EduVision: Journal of Innovations in Pedagogy and Educational Advancements
Volume 2, Issue 5, May 2026
brightmindpublishing.com
ISSN (E): 3061-6972

PERFORMANCE-BASED FOUNDATION DESIGN ON COLLAPSIBLE LOESS SOILS UNDER SEASONAL MOISTURE AND SEISMIC EFFECTS

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Abstract
The reliability of foundations constructed on collapsible loess soils remains one of the most complex problems in geotechnical engineering because such soils may appear sufficiently strong in their natural dry or low-moisture state but experience sudden structural breakdown, volume reduction and differential settlement after wetting. This article investigates a performance-based approach to shallow and deep foundation design on collapsible loess deposits under the combined influence of seasonal moisture variation, irrigation leakage, accidental water infiltration and seismic loading. The research is based on analytical interpretation of published geotechnical studies, comparative assessment of international design principles, and a conceptual engineering model that links soil collapsibility, foundation stiffness, allowable settlement, drainage reliability and structural serviceability. The study demonstrates that traditional bearing-capacity-oriented design is not sufficient for loessial ground because the decisive limit state is often not ultimate failure but wetting-induced deformation, tilting and loss of operational performance. The article argues that foundation design on collapsible soils should include staged site investigation, laboratory collapse-potential testing, assessment of hydrogeological risk, control of surface and subsurface water, improvement of weak loess layers where necessary, and selection of foundation systems according to predicted deformation rather than only calculated bearing resistance. The results indicate that the most rational solutions are obtained when shallow foundations are combined with soil replacement, compaction or stabilization for lightly loaded buildings, while pile foundations, rigid rafts or combined pile-raft systems become preferable where collapsible layers are thick, water exposure is probable, or seismic demand is significant. The article concludes that a performance-based framework can reduce differential settlement risk, improve long-term serviceability and provide a scientifically grounded basis for foundation decisions in regions where loess soils, irrigation networks and seismicity interact.

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brightmindpublishing.com
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Keywords: Collapsible soil, loess, foundation design, wetting-induced settlement, seismic loading, shallow foundation, pile foundation, soil improvement, performance-based design, geotechnical risk.

Introduction

Collapsible loess soils occupy a special place in foundation engineering because their behavior does not fit the simple logic of strong soil and safe foundation or weak soil and unsafe foundation; in natural conditions such ground may have an apparently stable open structure, moderate strength and acceptable deformation characteristics, but after wetting the same soil may lose suction, weaken interparticle bonding, rearrange its skeleton and undergo rapid settlement under existing structural loads. This contradiction is the technical core of the foundation problem on loessial deposits. In ordinary foundation design, the engineer often begins with bearing capacity, allowable pressure and calculated settlement under service load, but in collapsible soils the decisive question is different: what will happen when water reaches the loaded soil mass? The answer depends on the initial dry density, void ratio, cementation, clay fraction, soluble salts, carbonate bonding, overburden pressure, imposed foundation stress, wetting path and drainage conditions. For this reason, collapsible soil is now commonly understood as unsaturated soil that may suffer particle rearrangement and reduction in volume when wetted, loaded, or subjected to both processes together; recent technical guidance emphasizes investigation, identification, mitigation and reporting of such soils because they can create serious serviceability risks for transportation and building foundations [1]. In Central Asian conditions this problem is especially important because loess and loess-like soils are widespread, irrigation and urban water networks may change the natural moisture regime, and many territories are also influenced by seismic action. Earlier studies of Uzbekistan and Central Asia note the importance of loess deposits, hydrocollapse and erosion processes, especially in areas where soil-water interaction is intensified by irrigation or natural drainage changes [2]. From an engineering viewpoint, the danger is not only total settlement but differential settlement: one part of the building may remain on relatively dry and stiff soil while another part is wetted by leakage, precipitation concentration, pipe failure or groundwater rise, producing angular distortion, cracks in masonry walls, jamming of doors and windows, damage to utility

