Experimental studies of bearing capacity and settlement of foundations on clays under regime block cyclic loading

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Abstract. Experimental studies of bearing capacity and settlement of foundation on clay soils under regime cyclic loading are conducted in this paper. Tests were conducted in trays using a hydraulic system (ASIS); it allowed determining the base settlement, stress and deformation in the soil. The results of experimental studies are presented in graphs of the dependence of settlement and deformation on the loading mode. New data on the regularities of the stress-strain condition of clays under cyclic loading were obtained. The significance of the results obtained for construction is that under regime cyclic loads, soil deformation increases within the compressible thickness, as well as the base settlement with different intensity in all loading blocks. The most intensive development of soil deformations and base settlement occurred at the initial stage of loading up to 300 cycles, during the transition to the second stage, stabilization occurred up to 2700 cycles. Loss of bearing capacity occurred at the third stage of loading after reaching the limit state of the soil mass in the compressible thickness of the slab foundation.

Keywords: cyclic loading, clay soil, settlement, stress.

1 Introduction

In modern conditions, the ground bases of buildings and structures are exposed to static and various types of regime cyclic loads. The existing methods for calculating bases by 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[1-2]. The stability of geotechnical structures under repeated loading largely depends on induced cyclic shear stresses. The design of these structures usually requires engineers to use advanced soil models in their analysis. In particular, the effect of the initial clay structure and its subsequent degradation under cyclic loading seems insufficiently studied from both the experimental and constitutive point of view of modeling [3-6]. Elia and Rouainia 2016, they make a new contribution to the theoretical understanding of the cyclic response of clay materials by presenting an extensive validation of an improved kinematic hardening model based on laboratory data on a number of natural and reconstituted clays found in the literature. The results show that the enhanced kinematic hardening model gives very satisfactory predictions of clay behavior to cyclic loading [7]. Gu; Wang; Cai; Sun; Dong et al. 2016, series of one-way cyclic triaxial tests were performed on 30 specimens under partially-drained conditions, and the emphases were placed on the coupling effects of the over consolidation ratio, the cyclic stress ratio, and the cyclic confining pressure on the deformation characteristics of the saturated clay. The test results show that increasing the amplitudes of cyclic confining pressure will cause a remarkable acceleration in the accumulation of both the permanent volumetric strain and the axial strain, whether the sample is over consolidated or normally-consolidated[8]. Hicher et al. 2016, conducted tests on reconstituted clay at different levels of stress and strain in triaxial loading–unloading–reloading phases and analyzed by
way of the viscoplastic mechanism terms from Perzyna’s over-stress theory and obtained that the existence of a primary yield mechanism activated at the maximum loading point. A kinematic mechanism becomes activated during the unloading and reloading phases, controlling from this moment on the viscoplastic behaviour within the primary yield locus [9]. Hu and Liu et al. 2015, new simple bounding-surface plasticity model with three important features for the cyclic behaviors of saturated clay is developed. Secondly, the continuous cyclic loading is divided into the first loading, unloading and reloading phases and they are treated differently when calculating the hardening modulus to describe the soil responses accurately. The behaviors of saturated clay for the monotonic and cyclic stress-controlled and strain-controlled triaxial tests are simulated by the model. The prediction results show an encouraging agreement with the experimental data [10]. Wang, Gao, Guo, Cai, Li, Qiu et al. 2017, studied the cyclic deformation behaviour of natural soft marine clays under General stress conditions. It was found that the pore pressure, the stress-strain hysteresis contour, and the dynamic modulus of the samples under study significantly depend on the CSR and limiting pressures. A tensile axial strain occurs in initial loading cycles, and development styles are different with different CSR and limiting pressures. For CSR with the continuous rotation of the main stresses, a new critical value is proposed in the range from 0.16 to 0.18 [11]. Ni, Indraratna, Geng, Carter, Chen et al. 2015, presented a new constitutive model for cyclic loading of soil to predict the behaviour of soft clays under undrained cyclic triaxial loading. The new model is used to simulate cyclic triaxial tests on kaolin, and the model predictions are generally found to be in agreement with the measured excess pore pressures and axial strains. Numerous factors that influence the cyclic performance of soft soils can be considered in the new model, such as cyclic stress ratios, pre shearing, and cyclic loading frequency. The critical cyclic