Features of clay soil deformation under triaxial block regime cyclic loading, taking into account the formation of micro and macro-cracks

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Abstract. The main purpose of this paper is to study the parameters of strength and deformation of clay soil in conditions of triaxial compression under block regime cyclic loading. To date, there are no data on the results of studies under this loading mode. Theoretical and experimental studies of the strength and deformability of clay soil of triaxial compression \( \sigma_1 \neq \sigma_2 = \sigma_3 \) under block regime cyclic loads are carried out. A distinctive feature of the experimental studies is that they were carried out in devices of triaxial compression of a prismatic shape with an aspect ratio of 100×100×200mm. In the study of vibration creep deformations and changes in the fatigue resistance to the destruction of clay soils under triaxial regime block cyclic loading. It is established that the stress-strain state, deformation, and fatigue strength of soil vary depending on the sequence of alternating blocks with different values of the maximum load of the cycle. The developed and obtained equations describing the deformation of the soil under these conditions with the development of micro-cracks observed in experiments of hardening and softening effect of inhibition at different stages of cyclic triaxial compression allow to accurately estimate vertical deformation (settlement) bases under regime loading and to obtain reliable and economical design solutions.

1. Introduction
The In modern conditions, the ground bases of buildings and structures are exposed to static and various types of mode cyclic loading. Existing methods for calculating the bases for bearing capacity and deformations are mainly developed for the case of a single short-term static loading or cyclic loading with constant parameters for the entire period of exploitation, Mirsayapov I T and Koroleva I V [1]. Exploitation of buildings and structures with equipment that create cyclical impacts, loading modes of Foundation bases in real conditions are not constant, they change at various stages of the technical process, Pecker A, Rasch C and Hicher P Y [2-4].

Ahmad J D investigated the evaluation of the reduction in the strength of saturated undrained clay soil under direct shear cyclic stress, the test results showed that the reduction increases with increasing cyclic stress amplitude, limiting pressure, number of loading cycles, and with decreasing sample thickness, and also show that there is a lower limit to the cyclic stress ratio, below which cyclic loading has little effect on clay softening. It is also observed that the forward cyclic strength is greater than the triaxial cyclic strength [5].
Chuan G found that an increase in the amplitude of the cyclic limiting pressure will lead to a noticeable acceleration in the accumulation of both constant volumetric strain and axial strain, regardless of whether the sample is over-compacted or normally compacted [6].

Chia-Huei Tu and Chao-Shi Chen developed a computer program with the FORTRAN code for the calculation of the effective stress intensity factors, the angle of crack initiation and propagation for anisotropic bi-material, the result shows that numerical analysis can predict the direction of crack origin and the path of crack propagation relatively well [7].

One of the most important characteristics of the stress state in the vicinity of the crack tip is the stress intensity coefficient $K_{IC}$, if two bodies with cracks have the same values of the stress intensity coefficient, then the stress states in the vicinity of the crack vertices will be the same in both cases, Gevorgyan S. G [8]. According to the Griffiths-Irwin criterion, crack development will begin if the stress intensity coefficient at the crack tip reaches a certain critical value, Li L, Dan H-B and Wang L-Z [9].

This value is a physical constant of the material and is called the critical stress intensity coefficient or the fracture toughness coefficient. For separation cracks, the critical $K_{IC}$ is usually denoted by the symbol $K_{IC}$, Yun S. J and Palazotto A [10]. The cracks are result of an internal energy imbalance in the soil mass caused by no uniform moisture distribution, temperature distribution, or distribution of compaction energy during construction Fang H Y and Feng J [11, 12].

Characterization of crack patterns is useful in different fields of science and engineering. In Soil Mechanics, structural cracks are of much interest: their shape, size, and ruggedness carry with them clues to past stresses and strains imposed to the soil, with implications into their future stability and functionality, Preston S, Griffiths B S and Young I M [13].

