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**Adilzhan Marufii**

Doctor of Technical Sciences, Professor  
Osh Technological University named after M.M. Adyshev  
723503, 81 Isanov Str., Osh, Kyrgyz Republic  
<https://orcid.org/0000-0003-4138-8892>

**Umetali Dzhusuev**

Doctor of Technical Sciences, Associate Professor  
Osh Technological University named after M.M. Adyshev  
723503, 81 Isanov Str., Osh, Kyrgyz Republic  
<https://orcid.org/0009-0004-5632-8096>

**Elnura Turdazhieva\***

Master, Lecturer  
Osh Technological University named after M.M. Adyshev  
723503, 81 Isanov Str., Osh, Kyrgyz Republic  
<https://orcid.org/0009-0000-9302-0155>

**Musa Zhalaldinov**

Postgraduate Student  
Osh Technological University named after M.M. Adyshev  
723503, 81 Isanov Str., Osh, Kyrgyz Republic  
<https://orcid.org/0009-0002-2685-7750>

**Anara Alieva**

Master, Lecturer  
Osh Technological University named after M.M. Adyshev  
723503, 81 Isanov Str., Osh, Kyrgyz Republic  
<https://orcid.org/0009-0005-5573-1286>

## **Calculation of strip foundations in complex conditions of its operation based on digital technologies**

**Abstract.** The study aimed to develop a methodology for calculating strip foundations with due regard for difficult operating conditions. For this, the peculiarities of foundations on weak and subsiding soils were considered, the effect of incomplete contact with the foundation was investigated, as well as the influence of longitudinal forces arising from pretensioning of reinforcement and temperature changes. The calculation methodology was based on modelling the foundation as a finite beam resting on a two-parameter elastic foundation. The study analysed the effect of incomplete contact between the base and the foundation, which occurs in the case of localised dips or soil weakness, as well as longitudinal forces caused by external loads. A calculation program was developed for numerical modelling and implemented in Delphi. The study determined that the absence of full contact between the foundation and the substrate leads to stress redistribution, which can cause localised deformation concentrations. Longitudinal forces have

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\*Corresponding author



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different effects on the performance of the foundation: tensile reduce deflections and compressive – increase them. Analytical and numerical calculations have confirmed the need to incorporate these factors during design, as ignoring them can lead to significant deviations in the stress-strain state of the structure. The developed mathematical model incorporates these effects and identifies critical areas requiring adjustment of design parameters. The data obtained can be used in the design of strip foundations in difficult ground conditions, increasing their reliability and efficiency, as well as minimising the risk of cracking and uneven settlements. The proposed methodology can be used to calculate the foundations of buildings and structures operating in heterogeneous soils

**Keywords:** soil foundation model; Heaviside function; bending stiffness; generalised soil characteristics; bedding coefficient; elastic modulus; moment of inertia

## INTRODUCTION

In modern construction, the reliability and cost-effectiveness of the designed structures are essential, especially when designing strip foundations operating in difficult ground conditions. To ensure the safety and durability of such foundations, several factors must be incorporated: the heterogeneity of the soil base, the possibility of subsidence, the impact of temperature and mechanical loads, as well as the specifics of the interaction between the foundation and the soil. Traditional calculation methods do not always provide an accurate estimation of the behaviour of such structures, which often causes errors at the design stage and increases the cost of building construction and operation. A.T. Marufiy *et al.* (2021) developed a methodology for calculating strip foundations with consideration of incomplete contact with the ground and the action of longitudinal forces. The study determined that incomplete contact led to a redistribution of loads and an increase in deflections, while tensile forces reduced deflections by 10-5%, and compressive – forces increased them by 5-10%. The implemented methodology improved the accuracy of prediction of the stress-strain state of foundations and increased the reliability of design solutions.

The development of digital technologies can analyse complex engineering problems related to the calculation of building structures, including strip foundations, in more detail. Modern software systems implementing numerical methods made it possible to consider various factors affecting the behaviour of the foundation and improve the accuracy of predicting its performance. For instance, M. Alabi (2024) considered the effectiveness of computational methods in the design of responsible building systems, and H.F. Schweiger *et al.* (2018) described approaches to the correct formulation of numerical modelling for complex interactions “structure-soil”.

One of the key factors affecting the behaviour of foundations is incomplete contact with the subgrade. This situation often occurs on weak and subsiding soils, where there is a loss of bearing capacity in individual sections, which leads to a redistribution of loads and a change in the stress state of the structure. This effect was analysed by Q. Liu (2023) in an assessment of the capabilities of modern algorithms in evaluating deformed beam structures on elastic foundations. In addition, M. Ertz *et al.* (2024) highlighted that the local absence of support can provoke

significant deformations that require mandatory consideration in design models.

Another significant aspect was the impact of longitudinal forces caused by temperature fluctuations, pre-tensioning of reinforcement or uneven load distribution. These factors could affect the strength and stability of the structure, adjusting the design characteristics. For instance, the study by M. Clement (2025) analysed the features of compressive effects and their impact on the stress distribution in the elements, and A.N. Hoshyar *et al.* (2019) demonstrated that the consideration of longitudinal forces improved the accuracy of prediction of the risk of localised loss of stability.

To solve this problem, the method of modelling a strip foundation in the form of a finite beam on a two-parameter elastic foundation was used. This approach incorporated both local disturbances in contact with the ground and the influence of longitudinal forces, bringing the design conditions as close as possible to actual operation. This was confirmed by the findings of Y. Fissaha *et al.* (2024), which emphasised the importance of a correct assessment of the load distribution and stress state of structures in the context of soil heterogeneity. The importance of architectural software tools was demonstrated by I. Zgoda (2023), who highlighted the speed and convenience of performing complex calculation operations with subsequent graphical interpretation.

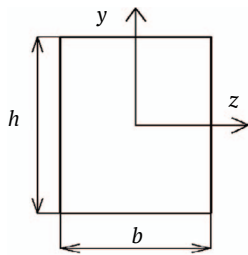
Analysis of existing research determined that previously published works did not fully consider the combination of incomplete contact between the strip foundation and the subgrade and longitudinal tensile or compressive forces, especially in conditions of significant soil heterogeneity and its subsidence properties. In several cases, possible temperature effects and dynamic factors were not incorporated, which distorted the real picture of the stress-strain state of the structure. In this regard, it became necessary to determine the influence of the combined action of incomplete contact and longitudinal forces on the distribution of deflections, bending moments and critical stress zones. The study aimed to develop a methodology for calculating strip foundations with consideration of incomplete contact and longitudinal forces, which ensured a more accurate prediction of the stress-strain state of the structure under difficult operating conditions.



