A soil base model of adjacent various story structures

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ABSTRACT

The paper proposes an improved soil base model in the form of a continuous layer of finite distribution capability to simulate and calculate adjacent multistory structures in the base - foundations - structures system using powerful calculation packages such as SOFiSTiK, ABAQUS, PLAXIS, SCAD, Lira and others. The improved model considers the parameters of the stress-strain properties of the soils of the bases, the geometric profile taking account of the distribution capability of the base and different boundary conditions, but differs from the existing models in that it has a stepped geometric profile at the lower boundary of the model because of different compressible layer depths under each foundation of the structures. The use of this model improves the accuracy of simulating a soil base for large-sized foundations of adjacent structures to obtain reliable results of the stress-strain state of the base - foundations - structures system. An example demonstrates how to simulate and calculate raft foundations of a two-section multistory building in the base - foundations - structures system that interacts with an improved soil base model (linear strains of soils under loads are considered here) with reference to different numbers of stories of the sections. The numerical study results show on a specific calculation example that considering different compressible layers depths in the model under differently loaded foundations results in an increase in moment forces of up to 65% as compared with simulating the whole compressible layer, which may lead to the disruption of large-sized raft foundations.

Keywords: raft foundations; soil base; model; compressible layer; stress-strain state.

1. Problem statement

In modern geotechnical engineering, owing to the development of information technology and availability of powerful packages for the calculation of the entire base - foundation - structure system, one of the main research areas is to develop, improve and investigate soil base models to ensure the adequate interaction between the components of the system during the construction and operation of buildings and structures (hereinafter referred to as the “structures”).

It is well known that to obtain reliable and valid calculation results for the stress-strain state of the foundation structures of adjacent various story structures in the base - foundations - structures (BFS) system a soil base model with appropriate parameters must be chosen that is adequate to the behavior of the actual soil mass under the loads from the foundations according to two criteria: the distribution capability and the deformability of the foundations of structures.

The drawback of the well known soil base models and classical approaches to their geometric construction in calculation packages is the difficulty of considering different compressible layer depths (active strain zones) under each foundation of structures when simulating the interaction between the adjacent large-sized foundations of structures. This drawback can result in significant errors in determining the stress-strain state of adjacent large-sized foundations of various story structures.

2. Prior research analysis

More than 200 years ago, N.I. Fuss proposed the first simplest linear one-parameter model of a soil base, which had no distribution capability at all. Subsequently, more advanced multiparameter and combined models with the capacity of describing various properties of soil bases were developed, which were mainly designed for engineering calculations of structures interacting with the soil base. A detailed description of various soil base models is given in articles (Wani & Showkat 2018) (Briaud 2013), as well as in theses and scientific works of modern Ukrainian scientists (Luchkovsky 1972, 2000), (Boyko 2012), (Vynnykov 2005), (Kushner 2008).

Since the last century, a soil base model in the form of a continuous linearly strained layer has been widely used in engineering calculations of bases and foundations, as it was provided by the Ukrainian National Building Code DBN B.2.1-10:2018 and required setting only the thickness of the layer H (compressible layer) and the stress-strain properties of the soil (the total strain modulus E and Poisson's ratio ν). Furthermore, this analytical model has no constraints in plan. Today, with the expansive growth of information technology, when simulating and performing numerical calculations of the BFS system in the powerful calculation packages such as SOFiSTiK, ABAQUS, Plaxis, SCAD, Lira and others, the three-dimensional formulation generally uses a soil base model in the form of ***a continuous layer of finite***

distribution capability (Fig.1) (Empfehlungen des Arbeitskreises "Numerik in der Geotechnik", 2014) (Nosenko 2012, 2020) (Skochko 2020) (the concept is introduced for the first time), which, in addition to the vertical strain constraints at a certain depth H, also has the horizontal strain constraints at a certain distance from the load in plan ($L_x \times L_y$). These boundary conditions for the model are based on the fact that under the action of external loads on the soil base a stress-strain region is formed, beyond which the soil strains can be neglected, since the additional load at the boundaries of the soil mass does not exceed the structural strength of soil (Ter-Martirosyan 2009). In addition, any patterns of soil straining under loads, including time patterns, can be set for the model itself.

