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Climate-Resilient Foundation Design for Coastal Infrastructure Under Rising Groundwater Conditions: A Review

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ABSTRACT:
Background: Sea-level rise poses not only a threat to coastal infrastructure through surface inundation, but also through coastal groundwater table rise, which occurs slowly, over a long period of time, and is difficult to see, before it even reaches the surface.
Methods: The methods for this review involve a synthesis of the mechanisms of coastal groundwater rise, the structural and geotechnical implications, and the new strategies in foundation design and site characterisation based on peer-reviewed literature (2021–2025) from journals in Earth and environmental science, geotechnical engineering literature, and civil engineering case studies.
Results: Rising groundwater causes decrease in unsaturated buffer above foundations, enhances buoyant uplift, raises pore pressure, and speeds up chlorides-induced corrosion of substructure concrete and buried steel. Data from the USA, the Netherlands and the city of Lagos, Nigeria, demonstrates that these forces exacerbate low-lying deltaic cities' experience of land subsidence. A climate resilient foundation design framework is built on the foundation of the integrated borehole-cone penetration test (CPT) characterisation, new liquefaction and bearing-capacity correlations, ground improvement, and probabilistic uncertainty-aware design.
Conclusion: Coastal foundation engineering needs to move beyond the precepts of the past, relying on water-table assumptions, to one based on monitoring and knowledge of uncertainty, and prepared to face decades of groundwater rise.

KEYWORDS: rising groundwater, sea-level rise, foundation design, coastal infrastructure, cone penetration test, climate resilience.

INTRODUCTION

Sea-level rise (SLR) is commonly known as a surface hazard, but the subsurface manifestation, a rising coastal groundwater table, is a unique and much less recognised hazard to the built environment [1]. Coastal aquifers are hydraulically linked to the ocean, and as sea level rises, the freshwater table rises above denser saline water, reducing the unsaturated zone between foundations, basements and buried utilities and saturated, increasingly corrosive ground [1]. A thorough study of this effect concluded that groundwater-related damage to the underground infrastructure can start decades before the onset of surface flooding, as the damage is hidden and rarely accounted for in infrastructure asset management [2]. Modelling across the globe suggests that about 60 million people reside within 10 km of the current coastline who would see a reduction in fresh groundwater supply of over 5% under moderate sea-level-rise scenarios, with this loss focused in low-lying unconsolidated coastal sediment, of the type where many tropical port cities are located [3].

The implications for engineering are big. Conventional design groundwater tables fail to represent the episodic infiltration pulses from storm-related sea-level rise, and a recent synthesis published in Nature Reviews Earth & Environment found that the impact of climate on the coastal groundwater system – its salinisation, water-table rise and recharge changes – is now a hazard that should be explicitly considered in coastal infrastructure planning [4]. These processes are superimposed on anthropogenic land subsidence in coastal cities that have been reclaimed and extensively pumped, thereby intensifying relative groundwater rise in these cities relative to eustatic sea-level rise [5]. The purpose of this review is to provide a synthesis of the mechanisms by which coastal groundwater rise may affect foundations and buried infrastructure, and the geotechnical site characterisation and design approaches needed to develop a climate-resilient foundation-design framework.

METHODS

This is a narrative review. The terms "groundwater rise", "sea-level rise", "coastal foundation", "land subsidence", "cone penetration test", "liquefaction", and "chloride corrosion" were used to search the following databases: PubMed, PubMed Central, Web of Science, and publisher databases (Wiley, Elsevier, Springer Nature, MDPI, Emerald). Peer-reviewed studies, systematic reviews and key geophysical modelling papers published from 2021 to 2025 were prioritised. Hand searching of reference lists of key articles was conducted to find further sources relevant to the study. The review is a narrative synthesis and therefore was not performed using formal risk-of-bias scoring, although formal risk-of-bias scoring was performed on systematic reviews cited, as described in those reviews.

