Investigation of particularities of the stress-strain state of the sandy basis under loading conditions of rough stamps

G M Skibin¹,²

¹ Platov South-Russian State Polytechnical University (NPI) 132 Prosveschenia Str.,
Novocherkassk, Rostov Region, 346428, Russia

² skibingm@mail.ru

Abstract. The analysis of the results of the experimental researches conducted in Platov South-Russian State Polytechnic University (Novocherkassk Polytechnic Institute), in conditions of tape and axisymmetrical basis loadings permits to identify general patterns of the sand basis operating in case of different loading conditions, to consistently trace the development of ranges of strains, compaction and decompaction and the formation of a condensed core under stamps and to assess this process with the phases of the stress - strain state of the basis.

1. Introduction
Experimental studies on the stress-strain state of the foundation were carried out by the laboratory "Bases and Foundations" of Platov South-Russian State Polytechnic University (NPI) by force of the MF-1 testing machine (figure 1) designed by Yu.N. Murzenko [1], serving central element of the automated system of scientific research (ASNI) of bases and foundations on models.

Characteristic of machine
1. Hydraulic device with centralized control.
2. Hydraulic system working pressure – 250 kg cm⁻².
3. The greatest short-term and long-term load:
   - during the operation of one jack – 50 ton-force;
   - during the operation of two jacks – 100 ton-force;
   - during the operation of three jack – 150 ton-force.
4. Limit error of readings from actual load ± 1%.

2. Experimental equipment
The MF-1 machine is designed to test in the model form bases in a sandy base and ranks among vertical testing machines with a hydraulic drive, a pendulum hydraulic force measuring device and a centralized control panel.

The load frame of the machine has vertical columns and a traverse beam, to which hydraulic jacks are pivotally suspended through a movable hand cart. Depending on the test plans, one or more jacks can be included in the work, which can be fixed on any part of the guide. The jacks are located with the plunger down and are equipped with return springs. The load transfer is regulated through the machine command panel which contains measuring scale with three measurements: up to 100, 200 and 500 kN and a the scale value of 200, 500 and 1000 N respectively. The tray of the MF-1 machine has
inner dimensions 3.0 x 3.0 x 2.2 (depth) m. The base is medium-grained air-dry sand, simulating a sandy ground. The angle of repose was 33°, the angle of internal friction was 40°.

The command panel has a high-pressure pumping station, a force-measuring device with a load scale, a "load-sludge" diagram apparatus, electrical equipment and machine controls. The total force the jacks can create is 1500 kN (up to 500 kN each). The error of readings from actual load is no more than ± 1 %. The high-pressure pumping station with variable production capacity located inside the control panel allows gently increasing and recording a steady load at any loading step for a long time.

Stresses and strains in the base of the foundation were measured by highly sensitive stress transducers (mesdoza) MK-37, MK-26 (measurement range 0÷0.25 MPa) and MK-54 (measurement range 0÷0.5 MPa) of the mechanism of Yu.N. Murzenko; deformation transducers (deformation gauges) D-2 designed by Yu.V. Galashev and Yu.N. Murzenko (figure 2).

To register and process the experiments results, the automated research system was equipped with a unit included a digital strain gauge station SIIT-3, connected through a special adapter with a computer. The control of the experiment and processing of the results are conducted with the help of
special developed software. The work [2] introduces the possibilities of the updated version of the automatic measurement system.

2.1. Experimental technique

The strip load in experiments with strip foundations [3] was simulated by three rough stamps (the roughness of the foot was provided with glued sandpaper) with dimensions $b = 180$ and $l = 700$ mm, located along the length leaving 5 mm gap. Thus, a strip $B = 180$ and $L = 2110$ mm is obtained where the ratio $L / B = 11.7 > 5$ corresponds to the condition of formulating the planar problem. The relative deepening is taken $H / B = 0.5$, that is similar to natural bases for the most common cases. The research program contained experiments to study the changes of rated voltage $\sigma_z$, $\sigma_y$ and normal deformation $\varepsilon_z$ while loading along the axis of the tape foundation model, as well as to study the path of motion of sandy basis particles under conditions of limit state. In the study of cooperation of the sandy basis under the rough tape foundation model, the deformations, stresses in the solid of the basis and the settlement of the stamp were simultaneously measured. To measure subsurface deformations in the basis to a depth of $3.75B$, strain gauges D-2 with $0.5B$ increments were installed; for measuring normal vertical and horizontal deformations in two planes along the model axis to a depth of $4B$, with the same increment some correspondingly oriented structural load cells of NPI (lower range limit) construction were installed. The paths of the particle were recorded on tinted screens that moved along with the stamp. Sand particles moving relative to the screen cause scratches on its surface – light traces of particles’ movement. After the experiments, the screens were carefully removed from the base and photographed.