## MATERIALS AND METHODS

Since the method for calculating strip foundations was based on universal modelling principles, no attention was initially paid to possible regional characteristics. In real-life conditions, specific geotechnical factors were observed to have an impact. The research established that the soils of the Fergana Valley had several characteristic properties, including high heterogeneity, pronounced subsidence, the presence of loess layers, and significant fluctuations in the groundwater level. These features significantly influenced the behaviour of the foundations, requiring adjustments to the standard calculation models. In this regard, it was appropriate to account for the properties of the soils of the Fergana Valley to improve the accuracy of the calculations.

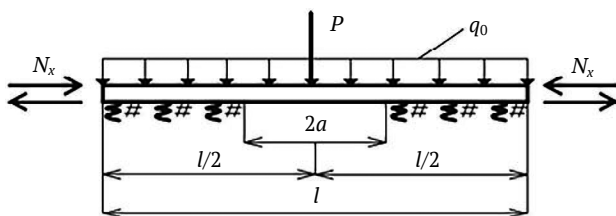
A rectangular beam (width  $b = 1.25$  m, height  $h = 1.5$  m) was used as the initial modelling object, which operates as a strip foundation with a length of  $l = 18$  m. The beam material was characterised by a density of  $\rho = 2,500$  kg/m<sup>3</sup> and an elastic modulus of  $E = 21 \cdot 10^3$  MPa. The external forces considered were the dead weight of the structure, a concentrated load in the centre of the span  $P = 100$  kN, and longitudinal tensile or compressive forces  $N_x = 200$  t/m acting in the midplane of the beam. The initial data of the beam with a rectangular cross-section are shown in Figure 1.



**Figure 1.** Rectangular beam section

Source: compiled by the authors

The incomplete contact is represented by a trench of size  $2a$  located in the centre of the end beam and subjected to longitudinal forces (Fig. 2). The beam is subjected to the beam's weight  $q_0$  and a concentrated force  $P = 100$  kN applied in the centre of the beam.



**Figure 2.** Design diagram of the end beam

Source: compiled by the authors

The subgrade was modelled using a two-parameter model that considers not only vertical elastic displacements (bedding coefficient  $k_0$ ) but also shear deformations (additional stiffness parameter). The complexity of the problem

is due to the incomplete contact in width  $2a$  located in the central zone of the beam. Three variants of  $2a$  were considered: 3 m, 4.5 m and 6 m, reflecting different scenarios of weakening or absence of support under the foundation. To improve the accuracy of the calculations, it is necessary to incorporate the soil properties of the Ferghana Valley, characterised by high heterogeneity, the presence of subsidence and loess soils, and significant fluctuations in the groundwater level.

To describe the bending of a finite beam on an elastic base with incomplete contact, a fourth-order differential equation was adopted, supplemented by terms that consider longitudinal forces and the Heaviside function to model the "interruption" of contact in section  $2a$ . In general, it will be presented as follows (1, 2):

$$EJ \frac{d^4 w(x)}{dx^4} - 2r^2 \frac{d^2 w(x)}{dx^2} + s^4 w(x) \theta(x-a) - N_x \frac{d^2 w(x)}{dx^2} = q(x), \quad (1)$$

where  $w(x)$  – deflection function of the beam;  $\theta(x-a)$  – heaviside function reflecting the absence of soil support in the area  $[a, l-a]$ ;  $N_x$  – intensity of longitudinal forces (tensile or compressive);  $EJ$  – bending stiffness;  $r$  and  $s$  – parameters characterising the elastic properties of the foundation;  $q(x)$  – external load.

$$E = 21 \cdot 10^3 \text{ MPa} \cdot r, \quad (2)$$

where  $E$  – modulus of elasticity characterises the resistance of a material to deformation in tension or compression;  $r$  – dimensionless coefficient equal to 10.19716, which is used to convert the modulus of elasticity from megapascals to the required system of units.

The analytical transformations performed obtained solutions for various combinations of parameters  $2a$  and  $N_x$ . The influence of the coefficient  $\alpha$ , which relates the longitudinal forces and stiffness characteristics of the beam, is notable (3):

$$\alpha = \frac{N_x l^2}{EJ_z}. \quad (3)$$

By introducing correction terms in the differential equation, both the effect of the "hanging section" and deformations caused by longitudinal forces are incorporated. As part of the calculations, the dead weight of the beam was determined using the following formula:

$$q_0 = \rho \cdot b \cdot h, \quad (4)$$

where  $q_0$  – evenly distributed load produced by the dead weight of the beam (in kg/m or t/m);  $\rho$  – density of the beam material, measured in kilograms per cubic centimetre (kg/cm<sup>3</sup>);  $b$  – beam (base) width, measured in metres (m) or centimetres (cm);  $h$  – beam height, measured in metres (m) or centimetres (cm).

To verify the analytical solutions and their subsequent engineering application, the developed algorithm was implemented in the Delphi environment. This platform was chosen due to the convenience of creating a user interface, as well as the high speed of processing data arrays, which

is critical for numerical experiments. The numerical experiment consisted of several stages. In the first stage, the initial geometric and mechanical parameters were set, including cross-sectional dimensions, beam length, physical properties of the material and the magnitude of loads such as dead weight and concentrated force  $P$ . Next, the variants of incomplete contact were considered, where the program sequentially calculated the cases of  $2a = 3$  m, 4.5 m and 6 m, while all other parameters remained unchanged.

At the next stage, longitudinal forces were modelled, with  $N_x$  values entered as both positive (tension) and negative (compression) at a fixed angle of inclination  $\alpha \approx 0.102$ . Then, calculation iterations and convergence analysis were performed: for each combination  $\{2a, N_x\}$ , the program calculated deflections, bending moments, and base reaction diagrams. Convergence was verified by comparing the results of the iterations and comparing them with analytical expressions, which confirmed the correctness of the algorithm.

The graphical dependencies demonstrated how an increase in the partial contact zone or a change in the sign and value of  $N_x$  affects the deflection shape and the nature of the moment distribution. Thus, a comprehensive methodology combining an analytical approach and numerical modelling was used for a detailed analysis of the effect of both incomplete contact and tensile/compressive longitudinal forces on the behaviour of strip foundations.

