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The effect of design on interaction of foundation slabs with the base

S.V. Ikonin, A.V. Sukhoterin***
Voronezh State Technical University, Voronezh, Russia
** E-mail: asuhoterin@list.ru*

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Abstract. The paper suggests advanced trend in reduction of materials consumption for the base slabs owing to their design. As an example, the stress and strain state of the models of solid slabs and slabs with controlled forces interacting with sand base, are addressed in the paper. The models were loaded by static system of concentrated vertical forces. Stress and strain state of the models was assessed by the results of laboratory tray experiments with strain measurement and by the data of numeric calculations by finite element method with application of Coulomb-Mohr soil model. Based on the comparison of obtained results, it is demonstrated that the slab with controlled forces has advantages over a solid slab. For example, owing to the control of forces, it becomes possible to avoid alternation in bending moments diagram, flatten the values of support bending moments for intermediate supports and achieve more smooth deflection of the slab, thus creating prerequisites for significant reduction of materials consumption. Apart from this, it was established that experimental values of bending moments and slab deflection are qualitatively consistent with numerical prediction, while the finite element calculation gives slightly inflated absolute values as compared to the experiment results. The results of the studies may appear useful in the design of base slabs for supports of overhead roads, trestlework along with industrial civil buildings and frame type structures with regular grids of columns.

1. Introduction

Solid reinforced concrete slab foundations on soil base are widely used in foundation engineering. The basic advantage of this type of foundations is their ability to distribute significant external loads from buildings and structures on a large contact area with the base. This feature enables us to use upper soil layers with low strength deformation characteristic and soil masses with complex bedding of engineering and geological elements as bases. Apart from this, ease of manufacture and no need for backfilling and under-floor waterproofing in underground part of buildings and structures are deemed the advantages of slab foundations.

The shortcoming of the foundation structure discussed in this paper is high materials' output ratio, mainly related to the cost of steel used for reinforcement. The article addresses the aspect of reducing the materials output ratio and improving the technical-economic and performance indicators of foundation slabs.

Analysis of the existing sources show that the materials output ratio for the slab foundation structure can be reduced due to the use of refined calculation models namely, calculation of slab foundations in «superstructure-foundation-base» system with account of non-linear properties of soil base and foundation material. Such approaches are outlined in papers [1-16].

Recently, the base-foundation systems with controlled properties have been widely used in foundation engineering. Their use provides for generation of a set deflected mode at the design and construction phases to improve technical-economic and performance indicators of the bases and foundations.

The aforementioned systems with controlled properties are being implemented due to design solutions related to targeted change of the base and foundation stiffness. Such design solutions are described in papers [17-28].

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The research results published by the authors in this article are related to this subject and are elaboration of paper [29].

2. Methods

The key goal of this paper is to research on the deflected mode of foundation slab structure with controlled forces on specially developed scale model, along with performance evaluation of foundation slab structure with controlled forces.

The following tasks were identified to attain the goal:

- Experimental and numerical studies of a scale model of foundation slab structure with controlled forces;
- Analysis of deflected mode of foundation slab structure with controlled forces;
- Establishing the qualitative and quantitative patterns based on experimental and numerical studies;
- Efficiency evaluation of the foundation slab structure by comparison of calculation results for the proposed structure of foundation slab with controlled forces against a solid foundation slab.

2.1. Description of tested models

As part of the experiment, scale models of foundation slab with controlled forces and solid foundation slab were tested.

The model of foundation slab with controlled forces comprises five separate sections with dimensions in the plane 200×200 mm interconnected with hinged units (Figures 1–3). Foundation model is made of sheet steel S245, 5 mm thick.

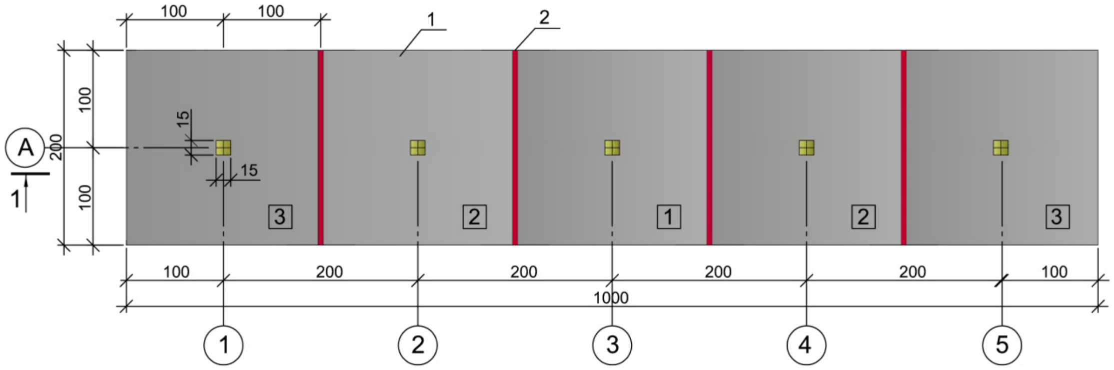


Figure 1. Design of foundation slab with controlled forces, plan: 1 – separate slab section; 2 – hinged unit.

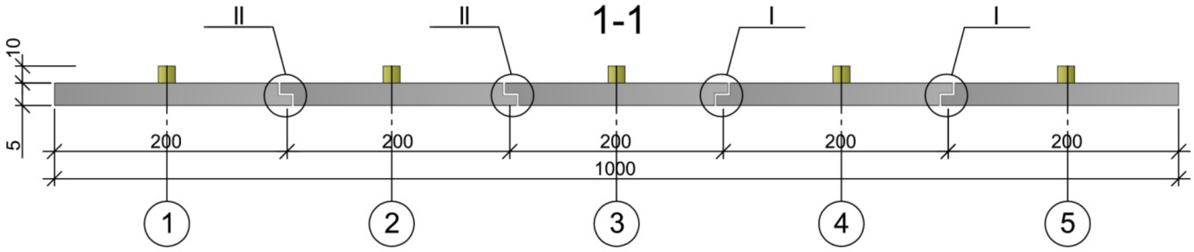


Figure 2. Design of foundation slab with controlled forces, cross-section 1-1: I, II – hinged units.

