



A FOUNDATION DESIGN ON COLLAPSIBLE SOILS: AN INTEGRATED GEOTECHNICAL APPROACH

Askar Zhussupbekov¹, *Gulnaz Zhairbayeva¹ and Ankit Garg^{1,2}

¹Department of Civil Engineering, L.N. Gumilyov Eurasian National University, Kazakhstan,

² Xi'an Jiaotong – Liverpool University, Suzhou, China,

*Corresponding Author: Received: 12 Jan. 2026, Revised: 26 Mar. 2026, Accepted: 24 Apr. 2026

ABSTRACT: Collapsible soils are characterized by structural instability and a substantial decrease in stiffness upon wetting, which leads to significant additional settlements under external loading. This behavior introduces considerable uncertainty into foundation design, particularly when the combined effects of wetting and mechanical loading are not explicitly considered within an integrated framework. In this study, a multi-stage experimental methodology was employed, comprising controlled wetting, plate load testing under saturated conditions, and full-scale static load testing of driven piles. This approach enabled the evaluation of soil deformability across multiple scales, ranging from localized stiffness degradation to the overall response of foundation elements subjected to vertical loading. The relationship between the deformation modulus derived from plate load tests and the ultimate load-bearing capacity of piles provided a comprehensive interpretation of foundation performance under conditions of developing soil collapsibility. Based on the integrated experimental analysis, a set of engineering recommendations was formulated, emphasizing the necessity of combining controlled wetting procedures, plate load testing, and full-scale pile testing to ensure reliable foundation design on collapsible soils.

Keywords: Collapsible soils; Controlled saturation; Plate load test; Static pile load test

1. INTRODUCTION

Collapsible soil refers to a metastable dispersed soil characterized by a significant volumetric reduction upon wetting under self-weight or applied loads, caused by the loss of structural integrity of its natural fabric [1]. Under saturated conditions, such soils can experience significant vertical deformation, accompanied by a decrease in deformation modulus and bearing capacity. In practice, collapsible soils are commonly encountered under complex geotechnical conditions [2], characterized by heterogeneous stratigraphy, spatial variability of soil properties, and transient hydrogeological regimes [3]. Such conditions lead to non-uniform wetting, uneven stress redistribution, and depth-dependent deformation behavior, significantly complicating the prediction of foundation performance.

This behavior poses significant risks to the operation and long-term stability of foundations, especially in areas where seasonal changes in humidity [4], irrigation [5], or rising groundwater levels [6] can initiate structure-destroying processes. Ensuring the reliability of engineering solutions in such conditions requires an accurate assessment of the hydromechanical response of

subsiding soils at various depths, both in the near-surface zone and in the area where load-bearing foundations are laid.

In this context, several studies have focused on the design of foundations in collapsible soils [7-9]. The work [10], conducted on collapsible loess deposits, demonstrates that variations in moisture conditions exert a decisive influence on the performance of pile foundations.

Large-scale field tests under artificial wetting conditions reveal the mechanisms of collapse settlement, the redistribution of axial forces, and the development of negative skin friction along the pile shaft. These findings underscore the importance of considering the hydro-mechanical state of the soil mass when assessing the load-bearing capacity of piles in collapsing environments.

Since the influence of wetting is closely intertwined with issues of load redistribution, particularly in foundations with complex stratigraphy, an important contribution to understanding pile behavior is provided by the study [11], which focuses on the performance of pile groups. Full-scale load tests on driven piles in clayey silt demonstrated that close pile spacing and group interaction significantly modify load-transfer

mechanisms and the stiffness characteristics of the system. The comparison of single-pile and group-pile tests enables the evaluation of the applicability of analytical and numerical models, expanding the field database that underpins engineering practice.

The topic of soil–pile interaction is reflected in the work [12], which investigated the influence of pile installation method on the response of piles in collapsible soils. A comparison between driven and bored piles demonstrated that variations in moisture conditions lead to substantial differences in load-bearing capacity, while the dominant load-transfer mechanism is influenced by the way the pile shaft is formed [13]. Additional field investigations have also examined the bearing capacity and settlement behaviour of pile foundations in complex soil conditions using full-scale testing and analytical approaches [14]. Other studies [15,16] have also examined the improvement of loess foundations using bored piles. Field investigations have demonstrated that the installation of bored piles can densify the soil mass between pile shafts, thereby enhancing the deformation characteristics of the foundation and increasing positive shaft resistance, ultimately improving the load-bearing capacity of the piles.

