Numerical methods for determining the stressed-deformed state of the electric transmission lines supports

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Abstract. The study examines the influence of the docking nodes reinforcement geometric, mechanical and structural parameters on the stress-strain state of the overhead power lines supports structure taking into account the supports concreted base interaction with the surrounding soil. The steel supports of the overhead power lines, which are thin-walled shell-rods of a closed profile, are modeled by the finite elements of the Tymoshenko-type shell. The concrete base of the support and the surrounding soil are sampled by three-dimensional finite elements of a continuous medium with the corresponding physical and mechanical properties. The influence of the kinematic conditions options for securing the support and taking into account the contact interaction of the concrete support and soil on the VAT design calculation is studied. A methodology for calculating the structures of steel supports and their docking catches was implemented as a part of the ANSYS 14.5 numerical simulation software package. Based on the proposed methodology, a computational experiment was conducted, during which the analysis of the stress-strain state of the overhead power transmission towers fixed in the ground for various types of the docking nodes reinforcement.

Introduction

When calculating the high-rise structures, which are steel rods-shells of a closed profile, the most difficult is to determine the stress-strain state (SSS) of such structures and their nodal joints. The modern literature describes various approaches to calculating the SSS in shell rods, based both on the complete discretization of the structure (for example, within the framework of the finite element method) [9], and on the private calculation methods for assessing the SSS of structures and their nodal joints [11, 18]. However, for the nodal joints’ calculation, especially in the case of their local reinforcement with stiffeners, “skirt”, etc., a finite element approach based on the shells’ finite elements of the Tymoshenko type with a rather high degree of design discretization will be more preferable.

Most often, the steel poles’ designs of the overhead power lines (PL), which are exposed to a wide class of external static and dynamic effects, are calculated [13, 21]. Usually the base of the support is concreted, and the concrete mass is placed in the ground. In some cases of calculating the support for strength and stiffness, it becomes necessary to take into account the concrete supports’ construction interaction with soil. In this case, the concrete base and the surrounding soil are modeled by three-dimensional finite elements of a continuous medium, and the special contact finite elements are used to describe their interaction.
1. The theoretical basis for calculating the overhead power lines’ steel support

A workable and adequate numerical model is proposed for the joint work of a steel support of the overhead power lines mounted in a concrete base and underlying soil on the basis of the finite-element approach to discretization of the structure.

The convergence of the numerical model will help to evaluate and derive some design characteristics, and will also make it possible to form more complex models of the support interaction mounted in concrete with soil for use in various operating conditions of structures. Many models of the three-dimensional structures’ deformable elements interaction and soil are known.

Some works of the authors in which, on the basis of finite element models, the processes of deformation of structures are realized within the framework of the structural elements’ contact interaction within each other and with the soil surrounding them [16–18] can be noted. There are limitations applied during the use of software systems for numerical simulation: ANSYS, Nastran, ABAQUS, Midas, LIRA-SAPR and others that affect the calculation results, so the model was generated in the ANSYS 14.5 program [19].

To simulate the steel support, a lower base pipe, a flange, reinforcing ribs, and a skirt, the ANSYS 14.5 uses four shell end elements of the Shell181 type with a linear approximation of displacements in terms of the element. As unknowns in each node, three components of the displacement vector in the Cartesian global coordinate system and three components of the rotation angles of the normal to the middle surface of the element are selected. Modeling the concrete block of the support base and a three-dimensional eight-node finite element of a continuous medium of type Solid185 with three unknown components of the displacement vector in each node was selected, and the faces of such an element are considered as the ruled surfaces. To take into account the contact interaction of the base concrete block and the soil mass, we used the “master-slave” contact interaction technique implemented in the ANSYS 14.5 numerical simulation complexes. To implement these complexes, we used two contact elements of the Target170 and Contact174 type, which make it possible to automatically take into account the possibility of contact interaction with friction.