## RESULTS

The study provided the analytical solution to the problem of bending a finite beam on a two-parameter elastic foundation with consideration of incomplete contact with the soil foundation and the action of tensile and compressive longitudinal forces applied in the midplane of the beam. This calculation is based on the analytical solution of the problem of bending a finite beam resting on a two-parameter elastic foundation, considering two key factors. The first factor is the incomplete contact between the foundation and the subgrade, which occurs in width  $2a$  (trench) located in the central part of the beam. This phenomenon can significantly affect the distribution of stresses and strains, changing the traditional patterns of interaction between the beam and the foundation.

The second factor is the longitudinal forces that occur in the centre plane of the beam. These forces can be either tensile or compressive, and their occurrence is caused by various external influences, such as pre-tensioning of reinforcement, temperature fluctuations or other operating conditions. Their inclusion in the design model improves the accuracy of description of the behaviour of the beam in real-world conditions.

The modulus of elasticity of the beam material is equal:

$$E = 21 \cdot 10^5 \text{ MPa} = 21 \cdot 10^5 \cdot 10.19716 \frac{\text{kg}}{\text{cm}^2} = 214.14 \cdot 10^5 = 214,140 \frac{\text{kg}}{\text{cm}^2} = 2,141,400 \frac{\text{t}}{\text{m}^2}.$$

The dead weight of the beam is calculated using formula (4):

$$q_0 = 2,500 \frac{\text{kg}}{\text{cm}^3} \cdot 1.25 \text{ m} \cdot 1.5 \text{ m} = 2,500 \frac{\text{kg}}{\text{cm}^3} \cdot 125 \text{ cm} \cdot 150 \text{ cm} = 4,687.50 \frac{\text{kg}}{\text{m}} = 4,687.5 \text{ t/m}.$$

To determine the total load acting on the beam, the dead weight of the beam was converted into a concentrated force:

$$P_{\text{general}} = P + q_0 \cdot l = 100 \text{ kN} + 4,687.50 \frac{\text{kg}}{\text{m}} \cdot 18 \text{ m} = 100 \text{ kN} + 84,375 \text{ kg} = 100 \text{ kN} + 84,375 \text{ kg} + 9.80665 \text{ N} = 100 \text{ kN} + 827,436 \text{ N} = 927.436 \text{ kN},$$

where  $P_{\text{general}}$  – total load acting on the beam (in kN);  $P$  – concentrated load applied to the beam (in kN);  $q_0$  – uniformly distributed load from the beam's weight (in kg/m);  $l$  – beam length (in m).

The Fergana Valley is characterised by complex soil conditions, predominantly loess and loess-like soils, which often have subsidence properties and high layer heterogeneity. According to geotechnical surveys by M. Alabi (2024), deformation modules can vary within the range of 10-25 MPa, cohesion ( $c$ ) from 10 to 30 kPa, and internal friction angle ( $\varphi$ ) from 18 to 26°. In addition, such soils are sensitive to changes in moisture content and can lose part of their bearing capacity when moistened. All this significantly affects the performance of strip foundations and requires correct consideration in the design model.

An additional complicating factor in the region is seismic activity: The Ferghana Valley is classified as an area with seismicity levels of 7-9 on the MSK-64 scale. When designing foundations, it is necessary to incorporate dynamic effects that cause vibrations of the structure and additional load on the "hanging" sections of the foundation (if there are areas of incomplete contact). In this study, the seismic load was modelled by introducing a horizontal component proportional to the beam mass and the site seismicity factor. This can be used to estimate the increase in deflections and stresses, especially in weak or subsiding soil conditions.

Digital technologies were used to verify and improve analytical solutions. A software module was developed in the Delphi environment that accounted for all key factors affecting the object under study. The numerical experiment included solving a system of equations (finite difference method or finite element method) for various combinations of  $\{k_0, 2a, N_x\}$  and variations in seismic load. The results of the deflection and bending moment diagrams along the beam were compared with analytical expressions. With correct parameter settings, the discrepancies between the results of the analytical and numerical methods did not exceed 5-10%.

Thus, the integration of real geotechnical data from the Fergana Valley, consideration of the seismicity of the site and the use of digital technologies for numerical modelling provides a comprehensive and accurate approach to the design of strip foundations. In practice, this can be used to optimise cross-sectional and reinforcement dimensions, as well as to provide timely reinforcement measures in potentially dangerous areas with increased deflections or stresses.



To incorporate the effect of longitudinal forces, it is necessary to determine the value of the proportionality coefficient of the intensity of longitudinal forces. The intensity of longitudinal forces was assumed to be  $N_x = 200 \text{ t/m} = 2,000 \text{ kg/cm}$ .

The beam's mass was calculated by multiplying the volumetric mass by the cross-section and length, and, if necessary, the forces were converted into concentrated equivalents. To account for longitudinal forces, a dimensionless value  $\alpha$  was introduced into the problem, characterising their relative value concerning the stiffness of the beam and the base. The value of  $\alpha$  is defined as (5):

$$l = \sqrt[4]{\frac{E \cdot J_z}{k_0}}, \tag{5}$$

where  $l$  – characteristic length of the beam (in metres);  $E$  – modulus of elasticity of the beam material (in Pa, MPa or kN/m<sup>2</sup>);  $J_z$  – moment of inertia of the beam cross-section relative to the z-axis (in m<sup>4</sup> or cm<sup>4</sup>);  $k_0$  – bedding coefficient, which characterises the elasticity of the subgrade (in N/m<sup>3</sup> or kN/m<sup>3</sup>).

Where:

$$k_0 = 5 \frac{\text{MN}}{\text{m}^3} = 5 \cdot 10^6 \frac{\text{H}}{\text{m}^3} = 5 \cdot 0.10197162 \cdot 10^6 \frac{\text{kg}}{\text{cm}^3} = 5.1 \cdot 10^5 \frac{\text{kg}}{\text{cm}^3} = 0.51 \frac{\text{kg}}{\text{cm}^3} = 510 \frac{\text{t}}{\text{m}^3},$$

where  $k_0$  – bed coefficient, characterising the stiffness of the ground base (in various units of measurement);  $5 \text{ MN/m}^3$  – initial value of the bedding factor in meganewtons per cubic metre;  $5 \cdot 10^6 \text{ N/m}^3$  – conversion to Newtons per cubic metre.