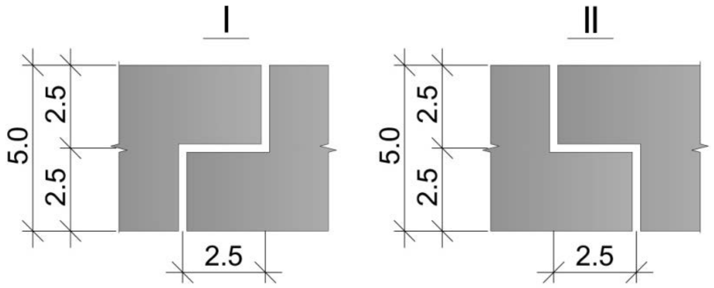


Figure 3. Hinged units I, II.

The proposed hinged unit provides for reciprocal turn of two adjacent sections of foundation slab relative to each other, thus creating a hinge effect to its work. Moreover, joint work of adjacent parts of the foundation slab in vertical direction is provided for.

According to paper [29] such design solution provides for unloading of foundation slab cross-sections both in spans and under the columns while retaining the foundation distribution capacity.

The model of a solid foundation slab dimensions in the plane are 200×1000 mm, made of sheet steel S245, 5 mm thick (Figure 4).

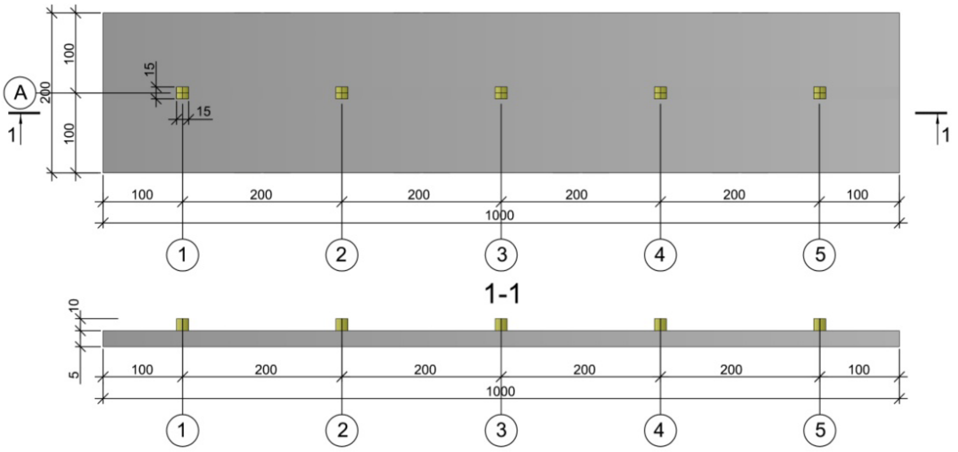


Figure 4. Design of a solid foundation slab, plane, cross-section 1-1.

2.2. Experiment method

Experimental studies were carried out in the center of collective use named after professor Yu. M. Borisov of Voronezh State Technical University.

As part of the experiment, it was required to identify the actual distribution of forces in the models and the foundation settlement.

In the course of foundation models' tests, the following data were recorded at each loading stage: the actual applied loads, relative deformations in characteristic points of the model and foundation settlement.

To determine the relative deformations in characteristic points of foundation models, a tensometric complex, comprising an instrumentation amplifier, connection blocks, resistance strain gauges and personal computer with specialized software, was used.

To measure the longitudinal and lateral deformations, strain gauges with the base of 20 mm were pasted on the foundation models. Foundation settlement was measured with Maximov flexometers with scale interval of 0.1 mm. Schemes of strain gauges' pasting and installation of Maximov flexometers are given on Figure 5.

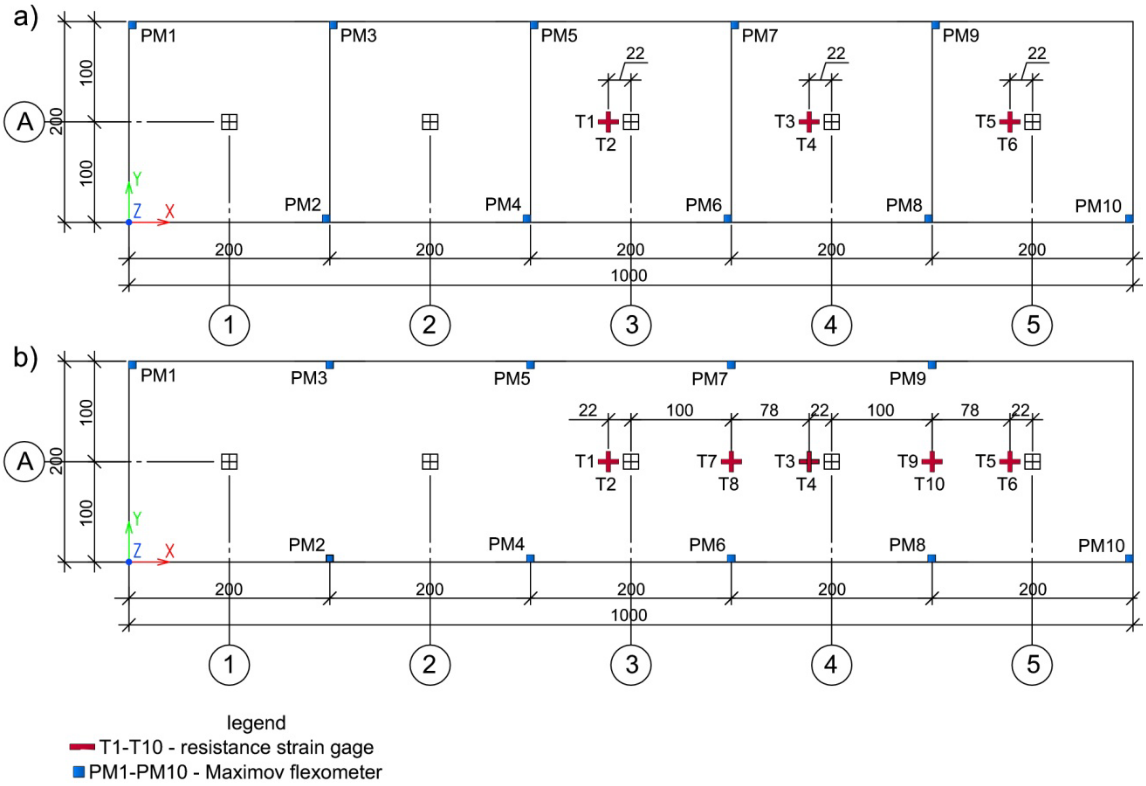


Figure 5. Schemes of strain gauges' pasting and installation of Maximov flexometers:
a) Model of foundation slab with controlled forces; b) Model of solid foundation slab.