Thus, a research gap remains in integrated multi-scale field validation under controlled saturation conditions. In practical foundation design, deformation parameters derived from plate load tests are often extrapolated to predict pile performance without systematic verification.

The present study addresses this gap by implementing a field-based hydro-mechanical testing framework at a site characterized by Type I collapsible soils. The investigation is supported by an extensive geotechnical database comprising 286 boreholes with a total drilling length of 5,490 m. A controlled-saturation procedure was performed to a depth of 3.8 m before testing, in accordance with relevant field standards [17,18].

The structure of the paper is as follows: Section 3 describes the geological and geotechnical conditions of the test site and the controlled-saturation procedure applied before testing; Section 4 presents the field testing program, including plate load tests and static tests of driven piles; Section 5 analyzes the results obtained from the plate load tests and pile load tests and evaluates the applicability of deformation parameters for predicting pile performance; and Section 6 summarizes the main findings and provides practical recommendations for foundation design.

2. RESEARCH SIGNIFICANCE

This study presents a novel integrated geotechnical framework for foundation design on collapsible soils by explicitly linking shallow soil deformation characteristics with deep foundation performance under controlled hydro-mechanical conditions. The originality of the research lies in combining controlled large-scale saturation, in-situ plate load tests, and full-scale static pile load tests within a unified field investigation. Unlike previous studies that examine these aspects separately, this approach establishes a direct quantitative relationship between the deformation modulus obtained from plate load tests and the load–settlement response of piles. The proposed cross-scale correlation provides a validated basis for predicting pile behavior and significantly reduces uncertainty in deformation-based foundation design for moisture-sensitive collapsible soils.

3. MATERIALS AND METHODS

3.1 Theoretical Aspects of Design Structures in Collapsible Soils

The design of buildings and structures on subsiding soils requires consideration of the specific deformation properties of the foundation, associated with the possibility of soil subsidence when the soil is wet or loaded. In accordance with the requirements of the standard, when developing design solutions, it is necessary to consider differences in soil behavior under conditions of type I and II subsidence. For type I soils, calculations include subsidence resulting from external loads and dead weight. For type II conditions, horizontal surface deformations resulting from the development of a subsidence funnel are additionally considered. If the soil can't become saturated throughout its entire service life, its subsidence properties may be disregarded.

If there is a risk of foundation soaking, the protection principle is selected using one of three methods. The first involves eliminating the subsidence properties of soils within the subsidence thickness through compaction or reinforcement, ensuring their transition to a state close to non-subsidence. The second method involves completely cutting through the subsidence thickness with foundations (particularly pile foundations), thereby transferring the structure's load and negative friction forces to the underlying non-subsiding layers. The third method is a set of measures that includes partial elimination of subsidence properties, protection of

the remaining part of the thickness from soaking, the use of structural solutions that increase the building's resistance to uneven deformation, as well as the organization of water protection for the foundation, and ensuring the possibility of subsequent leveling of the structure.

For construction on Type I soils, it is recommended to eliminate the subsidence properties of the upper zone of the foundation or to cut through the entire subsidence thickness with deep foundations. In this case, the design of structures may be carried out as conventional non-subsiding foundations without the need for additional protective measures. For type II conditions, characterized by more pronounced deformation manifestations, it is usually necessary to eliminate the subsidence of the entire thickness or cut through it with deep foundations. The bearing capacity of compacted and reinforced rock masses, as well as pile foundations, is calculated considering the negative friction forces arising from the subsidence of the surrounding soils under their own weight. If the complete elimination of subsidence or cutting through the base is economically or technically impractical, a set of measures is applied with mandatory calculation of structures for uneven deformation.

When designing buildings with a rigid structural scheme, it is necessary to determine the dimensions of expansion joints between sections of the structure, considering relative horizontal deformations, the length of the section, and the calculated length of the settlement zone. The standard establishes the minimum joint sizes: at least 10 cm for buildings up to 10 m high and at least 30 cm for buildings over 30 m high; for intermediate values, the size is determined by interpolation. In projects for structures erected on Type II subsidence soils, it is mandatory to install marks for subsequent instrumental monitoring of settlements using a set of measures.

In cases where the calculated deformations of the foundation may exceed the permissible values, it is necessary to provide for the possibility of leveling buildings and structures during operation. This measure is applied at sites with Type II soil conditions, on consolidated foundations, and in other situations where probable foundation deformations may significantly impact the load-bearing capacity and operational suitability of buildings.