Experiments with axisymmetrical load [4] were modeled by round steel stamps with a rough base (the roughness of the foot was provided with glued sandpaper) with various diameters in the range of 200-560 mm; the main diameter is taken as $D = 280$ mm. The relative deepening for the models, as it was in the experiments with tape loading, was $H/D = 0.5$. In experimental studies, an extensive program was carried out to study the change in normal deformations $\varepsilon_z$, $\varepsilon_y$, $\varepsilon_r$ and $\varepsilon_\theta$ in the base of sandy ground in conditions of its loading, up to the ultimate load. It was developed and applied for the first time an original method to identify normal deformations by the means of remote strain gauge transducers of the D-2 type of NPI construction.

During each of the conducted experiments the loading of stamps (models of foundations) was implemented in steps up to the ultimate load, when there was a constant growth of settlement and foundation uplift, suggestion the destruction of the sandy base in conformity with the first scheme described in the research of A. Vezis [5]. Further, when processing the results, the load at each step was recalculated in fractions of the limit value.

3. Results of the experiment

Diagrams of stress distribution across $\sigma_z$ and $\sigma_r$ in the base along the axis of the tape stamp (figure 3) are similar in shape to the experimental diagrams in experiments for other forms of loading [6], [7]. The values of vertical stresses $\sigma_z$ in the contact layer are recognized as maximum in depth only at the initial loading steps. Starting with the level of 0.38 MPa, the maximum stresses are recorded at a depth of 0.5$b$, and the value of $\sigma_z$ exceeds the average stress along foundation level. Stresses $\sigma_r$ are small enough, 5-7 times less than $\sigma_z$, measured at the same level, and rapidly decrease with depth. At all loading steps, excluding the last two, where the diagrams $\sigma_r$ and $\sigma_z$ have similar configurations, the values of $\sigma_r$ reach their peak in the contact layer.

Diagrams $\varepsilon_z$, $\varepsilon_r$ (figures 4 and 5) for round and tape stamps at the initial steps of loading are wave-shaped. It should be noted that, the intensity of strains growth in depth differs in the course of loading. The greatest changes take place in the layer $0.250D (b) < z < 2.0D (b)$. When the load reaches the value of 0.4 MPa of the round stamp and 0.6 MPa, – of the tape stamp, the diagrams are aligned, the strains values along the depth constantly increase to the depths $z = 1.0D$ and $z = 1.75b$ where the maximum value is recorded (respectively for the round and tape stamps), and then the values decrease.
The shape of the experimental diagrams $\sigma_z$ for a tape stamp in the loading range of 0.6 MPa - 0.98 MPa (figure 5, right side) requires the presence of a point in the layer $1.25 < z < 1.75$ where $\sigma_z$ reaches its maximum value. “Levelling” of the experimental diagrams with a cubic spline (figure 5 left part) allows to approximately evaluating the depth with the greatest vertical strains. Analysis of thus received diagrams proves that at loads greater than 0.6 MPa, the depth where $\varepsilon_z$ reaches its maximum value increases with loading growth, but does not exceed $z = 1.75b$. The wavy shape of $\varepsilon_z$ diagram along the stamp axis at the initial steps of loading, and its “levelling” at loadings close to 0.6 MPa, is also common to a concrete rectangular foundation that is noted in the research [7]. A similar effect on the distribution of vertical relative strains along the axis of the foundation is also established in experiments with loading foundations with a complex base contour [8].
4. Discussion of the results

On the base of the obtained results, it is logical to suppose that the wavy shape of the diagrams of normal relative strains $\varepsilon_z$ and $\varepsilon_y$ along the axis of the rough stamp, the transformation of their shape, as well as growth of the values of compression stresses at a certain depth in respect to the contact ones, are the results of the presence of some variable stress concentration. It is presented most likely with the sand core appearing and developing during loading.

Experimental studies of the destruction of bases under the models of rough foundations revealed that in all cases of the limit states, a condensed V-shaped sand core is formed directly under the rough foundation and is a natural continuation of the foundation. According to V.G. Berezantseva “…The condensed V-shaped core is a transitional volume of soil, forming thus the stresses arises along its surface, that can cause a continuous state of limit equilibrium in the rest displacing part of the foundation” [9].