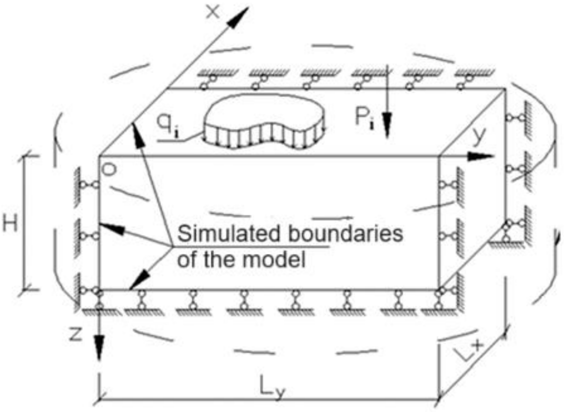


Figure 1. Soil base model in the form of a continuous layer of finite distribution capability (for three-dimensional problems)

To calculate foundations under plane strain conditions, this model can also be a two-dimensional model as a special case, which is well known as a ***model of a continuous layer of finite width***. Professors I.Ya. Luchkovsky (2000) and Z.G. Ter-Martirosyan (2009) obtained analytical solutions to the stress-strain state of the soil base under surface loads using the model of a continuous linearly strained (elastic) layer of finite width.

In previous publications, the authors proposed a method for setting the parameters of the linearly strained layer (the reduced stress-strain modulus of soil E_0 and reduced compressible layer H_0) to properly simulate the interaction between the large-sized raft foundations and the soil base, which allows you to obtain adequate settlements and reduce the distribution capability of the model (Luchkovsky 2015).

3. Purpose of the work

The purpose of this work is to improve the soil base model of adjacent differently loaded and structurally separated large-sized foundations of structures and perform numerical studies of the effect the model has on the stress-strain state of raft foundations of a two-section multistory building in the system base - foundations - structures system.

4. Main research

We propose an improved soil base model in the form of a continuous layer of finite distribution capability (CLFDC), which allows you to adequately consider the interaction between large-sized foundations of adjacent various story structures (Samorodov & Tabachnikov 2023). A soil base model in the form of CLFDC has the parameters of the stress-strain properties of the soils of the base and the piles, the geometric profile taking account of their distribution capability and different boundary conditions to simulate and calculate the base - foundations - structures system, and yet the model is different in that its lower boundary has a stepped geometric profile because of different compressible layer depths under each foundation of the structures. The different compressible layer depths $H_{p,i}$ can be determined taking into account the distribution and attenuation with depth of additional stresses arising under the foundation of each individual section of the structures within this compressible layer, depending on the load level, which in turn causes additional deformations of the soil base. Below the boundary of the compressible layer, soil compressibility has practically no effect on the deformation of the foundation (DBN B.2.1-10:2018, 2018).

Figs. 2 and 3 show the examples of building the boundary of the improved soil base model in the form of a layer of finite distribution capability *1*, which has the parameters of the stress-strain properties of the soils of the base and the piles and distribution capability factored for by the angle α, and different compressible layer depths (active strain zones) $H_{p,i}$ under each foundation of the structures of the width b_i, which transmit the load to the base p_i.

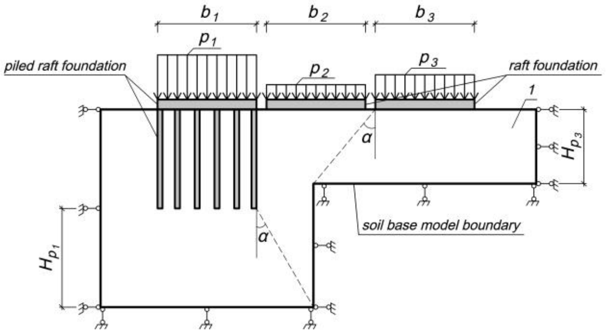


Figure 2. Examples of building the lower boundary of the improved soil base model in the form of CLFDC, where the load is $p_1 > p_2 < p_3$

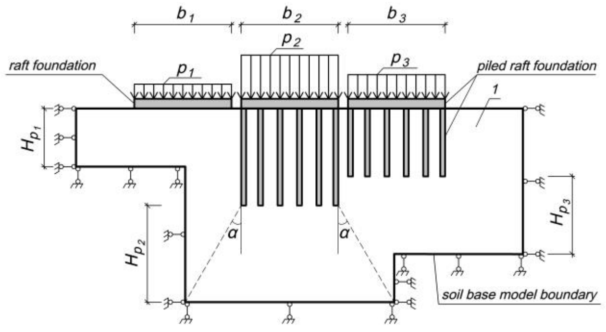


Figure 3. Examples of building the lower boundary of the improved soil base model in the form of CLFDC, where the load is $p_1 < p_2 > p_3$.