3.2 Site Characterization

The construction site is located in Pavlodar, Kazakhstan (52.29°N, 76.97°E), within the second

above-floodplain terrace of the Irtysh River. The terrain is generally flat with a slight northwestward slope. The region is characterized by a sharply continental climate (subzone III A according to SP RK 2.04-01-2017). The mean annual air temperature is approximately +3–4 °C. Winter temperatures may drop to –42 °C, while summer temperatures can reach +29°C. Annual precipitation ranges from 250 to 300 mm, with the main moisture input occurring during spring snowmelt. The normative seasonal freezing depth ranges from 1.76 to 2.60 m, depending on the soil type. Hydrogeological investigations identified three aquifer horizons within the site. The upper unconfined groundwater horizon was encountered in all boreholes at depths of 3.0–4.0 m. Seasonal fluctuations and snowmelt may temporarily increase groundwater levels, contributing to periodic wetting of the upper collapsible soil layer. Groundwater recharge occurs primarily through atmospheric infiltration. The hydraulic conductivity of the upper water-bearing soils ranges from 1.8–2.8 m/day (laboratory data) to 5.4 m/day (field test results), indicating moderate permeability and the potential for moisture migration into the near-surface zone.

Two deeper aquifers were identified within the Pavlodar suite deposits. The second horizon occurs at depths of 6.6–26.3 m and exhibits semi-confined behavior with partial hydraulic connection to the upper groundwater horizon. The third horizon is confined and located at depths of 16–29 m. However, from an engineering perspective, the upper unconfined aquifer plays the dominant role in influencing the hydro-mechanical behavior of the collapsible soils.

The geological structure of the site consists of middle–upper Quaternary alluvial deposits (aQII–III) overlying Oligocene–Miocene sediments of the Pavlodar suite (N1–2pv). The thickness of the Pavlodar suite ranges from 20 to 50 m, while Quaternary deposits vary between 3 and 20 m depending on geomorphological conditions.

To detail the lithological structure, 286 boreholes were drilled to a maximum depth of 37.0 m, with a total drilling length of 5.490 m. Based on soil classification requirements [19], seven Engineering-Geological Elements (EGE) were identified:

- EGE-1: Sandy loam (1.6–4.0 m);
- EGE-2: Silty sand (1.2–12.0 m);
- EGE-3: Loam (0.6–7.2 m);
- EGE-4: Medium-grained sand (0.8–14.6 m);
- EGE-5: Clay (0.3–9.9 m);
- EGE-6: Fine sand (3.1–10.2 m);
- EGE-7: Clay (up to 31.0 m).

The upper sandy loam layer (EGE-1) exhibits Type I collapsible properties and therefore governs the foundation behavior under wetting conditions.

Laboratory testing was conducted to determine the physical and mechanical properties of the soils in accordance with applicable standards; the summarized design parameters are presented in Table 1. Laboratory oedometer tests were performed on undisturbed samples of the upper collapsible layer (EGE-1) from depths of 1–3 m under stepwise vertical loading (0.05–0.30 MPa) using the single-curve method.

The relative collapse strain (ε_{sl}) was below 0.01 at 0.05 MPa and increased to 0.02–0.03 at 0.10–0.30 MPa, with maximum values exceeding 0.04–0.05 in individual samples. According to GOST 25100–2020 [19], soils with $\varepsilon_{sl} \geq 0.01$ are classified as collapsible (Type I). The initial collapse pressure (P_{sl}), determined within 0.05–0.10 MPa, averages 0.064–0.10 MPa, indicating structural instability at relatively low stress levels during wetting. These hydro-mechanical characteristics were incorporated into the subsequent field testing program and foundation design analysis.

4. FIELD SOIL TESTS

4.1 Field testing procedure

Due to the identified collapsible properties of

the upper sandy loam layer (EGE-1), controlled pre-soaking of the foundation soil was performed to a depth of 3.80 m in accordance with GOST 5686–2020 [17]. According to Clause 6.11 of this standard, the minimum required water consumption for pre-saturation is not less than 20 m³ per meter of pile length. This requirement was maintained during the soaking procedure to ensure uniform saturation of the entire collapsible stratum prior to testing.

