Calculation of effective schemes for strengthening pile foundations by contour reinforcement with hard elements

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ABSTRACT: The article discusses the method of strengthening of pile foundations with contour reinforcement. Solid injection bodies formed by batch high-pressure injection serve as reinforcing elements. Numerical calculations of the stress-strain state of the ground base were performed in the MIDAS GTS NX 2019 software package (v1.1) for determination of the efficiency of different contour reinforcement patterns.

Several strengthening patterns were considered: intermittent and continuous contour reinforcement along two opposite sides and along the entire perimeter of the grillage.

It was recommended to strengthen pile foundations in stages – by increasing the number of reinforcing elements: from intermittent contour reinforcement to continuous reinforcement; from reinforcement along two opposite sides to reinforcement along the entire perimeter of the grillage. In addition, the requirement for subsequent work must be determined by the results of monitoring of deformations development during and after the completion of work of each stage.

1 INTRODUCTION

In construction practice, a necessity often arises for strengthening of pile foundations, for example, in case of an increase in load on the base or due to deterioration of soil conditions [1-4]. The contour reinforcement – injection of solid bodies (reinforcing elements) along the perimeter of the grillage is an effective strengthening method [5-9]. Reinforcing elements can be made of various materials and be of different structures, injection bodies formed by injection of movable cement-sand grouting compound can also serve as reinforcing elements.

The technology of batch high-pressure injection is an effective injection method. Its essence lies in the simultaneous supply of grouting compound through a group of injectors in the hydraulic fracturing mode. Injection through several injectors that are located along a straight line allows forming a vertically oriented disk of a conditionally rectangular shape in the soil body. The formation of a number of injection bodies along the contour of a pile cluster creates a semblance of compression conditions and positively affects the change in the stress-strain state of the base of the foundation under strengthening.

Numerical studies were conducted in the MIDAS computing package to determine the efficiency of different contour reinforcement patterns (intermittent or continuous; near two opposite sides or along the entire perimeter of the grillage; at different depths: from $0.25l$ to l).

2 SETTING THE TASK

Studies of the stress-strain state of the ground base, strengthened with solid injection bodies – reinforcing elements formed by batch high-pressure injection of cement-sand grouting compound were conducted in the MIDAS GTS NX 2019 software package (v1.1).

The calculations were performed in a spatial setting, taking into account the non-linear nature of the work of soil. The base was represented by Mohr-Coulomb elastoplastic model, and the reinforcing elements that had significantly greater rigidity by a linearly elastic model.

The calculation scheme in MIDAS was developed from a grid of hexahedral and tetrahedral elements, which includes 54,584 elements, 29,416 nodes, 88,824 degrees of freedom, 85,448 equations. The dimensions of the calculated area were assumed to be 11.6×11.6×20.0 m.

16 strengthening patterns were estimated, while the calculations were conducted taking into account the loading history sequentially in 3 stages: by the soil's own weight; after foundation work and installation of reinforcing elements; after applying the load.

The foundation with the following parameters was taken as an example: it consisted of 9 piles with a cross section of 0.3×0.3 m, a length of l = 6.0 m, which are arranged on a grid of 0.9×0.9 m, united by a square grillage with dimensions in the plan of 2.4×2.4 m and a height of 0.6 m. The vertical load on the foundation was assigned to be equal to N = 5,400 kN, the base soil is of stiff loam of medium degree water saturation (p = 1.95 g / cm^3, φ = 14°, C = 15 kPa, E = 4.5 MPa).

The physical and mechanical characteristics of the reinforcing elements in all calculations were fixed as follows: γ = 20 kN/m^3, ν = 0.2, E = 100 MPa. The material of piles and pile grillage is concrete γ = 24 kN/m^3, E = 30×10^3 MPa.

The following dimensions were taken for the contour reinforcing elements: length d = 0.50 m, width s = 0.20 m, height h = 0.70 m. Clearance between reinforcing elements in the plan is 0.075 m, clearance in height is 0.05 m, distance from the row of reinforcing elements to the edge of grillage is 0.25 m.

The following reinforcement patterns were considered: continuous and intermittent contour reinforcement (5 and 3 columns near each side) along the entire perimeter of the grillage; continuous and intermittent contour reinforcement (5 and 3 columns each) along the two opposite sides of the grillage.

For each case of patterns, variants with 8-, 6-, 4- and 2 levels of reinforcement to the depths of l, 0.75l, 0.5l and 0.25l from the base of the grillage were calculated, where l is the length of the pile.

The efficiency of strengthening was estimated by the coefficient of reduced consumption of material C_{RCM}, equal to the ratio of the used volume of solids in cubic meters to the difference in settlement of foundation after strengthening and before it, expressed in centimeters. This means that the C_{RCM} coefficient shows the volume of reinforcing elements in cubic meters required to reduce the settlement of the foundation by 1 centimeter.