According to the above initial data, the value of the axial moment of inertia for a rectangular section (Fig. 1) was determined by the formula (6):

$$J_z = \frac{b \cdot h^3}{12} = \frac{1.25 \cdot 1.5^3}{12} = \frac{125 \cdot 150^3}{12} = 35,156,250 \text{ cm}^4 = 0.3515625 \text{ m}^4, \tag{6}$$

where  $J_z$  – axial moment of inertia of the beam cross-section relative to the axis;  $b$  – beam width (in m or cm);  $h$  – beam height (in m or cm);  $\frac{b \cdot h^3}{12}$  – formula for calculating the moment of inertia of a rectangular section relative to its central axis; 1.25 m – beam width in metres; 1.5 m – beam height in metres; 12 – coefficient in the formula for the moment of inertia for a rectangular section.

The bending stiffness was determined:

$$E \cdot J_z = 21 \cdot 10^3 \text{ MPa} \cdot J_z = 214,140 \frac{\text{kg}}{\text{cm}^2} \cdot 35,156,250 \text{ cm}^4 = 2,141,400 \text{ t} \frac{\text{t}}{\text{m}^2} \cdot 0.3515625 \text{ m}^4 = 752,835.94 \text{ tm}^2,$$

where  $E \cdot J_z$  – bending stiffness of the beam (bending stiffness);  $E$  – modulus of elasticity of the beam material (in Pa, MPa, kg/cm<sup>2</sup> or t/m<sup>2</sup>);  $J_z$  – moment of inertia of the beam cross-section relative to the axis z (in m<sup>4</sup> or cm<sup>4</sup>);  $21 \cdot 10^3 \text{ MPa}$  – value of the elastic modulus in megapascals.

Substituting the values of  $E \cdot J_z$  and  $k_0$  in (3), the value of  $l$  was determined:

$$l^2 = \sqrt{\frac{E \cdot J_z}{k_0}} = \sqrt{\frac{752,835.94 \text{ tm}^2}{510 \frac{\text{t}}{\text{m}^3}}} = \sqrt{1,476.15} \approx 38.42.$$

$$\alpha = \frac{N_x \cdot l^2}{E \cdot J_z} = 2,000 \cdot \frac{38.42}{752,835.94} = \frac{76,840}{752,835.94} \approx 0.102.$$

The absence of beam support in this area leads to a redistribution of loads and, as a result, to changes in deflections and stresses. Table 1 shows the calculation results for each of the above cases.

**Table 1.** Calculated deflections of a foundation beam on a two-parameter elastic foundation under tensile longitudinal forces

No.	x	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	$\alpha$	$N_x$ , t/m	W excluding tensile stress
1 <sup>st</sup> row	$W^p$	-0.0053	-0.0052	-0.0049	-0.0043	-0.0037	-0.0031	-0.0023	-0.0014	-0.0007	0.00	0.0102	200	0.0059
2 <sup>nd</sup> row	$W^p$	-0.0067	-0.0066	-0.0061	-0.0055	-0.0047	-0.0038	-0.0028	-0.0018	-0.0008	0.00	0.0102	200	0.0074
3 <sup>rd</sup> row	$W^p$	-0.0077	-0.0075	-0.0070	-0.0063	-0.0053	-0.0043	-0.0032	-0.0021	-0.0009	0.00	0.0102	200	0.0085
4 <sup>th</sup> row	$W^p$	-0.0088	-0.0085	-0.0080	-0.0072	-0.0061	-0.0050	-0.0036	-0.0023	-0.0011	0.00	0.0102	200	0.0098

**Source:** compiled by the authors

One of the most important factors affecting the performance of strip foundations is the heterogeneity of the soil, as well as the probability of localised failures or subsidence. In this study, the incomplete contact was modelled as a  $2a$ -wide trench located in the central part of the beam. Three options were considered:

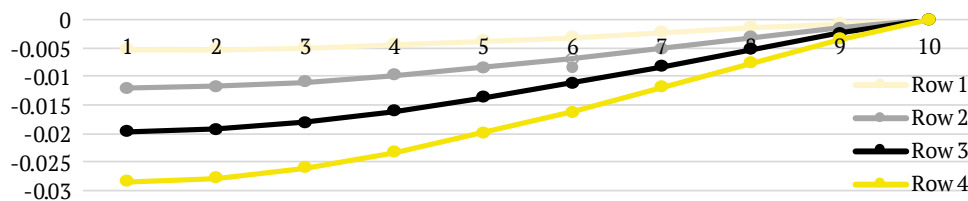
- row 1 – when the beam is in full contact with the subgrade;
- row 2 – with incomplete contact in an area of trench width:  $2a = (1/6) \cdot l = (1/6) \cdot 18 = 3 \text{ m}$ ;
- row 3 – with incomplete contact in an area of trench width:  $2a = (1/4) \cdot l = (1/4) \cdot 18 = 4.5 \text{ m}$ ;

● row 4 – with incomplete contact in an area of trench width:  $2a = (1/3) \cdot l = (1/3) \cdot 18 = 6 \text{ m}$ .

The analysis of beam bending on a two-parameter elastic foundation, considering incomplete contact, revealed several key trends. First, an increase in deflection is observed with an increase in trench width. As parameter  $2a$  increases, the bearing area of the beam on the foundation decreases, which leads to increased displacements in the central zone. This is due to a decrease in the stiffness of the beam-foundation system and an increase in the free section without support.

Secondly, there is a redistribution of forces along the beam. The areas immediately adjacent to the trench zone experience increased bending moments, since they have to take an additional part of the load, which would be distributed more evenly under full contact conditions. Thus, an increase in internal forces is observed in these zones, which should be incorporated when calculating the strength of the structure. Third, the shape of the deflection diagram changes. With full contact, the deflection is distributed smoothly, providing a uniform change in bending moments. However, in the case of incomplete contact, a sharp increase in deflection occurs in the “hanging” zone, which leads to localised deformations and a potential change in the stress-strain state of the beam.

