Application of variable pitch reinforcement with horizontal geosynthetic elements in pads made from cohesive soils

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Abstract. The paper is devoted to researching into the behaviour of reinforced pads made from cohesive soil. Compacted soft-plastic loam was considered as a pad material, and woven geotextile was used as an reinforcing element. The research was aimed at testing a well-known approach to the usage of a variable reinforcement pitch in cohesive soil pads. The goal was achieved by solving test problems for various types of reinforcement in the Plaxis 2D software package. Based on the results of the research, the formula for determining the arrangement of reinforcing layers at a variable reinforcement pitch in cohesive soil pads was adjusted. It was also found that when the layers were arranged at a pitch of 200 mm or less, the reinforcing effect in cohesive soils practically did not occur. In addition, it was confirmed that at a variable pitch of reinforcement, there was the most complete "inclusion of geosynthetic materials in work" in comparison with other considered cases of reinforcement.

1. Introduction

As it is well known, the use of soil pads when arranging shallow foundations is a cost-effective solution in a number of cases [1, 2]. Basically, soil pads are made from inert materials: sand, sand and gravel mix, crushed aggregate, etc. However, there are examples when industrial waste and cohesive soils have been used as a filler [3]. This technical solution is advisable to use for construction in remote areas, where the delivery of building materials bears extremely great transportation expenses. Such examples include oil and gas complex facilities, which are often located at a distance of more than 250 km from regional centers. In this case, the design organizations, trying to reduce costs, consider compacted pads from local soil, which, as a rule, is represented by loams, clays of different consistency, from soft-plastic to semi-solid. However, the use of these materials imposes certain difficulties in the further operation of structures.

Implementation of geosynthetic reinforcing materials can significantly improve soil pad structure [1, 2, 4-6]. In this study, the authors propose to test a variable pitch reinforcement of horizontal geosynthetic elements in pads made from cohesive soils. The principle of the variable pitch reinforcement method is described in detail in [2, 5]. With a variable reinforcement pitch, the distance between the reinforcing layers is determined by the following relationship: \( \Delta h = (n-1) \times 100 + 200 \) (variable pitch), where \( n \) is the number of a reinforcing layer at the same pad height. Regardless of the pitch, for a variable reinforcement pitch, the final reinforcing layer must be put along the pad border and the top of the foundation soil.
2. Experiment
To test the effectiveness of a variable reinforcement pitch in pads made from cohesive soils, test activities were carried out by doing numerical simulations of a highly deformable base soil that was improved with a reinforced pad. The simulation was performed in the Plaxis 2D using the Mohr-Coulomb model. The conditions of the site located in the settlement of Osentsy, Perm district, were taken as engineering and geological conditions [7]. The obtained data are presented in Table 1.

The characteristics of the soil filling the pad were accepted following the test results for monitoring structure excavation in the oil fields of Perm Krai.

The load on the pad was transmitted through a conventional rigid strip foundation of 1 m wide. The foundation depth for the city of Perm was assumed to be equal 1.9 m, based on soil freezing depth.

| Soil                        | Thickness m | $\gamma$, kN/m$^3$ | $\varphi$, degree | $c$, kPa | $E$, MPa | $\nu$ |
|-----------------------------|-------------|---------------------|-------------------|----------|----------|-------|
| Stiff loam                  | 0.8         | 19.9                | 21                | 29       | 13.5     | 0.35  |
| High plastic loam           | 7.2         | 19.1                | 16                | 14       | 8.7      | 0.35  |
| Stiff loam                  | 0.8         | 20.0                | 24                | 40       | 25       | 0.35  |
| Highly weathered, fractured mudstone | 10.3      | 21.0                | 12.7              | 52       | 30       | 0.35  |
| Pad material                | High plastic loam | 19.1               | 10                | 37       | 10.5     | 0.35  |

Based on the studies devoted to the analysis of the reinforced soil behaviour [1-6], which show that geosynthetic materials as reinforcing layers are included in work at loads close to the limit, the maximum critical load [2], which can be perceived by the pad structure without destroying the base, was taken as an evaluation criterion in this study.

The calculation was performed under conditions of flat deformation. The dimensions of the pad were taken on the basis of the previous studies [7] and were equal to $h_n = 1.2$ m (height of the pad), $b_n = 2.5$ m (width of the pad sole), and $l = 2.5$ m (width of the reinforcing element). The pressure distribution angle in the pad body was assumed to be 30° [3]. A general view of the model with a non-reinforced pad made from cohesive soil for calculation in the Plaxis 2D is shown in figure 1.

![Figure 1. General design scheme view of the cohesive soil pad in the Plaxis 2D: $h_n$ is the pad height; $b_n$ is the pad sole width.](image-url)
Woven geotextile was used as reinforcing geosynthetic elements [5, 7], since this material is most often used for reinforcement in our country. The characteristics of the reinforcing material are shown in table 2.

**Table 2. Mechanical characteristics of the reinforcing material.**

| Material          | Maximum linear stiffness value (kN/m) | Relative strain limits (%) | Breaking force, (kN/m) |
|-------------------|--------------------------------------|---------------------------|------------------------|
| Woven geotextile  | 350/282<sup>a</sup>                  | 3-6/10-16<sup>b</sup>    | 47.4/46.6<sup>c</sup> |

<sup>a</sup>The numerator shows the values along the material, whereas the denominator shows them across the material.