The models were loaded stage-wise by installation with hydraulic jacks. The loads were controlled by force-measuring sensors and dynamometers. The maximal load and the number of loading stages were determined on the basis of preliminary calculations. Each loading stage was sustained till conventional stabilization.

Validity of the test results is ensured by tensometric complex registered in the State Registry of Measurement Instruments (RF SRMI), pre-calibration of dynamometers on calibrated pressure equipment (INSTRON (USA) model 5982), use of materials for the models conforming with the effective codes and standards.

Basic parameters of experimental installation are presented in Table 1 below.

Table 1. Basic parameters of experimental installation.

General view of experimental installation

Equipment used:

1. A rig for testing the soils and foundation models in special arrangement
2. Strain gauge equipment:
   - Amplifiers MGCplus and QuantumX;
   - Communication processor CP42 with Ethernet and USB-interface
   - Measurement module DC;
   - Multimode amplifier 8-channel
   - CATMAN-AP software
3. Force-measuring tensoresistive sensors C6A 200 kN
4. Resistance strain gauges with the base of 20 mm KF 5P1-20-120-A12 according to Specifications 3.06 7710-0001-93
5. Lifting jacks, weight-carrying 5 tons
6. Dynamometers, brands: DOSM-3-1 ultimate load 1t, DOSM-3-5 ultimate load 5t;
7. Maximov flexometers with scale interval of 0.1 mm.

Schemes of models' loading:

1. The models' loads were incremented
2. Each load increment was retained till conventional stabilization of 0.1 mm over the last 15 minutes of observation
3. The following load increments were assumed:
   - For intermediate supports – 0.5 kN;
   - For end supports – 0.25 kN;
4. Maximum load:
   - For intermediate supports – 4.0 kN;
   - For end supports – 2.0 kN.

Base characteristics:

1. The base is represented by homogeneous layer of sand of average size and density with the following physical and mechanical characteristics:

1. $\rho = 1.72$ g/cm^3, $W = 2.4$ %, $\varphi = 36°$, $C = 1.6$ kPa, $E = 21.8$ MPa, $\nu = 0.3$

2. Deformation characteristics of the base are determined by the stamping tests.

3. Results and Discussion

As a result of tests, we have obtained data arrays for each load increment characterizing the relative deformations of models in places of resistance strain gauges installation, and model base settlement in points of flexometers' string fixture. The total amount of processed and analyzed data characterizing the relative deformations comes up to approximately 90000 for each foundation model.

Experimented foundation models are classified as thin plates [30]. Therefore, thin plate theory equations were used to determine the internal forces by tensometry data: (1), (2):

$$M_x = -D \cdot \left(\frac{\partial^2 W}{\partial x^2} + \mu \frac{\partial^2 W}{\partial y^2} \right) = \frac{D}{z} \cdot (\varepsilon_x + \nu \cdot \varepsilon_y); \tag{1}$$

$$M_y = -D \cdot \left(\frac{\partial^2 W}{\partial y^2} + \mu \frac{\partial^2 W}{\partial x^2} \right) = \frac{D}{z} \cdot (\varepsilon_y + \nu \cdot \varepsilon_x), \tag{2}$$

where M_x, M_y are bending moments in x and y direction;

ε_x, ε_y are relative deformations in x and y directions;

$D = \frac{Eh^3}{12(1-\nu^2)}$ is cylindrical rigidity;

E is modulus of elasticity for plate material;

ν is Poisson ratio,

h is plate thickness;

z is distance to neutral plane of the plate.

Based on the results of a series of experiments, we obtained averaged values of relative deformations and forces in characteristic points. Averaged results are given for the final load increment corresponding to the load of 4 kN for intermediate supports and 2 kN for the end supports. The results are presented below in Tables 2 and 3.

Table 2. Tensometry results.

Relative deformations	Solid foundation slab				Foundation slab with controlled forces			
	Experiment 1	Experiment 2	Experiment 3	$\overline{\varepsilon}$	Experiment 1	Experiment 2	Experiment 3	$\overline{\varepsilon}$
ε_{t1} μm/m	117.379	114.262	180.512	137.384	369.671	305.898	242.824	306.131
ε_{t2} μm/m	608.991	400.236	577.123	528.783	467.436	348.594	293.983	370.004
ε_{t3} μm/m	242.76	311.815	378.614	311.063	231.02	282.628	310.105	274.584
ε_{t4} μm/m	579.472	476.83	661.339	572.547	461.628	260.000	334.828	352.152
ε_{t5} μm/m	17.340	79.611	131.482	76.144	174.119	78.606	118.842	128.069
ε_{t6} μm/m	189.61	219.539	300.405	236.518	189.612	133.934	215.273	236.519
ε_{t7} μm/m	–158.770	–187.952	–200.144	–182.289	–	–	–	–
ε_{t8} μm/m	351.166	167.079	468.945	329.063	–	–	–	–
ε_{t9} μm/m	–234.175	–158.978	–33.445	–142.199	–	–	–	–
ε_{t10} μm/m	260.785	119.855	63.734	148.125	–	–	–	–

Table 3. Summary of experiment results.

	Solid foundation slab				Foundation slab with controlled forces			
	Experiment 1	Experiment 2	Experiment 3	$\bar{n}$	Experiment 1	Experiment 2	Experiment 3	$\bar{n}$
M_x, kN·m (axial section 3)	0.283	0.221	0.334	0.279	0.481	0.387	0.312	0.393
M_y, kN·m (axial section 3)	0.608	0.410	0.595	0.538	0.545	0.415	0.346	0.435
M_x, kN·m (axial section 4)	0.393	0.429	0.544	0.455	0.346	0.340	0.387	0.358
M_y, kN·m (axial section 4)	0.615	0.538	0.731	0.628	0.501	0.325	0.404	0.410
M_x, kN·m (axial section 5)	0.070	0.137	0.209	0.139	0.216	0.112	0.173	0.167
M_y, kN·m (axial section 5)	0.184	0.230	0.321	0.245	0.222	0.149	0.237	0.203
M_x, kN·m (section between axes 3-4)	–0.050	–0.130	–0.056	–0.079	–	–	–	–
M_y, kN·m (section between axes 3-4)	0.286	0.104	0.386	0.259	–	–	–	–
M_x, kN·m (section between axes 4-5)	–0.147	–0.116	–0.014	–0.092	–	–	–	–
M_y, kN·m (section between axes 4-5)	0.180	0.068	0.051	0.010	–	–	–	–
Average settlement by indications of flexometers: PM4, PM5, PM 6, PM7, mm	0.74	0.46	0.72	0.64	0.69	0.50	0.57	0.59
Average settlement by indications of flexometers: PM2, PM3, PM8, PM9, mm	0.54	0.59	0.71	0.61	0.41	0.59	0.52	0.51
Average settlement by indications of flexometers: PM1, PM10, mm	0.17	0.30	0.27	0.25	0.32	0.25	0.6	0.39

Based on the data of Table 3, we plotted the bending moments' and settlement diagrams for the foundation models under review (Figure 6).