Firstly this phenomenon was recorded in 1929 by M.Kh. Pigulevsky when pressing-in a stamp into the sand. Researchers of many scientists are devoted to the experimental study of the shape of the core by various methods. In particular, M.V. Malyshev applied the method of photographing sand particles with an apparatus moving along with the stamp. Using the same method M.Sh. Mintskovsky [10] fixed the shape of the core. According to the method of V.I. Kurdyumov (method of photographing) V.G. Berezantsev investigated the paths of sandy particles in a transparent tray at various depths of the stamp. P.N. Kashkarov [11] used waxed and paper screens to study the shape and sizes of the core.

When calculating the base load-bearing capacity, the shape and sizes of the core play an important role; the first mention about the core shape within vertical central load was made by K. Terzaghi [12]. He took a cross-section of the core in the form of an isosceles triangle, the sides of which are at the angle $\varphi$ to the foot of the foundation. The same form was adopted by M.I. Gorbunov - Posadov and V.S. Khristoforov. M.I. Gorbunov - Posadov, when setting the ultimate load on the foundation of a rough tape foundation and with the account of the results of experimental studies, accepted starting point the existence of two parts of the condensed sand core – “elastic” part, adjacent to the foot and “plastic” – continuation of the first.
Firstly, an original analytical solution to determine the shape of a condensed core is given in work of V P Dyba [13], in which the parametric equations of the core shape are determined in the process of obtaining permissible stress limits in a weightless foundation loaded with an ultimate tape load.

To assess qualitatively formed condensed core during the experiments on tinted screens, a coordinate scale was applied to the photographs to reveal the sizes of typical zones of paths of sandy base particles (figure 6). The analysis of the obtained results led to the following findings: 1. The most intensive movement of particles occurs directly under the stamp at a depth of 0.5b to 1.5b (light spots on screens of the photographs). 2. Directly below the foot a dark zone is located, it is almost triangular-shaped – the area of the core. 3. A darker spot can be distinguished in its turn in the core area – the “elastic” part of the core and the adjacent “plastic” less dark one. 4. In the limit state, the distance from the base of the foundation to the top of the “elastic” part of the core is within 0.2b-0.25b and respectively, its edges are oriented to the horizontal at an angle of 12°-15°. 5. At limit loads, the outer edges of the “plastic” part of the core are oriented to the horizontal at an angle of 41°-43°, close to the parameter of angle of internal friction. 6. Comparing the particle trajectories in the pre-limiting state (the screens are removed before registering the limiting state of the base) with the limit state, it can be supposed that the elastic part of the core is completely formed before the limit state, and the plastic part is formed in the whole loading interval up to the limiting state.

![Figure 6. Trajectories of particles motion on a tinted screen under a tape load.](image)

The formation and sizes of the condensed core at the base under the foot of the foundations at various loading steps can be seen in the density fields’ distribution in the base if the values of all components of the relative normal strains are registered. The values of these components were determined by measurement in the experiments of Yu.V. Galashev. with round stamps [9].

Taking into account that the density of the base mainly varies as the ratio of three linear strains $\varepsilon_z$, $\varepsilon_r$ and $\varepsilon_\theta$, correlate, i.e. spherical tensor of strains, and strain deviator changes the shape of the elementary volume, the components obtained in the base mass when experimenting under a round stamp, permit to calculate the changes in density with increasing load at each considered point of the base at each loading step according to formula 1:

$$\gamma' = \frac{\gamma}{1-(\varepsilon_z + \varepsilon_r + \varepsilon_\theta)}$$

(1)

Based on the density fields thus obtained, isolines of equal densities were constructed (figure 7), with the help of which it is possible to more clearly represent the view of the deformed base.
Figure 7. Isolines of equal densities in the massif of a sandy base under a round stamp at loads of 0.4 MPa, 0.6 MPa, 0.8 MPa, and 0.99 MPa.

Studies of the change in the strain fields in the sandy base mass at increasing loading steps made it possible to consistently investigate the development of strains areas, compaction and decompaction, the formation of a condensed core under the stamp and to assess this process with revealing of the phases of the stress-strain state of the base and the limits between them.