In our publication (Samorodov O.V. et al. 2023), we investigated the effect of the distribution angle *α* on the distribution capability and deformability of the model from the loaded foundation on the surface, where, based on the analysis of the numerical calculation results for a plane problem (plane strain), we justified the width of the model of a linearly strained layer of finite width, which considers the distribution of compressive stresses along the depth at an angle of α≈20÷25° to the vertical from the edges of the loaded foundation (see Figs. 2 and 3). In this case, the width of the model according to the distribution angle of α≈20÷25° has almost no effect on the average settlements and maximum moment forces of the foundation in comparison with the increased width of the model.

To investigate the effect of the improved soil base model, a finite element model of the base - foundations - structures system, comprising a soil base and a two-section 21-story building on raft foundations, was developed using the PLAXIS 3D package (Fig. 4).

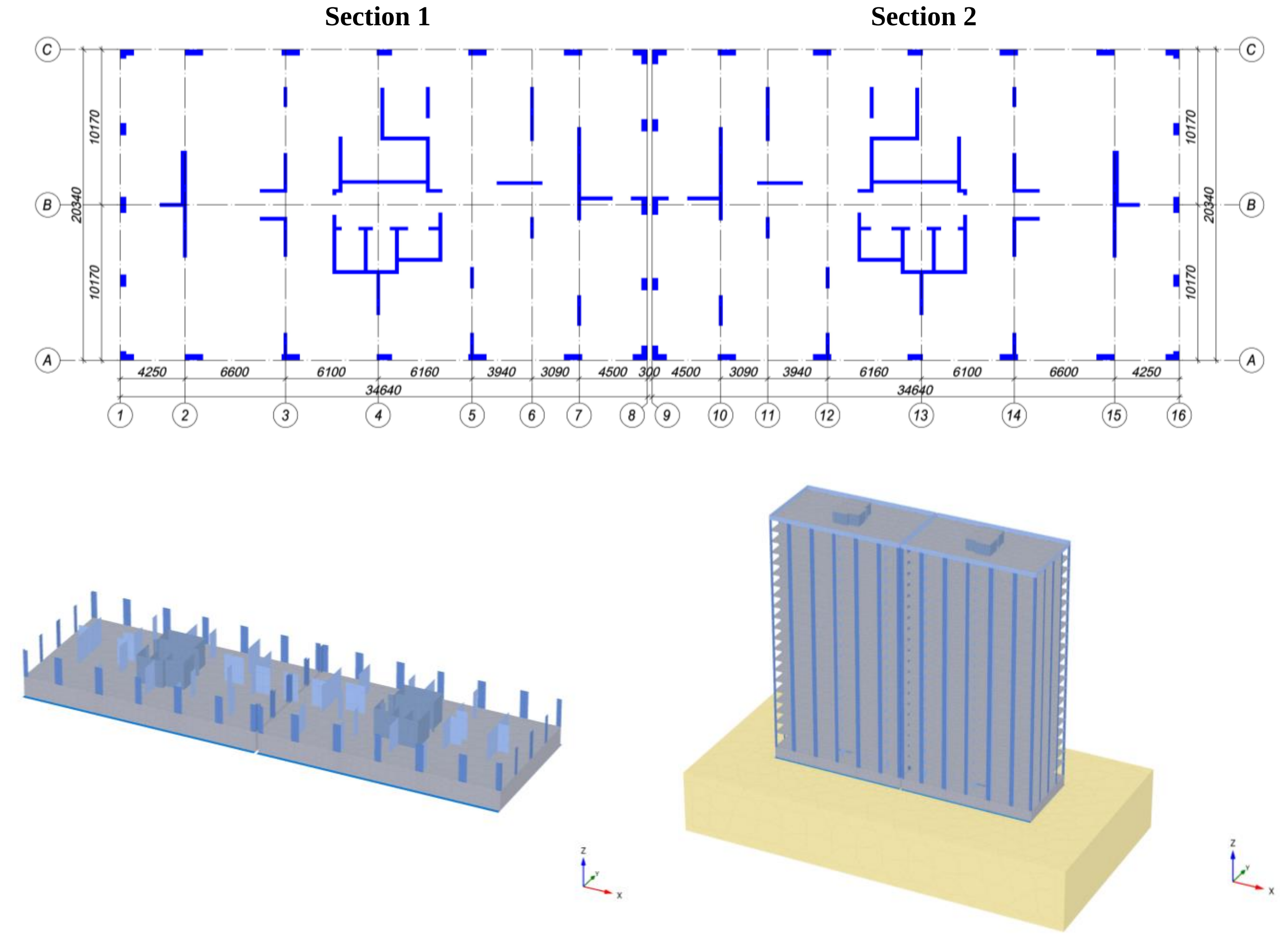


Figure 4. General views of the stepwise building of the studied base - foundations - structures system: a) layout of the frame elements; b) connection layout between the frame elements and the raft foundations; c) base - foundations - structures system.

The building has a combined framed and diaphragm structural system. The flooring is a cast-in-situ girderless floor structure. The building system uses a cast-in-situ frame with reinforced concrete cast-in-situ girderless floor slabs. The spatial stiffness of the building is provided by the horizontal and vertical load-bearing structures of the building, frame pylons, cast-in-situ floor slabs, and cast-in-situ stairwells, stiffening diaphragms and elevator shafts (Fig. 4).