The selected soaking depth of 3.80 m was determined based on the identified thickness of the upper collapsible sandy loam layer (EGE-1). According to site investigation data obtained from 286 boreholes, the thickness of this layer varies from 1.6 to 4.0 m across the construction area. The soaking depth was therefore defined to encompass the full collapsible stratum governing foundation deformation behavior, ensuring saturation of the hydro-mechanically active zone. Soils below this depth were classified as non-collapsible based on laboratory testing results.

A perimeter trench 0.50–0.60 m wide and 1.10 m deep was constructed around the test site. From the bottom of the trench, drainage boreholes with a diameter of 0.30 m and a depth of 2.70 m were drilled and subsequently filled with crushed stone to facilitate uniform water infiltration into the collapsible layer. A schematic layout of the soaking system is shown in Fig. 1.

Table 1 Physical and mechanical properties of the investigated soils

Parameter name	Engineering and geological elements						
	EGE-1	EGE-2	EGE-3	EGE-4	EGE-5	EGE-6	EGE-7
Natural humidity, %	6.4	12.9	22.8	23.4	22.0	21.3	23.5
Humidity at the border:							
- flow	16.9		36.4		44.0		52.3
- rolling out, %	12.1		22.2		24.0		28.2
Plasticity index, %	4.8		14		20		24.1
Index of liquidity, %	-1.3		0.00		-0.11		-0.20
Soil stability	1.80	2.01	1.99	2.03	1.98	1.99	2.00
Soil particles density, kg/m ³	2700	2600	2740	2630	2740	2600	2700
Dry soil density, kg/m ³	1600	1670	1620	1690	1620	1610	1600
Void ratio	0.60	0.55	0.70	0.55	0.69	0.6	0.70
Specific cohesion, kPa	13.0/34.0*	20.0*	63.0/49.0*	23.0*	70.0/68.0	30.0	57/70
The angle of internal friction	13/20*	34*	16/24*	33*	19/22	31	19/20
Modulus of deformation, MPa	16.8	61.2	14.6	70.9	17.78	76.3	20.8

*characteristics are given for soil at a water-saturated state

The borehole diameter was 325 mm. The plate was mechanically rotated into the soil below the borehole bottom, ensuring synchronized rotation and penetration corresponding to the helical pitch of 50 mm. The embedment depth below the borehole bottom ranged from 0.30 to 0.50 m, depending on soil type.

Vertical loading was applied using a pneumatic loading system with a calibrated pressure control unit. Settlement measurements were recorded using three high-precision displacement gauges with a resolution of 0.01 mm, mounted on an independent reference frame. The duration of soaking was selected to ensure stabilization of moisture conditions within the collapsible layer prior to testing. Stabilization was confirmed through laboratory measurements of water content and degree of saturation, ensuring that the soil reached a consistent hydro-mechanical state before the initiation of plate and pile load tests. Applied pressure was controlled using a class 0.4 accuracy manometer (Fig. 3).



Fig.3 During the test procedure

Loading was applied incrementally. Depending on soil conditions, pressure increments ranged from 0.06 to 0.10 MPa, with maximum applied pressures between 0.42 and 0.52 MPa. Each loading stage was maintained for 60–120 minutes in accordance with stabilization time requirements specified in [20].

Settlement stabilization at each stage was monitored by measuring incremental settlement dS . Stabilization was considered achieved when the rate of settlement satisfied the criteria defined by the standard.

The deformation modulus E was determined (1) from the linear portion of the load–settlement curve (using equation 1) $S = f(p)$, within the stress interval from the initial effective vertical stress p_0 to the stress corresponding to the straight-line segment of the curve p_n .

The modulus was calculated using the elastic solution for a rigid circular plate:

$$E = \frac{(1-\nu^2)\Delta p r}{\Delta s} \quad (1)$$

Where, ν is Poisson's ratio, Δp is the pressure increment within the selected linear stress range, r is the plate radius, and Δs is the corresponding settlement increment.

For screw-type plates installed below the borehole bottom, the correction coefficient Kr was applied depending on the embedment ratio h/D , in accordance with Table 5 of GOST 20276-2012 [18]. Poisson's ratio was assumed as 0.30.

Additional plate testing was conducted within the static pile load test area to obtain deformation parameters directly comparable with full-scale pile response under identical ground conditions.

4.3 Static Tests of Driven Piles

Two trial precast reinforced concrete driven piles (type C120.30-13), designated TR-3 and TR-6, were subjected to static vertical compression testing. The piles had a square cross-section of 300 × 300 mm and a total length of 11.40 m.