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networks and progressive deterioration of structural performance. Eurocode 7 states that geotechnical design must be applied to the geotechnical aspects of buildings and civil engineering works and should be used together with general principles of safety and serviceability; this principle is very relevant to collapsible soils because serviceability limit states are frequently more critical than complete bearing failure [3]. However, the direct transfer of ordinary design methods to loessial ground may be misleading when the design does not include hydro-mechanical collapse, seasonal wetting and local water accidents. Contemporary research confirms that loess can experience significant wetting-induced settlement because increase in water content causes permanent changes in microstructure and sudden volume reduction [4]. Other recent studies propose methods for estimating wetting-induced collapse from soil-water characteristic behavior and index properties, showing that modern foundation design must treat moisture as an active design variable rather than a secondary environmental factor [5]. The scientific novelty of this article lies in the integrated interpretation of collapsibility, foundation type, water-management measures and seismic performance within a single performance-based design concept. The aim of the study is to develop a technically consistent framework for selecting and justifying foundation systems on collapsible loess soils where seasonal wetting and seismic effects may act together. The research tasks are: first, to clarify the engineering mechanism of loess collapse relevant to foundation behavior; second, to compare the suitability of shallow, raft, pile and improved-ground solutions; third, to identify the role of drainage and moisture control as structural safety measures rather than only site-improvement details; fourth, to formulate performance criteria that can be used at preliminary and detailed design stages; and fifth, to show why deformation-based verification is more reliable than a narrow bearing-capacity check. The object of the research is the soil-foundation system formed by loessial ground, water regime and structural load, while the subject is the engineering decision-making process for foundations constructed on collapsible soils under long-term service and seismic conditions. The article does not claim that one universal foundation type is optimal for all loess sites; such a claim would be technically careless, and geotechnics does not forgive carelessness, it only sends the invoice later through cracks and settlements. Instead, the article proposes a hierarchy of decisions in which site investigation, collapse potential, thickness of problematic layers, water exposure, load level, structural sensitivity and seismic demand jointly determine the foundation concept.

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The practical significance of the work is that it can support academic research, diploma projects and preliminary engineering analysis in the field of soil mechanics and foundations, especially in territories where loess, irrigation infrastructure and urban construction overlap.

IMRAD STRUCTURE OF THE ARTICLE

Section	Main scientific focus	Expected output
Introduction	Problem relevance, scientific aim and research tasks	Justification of performance-based foundation design
Materials and Methods	Analytical comparison of soil, foundation and water-control factors	Framework for evaluating collapsible loess sites
Results	Foundation response under wetting and seismic scenarios	Decision hierarchy for shallow, raft, pile and improved-ground options
Discussion	Interpretation of design reliability and engineering practice	Integrated soil-foundation-water concept
Conclusion	Generalized scientific and practical findings	Recommendations for design and further research

MATERIALS AND METHODS

The methodological basis of the research is an analytical and comparative geotechnical approach that combines soil mechanics theory, published studies on collapsible loess, international design principles and conceptual performance evaluation of foundation systems. The materials used in the study include scientific literature on collapsible soils, recent works on wetting-induced settlement, guidance documents on geotechnical design and technical studies concerning loessial ground in Central Asia. A state-of-the-art review of collapsible soils emphasizes that such soils may cause rapid differential settlement, ground fissuring and damage to civil structures, and that correct identification requires understanding soil type, collapse mechanism, laboratory and field test procedures, stabilization options and foundation design methods [6]. In addition, classical and modern interpretations of loess behavior show that loess is among the most important collapsible soils because its open, metastable particle packing may reduce to a denser and more stable structure after wetting [7]. These ideas form the theoretical foundation of the present article. The research method is structured in five stages. In the first stage, the soil behavior mechanism is interpreted through the relationship between unsaturated structure,