The soil base was simulated as CLFDC by solid finite elements with the constant stress-strain properties as follows: specific weight γ=18.0 kN/m^3; Young's modulus (modulus of elasticity) E=30000.0 kN/m^2; and Poisson's ratio ν=0.3.

The structural elements of the building such as raft foundations, walls, pylons, floor slabs and roof slabs were simulated by plate finite elements using an elastic material model with the properties as follows: specific weight γ=25.0 kN/m^3; modulus of elasticity E=30.0·10^6 kN/m^2; Poisson's ratio ν=0.2.

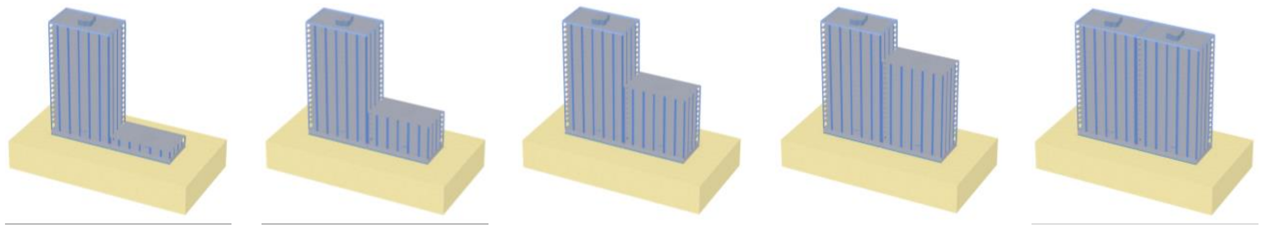
The dead weight of load-bearing and enclosing structures was considered as loads.

At Stage 1, we carried out numerical calculations using the finite element method of the stress-strain state of the base - foundations - structures system with the uniform maximum compressible layer depths for the soil base model in the form of CLFDC, as shown in Fig. 1.

The vertical (in depth) and horizontal (in plan) boundaries were limited at a distance equal to the depth of the compressible layer *H* at full load. That is, the depth distribution of compressive stresses was taken to be at an angle of α=45° to the vertical from the edges of the loaded foundations (Empfehlungen des Arbeitskreises "Numerik in der Geotechnik" 2014).

According to calculations as per Ukrainian National Building Code DBN B.2.1-10:2018 the compressible layer depth of the base was taken to be H=17.1 m at the average pressure of p_{average}=273.53 kPa under the bottom of the foundation slab of the multistory sections, which is equivalent to the total load of N_{21}=206787.5 kN at the number of stories of n=21 that corresponds to 21 erected stories.

