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Centrifugal modeling of underground polymer pipes under temperature effect

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Abstract. Experimental study of underground polymer pipes under temperature effect is developed in this paper by the method of centrifugal modeling to study the process of polymer pipes elongation depending on the depth of laying and physical and mechanical properties of soil. The method is based on the use of centrifugal installation with PC and software. The experiments were carried out in a centrifuge with an effective radius of centrifuge rotation at a working scale of modeling $n = 40$. Experimental studies were carried out at various laying depths of the underground polymer pipes. In the process of conducting experiments, the polymer pipe model was subjected to various temperature influences. The temperature effect on the polymer pipe model was created using an electric spiral. As a result, it is established that the process of polymer pipes elongation over time under soil pressure and temperature factor has a non-linear character; the value of the absolute strain depending on the laying depth and the temperature factor may differ by several times.

1. Introduction

In the life support system for the population, the pipes made from various materials and of various configurations are widely used as water pipelines, gas pipelines, oil pipelines, for transportation of toxic and explosive substances in various industries and manufactures.

Pipelines are widely used in the cities, between the cities and populated localities and in the recent decades have been widely used between the countries. Therefore, pipelines are often called “life lines” and this shows, that pipelines play an important role in human life. Due to the enormous length and wide geographical distribution, the pipelines are located at different laying depths in complex ground conditions and under water, in cross profile areas with tectonic faults and in zones of different seismic intensity; they are exposed to great exploitative and seismic hazard. Due to the fact that pipelines play a significant role in country’s economy, much attention has been paid to their reliable operation, ensuring their seismic safety during the exploitation.

Pipes, as a conducting system, have a rather complex structure, consisting of the straight line and curved line areas, intersections nodes and fixing elements. Depending on the complexity of the pipeline system designs, considerable length and wide geographical location the pipelines are subject to various seismic hazards, such as destruction, soil liquefaction, wave propagation process, pipe-soil interaction, pipe displacement relative to soil, pipe separation from soil, etc.

To solve these problems, a regularity of strain was established. Many researchers from different countries have studied the issues of seismic effect on the pipelines stress state. Here we present some results of other researchers, close to the subject of the proposed study. As is known, earthquakes can pose a threat to the structure integrity of buried pipelines. As a result of constant soil strain around the pipeline in a quasistatic way, not necessarily associated with high seismic intensity, the earthquake aftermath can cause serious damage. Analysis of the effect of earthquakes showed, that the damage in linear steel pipelines was caused by permanent soil strain, such as fracture movements, landslides, lateral compression caused by soil

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strain; only a few pipelines were damaged as a result of wave propagation [1, 2]. For example, such pipelines were damaged during earthquakes in San Fernando [3], in Kobe [4], in Kojaeli [5] and in Chi-Chi [6].

Studies of the seismic stress state of buried pipelines are based on certain assumptions that allow simulating consideration process with some simplifications, the process requires further refinement. In the study of the stress state of underground pipelines under seismic effect, the main point is to simulate the process of the pipe interaction with surrounding soil. A seismic analysis of soil interaction with a pipe of finite length based on the Winkler model has been carried out and the approach is focused on account for axial strains, since bending strains in a buried pipe due to wave propagation have usually a second-order effect [7]. To solve the problems of the joint seismic vibrations of the underground pipeline and elastic soil, it is assumed that a slippage occurs at the boundary and the shear stresses arising on it are proportional to the relative displacement of soil and pipeline particles or their relative velocities of motion [8]. On the basis of the Hamilton-Ostrogradsky variational principle a system of equations was obtained and the stress state of the pipeline was studied, taking into account the displacement relative to the soil medium under arbitrary direction of seismic effect [9]. The problem of dynamic stability of underground pipelines of finite length, located in water-saturated soils [10] has been solved, the effect of geometric and mechanical characteristics of a pipeline on dynamic stability of the “soil-pipe” system has been revealed. The dependence of interaction coefficient of a polymer pipe with soil was experimentally determined using data obtained at longitudinal vibrations of underground polymer pipelines under seismic loads [11].

In recent years the effect of wave propagation on the buried pipeline with a curved axis and their interaction with soil was studied in several publications. Numerical analysis of underground pipeline seismic behavior at right angle of bending showed an increase in strain in a curved section with increasing radius of curvature [12]. Using the elastic model, the quasi-static problems of pipes response at right angle of bending to Rayleigh waves were solved and the effect of some basic parameters, such as the wavelength and soil strain was determined [13].

