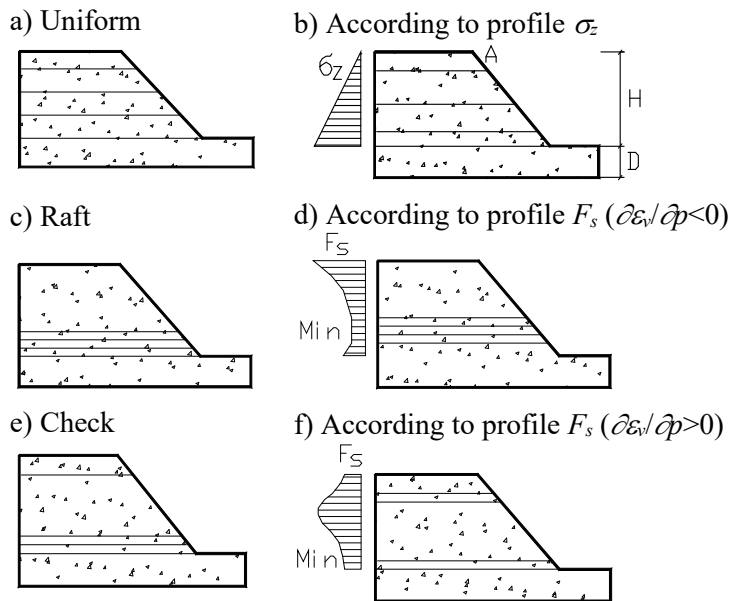


Figure 2 : Diagrams of reinforcement

In the third series of the computations, the influence of non-compressed foundation on the distribution of reinforcement along the height of the embankment has been studied. For this purpose the computations of SSS with the main structures (the most and the least stable ones) were repeated at different distances $\chi = D/H$ up to non-compressed layer (Figure 2, b).

An increase of the distance till the non-compressed layer has led to redistribution of SSS of the slope in such a way, that the zone of minimal F_s with χ growth has displaced from the embankment body to the foundation (Figure 1). In its turn, it has led to the change of optimal height position of reinforcement: "d" diagram has been transformed into "c" variant for contracting soils. The same results have been obtained for dilative soils taking into consideration the corrections for a change of the reinforcement diagram according to the method being suggested.

Improvement of equality of strength as far as the height of the embankment is concerned (plain task, longitudinal section)

If the construction is long and is situated on rugged terrain (gully, ravine, streams, etc.), physical and chemical characteristics of soils at the foundation can be changed at a relatively small distances within the wide ranges, and the construction can change its height. Under such conditions uniform reinforcement along the whole length of the embankment leads to non-equality of strength of the construction in the longitudinal direction.

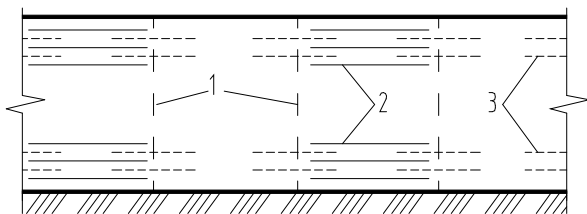


Figure 3 : Longitudinal section of embankment

All the above-mentioned computational results belong to the case when $\partial \varepsilon_v / \partial p < 0$ (ε_v – are volumetric strains of soil; p – is external load, kN), i.e. soil has endured volumetric strains of compression when loading has taken place (contacting soil). But in construction practice (mainly in hydrotechnical construction) one often encounters embankments for which this dependence has a reverse sign (dilative soils³). For these qualitatively different (polyextremal) distribution F_s is characteristic in cross section, the weakest zones are located at the foot and the ridge of the embankment, as a rule. As it has been demonstrated earlier, the introduction of reinforcement into these zones gives the largest effect of the increase of stability of the construction (Figure 2 f).

In order to solve this problem one can divide the whole length of the embankment into the parts with different degree of reinforcement with transversal reinforcement 2 (Figure 3). The boundaries of differently reinforced parts 1 can correspond to the borders of the zones with various physical and mechanical characteristics of foundation soil (it allows to save reinforcement observing rather high bearing capacity of the foundation). In order to provide compatibility of deformations the neighbouring parts can be connected with the

³ The division of soils into dilative and contractive ones is given only in relation to maximal permissible deformations of reinforcement and in general it cannot coincide with the conventional one.

longitudinal reinforcing elements 3 (patent of Russia No. 1587136).

PRINCIPLE OF PREDEFINED FORM OF STABILITY LOSS

Further analysis of the work of the reinforced embankment has shown that stability of the slope depends mainly on the failure surface form (in this case - on the form of the boundaries between the parts with various degree of reinforcement). According to the principle being discussed, the construction will have maximum stability if it has such form and properties of materials which provide the only (predetermined) type of stability loss at any calculation loads. On the other hand, according to the principle of system energy stationarity this form should be such that the work of destructive forces should be maximal.

In order to solve this problem a number of computations with the use of 'SFERA' program have been carried out (limit equilibrium theory, 3D-optimization, elaboration of the authors) as well as model tests with the use of the method of equivalent materials. As a synthetic net was used for reinforcement of the models, two new criteria of similarity were added to the standard ones:

$$\begin{aligned} L_N/D_N &= l_M/d_M \\ I_d^N &= I_d^M \end{aligned} \quad (1)$$

where I_d – material density degree, respectively; N - nature, M - model; L_N and l_M – sizes of net mesh for nature and model, m; D_N and d_M – mean diameters of the particles of the material of nature and model, m.

