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LONG-TERM SETTLEMENT OF BUILDINGS ERECTED ON DRIVEN CAST-IN-SITU PILES IN LOESS SOIL

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Results are presented for long-term geodetic observations of the settlement of residential buildings erected on driven cast-in-situ piles that are part of foundation frames on loess soil. Stabilized deformations of building foundation beds are compared to the results of analysis using normative methods and simulation of the stress-strain state of the system using two- and three-dimensional versions of the finite element method and a plastic-elastic soil model.

Driven cast-in-situ piles (DCSP) are distinguished by a high bed load-bearing efficiency resulting from the creation of a compacted zone with soil the exhibits lower deformation properties. Such piles reduce the scope of earth-moving operations, reduce concrete use by between 15% and 50%, reduce metal use by between 33% and 75%, reduce overall cost and labor requirements by between 33% and 50%, and shorten initial construction work by between 33% and 50% as compared to foundations built by excavating soil or sinking prefabricated elements into the soil mass [1-4]. It makes sense to use DCSP in loess macroporous soil containing native moisture when erecting buildings with strip foundation frames. Currently, the use of DCSP has met with success. For example, a technique has been approved for driving broken stone into a weak, 1-2-m thick intermediate layer to improve the geoengineering properties of alluvial beds [5].

DCSP are set up by driving holes in the ground using a cylindrical ramming appliance and then filling the holes with concrete. To improve resistance to load, a portion of the hole is widened (Fig. 1) using driven broken stone (up to V_{cr} = 2 m^3 in volume) or low-slump concrete. The DCSP dimensions are: bore diameter b = 400-800 mm; pile height h_k = 1.5-10 m (sometimes up to 20 m); diameter of widened portion d_{br} = 700-1200 mm. If, in response to watering, the loess moisture reaches $W > W_p$ + (0.01-0.03), where W_p is the soil moisture at the plastic limit, an effect occurs in which the ramming appliance is drawn in by the soil, which is lessened by pouring some additional broken rock into the hole.

This DCSP method has proven itself as one of the most economically effective and universal ways of creating foundations in large-scale construction, which is largely conditioned by the use of mobile equipment as basic rigs [1-6].

The authors have worked out a procedure for DCSP calculation [4, 6], in accordance with which the dimensions of the widened portions and compacted zones of the pile are related to ramming appliance parameters, materials used for widening, soil properties, and the distance between pile centerlines. In order to expand the normative base for DCSP design and to improve DCSP reliability, the procedure for determining settlement of buildings that rest on DCSP strip foundations must be improved.

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Fig. 1. Widened portion of a cast-in-situ pile in a driven hole.

The most reliable path to solve this problem is to compare the stabilized settlement for full-scale objects calculated using different methods with measurements made over long-duration geodetic [7-10]. In particular, the work done in [7] to study "strip foundation-cast-in-situ piles-soil" systems established that when the distance between pile centerlines is between three and four diameters *d* of the pile cross section, the soil between them may be considered to be a single mass; the foundation frame becomes engaged at a settlement of 1.5-4 mm; the greater part of the settlement is due to the layer under the compacted zone.

A shortcoming of the method of determining the settlement of buildings that rest on DCSP strip foundations using a scheme of individual piles with widened portions [11] lies in ignoring the mutual influence between neighboring piles, in which bed settlement goes down as the distance between centerlines is reduced, especially down to (3-4)*b*. To improve the procedure for calculating the settlement of buildings with DCSP, the solution to the two-dimensional problem may be taken as the basis.

Long-duration geodetic observations of the settlement of buildings that rest on DCSP strip foundations in loess soil (including wet loess soil) are used to determine patterns in the development of such deformations over time and their stabilized (final) values.

Discussion of results

Observations of the settlement of buildings with DCSP, begun in 1984 and continuing to this day (involving approximately thirty sites) were carried out using an accuracy class 3 method of spirit leveling [12] using marks on deformation surfaces and reference transit points [7-10]. After erecting the base course, 20-mm diameter rebar pins-surface marks-were embedded 130 mm into the brickwork (or between blocks) at selected points in the building load-bearing wall. The distance between these marks was up to 15 m. At some sites, the marks were also created in interior load-bearing walls. Settlement marks were created during building erection in the ordinary manner, i.e., on every other floor. At the same time, the scope of performed activities to determine pile loads were recorded. These data were used to plot curves of mark settlement over time.