In [14], mechanical reaction of continuous (welded) underground steel pipelines, crossing active seismic faults was considered. These pipelines are subject to strains due to axial, shear and bending loads, and create high stresses and strains in critical places that can lead to a pipe breakage. The studies in [15] were based on modeling the “soil-pipeline” system using nonlinear finite elements, taking into account inelastic behavior of surrounding soil, the soil-pipe interaction and contact, the development of the large inelastic strains in steel pipeline, the distortion of the pipeline cross-section and possible local strain and internal pressure. At various soil parameters, both for cohesive and non-cohesive soils, the effect of the diameter-thickness ratio of the pipeline and the stress-strain of the steel material were studied.

In addition to the above numerical studies one can cite separate experimental studies for studying the stress state of buried polyethylene pipelines [16, 17, 18]. An experimental study was conducted on a centrifuge based on the modeling the pipeline response to a seismic discontinuity. During the tests the effect of the fault type, fault angle of displacement on mechanical behavior of the pipeline was studied, as well as the effect of the pipeline laying depth and diameter, the moisture content in soil.

In [19] the issue of the interaction effect on the stress-strain state of underground structures in the form of a rigid body with a base soil was studied. Viscoelastic characteristics of the bodies interaction were determined by theoretical and experimental studies and the graphs of viscoelastic characteristics interaction were plotted.

The results of experimental studies of physico-mechanical properties of the centrifuged and vibrated samples were given in [20]. The properties of inhomogeneity of a fresh concrete mix were evaluated to determine the changes in water-cement ratio, residual water content and density along the thickness of the centrifuged sample, as well as the changes in strength properties of hardened concrete. As a result, a numerical experiment to study the carrying capacity of the centrifuged supports of the power lines was conducted, taking into account the obtained dependence of the change in concrete strength along the wall thickness of the product.

In [21], an issue of temperature wave propagation along the wall of the hollow cylinder with an abrupt change in temperature of internal medium arising from the motion cessation or circulation of a heated flow was considered. An algorithm for calculating the temperature field by a numerical method was shown using an explicit finite-difference scheme of enhanced accuracy under cylindrical symmetry conditions, under boundary conditions of the first kind. The results of calculation of the temperature wave penetration depth were given by the considered algorithm depending on time passed after thermal effect.

The results of numerical solutions of underground and aboveground structures spatial problem taking into account the work of the surrounding infinite massif in homogeneous and inhomogeneous areas were given by a combined method [22−24].

In [25] the definition of rational parameters of the developed compensating device of the pipeline in a triangular form was given using the computational-experimental research methods. The coefficient of the compensating device form refinement was obtained by computational-experimental research methods, structurally performed using the curved pipe bends, to reduce longitudinal compressive force arising from temperature difference to the level of the overall stability of the pipeline in longitudinal direction.

An aspect of numerical simulation to assess the possibility of the centrifugal modeling of the solute substances in adsorptive, radionuclide and reactive solutions [26] was studied. As a result, it was shown that it is possible to conduct centrifugal experiments to evaluate physical processes or chemical reactions.

In the above scientific studies the actual problems of underground pipeline-soil interaction under temperature effects have not been experimentally studied. So, the study of underground pipeline-soil interaction using the method of the centrifugal modeling is of great scientific and practical interest.

2. Methods

2.1. The methods to conduct experimental studies

Conducting field experiments to study the stress-strain state of pipelines and determine the parameters of pipeline interaction with surrounding soil requires large capital expenditures and a long period of time. Besides, creating dynamic and static loads identical in each series of experiments is extremely difficult [27]. These difficulties in experimental studies can be overcome if to proceed to model experiments, in particular, to use the method of centrifugal modeling − one of the most progressive experimental modeling methods [28]. In the most complex cases, which are beyond the approximate mathematical modeling and to check the results of calculations and design, experimental modeling is used, in which centrifugal modeling is practically the only procedure that could predict the state of the system over time [29].

Currently, the centrifugal modeling method is widely used in various fields of science and technology. Centrifugal modeling as a method is rapidly developing in the world; the importance of the method in construction has increased significantly; extensive material has been accumulated that is directly related to the solution of actual practical problems [30, 31].