The mechanical response of clays is dictated by their fabric as well as by flaws or discontinuities that may exist in the material. These flaws, often in the form of cracks (or notches) and inclusions, result in shear bands that spread from the crack and form a zone in which most of the deformation is localized, Saada A S, Bianchini G F and Liang L [14]. The development of significant tensile strain causes tension cracks in well-developed tension zones in brittle soils, Lee F H, Lo K W and Lee S L [15].

Vallejo L E found that, two basic approaches have been taken to examine fissures in clays. The first approach is from geological point of view and is concerned with the genesis and classification of fissures. While, the second approach concentrates on the effects of fissures on the in-situ strength or strength measured in the laboratory and using this value the relative performance of the fissured clays in slopes and earth dams were determined [16].

The results of a few experimental studies show that the regularities of the development of deformations and changes in the strength of soils under regime cyclic loads differ from the behavior of soils under stationary cyclic loads. For this reason, it is necessary to develop methods for calculating the load-bearing capacity and deformations of the foundation bases, taking into account the formation of micro and macro crack under regime cyclic loading. In this regard, experimental and theoretical studies of the deformation of clay soils under triaxial block regime cyclic loading were carried out, taking into account the formation of micro and macro-cracks.

2. Materials and Methods

To establish the regularities of the development of soil deformation under block cyclic loading, studies were carried out Mirsayapov I T and Sharaf H M, strength and deformation of clay soil under conditions of triaxial compression under block regime cyclic loading [17].

An analysis of the results of experimental studies under regime block cyclic triaxial compression showed that with an increase in stresses and the number of load cycles, the development of both volume change deformation and shape change deformation during soil compaction in the integral volume occurs, under the action of block regime cyclic loading in the case of a consistently increasing regime, an increase in soil deformation occurred.
The most intensive development occurs in the first block, in the initial loading period of 100 cycles, when switching to blocks with a high load level, a jump in the total deformation was observed at the time of switching to another block. Then, within the second block, the smooth development of deformation begins as the number of loading cycle’s increases, similar to the development of deformation in the second stage of the first loading block.

However, the rate of development of these deformations was higher than in the first block, and there was a continuous subsiding development of deformations. When passing to other blocks, the above patterns were repeated, but in each block, the subsequent block, the rate of deformation development increased. On the last block before the destruction, there was a spontaneous avalanche-like increase in deformations; the nature of changes in soil deformations with an increase in the number of loading cycles with a consistently increasing one is shown in figure 1, figure 2 and figure 3.

These graphs clearly show the increase in deformations with an increase in the number of loading cycles and an increase in the rate of development of deformations after the transition to a block with a higher load level, which once again confirms the hypothesis that after (100-500) cycles, the development of micro and macro-crack in the planes of ultimate equilibrium in the soil structure is decisive in the process of increasing deformation.

![Figure 1](image)

In the case of a successively decreasing regime of block cyclic loading, when the loads decrease from block to block in stages, the changes in the soil deformation occurred in all the tested samples in the rework of each block as the number of loading cycles increased figure 1, figure 2 and figure 3 in the processing of the first block, the regularities of the development of deformations depending on the load level and the number of loading cycles were the same as in the case of stationary loading.

At the transition with a lower load level, at the moment of load reduction, there is an abrupt decrease in deformations due to the elastic component and aftereffect deformations.

Then, for some time, there is either a further decrease in deformations as the number of loading cycle’s increases, or their complete stabilization. The duration of this period and the nature of the development of deformation after reducing the load depend on the magnitude of the load drop and the duration of its action in the block under consideration. The greater the load jump, the greater duration of this period and the degree of reduction of deformations. The nature of this phenomenon is explained by the effect of delaying the development of micro and macro-cracks after switching to a lower load level.
Thus, the regularity of the development of soil deformations under block cyclic loads depends on the regularity of the development of micro and macro-crack in the soil structure. Consider the development of soil deformation, taking into account the formation and development of micro and micro-crack in the soil.