Several types of reinforced pad structures were considered: at a pitch of Δh = 0.2 m, Δh = 0.3 m, Δh = 0.4 m, as well as at a variable reinforcement pitch of Δh= (n-1) ×100+200. To show the interaction of the geosynthetic material with the soil, special interface elements were introduced [8]. The coefficient of the geosynthetic material soil friction according to Recommendation for Design and Analysis of Earth Structures using Geosynthetic Reinforcements EBGEO was taken equal to 0.5 tan φ=0.29, since there are no data on the shear test [9].

3. Results

When making the initial calculations, it was found that after the first reinforcing layer had been put at a distance of 200 mm or less from the foundation base, there happened underestimation of the ultimate critical load on the foundation soil. That effect presumably occurred due to the material “slippage” over the soil. That is why, the formula for determining the variable pitch of reinforcement needed adjusting. It got the following form: Δh= (n-1) ×100+300.

As a result of calculation in the PC Plaxis, diagrams which show the stress-strain state of the soil after loading were obtained for each type of reinforced pad structure. The calculation results are presented in figures 2 in the form of stress diagrams [2, 10] for a base improved by a geotextile pad reinforced at various pitches, σ<sub>z</sub>, kN/m<sup>2</sup>. 

![Stress Strain Diagrams](image-url)
Figure 2. Vertical stress distribution of the base improved by a pad reinforced with geotextiles at a
reinforcement pitch of: (a) is 200 mm; (b) is 300 mm; (c) is 400 mm; (d) is variable pitch (300/400/500 mm).

As it is seen from the vertical stress distribution patterns obtained from the calculation results in the
Plaxis 2D software, the highest stress concentration in the soil foundation occurs in the edge sections,
which confirms the classical laws of soil mechanics on the development of stress state phases. Further
in depth, the vertical stresses fade due to the use of reinforcing elements. The highest absolute values
of vertical stresses are noted in the case of a pad reinforced with geotextile in 4 layers at a pitch of 300
mm (210 kPa), and a pad reinforced with geotextile in 3 layers at a variable pitch (220 kPa). In these
cases, the highest values of the maximum loads that the soil base could perceive without destruction
were also observed (see table 3).

Table 3. Numerical simulation results.

| Structure                  | Maximum load, kN/m (N) | Specific load capacity (N/Rein) |
|----------------------------|------------------------|---------------------------------|
| Non-reinforced pad         | 210                    | -                               |
| Six-layer reinforced pad   | 250                    | 17                              |
| at a pitch of 200mm        |                        |                                 |
| Four-layer reinforced pad  | 330                    | 33                              |
| at a pitch of 300 mm       |                        |                                 |
| Three-layer reinforced pad | 300                    | 40                              |
| at a pitch of 400 mm       |                        |                                 |
| Three-layer reinforced pad | 340                    | 45.3                            |
| at a pitch of 300/400/500 mm|                       |                                 |
4. Discussion
As it can be seen from the analysis of the obtained specific load capacity values, the most effective structure of reinforced pads made from cohesive soils is a variable reinforcement pitch structure. The effect of increasing the maximum load with an increase in the number of reinforcing geosynthetic layers begins to decrease if the number of layers reaches more than 4 at a constant reinforcement pitch. It was also found that at a reinforcement pitch of 200 mm or less, due to the low coefficient of friction between the geosynthetics and the cohesive soil, “material slippage” was observed [12]. The reinforcing layers failed to act as a single geomass [10].

It should be noted that when using a pad structure with a variable pitch in three-layered reinforcement, this pad is able to perceive a higher value of the maximum load than that with 4 uniform layers of reinforcement. This allows us to conclude that under a variable pitch of reinforcement, there is the most complete “inclusion of geosynthetic materials in work” in comparison with other considered cases of reinforcement.

5. Conclusions
1. The use of reinforcement in soil pads made from cohesive soil has a positive effect of the increase in the maximum load on the base.
2. When using constant reinforcement pitches (200 mm, 300 mm, 400 mm), the increase in the number of geosynthetic layers to 4 allows us to get a significant increase in the maximum load up to 330 kN/m. However, a further increase in the reinforcement layers up to 5 leads to the opposite effect. There is a decrease in the load-bearing capacity, since the geosynthetic material fails (it does not have time) to interact with the cohesive soil.
3. The highest absolute values of vertical stresses are noted in the case of a pad reinforced with geotextile in 4 layers at a pitch of 300 mm (210 kPa), and a pad reinforced with geotextile in 3 layers at a variable pitch (220 kPa). In these cases, the highest values of the maximum loads transmitted to the soil base are also determined. The use of a variable reinforcement pitch makes it possible to use the reinforcing effect of geosynthetic materials most completely.
4. The most effective pad structure is the one reinforced at a variable pitch. But for cohesive soils, the formula for determining the reinforcement pitch has been adjusted. It has the following form: \( \Delta h = (n-1) \times 100 + 300 \), where \( n \) is the number of reinforcing layers.

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