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Full-scale investigation of the basement and the cellular foundation of the nuclear reactor section

Investigation à grande échelle du sous-sol et de la fondation cellulaire de la section du réacteur nucléaire

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SYNOPSIS: The nuclear power station (NPS) reactor section building (RS building) weighing about 250000 metric tonnes is based on a 2I m thick sand layer. Granite is deposited at a depth of 70 m from the foundation footing. The foundation dimensions are 68 x 68 m, its height is 20 m and its laying is about 7 m. Vibrating-wire devices have been used to measure the contact pressure between the foundation footing and the basement, the stresses in the steel reinforcement and in the concrete. The foundation settlement as well as the deformations of the basement layers are determined by the geodetic method. The real modulus of the deformation is calculated for the foundation as well as for two similar RS buildings constructed on the same site. The measured forces in the steel reinforcement and in the concrete confirm the experimentally recorded pattern of contact pressure distribution which is favourable with respect to the function of a centrally loaded foundation.

I INTRODUCTION

The geological structure of the site is represented by the following strata (from top to bottom): river quartz sand (medium and fine, of the medium density and dense, with the angle of internal friction $\varphi = 32^\circ$ and cohesion $c = 0.001$ MPa, thickness about 28 m); sand loam and loam with $\varphi = 25^\circ$, $c = 0.019$ MPa, thickness in the average is 18 m; dusty sand $\varphi = 24^\circ$, $c = 0$, thickness 11 m; sandstone, $\varphi = 23^\circ$, $c = 0,027$ MPa, thickness 18,5 m; firm granite.

The ground water level is at a distance 6 m from the surface.

The cellular foundation of the RS building is made of cast-in-situ and pre-cast reinforced concrete. Monolithic are the lower I and the upper 2 slabs, Fig.I. The thickness of each slab is 2,4 m. The internal walls and diaphragms are made of pre-cast reinforced concrete. The mean value of the concrete modulus of elasticity is $30 \cdot 10^3$ MPa. The mean pressure from the foundation weight $q_1 = 0.22$ MPa. The RS building consists of the inner cylinder-shell 47,4 m in diameter. The wall

thickness of the cylinder made of prestressed reinforced concrete is 1,2 m. The shell containing the structures and the production

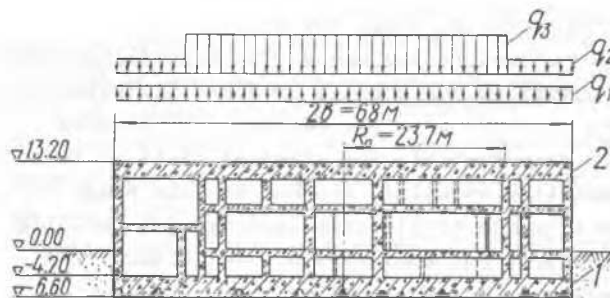


Figure I. Schematic sectional view of the foundation and the acting external loads

equipment transfers mean pressure $q_3 = 0.511$ MPa to the upper slab of the foundation. A rectangular in plan construction is build around the cylindrical shell productind mean pressure $q_2 = 0.203$ MPa. The resultant load from the building is applied to the centre of the foundation.

The following construction stages can be separated, which influence the stressed and deformed state of the basement grounds and

the foundation itself. The first stage is the construction of the cellular foundation and the concreting of the upper monolithic slab until it gains strength. The duration of the construction work is from 1.5 to 2 years. At this stage, the external load is transferred to the basement via the lower slab and the distribution of the ground contact pressures over the slab bottom is determined by the large dimensions and the large flexibility of the slab, by the absence of the backfilling, by the rather low unit load on the basement q_{I} . The slab settlement and deflection depend, among other things, on the degree of the basement thinning (dispersion) due to the removal of the natural ground pressure in the excavation work.

The second stage of the construction and the structure functioning begins once the upper slab "closing" the foundation box gains in strength and, in consequence, a sharp increase of the stiffness of the whole structure takes place. In erecting the cylindrical part of the RS building and in building the construction around the cylinder, the pressure on the ground basement is transferred by this rigid box. In addition, once the construction of the shell is over, the stiffness of the whole structure increases. The backfilling has an effect on the contact pressure distribution. Mean pressure over the footing "p" becomes more than doubled. The stressed state of the foundation structure depends at this stage on the sequence of its area loading with building structures and equipment mounted within the shell and the construction.

