Numeric Simulation of Subsidence of Loess Soil under Wetting in a Limited Area

Khusanov Bakhtiyar[1,*], Rikhsieva Barno[1]

[1] Department of Dynamics of Grounds Structures, Institute of Mechanics and Seismic Stability of Structures named after M.T. Urazbaev, AS RUz,Tashkent, Uzbekistan

ARTICLE INFO

ABSTRACT

Loess and loess-like soils, when exposed to water, lose their strength characteristics, and physical and mechanical properties and change their original structure. The stress-strain state is transformed in these soils when wetted. Therefore, the problem of building on loess soils and studying the mechanisms of subsidence of loess soils is relevant. In this article, we consider the problem of determining the subsidence and stress state of the loess soil stratum under its own weight on a limited wetted area. To determine the distribution of water in soil, the method of changing stationary states is used, and to determine the subsidence and stress state, the finite difference method is used. The initial conditions are obtained by solving problems for the natural wetting of the layers of loess soil. The numerical results obtained of the subsidence of the free surface of the layer of loess soil 40 m thick agree well with experimental data on the duration of wetting at a limited size of the source of water. The effect of the duration and moisture content on the process of subsidence and transformation of the stress state are determined. An increase in the size of the water source in soil led to an increase in the high moisture content of the area and an increase in the subsidence of the free surface of loess soil.

1. Introduction

A certain class of soils in nature is structurally unstable. One of the most common structurally unstable soils in Uzbekistan is loess soil. Loess soils, when exposed to water, significantly lose their strength characteristics, physical and mechanical properties, and change their original structure [1-9]. These changes in soil are referred to as subsidence. The subsidence is the strain large in size and non-uniform, accompanied by a decrease in the wetted volume of soil and a significant change in their physical and mechanical parameters. Consequently, in these soils, the stress-strain state (SSS) is transformed when wetted. Naturally, the construction of buildings and structures on such soils needs special requirements. The feature lies in the fact that at a high moisture content of soil, the foundation of the structure's sags, and the structure loses its stability or may become unsuitable for

* *Corresponding author.*
E-mail address: khusanov@mail.ru

further operation. If we take into account that the cost of repair and restoration can be up to 40% of the cost of construction, then the problem of construction on loess soils and the study of the mechanisms of subsidence of loess soils become of particular relevance.

Studies given in [1-6,10-18] have made a great contribution to the development of construction on loess soils. These studies are mainly experimental and theoretical in nature, revealing the physical essence of the mechanism of the phenomenon of subsidence and its behavior. Recently, in the field of construction on structurally unstable soils and in the study of the mechanical properties of loess soils, rich experience and vast experimental material have been accumulated [10-23]. Despite a certain success in the field of foundation engineering on these soils, the calculation models of soil settlements have not been developed and the possibility of a reliable description of the stress-strain state of these soils by methods of continuum mechanics has not been stated. The calculation methods currently used in the theory of subsidence, based on the so-called semi-empirical theories, are not universal [3-4,10]. Determinant values for the study of the processes of subsidence are the results of a direct experiment. They serve as the starting point for creating design schemes and criteria for their suitability at the final stage of the study.

According to [4] and from the results obtained in [12-18], it follows that there is not even a rigorous formulation of this problem, the solution to which is necessary to form a special section in soil mechanics with the involvement of the mathematical apparatus of mechanics of a continuous deformable medium. The existing methods for calculating the stress-strain state of loess soil massif are based on the principle of linear deformability, based on the theory of elasticity and creep [3-6,24-26].

According to the results of experimental studies [3-4], it was revealed that the process of increment of subsidence deformation of loess soils under constant load and with increasing moisture content is similar to the deformation of a continuous medium subjected to temperature effects. With this assumption, a theory of thermal-moisture analogy (moisture elasticity) was developed by Ter-Martirosyan Z.G. to study the stress-strain state of wetted soils. In accordance with the theory of thermal-moisture analogy, wetting has a dual and simultaneous effect on soil: first, it weakens its structure; and, second, it changes the stress state of the massif, which is the main cause of deformation and subsidence. In practice, there is often a problem of determining the stress-strain state and subsidence of loess soils under increasing compaction load. Sometimes subsidence develops significantly even with minor changes in moisture content. In these cases, there is no mechanical analogy between the deformation of soils as a function of moisture content and the deformation of a continuous medium as a function of temperature, and the theory of thermal-moisture analogy does not quite correspond to the behavior of soils.

The transformation of the stress-strain state under wetting leads to a change in the structural strength of soils [1-2,4,26-28]. The reasons for the structure destruction of loess soils when moistened under load [4] are the non-water resistance of colloidal and cementation bonds of loess soils. Naturally, under the action of water, the structural bonds between the solid mineral particles of soil begin to weaken as a result of the dissolution of mineral salts in water, and the solid skeleton of soil begins to "break down". Obviously, there is a significant difference between the destruction of the soil structure under the action of loads at large strains and the "destruction" of the soil structure under wetting. If the structural failure of soils under strain is a purely mechanical process, then the structural "destruction" under the action of moisture is most likely a physical and chemical process. However, in both cases, the soil structure changes, therefore, the mechanical characteristics change as well, and the strength properties decrease. Therefore, in the case of structural destruction of soil (under loads exceeding the elastic limit, or at significant moisture content), the theory of moisture elasticity becomes unacceptable.

Structural destruction of soils leads to a change in the mechanical properties of soils. Changes in the physical and mechanical characteristics of loess soils depending on moisture content were experimentally studied in [3-4,10-15,29-37]. According to the results of experiments [4], deformation patterns of loess soils considering the change in moisture content were proposed in [28,38] and applied in [38-40]. Of particular interest are studies of subsidence and the stress-strain state of subsiding loess soils, which have a limited area of the source of wetting (channels, long pits, etc.) in the initial stages of their operation. This study is devoted to numerical modeling of the subsidence of the loess soil stratum with a limited wetting area. Determination of subsidence and stress-strain state of loess soils in theoretical calculations by solving a boundary value problem is a novelty of this work.