3. Results
Development of the nonlinear part of creep deformations under various regimes many times of repetitive cyclic loading, due to the fact that the development of the nonlinear part of the vibration creep deformations depends on the regularities of the development of micro and macro-crack, it is necessary to distinguish nonlinear vibration creep deformations corresponding to the initial and main stages of the development of cracks in the soil body.

In the initial stage, the development of the nonlinear part of the deformations is described by the laws of the development of microcracks. The main stage for the development of the nonlinear part of the vibration creep deformations corresponds to the stage of the development of microcracks in the soil body and is described by the laws of the development of microcracks. Then the equations of nonlinear deformations of soil vibration creep under stationary and non-stationary cyclic loading conditions at different stages of crack development in the soil have the form:
3.1 Stationary regime of the initial stage

\[ \varepsilon_{\text{pil}}^\nu(t, \tau) = \frac{\sigma_{\text{gr}}^\text{max}}{E_{\text{gr}}(t_0)} \left[ \frac{l^2(t, \tau)}{2l_u} \left( \arctan \frac{1}{P(t, \tau)} - \frac{P(t, \tau)}{1 + P^2(t, \tau)} \right) \right] = \frac{\sigma_{\text{gr}}^\text{max}}{E_{\text{gr}}(t_0)} \cdot \left\{ \frac{1}{l(t_0)} \left( \frac{1}{l^2(t_0)} \right)^2 \right\}^{1/2} \cdot \left( \frac{\arctan \frac{1}{P(t, \tau)} - \frac{P(t, \tau)}{1 + P^2(t, \tau)}}{l(t_0)} \right) \right\}^{1/2} \]

Where \( \varepsilon_{\text{pil}}(t, \tau) \) is a nonlinear deformation of soil vibration creep under stationary and non-stationary modes of cyclic loading; \( \sigma_{\text{gr}}^\text{max} \) – maximum cycle stress at the crack peak; \( P(t, \tau) \) – coefficient of asymmetry of the soil stress cycle; \( f_{ij}(\theta) \) – function depending on the polar coordinates of the crack peak; \( l_m \) – dimensionless coefficient; \( k_{\text{gr}} \) – relative strength of the soil under stationary cyclic loading; \( m^2(t, \tau) \) – coefficient of strengthening of soil; \( E_R \) – limiting shear strain of soil; \( \Delta W_i \) – energy of preliminary plastic deformation of the soil at the crack peak; \( \sigma_{ij}, \epsilon_{ij} \) – stresses and deformations at the crack peak; \( l_0 \) – the coefficients of the cubic spline and \( \Delta N_1 = N_1 - N_{\text{litk}} \); \( N_{\text{litk}} \) – duration of the incubation period in cycles.

3.2 Stationary regime of the main stage

\[ \varepsilon_{\text{pil}}^\nu(t, \tau) = \frac{\sigma_{\text{gr}}^\text{max}}{E_{\text{gr}}(t_0)} \left[ \left\{ \frac{l(t_0)}{l(t_\tau)} + \frac{m^2(t, \tau) \Delta N}{2l_u} \right\} \cdot \left( \arctan \frac{1}{P(t, \tau)} - \frac{P(t, \tau)}{1 + P^2(t, \tau)} \right) \right] = \frac{\sigma_{\text{gr}}^\text{max}}{E_{\text{gr}}(t_0)} \cdot \left\{ \frac{l(t_0)}{l(t_\tau)} + \frac{m^2(t, \tau) \Delta N}{2l_u} \right\}^{1/2} \cdot \left( \frac{\arctan \frac{1}{P(t, \tau)} - \frac{P(t, \tau)}{1 + P^2(t, \tau)}}{l(t_0)} \right) \right\}^{1/2} \]

Where \( A^* = \left( k_{\text{gr}} R_{\text{gr}, i, j} \right)^2 \cdot m^2(t, \tau) \left( \frac{1}{l(t_0)} + C_{\partial} \prod_{k=1}^{k=g} k_k a_k \psi_{\theta} \right) \); \( \Delta N_1 = N - N_1 \) – the number of loading cycles at the initial stage of development of cracks in the soil, i.e. at \( l(t, \tau) < 2 \); \( N \) – the total number of loading cycles; \( C(t, \tau) \) – a measure of soil creep; \( l(t, \tau) \) – total length of the macro-crack at a given time; \( l_0 \) – critical length of the conditional main crack; \( k_0 \) – stress intensity coefficients of normal separation and longitudinal shear, respectively; \( \psi_{\theta} \) – correction factors.