Of greatest interest are the results of long-term observations of the settlement of buildings that rest on DCSP strip foundations in wet loess. The bearing layer of the pile bed consists of clay loam with a water-saturation factor $S_r > 0.80$ and deformation modulus $E = 4\text{-}7$ MPa, while the underlying layer consists of clay loam with $E = 5.5\text{-}19$ MPa. Under these conditions the most complete information was obtained for seven residential buildings (Table 1): two 10-story buildings, three 9-story buildings, and two

TABLE 1

Site description, No. of stories	E, MPa of load-bearing layer	E, MPa of underlying layer	h_k, m	V_{cr}, m³	Settlement, mm, prior to operation $S_{max}(t)$	prior to operation $S_{min}(t)$	prior to operation $S_{avg}(t)$	stabilized $S_{max}(t)$	stabilized $S_{min}(t)$	stabilized $S_{avg}(t)$	S_u, mm	Measured inclination, i	Maximum inclination, i_u [11]	Settlement stabilization time, yr	Settlement during period of construction and as fraction of final settlement
Poltava, ul. Kurchatova, 17; 9 floors	7	16	5.0	1.5	115.5	60	81	166	80	111.5	180	0.0005	0.005	15	0.725
Poltava, Stepnoy Front ul., 29; 9 floors.	6	14	2.5	2.0	93	48	79.5	175	101	124.3	120	0.0004	0.005	12	0.64
Poltava, ul. Petrovskogo, 31; 10 floors	6	9	2.5	1.5	81	59.5	62.1	122	72.5	90.0	120	0.0004	0.005	11	0.69
Poltava, ul. Gozhulyanskaya, 9 floors	6	7	2.0	2.0	49/55	31/36.5	39.7/45.9	67.5/78	45/52	54.4/64.6	120	0.0002	0.005	10	0.73/0.71
Poltava, b-r. Borovikovskogo, 7; 10 floors	6	5.5	2.0	2.0	58/70	38/58	45.6/64.5	77/96	52/78	61.4/87.9	120	0.0002	0.005	11	0.74/0.73
Rassoshentsy village, ul. Gorbanevskaya, 4; 5 floors	4	6	1.6	0.75	73	28.5	46.5	105	49.5	66.6	120	0.0003	0.005	8	0.70
Zen'kov, ul. Pogrebnyaka, 18; 5 floors	4.5	19	2.5	1.5	34	14.5	24	58	20	32.7	120	0.0004	0.005	7	0.73

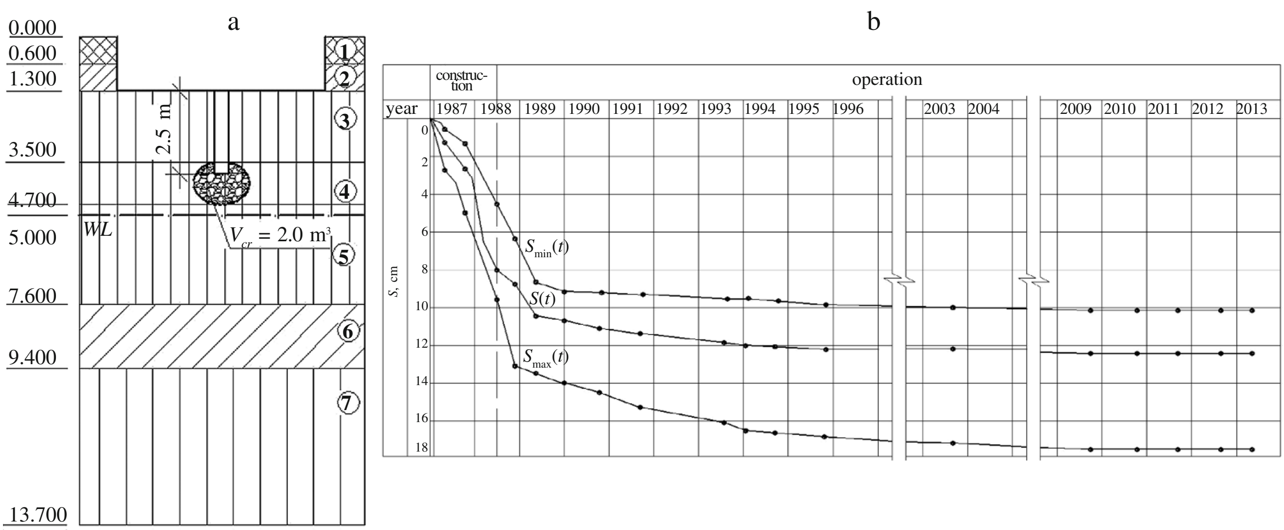

Fig. 2. Typical geological engineering cross-section of the studied sites (a) and plots of the evolution of building surface mark settlement (b): 1) fill and unpaved top soil; 2) humous clay loam; 3) hard and stiff loess clay loam; 4) stiff loess clay loam; 5) high-plasticity loess clay loam; 6) stiff clay loam; 7) low-plasticity loess clay.