Mechanisms Driving Coastal Groundwater Rise

Multiple mechanisms contribute to coastal groundwater rise, but not all of them are necessarily acting together. There is a dominant driver: where unconfined coastal aquifers are present, and where they are not locally pumped, a rising mean sea level causes the depth to the water table to decrease due to the lift of the freshwater lens by the rise in ocean level. In addition, explicit simulations of the Earth system indicate that inundation events lead to further lateral and vertical seawater infiltration, in addition to steady-state sea-level projections, resulting in episodic peaks of the water table over a long-term projection time-scale [6]. Concurrently, landward salinisation decreases the available water volume of fresh groundwater, leads to changes in the density-driven flow regime and impacts the geochemical environment around underground infrastructure even if the elevation of the water table merely changes slightly [3,5]. Where the cities are also subsiding, due to natural compaction of sediment, extraction of groundwater or hydrocarbons, or the subsidence of poorly consolidated reclaimed land, relative groundwater rise can also be accelerated, as is happening in parts of Lagos, Nigeria, where satellite radar tracking revealed that parts of the city are subsiding at rates significantly greater than sea-level rise [7]. These mechanisms and their direct connection to foundation design have been summarised in Table 1. Figure 1 illustrates the Coastal Groundwater Rise and its Interaction with Building Foundations.

Table 1. Mechanisms driving coastal groundwater rise and their relevance to foundation design.

Driving mechanism	Physical process	Relevance to foundation design
Sea-level rise (direct)	Ocean-groundwater connectivity elevates the coastal water table as the marine boundary condition rises	Reduces effective stress and available unsaturated zone above foundations
Land-ocean hydrologic coupling	Lateral seawater exchange and vertical infiltration during inundation events raise groundwater independent of steady-state SLR	Introduces episodic, storm-linked water-table spikes not captured by mean SLR alone
Freshwater volume decline/salinisation	Landward salt-water intrusion reduces usable fresh groundwater and shifts density-driven flow	Alters pore-water chemistry and corrosivity around buried elements
Land subsidence	Compaction of soft sediments and groundwater/hydrocarbon extraction lowers ground surface relative to sea level	Compounds relative water-table rise independent of eustatic sea level
Anthropogenic infrastructure interaction	Ageing drainage and sewer networks leak into or receive infiltration from rising groundwater	Groundwater infiltration into buried utilities accelerates corrosion and capacity loss

Sources: Data synthesised from References [1,3,5,6,7]

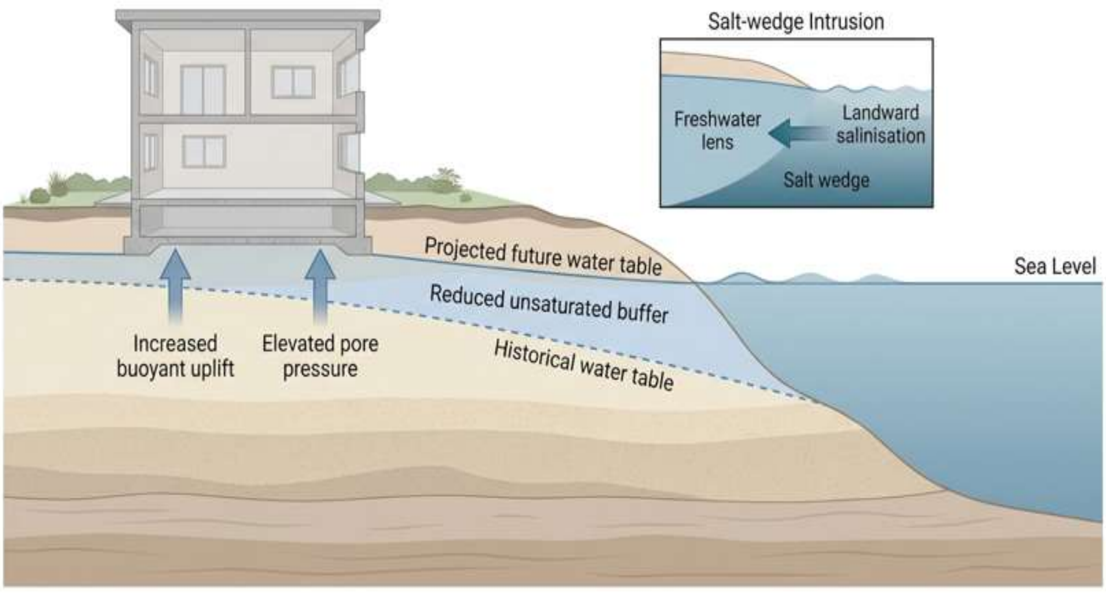

Figure 1: Coastal Groundwater Rise and its Interaction with Building Foundations.
Sources: Adapted from references [1,3,5,6,7].

