Geotechnical evaluation of soil composition and mechanical properties for foundation stability

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Received 14 January 2026; accepted 12 March 2026; published online 8 June 2026
DOI https://doi.org/10.21595/vp.2026.26013

76th International Conference on Vibroengineering in Tashkent, Uzbekistan, April 28-29, 2026

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Abstract. This study presents a geotechnical evaluation of soil composition and mechanical properties with emphasis on their implications for foundation stability. Natural soils are characterized with respect to particle-size distribution, mineralogical features, and hydro-mechanical behavior. The analysis considers internal bonding mechanisms – crystalline and aqueous-colloidal interactions – as key factors governing strength and deformation response. Field investigations and laboratory testing were conducted to quantify the main physical and mechanical parameters, including gradation, shear strength, compressibility, porosity, permeability, swelling/shrinkage potential, coagulation behavior, and capillary rise. The results show that soil properties may evolve under changing moisture and loading conditions due to microstructural rearrangement, which can alter bearing capacity and settlement performance over time. Particular attention is given to water–soil interaction in fine-grained soils, as moisture-driven mechanisms substantially modify shear resistance and deformation characteristics.

Keywords: geotechnical engineering, soil classification, soil composition, mechanical properties, shear strength, compressibility, hydro-mechanical behavior, foundation stability, soil-structure interaction.

1. Introduction

Soil is one of the most complex and heterogeneous natural materials used in civil and geotechnical engineering, and its behavior strongly affects the safety, stability, and durability of engineering structures. The composition, classification, and mechanical performance of soils are largely governed by the nature of interparticle bonding mechanisms. These mechanisms are commonly classified into two principal types: crystalline bonds and aqueous-colloidal bonds [1-3].

Crystalline bonds are controlled by mineralogical composition and crystal structure and are typical of rock and cemented soils. They are generally brittle and largely irreversible once disrupted, and their strength depends on dominant mineral phases such as quartz, feldspar, and carbonate minerals. This bonding mechanism explains the high bearing capacity and low compressibility often observed in rock masses and lithified soils [4]. In contrast, aqueous-colloidal bonds arise from physicochemical interactions between fine particles and pore water. These bonds are characterized by plasticity, adhesion, and partial reversibility, which makes fine-grained soils especially sensitive to moisture variations and environmental conditions [5].

Soils form through long-term weathering, erosion, transportation, and sedimentation processes, producing a broad spectrum of particle sizes and structural arrangements. A higher proportion of fine particles intensifies soil–environment interactions, including moisture migration, temperature effects, and chemical processes. From a geotechnical standpoint, soils are multiphase systems consisting of solids, pore water, and air; the relative proportions of these phases largely determine the mechanical response under applied loads [6].

Based on engineering-geological characteristics and mechanical behavior, soils used as foundation materials are commonly grouped into four principal categories: rock soils, coarse-grained soils, sandy soils, and clay soils. This classification is widely adopted because it reflects fundamental differences in bearing capacity, compressibility, permeability, and deformation behavior [7].

Rock soils are characterized by strong crystalline bonding and tightly cemented grains, resulting in compressive strengths commonly exceeding 5 MPa. Due to their high load-bearing capacity and low deformability, rock masses often provide reliable foundations for heavy structures. However, surface weathering, jointing, and cracking may progressively reduce rock mass strength, particularly under repeated wetting-drying cycles and long-term environmental exposure [8].

Coarse-grained soils, composed of particles larger than 2 mm (e.g., gravel and crushed stone), typically exhibit high shear resistance, low compressibility, and favorable drainage. Their high permeability promotes rapid dissipation of pore-water pressure, which supports foundation stability under both static and dynamic loading [9].

Sandy soils, with particle sizes ranging approximately from 2 mm to 0.05 mm, represent an intermediate category between coarse-grained and fine-grained soils. Their mechanical behavior is strongly influenced by density and moisture conditions. Under saturated conditions, sands may experience structural instability due to particle rearrangement and reduced effective stress, which can lead to excessive deformation and, in certain cases, liquefaction-type behavior [9], [10].

Novelty and aim. This study provides an integrated evaluation of typical foundation soils of Eastern Uzbekistan with emphasis on moisture-sensitive behavior, combining granulometric, hydraulic, and mechanical indicators and interpreting their implications for foundation stability (bearing capacity and settlement). The aim is to assess soil composition and hydro-mechanical properties and relate them to long-term foundation performance under unfavorable moisture regimes.