Experiment results show that availability of hinged nodes changes the diagrams of bending moments for foundation slabs in a positive way. Comparison of the diagrams shows that the proposed design solution ensures unloading of foundation slab section in each span, in locations of maximal span bending moments, and excluding the sign difference in bending moments' M_x diagram.

It should be noted that in foundation slab with controlled forces, the non-uniformity distribution of bending moments in foundation slab with controlled forces is less expressed, which will have positive effect on reinforcement. The values of support moments differ:

- for bending moments M_x in solid foundation slab by 38.7 %;
- for bending moments M_x in foundation slab with controlled forces by 8.91 %;
- for bending moments M_y in solid foundation slab by 14.33 %;
- for bending moments M_y in foundation slab with controlled forces by 5.74 %;

The advantage is that the settlement line in the foundation slab with controlled forces is smoother, which in its turn will have positive affect on distribution of forces in superstructure components.

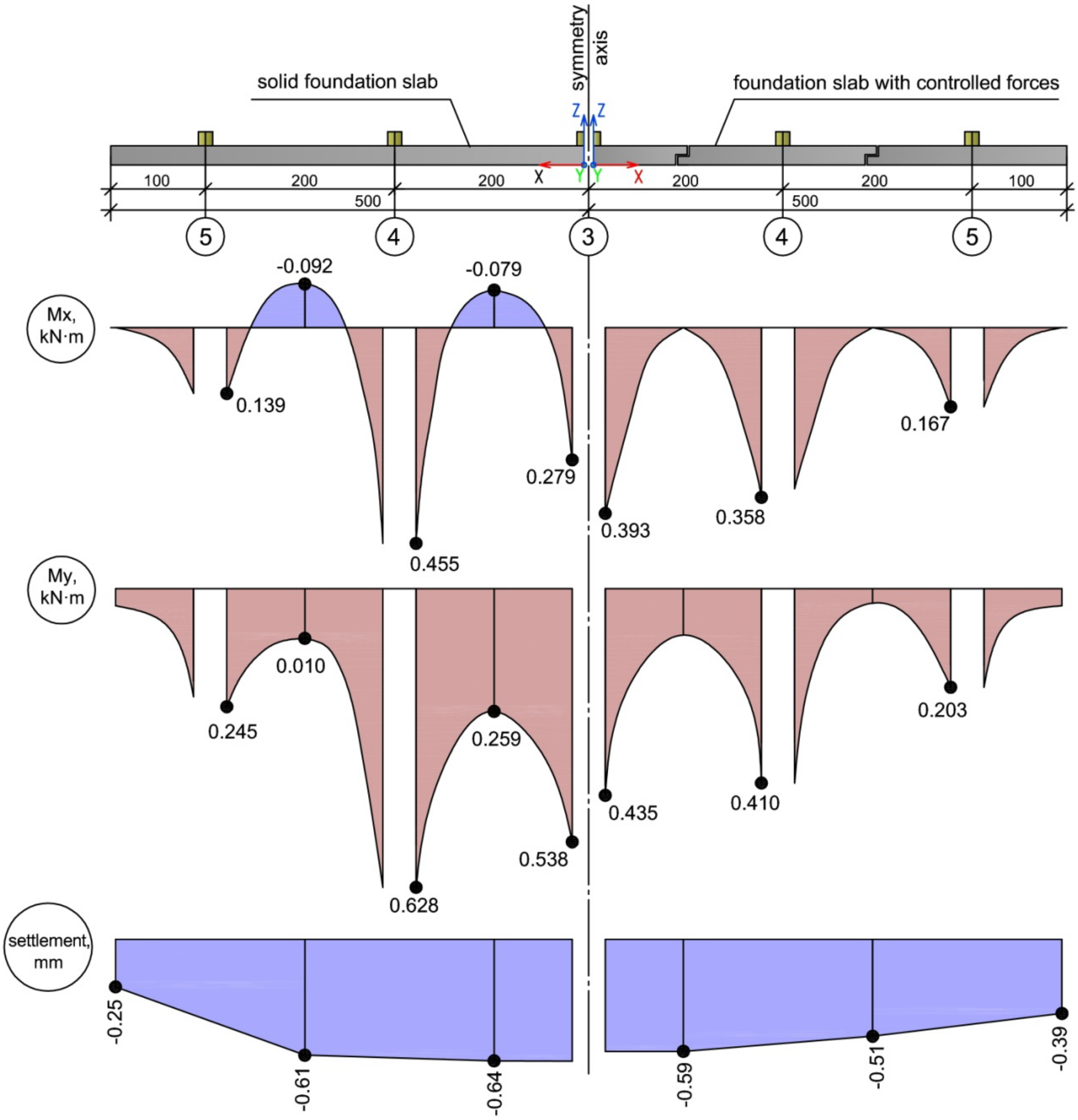


Figure 6. Diagrams of bending moments and settlement for foundation models under review, based on the results of experimental studies.

For the purpose of comparison with experimental results, we made a series of comparative FEM calculations. Calculation of “base-foundation” system was carried out in a software complex MIDAS GTS NX.

The following types of finite elements were used for modeling the “base-foundation” system:

- For soil mass – volume elements of “Solid” type (with three translational degrees of freedom in the nodes)
- For foundation – plate elements of the “Shell” type (with three translational and two rotational degrees of freedom in the nodes).

To create a hinged effect for two adjacent sections of a foundation slab, the “Add End Release (Shell)” function was applied enabling control of the amount of freedom degrees in the plate elements’ nodes.

Elastic perfect-plastic Mohr-Coulomb model was used as soil calculation model.