Impacts on Foundations and Buried Infrastructure

The effects of high groundwater on structures are very broad. Under an extreme sea-level-rise scenario, the national-scale assessment of almost 137,000 residential buildings around Mobile Bay, AL, estimated yearly costs of up to US$90 million for repairs due to foundation reinforcement corrosion caused by saltwater intrusion; the authors classify this as “hidden,” because it is not easily noticed and is not usually covered by homeowner insurance. The authors concluded that 326 sites in the US Superfund program are potentially vulnerable to changes in flow direction caused by groundwater rise, and could remobilise legacy contaminants from previously stable subsurface environments [8]. In addition to corrosion and contamination, high groundwater can also cause a reduction in the effective stresses imposed on foundation soils, buoyant uplift forces on basements and shallow footings, and affect gravity-fed drainage and sewer systems which were designed based on historical groundwater-table assumptions [9,10]. An underground climate change synthesis focused on underground thermal and hydrological changes found that the deformations of this type can be considerable, case-by-case, and that they are not compatible with the operational tolerances of civil structures. Reinforced-concrete substructures pose a special problem in terms of corrosion: the corrosion of reinforcement is enhanced by well-studied diffusion and threshold mechanisms by the transport of chloride ions in rising, progressive and increasingly saline groundwater, and the service life reductions in reinforced-concrete structures in tropical and marine-exposed environments have been well documented [11].

Case Context: Coastal Lagos and Comparable Subsiding Deltas

How all these three factors (groundwater rise, land subsidence, and inadequate site characterisation) come together in the ground, in practice, is exemplified in coastal Lagos. An analysis of the city's deformations, based on satellite observations, revealed that large parts of the city were sinking, including in some places at a rate that made near-term building failure likely even if sea level were not changing [7], in agreement with geotechnical studies carried out many times in Lagos, which have shown that weak, compressible peat and clay underlie many parts of the city, particularly in areas that have been reclaimed and along the edge of the lagoon [12]. It is the same investigations that directly correlate the near-surface environment with corrosion risk, including moisture and dissolved salt content in soils that increase the corrosivity of the ground around buried steel and concrete structures [13]. The nature of the challenge is not confined to low- and middle-income deltaic cities, however: modelling of the low-lying coastal groundwater systems of Northwestern Germany revealed that land subsidence and abstraction rates could be as great as sea-level rise itself in driving future salinisation rates [5], suggesting that this is a challenge common to all soft, low-lying coastal geologies.

Site Characterisation and Geotechnical Assessment Under Rising Groundwater

To design foundations that perform well when the water table fluctuates, site characterization must be based on techniques that are able to monitor a site's subsurface conditions over time, not historical conditions that cannot be assumed. Cone profiling (CPT) overcomes these disadvantages and is a method which is repeatable and easily available for monitoring purposes; recent developments have extended the ability to automatically classify soil types using the CPT, accounting explicitly for cross-correlation effects between the CPT channels and the effects of measurement noise [14], and back-analysis frameworks which combine both discrete borehole stratigraphy and continuous CPT profiles have been demonstrated to improve estimates of the layer boundaries compared to those provided by either method alone [15]. A simplified cone-penetration-index approach has also shown that it can predict soil-behaviour-type without a large amount of computation and instrumentation, which is important for the frequent re-surveying that may be required with rising groundwater conditions [16]. Historically, liquefaction and flow-failure screening methods have been based on the assumption of a stable water table, which has been updated: A new liquefaction and flow-failure screening method using the CPT addresses how liquefaction should be reconsidered as site conditions change [17]. The abilities and restrictions of these techniques are summarised in Table 2, in the context of rising groundwater. Figure 2 presents the Integrated Site Characterisation Workflow for Rising Groundwater Conditions.

Table 2. Site-characterisation methods and their limitations under rising groundwater conditions.

Method	Capability	Limitation under rising groundwater conditions
Cone penetration test (CPT)	Continuous, repeatable profiling of tip resistance and sleeve friction; supports soil behaviour-type classification	Classification schemes calibrated on historical water-table depths may misclassify soils once the phreatic surface shifts upward
Borehole/SPT with sampling	Direct soil recovery for index and strength testing; only reliable ground-truth for stratigraphy	Discrete depth intervals miss thin transitional layers; costly to repeat as monitoring wells
Integrated borehole-CPT back-analysis	Combines discrete stratigraphic control with continuous CPT profiles to refine layer boundaries	Requires spatial co-location and consistent datum referencing to remain valid as water levels change
Piezocone/pore-pressure dissipation	Measures in-situ pore pressure directly, tracking real-time phreatic surface position	Point measurements require a monitoring network to characterise basin-wide trends
CPT-based liquefaction/flow assessment	Updated procedures relate cone resistance to liquefied strength ratio for flow-liquefaction screening	Original correlations assume a static water table; rising groundwater requires re-screening over the design life