Paper organization. Section 2 describes the methods and calculation basis. Section 3 presents the results and interpretation. Section 4 discusses engineering implications for foundation stability. Conclusions summarize the key outcomes.

2. Methods

Accurate assessment of soil composition and mechanical properties is a prerequisite for reliable foundation design, because these characteristics control bearing capacity, settlement, and long-term stability. The present study focuses on soils of Eastern Uzbekistan, where loess deposits, alluvial sands, clayey soils, and coarse gravels are widely encountered as foundation materials.

2.1. Field sampling and site characterization

Field investigations were conducted at multiple representative sites to capture spatial variability under local climatic and geological conditions. At each site, disturbed and (where possible) undisturbed samples were collected from the surface and subsoil layers at depths relevant to foundation construction. Special attention was paid to zones with pronounced variability in natural moisture and particle-size distribution, as these factors strongly affect compaction quality, stiffness, and settlement behavior [5-7]. Stratigraphic descriptions, lithological features, and groundwater-related observations were documented during fieldwork.

2.2. Laboratory testing program

Collected samples were transported to the laboratory for detailed characterization. The laboratory program included the following groups of tests:

(i) Particle-size distribution (granulometry). Coarse fractions were evaluated by sieving, while fine fractions were determined by sedimentation (pipette method). The granulometric composition was expressed as the mass percentage of each size fraction (gravel, sand, silt, clay), which forms the basis for soil classification and provides an initial indication of permeability and compressibility tendencies [7], [8].

(ii) Physical and hydro-mechanical indices. Bulk density, natural water content, plasticity indices, and shrink-swell potential were measured using standard geotechnical procedures to characterize moisture sensitivity and volume-change behavior of fine-grained soils.

(iii) Permeability and water-retention/capillarity. Permeability and capillary rise/water-retention tests were performed to assess drainage capability and moisture migration mechanisms, which are critical for foundation stability in cohesive and fine-grained soils.

(iv) Compaction and deformation behavior. Laboratory compaction tests were carried out to determine optimum moisture content and maximum dry density for each soil type. Compressibility and deformation characteristics were evaluated to interpret settlement susceptibility under structural loading. Where applicable, stiffness and deformation response were additionally assessed using oedometer testing and field plate load testing to support engineering interpretation of settlement behavior.

2.3. Methodological considerations

The study design accounts for regional factors relevant to Uzbekistan, including seasonal moisture fluctuations, semi-arid conditions, and alluvial deposition processes, which may alter soil fabric, moisture regime, and mechanical response. By integrating field observations with laboratory measurements, the work develops a site-relevant geotechnical profile that supports engineering assessment of soil suitability for foundation construction.

2.4. Main research methods (summary)

The research is based on an integrated approach combining (i) field sampling and site characterization, (ii) granulometric assessment, (iii) hydro-mechanical testing (permeability, capillarity, swelling/shrinkage), and (iv) compaction and deformation testing (including oedometer/plate load where applicable). This combination provides the parameter set needed to evaluate both bearing capacity and settlement-related aspects of foundation stability.

2.5. Theoretical and calculation basis

The interpretation follows classical soil mechanics concepts linking composition, hydraulic behavior, and strength/deformation response under effective stress conditions.

Particle-size distribution. The fraction content is defined as:

$$P_i = \frac{m_i}{m} \times 100\ \%, \tag{1}$$

where m_i is the mass of fraction i, and m is total sample mass.

Soil structure (void ratio). The structural state of the soil skeleton is described by the void ratio:

$$e = \frac{V_v}{V_s}, \tag{2}$$

where V_v is the volume of voids and V_s is the volume of solids. This index governs compressibility and stiffness trends.

Hydraulic behavior (Darcy's law). Permeability is quantified using Darcy's relationship:

$$k = \frac{QL}{Aht}, \tag{3}$$

where k is permeability, Q is discharged volume, L is sample length, A is cross-sectional area, h is hydraulic head difference, and t is elapsed time.

Effective stress principle. Mechanical response is interpreted using effective stress:

$$\sigma' = \sigma - u, \tag{4}$$

where σ' is effective stress controlling strength and deformation, σ is total stress, and u is pore-water pressure.