At the third stage of the construction which comprises the final assembly of the structures and the equipment, a further change in the deformed and stressed state of the foundation and the basement takes place which is caused by the concrete and ground creep flow, the ground water level variation after dismantling the water lowering system etc.

2 TEST EQUIPMENT

The upper and the lower monolithic slabs of the foundation have been provided with earth pressure cells, reinforcement dynamometers and concrete extensometers. The foundation

settlement and inclination have been measured by means of optical levelling. To this end, settling marks have been set along the lower slab perimeter at 20 points after its arrangement. The measurement of the settlements has been carried out by the Foundation and Base Chair of the Dnepropetrovsk Construction Engineering Institute.

Deformations in the basement layers have been determined by means of 9 depth marks with the anchors located at a distance of 6, 9, 12, 15 and 20 meters from the foundation footing. A diagram illustrating the arrangement of the measuring equipment in the lower slab is shown in Fig. 2. Altogether 36 soil dynamometers of the SDKS-6VMR and SDKS-7 types are installed in both monolithic slabs (Lazebnik 1982, 1985), 38 reinforcement dynamometers, 21 concrete extensometers and 11 vibrating-wire thermometers.

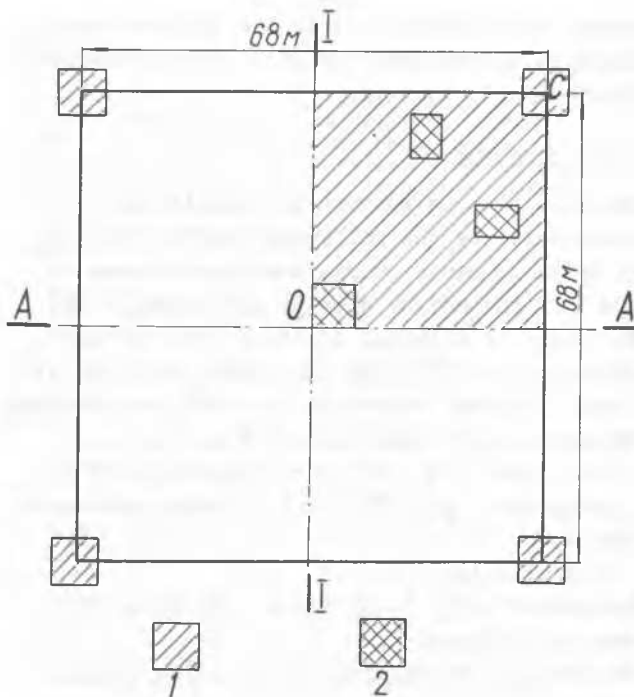


Figure 2. Diagram illustrating the arrangement of the measuring devices in the lower cast-in-situ foundation slab: I - the places of installation of the earth pressure cells; 2 - the places of installation of the reinforcement dynamometers and concrete extensometers

The whole equipment as well as the PDS transducers used in the earth pressure cells

are of the domestic fabrication. A sectional view of the SDKS-7 earth pressure cell is presented in Fig. 3.