3.3 Consistently increasing regime of non-stationary cyclic loading of the initial stage

The equation of nonlinear deformations of vibration creep at this stage is written based on the equation (1) and (2).
\[
\varepsilon_{pl}^{V}(t, \tau) = \frac{\sigma_{\text{max}}}{E_{gr}(t_0)} \left\{ \frac{1}{2t_0^2} \left( \text{arctg} \frac{1}{p(t, \tau)} - \frac{p(t, \tau)}{1 + p^2(t, \tau)} \right) \right\} = \frac{\sigma_{\text{max}}}{E_{gr}(t_0)} \cdot \left\{ \frac{1}{2t_0^2} \left( \text{arctg} \frac{1}{p(t, \tau)} - \frac{p(t, \tau)}{1 + p^2(t, \tau)} \right) \right\} ^2
\]

Where \(\Sigma_1 = \Sigma_1 N_1 - N_i \mu H_k; y = \) the number of increasing blocks (stages) of loading during which the crack can be classified as microcracks; \(N_i \mu H_k\) = the duration of the incubation period in cycles.

### 3.4 Consistently increasing regime of non-stationary cyclic loading of the main stage

Nonlinear vibration creep deformations in a system of developed cracks in the material are described based on the expressions, taking into account the influence of previous loading stages, which is manifested in changes in \(k_1, k_2, \Delta W_{n pi(i-1)}\), (i.e., in the preliminary plastic deformation of microelements in the pre-fracture zone and an increase in the crack length at the previous stage)

\[
\varepsilon_{pl}^{V}(t, \tau) = \frac{\sigma_{\text{max}}}{E_{gr}(t_0)} \left\{ \frac{1}{2t_0^2} \left( \text{arctg} \frac{1}{p(t, \tau)} - \frac{p(t, \tau)}{1 + p^2(t, \tau)} \right) \right\} = \frac{\sigma_{\text{max}}}{E_{gr}(t_0)} \cdot \left\{ \frac{1}{2t_0^2} \left( \text{arctg} \frac{1}{p(t, \tau)} - \frac{p(t, \tau)}{1 + p^2(t, \tau)} \right) \right\} ^2
\]

Where \(A^* = (k_{\text{gr}, R_{gr,t,t}})^2 \cdot m^2(t, \tau) \left[ \frac{1}{E_{gr}(t)} + C_0 \prod_{k=1}^{k_{\text{gr}}} k_{k} \psi_0 \right]: \Delta N_2 = \Sigma_2 N_2 - N_1 \mu H_k; N_1\) = the number of loading cycles at the initial stage; \(N_i \mu H_k\) = the duration of the incubation period in cycles.

### 3.5 Successively decreasing regime of non-stationary cyclic loading of the initial stage

The equation of nonlinear vibration creep deformations at the initial stage is written taking into account the delay in the development of cracks, based on equation (1), (2), (3), and (4).

\[
\varepsilon_{pl}^{V}(t, \tau) = \sum_{k} \sum_{i=1}^{k_{\text{gr}}} \frac{\sigma_{\text{max}}}{E_{gr}(t_0)} \left\{ \frac{1}{2t_0^2} \left( \text{arctg} \frac{1}{p(t, \tau)} - \frac{p(t, \tau)}{1 + p^2(t, \tau)} \right) \right\} \cdot \left\{ \frac{1}{2t_0^2} \left( \text{arctg} \frac{1}{p(t, \tau)} - \frac{p(t, \tau)}{1 + p^2(t, \tau)} \right) \right\} ^2
\]
Where $\sum_{i=1}^{n} N_{i} = \sum_{i=1}^{m} N_{i} - N_{uHk} - N_{D}$; $N_{D}$ – holding time in cycles; $N_{uHk}$ – the incubation period in cycles.

