The Influence of the Negative Properties of Heaving Soil on the Stability of Frame-Rod Structural Systems

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Abstract. This article discusses the influence of the negative properties of heaving soil on the stability of frame-rod structural systems during the operation of buildings and structures. It is known that the loads and influences arising during the operation of buildings and structures can lead to loss of stability of both an individual element and the entire structural system as a whole. It is extremely difficult to ensure accident-free operation of buildings and structures, the foundation layer of which are heaving soils. Therefore, it is necessary to develop a methodology for determining the critical stability parameters of frame-rod structural systems that takes into account the heaving properties of base soils. In the process of loss of stability, elements of frame-rod structural systems under the influence of force factors due to the influence of constrained conditions can experience both passive and active bifurcation. With the manifestation of the negative properties of heaving soils, vertical deformations of the base occur, which can lead to a change in the type of bifurcation of both an individual element and the entire structural system as a whole. Based on the assumption that the element will pass from passive bifurcation to active at the moment when the work performed by internal forces is compensated by the work of the heaving forces, an expression is obtained to determine the critical deformation of the base soil. A statically indefinable single-span frame is considered, the right strut of which is loaded with force P and the left one with force αP. Using the displacement method, the critical stability parameters of the specified rod system were determined before and after the manifestation of the negative properties of the base soil. Based on the numerical analysis, it was concluded that the right pillar of the frame loses stability actively, involving the left one in the general bifurcation. After manifestation of the negative properties of the base soil, the type of bifurcation of the frame elements changes, leading to significant changes in the stability parameters. In this case, the critical deformation of the heaving linearly increases with an increase in the geometric dimensions of the frame and decreases with an increase in the load application coefficient α at 0.6<α<0.8 and 1.0<α<1.1. In the range 0.8>α>1.0, these parameters are directly proportional.

1. Introduction

Loads and influences arising during the operation of buildings and structures can lead to loss of stability of both an individual element and the entire structural system as a whole [1-8, 10, 11, 14-20]. An important factor affecting the value of critical forces is the deformation of the base. It is extremely difficult to ensure accident-free operation of buildings and structures, the foundation layer of which are heaving soils. Inaccuracies when conducting engineering surveys, designing, or during work, inaccurate data on physical and mechanical characteristics, designation of insufficient foundation depth, significantly affects the value of critical stability parameters and can lead to the destruction of buildings.
or structures before the end of its life [9, 12, 13]. Therefore, it is necessary to develop a methodology for determining the critical stability parameters of frame-rod structural systems that takes into account the heaving properties of base soils.

2. Formulation of the problem

In the process of loss of stability, elements of frame-rod structural systems under the influence of force factors due to the influence of constrained conditions can experience both passive and active bifurcation. With the manifestation of the negative properties of heaving soils, vertical deformations of the base occur, which can lead to a change in the type of bifurcation of both an individual element and the entire structural system as a whole.

Considering that the element will pass from passive bifurcation to active at the moment when the work performed by the internal forces \( A_i(M_i, Q_i) \) will be compensated by the work of the shear forces \( A_i(F_k) \):

\[
A_i(M_i, Q_i) = A_i(F_k). \tag{1}
\]

To determine the unknown internal forces in the calculation of nonlinear and nonequilibrium deformable statically indeterminate structures, we use the displacement method.

Consider a single-span frame in which the nodal load cannot cause linear displacements of the nodes as a result of the bending of the rods until they become unstable under conditions of heaving soils and determine the critical stability parameters (Fig. 1).

We choose the basic system of the displacement method taking into account its kinematic definability. The loss of stability of the rod is characterized by the appearance of both bending and torsion, which is reflected in the equivalent system of the displacement method. (Fig. 1b).

Applying unit angular displacements at nodes B and C and plotting bending moments in the equivalent system, we determine the unknown variables \( r_{ij} \) by the method of cutting nodes and compose the system of equations of the deflection method:

\[
\begin{align*}
(1) & \quad r_{11} z_1 + r_{12} z_2 = 0; \\
(2) & \quad r_{12} z_1 + r_{22} z_2 = 0.
\end{align*} \tag{2}
\]

The determinant of system (2) is determined from the expression:

\[
(2(\varphi_2(\theta_1)))(2(\varphi_2(\theta_2)) + 8(\varphi_2(\theta_1)) + 4(\varphi_2(\theta_2)) + 8 - 1 = 0; \tag{3}
\]

\[
(3)
\]
3. Theoretical part
After calculating the unknown reactions of the supports and finding the work of the internal efforts of each of the pillars of the frame until the negative properties of the base soils are manifested, we determine the type of bifurcation of the elements depending on the load application coefficient. In the event that the indicated work is negative $A_i(M_iQ_i)<0$, the element loses stability actively, if $A_i(M_iQ_i) > 0$ is passively.