The data obtained suggests that even a relatively small “break” in contact leads to a noticeable increase in displacements and stresses near the trench edges. Thus, when designing, it is necessary to carefully assess the probability of ground subsidence and possible local failures. Ignoring these factors can lead to an underestimation of the stresses in the foundation, which in real life can mean an increased risk of cracking and reduced bearing capacity. The calculations (Table 1) demonstrated that, without factoring in longitudinal forces, the maximum deflections could increase to  $-0.0098 \text{ m}$  when the area of incomplete contact increased by  $2a = 6 \text{ m}$ , which is approximately 6,670% more than in the case of a smaller trench area ( $2a = 3 \text{ m}$ ). This indicates that the structures are highly sensitive to the length of the section where there is no support on the ground. Based on the results shown in Table 1, graphs of the deflections of the end beam on a two-parameter elastic foundation were constructed, incorporating the incomplete contact of the beam with the soil settlement in the form of a single trench  $2a$  wide, located in the centre of the beam, and the action of longitudinal tensile forces applied in the median plane of the beam. Figure 3 demonstrates the deflection graph of the end beam on a two-parameter elastic foundation, incorporating the parameters that ensure the approximation of the design conditions to the actual operation of the structure.



**Figure 3.** Deflection diagram of a finite beam on a two-parameter elastic base with consideration of the parameters providing conditions close to its actual operation

Source: compiled by the authors

Incomplete contact between the foundation (beam) and the subgrade was modelled as a central trench with a width of  $2a$ , which redistributed loads and locally increased deflections and stresses. Four scenarios were considered in the study: full contact (control case) and three variants of the trench with width  $2a = 3 \text{ m}$ ,  $4.5 \text{ m}$  and  $6 \text{ m}$ . The study determined that an increase in the “hanging” area caused a significant increase in deflections and internal forces in the trench adjacent to the trench. The calculations demonstrated that with a trench width of  $2a = 6 \text{ m}$ , deflections in the central part of the beam increased by 66-70% compared to the  $2a = 3 \text{ m}$  variant, which emphasised the high sensitivity of the structure to the unsupported zone.

The analysis of the results demonstrated that incomplete contact significantly increased deflections in the area of the “hanging” section. The distribution of internal forces became uneven, and the extreme sections of the trench experienced increased bending moments. With the increase in the width of the trench, the probability of deformation concentration and cracking significantly increased. The

study established that the weakened contact zones should be taken into account at the design stage to prevent the underestimation of stresses and increase the reliability of the foundation. In real-life conditions, strip foundations are often subjected to tensile longitudinal forces caused by preliminary tensioning of reinforcement, uneven heating or cooling of structures (temperature gradients), as well as design schemes that assume external influences creating tensile effects (Baida *et al.*, 2024). In the presented calculations, the intensity of tensile forces  $N_x$  was taken to be equal to  $200 \text{ t/m}$  with a coefficient  $a \approx 0.102$ . Comparative data for beam deflections with and without tensile stress are given in Table 1 (rows marked  $W_p$ ).

The main conclusions on the effect of tensile forces demonstrated that the beam works somewhat more rigidly under tension, which leads to a reduction in deflections. The analysis of analytical and numerical data shows that, on average, deflections are reduced by about 10-11%. In addition, a levelling of the stress-strain diagram is observed, as tensile forces counteract the local loss of stability and



increase in deflections. In addition, the redistribution of forces near the edge of the trench becomes less sharp when in incomplete contact with the ground, which reduces the probability of excessive moments and concentrated deformations.

For instance, when the beam was in full contact with the substrate without longitudinal forces, the maximum deflection was -0.0059 m, while when tension was considered, it reached -0.0053 m. Although the difference in absolute values seems insignificant, in real-world construction, a 10-15% reduction in deformation can mean a significant safety margin and a reduction in the probability of damage. For the variants with incomplete contact, a similar pattern is observed: with a trench zone of 3 m in length, the deflection decreases on average from -0.0074 m to -0.0067 m, which confirms the favourable effect of tensile forces on the overall stiffness of the foundation-soil system. When the width of the incomplete contact is increased to 6 m, the tensile effect also results in a reduction of the ultimate deflection values by approximately 10-11%. Thus, the incorporation of tensile longitudinal forces improves the accuracy of determination of the actual stiffness of the foundation and predicting its behaviour under real loads.

In the presence of tensile longitudinal forces ( $N_x > 0$ ), the beam demonstrated stiffer operation, which was reflected in a reduction of deflections and a smoother distribution of the stress-strain state. Calculations demonstrated that at an intensity of  $N_x = 200$  t/m and a coefficient of  $\alpha \approx 0.102$ , deflections decreased by an average of 10-11%. This effect was observed both in the case of full contact of the beam with the base and various variants of incomplete contact (different values of  $2a$ ). Even with large areas of incomplete contact ( $2a = 6$  m), the tensile force remained a stabilising factor, reducing the risk of local deformation.

The analysis of the results confirmed that tensile longitudinal forces contributed to a reduction in deflections and an increase in the overall stiffness of the foundation-soil

system. The reduction in maximum deflections reached 10-15%, which significantly increased the safety margin of the structure in real construction conditions. Stress diagrams in the trench zone became smoother, reducing the risk of excessive deformation concentrations. These results enabled the use of prestressed reinforcement in strip foundations as an effective technique for stabilising the structure and increasing its reliability.

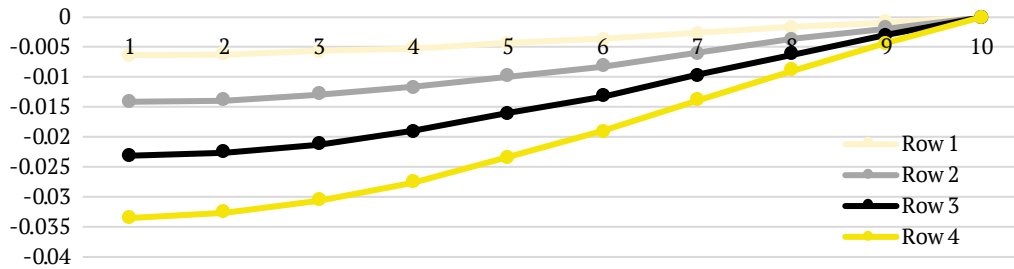
In addition to tensile forces, compressive forces can be substantial in the operation of strip foundations, which arise under various operating conditions. For instance, temperature exposure leads to linear expansion of the structure, as a result of which the foundation can rest against rigid elements, creating significant longitudinal compressive forces. In addition, the transfer of loads from overlying structures under specific support patterns can also contribute to compression, especially in places of concentration of forces. The peculiarities of installation and operation, such as the overstretching of supports or the presence of expansion joints, which can change the nature of the distribution of compressive stresses in the foundation, are also substantial.