Sources: Compiled from references [12,14,15,16,17]

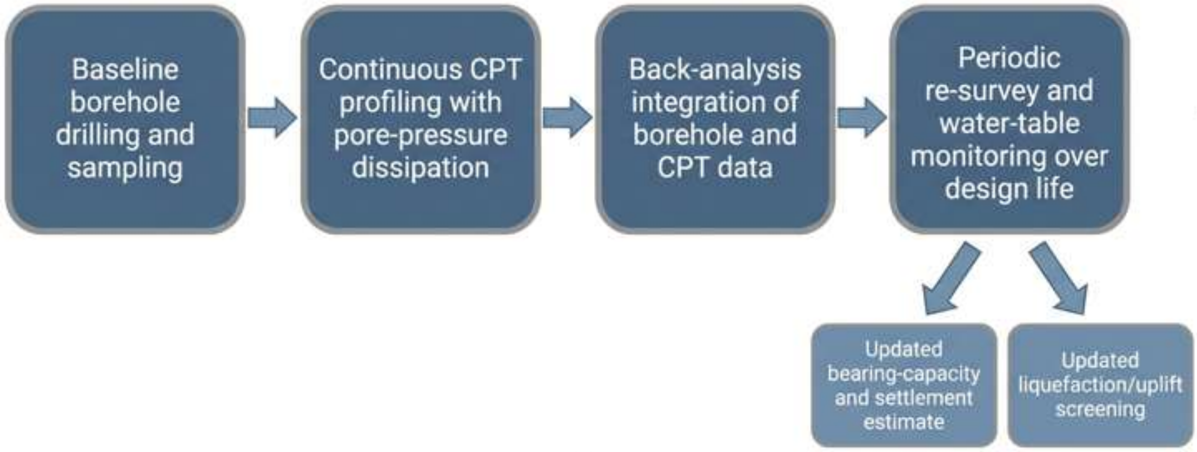

Figure 2: Integrated Site Characterisation Workflow for Rising Groundwater Conditions.
Sources: Adapted from references [14,15,16,17]

Foundation Design Strategies for Climate Resilience

If shallow foundations are unsuitable because of soft, saturating soils or shallow water table, piled and piled-raft foundations carry the structural loads deeper to less water-table sensitive soils. Piled-raft foundations in soft clayey soils have been numerically analysed for differential settlement in conditions broadly analogous to soft coastal deposits, and direct cone-penetration-test methods for calculating pile shaft capacity (in tension) are particularly applicable as the uplift that will be generated by rising groundwater may result in deep foundations operating in net tension, rather than compression, and therefore may experience greater shaft capacity in tension than in compression [18,19]. If ground improvement is feasible, both chemical stabilisation methods and field trials of vibratory compaction have shown that there are significant improvements in bearing capacity and decreases in settlement when the soils near the surface are loose or soft and susceptible to saturation [20,21]. Clusters of corrosion resistant detailing (increased cover, corrosion inhibitors, or non-metallic reinforcement) are required to be a part of geotechnical design, as chloride-driven corrosion of substructure reinforcement has been well established as a consequence of saline groundwater rise, and is not subject to a separate consideration [11]. Finally, since both the site investigation data and future groundwater trajectories are inherently uncertain, incorporating uncertainty into geotechnical design decisions can be propagated explicitly through probabilistic and artificial-intelligence-assisted frameworks, rather than being hidden within a single deterministic value [22,23]. Updated relationships between compression index and geotechnical index properties enable more long-term settlement forecasting, as effective stress in soft coastal clays is constantly changing [24]. Climate-resilient foundation design must account for the long-term effects of rising groundwater and sea-level rise, as these conditions can increase foundation vulnerability, deterioration, and associated repair costs, highlighting the importance of incorporating climate projections into coastal infrastructure planning and design [25]. These strategies have been summarised in Table 3. Figure 3 shows the Climate-Resilient Foundation Design Framework for Coastal Infrastructure.

Table 3. Foundation-design and adaptation strategies for climate-resilient coastal infrastructure.