stress ratio is also predictable using the proposed model in terms of excess pore pressures and axial strains [12]. Lei, Li, Lu, Ren et al. 2016, studied, series of cyclic triaxial tests with different vibration frequencies, f, and cyclic stress ratios, CSRs, has been conducted to investigate the dynamic deformation and cyclic degradation of ultra soft soil from Binhai, China. It was studied, that the vibration frequencies have a substantial influence on the dynamic deformation of the ultra soft soil. The inflection frequency is 3 Hz. The value of the strain at failure of ultra soft soil is between 0.99 and 1.6%, lower than that of general soft soils. The effect of f on the degradation index, δ, of ultra-soft soil is different from that of general clay soils. In addition, CSRs have a significant influence on the axial strain development mode. Compared with general soft soil, the effect of CSRs on the degradation index of ultra-soft soil is discussed [13]. Ren, Xu, Teng, Zhao, Lv et al. 2018, long-term cyclic loads with a stress level lower than the critical cyclic stress applied on soft soil can lead to soil deformation but not to failure. The Monismith model is known for its simplicity and capacity to describe the cumulative plastic strain of soil under cyclic loads. therefore be a proposed model is verified by experimental data from existing literature and it has a better capability and performance than the Monismith model in predicting the cumulative plastic strain of soft soil subjected to long-term low cyclic loads [14]. Khan, Nakai, and Noda et al. 2020, as the loading speed and number of cycles decrease, the strain decreases. Therefore, the degree of strain evolution varies depending on the loading rate and the undrained shear strength also varies depending on the cyclic loading rate. This is because when the cyclic loading rate was high; the pore water did not migrate sufficiently, leading to the non-uniform distribution of the excess pore water pressure inside the specimen. This means that if sufficient time is left after cyclic loading, the final mean effective stress value becomes equal regardless of the loading rate [15]. Hirai et al. 2018, cyclic behaviour of clay up to failure is made clear from the relationship between cyclic tensile loads, vertical and lateral displacements, and rotation and that between depth, vertical, and lateral pressures [16]. Many scientists have conducted field laboratory experimental studies to determine the bearing capacity and settlement, deformation of soil bases and the behavior of sandy and clayey soils under cyclic loading and using these tests have proposed theoretical methods and mathematical empirical and semi empirical models such as: Liu, Huang, and Ma 2020; Feng et al. 2015; Zhao, Heng, and Zheng 2017; Liu et al. 2020; Liu, Cui, Zhu, et al. 2019; Li, Dan, and Wang 2011; Alam, Gnanendran, and Lo 2017; Tafreshi, Mehrjardi, and Ahmadi 2011; Zhang, Kong et al. 2009; Al-Naddaf, Han, Xu, Rahmaninezhad et al. 2019 [17-23]. Exploitation
of buildings and structures with equipment that creates a cyclic effect, loading regimes of foundation bases in real conditions are not constant, they change at various stages of the technical process. The results of the few available experimental studies show that the regularities of the development of deformations and changes in the strength of soils under regime cyclic loading differ from the behavior of soils under stationary cyclic loading [24-29]. For this reason, it is necessary to develop methods for calculating the bearing capacity and deformations of foundation bases under regime cyclic loads. In this regard, experimental studies of the bearing capacity and settlement of soil bases of the foundation model in a volumetric tray under regime cyclic loads were conducted.

2 Materials and methods

Experimental studies were conducted in a volumetric metal tray with 1000×1000×1000 mm sides (figure 1) and the base were represented with two layers of soil with different physical and mechanical characteristics. Two-layer soil of the base in all the experimental studies consisted of the following soils in table 1.

| Type of soil | Layer thickness, h mm | Density, ρ, g/cm$^3$ | Moisture content, W% | Friction angle, φ, deg | Cohesion, C, kPa | Deformation modulus, E, MPa |
|-------------|----------------------|-----------------------|----------------------|-----------------------|-----------------|--------------------------|
| clay        | 600                  | 1.8                   | 26                   | 14                    | 30.4            | 15                       |
| sand        | 400                  | 1.93                  | 5                    | 22                    | 63.1            | 7.2                      |

The following steps are carried out to prepare a soil sample for testing. Firstly, the tray is filled with sand up to the 400 mm mark and compacted with a rammer to the specified density value. Then the clay is placed in layers of 5 mm to the mark of 1000 mm without compaction. As soon as the two-layer soil base in the center of the tray is filled up, a model of the raft foundation is installed – a stamp in the form of a reinforced concrete slab with length and width of 400×400 mm and thickness of 40 mm. Loading is performed by a hydraulic automated system (ASIS) blocks depending on the specified loading regime.