Modeling is a tool to study the state of objects and the processes occurring in them. In physical modeling, the system under study (a full-scale structure) is reproduced using an equivalent system (model of the structures, as a rule, having a smaller size). At the same time, natural processes are reproduced in the model in such a way as to obtain the necessary information in the most reliable, simple, quick and cheap way, and in some cases even more completely than when observed on a full-scale object or by calculation.

However, at ordinary physical modeling of earth structures, the nonlinear relationship between stresses and strains distorts the entire picture of the stress state of the model compared to a full-scale object, the strength in a small model increases. In this case, as a rule, only qualitative information about the object can be most easily obtained. In order to achieve complete similarity between the model and the structure (to ensure equality of stresses and strength and proportionality of strains) and to obtain the necessary quantitative information about the object, it is necessary to increase the weight per unit volume of the model material.

Only one method opens up this possibility − the method of centrifugal modeling, which is qualitatively different from other methods of physical modeling. The qualitative and fundamental difference of the centrifugal modeling method is as follows:

- in centrifugal modeling, the material of full-scale objects is used in models;
- the model is placed in the field of centrifugal forces (similar to the gravitational field), which increases the weight of a unit volume of the model material;
- in a model located in the field of centrifugal forces, a stress state is created which is identical to the one in a full-scale object.

All this ensures the complete preservation of the physical nature of phenomena and processes under study. Compared with the natural conditions, only the time scale of their occurrence changes; this makes the centrifugal modeling method progressive and most effective. Using this method, it is possible to make significant additions to the calculations, in many cases to get more accurate results; in some cases this method allows researchers to solve such complex and not studied until now issues that so far are beyond research either by analytical (calculated) way or by field observations.

Principal relationships. The centrifugal force field (used as a force field, similar to a gravitational one) created by the centrifugal machine has n times greater intensity; here n is the linear scale of modeling

$$n = \sqrt{\frac{\omega^2 R_{ef}}{g} + 1}, \tag{1}$$

where ω is the angular velocity of the centrifuge; R_{ef} is the effective radius of rotation; g is the gravitational acceleration.

The model of the structure is placed in the field of centrifugal forces, so far from the axis of rotation and the intensity of the centrifugal field is taken so significant that the influence of gravitational forces that distort the field of forces in modeling can be neglected.

The main point of the method can be understood from the following simple example. When modeling static stresses under structure own weight, it is necessary to satisfy the condition

$$\gamma H = idem, \tag{2}$$

where γ is the weight per unit volume of material (soil); H is the thickness of the soil layer.

For the natural conditions (full-scale conditions)

$$\gamma_n = m_v g, \tag{3}$$

where γ_n is the force acting per unit volume of material (soil) in the gravitational field, m_v is the mass of a substance per unit volume.

The acceleration can be changed by causing inertial forces in the system (model) under consideration, for which the system must be subjected to some acceleration i. Then the total acceleration vector of the model is:

$$a_m = g + i \tag{4}$$

and

$$\gamma_m = m_v a_m \tag{5}$$

where, γ_m is the force acting on a unit volume of this material (soil) in the model in total force field of inertia and gravity.

If the model is done n times less than a full-scale structure, then according to (2) the equality of stresses is expressed by

$$\gamma_n H = \gamma_m \frac{H}{n} \tag{6}$$

or

$$\gamma_m = \gamma_n n \tag{7}$$

Substituting (3) and (5) in (7), we get

$$m_v a_m = n m_v g, \;\; a_m = gn \tag{8}$$

that is, the basic rule of centrifugal modeling under considered conditions is that the model is affected by volume forces that exceed the force of gravity as many times as the model is smaller than the actual structure [29].

With this method of modeling, the quantitative characteristics of the phenomena and processes observed in the model are directly transferred to the natural conditions through appropriate scale factors, in particular:

$$\begin{gathered} \ell_n = n\ell_m;\; S_n = n^2 S_m;\; V_n = n^3 V_m;\; P_n = n^2 P_m;\; \sigma_n = \sigma_m;\; \gamma_n = \frac{1}{n}\gamma_m; \\ T_n = T_m;\; t_n = nt_m;\; \left(t_n = n^2 t_m\right), \end{gathered} \tag{9}$$

where ℓ is the length; S is the area; V is the volume; P is the force; σ is the stress; γ is the volume weight; T is the temperature; t is time; n, m are the indices corresponding to the full-scale structure and the model.