This model is widely used for modeling non-linear behavior of soil and demonstrates reliable results in solution of geotechnical tasks. It accounts for basic properties of soil, such as elastic behavior at small loads, degradation of material rigidity in case of destruction, destruction criterion and possibility of elastic unloading after the flow. Mohr-Coulomb strength criterion takes the form given below:

$$\sigma_1-\sigma_3=(\sigma_1+\sigma_3)\cdot\sin\varphi+2\cdot C\cdot\cos\varphi, \tag{3}$$

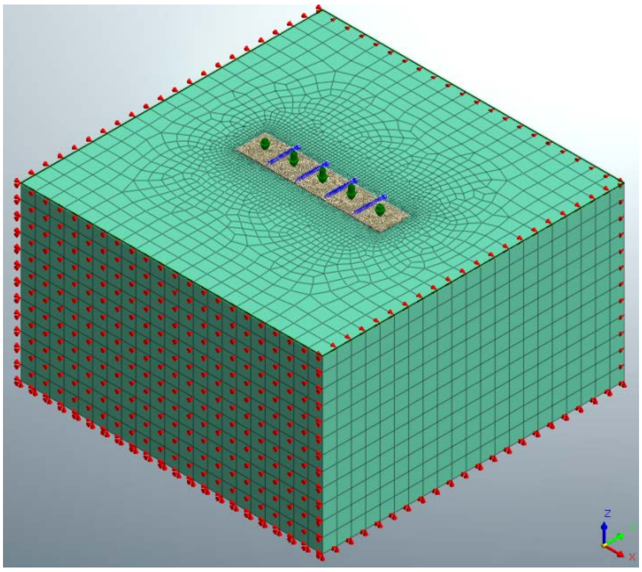
where σ_1, σ_3 are principal stresses;

φ is angle of internal friction;

C is cohesion.

The remaining parameters of the «base-foundation» system are presented in Table 4 below.

Table 4. Initial data of the “base-foundation” system.

General view of “base-foundation” calculation scheme	
	
Foundation characteristics	**Solid foundation slab model:** 1. Geometric dimensions in a plane 200×1000 mm 2. Foundation slab thickness h = 5 mm 3. Material: steel S245, $E = 2.06 \cdot 10^8$ kN/m^2, R_y = 240 mPa 4. Load on the foundation slab: • intermediate supports is 4.0 kN • end supports is 2.0 kN. **Model of foundation slab with controlled forces:** 1. Comprises five separate sections with geometric dimensions in a plane 200×200 mm 2. Foundation slab thickness h = 5 mm 3. Material: steel S245, $E = 2.06 \cdot 10^8$ kN/m^2, R_y = 240 mPa 4. Load on the foundation slab: • intermediate supports is 4.0 kN • end supports is 2.0 kN.
Base characteristics	The base is represented by homogeneous layer of sand of average size and density with the following physical and mechanical characteristics: ρ = 1.72 g/cm^3, W = 2.4 %, φ = 36°, C = 1.6 kPa, E = 21.8 mPa, ν = 0.3.

Based on calculation results for two options of foundation slabs, we obtained isofields of bending moments, shears and settlements presented on Figures 7–12 as appropriate. The graphical materials presented on Figures 7–12 are summarized in Table 5.

In Table 5 the values of bending moments in places of resistance strain gauges installation are given in numerator, and maximal support bending moments are given in denominator.

A bar chart (Figure 13) based on the data of Table 5 reflects distribution of forces for the reviewed foundation models in FEM calculation and experiment.

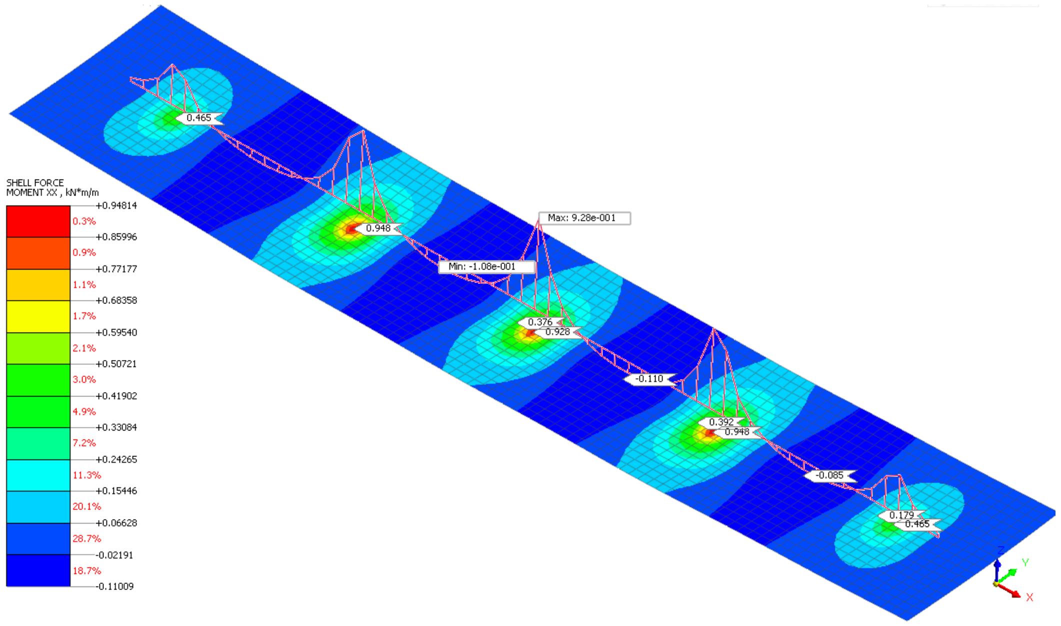


Figure 7. Isofields of bending moments M_x (kN·m) for solid foundation slab model.