3.6 Consistently decreasing regime of non-stationary cyclic loading of the main stage

$$
e_{\text{p1}}(t, \tau) = \sum_{i=1}^{n} e_{\text{p1}}(t, \tau) = \sum_{i=1}^{n} \frac{\sigma_{\text{max}}}{E_{\text{fr}}(t_0)} \left( \left( \frac{1}{\tau} + \frac{1}{\tau_{H}} \right) \sum_{i=1}^{n} \Delta N_{i} \right)^{2} \left( \arctg \frac{1}{(1+\tau_{H})} \right) = \sum_{i=1}^{n} \sum_{k=1}^{m} \frac{\sigma_{\text{max}}}{E_{\text{fr}}(t_0)} \left( \left( \frac{1}{\tau} + \frac{1}{\tau_{H}} \right) \sum_{i=1}^{n} \Delta N_{i} \right)^{2} \left( \arctg \frac{1}{(1+\tau_{H})} \right)
$$

$$
\left( \left[ \frac{k_{1}\varphi(\sigma) + k_{2}\varphi_{2}(\sigma)}{E_{\text{fr}}(t)} \right]^{2} \right) = \left( \frac{1}{\tau} + \frac{1}{\tau_{H}} \right) \sum_{i=1}^{n} \Delta N_{i} \left( \arctg \frac{1}{(1+\tau_{H})} \right)
$$

Where $A^{*} = \left( k_{pgr}, R_{gr}, t \right)^{2} \cdot m_{2}(t, \tau)$ and $\sum_{i=1}^{n} \Delta N_{i} = \sum_{i=1}^{n} N_{i} - N_{1} - N_{uHk} - \sum_{i=1}^{n} N_{D}$.

4. Discussion

The total deformations of vibration creep depending on the stage of development of cracks in the soil and the regime of cyclic loading are described by the following equations:

4.1 The equation of the total inelastic deformations in the stationary regime of the initial stage

$$
e_{\text{p1}}(t, \tau) = \sigma_{\text{max}} \left( \sum_{i=1}^{n} \frac{1}{E_{\text{fr}}(t_0)} \left[ 1 + \left( 1 - \frac{1}{\tau} \right) \frac{1-\varphi_{1}(\sigma)}{\varphi_{1}(\sigma)} \right] + P_{1} C_{\infty}(t, \tau) f(t, \tau) + \frac{1}{E_{\text{fr}}(t_0)} \cdot \left( \arctg \frac{1}{(1+\tau_{H})} \right) \right) \right)
$$

4.2 The equation of the total inelastic deformations in the stationary regime of the main stage

$$
e_{\text{p1}}(t, \tau) = \sigma_{\text{max}} \left( \sum_{i=1}^{n} \frac{1}{E_{\text{fr}}(t_0)} \left[ 1 + \left( 1 - \frac{1}{\tau} \right) \frac{1-\varphi_{1}(\sigma)}{\varphi_{1}(\sigma)} \right] + P_{1} C_{\infty}(t, \tau) f(t, \tau) + \frac{1}{E_{\text{fr}}(t_0)} \cdot \left( \arctg \frac{1}{(1+\tau_{H})} \right) \right) \right)
$$
Where \( A^* = (k_{gr} R_{grr,t})^2 \cdot m^2(t, \tau) \left[ \frac{1}{E_{gr}(t)} + C_\delta \prod_{k=1}^{k=g} k_k a \psi_{\theta i} \right] \)

