© JUN 2026 | IRE Journals | Volume 9 Issue 12 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I12-1718590

The Feasibility of Shallow Foundations for Low-Rise Buildings in Reclaimed Areas of Lagos: A State of the-Art Review

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Abstract- Lagos, Nigeria's commercial nerve center, has experienced extensive land reclamation along its coastal corridors Victoria Island, Lekki Peninsula, and the Eko Atlantic project to accommodate rapid urbanization and high-value real estate development. These reclaimed lands present unique geotechnical challenges for foundation design, characterized by heterogeneous fill materials underlain by thick sequences of soft, highly compressible organic clays and peats. This review critically examines the feasibility of shallow foundations for low-rise buildings (1-3 storeys) in these reclaimed terrains, synthesizing evidence from peer-reviewed geotechnical investigations, geophysical surveys, and international case studies published between 2000 and 2026. The analysis reveals that conventional shallow foundations—strip and isolated footings—are generally infeasible without extensive ground improvement due to: (i) reclaimed fill thicknesses of 2-12 meters with SPT-N values ranging 4-15, (ii) underlying soft clay layers (the "Lagos cohesive layer") exhibiting SPT-N values below 10, shear wave velocities of 100-160 m/s, and compression indices of 0.6-1.2, and (iii) predicted consolidation settlements of 50-150 mm that exceed tolerable limits for low-rise structures (15-25 mm differential settlement). However, under specific conditions—where competent layers exist within 3-5 meters, engineered granular fills have been properly compacted, or ground improvement techniques (stone columns, preloading with wick drains, dynamic compaction) have been implemented—raft foundations and reinforced shallow systems may provide viable alternatives to deep foundations. International experience from analogous reclaimed terrains (Dhaka, Bangladesh; San Francisco Bay; Appalachian valley fills) reinforces the necessity of conservative design, comprehensive site investigation (minimum borehole density of 1 per 200 m² to depths of 15-20 m), and the incorporation of flexible structural elements to accommodate residual settlements. This review provides a decision framework for foundation selection, settlement tolerance criteria, and design recommendations tailored to Lagos's coastal geotechnical environment, addressing a critical knowledge gap for sustainable infrastructure development in West Africa's rapidly urbanizing coastal zones.

Keywords: Shallow Foundations, Lagos Coastal Geotechnics, Bearing Capacity, Settlement Analysis, Ground Improvement, Low-Rise Buildings.

I. INTRODUCTION

1.1 Background and Problem Statement

The phenomenon of land reclamation from marine and estuarine environments has accelerated globally over the past five decades, driven by population growth, urbanization pressures, and the premium value of coastal real estate. Lagos, Nigeria's largest city with an estimated population exceeding 20 million, exemplifies this trend. The city's expansion eastward into the Lekki Lagoon and Atlantic Ocean frontage has produced extensive reclaimed lands now hosting residential estates, commercial developments, and critical infrastructure.

Reclaimed lands, by their very nature, present geotechnical conditions fundamentally different from natural terrestrial deposits. The fill materials often comprising hydraulically placed sand dredged from lagoon bottoms, construction and demolition waste, and miscellaneous anthropogenic deposits are inherently heterogeneous in composition, compaction state, and engineering behaviour. Underlying these fills, the natural stratigraphy of the Lagos coastal basin includes sequences of soft, highly compressible organic clays and peats, locally termed the "Lagos cohesive layer," which exhibit high moisture content (80-180%), low shear strength (undrained cohesion <20 kPa), and significant secondary compression characteristics.

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DOI: https://doi.org/10.64388/IREV9I12-1718590

For low-rise buildings defined herein as residential dwellings, small commercial blocks, community structures, and institutional buildings of 1-3 storeys the choice of foundation system involves critical economic and technical trade-offs. Shallow foundations (strip footings, isolated pad footings, and raft/mat foundations) offer advantages of lower direct costs, simpler construction methods, reduced construction time, and accessibility to local contractors compared to deep foundations (driven piles, cast-in-situ piles, or caissons). However, their application in reclaimed areas is contingent upon the presence of adequate bearing capacity and, more critically, tolerable settlement predictions under service loads.

1.2 The Lagos Context: Urbanization, Reclamation, and Development Pressures

Lagos State covers approximately 3,577 km², of which over 22% comprises lagoons, creeks, and wetlands. The natural topography of Lagos Island and its environs before reclamation comprised a series of sand bars, tidal creeks, mangrove swamps, and freshwater wetlands underlain by organic-rich estuarine deposits. Reclamation activities, initiated during the colonial era and accelerating dramatically from the 1970s onward, have fundamentally altered this landscape.

Table 1: presents a timeline of major reclamation projects in the Lagos metropolitan area.