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suction, bonding and wetting. Collapsible loess is not simply weak soil; it is a metastable soil whose strength and stiffness partly depend on capillary forces and fragile bonding. When the soil is dry, the skeleton may resist ordinary loading; when wetted, suction decreases, clay bridges soften, soluble bonds weaken, and particles rearrange under vertical stress. Therefore, the design problem is not only the magnitude of building load but the combination of load and moisture path. In the second stage, the article classifies the foundation design problem according to three engineering variables: collapsible layer thickness, probability of wetting and structural sensitivity. Thin collapsible layers located close to the surface may often be treated by excavation, replacement, pre-wetting, compaction or chemical stabilization. Medium-depth collapsible layers may require a stiff raft, soil improvement columns or controlled load distribution. Thick collapsible deposits, particularly where water infiltration cannot be reliably excluded, may require pile foundations transferring load below the problematic zone or a combined pile-raft system limiting settlement and rotation. In the third stage, the article introduces performance criteria rather than only traditional factor-of-safety criteria. Performance-based design evaluates whether the foundation will satisfy allowable total settlement, differential settlement, angular distortion, rotation, bearing resistance, serviceability of utilities and post-seismic operability. This is consistent with the general direction of modern geotechnical earthquake engineering, where permanent ground deformation, differential subsidence and loss of bearing capacity are recognized as critical consequences of seismic action, not merely secondary effects [8]. In the fourth stage, the article compares potential foundation solutions using a qualitative decision matrix. The criteria include constructability, cost rationality, sensitivity to wetting, seismic reliability, repairability, environmental impact and compatibility with local construction practice. In the fifth stage, design recommendations are formulated by linking the ground model to foundation choice, water-control measures and monitoring requirements. The conceptual analysis assumes that the investigated site contains loessial soil of variable thickness and natural moisture content, that foundations may be subjected to ordinary building loads, and that wetting may occur through precipitation infiltration, irrigation leakage, damaged water supply pipelines, rising groundwater, poor stormwater disposal or accidental technological discharge. This assumption is realistic for many urban and rural construction areas where the moisture regime after construction differs from the

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ISSN (E): 3061-6972

natural moisture regime before construction. The article also considers seismic action because loessial soils may undergo additional deformation when cyclic loading acts on an already weakened or wetted structure. Earlier studies on earthquake-triggered collateral hazards in Uzbekistan describe the distribution of loess soils and the importance of subsidence-related hazards in different geomorphological zones [9]. The present article does not perform a numerical finite-element simulation, because the purpose is not to produce a site-specific design for one building but to construct a general scientific framework applicable to foundation decision-making. Nevertheless, the approach is compatible with numerical modeling: parameters such as compression index, collapse potential, modulus variation with moisture, shear strength reduction and cyclic degradation can be introduced into finite-element or finite-difference models at detailed design stage. Laboratory evaluation assumed in the framework includes natural moisture content, density, grain-size distribution, Atterberg limits, carbonate or soluble salt content where relevant, oedometer compression tests at natural and wetted conditions, collapse potential tests, direct shear or triaxial tests, and determination of soil-water characteristic behavior where unsaturated analysis is required. Field evaluation includes trial pits, boreholes, cone penetration tests where available, plate load tests, groundwater observation, mapping of drainage paths, identification of existing irrigation channels and water networks, and examination of nearby structures for settlement damage. For foundation design, the article follows the principle that the ground investigation model must be conservative enough to include unfavorable wetting scenarios; ignoring probable water infiltration only because the soil is dry during exploration is not engineering optimism, it is a politely written mistake. The method therefore treats moisture control as part of the foundation system. Surface grading, blind areas, stormwater drainage, waterproof utility trenches, inspection wells, anti-leakage measures and controlled landscaping are considered together with footing dimensions, raft stiffness, pile length and soil improvement depth. This integrated method reflects the practical reality that many failures on collapsible soils begin not with insufficient concrete strength or reinforcement but with uncontrolled water entering a soil mass that was never designed to become wet.

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RESULTS

The analytical results show that foundation reliability on collapsible loess soils is governed by four interacting mechanisms: structural collapse of the soil skeleton after wetting, redistribution of stress beneath the foundation, development of differential settlement due to non-uniform moisture distribution, and possible amplification of deformation under seismic loading. The first result is that bearing capacity calculated for the natural moisture condition may considerably overestimate long-term performance if collapse settlement is not included. A shallow strip or isolated footing may appear safe under ordinary allowable pressure, but if the loaded bulb of soil becomes wetted, the soil fabric may densify suddenly and the foundation may settle more than permitted by serviceability criteria. Research on shallow foundations over loess has shown that wetting may produce significant settlement and that hydro-mechanical models are needed to represent the response of strip foundations on loessial ground [4]. Therefore, the design check must include both initial settlement under construction load and additional wetting-induced collapse settlement. The second result is that the location and thickness of the collapsible layer strongly influence foundation choice. If the collapsible layer is shallow and limited in thickness, removal and replacement with compacted non-collapsible fill may provide a reliable solution for low-rise buildings, provided that the replacement extends beyond the foundation influence zone and is protected against future water infiltration. If the layer is deeper but not very thick, dynamic compaction, pre-wetting with compaction, lime or cement stabilization, stone columns, grouting or reinforced soil methods may be considered depending on soil composition and local equipment availability. If the collapsible layer is thick and extends below the economically treatable depth, piles or pile-raft systems become more rational, but even piles must be checked for negative skin friction because wetting-induced settlement of surrounding loess can drag the pile downward. Recent research on estimation of wetting-induced collapse also notes the relevance of collapse settlement for determining negative skin friction on piles [5]. The third result is that stiffness distribution in the foundation system is as important as ultimate strength. A flexible foundation on non-uniformly wetted loess can produce high angular distortion even when average settlement is moderate. A rigid raft may reduce differential settlement by redistributing load, but it cannot eliminate collapse if the entire loaded zone becomes wetted. Piles may bypass collapsible layers, but pile caps and grade beams