In case of modeling the motion of mechanical system, time t in centrifugal modeling will be n times less than in natural conditions, while in modeling the processes with viscous strains it will be n^2 times less. Varying the speed of rotation of the centrifuge, according to (2) the desired simulation scale can be selected. An account of all possible errors associated with the measurement accuracy and with the accuracy of the gravitational field modeling is given in [30–32].

Currently, the use of polymer pipes to convey various media (water, gas, oil, etc.) is growing rapidly. This is due to the advantages of the pipes made of polymer materials as compared to metal pipelines. Therefore, studies of the polymer pipe behavior under various static and dynamic loads are relevant. With this in mind, we have investigated the effect of the temperature factor on the stability of polymer pipes laid in the ground at various depths.

The proposed experimental research technique can be used to study the behavior of underground pipelines made of various materials, taking into account their geometric parameters and soil conditions under temperature effect.

2.2. Experimental studies

Experimental studies of polymer pipes under temperature effect have been carried out on a modernized centrifugal installation of the Institute of Mechanics and Seismic Stability of Structures of the Academy of Sciences of the Republic of Uzbekistan. The existing measuring complex based on the light-beam oscillographs was replaced by a new recording system “sensor + amplifier + analogous digital converter + personal computer + software”. The created program of sensor signals registration allowed us to avoid the use of photographic paper and chemical processing, to significantly reduce the processing time and to observe the experiment in real time on the computer monitor. The results of instrumental measurements in numerical and graphical form are given immediately after the end of the experiment. The data obtained during the experiment are saved as files and can be reused later.

A four-channel measuring complex was used to conduct model experiments on a centrifugal unit. Three measuring channels were intended for recording signals from strain gauges installed on the object under study and one channel for recording the centrifuge speed using an optical sensor.

It should be noted that in recent decades, the use of polymer pipes for transporting various media (water, gas, oil, etc.) has increased rapidly. This is due to the advantages of the pipes made from polymeric materials when compared to metal pipelines. Therefore, the studies of the behavior of polymer pipes under various static and dynamic loads are relevant.

With this in mind we have investigated the effects of the temperature factor on the strain in polymer pipes embedded in ground at different depths. The experiments have been carried out in a centrifuge with an effective radius of rotation R_{ef} = 1.75 m, with a working scale of modeling n = 40 (Fig. 1). Experiments have been carried out using the carriage 1 (Fig. 2, a) with dimensions: working section length – 35.2 cm; working section width − 23.8 cm; working section height – 30.0 cm.

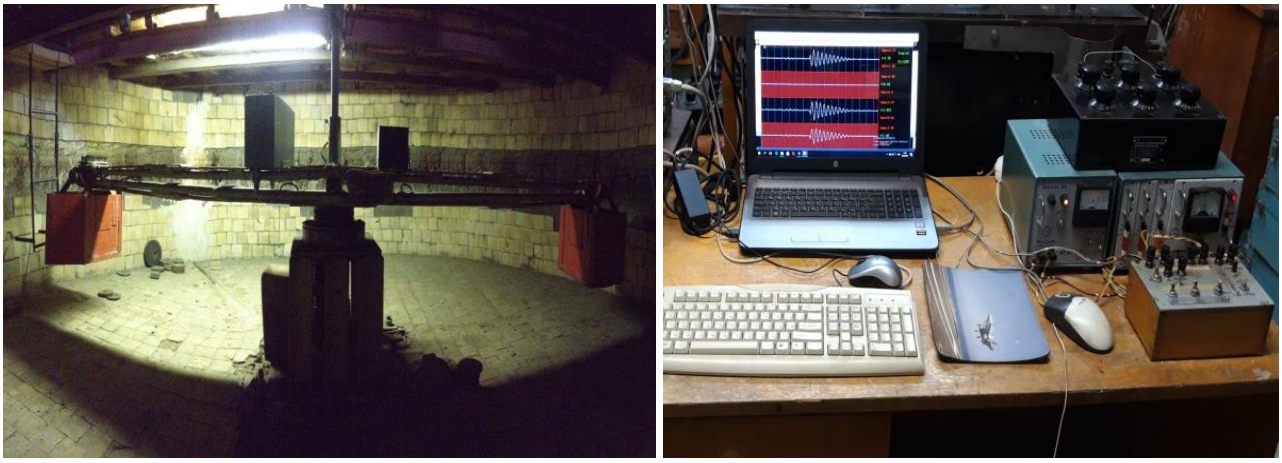

Figure 1. General view of a centrifugal installation with a measuring complex.