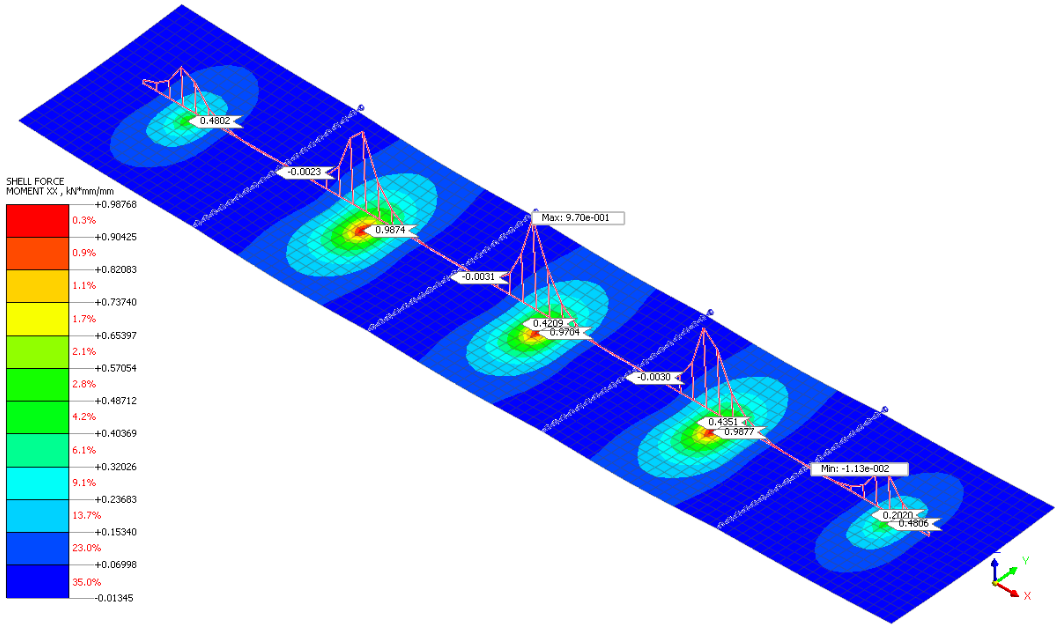


Figure 8. Isofields of bending moments M_x (kN·m) for foundation slab model with controlled forces.

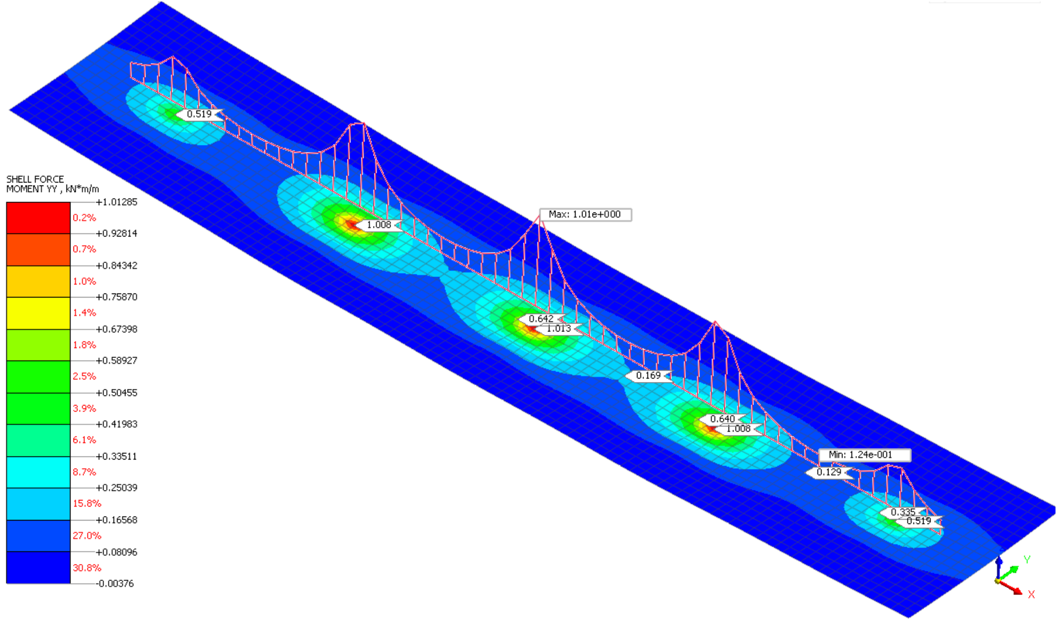


Figure 9. Isofields of bending moments M_y (kN·m) for solid foundation slab model.

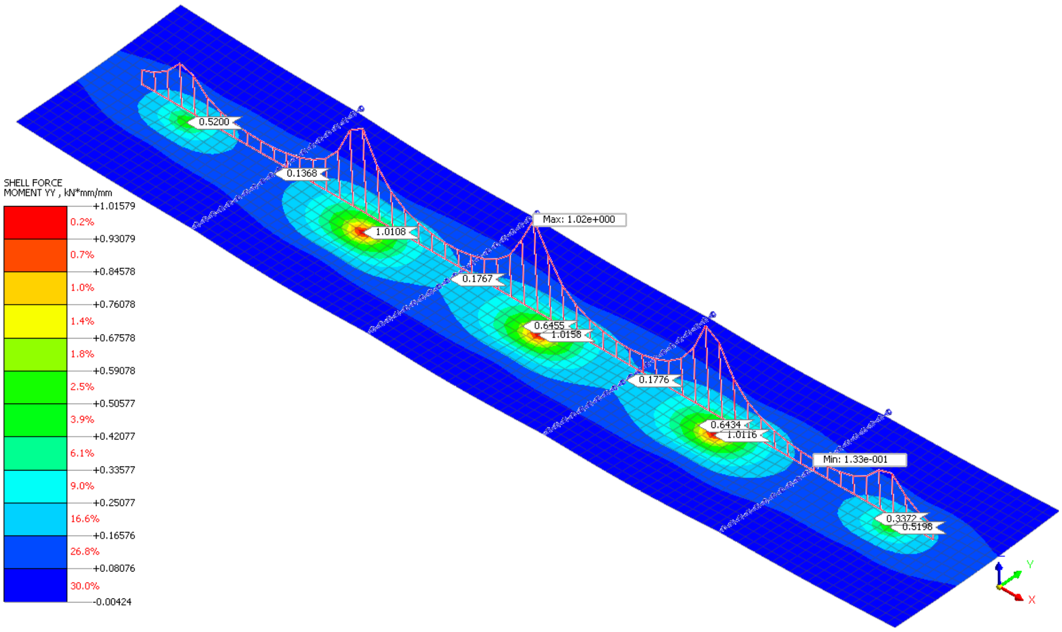


Figure 10. Isofields of bending moments M_y (kN·m) for foundation slab model with controlled forces.