In this study, compressive forces were modelled with the same intensity ( $N_x = 200$  t/m), but with the opposite sign. The calculation results are shown in Table 2 (rows  $W_{cp}$ ). The analysis demonstrated that compression can increase beam deflections, but the magnitude of this increase is usually less than the reduction effect from tension. The reason lies in the fact that a compressed beam is more prone to losing stability in the transverse direction, especially if there is weak or no contact with the ground in section 2a. Figure 4 demonstrates a deflection distribution graph of the final beam calculated on a two-parameter elastic basis with the above parameters. The graph showed the change in deflections along the length of the beam, and their maximum values were recorded, to assess the impact of the selected parameters on the behaviour of the structure under conditions close to real ones.

**Table 2.** Comparison of response times and computing costs

No.	$x$	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	$\alpha$	$N_x$ , t/m	$W$ without compression
1 <sup>st</sup> row	$W_{tp}$	-0.0063	-0.0061	-0.0057	-0.0051	-0.0043	-0.0036	-0.0027	-0.0017	-0.0009	0.00	0.0102	200	0.0059
2 <sup>nd</sup> row	$W_{tp}$	-0.0078	-0.0077	-0.0072	-0.0065	-0.0055	-0.0045	-0.0033	-0.0020	-0.0010	0.00	0.0102	200	0.0074
3 <sup>rd</sup> row	$W_{tp}$	-0.0009	-0.0088	-0.0083	-0.0074	-0.0063	-0.0051	-0.0037	-0.0024	-0.0011	0.00	0.0102	200	0.0085
4 <sup>th</sup> row	$W_{tp}$	-0.0104	-0.0100	-0.0094	-0.0085	-0.0072	-0.0058	-0.0042	-0.0028	-0.0013	0.00	0.0102	200	0.0098

**Source:** compiled by the authors



**Figure 4.** Deflection diagram of a finite beam on a two-parameter elastic base with the above parameters considered  
**Source:** compiled by the authors

Several key points can be identified from a comparison of the results for different scenarios. With incomplete contact with the foundation, when the width of the trench section is  $2a = 3$  m, the maximum deflection without compression reached  $-0.0074$  m, while with compression forces incorporated, it increased to  $0.0078$  m, which corresponds to an increase of about 5%. For a wider trench section,  $2a = 6$  m, the increase in deflection was even more noticeable and amounted to about 6-7%. Without consideration of compression, the deflection was  $-0.0098$  m, and with consideration of compression, it increased to  $-0.0104/-0.0105$  m and more. Separate calculations also indicate a range of values of  $-0.0100$  -  $-0.0104$  m.

In most of the combinations considered, especially at higher values of  $2a$ , deflections increase and beam warping is possible, which can be a serious hazard. This effect can cause cracks in the foundation, especially if the reinforcement is insufficient or if the necessary structural measures are not taken. Thus, compressive forces can exacerbate the negative effects of incomplete contact with the foundation by increasing deformations. However, the extent of this effect is determined by the stiffness of the soil and the magnitude of the longitudinal forces.

In designing strip foundations, it is necessary to account for compression that can cause more significant deformations than assumed in simplified design models where longitudinal forces are not considered. The analysis of the calculations demonstrated that the difference in the maximum deflections with and without compression for large sections of the trench reaches 5-10%, which is a significant value for structures with a high level of responsibility.

Compressive longitudinal forces ( $N_x < 0$ ) had the opposite effect, contributing to an additional increase in deflections, especially in conditions of incomplete contact. The calculations showed that at  $N_x = 200$  t/m, the ultimate deflections increased by 5-10% compared to similar scenarios without compression. In the case of a longer "hanging" section of the foundation ( $2a = 6$  m), the deflection increase was most pronounced and reached 6-7%. This effect was accompanied by an increase in internal stresses and an increased risk of crack development, which made it necessary to account for compressive forces in the design of structures, especially concerning possible temperature effects.

The analysis of the effect of compressive longitudinal forces demonstrated that their presence exacerbated

the negative effects of incomplete contact and led to an increase in deflections by 5-10%. At values of  $2a$  up to 6 m, a significant increase in deformations and stresses in the central zone of the beam was observed. In conditions of weak or subsiding soil, the risk of localised damage increased significantly, especially if the influence of longitudinal compressive factors was underestimated. To compensate for such effects, it was advisable to include design measures such as expansion joints and reinforced reinforcement in the design, which reduced the negative impact of compressive effects and increased the overall reliability of the structure.

## DISCUSSION

The results of the study confirm that the consideration of incomplete foundation-base contact and longitudinal forces is one of the determining factors in the design of strip foundations in difficult operating conditions. Increased attention to stabilisation and optimisation of the structure's performance plays a significant role here, as it can increase deflections in the central part of the beam and increase stress concentration. Since even a relatively small unsupported zone (e.g., a 3 m long trench) leads to a noticeable increase in deflections and stress concentration, it should be noted that the greatest impact on the stress-strain state of a structure is exerted by increasing the size of the incomplete contact zone, and not just the fact of its presence. The larger the area where the foundation does not rest on the ground, the greater the redistribution of forces and the increase in local deformations, which must be considered in the design.

The results of the study confirmed the importance of the incomplete contact of the foundation with the subgrade and the influence of longitudinal forces. The study determined that even a relatively small zone of "hanging" area significantly increased deflections and the appearance of local stress concentrations in the parts of the foundation adjacent to the trench. The largest increase in deformations was observed with the expansion of the unsupported zone, which was consistent with the conclusions drawn by A.T. Marufiy & A.S. Kalykov (2019), where incomplete contact between the beam and the soil was noted to cause a significant redistribution of bending moments. B. Messaouda *et al.* (2023) emphasise the importance of numerical modelling of the behaviour of a surface foundation



located near a slope. Their results demonstrated that the geometrical location of the foundation relative to natural objects has a significant impact on the load distribution, which harmoniously complements conclusions about the effect of the expansion of the incomplete contact zone on the local deformation of the structure.

The effect of longitudinal forces was ambiguous: tensile forces contributed to a reduction in deflections, increasing the stiffness of the beam-foundation system, while compressive forces, on the contrary, increased the magnitude of displacements and could provoke additional buckling. Similar trends were observed by A.T. Marufiy & A.S. Kalykov (2019), specifying that the presence of compressive forces can exacerbate the negative effects of incomplete contact, especially in the central zone of the structure. These conclusions were consistent with the results obtained earlier and described by A.T. Marufiy *et al.* (2021), who analysed various schemes of longitudinal load distribution and their influence on the flexibility of beams on an elastic foundation.