2. Statement of the Problem

Let us consider a plane problem of determining the SSS and subsidence of loess soil, which has a limited area of wetting and is in the field of its own forces. Suppose that on the upper surface of the loess soil half-plane, there is an area of water-wetted section 2b wide (Figure 1). Then, the moisture distribution in soil is determined from the solution of a two-dimensional equation on the moisture distribution over the thickness of the loess soil with certain initial and boundary conditions.
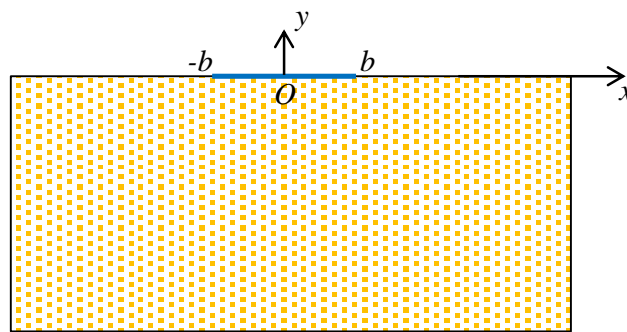

Fig. 1. Calculation scheme

The water distribution in loess soil is determined by solving the following equation [4,40]

$$\frac{\partial W}{\partial t} = \theta_w(t) \cdot \left(\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial y^2} \right) \tag{1}$$

where W is the moisture content (water-saturation) of soil; $\theta_w(t)$ is the coefficient of moisture conductivity of soil and its dimension is $L^2 T^{-1}$, x and y are the horizontal and vertical coordinates of the soil sections, respectively. According to the statement of the problem shown in Figure 1, the initial and boundary conditions are taken in the following form:

initial conditions

$$W(x,y,0) = W_0 \quad \text{at} \quad t = 0; \tag{2}$$

boundary conditions

$$W(x,y,t)=\begin{cases} W_{sat}, & y=0,\ x\in\left[-b;b\right]; \\ W_0, & \text{with other boundaries}, \end{cases} \tag{3}$$

where $y=0$, $x\in\left[-b;b\right]$ is the area of soil saturated with water; W_0 is the natural moisture content of soil; W_{sat} is the moisture content corresponding to the total water saturation of soil. Naturally, Eq. (1) with initial Eq. (2) and boundary Eq. (3) conditions is solved together with the equations that describe the process of loess soil subsidence.

The equations of "motion" (balance) of loess soil in the process of subsidence have the following form [40]

$$\rho\frac{d^2u_x}{dt^2}=\frac{\partial\sigma_{xx}}{\partial x}+\frac{\partial\sigma_{xy}}{\partial y}, \quad \rho\frac{d^2u_y}{dt^2}=\frac{\partial\sigma_{yx}}{\partial x}+\frac{\partial\sigma_{yy}}{\partial y}-\rho g. \tag{4}$$

Here ρ is the soil density, u_x, u_y are the displacement vector components, $\sigma_{xx},\sigma_{xy}=\sigma_{yx},\sigma_{yy}$ are the stress tensor components, g is the gravitational acceleration.

The equation of state of soil, taking into account the degree of moisture content, is taken as [28]

$$\frac{dP}{dt}=K_{sat}\exp(\alpha_K(1-I_W))\frac{d\theta}{dt}; \tag{5}$$

$$\begin{aligned} \frac{dS_{xx}}{dt}+\lambda_0 S_{xx}&=2G_{sat}\exp(\alpha_G(1-I_W))\left(\frac{d\varepsilon_{xx}}{dt}-\frac{d\theta}{dt}\right),\\ \frac{dS_{yy}}{dt}+\lambda_0 S_{yy}&=2G_{sat}\exp(\alpha_G(1-I_W))\left(\frac{d\varepsilon_{yy}}{dt}-\frac{d\theta}{dt}\right),\\ \frac{dS_{zz}}{dt}+\lambda_0 S_{zz}&=2G_{sat}\exp(\alpha_G(1-I_W))\left(0-\frac{d\theta}{dt}\right),\\ \frac{d\sigma_{xy}}{dt}+\lambda_0\sigma_{xy}&=G_{sat}\exp(\alpha_G(1-I_W))\frac{d\varepsilon_{xy}}{dt} \end{aligned} \tag{6}$$

for the case of plastic flow [28]

$$J_2=F^2/3, \quad J_2=\left(S_{xx}^2+S_{yy}^2+S_{zz}^2+2\sigma_{xy}^2\right)/2, \tag{7}$$

$$F(P,I_W)=c(I_W)+\mu(I_W)P, \tag{8}$$

where

$$K(I_W)=K_{sat}\exp(\alpha_K(1-I_W)), \quad G(I_W)=G_{sat}\exp(\alpha_G(1-I_W)), \tag{9}$$

$$c(I_W)=c_{sat}\exp(\beta(1-I_W)), \quad \mu(I_W)=\mu_{sat}\exp(\gamma(1-I_W)), \tag{10}$$

where P and θ - are the volumetric stress and strain; $S_{xx} = \sigma_{xx} - P$, $S_{yy} = \sigma_{yy} - P$, $S_{zz} = \sigma_{zz} - P$ are the components of stress deviator; $K_{sat}, G_{sat}\, c_{sat}, \mu_{sat}$ are the moduli of volumetric compression and shear, the cohesion force and the coefficient of the angle of internal friction of totally saturated soil, respectively; α_K, α_G, β and γ are empirical dimensionless coefficients characterizing the degree of change in the corresponding mechanical characteristics of loess soil; $I_W = W/W_{sat}$ is the parameter characterizing the degree of soil moisture content; F is the yield strength (plasticity function) of soil; for plastic flow, when relation Eq. (7) is satisfied

$$\lambda_0 = \left(2G_{sat}\exp(\alpha_G(1-I_W))\cdot\Omega - dJ_2/dt\right)/(2J_2),$$

$$\Omega = S_{xx}\frac{d\varepsilon_{xx}}{dt} + S_{yy}\frac{d\varepsilon_{yy}}{dt} + S_{zz}\frac{d\varepsilon_{zz}}{dt} + 2\sigma_{xy}\frac{d\varepsilon_{xy}}{dt},$$
(11)

if conditions Eq. (7) are not satisfied, then $\lambda_0 \equiv 0$; $\varepsilon_{xx}, \varepsilon_{xy}, \varepsilon_{yy}$ are the components of the strain.

The connection between strain and displacement is realized through their increments by the following relationships

$$\frac{d\varepsilon_{xx}}{dt} = \frac{\partial}{\partial x}\left(\frac{du_x}{dt}\right), \quad \frac{d\varepsilon_{yy}}{dt} = \frac{\partial}{\partial y}\left(\frac{du_y}{dt}\right), \quad \frac{d\varepsilon_{xy}}{dt} = \frac{1}{2}\left\{\frac{\partial}{\partial x}\left(\frac{du_y}{dt}\right) + \frac{\partial}{\partial y}\left(\frac{du_x}{dt}\right)\right\}.$$
(12)

For the system of Eq. (4), Eq. (5), Eq. (6) and Eq. (12) to be closed, we add the continuity equation in the following form

$$\frac{d\rho}{dt} + \rho\left\{\frac{\partial}{\partial x}\left(\frac{du_x}{dt}\right) + \frac{\partial}{\partial y}\left(\frac{du_y}{dt}\right)\right\} = 0$$
(13)

The initial conditions for this system are assumed the stress state that satisfies the static equation for the equilibrium of loess soil of natural moisture content. For boundary conditions, $y = 0$, $x \in (-\infty; +\infty)$ stresses (normal and shear ones) are considered to be absent.

Thus, the problem of determining the subsidence and the stress-strain state of the loess soil is reduced to the coupled solution to the reduced systems of equations with the corresponding initial and boundary conditions.

3. Method for Solving the Problem

The problem posed is solved numerically. The use of the step method in calculation requires a huge amount of computer time even with modern computers. Therefore, we will try to solve the problem posed by the modified method of changing stationary states both for Eq. (1), Eq. (4), Eq. (5), Eq. (6), Eq. (12) and Eq. (13). This approach is considered the most optimal because the moisture transfer rate is much slower than the velocity of soil excitation.