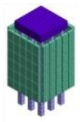
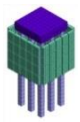
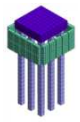
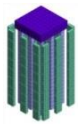
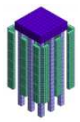
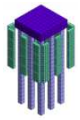
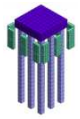
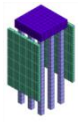
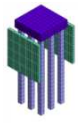
3 CALCULATION RESULTS AND ANALYSIS

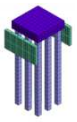
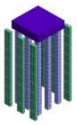
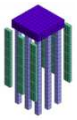
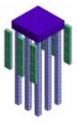
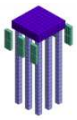
The calculation determined that the settlement of the pile foundation on the natural base is S_e = 141 mm, which corresponds to the actual value of the settlement of the real foundation in these soil conditions.

The accepted patterns of contour reinforcement of the pile foundation and the results of calculations of settlement after strengthening are presented in Table 1.

Table 1. Schemes of contour reinforcement of the pile foundation and calculation results

Scheme number	Schemes of contour reinforcement	Reinforcement step	Depth of reinforcement	The volume of armoelements, m^3	Calculation result
1	2	3	4	5	6
20 / 8		d	l	11,20	S = 129 мм ΔS = 12 мм ΔS / S_e = 9% C_{RCM} = 9,33

1	2	3	4	5	6
20 / 6		d	0,75*l*	8,40	S = 131 мм ΔS = 10 мм ΔS / S_e = 7% C_{RCM} = 8,40
20 / 4		d	0,5*l*	5,60	S = 133 мм ΔS = 8 мм ΔS / S_e = 6% C_{RCM} = 7,00
20 / 2		d	0,25*l*	2,80	S = 135 мм ΔS = 6 мм ΔS / S_e = 4% C_{RCM} = 4,67
12 / 8		2d	*l*	6,72	S = 133 мм ΔS = 8 мм ΔS / S_e = 6% C_{RCM} = 8,40
12 / 6		2d	0,75*l*	5,04	S = 134 мм ΔS = 7 мм ΔS / S_e = 5% C_{RCM} = 7,20
12 / 4		2d	0,5*l*	3,36	S = 135 мм ΔS = 6 мм ΔS / S_e = 4% C_{RCM} = 5,60
12 / 2		2d	0,25*l*	1,68	S = 137 мм ΔS = 4 мм ΔS / S_e = 3% C_{RCM} = 4,20
10 / 8		d, along the two opposite sides	*l*	5,60	S = 135 мм ΔS = 6 мм ΔS / S_e = 4% C_{RCM} = 9,33
10 / 6		d, along the two opposite sides	0,75*l*	4,20	S = 136 мм ΔS = 5 мм ΔS / S_e = 4% C_{RCM} = 8,40
10 / 4		d, along the two opposite sides	0,5*l*	2,80	S = 137 мм ΔS = 4 мм ΔS / S_e = 3% C_{RCM} = 7,00

1	2	3	4	5	6
10 / 2		d, along the two opposite sides	0,25*l*	1,40	S = 138 мм ΔS = 3 мм ΔS / S_e = 2% C_{RCM} = 4,67
6 / 8		2d, along the two opposite sides	*l*	3,36	S = 137 мм ΔS = 4 мм ΔS / S_e = 3% C_{RCM} = 8,40
6 / 6		2d, along the two opposite sides	0,75*l*	2,52	S = 138 мм ΔS = 3 мм ΔS / S_e = 2% C_{RCM} = 8,40
6 / 4		2d, along the two opposite sides	0,5*l*	1,68	S = 138 мм ΔS = 3 мм ΔS / S_e = 2% C_{RCM} = 5,60
6 / 2		2d, along the two opposite sides	0,25*l*	0,84	S = 139 мм ΔS = 2 мм ΔS / S_e = 1% C_{RCM} = 4,20

The pattern designations in Table 1: the first digit is the total number of columns; the second digit is the number of reinforcement levels in depth.

Analyses of the calculation results allow drawing a conclusion about good performance of strengthening of pile foundations using the contour reinforcement method. Any reinforcement pattern leads to a change in the stress-strain state of the ground base and a decrease in the level of settlements.

Thus, at strengthening with continuous contour reinforcement in the plan along the entire perimeter of the grillage with 8-level reinforcement (from the foot to the lower end of the piles) on depth (20 / 8), deformations decrease by 12 mm or 9% relatively to the value of settlement of the pile foundation on a natural base. In case of 6-level reinforcement, the settlement decreases by 10 mm or 7%, at 4-level reinforcement – by 6 mm or 4%. At intermittent contour reinforcement, the settlement is less by 4...8 mm or by 3... 6%, subject to the number of layers of reinforcing elements.

Continuous contour reinforcement along the two opposite sides of the grillage leads to a decrease in deformations by 3...6 mm or by 2...4%, while at intermittent reinforcement - by 2...4 mm or by 1...3%, respectively.