Pile driving was performed using a Junttan PM25LC piling rig equipped with an HHK-8A hydraulic hammer with a ram mass of 8000 kg and a driving cap weight of 990 kg. Leader drilling was carried out prior to installation. Driving records were maintained during installation. Refusal was not reached during driving.

The piles were installed from ground surface elevations of 120.186 m (TR-3) and 120.221 m (TR-6) to toe elevations of 108.786 m and 108.821 m, respectively.

Static pile load testing was performed in accordance with [17]. The testing program included compression, tension, and horizontal loading configurations. However, the present study focuses exclusively on axial compression results, as vertical loading governs settlement behavior under serviceability conditions in collapsible soils and allows direct comparison with plate-derived deformation parameters. Investigation of lateral pile response under wetting-induced degradation was beyond the scope of the current research and may be considered in future studies.

The piles were installed prior to the soil soaking procedure. Static load testing was conducted after stabilization of the pre-saturated soil mass to ensure methodological consistency between deformation parameters obtained from plate testing and full-scale pile response.

The test-driven pile scheme is shown in Fig. 4.

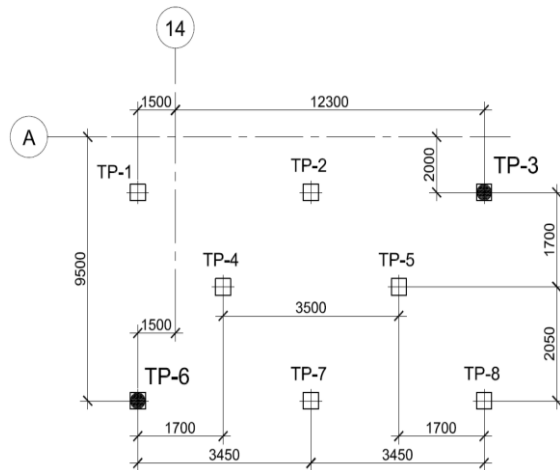


Fig. 4 Scheme of the test-driven piles

The applied load was monitored using an MA100VU100 pressure gauge. Pile settlements were measured using dial gauges with an accuracy of 0.01 mm mounted on independent reference beams to eliminate frame-induced displacement.

The design load was 678 kN. Loading was applied incrementally: the first three stages were 123 kN each, followed by increments of 61 kN until the maximum load of 1047 kN was reached.

The ultimate limit state was defined as continuous settlement growth without stabilization or pile displacement exceeding 40 mm. Failure was not reached within the applied load range.

Unloading was performed in double increments with a minimum holding time of 15 minutes per stage. After complete unloading, elastic rebound was monitored for 60 minutes with readings taken every 15 minutes.

Time-dependent effects were evaluated during unloading and the subsequent 60-minute rebound monitoring period. The recorded settlements showed rapid stabilization, and no significant delayed deformation was observed. This indicates that the primary consolidation process had largely completed prior to static loading, and viscoelastic effects were negligible under the applied stress levels.

The two test piles were installed within a geotechnically homogeneous zone confirmed by prior site investigation (286 boreholes). The purpose of testing was not statistical generalization, but calibration and cross-scale validation of settlement predictions derived from plate load tests under controlled saturation conditions. Therefore, the tests represent verification case studies within a well-characterised soil environment.

5. RESULTS AND DISCUSSIONS

5.1 Results of Plate Load Test

The Deformation modulus E from plate load tests in Table 3 [17].

Table 3 Deformation modulus E (plate load test)

EGE	EGE-1	EGE-2	EGE-3	EGE-4
Soil type	Loamy soil	Silty sand	Loam	Medium-grained sand
n	6	12	6	6
Mean E (MPa)	36.0	39.7	21.8	36.5
SD (MPa)	7.0	3.9	4.6	11.9
V	0.20	0.10	0.21	0.30
95% CI (MPa)	30.93	37.70	18.43	27.08
Min (MPa)	23.4	31.9	15.1	20.1
Max (MPa)	41.8	45.5	25.6	55.2

The calculated 95% confidence intervals indicate moderate variability of deformation modulus within the investigated engineering-geological elements. The narrowest confidence interval was obtained for EGE-2, confirming relatively homogeneous stiffness characteristics, whereas EGE-4 exhibits the widest interval, reflecting increased spatial heterogeneity of the soil layer.