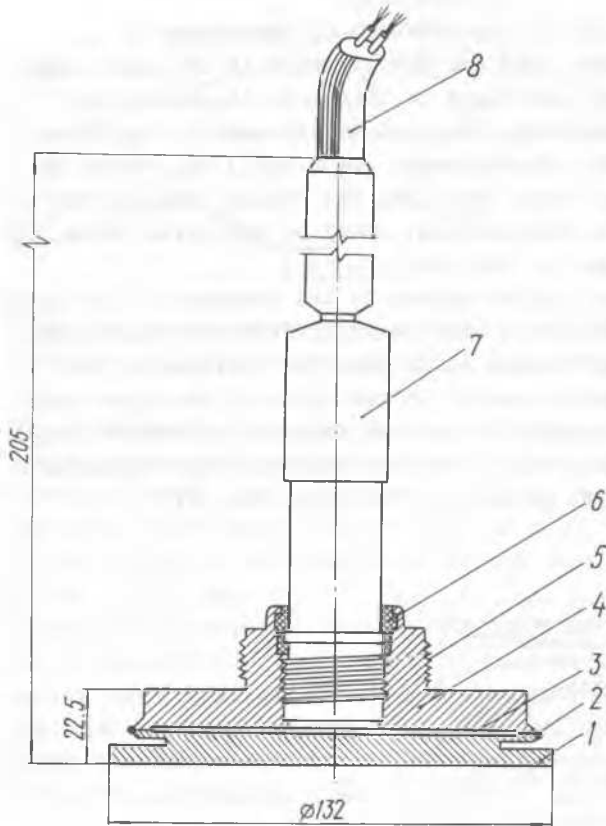


Figure 3. Schematic diameter section of the SDKS-7 earth pressure cell: 1 - contact platform; 2 - electrical weld; 3 - hydraulic cavity; 4 - body; 5 - adjusting thread; 6 - epoxy-based cement; 7 - PDS transducer; 8 - double-conductor flexible cable

3 EXPERIMENT RESULTS AND DISCUSSION

Once concrete of the lower slab was placed, the contact pressure distribution was practically uniform with a slight increase in the center. As the external load grows, the convexity increases, not only at the first stage of the construction, when the slab flexibility is high, but also at the second stage, after an increase in stiffness of the whole foundation. The pressures under the slab edge are lower than those obtained by calculations based on the Boussinesq hypothesis or on that of the elastic layer on a rigid basement.

Prior to the backfilling of the pockets with soil the pressures under the slab edges in sections O - A and O - I, Fig. 2 do not exceed on the average 0.08 MPa (ref. to curves I and 2 in Fig. 4, a). After the backfilling of the ground and the increase load on the foundation, the pressures under the edges increase more intensively, but they do not reach the values of the footing central part. In the diagonal section O - C, Fig. 2, the pattern of the pressure distribution is similar to the described one, but the pressure concentration in the corners is higher, ref. to Fig. 4, b. The percentage of the pressure under the slab corner to that in its center is about 93%.

The cause of the pressure increase in the center is the impossibility of horizontal displacement of basement ground under the central portion of the slab footing due to its large dimensions. Because of this, this portion of the foundation functions under conditions of the uniaxial compression. A compressed zone is formed here, which can be considered as the first stage of the formation of the well-known "ground core" under the foundation. The cause of the pressure concentration under the corners of the square slab is obvious. A foundation that is round in plan is more preferable from the point of view of uniform pressure distribution.

With the external load at its permanent value, some change of the chart shape takes place in the course of time after the completion of the construction. The reacting pressures in the center become larger; the increase of the pressures under the slab edges and corners lags behind. Fig. 5 presents an approximate axonometry of the contact pressure charts measured at the end of 1987, i.e. several months after the construction is over. The percentage of pressure under the slab edge with respect to the pressure in the center is 55% (as compared to 61% immediately after the end of construction); under the slab corner it is equal to 76% (as compared to 93% mentioned above). The cause of this is the creep flow of the concrete and the ground with the substantial external load.

The discrepancy between the measured and the

applied external load calculated from the volume of the contact pressure chart did not exceed 5%. The reinforcement dynamometers of the monolithic slabs have fixed the qualitative and the quantitative aspects of the structure state resulting from its varying stiffness and from the succession of the executed work, when the load on the foundation is created alternately along the perimeter (by the rectangular construction) and in the center.

In this connection, stress in the reinforcement and in the concrete varies in a wave-like manner alternately increasing and again decreasing (ref. to Fig. 6, curves 3 to 6). Up to the mean pressure $p \approx 0.4$ MPa, tensile (+) stress in the middle portion of the upper reinforcement belt of the lower slab (ref. to curve 4, Fig. 6) was always greater than the stress in the lower belt (ref. to curve 3, Fig. 6) which points

to the tendency of the slab to arch with its middle part upwards. This is in good agreement with the originating distribution of the reaction pressures along the footing. Then, to judge by the increase of the stress in the lower belt and the decrease in the upper one, the slab tends to bend with its convexity downwards. The maximum stresses in the lower slab reinforcement reach -55.3 MPa, which is 6,5 times less than the design stresses for the reinforcement steel of the given brand equal to 360 MPa.

The tensile stress in the concrete of the lower monolithic slab obtained from the experiment has reached -4.48 MPa. The stresses in the reinforcement of the belts of the upper slab vary also as the building is constructed. Their values are negative from the very beginning (ref. to curves 5 and 6 in Fig. 6).