Figure 1. Scheme of structures and arrangement of devices:
1 – Volume tray; 2 – raft foundation model; 3 – vertical electronic sensors; 4 – soil load cells; 5 – automatic Jack; 6 – Jack installation; 7 – beam for installing vertical sensors; 8 – automated program system (ASIS).
The values of the base settlement are recorded according to the indicators of vertical electronic sensors at each loading block, as well as, the stress and strain in the soil of the base. The parameters of the block cyclic loading regime are shown in table 2. The location of the load cells is shown in (figure 1). The relative deformations and stresses in the ground of the Foundation are determined from the sensor readings, and the settlement of the raft foundation model is measured during the process.

Table 2. Parameters of the block-cyclic loading mode.

| Experimental model | Number of blocks of loading | \( P_{\text{max}} \), kN | \( P_{\text{min}} \), kN | Number of cycles in various stages of loading | Number of cycles loading in blocks | Number of cycles loading |
|--------------------|-----------------------------|--------------------------|--------------------------|---------------------------------------------|----------------------------------|--------------------------|
| SF                 | N1;3;5;7;9;11;13;15         | 7                        | 3.5                      | 100                                         | 100                              | 2400                     |
|                    | N2;4;6;8;10;12;14           | 7                        | 3.5                      | 100                                         | 100                              | 1050                     |

3 Results

Based on the results of experimental studies, graphs of changes in the stress-strain state of the soil in the process of regime block cyclic loading are constructed.

Figure 2. The change of stresses in the soil depending on the loading conditions.
In (figure 2) graphs of stress changes in different zones and depths of the soil base are shown. The graphs show that with an increase in the number of cycles on each block, there is an increase in the stress in the ground in all zones and depths of the ground base of loading. At the same time, the greatest increase in stress in the ground is shown by load cells № 2, № 5, № 8, which are located in the center under the raft Foundation at a depth of 2, 20, 40 cm, while the stress reached from 25 to 27 kPa. A smaller increase in ground stress is shown by load cells № 1, № 4, № 7, which are located on the left edge of the plate at a depth of 2, 20, 40 cm, while the stress reached from 15 to 19 kPa. Block cyclic loads cause increases in base deformation and precipitation within the raft foundation model and beyond.

![Figure 2. Loading regime](image)

![Figure 3. Changes in vertical deformation under and beyond a plate of foundation depending on the regime of loading.](image)

The graph of changes of deformations in clay under block cyclic loading under the raft foundation model and beyond it within each loading block is shown in (figure 3). The graphs show that the loading mode leads to an increase in relative deformations. At the same time, significant vertical deformations occur at the first stage of loading up to 300 cycles. The most deformations are shown by...
sensors № 4-7, which are located under the model of the plate foundation, and were 44.77-47.17 mm. during the transition to the second stage, the deformation stabilizes, and the intensity of deformation development decreases. Within the second stage, the raise in deformation for 2700 cycles is 8.83-10.39 mm. in the third stage, there is a more intense grow in deformation, and the grow is 2.5 times compared to the second stage before destruction.

Figure 4. Development of raft foundations settlement under block cyclic loading.

The development of raft foundation settlement at each loading stages is shown in (figure 4). The graphs show that there is an intensive development of settlement at the first stage of the loading regime up to 300 cycles, while the settlement is equal to 47.79 mm and amounted to 58 % of the total settlement. The intensity of settlement development decreases during the transition to the second stage up to 2700 cycles, but the complete stabilization of the settlement does not occur and the precipitation is equal to 55.85 mm and amounted to 12% of the total settlement. With further loading, the third stage begins up to 3450 cycles, the development of settlement increases intensively until the loss of the bearing capacity of the soil base. At the same time, the settlement is equal to 81.80 mm and made up 33 % of the total settlement. It should be noted that when unloading to zero, the draft decreases within 1-2 mm on all loading blocks.
Figure 5. Changes in the development of raft foundation settlement in certain blocks depending on the loading regime.