### 4.3 The equation of total inelastic deformations consistently increasing regime of no stationary loading of the initial stage

\[
\varepsilon_{p1i}^v(t, \tau) = \sum_{i=1}^{N_i} C_\delta \prod_{k=1}^{k=g} k_k a \psi_{\theta i} \cdot \sigma_{gr1}^{\text{max}} (1 - P_1) \left[ 1 + (1 - a \psi_{\theta i})^{N_i-1} \right] + \\
\sum_{i=2}^{N_i} \left( C_\delta \prod_{k=1}^{k=g} k_k \right)^i a \psi_{\theta i} \left[ 1 + (1 - a \psi_{\theta i})^{N_i-1} \right] \Delta \varepsilon_{gr1} + \sum_{i=1}^{N_i} \sigma_{gr1}^{\text{max}} C_\varepsilon(t, f_i(t, \tau)) + \\
\frac{2 \pi \varphi_{\theta i}^2 \left( \frac{1}{E_{gr}(t)} + C_\delta \prod_{k=1}^{k=g} k_k a \psi_{\theta i} \right)}{(\arctan \frac{1}{p} + p+2)} \\
\Delta N_1 + (t(t_0) + t_i(t, \tau))
\]

\[
= \sum_{i=1}^{N_i} C_\delta \prod_{k=1}^{k=g} k_k a \psi_{\theta i} \cdot \sigma_{gr1}^{\text{max}} (1 - P_1) \left[ 1 + (1 - a \psi_{\theta i})^{N_i-1} \right] + \\
\sum_{i=2}^{N_i} \left( C_\delta \prod_{k=1}^{k=g} k_k \right)^i a \psi_{\theta i} \left[ 1 + (1 - a \psi_{\theta i})^{N_i-1} \right] \Delta \varepsilon_{gr1} + \\
\sum_{i=1}^{N_i} \sigma_{gr1}^{\text{max}} C_\varepsilon(t, f_i(t, \tau)) + \sum_{i=1}^{N_i} \frac{2 \pi \varphi_{\theta i}^2 \left( \frac{1}{E_{gr}(t)} + C_\delta \prod_{k=1}^{k=g} k_k a \psi_{\theta i} \right)}{(\arctan \frac{1}{p} + p+2)} \\
\Delta N_2
\]

Where \( A^* = (k_{gr} R_{grr,t})^2 \cdot m^2(t, \tau) \left[ \frac{1}{E_{gr}(t)} + C_\delta \prod_{k=1}^{k=g} k_k a \psi_{\theta i} \right] \)

### 4.4 The equation of total inelastic deformations consistently increasing regime of no stationary loading of the main stage

\[
\varepsilon_{p2i}^v(t, \tau) = \\
\sum_{i=1}^{N_i} C_\delta \prod_{k=1}^{k=g} k_k a \psi_{\theta i} \cdot \sigma_{gr1}^{\text{max}} (1 - P_1) \left[ 1 + (1 - a \psi_{\theta i})^{N_i-1} \right] + \\
\sum_{i=2}^{N_i} \left( C_\delta \prod_{k=1}^{k=g} k_k \right)^i a \psi_{\theta i} \left[ 1 + (1 - a \psi_{\theta i})^{N_i-1} \right] \Delta \varepsilon_{gr1} + \\
\sum_{i=1}^{N_i} \sigma_{gr1}^{\text{max}} C_\varepsilon(t, f_i(t, \tau)) + \sum_{i=1}^{N_i} \frac{2 \pi \varphi_{\theta i}^2 \left( \frac{1}{E_{gr}(t)} + C_\delta \prod_{k=1}^{k=g} k_k a \psi_{\theta i} \right)}{(\arctan \frac{1}{p} + p+2)} \\
\Delta N_2
\]