The coefficients of the reduced consumption of material for contour reinforcement of pile foundations are in the range of C_{RCM} = 4.20... 9.33. At the same time, the reinforcement patterns with intermittent reinforcement, both along the entire perimeter and along two opposite sides of the grillage, are more material saving – at 8-level reinforcement in depth (12 / 8 and 6 / 8) the C_{RCM} = 8.40; at continuous contour reinforcement (20 / 8 and 10 / 8), the value of the coefficient of reduced consumption of material is C_{RCM} = 9.33.

For all patterns of placement of reinforcing elements in the plan, the coefficient of reduced consumption of material increases with an increase in the number of reinforcement levels in depth.

Summarizing the obtained results, it is fair to conclude that the deformations of the ground

base directly depend on the volume of injection bodies: an increased number of reinforcing elements leads to a decrease in settlement, however, even minimal reinforcement has a positive effect on the stress-strain state of the soil mass. It is important to note here that the specific efficiency decrease along with the increased number of reinforcing elements.

As a result, it is expedient to perform strengthening by batch high-pressure injection in stages: by increasing the number of reinforcing elements, and accordingly changing the pattern of their placement in the plan (from intermittent contour reinforcement along two opposite sides to continuous one along the entire perimeter of grillage).

Two patterns for staged strengthening of pile foundations by contour reinforcement with solid injection bodies are proposed.

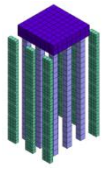
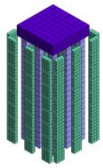
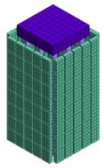
The first pattern contains the following sequence (Table 2):

Stage 1: intermittent contour reinforcement along two opposite sides of the grillage;

Stage 2: intermittent contour reinforcement along the entire perimeter of the grillage;

Stage 3: continuous contour reinforcement along the entire perimeter of the grillage.

Table 2. The sequence of reinforcement of a pile bush by contour reinforcement (1st option)

Stage 1	Stage 2	Stage 3
		
$\Delta S / S_e = 3\%$ $C_{RCM} = 8{,}40$	$\Delta S / S_e = 6\%$ $C_{RCM} = 8{,}40$	$\Delta S / S_e = 9\%$ $C_{RCM} = 9{,}33$

The second pattern of strengthening (Table 3):

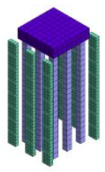
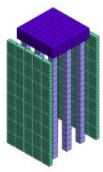
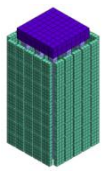
Stage 1: intermittent contour reinforcement along two opposite sides of the grillage;

Stage 1: continuous contour reinforcement along two opposite sides of the grillage;

Stage 3: continuous contour reinforcement along the entire perimeter of the grillage.

The difference in the settlement of the pile foundation after and before the strengthening indicates a higher productivity of the first pattern: $\Delta S / S_e$ at stage 2 is 6% at $C_{RCM} = 8.40$ versus 4% at $C_{RCM} = 9.33$. However, laboratory experiments show that continuous reinforcement along two opposite sides of the grillage is more efficient than intermittent reinforcement along the entire perimeter [4].

Table 3. The sequence of reinforcement of a pile bush by contour reinforcement (2st option)

Stage 1	Stage 2	Stage 3
		
$\Delta S / S_e = 3\%$ $C_{RCM} = 8{,}40$	$\Delta S / S_e = 4\%$ $C_{RCM} = 9{,}33$	$\Delta S / S_e = 9\%$ $C_{RCM} = 9{,}33$

In practice, it is obvious that the choice of the pattern of contour reinforcement of pile foundations will be subject to the possibility of placement of injection equipment and other circumstances. Meanwhile, it is also possible to gradually increase the reinforcement depth at a constant number of reinforcing elements in the plan.

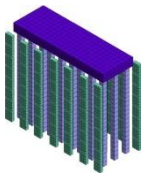
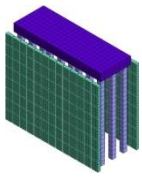
Strengthening of strip pile foundations can be carried out in two stages (Table 4):

Stage 1: intermittent contour reinforcement along the strip pile foundation;

Stage 2: continuous contour reinforcement along the strip pile foundation.

Contour reinforcement refers to the adaptive strengthening method – the necessity for performing the subsequent work is determined by the results of monitoring the dynamics of the development of deformations of the ground base during and after the completion of each stage.

Table 4. The sequence of reinforcement of the tape pile foundation by contour reinforcement

Stage 1	Stage 2
	
$\Delta S / S_e \approx 6\%$ $C_{RCM} = 8{,}40$	$\Delta S / S_e \approx 9\%$ $C_{RCM} = 9{,}33$

4 CONCLUSION

The performed studies show that any contour reinforcement pattern has a positive effect on the stress-strain state of the base, while the specific efficiency of strengthening reduces along with the increase in the number of reinforcing elements.

Strengthening of pile foundations is recommended to perform in stages by increasing the number of reinforcing elements: from intermittent contour reinforcement to continuous reinforcement or from reinforcement along two opposite sides to reinforcement along the entire perimeter of the grillage. In addition, the requirement for subsequent work should be determined by the results of monitoring of deformations development during and after the completion of work of each stage.

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