Experimental studies of the “foundation-soil” system operation with sudden loading

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Abstract. The experimental studies’ results of the foundations with a soil base interaction are presented. The relevance of the research is associated with increased accidents of buildings and structures in recent decades. The reasons for the occurrence and features of sudden foundations loading are considered. The experimental research methodology, the characteristic models of foundations are presented. The preliminary experimental studies’ results of the foundations with sudden loading are presented and analyzed. Some features of the “foundation-soil” system are determined. A decrease in the bearing capacity of the foundations during sudden loading, depending on the level and prestressing type, was revealed. It is established that the main reason for the decrease in the foundations’ bearing capacity is a change in the normal contact stresses diagram. The necessity and directions of further research in this area are substantiated.

Introduction
The increasing number of accidents of the buildings and structures in recent decades has determined the relevance of the study on the base and foundations’ operating at emergency loading. Such studies are of interest from the point of view of identifying the “foundation-soil” system’s behavior, creating a methodology for calculating the foundations for exorbitant loads, its use in the buildings and structures’ assessment to progressive collapse.

The calculation of foundations resistance and base in most countries is currently carried out on a standardized operational load. There are the studies examining the “foundation-base” system’s operation under complex types of loading, taking into account the nonlinear nature of the base [1, 2]. Various models of the soil base, taking into account the normal contact stresses’ redistribution under the foundation base with a different nature of the load, have been developed [3-6]. At the same time, the study of the “base-foundation” system’s operation with sudden loadings associated with emergency loads has practically not been carried out. Much attention is paid to the research and calculation for the progressive collapse buildings; various models and calculation methods have been created [7]. At the same time, the role of the foundations’ interaction with a soil base in the progressive destruction process development has not been studied properly.

Available separate laboratory studies evaluating the loading rate effect on the change in the stress-strain state of soils indicate an increase in soil strength and a decrease in deformations with an increase in the loading speed of the samples [8]. Accordingly, these factors cannot but affect the force interaction of the “foundation-soil” system with sudden loading, which confirms the relevance of the research topic.
The purpose of the work is to analyze the results of the preliminary experimental studies of the force interaction for the “foundation-soil” system with sudden loading.

The following tasks of the research can be underlined:

- To consider the preliminary experimental studies’ results of the foundations’ force interaction with a soil base with sudden loading;
- To identify the main features of the “foundation-soil” system’s behavior with sudden loading;
- To justify the need and direction for further research in this area.

Main part

By sudden loading, in the studies carried out, we mean a rapid increase in the foundation load, the increase rate of which is higher than the complete redistribution speed of the stresses in the soil mass from the increased external load. For the columnar-lined foundations, sudden loading can occur when the separate building structures are damaged or destroyed, loading falling on the floor, seismic effects, explosions and many other factors. Under the sudden loading influence, due to the different rate of the deformations and stresses increase in the foundation and base, the “foundation-soil” system is in a time-varying state until stabilization. In this case, a change in the efforts in the foundation construction occurs. The «foundation-soil» system duration after an increase in external force is the most determined transformation by the soil characteristics, since the forces redistribution processes proceed in it more slowly than in the foundation. It is assumed that in the considered period of time the nature of the foundation interaction with the base can significantly differ from that found in the studies with a stable state of the “foundation-soil” system. The consequences of neglecting the process of changing the system under the sudden reloading influence can be an incorrect assessment of the foundation bearing capacity, redistribution of forces between the foundations in an emergency, etc.

Experimental technique

To identify the changes in the “foundation-soil” system’s operation, the experimental studies were conducted. The experiments were carried out in a soil tray measuring 2.2 x 2.2 x 2.2 m filled with sand (Figure 1). The foundation models had 0.5 x 0.5 m dimensions in the plan, the slab part’s thickness was 0.07 m. The cross-sectional changes of the monolithic conjugate column fragment were 0.1 x 0.1 m. The foundations were loaded with an air hydraulic jack. A total of 5 models were tested. In the course of the experiments, the following parameters were measured: level and time of exposure and changes in external load, draft and deformation of the foundation plate, distribution of normal contact stresses under its base flange. To take the data during the loading process, a video recorder with a recording speed of 60 frames / sec was used.