The stress-strain state of the system was investigated for different load ratios N_n/N_{21} for each of the sections at the uniform maximum compressible layer of H_{const}= 17.1 m, where N_n is the load at the number of stories n, which corresponds to 1, 6, 11 and 16 erected stories. The load ratios were achieved by varying the number of stories of Section 2 (Fig. 5).



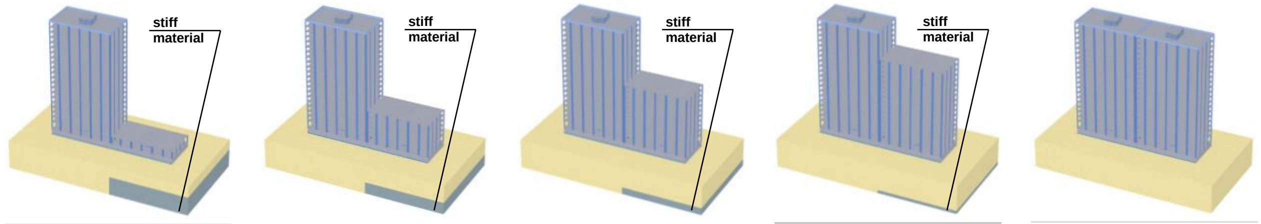
N_1/N_{21}= **0,2** N_6/N_{21}= **0,4** N_{11}/N_{21}= **0,6** N_{16}/N_{21}= **0,8** N_{21}/N_{21}= **1,0**

Figure 5. Calculation patterns for the model at Stage 1 of research for load ratios N_n/N_{21}.

At Stage 2, we carried out numerical calculations using the finite element method of the stress-strain state of the base - foundations - structures system with a stepped compressible layer for the soil base model in the form of CLFDC, which considers the angle α and different compressible layer depths under each foundation of the structures in relation to the load, as shown in Figs. 2 and 3.

The vertical (in depth) boundaries were limited at a depth equal to the depth of the compressible layer H_i for each single foundation, taking account of different load values. To form the active zone, the compressible layer, under each section of the building under different loads, the depth distribution of compressive was taken to be at an angle of α≈25° to the vertical from the inner edge of the more loaded foundation (Samorodov O.V. et al. 2023). The horizontal (in plan) boundaries, similarly to Stage 1 of research, were limited at a distance equal to the depth of the compressible layer H=17.1 m at maximum load.

When building the stepped lower profile of the soil base model, in view of different compressible layer depths, a simple simulation approach was used, where an almost nondeformable stiff material having a large modulus of elasticity of $E = 100.0 \cdot 10^9$ kN/m^2 was taken. The load ratios were achieved similarly to Stage 1 of research by varying the number of stories n of Section 2 (Fig. 6), i.e., the stiffness of the superstructure was considered.



N_1/N_{21}= **0,2** N_6/N_{21}= **0,4** N_{11}/N_{21}= **0,6** N_{16}/N_{21}= **0,8** N_{21}/N_{21}= **1,0**

Figure 6. Calculation patterns for the model at Stage 2 of research for load ratios N_n/N_{21}.

The stress-strain state of the raft foundations was obtained for the instantaneously elastic solution to the problem, and the absolute values were obtained.

Figure 7 below compares the distribution of settlements and longitudinal bending moments in the raft foundations of two sections for the soil base model in the form of a continuous linearly strained layer of finite distribution capability with the uniform and stepped compressible layer depths under the foundations of the sections for the most illustrative example with a load ratio of N_1/N_{21}= 0.2.

The following ratios were used as criteria to assess the effect of the model:

– Relative longitudinal *positive* bending moment $M^{+}_{x,\text{відн.}}$, U:

$$M^{+}_{x,\text{relative}} = \frac{M^{+}_{x,n}}{M^{+}_{x,21}}, \qquad (1)$$

where $M^{+}_{x,n}$ is the value of the extremum of the longitudinal *positive* bending moment at a load of n stories when applying the soil base model with the stepped compressible layer depth, kN·m;

$M^{+}_{x,21}$ is the value of the extremum of the longitudinal *positive* bending moment at a full load of 21 stories when applying the soil base model with the uniform compressible layer depth, kN·m;

– Relative longitudinal *negative* bending moment $M^{-}_{x,\text{відн.}}$, U:

$$M^{-}_{x,relative} = \frac{M^{-}_{x,n}}{M^{-}_{x,21}}, \qquad (2)$$

where $M^{-}_{x,n}$ is the value of the extremum of the longitudinal *negative* bending moment at a load of n stories when applying the soil base model with the stepped compressible layer depth, kN·m;

$M^{-}_{x,21}$ is the value of the extremum of the longitudinal *negative* bending moment at a full load of 21 stories when applying the soil base model with the uniform compressible layer depth, kN·m.