5-story buildings. The pile diameter was 0.5 m, the driven hole depth h_k = 1.6-2.5 m (5 m at one site), the amount of broken rock driven into the widened portion V_{cr} = 1.5-2 m³ (0.75 m³ at one site). The DCSP distribution is primarily single-row (with a distance between adjacent piles generally l_w = 3-4b, but not greater than l_w = 5b, and in individual cases, in double rows or a checkerboard pattern).

A typical geological engineering cross-section is shown in Fig. 2a. Plots of minimum $S_{min}(t)$, average $S_{avg}(t)$, and maximum $S_{max}(t)$ surface mark settlement over time at this site are shown in Fig. 2b.

An analysis of the results of geodetic measurements of the settlement of buildings that rest on DCSP strip foundations (see the table), established that

– average settlement S_{avg} and their relative difference $\Delta S/L$ did not exceed the maximum values set forth in standards [13] (for sites Nos. 1 and 2 with cast-in-situ concrete reinforcing belts and reinforced brickwork, the average maximum settlement was S_u = 180 mm, and for the five others, S_u = 120 mm); load-bearing wall deflection was 60%, and inclination was at least 90% smaller than limit values for bed deformation [13]; there were no visible defects or deformations in load-bearing structures, and the technical condition of the buildings met the criteria for "normal";

– the share of average building bed settlement over the period of their construction and residential settlement (1-1.5 yr) was 0.64-0.73 of the stabilized building settlement;

– the intensity of load growth on the DCSP over time approximately corresponds to a linear function; the rate of settlement evolution depends on the rate of loading (erection), which is approximated by an exponential function, but the final settlement values for buildings or their sections under identical soil conditions were close to each other;

– the bed settlement stabilization time (criteria: mark settlement increment exceeds 1 mm/yr) is up to 12 yr after residential settlement for 9- and 10-story buildings; up to 8 yr for 5-story buildings;

– at sites 4 and 5, bed settlement under interior walls exceeded settlement under exterior walls by 16%-30% for identical loads on an individual pile. This effects is conditioned by the smaller distance between pile centerlines under interior walls as compared to the same distance under exterior walls. Thus, owing to the stressing below the widened portions of adjacent DCSP, their total stress and settlement under interior walls turned out to be greater than under exterior walls.

An analysis of settlement S for beds with DCSP strip foundations was carried out using the methods:

a) as for an individual pile with a widened portion (using relation (7.36) from [11]);

b) of layer-by-layer summation [13] as for a provisional strip foundation of width b_y, which is equal to the diameter of the widened portion d_{br} for a uniform distribution of piles (for a double-row or checkerboard pattern of DCSP distribution, the width of the provisional diameter was taken as the sum of the distance between the centerlines of pile rows and the diameter of the widened portion). The load-bearing layer under the widened portion consists of an upper zone of sufficient compaction and a lower zone of natural soil. The deformation modulus in the zone of sufficient compaction may be taken to be 3 times that of natural soil [14]. For wet loess, the deformation modulus was determined from compression test data without the use of multiplier factors [15].

To assess the confidence level in the determination of DCSP building settlement, a calculation confidence factor proposed by Prof. S.N. Sotnikov [8], was calculated, equal to

$$k = S_\infty/S,$$

where S_∞ is the stabilized settlement, obtained from long-duration geodetic observations; S is the calculated settlement of the building bed.

From Fig. 3, which compares DCSP building settlement in wet loess soil calculated using different methods, it follows that:

– settlement for individual piles with widened portions [11] is always less than measured values for very wide dispersion of the factor k = 1.03-2.76. The relative error in determining settlement does not exceed 10% (and also 20%) in only 2 cases of 9 (Fig. 3a);

- settlement calculated using the layer-by-layer summation method as for provisional strip foundations are most close to measured values for a sufficiently narrow dispersion of k = 0.91-1.19. Here, the relative error in determining settlement does not exceed 10% in only 3 cases of 9; and 20% in another 6 cases (Fig. 3b), i.e., all calculated settlement values lay in the interval $\delta = \pm 20\%$.