A.T. Marufiy & A.S. Kalykov (2019) investigated the stress-strain state of strip foundations, incorporating the factors affecting their actual operation. Various characteristics of the foundation and their influence on the durability of the structure were considered. Earlier, a methodology for calculating slabs and beams on elastic foundations was also proposed by A.T. Marufiy *et al.* (2021), which emphasised the need to incorporate soil heterogeneity and possible subsidence of individual sections. The results of the present study were consistent with their findings, demonstrating that the expansion of the incomplete contact zone increased local deformations and increased the risk of cracking, especially under compressive forces. This confirmed the feasibility of using prestressed reinforcement, as mentioned in the study by A.T. Marufiy *et al.* (2021) when it was necessary to increase the stiffness of the foundation and reduce deflections in problem areas.

Thus, the consideration of incomplete contact and longitudinal forces was a crucial condition in the design of strip foundations. Ignoring these factors could lead to errors in the assessment of the stress-strain state and reduce the reliability of the structure. Together with the recommendations given in the above works, the presented analysis confirmed the importance of an integrated approach combining analytical and numerical methods, as well as enabling detailed consideration of the characteristics of weak and subsidence soils in real operating conditions.

The transition to the use of big data and complex analytics for engineering is becoming an increasingly prominent trend. The presented study is limited to the linear-elastic formulation, but the transition to more complex models can be made based on modern computing technology and integrated solutions described by these authors. The review of finite element methods presented by G.D. Dhadse *et al.* (2021) was dedicated to modelling the interaction of the soil-structure system, incorporating interface phenomena. This review demonstrated the complexity

of calculations in incomplete contact, which confirms the need for an integrated approach used in the current study to optimise computational methods. The situations of deep excavation and weakened soil under foundations were further considered by S. Yang *et al.* (2023). Their Grey Wolf Optimiser-Extreme Learning Machine (GWO-ELM) model demonstrated that hybrid algorithms can achieve high accuracy in deformation prediction. No such methods were used in the calculations, but the general idea is the same: incorporation of additional parameters that determine the behaviour of the soil increases the accuracy and reliability of model assumptions.

Similar themes are present in a study by A. Ramos *et al.* (2024), where the application of machine learning to predict deformations of railway tracks has similarities with the methodology: although they are dealing with tracks rather than foundations, both are important for correct prediction of subsidence and displacements in the base. The results obtained on how longitudinal compression or tension affects the deflection shape can be reinterpreted for various types of linear structures, where the effect of a “hanging” section can be relevant. In a study by M. Sadegh Es-haghi *et al.* (2021), a model based on machine learning methods is proposed to predict the seismic load-bearing capacity of a shallow strip foundation located over a void in heterogeneous soils. This approach demonstrates the potential of using modern computational methods to improve the accuracy of structural stability assessment, which is also reflected in current analytical and numerical experiments.

It is necessary to incorporate the uncertainty inherent in soil systems and loaded structures. Approaches to probabilistic modelling are demonstrated by S. Chen *et al.* (2022) demonstrate probabilistic modelling approaches by applying machine learning methods to assess performance. A study that determines the maximum deflections under different scenarios can easily be supplemented with probabilistic parameters if the engineer has statistics on variations in the modulus of elasticity of concrete, density or soil bedding coefficient. The use of advanced computing technologies in geotechnical design was discussed in detail by H. Jürgens & S. Henke (2021), demonstrating how numerical algorithms improve the quality of engineering solutions. In practice, the advantage of such a strategy using a combination of analytical formulas and numerical iterations has been convincingly confirmed. Digital technologies enable flexible change of the parameters: the length of the trench section, the sign and  $N_x$  value, and the comparison of obtained results.

The issue of the reliability of engineering solutions, especially under complex loads, was addressed by M. Amin-isharifabad *et al.* (2021), proposing a deep-learning model for survival analysis. Although the case is not directly related to bioengineering, the approach to processing large amounts of data is similar: it is necessary to identify critical factors affecting the state of a structure and predict the time to limit state. In the context of geotechnics, this is



the service life of a foundation before unacceptable deformations or cracks appear. The study by K.C. Onyelowe *et al.* (2022) demonstrated that the use of artificial intelligence algorithms to optimise design methods can significantly improve the efficiency of design solutions. The author's findings on the influence of longitudinal forces and incomplete contact are consistent with the conclusions of this paper, indicating the prospects for integrating AI technologies into future research in geotechnics.

Neural network solutions for assessing the reliability of different types of foundations described by A. Savvides & L. Papadopoulos (2024) complement the overall picture of current trends. In shallow foundations, it is necessary to assess the cohesive properties of the soil, and the study highlighted the elastic coefficients of the foundation, which can be considered as an analogue of shear stiffness. These two areas are quite compatible, as the combination of classical soil mechanics methods and artificial intelligence algorithms increases the adaptability of calculations. The topic of integrating analytical and machine methods for modelling bases is also present in a study by Z. Zhou *et al.* (2024). The authors analysed large-scale hydraulic structures, but the nature of the interaction "structure-soil" is in many ways similar to the situation with strip foundations, when the presence of weakened zones or trenches can cause local stress redistribution. The difference is only in the physical scale and type of structure, but the fundamental deformation mechanisms are similar.

The issues of algorithmic comparison of different machine learning methods for predicting complex states raised by S. Sasane & Z.A.S. Mulla (2024) demonstrated that the choice of a particular strain prediction technique (whether it is gradient boosting, random forest or neural network) depends on the nature of the input data. Therefore, this means that if it is necessary to verify the model when statistics of foundation deformations during operation are collected, different algorithms can be tried to clarify the "dangerous" zones of the hanging section and effectively assess the risk. The structured application of modern multivariate computing algorithms was studied by X.-M. Gao *et al.* (2023), classifying methods per number of dimensions. In the case of the basic calculation, it is still focused on a one-dimensional beam model but can be extended to a two- or three-dimensional formulation if it is necessary to incorporate the effects in the transverse direction or significant variations in soil properties along the width of the foundation. The use of higher dimensions implies an increase in computational costs, which in turn raises performance issues.