Let us first consider the process of the loess soil wetting. Even for such a "simple" equation Eq. (1), the exact solution under conditions that reflect the physical pattern of the phenomenon is extremely difficult. By introducing the dependent variable, equation Eq. (1)

$$\tau = \int_0^t \theta_w(t)dt \tag{14}$$

can be reduced to

$$\frac{\partial W}{\partial \tau} = \frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial y^2} \;. \tag{15}$$

The solution of Eq. (15) can be constructed based on the Fourier or Green methods [41-43]. To solve the problem, we proceed from an approximate nature of the phenomenon. First, we reduce this problem to a stationary one, assuming that at each fixed point in time the motion is steady, and the boundaries of the filtration region, relative to which certain assumptions are made, are displaced. The possibility of such an approach is based on the fact that the change in soil moisture in time is much slower than in space. This concept forms the basis of the well-known method of sequential change of stationary states, widely used in solving non-stationary filtration problems [44,45].

Thus, the interpretation of unsteady process as a set of instantaneous steady-state processes makes it possible to replace the parabolic Eq. (15) with an elliptic one

$$\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial y^2} = 0 \;. \tag{16}$$

In this case, Eq. (16) with initial and boundary conditions, Eq. (2) and Eq. (3) become the Dirichlet problem. The solution of this equation for a half-plane can be represented in the following form [4,41]

$$W(x,y) = \frac{1}{\pi} \int_{-b}^{b} \frac{W_{sat}y}{(x-\xi)^2 + y^2} d\xi. \tag{17}$$

Expanding the integral, we get

$$W(x,y) = \frac{W_{sat}}{\pi}\left(\text{arctg}\frac{b-x}{y} + \text{arctg}\frac{b+x}{y} \right). \tag{18}$$

Expression Eq. (18) gives a pattern of water distribution in soil when the source of water is located on the horizontal section $[-b; +b]$ of the half-plane boundary. Eq. (18) can be represented as

$$x = \pm\sqrt{b^2 - 2byctgm\pi - y^2} \;. \tag{19}$$

where $m = 1 - I_w$. Eq. (19) defines a curve of equal wetting. If the water is equated to the natural moisture content of soil, *i.e.,* $m_0 = 1 - W_0/W_{sat}$, then it will determine the wetting front. We note that these results are in good agreement with results of numerous field experiments [4].

Having the characteristics of a steady-state distribution of moisture content in soil, we proceed to the consideration of unsteady distribution of moisture content based on the method of changing stationary states. Let us assume that in the region lying sufficiently close to the *Oy*-axis, the motion

of water is considered to be slightly different from the one-dimensional case. Therefore, in a rather narrow band of water distribution along this axis, we establish, with a certain error, the solution of a one-dimensional problem. According to [4], the wetting front is determined by expression $y_0 = \alpha\sqrt{t}$, where $\alpha = 2{,}37\sqrt{\theta}$. Thus, we have an additional condition for $x = 0$

$$y = y_0 = \alpha\sqrt{t} \, . \tag{20}$$

Then Eq. (19) takes the form

$$b^2 - 2b\alpha\sqrt{t}\,\mathrm{ctg}\,m\pi - \alpha^2 t = 0 \, , \tag{21}$$

hence

$$t = \frac{0{,}18b^2}{\theta \mathrm{tg}^2 m\pi}\left(1 + \sqrt{1 + \mathrm{tg}^2 m\pi}\right)^2 . \tag{22}$$

According to the last formula, for each type of soil, it is possible to set the position of water isolines corresponding to a given time of wetting. From Eq. (21) we have

$$\mathrm{ctg}\,m\pi = \frac{b^2 - \alpha^2 t}{2b\alpha\sqrt{t}} = \frac{b^2 - 5{,}62\theta t}{4{,}74b\sqrt{\theta t}} \, . \tag{23}$$

Introducing this value into Eq. (19), we obtain the equation of water isolines depending on time

$$x = \pm\sqrt{b^2 - \frac{b^2 - 5{,}62\theta t}{2{,}37\sqrt{\theta t}}y - y^2} \, . \tag{24}$$

Therefore, the procedure for calculating moisture content is as follows. For a given point in time, according to Eq. (24), the boundary of the wetted area is set. The water distribution within this region, according to the assumption of the method of successive change of stationary states, is determined by expression Eq. (18). Thus, Eq. (18) determines the moisture content by the bounded curve given by Eq. (24).

Further, for a certain point in time, we solve the problem of stationary equilibrium state of the loess soil under the action of its own weight with a distributed moistened state at a given time. We solve the problem using the finite difference method given in [46-47]. When limiting the considered infinite part, the conditions for the continuity of the medium and soil parameters are set by introducing fictitious cells, as shown in [26,47-48].

4. Results
4.1 Initial Conditions for the Numerical Implementation of the Problem Under Consideration

As noted above, for the initial conditions such a state of soil is taken, which corresponds to the equilibrium state under the action of its own weight. To obtain such a state, it is necessary to solve the equilibrium equation with the required equations and boundary conditions.

The solution to such a problem is presented in Figure 2-3. Figure 2 shows the distribution of vertical stresses on the right side of the symmetrical soil area under consideration (as is known, the problem is symmetrical). This soil region is 40 m thick and located in a non-deformable rigid medium. On the right boundary of soil under consideration, the condition for this problem is observed by introducing fictitious cells [46, 47] and using the condition of the absence of tangential stresses and the equality of normal stresses to this boundary. On the left side in the region of the sought-for solutions, as shown in [46], the symmetry condition is set.
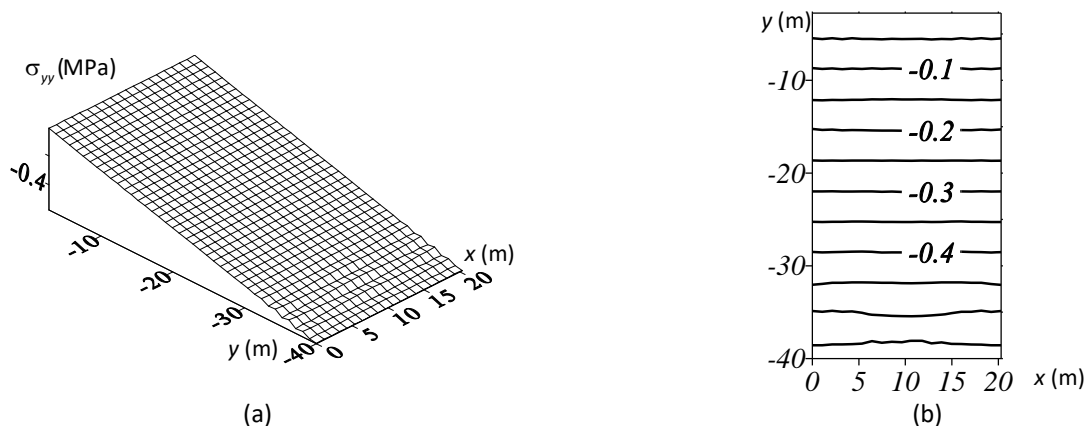
Fig. 2. (a) Distribution of vertical stresses of soil at natural wetting under its own weight and (b) the lines of equal stresses