5.2 Results of Static Load Test

Static loading was applied incrementally up to the maximum test load. The settlement values measured at each loading stage are summarized in Table 4. The maximum applied load on the pile heads reached 1047 kN. The measured settlements at this load level were 4.71 mm for pile TP-3 and 4.46 mm for pile TP-6. The calculated bearing capacity of the piles, based on static design calculations, is 1083 kN, which meets the design requirements for reliability and bearing capacity. The graph of the dependence of pile settlement on the applied load and time for the TP-3 and TP-6 piles is presented in Figs. 5-6. Analysis of the graph showing the dependence of pile settlement on load revealed uniform deformation, with no sharp changes in curvature.

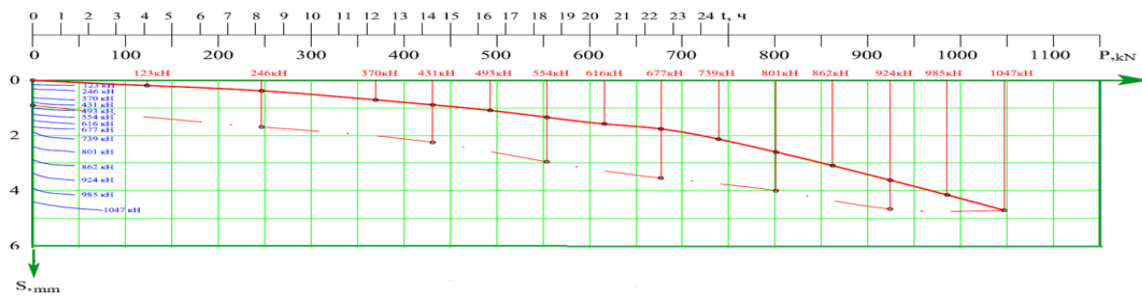


Fig. 5 Graph of results of the total settlement of pile TP 3

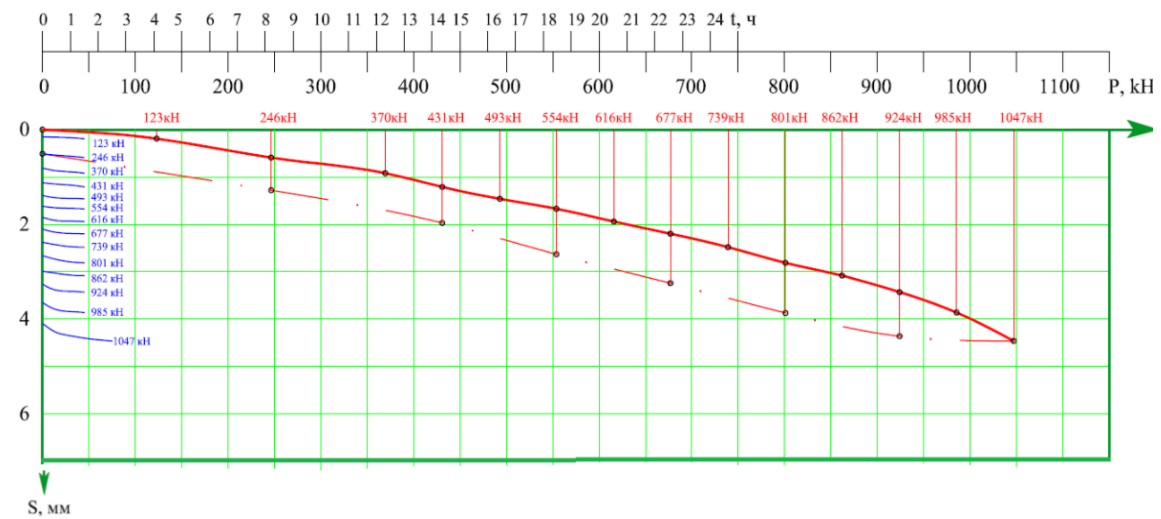


Fig. 6 Load-settlement curve of pile TP-6

Table 4 Static pile load test results

Load (kN)	Settlement	Settlement
	TR-3 (mm)	TR-6 (mm)
123	0.19	0.19
246	0.38	0.29
370	0.71	0.92
431	0.90	1.21
493	1.09	1.46
554	1.34	1.67
616	1.58	1.94
677	1.76	2.20
739	2.13	2.48
801	2.60	2.81
862	3.09	3.08
924	3.62	3.43
985	4.15	3.86
1047	4.71	4.46