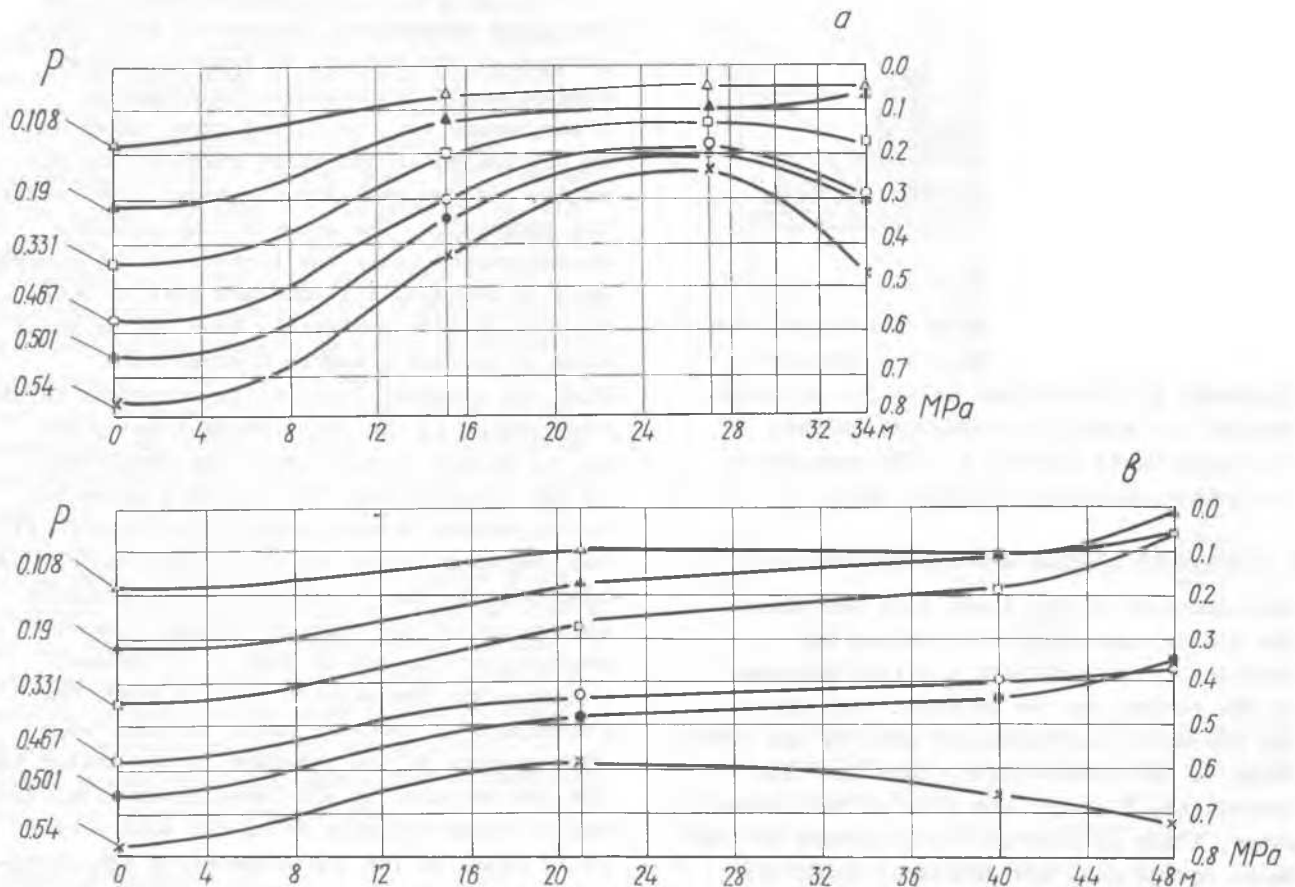


Figure 4. Diagram illustrating ground contact pressure on the foundation footing measured as the pressure p grows: a - mean values for section 0 - A and 0 - I ; b - mean values for section 0 - C (diagonal)