As seen in Figure 2, vertical stresses are absent only on the day surface of soil. With distance to a depth from the upper part of soil, these stresses increase, and this increase is approximately linear. A similar pattern is observed for other stress components. The distribution of volumetric stresses (pressures) and the vertical stress deviator in the soil plane is shown in Figure 3. Naturally, by quantitative value, the soil pressure exceeds the stress deviator. Note that a positive value of pressure corresponds to the case when the soil experiences all-around compression.
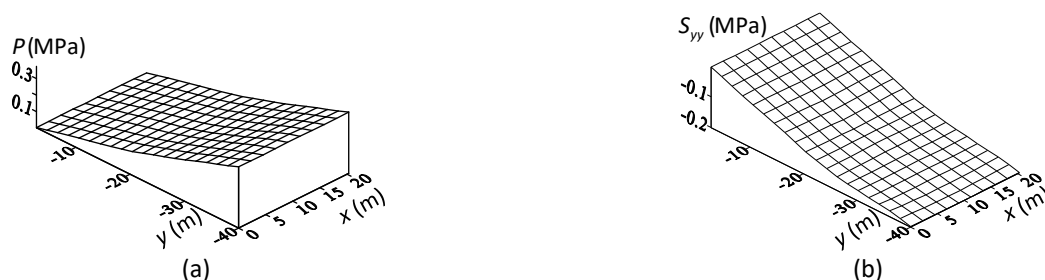
Fig. 3. Distribution of (a) volume stresses and (b) vertical stresses deviator of soil at natural wetting under its own weight

Thus, the resulting stress state of soil under its own weight is the initial condition for determining the subsidence and stress-strain state of loess soil when wetted.

4.2 Determination of Subsidence and Stress-Strain State of Loess Soil at Different Duration of Wetting

Taking half the width of the wetted area as b=1 m, we consider the formation of subsidence and the change in the stress-strain state of loess soil. The initial data, as in the determination of the initial conditions, are taken as follows: natural moisture content of soil W_0 =13 %; moisture content

corresponding to the total water saturation of soil W_{sat} =38 %; physical and mechanical characteristics and dimensionless coefficients K_{sat} =0.5 MPa; G_{sat} =0.096 MPa; c_{sat} =0.005 MPa; μ_{sat} =0.24; α_K =2.5; α_G =4.02; β=3.92; γ=1.09; θ_W =2 m/day. These data are taken from [4,28].

Let us consider the calculation results. Figure 4 shows the distribution of soil moisture, subsidence (vertical displacement) and volumetric strain after 10 days of continuous water moistening of a 2-meter segment of the upper layer of loess soil. During this time of moistening, the moisture front reached more than 10 meters in depth and 5-6 meters in width from the symmetry axis (Figure 4(a)). Moisture concentrates in this area, while the rest of the area under consideration has still a natural moisture content. The change in subsidence and vertical displacement of loess soil over this interval of wetting in depth is also non-linear. The largest displacement, naturally, occurs in the moistened area of soil (Figure 4(b)). The maximum subsidence on the segment $y=0$, $x\in\left[-b;b\right]$ (Figure 1) reaches 3 cm.

(a) (b) (c)
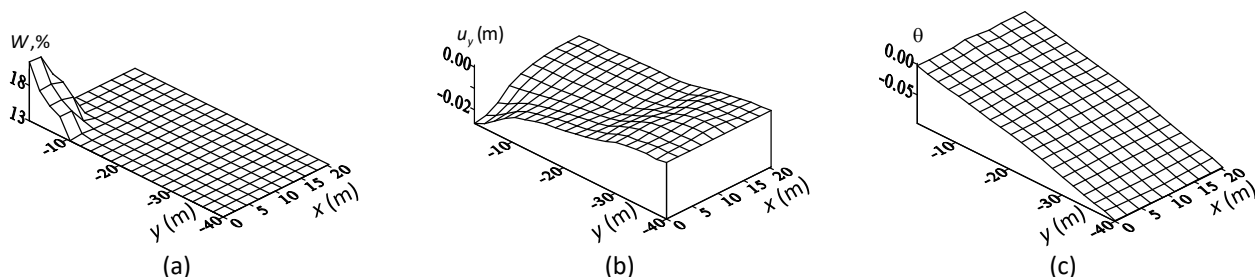
Fig. 4. Distribution of (a) moisture content, (b) subsidence and (c) volumetric strain of soil after 10 days of wetting

As expected, the maximum volumetric strain of soil under its own weight is reached on the lower part, near the boundary with the non-deformable medium. However, if the volumetric strain remains constant horizontally, then behind the moistened front, *i.e.,* in the wetted area, there is a slight increase in strain. Since these strains are negative in value, there is a decrease in the volume of soil.

An increase in the duration of wetting in segment $y=0$, $x\in\left[-b;b\right]$ (Figure 1) accordingly expands the moistened area of soil. The distribution of soil moisture after 20 days of wetting is shown in Figure 5(a). After 20 days of wetting, the front of water propagation increases and reaches 16-17 meters in depth. The distributions of vertical displacements and soil stress after 20 days of wetting are shown in Figures 5(b)-5(c). As seen from these results, the duration of the wetting time significantly affects the value of subsidence and vertical displacements of soil (Figure 5(b)). At the same time, a significant change occurs in the area with high moisture content in soil. There is also an increase in parallel displacements of horizontal soil layers at depth. However, these displacements of soil practically do not affect the stress state of soil (Figure 5(c)).
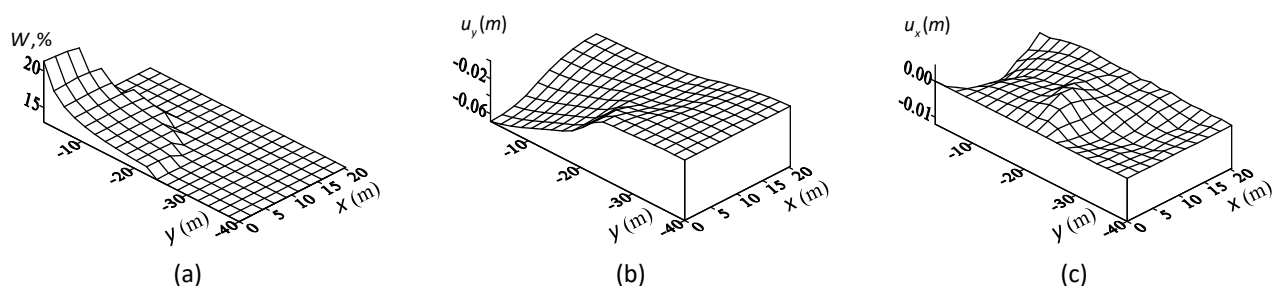