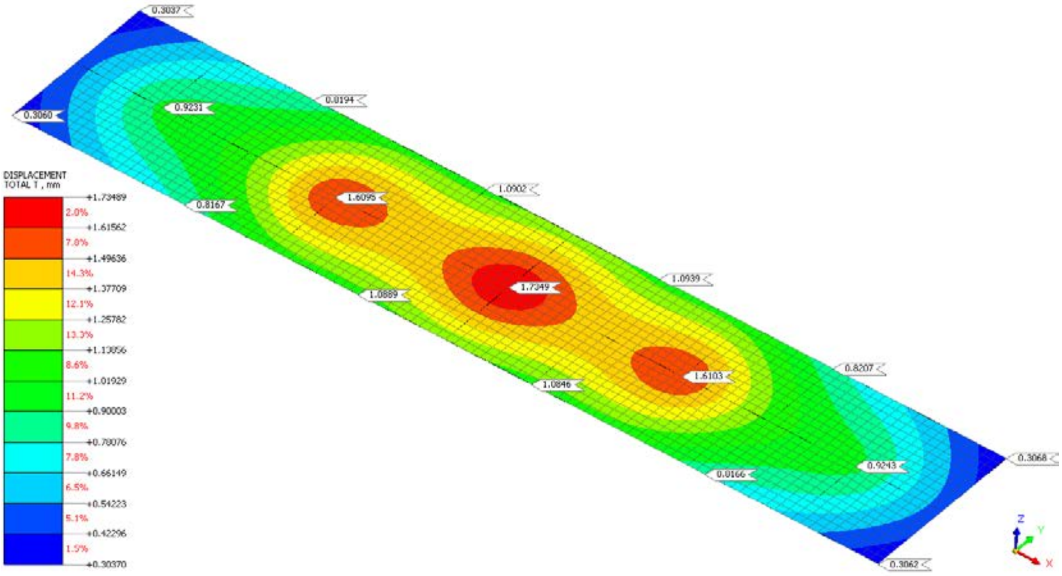


Figure 11. Base settlement (mm) for solid foundation slab model.

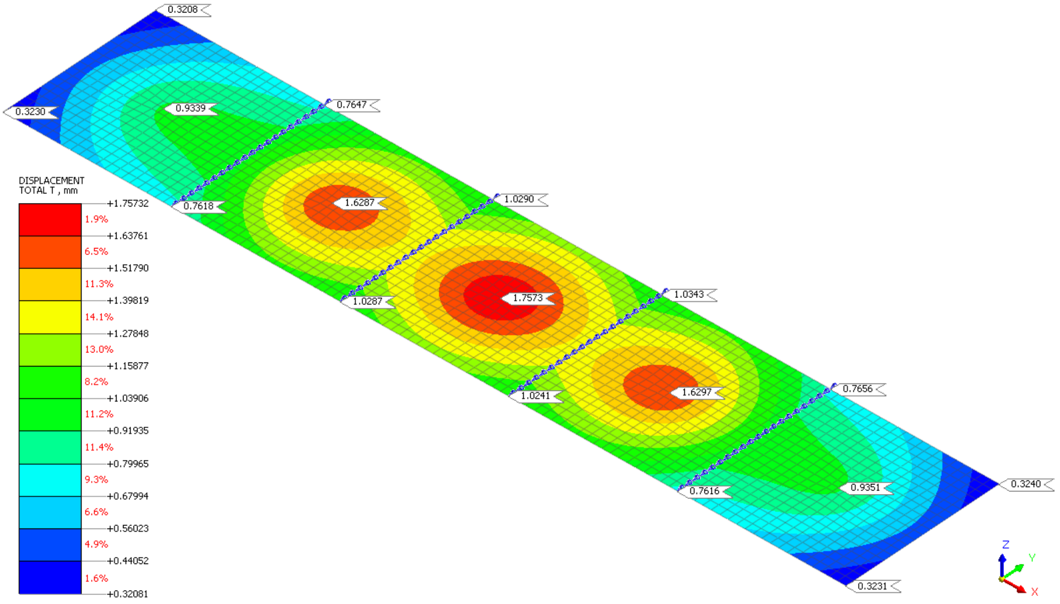


Figure 12. Base settlement (mm) for foundation slab model with controlled forces.

Table 5. Summary of FEM calculations and experiment for foundation models under review.

Compared parameters	FEM calculation results		Experiment results	
	Solid foundation slab	Foundation slab with controlled forces	Solid foundation slab	Foundation slab with controlled forces
M_x, kN·m (axis 3)	$\underline{0.376}$ 0.928	$\underline{0.421}$ 0.970	0.279	0.393
M_y, kN·m (axis 3)	$\underline{0.642}$ 1.013	$\underline{0.645}$ 1.016	0.538	0.435
M_x, kN·m (axis 4)	$\underline{0.392}$ 0.948	$\underline{0.435}$ 0.988	0.455	0.358
M_y, kN·m (axis 4)	$\underline{0.640}$ 1.008	$\underline{0.634}$ 1.012	0.628	0.410
M_x, kN·m (axis 5)	$\underline{0.179}$ 0.465	$\underline{0.202}$ 0.481	0.139	0.167
M_y, kN·m (axis 5)	$\underline{0.335}$ 0.519	$\underline{0.337}$ 0.520	0.245	0.203
M_x, kN·m (between axes 3-4)	–0.110	–0.003	–0.079	–
M_y, kN·m (between axes 3-4)	0.169	0.178	0.259	–
M_x, kN·m (between axes 4-5)	–0.085	–0.002	–0.092	–
M_y, kN·m (between axes 4-5)	0.129	0.137	0.010	–
Settlement in placements of PM4, PM5, PM6, PM7, mm	1.09	1.03	0.64	0.59
Settlement in placements of PM2, PM3, PM8, PM9, mm	0.82	0.76	0.61	0.51
Settlement in placements of PM1, PM10, mm	0.31	0.32	0.25	0.39