2. The geometric and finite element model of the overhead power lines’ steel support

The telescopic support design is a complex box construction, including: a telescopic support in the form of a lateral surface of a truncated pyramid with bases in the form of a regular octagon; a lower tube coaxial to the telescopic support in the form of a side surface of a prism with bases in the form of a regular octagon; a rectangular flange connecting the telescopic support and the lower pipe; stiffeners at the base of the support, joining the support with a flange; stiffeners in the upper part of the lower pipe joining the pipe with a flange; the “skirt” at the base of the support, the elements of which close the lower part support surface, the corresponding stiffeners and the flange into the closed box-shaped blocks.

Figure 1 schematically shows the support elements’ projection in various combinations with its structural elements under the elements on a vertical plane, where $h_1 = 6.85$ m – is the distance from the top of the pipe to the upper edge of the pipe stiffeners, $h_2 = 0.15$ m – is the height of pipe stiffeners (total support height $h_1 + h_2 = 7.0$ m), $h_3 = 0.15$ m – is the height of support stiffeners, $h_4 = 0.30$ m – is the length of the lower part of the lower pipe not buried in the ground, $h_5 = 0.30$ m – is the length of the bottom part of the lower pipe buried in the ground.

The pipe itself was buried in the ground, about the concrete base of the support surrounding it. The quantities $h_4$ and $h_5$ varied during the calculation process, their sum remained unchanged.

The diameter of the circle into which the support top regular octagon was inscribed as $d_1 = 0.068$ m, diameter of the circle into which the support top regular octagon was inscribed as $d_2 = 0.150$ m, the diameter of the circle on which the stiffener points are located as far as possible from the support axis – $d_3 = 0.300$ m, the support wall thickness $t_1 = 0.003$ m, the flange thickness $r_2 = 0.02$ m, the thickness of the walls of the lower pipe, stiffeners and elements of the “skirt” ranged from $t_1 = 0.003$ m and higher.
Figure 1. The support elements’ projections on a vertical plane: a - telescopic support with a lower pipe; b - added flange; c - support stiffeners added; d - pipe stiffeners added; e - “skirt” added

For greater clarity, the geometric modeling of the telescopic support joint zone and the lower pipe in Figure 2 shows some fragments of this connection.

Figure 2. The fragments of the support joint zone and the lower pipe: a - general view of the support with the lower pipe; b - the lower part of the support with stiffeners and a flange; c - “skirt”; d - the lower part of the support with the upper part of the lower pipe and the support stiffeners; e - the lower part of the support with the upper part of the lower pipe and the support and pipe stiffeners

The base of the lower pipe part is concreted. Figure 3 shows a support with a concreted base and fragments of this concreting.
Figure 3. The support with concreted base and fragments: a - general view of the support with concreted base; b - a fragment of the lower part of the support with a concreted base; c - concrete support base

The concrete support base is a parallelepiped with dimensions $1.2 \times 1.2 \times 0.6$ m, where the height of this box is $h_4 + h_5$ (figure 1), the lower part of the concrete base may be buried in the ground, the upper - cannot.

The basic finite element mesh used in the calculations and its fragments are shown in Figure 4.

Figure 4. Finite-element partition of the support and concrete base: a - general view of the finite-element partition for basic discretization; b - a fragment of the finite element decomposition general form for basic discretization; c - discretization of the concreting area; d - a fragment of the general form of the finite element decomposition for the refined support discretization
3. Calculation options

In total, 4 calculation options were selected, which are schematically shown in Figure 5. All of them differ from each other by the choice of the calculation area and the conditions for fixing it.

For calculation option 1, only the support with a part of the lower pipe is modeled, the lower edge of the pipe is fixed along the lower edge of the ribs under the flange. For calculation option 2, the entire support is modeled with a concrete block at the base, fixing is done along the bottom face of the concrete block. For calculation option 3, a soil mass is introduced into the calculation region (the dimensions of which are selected during the computational experiment), the lower edge of the concrete base is attached to the front surface of the soil without tearing and slipping. For calculation option 4, the concrete base can be partially or fully buried in the ground, contact interaction conditions are introduced between the contacting surfaces of the concrete base and the ground.