The experimental research methodology provided the following loading pattern:

- The 1st model: stage-by-stage static loading with a central load until the foundation is destroyed;
- The 2nd model: stage-by-stage static loading with a central load up to a force of 0.5% of the calculated breaking load. Subsequent quick loading up to the model breakdown;
- The 3rd model: stage-by-stage static loading with a central load up to a force of 0.75% of the estimated breaking load. Subsequent quick loading up to the model breakdown;
- The 4th model: stage-by-stage multiple static loading with a central load up to a force of 0.75% of the estimated breaking load. After the 10th cyclic loading, further static loading of the sample up to the failure;
- The 5th model: stage-by-stage multiple static loading with a central load up to a force of 0.5% of the calculated breaking load. After 10 loading cycles, quick loading up to the model breaks.

All preloads were carried out with the load steps in the amount of the calculated destructive load 10% and were maintained at each load step for at least 15 minutes.

The models were loaded after static loading by a pneumatic system of the air hydraulic jack with a pulse feed of each subsequent effort. The intervals between the load pulses were no more than 0.5 seconds. The average feed rate of the loading force was 1.0 kN/sec. With increasing force, the loading rate decreased slightly due to an increase in the foundation outflanking. The pulsed nature of the load
was necessary to more accurately record the results of the devices data and determine the foundations’ bearing capacity. This loading method was substantiated and tested in [9]. The absence of a significant pulsating qualitative effect on the experimental results, on the one hand, is explained by the stress redistribution’s slow process in the soil (for sand this time is at least 15-20 minutes). On the other hand, the accepted rate of increase in loads is possible during the frame buildings’ accidents and does not cause the significant dynamic effects on the soil, which could lead to its structural changes.

![Foundation test in the tray](image1.png)

**Figure 1.** Foundation test in the tray

When analyzing the experiments, we studied the sudden loading effect on the foundations’ bearing capacity, the draft and distribution of normal contact stresses under the sole, revealed a role in changing the force interaction of the foundations with the base during such sudden loading factors as the level of preload by the static load and the presence of preloads with low-cycle loads.

**Results and its discussion**

All the tested foundations models collapsed from bending lengthwise the normal section (Figure 2). The numerical values of the experimental and the calculated values of the breaking load are presented in Table 1.
Figure 2. Foundations F-1 - F-4 after destruction

Table 1. Foundation Model Test Results.

| Sample no. | Estimated Carrier foundation ability, $P_{est.}$ (kN) according to BC 63.13330.2018 Concrete and reinforced concrete structures | Level preliminary loading [kN] | The number of the preliminary loading cycles | The presence of sudden loading | Experimentional carrying ability, $P_i$ [kN] | $P_i/P_b$ | $P_i/P_p$ | Decrease d bearing capacity relative to the base foundation [%] |
|------------|-----------------------------------------------------------------------------------------------------------------|-------------------------------|---------------------------------------------|---------------------------------|------------------------------------------|-----------|-----------|--------------------------------------------------|
| F-1        | 35.40 31.70                                                                                                       | -                             | 0                                           | unavailable                     | 40.00                                    | 1.13      | 1.26      | -                                                 |
| F-2        | 35.40 31.70                                                                                                       | 15.00                         | 0                                           | available                       | 35.00                                    | 0.99      | 1.11      | $P_2/P_1=12.5$                                   |
| F-3        | 35.40 31.70                                                                                                       | 22.00                         | 0                                           | available                       | 36.00                                    | 1.02      | 1.14      | $P_3/P_1=10.0$                                   |
| F-4        | 35.40 31.70                                                                                                       | 15.00                         | 10                                          | unavailable                     | 48.00                                    | 1.36      | 1.51      | -                                                 |
| F-5        | 35.40 31.70                                                                                                       | 15.00                         | 10                                          | available                       | 39.00                                    | 1.10      | 1.23      | $P_5/P_4=18.8$                                   |

As it can be seen from Table 1, the bearing capacity of the F-2 foundation, tested with fast loading after a preload level of 50% of the estimated breaking load was 12.5% lower than that of the F-1 sample tested with traditional slow loading. With an increase in the preload level up to 75% of the calculated breaking load (sample F-3), the decrease in the bearing capacity was 10.0% relative to the basic model F-1. The use of preliminary multi-cycle loads with a destructive load 0.5% led to an increase in the bearing capacity of the F-4 foundation compared to the F-1 foundation. The effect of increasing the foundation bearing capacity after a cycle of the low-cycle loads is described in [10]. The bearing capacity of the F-5 foundation with the same preliminary low-cycle loading, tested with sudden loading, was 18.8% lower than the base sample (F-4), and did not reach the bearing capacity of the F-1 foundation.