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must be detailed to tolerate differential ground movement and to protect utilities. Thus, the foundation system should be evaluated as a soil-structure interaction problem rather than a set of isolated bearing-pressure calculations. The fourth result is that water-control measures are not auxiliary works but primary geotechnical protection. A shallow foundation on treated loess without reliable drainage may be less safe than a simpler foundation on well-controlled moisture conditions. The most important protective measures include positive site grading away from the building, continuous pavement or blind area around the perimeter, waterproofing of underground utilities, flexible pipe joints where differential movement is possible, inspection chambers for leakage detection, controlled discharge of roof water, prevention of uncontrolled irrigation near foundations, and maintenance instructions for building operators. In collapsible soils, the maintenance manual is part of the geotechnical design, not paperwork for a dusty shelf. The fifth result is that seismic loading increases design complexity because cyclic shaking can interact with moisture-induced weakening. Dry loess may exhibit different stiffness and damping than wetted loess, and if wetting has already reduced strength, earthquake-induced shear strains may increase settlement, rotation and cracking risk. Performance-based seismic foundation design studies emphasize that foundation settlement, rotation, soil layer properties, contact pressure and ground motion intensity influence building response on problematic ground [10]. Although liquefaction and loess collapse are different phenomena, both demonstrate the same broader lesson: foundation performance under seismic action depends not only on structural strength but also on permanent ground deformation. The sixth result is that foundation choice can be organized into a decision hierarchy. For lightly loaded one- or two-storey buildings on shallow low-to-moderate collapsible loess, compacted replacement and continuous strip foundations with strong drainage may be sufficient if collapse settlement after treatment remains within allowable limits. For medium-rise buildings, public buildings or structures sensitive to differential movement, reinforced raft foundations combined with partial soil improvement and strict water control are often more appropriate. For heavy structures, industrial buildings, water-retaining structures, buildings with high settlement sensitivity or sites with thick collapsible layers, piles or combined pile-raft systems should be considered. For hydraulic structures and irrigation-related facilities, the design must be especially conservative because the probability of wetting is not accidental but inherent to operation. Studies on hydraulic

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structures over loess subsidence soils underline the importance of ensuring long-term trouble-free operation of structures on such bases [11]. The seventh result is that laboratory classification alone is insufficient. Two soils with similar grain-size distribution may behave differently if their dry density, cementation, carbonate content, suction and fabric differ. Therefore, collapse-potential testing under representative stress states is essential. The test program should reproduce not only natural overburden pressure but also additional foundation pressure, because collapse can be stress-dependent. The eighth result is that foundation design should include scenario analysis. At minimum, three scenarios are necessary: natural moisture service condition, partial wetting condition and full wetting of the active zone. In seismic regions, an additional post-wetting seismic scenario should be included because the most unfavorable case may occur when earthquake loading acts after long-term moisture increase. The ninth result is that geotechnical monitoring can reduce uncertainty for important structures. Settlement marks, crack gauges, moisture sensors near foundations, groundwater observation wells and periodic inspection of drainage systems can detect early signs of unfavorable behavior. Monitoring does not replace correct design, but it provides a feedback mechanism for maintenance and risk management. The tenth result is that the most economical design is not always the cheapest foundation at construction stage. A shallow footing without soil treatment may have the lowest initial cost, but if it requires structural repair after wetting-induced settlement, the life-cycle cost becomes higher than a more robust foundation system. Therefore, the economic comparison should include probability of wetting, cost of repair, interruption of building use and consequences of structural damage. This performance-based economic logic is particularly important for schools, hospitals, administrative buildings, residential complexes and hydraulic infrastructure, where service interruption can be socially expensive.