(a) (b) (c)
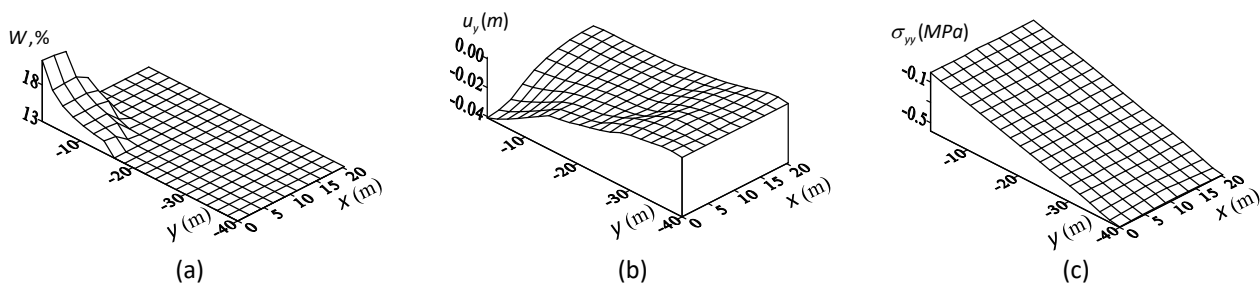
Fig. 5. Distribution of (a) moisture content, (b) subsidence and (c) vertical stresses of soil after 20 days of wetting

The distribution of soil moisture, vertical displacement of particles and volumetric stress in the area under consideration after 30 days of wetting is shown in Figure 6. As seen from the presented results, the highly wetted area spreads and the subsidence and vertical displacement of soil increase. Moreover, an increase in displacements is also observed at significant distances from the free surface of the soil area. This is most likely due to an increase in the density of soil, and hence, to an increase in the mass of soil and a decrease in mechanical parameters in the area of high moisture content. The decrease in the mechanical and strength characteristics of soil, respectively, does not lead to a general decrease in the values of the volumetric stress of soil.

(a)   (b)   (c)
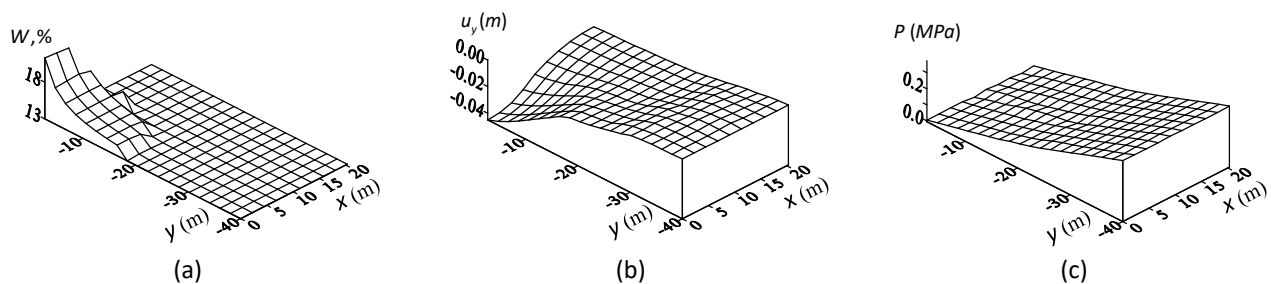
Fig. 6. Distribution of (a) moisture content, (b) subsidence and (c) volumetric stress of soil after 30 days of wetting

A similar pattern is observed with an increase in time of the loess soil wetting. Figure 7, a, shows the moistened area of loess soil after 50 days of wetting of segment $y = 0$, $x \in [-b; b]$ with water (Figure 1). As the time of wetting increases, the saturated area expands not only in depth, but also in width up to 10 meters. Judging by the calculations, the total water-saturated area of loess soil is located under the wetted segment, and it occupies a soil thickness of up to one meter. The fields of vertical and horizontal displacements of particles at a given time and corresponding wetted field are shown in Figure 7(b)-7(c). It can be seen that the vertical displacement of soil particles develops intensively at the left corner point of the considered soil area (up to 8 cm), i.e., in the area of wetted soil. The smallest value of displacements, as before, is observed on the lowest soil layer near the non-deformable medium. It is interesting to observe the horizontal component of displacements. As seen from Figure 7(c), soil particles on the fee surface (y=0) and at a depth of up to 10 meters move horizontally in a negative direction. This means that the particles are displaced toward the axis of symmetry of the soil stratum. An intense horizontal displacement is observed behind the source of wetting on the free surface. At the bottom of the soil layer (within 15-20 meters in depth), the particles move in the opposite direction, i.e., away from the axis of symmetry. Thus, the absolute displacement of the particles is as follows: on the upper part, the soil moves down and towards the wetted area, and in the lower part, the displacement gradually changes direction from the wetted area.

(a)   (b)   (c)

Fig. 7. Distribution of (a) moisture content, (b) subsidence and (c) horizontal displacements of soil after 50 days of wetting

It is known from the SNiP (Building Norms and Rules) that the process of wetting loess soils stabilizes after 80 days of wetting with water. The wetted field and the corresponding fields of vertical displacements after 70 (Figure 8) and 90 (Figure 9) days of water wetting are shown in Figures 8 and 9. As seen from these figures, after 70 days of wetting and longer, the wetted zone covers a wide area. The natural moisture content under the wetted segment remains at a depth of more than 30 m. The moisture content of soil expands in the horizontal direction too (Figure 9(a)). If the wetted area at the initial time of wetting developed intensively, then in the last 20 days of wetting, the wetted front went down by only 2-3 meters. In general, the wetted area begins to stabilize. However, the process of soil subsidence continues. The maximum subsidence of the free surface under the source of wetting now reaches 10 cm. The pattern of vertical particle displacements presented in Figure 9(b), which shows the changes in moisture content after 90 days of wetting, confirms the increase in displacements over time. The subsidence of the free surface of water-wetted soil reaches 90 cm, which is in full agreement with the experimental data obtained in [4] and set in the SNiP.
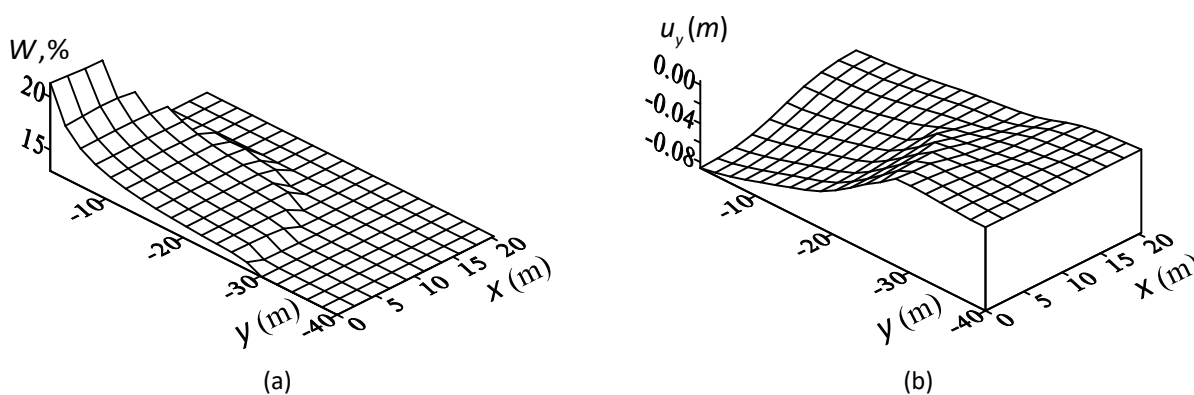