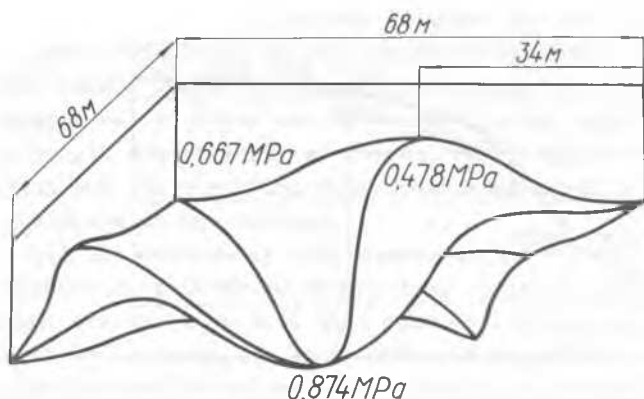


Figure 5. Axonometry of the curves of contact pressure on the foundation footing (end 1987)

The compressive forces in the reinforcement of the upper slab upper belt are at first somewhat lower than the forces appearing in the lower belt (curve 6). The maximum value of the stress in the reinforcement does not exceed - 34.5 MPa.

Rather low stresses in the reinforcement and in the concrete of the monolithic slabs obtained in the investigation are accounted for by the high strength and rigidity of the cellular foundation whose estimated flexibility index r (Gorbunov-Possadov & Malikova 1973) is

$$r = 0.35 < 4/a = 4,$$

as well as by the ground pressure distribution with the maximum in the central part of the bottom fixed in the experiment.

Ground basement deformation modulus E_0 is determined from the well-known formula for a rigid square footing:

$$E_0 = 0.88 \frac{p \cdot a' (1 - \mu_0^2)}{S_0}$$

where p is the mean pressure along the bottom resulting in settlement S_0 ;

a' is the footing side (68 m) ;

μ_0 is Poisson ratio (= 0.3).

The calculated E_0 values of the basement of the investigated foundation and of the foundations located adjacent to it are equal to 323, 314 and 259 MPa, respectively, and the mean value is 298.7 MPa. These E_0 values are close to those obtained in (Morel et.al. 1977) in investigations under the foundations of the

reactor sections of the NPS Bugey 2 and Bugey 3 which range from 200 to 360 MPa and they are approximately by an order of magnitude greater than those determined as a result of the footing tests carried out before the construction of the described installation. The mean value of E_0 according to these tests is approximately 30 MPa. It was previously established (Gorbunov-Possadov & Malikova 1973) that under slabs whose length and width come to tens of meters, the actual values of the ground deformation modulus are much greater than the modulus obtained in footing tests.

The mean value of the foundation settlement was approximately 8.5 cm with $p = 0.54$ MPa (ref. to curves I and 2, Fig. 6). The settlement chart comprises the measured part, i.e. the chart section to the right of the vertical line with the beginning date of the settlement instrumental observations 15.08.1985, and the part calculated using the settlement increment data for all three foundations arranged on the construction site with regard to the basement creep.

The inclination (tilting) of the foundation is directed to the north-west and it is probably caused by some non-uniformity of the basement. Its magnitude is 2.27 cm, i.e. it is equal to 1/4 of the mean settlement. This magnitude of the inclination is not dangerous for the normal functioning of the installed technological equipment.

The deformation of the basement layers decrease rather slightly with the depth. At a depth of 15 m, the settlement of the spread anchors of the depth marks exceeds 2 cm; at a depth of 20 m it is 1.8 cm. The depth of the compressed stratum under the large-sized foundation of the RS building is likely to be greater than that usually recommended by the calculations and design manuals.

4 CONCLUSIONS

(1) The contact pressure distribution on the cellular foundation footing of the RS building differs substantially from that obtained by calculation for a rigid slab using the Boussinesq hypothesis or that of the elastic layer on a rigid basement.

(2) The stresses in the longitudinal reinforcement of the upper and the lower monolithic