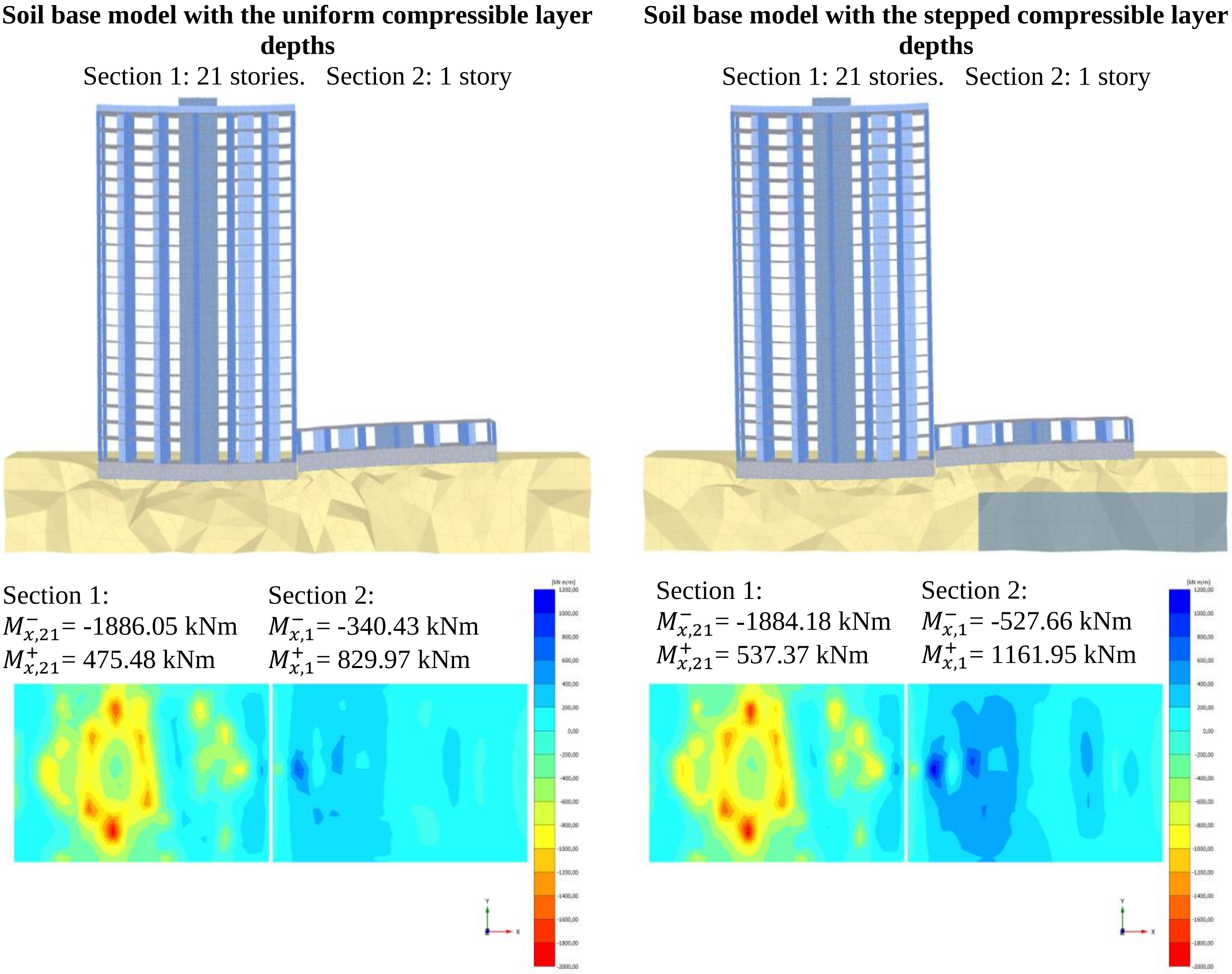


Figure 7. Comparison of the calculated flexural stresses (bending moments) in the raft foundation with and without the stepped compressible layer using a load ratio N_1/N_{21}=0.2.