(a)   (b)

Fig. 8. Distribution of (a) moisture content, (b) subsidence of soil after 70 days of wetting

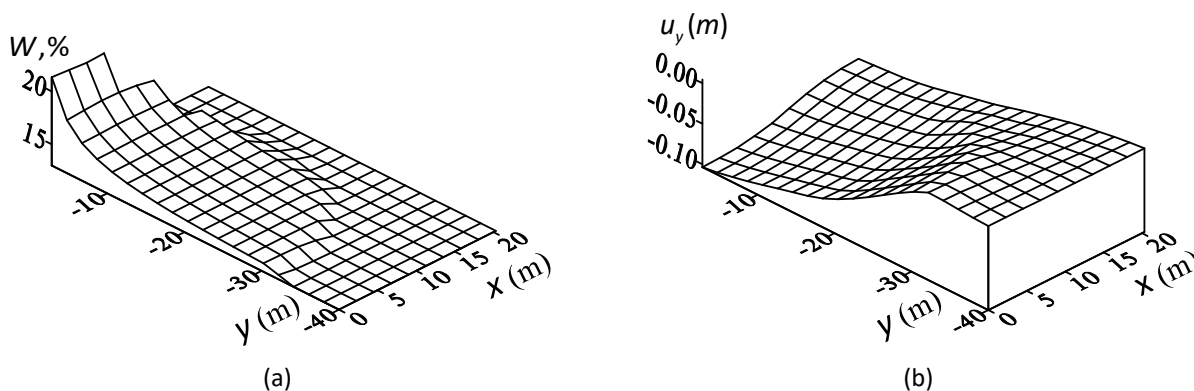(a)   (b)

Fig. 9. Distribution of (a) moisture content, (b) subsidence of soil after 90 days of wetting

Figure 10 shows the fields of horizontal displacements and volumetric strains after 90 days of wetting. The pattern of horizontal displacement fields remains qualitatively unchanged compared to Figure 7(c). A slight increase in volumetric stress is observed in the wetted area of soil.
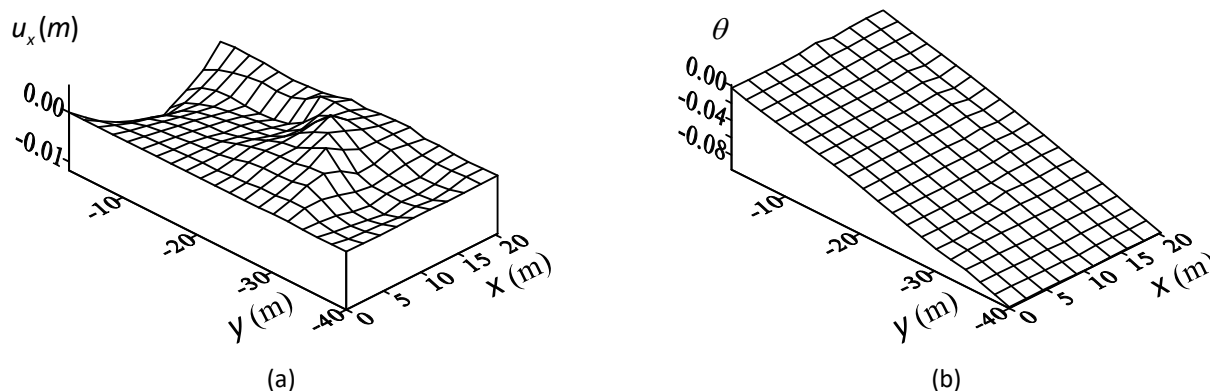
Fig. 10. Distribution of (a) horizontal displacements and (b) volumetric strains of soil after 90 days of wetting

An increase in particle strain leads to an increase in stresses (Figure 11). Therefore, the change in strain and stress also depends on the wetted state, and these changes appear in the late stage of wetting. The change in the subsidence of the free (upper) surface of loess soil under consideration in time of wetting is of great interest. Figure 12 shows the change in the free (upper) surface of loess soil for different duration of wetting. Curves 1-5 refer to *t*=10; 39; 50; 70 and 90 days of continuous wetting. As seen from this figure, in the initial period of wetting up to 50 days (curves 1-3), the soil surface settles intensively, and over time, as the stabilization period begins, the subsidence at various points of the soil surface becomes slightly slower compared to the expansion of the wetted area.
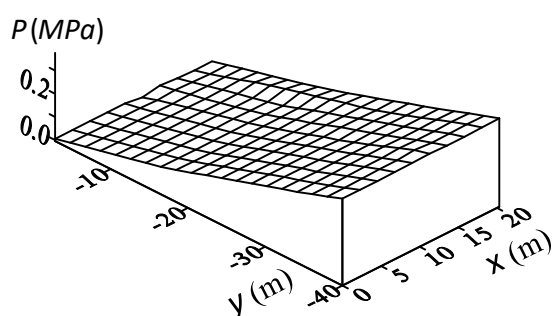
Fig. 11. Distribution of volumetric stresses in soil after 90 days of wetting
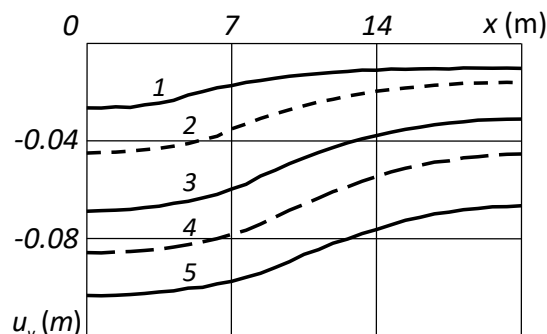
Fig. 12. Profiles of the free surface of soil at different durations of wetting

4.3 Influence of the Size of the Source of Wetting on Subsidence and Stress-Strain State of Soil

The patterns of the subsidence process under natural stress state (under its own weight) of loess soils, to a certain extent, are determined by the development of the wetting front and the change in soil moisture content at various points in wetted area. Therefore, one can naturally expect that the pattern of change in subsidence should be related to the size of the source of wetting.

By varying the value of *b,* i.e., the segment of water wetting, we determine the influence of the size of wetting on the subsidence and stress-strain state of the loess soil. The physical-mechanical and strength indices of soil are the same. We consider the periods corresponding to 50 and 90 days of wetting. Figure 13 shows the distribution of moisture content and vertical displacements of soil after 50 days of wetting at a 4-meter width of the water source. In this case, the value of *b* is 2.