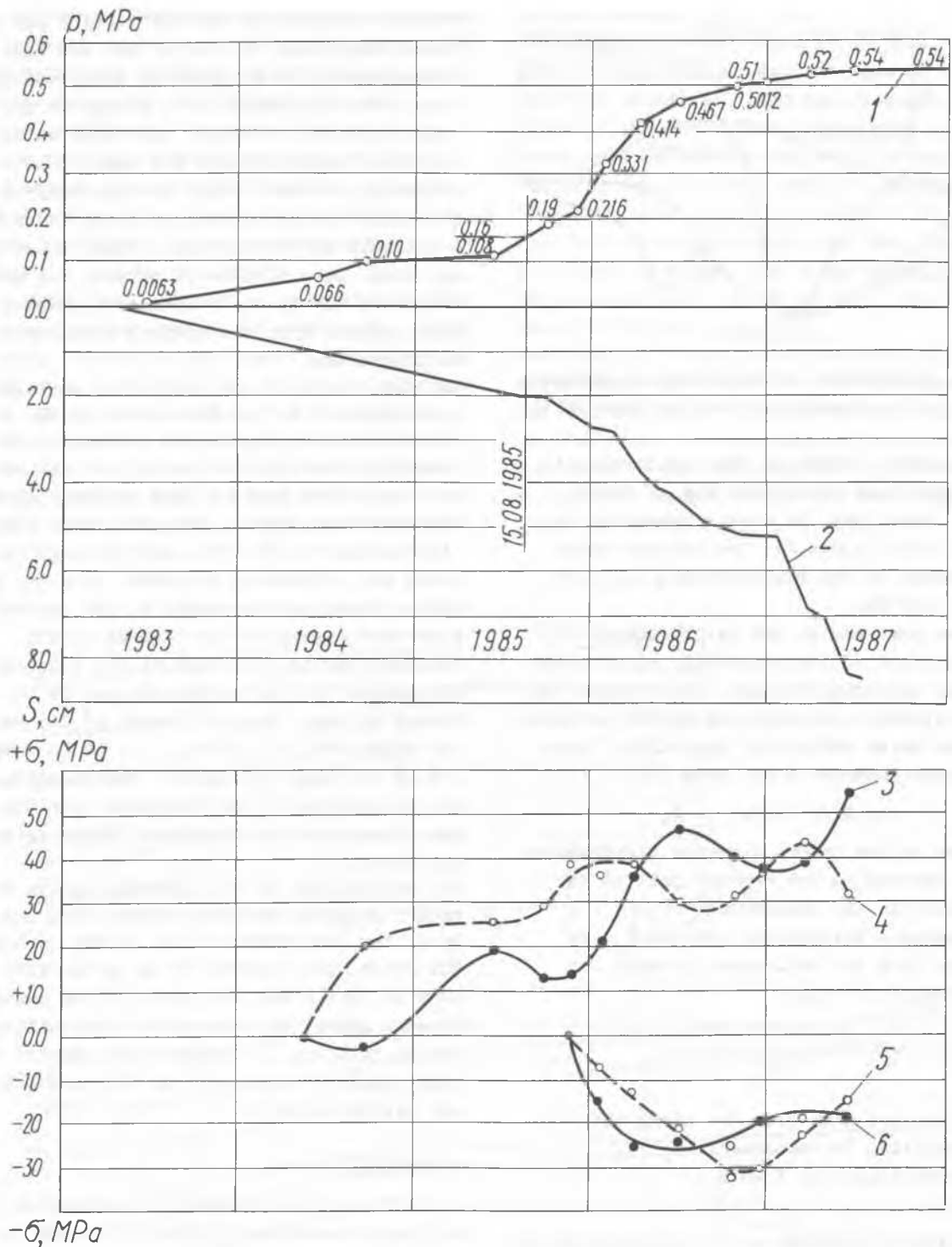


Figure 6. Measured values of the foundation settlement and the stresses in the reinforcement of the lower and the upper cast-in-situ slabs as the construction load grows: 1 - curve of the growing mean load p ; 2 - curve of the settlement S vs construction years; 3 - stresses in the reinforcement of the lower slab lower belt; 4 - ditto, in the lower slab upper reinforcement belt; 5 and 6 - stresses in the upper and in the lower belts of the upper slab respectively

slabs vary depending on the sequence and the order of execution of the construction work. The stress values are far from reaching the design values which are determined by the high strength and rigidity of the cellular foundation and the resulting distribution of contact pressures on the footing.

(3) The modules of deformation of the basements of three RS foundations built on the same construction site that were determined in full-scale tests are by an order of magnitude greater than those obtained by means of footing tests carried out in previous geotechnical surveys.

(4) The foundation settlement and inclination are within the allowable limits. The facts listed above point to the sufficient reliability of the foundation.

(5) Thickness of the compressed stratum of the basement is more than 20 metres according to the measurement data. The experimental investigations in this part require extension and development.

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