At a maximum load of 1047 kN, the settlement was less than 10 mm, indicating sufficient foundation rigidity and no signs of reaching the

limit state. The nature of the loading indicates that the pile is operating stably within the design loads. A key component of the integrated geotechnical assessment performed in this study is the comparison between the deformation modulus obtained from plate load tests and the actual load-settlement behavior of driven piles under static

vertical compression. While plate load testing provides a localized measure of stiffness in the saturated collapsible soil, full-scale pile tests reflect the interaction of the entire soil mass with a real foundation element. Establishing consistency between these two scales is crucial for verifying the reliability of deformation parameters and reducing uncertainties in foundation design.

The deformation modulus of the sandy loam (EGE-1) obtained from plate load tests under saturated conditions reached 36 MPa. This value was used as a reference parameter to estimate pile settlement under the test load of 1047 kN. Using a simplified elastic settlement model, the calculated displacement of the head pile was approximately 4.15 mm (Table 5). This value corresponds closely to the measured settlements

during static loading: 4.71 mm for pile TR-3 and 4.46 mm for pile TR-6. The difference between calculated and measured values did not exceed 15%, demonstrating a strong consistency between the small-scale stiffness estimate and the large-scale structural response.

Table 5 Comparison of Calculated and Measured Pile Settlements

E, MPa	Calculated settlement, mm	Measured settlement, mm
36	4.15	4.46-4.71

The obtained results are consistent with findings reported in previous studies [10,12,16], which demonstrate that soil saturation significantly influences stiffness degradation and pile performance in collapsible soils. The close agreement between calculated and measured settlements in the present study further supports the reliability of deformation modulus derived from plate load tests for engineering prediction under controlled hydro-mechanical conditions.

It should be noted that the settlement comparison was performed using an equivalent deformation modulus derived from plate load testing within the upper collapsible sandy loam layer (EGE-1). Although the geological profile consists of multiple stratified layers, laboratory testing confirmed that only EGE-1 exhibits collapsible behavior, while the underlying strata are classified as non-collapsible in accordance with GOST 25100–2020 [19].

Under service load conditions, deformation is primarily governed by the hydro-mechanically active upper compressible layer, which undergoes stiffness degradation due to controlled saturation. Deeper non-collapsible layers provide relatively stable support and contribute less significantly to collapse-induced settlement. Therefore, the adopted modulus represents an equivalent stiffness of the active deformation zone rather than a fully homogeneous soil profile.

The purpose of this calculation was not rigorous multilayer numerical modeling, but engineering-level cross-scale validation between plate-derived deformation parameters and measured pile settlements under controlled saturated conditions.

The collapse of the soil is hydro-mechanically associated with the reduction of matric suction and the dissipation of negative pore pressures during saturation. In unsaturated conditions, suction provides apparent cohesion and stiffness;

controlled soaking reduces suction, causing structural rearrangement and additional settlement.

The laboratory collapse strain magnitude corresponds to field settlements observed during plate and pile testing, confirming that wetting-induced structural degradation governs site deformation behavior.

5.3 Practical Recommendations

A comprehensive approach (Fig. 9) is essential when assessing collapsible soils, as their behavior is governed by the combined effects of wetting-induced structural degradation and external loading.

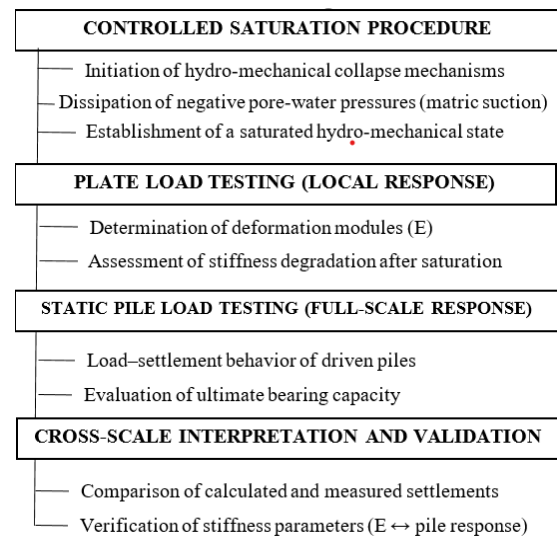


Fig.9 Integrated framework for assessing collapsible soils

Isolated testing methods often fail to capture the full spectrum of deformation mechanisms, resulting in underestimated settlements and unreliable design parameters.