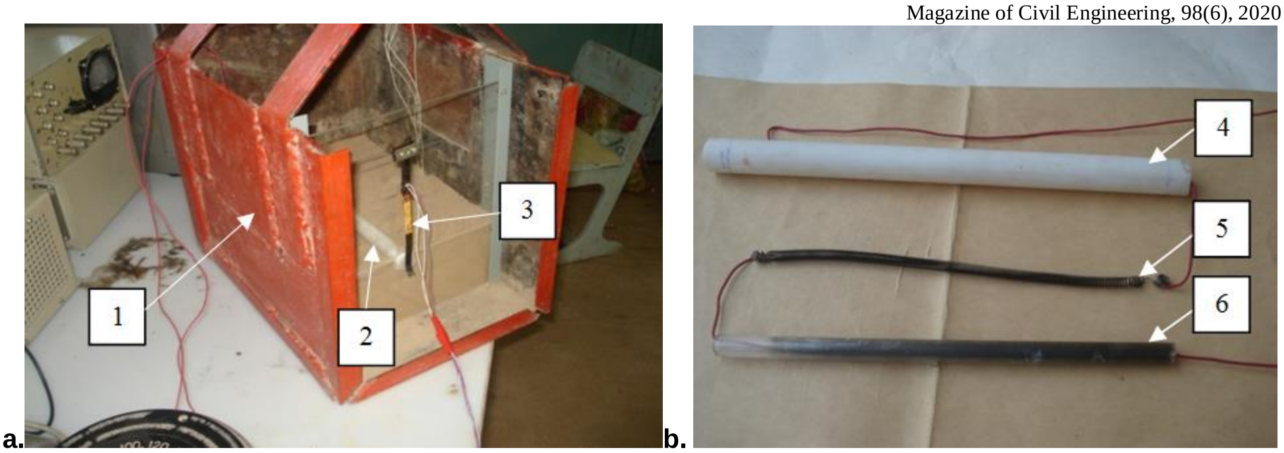

Figure 2. (a) – a carriage with a tube model located on an earth base: 1 – a centrifuge carriage; 2 – a tube model; 3 – a displacement sensor. (b) – a tube model with heating system: 4 – a tube model; 5 – a spiral, 6 – a quartz tube

A polymer tube 4 (Fig. 2, b) was used as an experimental sample (tube model P4004T) with the following geometrical dimensions: total tube length l_m = 28.2 cm, outer diameter of the tube d_{1m} = 2.2 cm, internal diameter of the tube d_{2m} = 1.5 cm, tube wall thickness Δ_m = 0.35 cm, working section length of the tube l_m = 26.3 cm.

Accordingly, the geometrical dimensions in full-scale conditions are: the total length of the pipe l_n = 11.28 m, the outer diameter of the pipe d_{1n} = 0.88 m, the internal diameter of the pipe d_{2n} = 0.60 m, the wall thickness of the pipe Δ_n = 0.14 m, the working section length l_n = 10.52 m.

Characteristic features of the sample material of polymer pipeline of P4004T brand are as follows: density 9.41–1.53 kN/m^3, tensile yield strength 23000 kN/m^2 and elongation of 250 %.

To carry out the experiments, a quartz tube 6 (Fig. 2, b) was placed inside a model made of a polymer tube to isolate and uniformly distribute the temperature along the contour. Inside the quartz tube, a spiral 5 was placed (Fig. 2, b), which heated up the system to the desired temperature, the value of which was controlled by the LATR autotransformer.

To determine the laws of temperature change under different heating conditions, preliminary an experiment has been conducted with a tube located on soil surface. A loamy soil of disturbed structure with a volume weight of γ = 14.5 kN/m^3 and moisture-content W = 9 % was chosen as the soil sample. One end of the tube model was rigidly fixed, and the other end could move freely along the tube axis. The displacements of the free end of the tube model ΔZ have been recorded using a strain gauge, calibrated in advance. When voltage was applied to the electric coil, the model of the tube heated up and lengthened, and the change in tube temperature ΔT has been determined from the relation:

$$\Delta Z_n = \alpha \cdot \Delta T \cdot Z, \tag{10}$$

where ΔZ is the elongation of the tube determined from the calibration data, Z is the tube length at room temperature, α is the coefficient of temperature expansion of the tube material α = 1.5 × 10^{-4} 1/deg.