DISCUSSION

The results indicate that the central weakness of many conventional approaches to foundations on collapsible soils is the separation of structural design, geotechnical design and water-management design into independent tasks. In reality, these three components form one system. A foundation may be structurally strong, but if water is allowed to enter the collapsible zone, the soil can deform and the structure will follow. A drainage system may be well drawn on a plan, but if it is not coordinated with

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brightmindpublishing.com
ISSN (E): 3061-6972

foundation depth, utility trenches and site slope, it may concentrate water where the geotechnical design least expects it. A soil-improvement method may improve density during construction, but if the treated zone is too shallow compared with the stress bulb or if untreated loess remains below the improved layer, delayed settlement may still occur. Therefore, the article supports a performance-based design philosophy: the design should begin by defining acceptable performance and then selecting a foundation-soil-water system capable of achieving it under credible scenarios. This approach is consistent with the broader principles of geotechnical design in which safety and serviceability must both be verified [3]. In collapsible loess, serviceability deserves special attention because damage often appears as cracks, uneven floors, utility breaks and door misalignment long before any classical bearing-capacity failure occurs. The discussion also shows that site investigation must be deeper and more purposeful than ordinary shallow drilling. The engineer must identify not only soil layers but moisture pathways. Old irrigation channels, leaking water lines, insufficient stormwater outlets, low-lying courtyards, basements, septic systems and landscaping practices may be more important for future performance than a single laboratory strength value. This is why preliminary design should include a geotechnical risk map of the site showing possible water entry routes, collapsible layer thickness and structural sensitivity zones. For shallow foundations, the most effective strategy is usually to convert an uncertain collapsible base into a controlled engineered base. This can be achieved by removing weak soil, compacting the subgrade, replacing it with granular material, stabilizing it with binders or using reinforced fill. However, this strategy is rational only where the problematic depth is limited. If collapsible soil extends many meters below the foundation, shallow improvement may simply create a stiff crust over a still-collapsible mass. Under such conditions, a raft foundation may distribute stresses better but cannot fully prevent settlement if wetting reaches deeper layers. Pile foundations can transfer structural loads below collapsible zones, but they introduce their own problems: downdrag, pile group interaction, lateral response during earthquakes, construction quality control and cost. The best solution is therefore not selected by habit but by evidence. The article's decision hierarchy suggests that the selection should be based on the thickness of collapsible soil, expected wetting depth, load intensity, allowable deformation and seismic demand. In seismic areas, the problem becomes even more sensitive because earthquake-induced strains may transform small pre-existing

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brightmindpublishing.com
ISSN (E): 3061-6972

weaknesses into visible structural damage. Geotechnical earthquake engineering increasingly emphasizes permanent ground deformation, differential subsidence and loss of bearing capacity as key hazards [8]. For loessial sites, the unfavorable interaction may be described as a sequence: long-term wetting reduces suction and stiffness; the building load maintains vertical stress; cyclic shaking produces additional shear strain; and the foundation experiences settlement or rotation beyond serviceability limits. This sequence explains why a site that has performed acceptably for several years can show sudden damage after an earthquake or after a major water leakage event. Another important issue is uncertainty. Collapsible soils are spatially variable because their fabric depends on depositional history, post-depositional processes, cementation and local moisture regime. Even within one construction site, one borehole may indicate weak collapsibility while another reveals stronger collapse potential. For this reason, conservative interpolation and targeted additional investigation are preferable to optimistic averaging. A design based on average properties may be statistically tidy but practically unsafe if the building's most sensitive corner rests over the worst soil pocket. The discussion also supports the use of observational methods for important structures. If a foundation is built on improved loess, monitoring of settlement and moisture can verify whether the design assumptions remain valid. If unexpected settlement begins, maintenance actions such as drainage repair, leakage elimination, local underpinning or controlled grouting can be implemented before serious damage develops. From a normative perspective, the proposed approach does not replace national codes; rather, it strengthens their application by emphasizing deformation, moisture and performance scenarios. National design standards and local construction rules should remain the formal basis of design, while international documents and scientific studies can support deeper analysis. In an OAK-level scientific context, this distinction is important: the article does not mechanically import foreign standards but uses their principles to improve local engineering reasoning. The practical implication for Uzbekistan and similar regions is clear. Because loessial soils, irrigation systems, seismicity and rapid urbanization may coincide, foundation design should not be reduced to tabulated allowable pressures. It should include a documented geotechnical model, collapse-potential assessment, drainage concept, foundation alternative comparison, life-cycle risk evaluation and construction-quality control. For example, when designing a public building on loess, the project documentation should specify not only footing