Deformation modulus. Settlement-related behavior is characterized using the deformation modulus:

$$E = \frac{\Delta\sigma'}{\Delta\varepsilon}, \tag{5}$$

where $\Delta\sigma'$ is effective stress increment and $\Delta\varepsilon$ is strain increment.

Shear strength (Mohr-Coulomb). Shear resistance is evaluated as:

$$\tau = c' + \sigma'\tan\varphi', \tag{6}$$

where c' is effective cohesion and φ' is effective friction angle.

These relationships provide a consistent framework linking laboratory measurements to engineering design parameters and supporting assessment of foundation stability in terms of both bearing capacity and settlement susceptibility.

3. Results and discussion

Soil consists of particles (fractions) that differ in size and physicochemical properties. Fraction composition governs permeability, capillary rise, compressibility, and shear resistance, which together determine the suitability of soils as foundation materials. In engineering practice, particle-size fractions are commonly defined as: gravel (2-70 mm), sand (0.05-2 mm), silt/dust (0.005-0.05 mm), and clay (< 0.005 mm).

Laboratory tests were performed to assess hydro-mechanical properties related to water–soil interaction, including water absorption, swelling, coagulation (water resistance), permeability, shrinkage, and capillarity [3], [4]. These properties are particularly important for fine-grained soils, where moisture changes can substantially modify effective stress conditions and therefore strength and deformation response.

3.1. Swelling, shrinkage, and water sensitivity

Fine-grained soils may exhibit swelling upon wetting and shrinkage upon drying. Swelling potential is largely controlled by mineral composition and the content of active clay minerals; montmorillonite-rich soils typically show the highest expansion. In this study, swelling was assessed using the A. M. Vasilev apparatus. As an engineering criterion, soils with $\delta > 0.04$ are treated as highly expansive.

Shrinkage occurs due to moisture loss through evaporation and/or vegetation uptake. This process reduces soil volume and can induce surface cracking, which alters both mechanical and hydraulic behavior and may contribute to non-uniform settlement.

3.2. Capillary rise and moisture migration

Capillary action is critical for fine-grained soils such as clays and loess. Small pore sizes generate capillary pressures that can raise water above the groundwater level. In loess soils, capillary rise may reach up to approximately 3 m, which can lead to progressive wetting of foundation soils and time-dependent reduction in stiffness and shear strength [6].

Table 1 summarizes representative particle settling velocities and corresponding particle diameters interpreted using Stokes, Sabanin, and Atterberg approaches.

Table 1. Settling velocity of soil particles (Stokes, Sabanin, Atterberg)

Particle sinking speed, cm/s	Time to sink 1 cm	Particle diameter, mm (Stokes/Sabanin/Atterberg)
0.2	5 s	0.05 / 0.05 / 0.06
0.022	45 s	0.0168 / – / 0.02
0.02	50 s	0.0156 / 0.01 / –
0.0028	6 min	0.0053 / – / 0.006
0.000046	36 min	0.0023 / 0.005 / –
0.00036	48 min	0.0020 / – / 0.002

3.3. Capillary height measurement procedure

Capillary height was measured using a laboratory setup consisting of a vertical glass tube connected to a funnel and reservoir. The soil was compacted incrementally inside the tube to minimize layering effects. The tube was fixed on a tripod and immersed into a water container. The wetting front was tracked visually by changes in soil color. To ensure consistency, the water level was maintained constant, and capillary height was recorded after 1, 2, 3, 5, 10, 20, and 30 minutes, as well as after 1 hour and 24 hours, until stabilization.

3.4. Coagulation (water resistance) and permeability

Soil behavior during immersion varies with texture and composition. Some soils disperse rapidly in water, while others retain structural integrity for extended periods. This behavior (water resistance/coagulation) is critical for structures where foundation soils are frequently exposed to water, including embankments, bridge approaches, and hydraulic structures [6-8].

Permeability was evaluated using standard laboratory devices (e.g., permeameter-type setups for sands and cohesive soils). For cohesive soils, specimens were prepared according to standard procedures to obtain representative filtration coefficients. The permeability coefficient is a key parameter for engineering calculations, influencing drainage conditions, consolidation rate, and long-term settlement development [4]. In field conditions, permeability may be assessed by pumping tests or water injection tests, providing hydraulic characteristics under in-situ conditions [9], [10].