Integrating controlled wetting, small-scale deformation assessment, and full-scale pile load testing enables a more accurate characterization of stiffness degradation and foundation performance under realistic field conditions. This multi-stage framework enhances the reliability of geotechnical evaluations and provides a robust foundation for developing engineering recommendations.

The proposed framework consists of four interrelated stages that reflect the sequential development of collapse behavior and the corresponding response of the foundation system:

1. Controlled saturation procedure aimed at reproducing the hydro-mechanical state in which collapsible soils lose structural integrity.
2. Plate load testing for evaluating local deformation characteristics and quantifying stiffness degradation after saturation.
3. Full-scale static load testing of piles to assess the load–settlement response under the modified soil conditions.
4. Cross-scale interpretation and validation to ensure consistency between surface-level deformation parameters and deep-foundation performance.

The controlled saturation stage plays a critical role in activating collapse mechanisms under well-regulated moisture conditions. Water is introduced into the compressible layer at a controlled rate to achieve a uniform and reproducible degree of saturation while preventing uncontrolled variations in matric suction. This establishes the hydro-mechanical state necessary for realistically evaluating the soil mass's deformation and strength characteristics. By applying plate load tests to the saturated ground, local deformation moduli can be quantified with greater accuracy, providing insight into the extent of stiffness reduction near the ground surface. These measurements serve as the basis for understanding the initial soil response and for calibrating parameters used in subsequent full-scale analyses.

Static pile load tests conducted under the same saturated conditions reveal how stiffness degradation propagates to deeper layers and influences the bearing performance of driven piles. The resulting load–settlement curves allow evaluating ultimate capacity, axial load transfer, and the degree to which saturation affects the mobilization of shaft and base resistance.

The final cross-scale interpretation ensures that the deformation module obtained from plate load testing corresponds to the field response observed during pile testing. This validation step strengthens the reliability of the stiffness parameters used for design and supports the development of engineering recommendations tailored to collapsible soil environments.

It should be noted that the deformation modulus obtained from plate load tests represents localized soil stiffness under shallow loading conditions. In contrast, pile settlement involves three-dimensional stress redistribution along the shaft and toe. The present comparison is therefore limited to service load conditions, where soil behavior remains approximately linear. Despite inherent scale differences, the close

agreement between calculated and measured settlements indicates that the adopted modulus provides a reasonable engineering approximation under controlled saturation conditions.

Although negative skin friction was discussed in the literature review, no instrumentation was installed along the pile shaft to directly measure axial force redistribution. Static loading was conducted after completion of controlled saturation and soil stabilization. The load–settlement curves did not show progressive settlement or additional downward movement under sustained loading, indicating that significant negative skin friction effects were not mobilized under the tested conditions.

Despite the robust experimental framework, this study has several limitations. The investigation is limited to Type I collapsible soils and controlled saturation conditions, which represent a conservative scenario. Long-term field behavior under natural wetting conditions and different soil types were not considered and require further investigation. Future research may focus on extending the proposed approach to other geological settings and incorporating long-term monitoring data to improve prediction reliability.

6. CONCLUSION

The main findings of the present study can be summarized as follows:

1. Controlled pre-soaking of the collapsible sandy loam layer (EGE-1) to a depth of 3.8 m achieved a degree of saturation $S_r \approx 0.80\text{--}0.83$, ensuring simulation of adverse hydro-mechanical conditions.
2. Plate load tests performed under saturated conditions yielded deformation modulus values ranging from 21.8 to 39.7 MPa across the identified engineering-geological elements.
3. Static pile load tests demonstrated maximum settlements of 4.71 mm (TR-3) and 4.46 mm (TR-6) under a load of 1047 kN, without reaching failure.
4. The calculated settlements based on plate-derived deformation modulus showed good agreement with measured pile settlements, with discrepancies not exceeding 15%.
5. The results confirm the importance of considering the hydro-mechanical state of collapsible soils when evaluating pile performance and designing foundations under potential wetting conditions.

The integrated application of controlled wetting, plate load testing, and static pile testing

provides a consistent cross-scale assessment of deformation behavior in collapsible soils. The findings emphasise the need to incorporate hydro-mechanical conditions into foundation design to improve the reliability of settlement prediction and bearing capacity evaluation under complex geotechnical conditions.

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