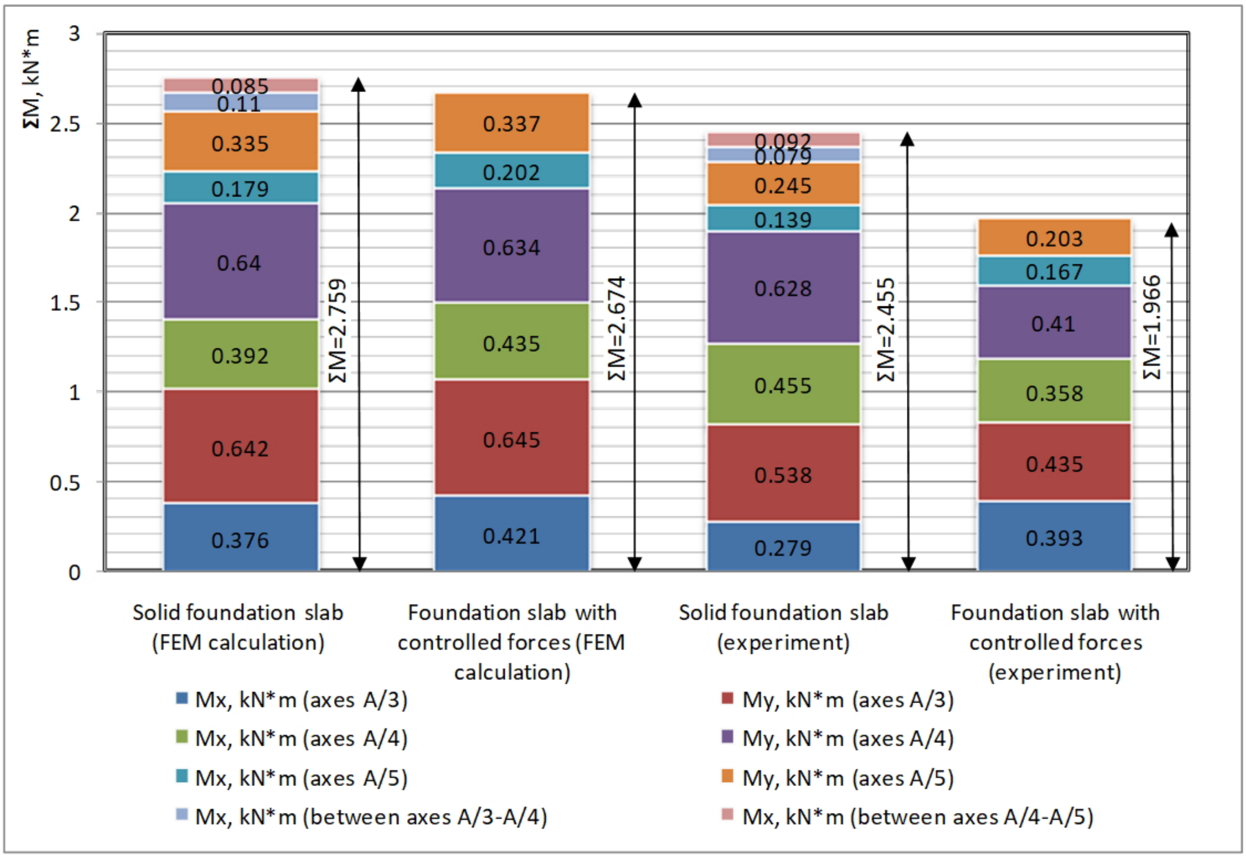


Figure 13. Bar chart of compared values of bending moments in characteristic points (in places of resistance strain gauges installation) for the reviewed foundation models.

Comparison of experimental and numerical results showed their qualitative and quantitative convergence for considered foundation models which is the evidence of correctness of the results obtained. Moreover, it is worth mentioning that the results of the studies are consistent with the results of the earlier publications [17–19].

4. Conclusions

Based on the analysis of obtained data, we may come to the following conclusions:

1. Analysis of the results of experiment and numerical calculations showed qualitative and quantitative convergence of the results for the considered foundation models.

2. According to the results of the experiment in a continuous slab there is more uneven distribution of the values of the reference bending moments in comparison with numerical calculations.

3. Due to the hinged nodes, it is possible to change the nature of the bending moments' diagram, namely:

- get rid of bending moments in the spots of maximal span bending moments
- get rid of difference of signs of the bending moments' diagram
- flatten the values of support bending moments for intermediate supports

4. Base settlements for the considered foundations do not have any significant difference in experiment and numeric calculations. However, it should be noted that according to the experiment results, the settlement line in the foundation slab with controlled forces is smoother, which will have a beneficial effect on distribution of forces in superstructure components.

5. Foundation slabs with controlled forces do not require reinforcement of the upper slab zone, and there is no need for mounting the structural anti-settlement reinforcement, as the sizes of sections for standard column meshes 6×6 and 6×9 m are small. Hence, mounting of supporting reinforcement frames for the upper mesh, due to the absence of the latter, is not needed, which considerably optimizes steel consumption per 1 m^3 of concrete for the proposed structure.

6. Use of foundation slab structure with controlled forces reduces the steel consumption for reinforcement, improves technical, economical and performance indicators, while retaining the basic favorable properties of solid slab foundations. The aforementioned factors enabled obtaining two patents of the Russian Federation for invention:

- "Design of foundation slab with controlled forces" No. 2641356 [31];
- "Hinged node for foundation slab with controlled forces" No. 2641357 [32].

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Contacts:

Sergey Ikonin, +7(4732)558328; эл. почта: fornag@inbox.ru
Andrey Sukhoterin, +7(952)5529563; эл. почта: asuhoterin@list.ru

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Влияние конструктивного исполнения на взаимодействие фундаментных плит с основанием

С.В. Иконин, А.В. Сухотерин*
Воронежский государственный технический университет, г. Воронеж, Россия
** E-mail: asuhoterin@list.ru*

Ключевые слова: экспериментальные исследования, системы с регулируемыми свойствами, плитные фундаменты, узел шарнирного действия

Аннотация. Предложено перспективное направление по снижению материалоемкости фундаментных плит за счет конструктивного исполнения. В качестве примера рассмотрено напряженно-деформированное состояние моделей сплошной плиты и плиты с регулируемыми усилиями при взаимодействии с песчаным основанием. Нагружение моделей осуществлялось статической системой сосредоточенных вертикальных сил. Напряженно-деформированное состояние моделей оценивалось по результатам лабораторных лотковых опытов с применением тензометрии и данным численных расчетов методом конечных элементов с использованием модели грунта Кулона-Мора. На основе сопоставления полученных результатов показано, что плита с регулируемыми усилиями имеет преимущества по сравнению со сплошной плитой. Например, за счет регулирования усилий удается избавиться от знакопеременности в эпюре изгибающих моментов, выровнять значения опорных изгибающих моментов для промежуточных опор, добиться более плавного прогиба плиты, следовательно создаются предпосылки для существенного снижения материалоемкости. Кроме того, установлено, что экспериментальные значения изгибающих моментов и прогибов плит качественно согласуются с численным прогнозом. При этом конечно-элементный расчет дает несколько завышенные абсолютные значения величин по сравнению с экспериментом. Результаты исследований могут быть полезны при проектировании фундаментных плит под опоры путепроводов, эстакад, а также промышленно-гражданские здания и сооружения каркасного типа с регулярной сеткой колонн.

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Контактные данные:

Сергей Вячеславович Иконин, +7(4732)558328; эл. почта: fornag@inbox.ru

Андрей Владимирович Сухотерин, +7(952)5529563; эл. почта: asuhoterin@list.ru