Similar studies were also carried out for buildings on DCSP (Fig. 4), the load-bearing layer of

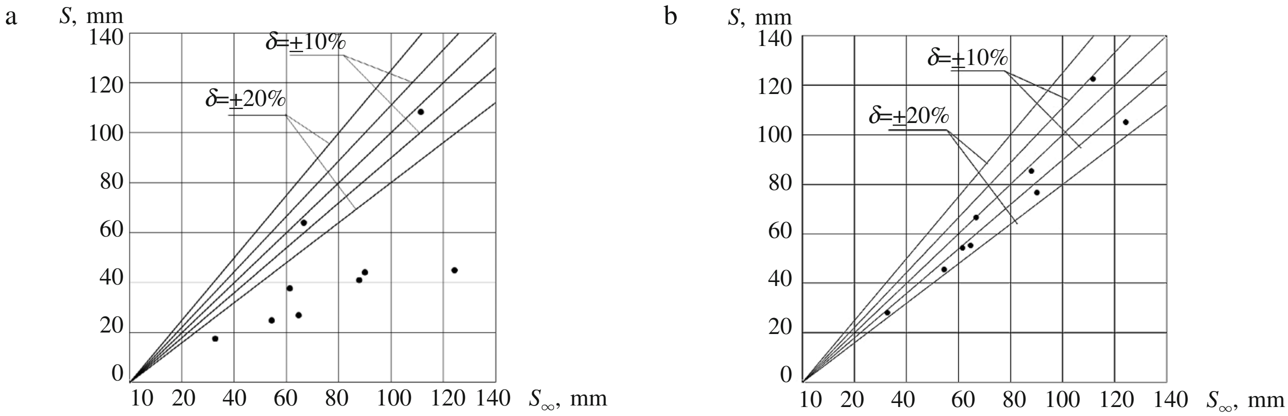

Fig. 3. Comparison of settlements S for buildings on DCSP, calculated using engineering methods and measured stabilized values S_∞: a) for an individual pile with a widened portion; b) for a provisional strip foundation using a layer-by-layer summation method.

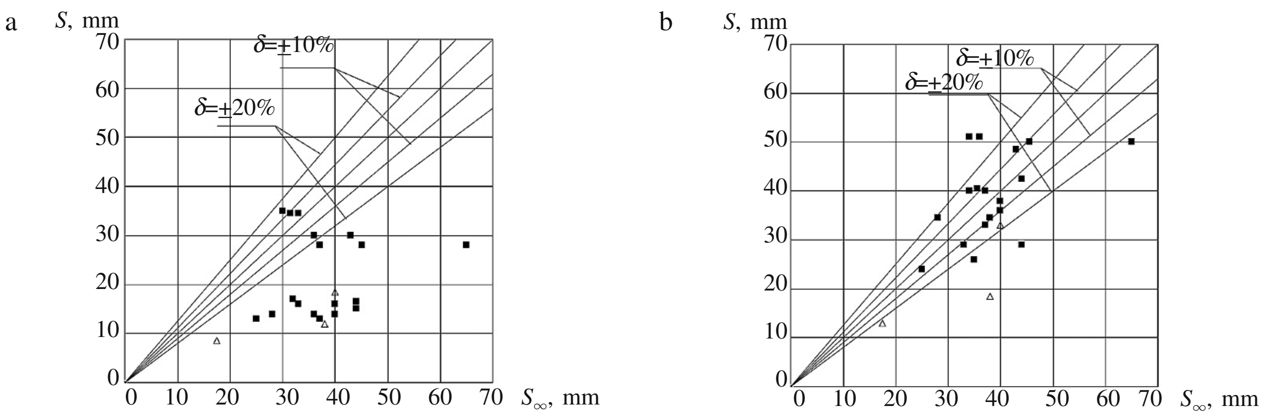

Fig. 4. Comparison of DCSP building settlement calculated using engineering methods S and measured stabilized values S_∞ in clay soil with water-saturation factors $S_r < 0.8$: a) as for an individual pile with a widened portion; b) as for a provisional strip foundation using the layer-by-layer summation method; △) clay loam and loam with E = 8-23 MPa; ■) sandy loam with E = 25-30 MPa.

which were composed of unwetted sandy loam, clay loam, or clay with $S_r < 0.8$ and E = 8-30 MPa. For these conditions, the most complete information was obtained for 21 buildings: nineteen 9- and 10-story buildings and two 5-story buildings. The pile parameters were: b = 0.5 m; h_k = 2-7 m; V_{cr} = 1.5-2 m^3. They are distributed in a single row, a double row, and in a checkerboard pattern in the foundation frame. In dense sandy loam with E = 25-30 MPa, the calculated settlement was always less than measured values, and in particular, using the method of layer-by-layer summation as for provisional strip foundations by a factor of almost two for k = 1.14-1.96. And for beds composed of clay loam and clay with E = 8-23 MPa, we have:

– settlement calculated as for individual piles with widened portions [11] is almost always less than measured values for k = 0.86-2.74. Here, the relative error in determining settlement does not exceed 10% in only 2 cases of 18; and 20% in one (Fig. 4a);

– settlement calculated using the layer-by-layer summation method as for provisional strip foundations are most close to measured values for a narrower dispersion of k = 0.65-1.57. Here, the relative error in determining settlement does not exceed 10% in only 6 cases of 18; and 20% in another 8 cases (Fig. 4b), i.e., all calculated settlement values lay in the interval δ = ±20%, or in 78% of the selected sites.

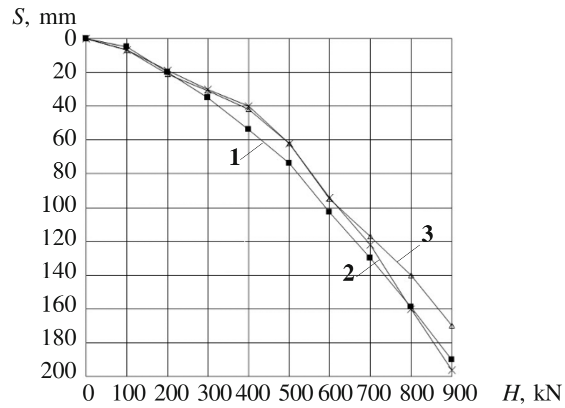

Fig. 5. Load-settlement plots using the results of 2D and 3D simulation and geodetic observations of an DCSP building: 1, 2) 3D and 2D simulation; 3) field observations.

Simulation was carried out using the Plaxis Foundation package [16] using three-dimensional (3D) and two-dimensional (2D) versions of the finite element method (FEM) for the "strip foundation frame-DCSP-bed" system at site No. 2 (see the table). The results were used to plot load-settlement curves that were compared to geodetic observation data (Fig. 5).

In the end, for 2D and 3D simulation using an elastic-plastic soil model with the Mohr-Coulomb strength criterion and stepwise-iterative procedures for the interaction between wet loess and DCSP strip foundations, the relative error did not exceed 15% compared to field observation data. The soundness of considering nonuniformity in the pile "zone of influence" [4, 14, 16] was demonstrated. Both simulated and experimental load-settlement plots exhibit curvilinear behavior.

When comparing DCSP bed settlement at site 2, relative errors are obtained in comparison to geodetic observations. For 2D simulation, 8.6%; for 3D simulation, 12.6%; for analytical calculations-63.8% as individual piles with widened portions; 15.5% as provisional strip foundations using the layer-by-layer summation method.

Research results suggest that the most reliable method for calculating settlement for beds with DCSP foundations is simulation using a two-dimensional finite element model; of analytical methods, layer-by-layer summation using an analytical model of the provisional strip foundation. Based on the approach to layer-by-layer summation, the engineering method of determining the settlement of buildings that rest on DCSP strip foundations, in which the width of the provisional strip foundation is taken to be the diameter of the rigid widened portion of the pile, and its depth of occurrence corresponds to the bottom of the widened portion [6]. The relative error of the method does not exceed 20% in comparison with measured stabilized settlement at the actual sites.

Conclusions

1. Data was obtained for the evolution, over time, of buildings that rest on DCSP for distances of 3b-5b between piles in loess and wet loess soil. The fraction of average DCSP settlement over the period of building erection and residential settlement was 0.64-0.73 of the stabilized building settlement. The stabilization time in wet loess beds for 9- and 10-story buildings after residential settlement was up to 12 yr; for 5-story buildings, up to 8 yr.

2. Two- and three-dimensional simulation using an elastic-plastic soil model with the Mohr-Coulomb strength criterion and stepwise-iterative procedures for the interaction between wet loess and DCSP strip foundations, showed the relative error to not exceed 15% compared to field observation data.

3. A modified engineering method (the relative error of which is up to 20%) for determining bed settlement for buildings that rest on DCSP. The load-bearing layer under the widened portion consists of an upper zone of sufficient compaction and a lower zone of natural soil. The deformation modulus in the compaction zone is properly assumed to be 3 times that of natural soil.

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