The role of supercomputing resources and adaptive algorithms in solving complex scientific and engineering problems is mentioned by H. Sharma *et al.* (2020). The study illustrated that modelling large and complex structures requires distributed computing. For research purposes, this approach would be an additional step that can analyse scenarios in greater detail or introduce additional physical nonlinearity. This would provide an even more accurate

picture of the foundation-soil interaction, incorporating dynamic factors and load variability. Y. Du *et al.* (2022) proposed a new model for predicting the bearing capacity of large strip foundations under combined loading, which can incorporate the mutual influence of different loads. This approach complements the current analysis of the influence of longitudinal forces and emphasises that comprehensive modelling using modern technologies is a key factor in assessing the strength characteristics of a foundation.

Thus, the results analysed in this study are closely related to many modern trends that involve a complex combination of numerical methods, new technologies and proper data analysis. The study in the context of these advances demonstrated the importance of the parameters of incomplete contact and longitudinal forces in the calculation of strip foundations: simplified schemes can lead to an incorrect assessment of the stress-strain state and an increase in deformation, while high-tech and intelligent methods, on the contrary, can incorporate many factors and building more reliable, optimised structures.

## CONCLUSIONS

The study developed a methodology for calculating strip foundations that considers incomplete contact with the ground and the effect of longitudinal tensile or compressive forces. The analysis demonstrated that if these factors are ignored, a significant discrepancy between the actual and calculated stress-strain state of the structure can occur, leading to errors at the design stage. The study was based on both analytical solutions reflecting the influence of the "hanging" section of the beam using the Heaviside function and numerical experiments performed in Delphi and verified by finite difference and finite element methods. The results demonstrated that incomplete contact causes a noticeable increase in deflections in the central zone of the foundation and an increase in bending moments in the areas adjacent to the trench. As the width of the unsupported section increased, local deformations increased, and stress concentrations increased. The tensile longitudinal forces created a favourable effect, which consisted of a reduction in deflections and a more even distribution of forces along the beam, leading to an increase in the stiffness of the foundation-soil system. The study determined that with a characteristic coefficient  $\alpha$ , the maximum possible tensile deflections were reduced by 10-15%.

The calculations yielded the following key numerical values. With full contact between the beam and the ground, the maximum deflection was 0.0059 m, and with partial contact with a trench width of  $2a = 3$  m, it was 0.0074 m; with an increase in  $2a$  to 6 m, the deflection reached 0.0098 m, which meant an increase in deflection by 66-70%. With the tensile longitudinal forces included a decrease in deflections of approximately 10-11% was recorded, and when compressive forces were modelled, an increase of 5-10% was observed. The coefficient characterising the influence of longitudinal forces was approximately 0.102. The numerical data obtained confirmed the



effectiveness of the proposed method for calculating strip foundations under conditions close to real ones and made it possible to optimise the cross-sectional dimensions and reinforcement scheme of the structure. Further research could focus on the development of 3D models that consider lateral interactions between the foundation and the ground to more accurately predict stresses and strains. In addition, the introduction of monitoring systems that combine theoretical calculations with actual measurements will enable prompt detection of critical changes in the condition of the foundation and timely correction of design solutions. These areas contribute to improvement of the calculation

methodology, increasing the accuracy of determining the parameters of foundation performance and reducing the risk of undesirable deformation or failure.

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## CONFLICT OF INTEREST

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**Аділжан Маруфій**

Доктор технічних наук, професор  
Ошський технологічний університет імені М. М. Адишева  
723503, вул. Ісанова, 81, м. Ош, Киргизька Республіка  
<https://orcid.org/0000-0003-4138-8892>

**Уметалі Джусуєв**

Доктор технічних наук, доцент  
Ошський технологічний університет імені М. М. Адишева  
723503, вул. Ісанова, 81, м. Ош, Киргизька Республіка  
<https://orcid.org/0009-0004-5632-8096>

**Ельнура Турдажієва**

Магістр, викладач  
Ошський технологічний університет імені М. М. Адишев  
723503, вул. Ісанова, 81, м. Ош, Киргизька Республіка  
<https://orcid.org/0009-0000-9302-0155>

**Муса Жалалдінов**

Аспірант  
Ошський технологічний університет імені М. М. Адишева  
723503, вул. Ісанова, 81, м. Ош, Киргизька Республіка  
<https://orcid.org/0009-0002-2685-7750>

**Анара Алієва**

Магістр, викладач  
Ошський технологічний університет імені М. М. Адишева  
723503, вул. Ісанова, 81, м. Ош, Киргизька Республіка  
<https://orcid.org/0009-0005-5573-1286>

## **Огляд та концепція пасивного індивідуального житлового будинку для умов континентального помірного клімату**

**Анотація.** Метою дослідження була розробка методології розрахунку стрічкових фундаментів з урахуванням складних умов експлуатації. Для цього було розглянуто особливості фундаментів на слабких та просідаючих ґрунтах, досліджено вплив неповного контакту з фундаментом, а також вплив поздовжніх сил, що виникають внаслідок попереднього натягу арматури та зміни температури. Методологія розрахунку базувалася на моделюванні фундаменту як скінченної балки, що спирається на двопараметричний пружний фундамент. У дослідженні проаналізовано вплив неповного контакту між основою та фундаментом, що виникає у випадку локалізованих провалів або ослаблення ґрунту, а також поздовжніх сил, спричинених зовнішніми навантаженнями. Була розроблена розрахункова програма для числового моделювання та реалізована в Delphi. У дослідженні було визначено, що відсутність повного контакту між фундаментом та основою призводить до перерозподілу напружень, що може спричинити локалізовані концентрації деформацій. Поздовжні сили по-різному впливають на характеристики фундаменту: розтягуючі – зменшують прогини, а стискаючі – збільшують. Аналітичні та числові розрахунки підтвердили необхідність врахування цих факторів під час проектування, оскільки їх ігнорування може призвести до значних відхилень у напружено-деформованому стані конструкції. Розроблена математична модель враховує ці ефекти та визначає критичні області, що потребують коригування параметрів проектування. Отримані дані можуть бути використані при проектуванні стрічкових фундаментів у складних ґрунтових умовах, підвищуючи їх надійність та ефективність, а також мінімізуючи ризик утворення тріщин та нерівномірних осідань. Запропонована методологія може бути використана для розрахунку фундаментів будівель та споруд, що експлуатуються в неоднорідних ґрунтах

**Ключові слова:** модель ґрунтового фундаменту; функція Хевісайда; жорсткість на згин; узагальнені характеристики ґрунту; коефіцієнт нашарування; модуль пружності; момент інерції