A significant difference in the nature of the foundation models’ destruction in the experiments was not revealed. The lower value of foundation settling during quick loading before destruction, compared with other models at the same load levels was observed (Figure 3).
Thus, a higher level of preloading the foundation or the cyclic loads presence before quick loading, determining the soil compaction degree and the formation of a compacted core under the central part of the structure, had a positive effect in the form of an increase in the structure’s bearing capacity. At the same time, the level of breaking load under the influence of sudden loading turned out to be lower than with the traditional slow foundations loading. In the presence of low-cycle loads against the background of an increase in the bearing capacity of the foundations, the difference between the strength of foundations loaded in a traditional way and experiencing sudden loading increases.

A preliminary analysis of the effect of reducing the bearing capacity of foundations with rapid loading showed that it is associated with a change in the shape of the diagram of normal contact stresses. With slow loading, the normal contact stresses redistribution occurs with an increase in the plot ordinates under the central part of the foundation and a decrease at the outer zones. It is primarily associated with an increase in plate bending and the development of plastic deformations in the soil at the outer zones of the base flange. Such a redistribution occurs during the loading process and leads to a decrease in the efforts in the foundation plate. With rapid foundation loading, the redistribution of normal contact stresses lags behind in time. Together with an increase in the ordinate of contact stresses, a relative shift of the gravity center of the normal contact stresses diagrams occurs in the direction from the center to the peripheral zones of the foundation, which leads to a higher level of bending moment in the foundation plate than under slow loading with an equal load.

![Figure 3. Foundation settlement F-1 – F-5](draftimage)

The effect of reducing the bearing capacity of the foundations under fast loading is influenced by the rate of the following processes:
- changes in the level ratio of the vertical and horizontal, normal and shear stresses in the soil mass;
- the plastic deformations’ development at the outer foundation zones, etc.

Probably, a certain role in reducing the foundation bearing capacity during rapid loading is played by the normal stresses diagram shape formation in the compressed zone of the foundation concrete in the sections along the column faces. The plastic deformations development in the compressed zone of
concrete foundations, leading to the plot’s transformation to a shape close to rectangular, also does not happen instantly.

For a detailed identification of the features of changing the force interaction nature of the foundations with the soil base during sudden loading, further studies are necessary. They should touch upon such issues as the effect on the changes in the nature of the loading rate foundation-ground system force interaction, the parameters of the base and foundation, the degree of the foundation loading, etc.

It is necessary to develop a methodology for calculating the bearing capacity and the foundations’ flanking during sudden loading. It is advisable to take into account the peculiarities of the “foundation-soil” system during sudden loading in the calculation of the buildings for progressive collapse, since they can affect both the forces redistribution in the vertical elements of the building after an emergency, and lead to the progressive collapse of the building caused by the foundations’ destruction.

Summary
The study of the “base-foundation” system’s operation with sudden loadings associated with emergency loads has practically not been carried out. Such studies are of interest from the point of view of identifying the features of changing the “foundation-soil” system’s operation, developing a methodology for calculating the foundations strength, and also taking into account when calculating the buildings for progressive collapse.

The conducted preliminary experimental studies showed that the sudden loading impact on the foundation starts the process of adapting the system to a new load, the duration of which depends on the soil and foundation’s characteristics, the type and level of an external load. The sudden loading foundation impact leads to a decrease in the structure’s bearing capacity at the stage of the system adaptation. This is primarily due to a change in the normal contact stresses diagram shape at the foundation base.

Such factors as the level of preliminary loading and the presence of cyclic loading have a significant effect on the decrease amount in the foundation bearing capacity for bending during sudden loading.

Further research is needed to identify the impact on changes in the force interaction nature of the “foundation-soil” system with sudden loading for such factors as the load rise rate, the foundation and soil base parameters, the load degree of the base before loading, etc.

It is advisable to develop the methods for calculating the bearing capacity and the foundations’ outflanking during sudden loading, including for the purpose of their application in the calculation of the buildings for progressive collapse.

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