As it can be seen from figure 7 (a) even the initial loads 0.2 MPa - 0.4 MPa immediately cause changes in density and a condensed core is formed under the stamp foot, that is limited by an isoline of 17.52 kN/m$^3$, and reaches the depth of approximately 0.75 D. A load of 0.4 MPa (figure 7 (a)) quickly results in formation of local density areas. The decompaction area, increasing in the sides, approaches to the periphery of the stamp and is limited by an isoline of 17.43 kN/m$^3$. The density under the foot of the stamp grows very rapidly and amounts to 17.57 kN/m$^3$. This is the highest density in the massif at this loading step. At a depth of 1.5 D a compaction area with an isoline of 17.55 kN/m$^3$ is observed along symmetrical axis, and one more is observed at a depth of 2.0 D under the edge of the stamp. A load of 0.6 MPa (figure 7 (b)) brings in further compaction in the core area up to 17.60 kN/m$^3$ and even in greater compaction 18.08 kN/m$^3$ in the area at a depth of 0.5 D apart from the stamp edge by 1.0 D. It also can be seen that the local area of decompaction sharply increased in sizes and at its pole this area reached a density of 17.19 kN/m$^3$. At a depth of 2.0 D of the stamp axis, a compaction area with an isoline of 17.60 kN/m$^3$ can be seen.

The load 0.8MPa (figure 7 (c)) brings in greater increase in the decompaction area and reaches a density of 16.03 kN/m$^3$. Under the stamp foot, the growth of compaction strains is much less intense and amounts to 17.70 kN/m$^3$. The area of maximum compaction strains seems to have moved towards
to 1.2 D from the edge of the stamp and amounted to 17.90 kN/m$^3$, having reduced its size. Along the stamp axis, the compaction area at a depth of 2.0 D remained in the same place, having kept its value of 17.60 kN/m$^3$. Consequently, starting with a load of 0.8MPa, the compaction zone almost does not change. The load close to the limit 0.99 MPa (figure 7 (d)) is characterized by a further increase in decompaction in the local area under the edge of the stamp at a depth of 0.5-1.0 D. Here the density decreased to 15.56 kN/m$^3$, having captured total space under the edge of the stamp. Along the axis of the stamp, a kind of «pillar» with the maximum density in the core area has been formed.

5. Discussion of the results

The investigation results clearly prove the presence of a condensed core at the base under the footings; its outlines and sizes are formed in the process of loading the foundation. It is should be noted that corresponding distinct analytical solutions to reveal the upper and lower estimates of supporting capacity of foundations with an formed core under the footing of the basement, were taken into account by V.P. Dyba have been proposed the method of limit analysis of the “foundation - basis” system [14], [15], which leads to more reliable estimation of soil foundations according to the first group of limit states. However, design practice shows that the loads from fou

References

[1] Murzenko Ju N 1967 Bases, Foundations and Soil Mechanics: coll. of art. (Moscow: Hihg School) 2 18–20
[2] Subbotin A I 2018 Int. Res. J. 1 (67) 142–9
[3] Murzenko Ju N and Skibin G M 1996 Research and Development on Computer-Aided Design of Basis and Foundations: proc. (Novocherkassk: NGTU) pp 53–7
[4] Murzenko Yu N, Galashev Yu V and Dyba V P 1977 Study of the Stress-Strain State of Basis and foundations (Novocherkassk: NPI) 1 23–7
[5] Vesic A S 1973 J. of the Soil Mechanics & Foundation Division 99 SM1 45–73
[6] Galashev Yu V 2008 Bulletin of higher educational institutions. North Caucasus Region. Technical Sciences 1 49–52
[7] Murzenko Ju N, Subbotin A I and Skibin G M 1988 Research and Calculation of Basis and Foundations under the Action of Static and Dynamic Loads (Novocherkassk: NPI) pp 85–90
[8] Glushkov A V 2015 Modern Problems of Sci. & Edu. 2 1 708
[9] Berezantsev V G 1970 Calculation of the Foundations of Structures (Leningrad: Stroyizdat)
[10] Mintskovski M Sh 1962 On Some Questions of the Plane Problem of Stability of the Foundations of Structures (Kiev: ASiSa)
[11] Kashkarov P N 1960 Improvement of the Waxed Screen Method for Investigating the Deformations of the Sand Base (Leningrad: VNIIG)
[12] Terzaghi K 1947 Theoretical Soil Mechanics (New York: Wileg)
[13] Dyba V P 1980 Experimental and theoretical studies of the processes of elastoplastic deformation of basis and foundations: proc. (Novocherkassk: NPI) pp 17–28
[14] Dyba V P, Shimatkov S B and Solomin V I 1997 Comptesrendus du quatorzieme congres international de mecanique des solset des travaux de fondations (Hambourg, 6-12 Sept. 1997) 1 pp 975–8
[15] Dyba V, Skibin G, Matvienko M and Osipova O 2019 Sciences and Technology. Engineering and Earth Sciences: Applied and Fundamental Research. Proc. of the Int. Symp., dedicated to the 85th anniversary of H.I. Ibragimov (ISEES 2019) 1 pp 461–4