Having determined the law of temperature variation over time, the experiments then have been carried out to determine the displacements of a model of an underground hot-water system made of polymer pipes at different depths of embedment in soil. So, in a compacted soil, by centrifuging for 30 minutes (which in nature conditions corresponds to 33 days), a foundation was built up on which the model of tube 2 was bedded (Fig. 2, a), and then it was filled up with soil. One end of the tube was fixed rigidly in the centrifuge carriage a specially made strain gauge sensor 3 was installed at the second free end to measure the tube displacements relative to soil at various temperatures.

At the level of the upper part of the pipe model, a sensor was installed to measure the soil pressure on the pipe. Before heating the tube, the filling was compacted by rotating the centrifuge for 25-30 minutes.

The values of displacements of the model of underground hot-water system under temperature changes depending on the voltage on the heating element have been determined by the readings of the computer based on the calibration data. The depth of laying the model pipe in the experiments was changed from 3.0 to 9.0 cm, which in full-scale conditions corresponds to the depth of laying from 1.2 to 3.6 meters. According to the results of the experiments and analysis of the data obtained, graphs of changes in the tube elongation were constructed for different heating modes and depths.

3. Results and Discussion

Fig. 3 shows the dependences of polymer tube elongations over time after stabilization of the centrifuge rotation at different depths and voltage variations on the heater.

Fig. 3 (a) shows the dependences of the tube elongation over time when the centrifuge is rotated within 20-25 minutes: curves 1, 3, 5 correspond to the elongations of the tube lying on the soil surface; curves 2, 4, 6 correspond to tube elongation located at a depth of H_m = 3 cm. Curves (1, 2), (3, 4), (5, 6) are obtained when the tube is heated, caused by a change in voltage on the heater at 15 V, 10 V, 5 V, respectively.

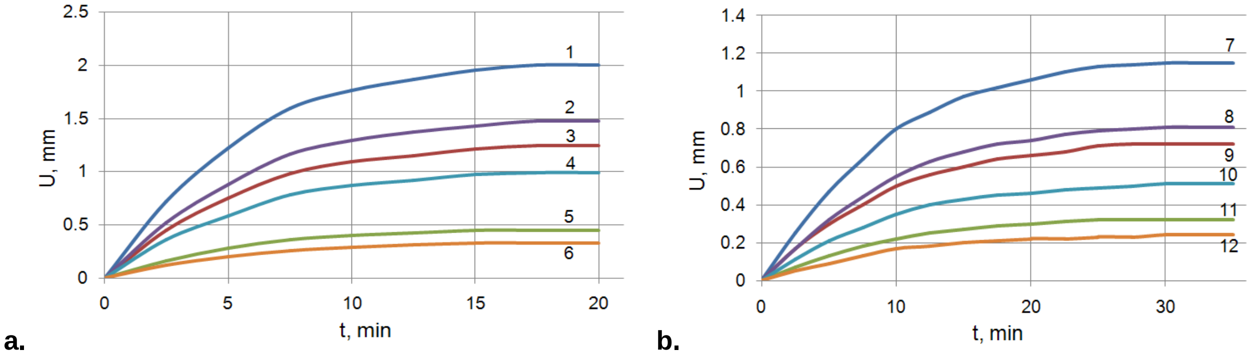

Figure 3. The dependence of polymer tube elongations over time on the voltage change in the heater at different depths.

Fig. 3 (b) shows the dependences of the tube elongation over time, located at the depth H_m = 6 cm (curves 7, 9, 11) and H_m = 9 cm (curves 8, 10, 12), caused by a voltage change on the heater. Curves (7, 8), (9, 10), (11, 12) are obtained by rotating the centrifuge for 30-35 minutes at the voltage of the heater 15 V, 10 V, 5 V respectively.

The instrumental data obtained show that the tube elongates with the temperature increase, and the tube deformation at the beginning of its heating process for 15-20 minutes is non-linear; then at constant temperatures, the tube displacements reach the maximum values and remain constant. The elongation of the tube lying on the soil surface differs significantly from the one of the embedded tube, depending on the depth. In general, with an increase in the depth of the tube, its elongation decreases markedly depending on the temperature acting on it.