Figs. 8 and 9 graphically show the calculations of $M^{+}_{x,relative}$ and $M^{-}_{x,relative}$ for the raft foundations of two sections for the soil base model in the form of a continuous linearly strained layer of finite distribution capability with the uniform and stepped compressible layer depths under the foundations of the sections at different load ratios N_n/N_{21}.

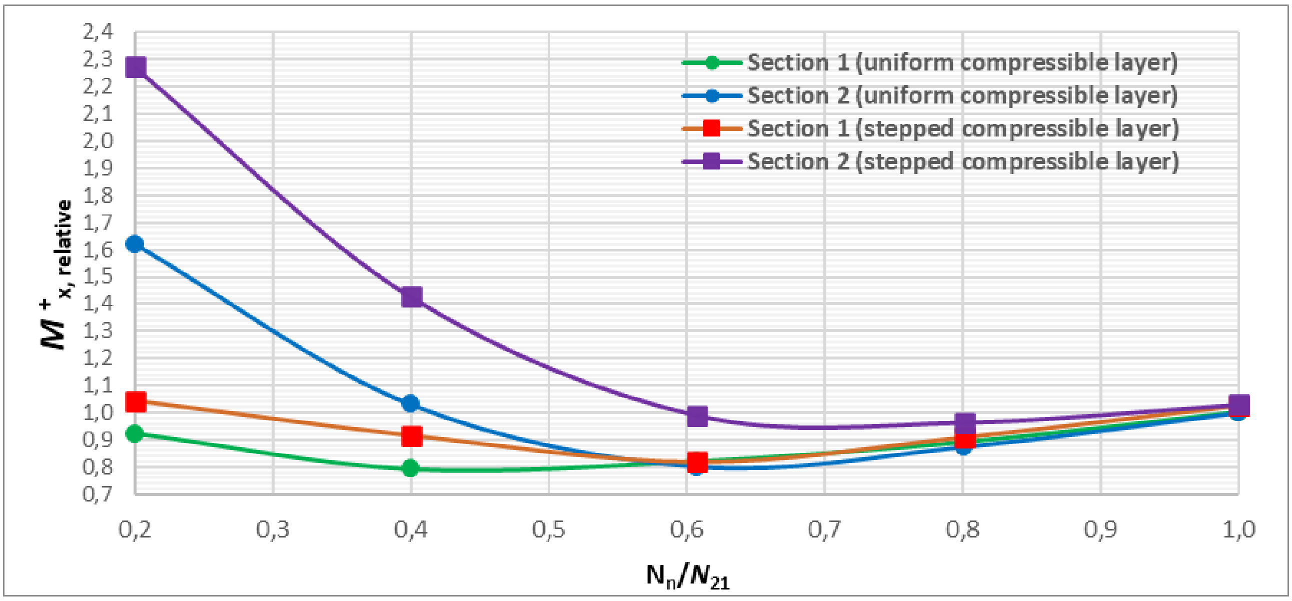


Figure 8. Relative longitudinal *positive* bending moment $M^{+}_{x,\mathrm{relative}}$.