As seen from Figure 13(a), the wetted area, which differs from the area with natural moisture content, expands significantly. Such a change in the calculations directly affects the values of the

other parameters of the problem. An increase in the size of the water source leads to an increase in the values of displacements (15 cm or 2.5 times) and soil strains (Figure 13(b)) compared with the results obtained in the previous sub section (Figure 7).


(a)   (b)
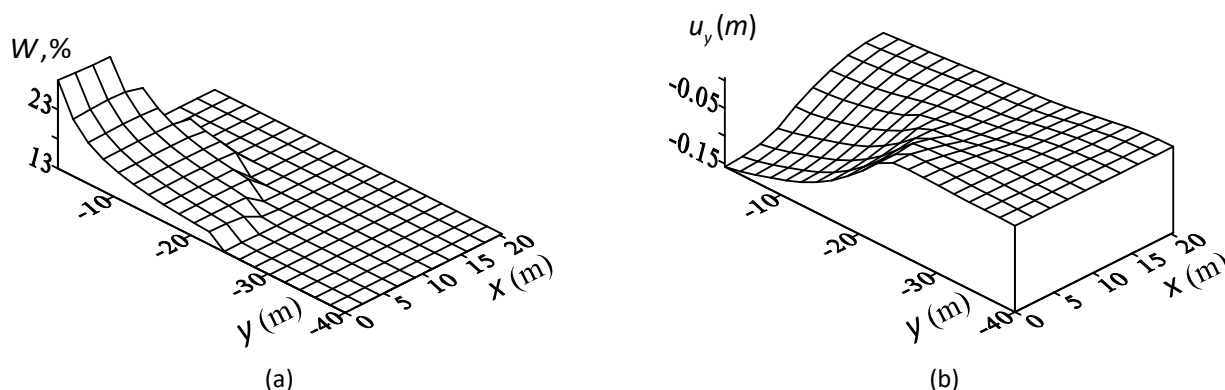
Fig. 13. Distribution of (a) moisture content and (b) subsidence of soil after 50 days of wetting for *b*=2 m

The fields of vertical displacements for various sizes of the water source after 90 days of continuous wetting are shown in Figures 14 and 15. Vertical displacements of particles of loess soil increase intensively with an increase in the area of wetting. In this case, for *b*=3 m, the maximum subsidence under the water source not considering the weight of water reaches 40 cm, for *b*=4 m - 60 cm, for *b*=5 m - 80 cm, and finally, for *b*=6 m (the width of the water source is 12 meters), the subsidence reaches 1 meter. Note that with an increase in the size of the water source, the subsidence increases in the area under the source. As seen from Figure 15(b), the displacement of particles of the free surface in the cross-sections *x*=0.3 and 6 meters is practically the same. In sections *x*=10 meters and more, particle displacements lag far behind the displacements of particles located under the water source in the upper part of the soil layer.


(a)   (b)
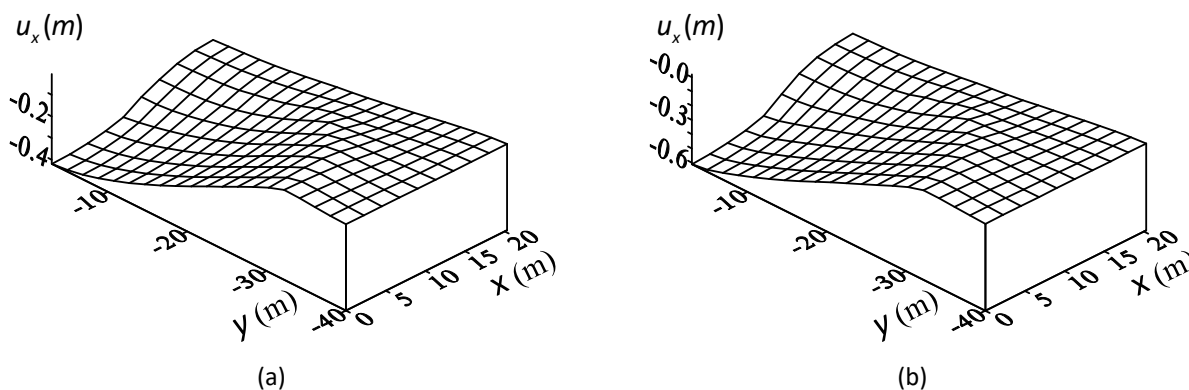
Fig. 14. Distribution of soil subsidence after 90 days of wetting for (a) *b*=3 m and (b) *b*=4 m
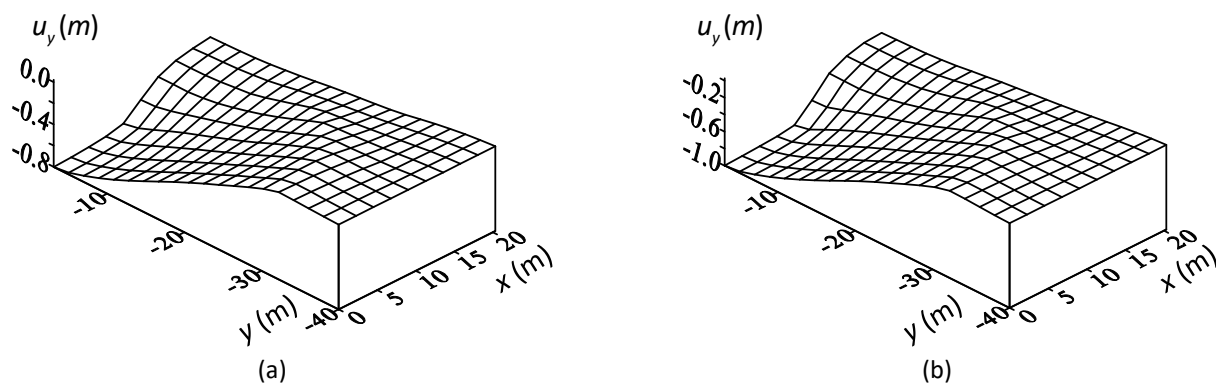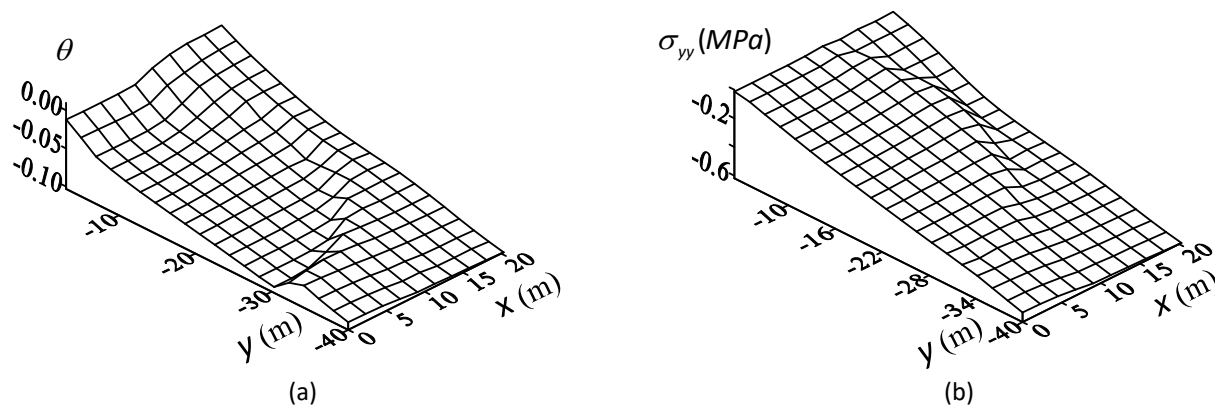
Fig. 15. Distribution of soil subsidence after 90 days of wetting for (a) *b*=5 m and (b) *b*=6 m