The investigations being carried out have shown that:

1. Special effects take place for reinforced embankments when

$$2L_s < 3 \div 4H \quad (2)$$

where L_s – half of the length of the ridge, m; H – height of embankment, m. It allows to increase stability of the construction type being discussed by means of artificial creation of the conditions for spatial destruction of weakly reinforced parts. Thus, the condition (2) will be a restriction of the size of weakly reinforced part.

2. Stability of the reinforced embankment is increased non-linearly (progressively) as an angle of internal friction of soil is increased, the difference between 2D and 3D computation is higher than in non-reinforced embankments and is 1,6 fold at average values.

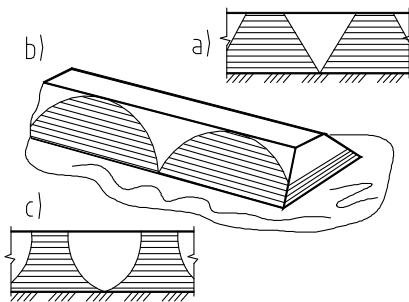


Figure 4 : Variants of form of boundaries of parts

$$F_s^{3D} / F_s^{2D} = 1,3 \div 1,4 \text{ for } 20^\circ \leq \varphi \leq 45^\circ \quad (3)$$

It is clear that to a certain extent it can serve as an explanation to the fact that standard (two-dimensional) computations reduce strength of the construction as compared with the one determined in natural experiments (Sims and Jones, 1974).

3. From the considered variants of the forms of the borders between the parts (Figure 4) the construction with the division surface with a convexity upwards (b) has provided the best stability. Besides, such surfaces provide maximal specific area of contact with strongly reinforced parts when the volume of weakly reinforced part is specified and the condition is observed (2). The analysis of various forms of such surfaces of the division has shown that the

curves of 4-6 order provide not less than 99% from maximal possible stability and it is possible to use any type from the specified range for practical purposes.

Depending on concrete conditions this construction can be added by various elements (patent of Russia No. 1668561). Thus, in case of construction on weak soils it is expedient to create strong reinforced raft under the whole structure. If the embankment is used for a motorway, it may become necessary to reinforce an upper part as well (the ridge of the embankment).

It is clear that from the point of view of economic efficacy it is expedient to use the effects being discussed only in relation to high and long structures, one can use other approaches for small embankments.

SYSTEM PRINCIPLE

This principle requires that the embankment will have such structure which can provide involvement into response of maximal number of elements of the construction at any external influence (i.e. it can provide "system" reaction). The term "involvement into response" has wider meaning than acceptance of load. For example, in this meaning the zero rods in the loaded frame are considered to be involved into response, because if they are eliminated from the construction the efforts in "working" rods are changed. The system principle use allows to reduce internal efforts in the elements due to external load redistribution or construction operation mechanism change.

It is known from the operation experience that reinforced soil structures have several forms of internal stability loss. Analysis of these failures shows that in all cases the possibility of independent horizontal movements of some layers of the structure is the reason of the distractions of this type. Thus, it is possible to prevent these forms of stability loss if compatibility of all or of the majority of parts of reinforcing elements are provided.

For this purpose we have worked out the construction of reinforced soil structure (patent of Russia No. 1631125), the reinforcing elements of this structure in the rear part are crossed by the braces performed with tension, and in the places of crossing of the brace and reinforcement the latter has higher strength than in other places or it is connected with a rigid plate with the possibility to provide joint displacement of reinforcement, the plate and the brace in the horizontal direction and independent displacement of

reinforcement and the plate from the brace in vertical direction (Figure 5).

The provision of compatibility of displacement of the brace and reinforcement in horizontal direction prevents the loss of internal stability of the structure and independence of the displacement in vertical direction preserves efficiency when filling soil is consolidated or the settlements of the foundation are observed. In order to increase efficacy of the embankment operation the braces which cross reinforcing elements are made with tension. It provides compatibility of operation of reinforcing elements even at small deformations of the structure.

Depending on the most probable form of loss of internal stability the braces can be vertical or inclined. Thus, for example, it is expedient to use the construction shown in Figure 5 (a) for motorways which receive significant vertical loads, and it is expedient to use the construction shown in Figure 5 (b) for the retaining walls which receive significant horizontal forces.

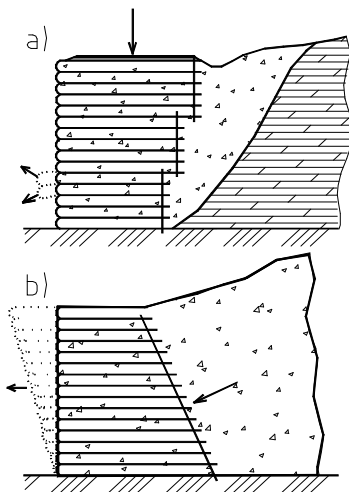


Figure 5 : Example of "system" principle use

CONCLUSIONS

The use of the principles of bionics allows to search purposefully the ways of optimization of the constructions, to adapt the structures for reception of specific types of loads and to reduce the cost of construction.

REFERENCES

- Eschenko O.Y. (1991). "Reinforced soil embankments and foundations". Dissertation presented for the degree of candidate of technical sciences, Krasnodar, Kuban State Agrarian University, pp. 206.
- Sims F.A., Jones C.J.F.P. (1974). "Comparison between theoretical and measured earth pressures acting on a large motorway retaining wall". *J. Inst. highway eng.*, Dec., pp. 26-35.