Figure 1. Consider the hinge-rod system: a - design scheme; b - equivalent system of the deflection method.
Figure 2. Diagrams of bending moments and the nature of the bifurcation of the elements of the frame under consideration, depending on the load application coefficient: a) $\alpha = 1.1$; b) $\alpha = 1.0$; c) $\alpha = 0.8$; d) $\alpha = 0.6$.

From the graphs (Fig. 2) it can be seen that, before the onset of the negative properties of the soil of the base, the right pillar of the frame loses stability actively, involving the left bifurcation.

Let us determine the value of the critical deformation of the heaving $\Delta_k$, at which the type of bifurcation of the elements of the considered single-span frame changes, for various values of the load application coefficient $\alpha$. The specified critical deformation can be found by presenting the expression (1) in the form:

$$M_i \cdot Z_i = P_i \cdot \Delta_k.$$  \hspace{1cm} (4)

With the value of the coefficient of application of the load $\alpha = 1$, $\vartheta = 5,2175$, critical deformation $\Delta_k = 5,03 \cdot l$; at $\alpha = 1,1$, $\vartheta_1 = 5,2322$, $\vartheta_2 = 5,21; \Delta_k = 4,88 \cdot l$; at $\alpha = 0,8$, $\vartheta_1 = 5,2139$, $\vartheta_2 = 5,26, \Delta_k = 1,01 l$; at $\alpha = 0,6$, $\vartheta_1 = 5,604$, $\vartheta_2 = 5,71$, $\Delta_k = 2,24 \cdot l$. The results of the above calculation are presented graphically in the figures 3, 4.

Figure 3. Dependence of critical deformation of heaving $\Delta_k$ on the span and height of the frame under consideration for various values of the load application coefficient $\alpha$. 
It can be seen from the graph (Fig. 3) that the critical deformation of soil heaving $\Delta k$ increases linearly with increasing height and width of the frame.

![Graph showing the relationship between $\alpha$ and $l \cdot \Delta k$.]

**Figure 4.** Dependence of the product of critical deformation of the heaving $\Delta k$ by the width of the frame on the load application coefficient $\alpha$: 1 - experimental; 2 – theoretical.

After analyzing graph 4, we can conclude that the critical heaving deformation $\Delta k$ decreases with increasing load application coefficient $\alpha$ for $0.6 < \alpha < 0.8$ and $1.0 < \alpha < 1.1$, in the range $0.8 > \alpha > 1.0$, these parameters are directly proportional.

4. **The practical part**
A qualitative assessment of the analytical dependencies presented is performed in relation to the study of the effect of the heaving properties of the base soil on the stability of the experimental frames in the laboratory of Southwestern State University.

The sample test setup and general setup are shown in Fig. 5. Experimental frames with a cross-section of racks and crossbars 30x10 mm span of 1.5 m were tested for central compression by a specially developed method.
Figure 5. Scheme (a, c) and general view (b) of the test setup: 1 - distribution beam; 2 - extreme racks of the experimental frame; 3 - a crossbar of an experimental frame; 4 - stationary support beam; 5 - the central rack of the frame; 6 - supporting beam movable; 7 - lever installation; 8 - cargo.

The results of calculating the change in the critical critical strain $\Delta_k$ are presented in Fig. 4. Here, for comparison, experimental curves are given.

5. Conclusion
A technique is proposed for determining the critical deformation of soil heaving, in which there is a change in the type of bifurcation of both individual elements and the entire structural system as a whole. Based on the numerical analysis, we can conclude that this deformation increases linearly with increasing geometric dimensions of the frame.

Satisfactory agreement of the theoretical values of the critical force with the test data of the experimental frames with a centrally compressed strut confirm the reliability of the method used in the calculation.

6. References
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