3.5. Porosity–strength relationship

Under external loading, soil particles rearrange and interparticle forces mobilize resistance. A strength-related coefficient M was used as an indicator associated with porosity and particle interaction. Table 2 presents the relationship between porosity level and M considered in this study.

The data show a monotonic increase in M with porosity from 26 % to 42 % (from 0.01187 to 0.05789), highlighting the role of soil structure in controlling mechanical response.

4. Foundation stability assessment and engineering implications

Foundation stability is governed by (i) ultimate limit state capacity (bearing capacity and shear failure resistance) and (ii) serviceability (settlement magnitude and differential settlement). The experimental results presented above demonstrate that moisture-driven mechanisms – capillary rise, swelling/shrinkage, and water-induced dispersion – can modify soil structure and the effective stress state in fine-grained soils, leading to time-dependent changes in both stiffness and shear resistance.

Table 2. Relationship between soil porosity and strength coefficient (M)

Porosity level (%)	M	Porosity level (%)	M
26	0.01187	35	0.03163
27	0.01350	36	0.03473
28	0.01517	37	0.03808
29	0.01697	38	0.04157
30	0.01905	39	0.04524
31	0.01905	40	0.04922
32	0.02356	41	0.05339
33	0.02601	42	0.05789
34	0.02878		

4.1. Bearing capacity implications

From a practical design perspective, the bearing resistance of soils is controlled by shear strength parameters mobilized under effective stress conditions. Moisture increase may reduce effective stress and weaken aqueous-colloidal bonding in fine-grained soils, which can decrease the mobilized shear resistance and reduce the margin of safety against bearing failure. Therefore, bearing-capacity verification should consider the most unfavorable moisture regime for soils exhibiting high capillarity or swelling sensitivity, especially where capillary rise can progressively wet the foundation zone [6].

4.2. Settlement and serviceability

Settlement susceptibility is directly related to compressibility and soil structure. Wetting may lead to microstructural rearrangement and loss of stiffness, which increases settlement under working loads. In addition, permeability controls drainage and the time scale of deformation development; therefore, filtration characteristics must be considered to evaluate the likelihood of time-dependent settlement and changes in pore-water conditions [4], [9], [10]. For moisture-sensitive deposits, compaction quality and moisture control (drainage) are essential to reduce long-term deformation.

4.3. Moisture control and durability-oriented measures

Because long-term performance is controlled by coupled “soil-foundation-structure” interactions, stability assessment should consider the combined effect of moisture on soil parameters and on structural materials in contact with the ground. Environmental interaction of structural elements with internal/external conditions may influence long-term performance, supporting the need for moisture control and durability-oriented design measures [11]. Furthermore, the influence of water on cement stone and concrete properties highlights the importance of accounting for moisture-related mechanisms when interpreting long-term foundation behavior and serviceability [12].

5. Conclusions

Particle-size fraction boundaries used for engineering interpretation were: gravel 2-70 mm, sand 0.05-2 mm, silt/dust 0.005-0.05 mm, and clay < 0.005 mm.

1) Swelling sensitivity was evaluated using the δ criterion; soils with $\delta > 0.04$ are classified as highly expansive, indicating increased risk of moisture-induced deformation in clay-rich deposits.

2) Capillary rise is a critical moisture-transfer mechanism in fine-grained soils; for loess deposits capillary height may reach up to ~3 m, which implies the potential for progressive wetting of foundation soils and time-dependent loss of stiffness and shear resistance [6].

3) Capillary-rise measurements were recorded at 1-30 min intervals and at 1 h and 24 h until stabilization, providing a consistent basis for comparing soils with different gradation and density.

4) The porosity-strength indicator M increased from 0.01187 at 26 % porosity to 0.05789 at 42 % porosity, confirming the strong influence of soil structure on mechanical response and settlement susceptibility.

5) For practical foundation design in moisture-sensitive conditions, hydro-mechanical behavior (capillarity, swelling/shrinkage, water resistance, and permeability) should be explicitly linked to stability checks (bearing capacity and settlement) and mitigated through compaction quality control and moisture management (drainage and protection measures) [4], [9], [10].

Acknowledgements

The authors have not disclosed any funding.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflict of interest

The authors declare that they have no conflict of interest.

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