Where \( A^* = (k_{gr} R_{grr,t})^2 \cdot m^2(t, \tau) \left[ \frac{1}{E_{gr}(t)} + C_\delta \prod_{k=1}^{k=g} k_k a \psi_{\theta i} \right] \)
4.6 The equation of total inelastic deformations successively decreasing regime of no stationary loading of the main stage

\[
\varepsilon_{pl,1}(t, \tau) = \sum_{i=1}^{N} \left( \frac{1}{C_{\partial}} \prod_{k=1}^{k=g} k_{k} \right) \alpha A_{\psi}(1 - P_{i}) \left[ 1 + (1 - \alpha A_{\psi,i})^{N_{i-1}} \right] + 
\]

\[
+ \sum_{i=1}^{m} \sigma_{gr}^{max} C_{w0}(t, \tau)f_{i}(t, \tau) - \sum_{i=2}^{n} e_{nc}^{i} + \sum_{i=1}^{m} N_{i} \sigma_{gr}^{max} C_{w0}(t, \tau) \cdot
\]

\[
 \cdot \left( \frac{1}{E_{gr}(t)} \right)^{2} \left[ \frac{1}{\partial_{\psi_{1}}} \left( k_{1} \psi_{1}(\sigma) + k_{2} \psi_{2}(\sigma) \right) \frac{1}{E_{gr}(t)} \right] \left( \frac{1}{C_{w0}^{2}} \right) \left( k_{1} \psi_{1}(\sigma) + k_{2} \psi_{2}(\sigma) \right) \cdot
\]

\[
\cdot \left( \frac{1}{E_{gr}(t)} \right)^{2} \left[ \frac{1}{\partial_{\psi_{1}}^{2}} \left( k_{1} \psi_{1}(\sigma) + k_{2} \psi_{2}(\sigma) \right) \frac{1}{E_{gr}(t)} \right] \left( \frac{1}{C_{w0}^{2}} \right) \left( k_{1} \psi_{1}(\sigma) + k_{2} \psi_{2}(\sigma) \right) \cdot
\]

\[
\cdot \left( \frac{1}{E_{gr}(t)} \right)^{2} \left[ \frac{1}{\partial_{\psi_{2}}^{2}} \left( k_{1} \psi_{1}(\sigma) + k_{2} \psi_{2}(\sigma) \right) \frac{1}{E_{gr}(t)} \right] \left( \frac{1}{C_{w0}^{2}} \right) \left( k_{1} \psi_{1}(\sigma) + k_{2} \psi_{2}(\sigma) \right) \cdot
\]

\[
\cdot \left( \frac{1}{E_{gr}(t)} \right)^{2} \left[ \frac{1}{\partial_{\psi_{1}}^{2}} \left( k_{1} \psi_{1}(\sigma) + k_{2} \psi_{2}(\sigma) \right) \frac{1}{E_{gr}(t)} \right] \left( \frac{1}{C_{w0}^{2}} \right) \left( k_{1} \psi_{1}(\sigma) + k_{2} \psi_{2}(\sigma) \right) \cdot
\]

Where \( A = \left( k_{pgr}, R_{grt}, t \right)^{2} m_{j}^{2}(t, \tau) \left( \frac{1}{E_{gr}(t)} \right) + C_{\partial} \prod_{k=1}^{k=g} k_{k} \alpha A_{\psi,i} \]

5. Conclusions

The studies performed allowed establishing regularities in the development of soil deformation under triaxial block cyclic loading, according to which the destruction and nonlinear deformation of the soil is characterized by the formation and development of micro and micro-cracks in the surface of ultimate equilibrium initiated by structural defects in the form of pores or empty shrinkage micro-cracks.

New data on the regularities of clay soil deformation under stationary conditions of repeated cyclic loading were obtained. The equations of clay soil deformation under triaxial cyclic loading mode for stationary, successively ascending and successively falling modes based on the theory of soil vibration creep are developed.

The obtained equations describe the deformation of the soil under the considered conditions, taking into account the processes of hardening and softening observed in experiments and the effect of braking at different stages of the cyclic triaxial state, allow us to accurately assess the vertical deformations (settlements) of foundation bases under regime loads and obtain reliable and economical design solutions.

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