![Figure 5. The finite-element partition of support and concrete base: a - general view of the finite-element partition for basic discretization; b - a fragment of the finite element decomposition general form for basic discretization; c - the concreting area discretization; d - a fragment of the finite element decomposition general form for refined support discretization](image)

For all the calculation options, static loading from its own weight, vertical and horizontal loads applied to the top of the support are considered.

4. The calculation results and their analysis

To illustrate the results obtained, Figures 6 and 7 show the distributions of the stress intensity according to Mises for the calculation variant from the action of its own weight and for calculation variant 2 from the action of horizontal load. The von Mises stress intensity is calculated by the formula:

\[
\sigma_v = \sqrt{\frac{1}{2} \left( (\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2 \right)}.
\]
Figure 6. The stress intensity distribution according to Mises in the support from its own weight for calculation option 1: a - there are no stiffeners of the support and the “skirt”, general view; b - there is no “skirt”, a general view; c - all amplifications available, general view; d - there are no stiffeners of the support and the “skirt”, fragment; e - there is no “skirt”, fragment; f - all amplifications available, fragment

Figure 7. The stress intensity distribution according to Mises in the support from the horizontal load for calculation option 2: a - there are no stiffeners of the support and “skirt”, general view; b - there is no "skirt", a general view; c - all amplifications available, general view; d - there are no stiffeners of the support and the "skirt", a fragment; e - no “skirt”, fragment; f - all amplifications available, fragment

For the case of mounting the support along the lower edge of the ribs under the flange (calculation option 1), the self-weight of the support causes a complex stress state in the area of the support, but the maximum stresses (according to Mises) do not exceed 0.5 MPa.
The presence of ribs and a “skirt” in the support attachment zone reduces the maximum stress by several percent and slightly increases the area of their location. The vertical load leads to the appearance of a maximum zone near the top of the support (per 100 kg - about 1.5 MPa).

The presence of ribs and “skirts” in the area of the support mounting practically do not affect the magnitude and location of maximum stresses. Horizontal load causes bending stress state in the support, maximum stresses - in the area of support mounting (per 100 kg - about 1.5 MPa). The presence of ribs and a “skirt” in the zone of the support fastening reduces the maximum stress by no more than 1-2%, but increases (almost by 1 meter) the area of their location.

For the case of mounting the support along the bottom of the concrete mass (calculation option 2), the stress distribution of all load types does not change compared to calculation option 1.

For the case of supporting a support lying on the ground without detaching and slipping (calculation option 3), the stress distribution of its own weight and vertical load does not change; for a horizontal load, the maximum stress value drops to 1.0% for sand and to 0.3% for clay.

For the case of contact interaction between the support and the soil (calculation option 4), the stress distribution of the dead weight and the vertical load does not change; for horizontal load, the maximum stress value drops to 3.0% for sand and to 1.0% for clay, but the results are highly dependent on the level and nature of the external load.

Figure 8 for one of the calculated cases shows a typical distribution of bending stresses along a generatrix along the support (starting from the top) for horizontal load for mounting options for the docking assembly of the support with a flange with and without a “skirt”.

Figure 8. A diagram of normal bending stresses (Pa) along the support: in red - with a “skirt”; in blue - without a “skirt”

It can be noted that the presence of a “skirt” in the support mounting unit not only slightly reduces the level of maximum stresses in the support, but also unloads the assembly itself.

Summary
In case of a sufficiently rigid and strong lower pipe and lower ribs, the soil can be ignored and fastening can be realized along the lower edge of the ribs below the flange. Taking into account the interaction of the support with the ground, especially contact interaction, somewhat reduces the level of stresses in the
support, but the results strongly depend on the level and nature of the external load. In some calculation options, ultimate tensile stresses may occur in concrete [21-23].

As a further development of the approach under consideration, it is possible to propose taking into account the plastic deformation of the soil with and without taking into account the contact interaction of the support with the soil. For the case of contact interaction (and physical nonlinearity of the soil), the application of the load is important at the stages of the support erection and its operation. For the same statically equivalent load, the results can be radically different [24-26].

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