Strategy	Design rationale	Supporting evidence
Piled or piled-raft foundations	Transfers load to deeper, less water-table-sensitive strata; piled rafts control differential settlement in soft coastal clay	Numerical and direct-CPT pile capacity studies in soft/marshland soils
Tension-resistant pile detailing	Rising groundwater increases buoyant uplift and reduces effective overburden, raising net uplift demand on piles	Direct CPT methods for pile shaft capacity in tension [18]
Ground improvement (chemical/mechanical)	Chemical stabilisation or vibro-compaction increases bearing capacity and reduces settlement of loose, saturating fill	Reviews of chemical ground-improvement methods and field vibratory compaction trials
Corrosion-resistant detailing	Elevated, more saline groundwater accelerates chloride ingress and reinforcement corrosion in substructure concrete	Reviews of chloride-induced corrosion mechanisms and mitigation in coastal RC structures
Uncertainty-aware, probabilistic design	Bayesian and reliability-based frameworks propagate site-investigation and climate-projection uncertainty into design decisions	Geotechnical uncertainty and AI-assisted decision-making frameworks
Settlement-aware serviceability checks	Compression-index correlations support long-term settlement forecasts as effective stress changes with the water table	Compression-index correlation reviews for soft clays

Sources: Synthesised from references [1,11,18,19,20,21,22,23,24,25]

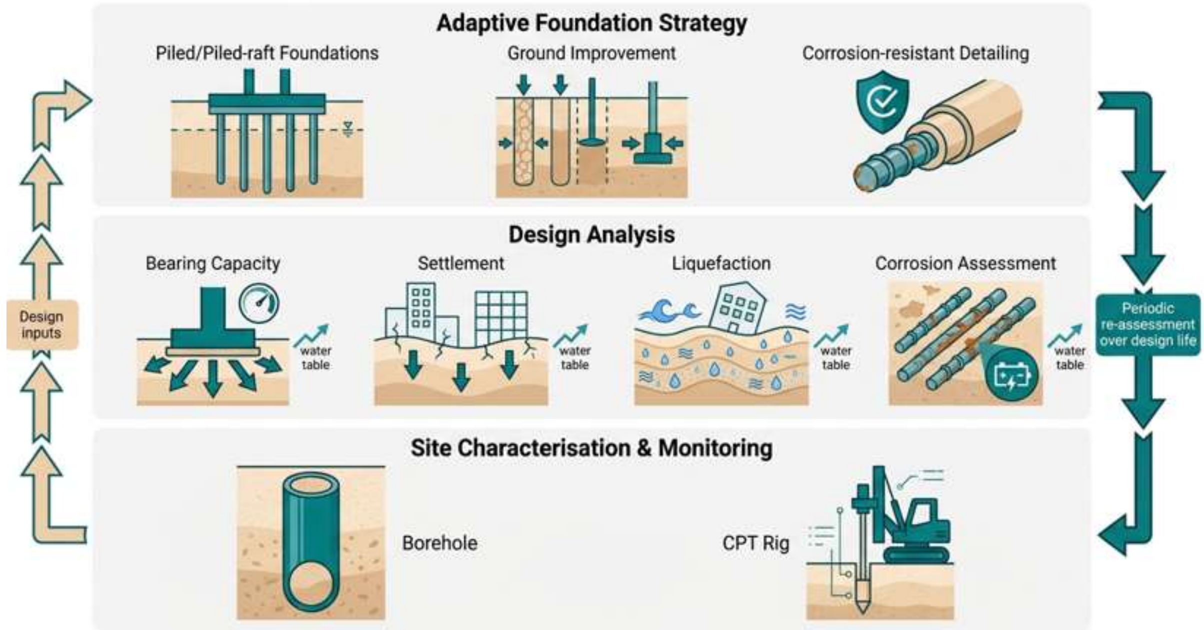

Figure 3: Climate-Resilient Foundation Design Framework for Coastal Infrastructure.
Sources: Author's conceptual framework adapted from references [11,18,20,22]

CONCLUSION

The ground-water rise is a very real threat to foundations and subsurface utilities that can compromise city infrastructure long before surface flooding can be observed, and it is an additional hazard in low-lying deltas like Lagos, where land subsidence is an issue. Advances in this hazard must go beyond the assumption of a water-table that remains static over time and move towards characterisation of sites through integrated borehole-CPT; revisions of liquefaction and bearing capacity relationships; where appropriate, deeper and more tension resisting foundation systems; detailing to resist corrosion; and probabilistic design methods that explicitly recognise uncertainty in ground conditions and future water-table changes. In order to make coastal infrastructure truly climate resilient, the concept of periodic re-assessment should be a part of the design life of structures, instead of a one-off investigation.

Conflict of Interest:

The authors declare no competing interests.

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