In (figure 5). Graphs of settlement changes in certain loading blocks are given. on the first block of loading with the vertical load of 7 to 0 kN is a reduction in settlement during the 15 hours of 1.6 mm, then as the load increases from 0 to 9 kN is an increase in the settlement by 2.81 mm, then when the load changes from 9 to 0 kN, settlement decreases by 1.6 mm, with 0 to 11 kN, settlement increases by 4.16 mm and a discharge of 11 to 0 kN, settlement reduced within 14 hours by 1.78 mm. In the fifth loading block, when the vertical load changes from 11 to 0 kN, settlement decreases by 1.6 mm for 30 hours, then when the load increases from 0 to 7 kN, the settlement increases by 0.84 mm, then when the load changes from 7 to 0 kN, the settlement decreases by 1.1 mm, when the load changes from 0 to 9 kN, the settlement increases by 1.07 mm, and when the load is unloaded from 9 to 0 kN, the settlement decreases by 1.35 mm in loading block 15, when the vertical load changes from 11 to 0 kN, settlement decreases by 1.72 mm for 20 hours, then when the load increases from 0 to 7 kN, the settlement increases by 2.41 mm, when the load changes from 7 to 0 kN, the settlement decreases by 1.78 mm, when the load changes from 0 to 9 kN, the settlement increases by 2.40 mm, and when the load is unloaded from 9 to 0 kN, the settlement decreases by 1.70 mm.
4 Discussions
Analyzing the results of experimental studies of clay in volumetric trays under regime cyclic loading, we can conclude that there is a change in all the deformation and strength parameters of clay, as can be seen from the graphs (figures 3-5). There is an increase in vertical deformations and settlement of the base of the raft foundation model in all blocks of the ascending loading regime under the action of cyclic loads within each block, there was an increase in vertical deformations and settlement. Deformations with different intensity developed throughout the tests. The most intensive development of deformations occurred at the initial stage of each loading block. Then came relative stabilization, but full stabilization of deformations was not observed when switching to blocks with a high level of stress. In the initial period, there are no sharp jumps in deformations this is due to the processes of self-hardening and self-healing of the soil and the redistribution of forces between the characteristic zones of the base in area and depth. Then, after 100-200 loading cycles, the increment of deformations and settlement of the ground base begins. When switching to other blocks, a similar pattern of deformation development is observed. When switching to blocks with a lower load level at the moment of changing the loading mode, there is a slight decrease in the total deformations due to the elastic component or the deformations are stabilized. Then, as the application time of the cyclic load increases, further increments of deformations occur. The nature of the development of deformations in blocks with a lower stress level depends on the duration of the cyclic load in blocks with high stresses and the duration of the considered loading block on (figures 3-5). The nature of this phenomenon is explained by the effect of delay in the development of micro-macro cracks and the effect of self-hardening and self-healing of clay due to the restoration of structural and coagulation bonds after switching to a block with a lower load level. It should be noted that the accumulation of General deformations occurs mainly due to the plasticity of the component. Elastic deformations within each block of cyclic loading change slightly (figures 3-5).

5 Conclusions
Based on the results of the experimental study, we can draw the following conclusions:
1. In case of regime block cyclic loading, the stress in the ground changes throughout the entire test period. The most significant change occurred in the center under the raft Foundation at a depth of 20 cm.
2. The development of deformation and settlement of the raft Foundation under block cyclic loading occurs at three stages of loading: at the first stage-the stage of compaction of the soil up to 300 cycles, there is an intensive development of settlement, and the settlement is 58 % of the total settlement. For the second stage-the stage of soil stabilization up to 2700 cycles: the intensity of settlement development decreases, but the complete stabilization of the sediment does not occur, and the settlement is 12% of the total settlement. For the third stage-the stage of soil destruction up to 3450 cycles: the development of settlement increases intensively until the loss of bearing capacity of the soil base. In this case, the settlement is 30 % of the total settlement.
3. After complete unloading (to zero) of each loading block, the settlement changes over a period of 12 hours to one day, with a decrease in the settlement of the raft foundation within 1-2 % of the total settlement.

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