Figure 16 and 17 show the water distribution (Figure 16(a)), horizontal displacements (Figure 16(b)), volumetric strains (Figure 17(a)) and vertical stresses (Figure 17(b)) in the region of the sought-for solutions after 90 days of wetting for the case when the width of the water source is 12 meters. As seen from Figure 16, a, the width of the water source has practically no effect on the leading front of wetting on the axis of symmetry of the soil stratum. This is due to the additional condition Eq. (20) accepted. The width of the water source significantly affects the moisture content and the lateral extension of the wetted area. There is a significant increase in the quantitative nature of horizontal displacements of particles, volumetric strains and vertical stresses (Figure 16 and 17).
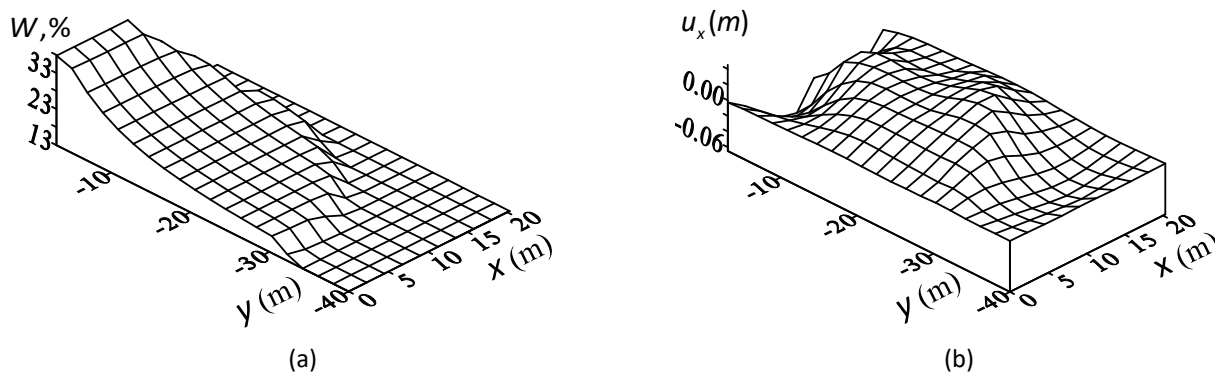
Fig. 16. Distribution of (a) moisture content and (b) horizontal displacements of soil after 90 days of wetting for *b*=6 m

Fig. 17. Distribution of (a) volumetric strains and (b) vertical stresses of soil after 90 days of wetting for *b*=6 m

As seen from the solutions obtained, the size of the water source directly affects the subsidence and the SSS of loess soil. Reducing the width of the water source leads to a narrowing of the area with natural moisture content (Figure 9(a)), therefore, the values of subsidence (Figure 9(b)) of the considered area of loess soil decrease. In the case of an increase in the width of the water source, the areas of high moisture content expand (Figure 13(a) and 16(a)). Hence, a significant decrease in the mechanical characteristics and strength characteristics of soil is observed. Consequently, this leads to a significant increase in subsidence (Figure 14 and 15) and an increase in volumetric strains (Figure 17(a)).

Figure 18 shows changes in the subsidence of loess soil (displacement of the free surface of soil) after 50 days (Figure 18(a)) and 90 days (Figure 18(b)) of wetting for different widths of the water source. Curves 1-6 correspond to the values *b*=1; 2; 3; 4; 5 and 6 meters. From this, it is seen, that a wide area of wetted soil at large sizes of the water source is accompanied by significant displacements (subsidence) of the free surface of the considered loess soil. The increase in subsidence until the stabilization state occurs with time. In conclusion, we note that the results presented in Figure 18(b) practically (with an error of 10%) coincide with the experimental data given in [4, 30] conducted on loess loams stratum of 30-35 m thick and having a source of continuous wetting of 30x30 m.
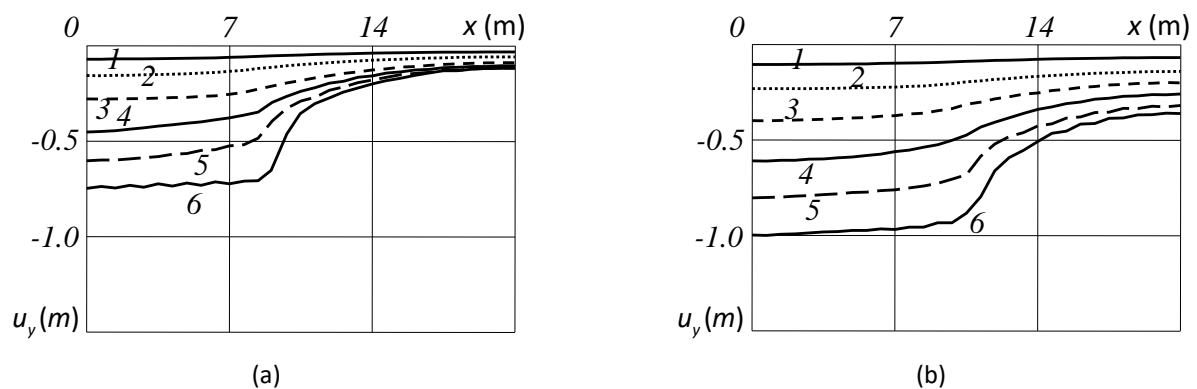
Fig. 18. Profiles of the free surface of soil at different widths of the wetted area after (a) *50* and (b) *90* days of wetting

Thus, the change in the subsidence and stress-strain state of loess soil in the natural state is affected not only by the duration of wetting, but also by the width of the water source. In general, using the equations of state [28], we can obtain qualitative results in theoretical calculations of applied importance, and clarify many facts found in experiments on subsidence of loess soils and the behavior of the stress-strain state.

5. Conclusions

The methods were developed for solving problems of the dynamics of the subsidence process by the method of changing stationary states using the method of finite differences. Initial conditions were obtained for a class of problems on subsidence of the loess soil layer, i.e., the stress state of loess soil under natural moisture content.

The subsidence and stress-strain state of the settled layer of loess soil 40 m thick were determined; they are consistent with the experimental results obtained depending on the duration of wetting at a limited size of the water source. The influence of the wetting on the process of subsidence and transformation of the stress-strain state was determined: it was shown that an

increase in the size of the water source leads to an increase in the area of high moisture content and an increase in the subsidence of the free surface of loess soil. It was shown that the pattern of deformation of loess soils applied in the study, taking into account moisture content, truly describes the process of loess soil subsidence.

Acknowledgement

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