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dimensions and reinforcement but also subgrade preparation procedure, compaction requirements, drainage slopes, waterproofing of utility trenches, prohibition of uncontrolled irrigation near the perimeter, and inspection schedule. Such details may look modest compared with impressive architectural renderings, but in foundation engineering modest details often save expensive buildings. The economic side also deserves discussion. Developers may prefer the cheapest foundation alternative, but on collapsible soils this preference can be deceptive. The initial saving from avoiding soil improvement may be much smaller than the later cost of crack repair, structural strengthening, tenant relocation, utility reconstruction or litigation. A life-cycle cost model should therefore compare alternatives under risk-weighted scenarios. For low-risk small buildings, shallow foundations with improvement and drainage may be rational. For high-importance structures, the additional cost of piles or raft systems may be justified by reduced failure probability and improved post-seismic performance. Environmental considerations should also be included. Large-scale soil replacement requires excavation, transport and disposal; cement stabilization increases embodied carbon; deep foundations require materials and equipment; but repeated repair and demolition also have environmental costs. The most sustainable foundation is not automatically the one using the least material at the start, but the one that provides durable service with controlled risk. Finally, the article highlights the educational value of performance-based thinking in the discipline of soil mechanics and foundations. Students often learn bearing capacity equations, settlement formulas and pile resistance calculations separately. Collapsible loess forces them to think like engineers: soil structure, water, load, time, earthquake and maintenance must be considered together. That intellectual integration is the real science of foundation engineering.

CONCLUSION

The study concludes that foundation design on collapsible loess soils must be based on performance under realistic moisture and seismic scenarios rather than only on bearing capacity under natural ground conditions. The principal mechanism of risk is wetting-induced breakdown of the metastable loess fabric, which can produce sudden settlement and differential deformation under existing structural loads. Because this process is strongly influenced by water infiltration, foundation reliability depends on the combined performance of soil, structure and drainage. The most important scientific conclusion is that collapsibility transforms moisture from an environmental parameter into a design action. Therefore, site investigation must identify not only strength and density but also collapse potential, wetting depth, hydrogeological pathways and the probability of future water exposure. Shallow foundations may be acceptable where collapsible layers are thin, loads are moderate, soil improvement is properly executed and water control is reliable. Raft foundations are suitable where load redistribution and control of differential settlement are required, but they must not be treated as a universal cure for deep collapsible deposits. Pile foundations and pile-raft systems are more appropriate where collapsible layers are thick, structural sensitivity is high, wetting cannot be excluded or seismic demand is significant; however, they must be checked for negative skin friction, group effects and lateral seismic response. The research also concludes that drainage, waterproofing and utility-leakage control are fundamental geotechnical safety measures. Without them, even technically correct foundation calculations may lose reliability during operation. A performance-based design framework should include collapse-potential testing, scenario-based settlement estimation, deformation limits, seismic considerations, alternative comparison, construction-quality control and monitoring for important structures. For regions where loess soils, irrigation networks and seismicity interact, such an approach provides a more reliable and scientifically justified foundation strategy than traditional design based mainly on allowable bearing pressure. The practical recommendation is that every project on collapsible loess should contain a documented soil-foundation-water concept: what soil can collapse, how water may reach it, what the foundation will do if it happens, and how the building operator will prevent or detect it. Only when these questions are answered can the foundation be considered not merely calculated, but genuinely engineered. Future studies should develop calibrated numerical models for regional loess deposits, compare laboratory collapse-potential tests with field wetting observations, and establish design charts that connect collapse strain, foundation pressure, layer thickness and allowable deformation for buildings of different importance categories.

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