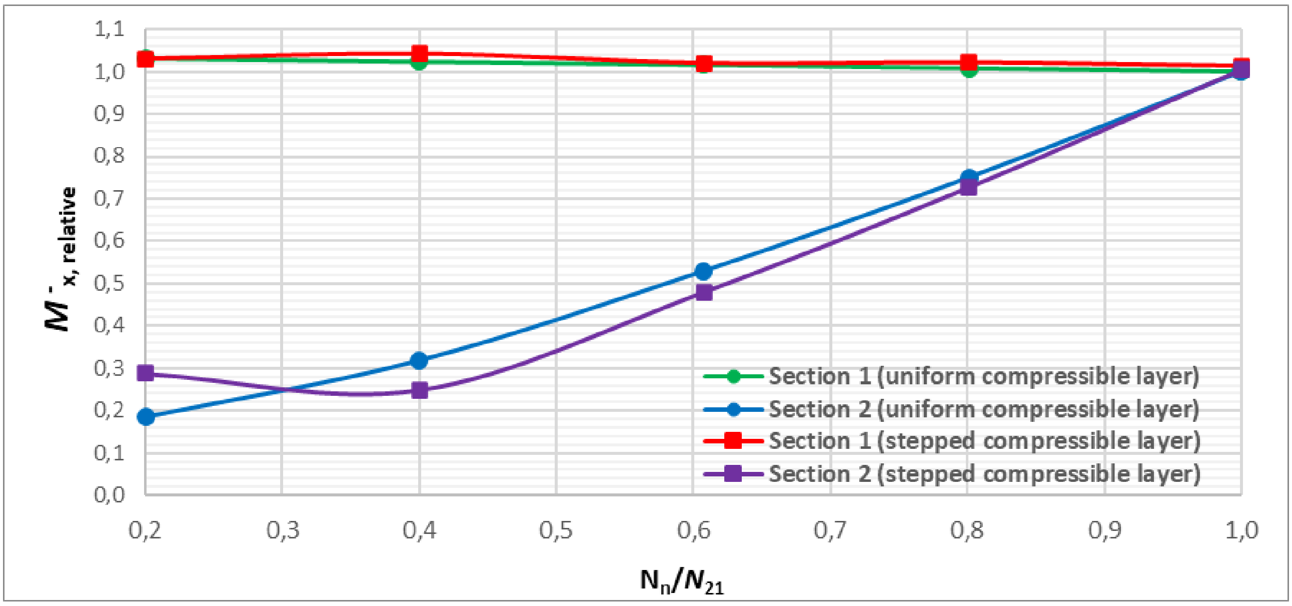


Figure 9. Relative longitudinal *negative* bending moment $M^{-}_{x,\text{relative}}$

The analysis of the calculations (Figs. 8 and 9) shows that for a two-section building on raft foundations, the soil base model with the uniform compressible layer taken at the maximum load at any load ratio, in comparison with the improved soil base model with the stepped compressible layer, does not significantly affect the absolute values of longitudinal bending moments in the foundation slab of the most loaded section 1. The found values differ in the range of 0 to 13% either upward or downward for longitudinal bending moments over the whole range of load ratios.

For the foundation slab of the variably loaded section 2, relative to the maximally loaded section 1, the found values of the longitudinal negative bending moments differ in the range of 1 to 10% either upward or downward. However, the found values of the longitudinal positive bending moments differ in the range of 3 to 65% downward for the soil base model with the uniform compressible layer, which is a fundamental underestimate.

5. Conclusions

An improved soil base model has been proposed in the form of a continuous layer of finite distribution capability, which has the parameters of the stress-strain properties of the soils of the base, the geometric profile taking account of their distribution capability and different boundary conditions to simulate and calculate the base - foundations - structures system, and which is different in that its lower boundary has a stepped geometric profile because of different compressible layer depths under each foundation of the structures.

Numerical calculations have been performed of the stress-strain state of the base - foundations - structures system to identify the effect the improved soil base model has on the distribution of longitudinal bending moments in adjacent large-sized foundations of various story structures. According to the analysis of the calculation results, a fundamental underestimate of the longitudinal positive bending moments in the less loaded foundation slab of up to 65% in the range of load ratios of N_n/N_{21}=0.2÷1.0 was found when using the soil base model with the uniform compressible layer in comparison with the proposed improved soil base model with the stepped compressible layer.

The obtained results are of practical value in that the load ratio range of at least N_n/N_{21}=0.8 must be adhered to when simultaneously erecting sections of buildings and structures to reduce the absolute values of longitudinal positive bending moments, which will reduce the cost of reinforcing the upper zone of the foundation slab of the less loaded section by 55 to 65%. Otherwise, as is commonly known, the more loaded section must be completely erected with the stabilization of foundation strains, and after that the less loaded section must be erected.

We recommend the use of the improved soil base model to improve the accuracy of simulating the soil base for adjacent large-sized foundations of various story structures to obtain reliable and valid results of the stress-strain state of the base - foundations - structures system.

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