Fig. 4 shows the change in soil pressure depending on the depth of the tube embedment at centrifuge rotation for 25-30 minutes. As seen from the figure, at the beginning of centrifuge rotation the soil pressure on the tube increases almost in direct proportion. During the first minutes, when the centrifuge begins its rotation, the pressure increases minimally. After 4 minutes of acceleration and stabilization of the rotational speed of the centrifuge, the pressure in soil is increasing for about 13 minutes; this is associated with soil compaction. The experiment shows an increase in soil pressure on the structure and its tendency to its asymptotic value depending on the duration of the centrifugal forces.

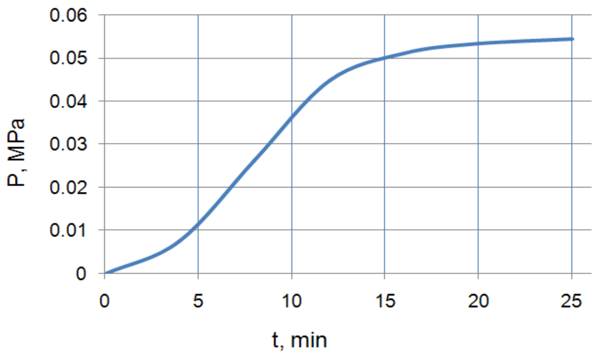

Figure 4. Pressure changes in soil depending on the tube depth.

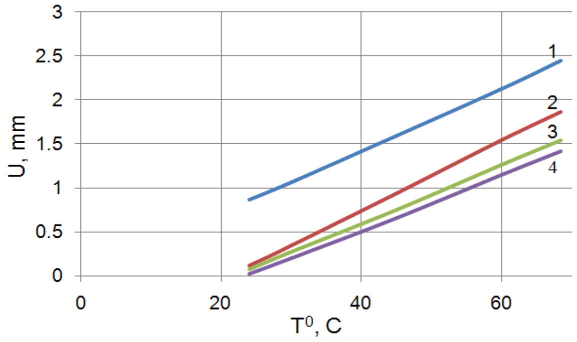

Figure 5. Dependence of tube elongation on temperature at different depths:
1 – free location; 2 − H_m = 3.0 cm;
3 – H_m = 6.0 cm; 4 − H_m = 9.0 cm.

Fig. 5 shows the dependences of the tube model elongation on temperature at different depths of its embedment: 1 − at free location on the soil surface; 2, 3, and 4 − at depths of embedment H_m = 3.0 cm,

H_m = 6.0 cm and H_m = 9.0 cm respectively, which in nature laying depth corresponds to H_n = 1.2 m, H_n = 2.4 m и H_n = 3.6 m.

At constant value of the tube depth its elongation increases with an increase in temperature, and at constant values of temperature with an increase in soil pressure, the elongation of the tube decreases depending on its depth.

4. Conclusion

As a result of the present work, the following conclusions can be outlined:

1. With an increase in the depth of the polymer tube at the same temperature, the tube elongation decreases markedly. At a constant temperature T = 60^0 C, the tube displacement in a free state is at H_m = 0 cm, U_m = 2.1 mm; at H_m = 3.0 cm, U_m = 1.6 mm; at H_m = 6.0 cm, U_m = 1.35 mm; and at H_m = 9.0 cm, U_m = 1.2 mm, which as a percentage is 76 %, 64 % and 57 % of the free state of tube displacement.

2. With an increase in the temperature effect at the same depth, the tube elongation increases. At a constant depth of tube embedment N_m = 6.0 cm, at an increase in temperature from T = 30 °C to 60 °C, the tube elongation increases from 0.26 mm to 1.3 mm.

3. With an increase in depth the values of soil pressure on the tube increase, tending to a certain asymptote.

4. The developed measuring system to record experimental data using a computer as a recording device made it possible to observe the experiment in real time and store the data obtained from the sensors in files.

5. The results obtained can be used in calculation and design of underground polymer pipelines for earthquake resistance.

6. In the future, the authors will conduct extensive research on this topic with various samples of polymer pipelines under various ground and temperature conditions.

7. At the moment, in scientific literature there are no results of experimental studies on underground polymer pipelines using the centrifugal modeling method. Therefore, the research results are not compared with the results of other scientific studies.

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