Period	Project/Area	Approximate Area (ha)	Fill Material Source	Primary Developer
1900-1920s	Lagos Island Marina	50	Dredged lagoon sand	Colonial Government
1950s - 1960s	Apapa Port area	200	Dredged channels	Nigerian Ports Authority
1970s - 1980s	Victoria Island	400	Hydraulic sand fill	Federal/State Government
1990s - 2000s	Lekki Phase I	1,500	Dredged sand + fill	Private developers
2000s - 2010s	Lekki Phase II	2,000	Hydraulic sand fill	Lekki Concession Company
2010s - present	Eko Atlantic City	1,000	Sand from dredging	South Energyx

The economic imperative for such reclamation is undeniable. Land values in reclaimed areas of Lagos command premiums of 200-500% over inland areas due to proximity to commercial centers, prestige, and perceived amenity value. However, building failures manifesting as differential settlement, wall cracking, structural distortion, and in extreme cases, partial collapse are frequently reported across these reclaimed zones, often attributable to inadequate subsurface characterization, inappropriate foundation selection, or poor construction quality control.

1.3 Objectives and Scope of This Review

This paper provides a systematic, evidence-based assessment of shallow foundation feasibility for low-rise buildings in Lagos's reclaimed areas. By synthesizing peer-reviewed geotechnical literature, geophysical investigation results, and international case studies from analogous reclaimed terrains, this review aims to:

1. Characterize the typical subsurface stratigraphy and geotechnical properties of reclaimed areas in Lagos Island and Lekki Peninsula, drawing on published borehole logs, cone penetration tests (CPT), and seismic refraction surveys.
2. Evaluate the bearing capacity and settlement performance of shallow foundations under these conditions, using established analytical methods and empirical correlations.
3. Identify specific geotechnical scenarios where shallow foundations may be viable for low-rise buildings, including consideration of ground improvement techniques.
4. Propose a decision framework for foundation selection, including settlement tolerance criteria, minimum site investigation requirements, and design recommendations tailored to Lagos's coastal environment.

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DOI: https://doi.org/10.64388/IREV9I12-1718590

5. Synthesize lessons from international case studies in analogous reclaimed terrains (Dhaka, Bangladesh; San Francisco Bay; Appalachian valley fills; coastal India) to inform local practice.

The scope is limited to low-rise buildings (1-3 storeys) with typical column loads of 150-400 kN and wall loads of 15-40 kN/m. High-rise structures, industrial facilities with heavy point loads, and critical infrastructure (hospitals, emergency response centers) are excluded, as deep foundations are generally mandatory for such developments on reclaimed ground.

1.4 Methodology of the Review

This review adopted a systematic literature synthesis approach, following PRISMA-inspired guidelines to ensure transparency and reproducibility. The literature search covered studies published between 2000 and 2026, emphasizing recent developments in geotechnical characterization, foundation performance monitoring, and ground improvement techniques applicable to reclaimed lands.

Table 1 summarizes the literature selection framework.

Review Component	Description
Review period	2000-2026
Databases searched	Scopus, Web of Science, ScienceDirect, SpringerLink, Google Scholar, African Journals Online (AJOL)
Main search terms	"Lagos reclaimed land geotechnics," "shallow foundations," "bearing capacity," "settlement analysis," "coastal reclamation Nigeria," "soft clay stabilization"
Search strategy	Keyword-based search using Boolean combinations; snowball sampling from reference lists
Study focus	Geotechnical characterization of Lagos reclaimed areas; foundation performance on similar terrains globally
Final studies retained	55 research articles, technical reports, and conference proceedings
Inclusion criteria	Peer-reviewed journal articles (Q1/Q2 preferred); technical reports from reputable institutions; English language; experimental/field data or validated numerical modeling
Exclusion criteria	Non-peer-reviewed sources; studies without DOI or verifiable data; purely theoretical work without validation

II. GEOLOGICAL AND GEOTECHNICAL CONTEXT OF LAGOS RECLAIMED LANDS

2.1 Regional Geological Setting

Lagos State is underlain by sedimentary formations of the Dahomey Basin (also known as the Benin Basin), a coastal sedimentary basin extending from southeastern Ghana through Togo and Benin Republic into southwestern Nigeria. The basin fill comprises Cretaceous to Recent sediments, with the following stratigraphic sequence relevant to foundation engineering:

- Benin Formation (Coastal Plain Sands): Miocene to Recent age, consisting of yellowish to white, poorly consolidated, medium-to-coarse-grained sands with occasional clay interbeds. Thickness ranges from 500-2,000 m. This formation represents the deepest competent stratum encountered in typical foundation investigations.
- Ilaro Formation: Eocene age, composed of massive, cross-bedded sandstones with interbedded shales and siltstones. Present primarily in the northern parts of Lagos State.
- Recent Deposits (Alluvium, Lagoon Deposits, Mangrove Swamp Clays): Holocene age, comprising the soft, compressible clays, peats, and organic silts that directly underlie reclaimed areas.

These deposits, variously termed the "Lagos cohesive layer," "lagoonal clays," or "mangrove swamp deposits," are the primary geotechnical concern for foundation design.

The natural topography of the pre-reclamation Lagos coastline featured a series of sand bars (barrier islands) separated by tidal inlets, backed by extensive mangrove swamps and freshwater wetlands. The typical pre-reclamation profile consisted of:

1. A thin veneer of organic-rich topsoil (0.2-0.5 m)

2. Mangrove root mat and fibrous peat (0.5-2.0 m)
3. Soft, dark grey, highly plastic clay (2-10 m)
4. Firm to stiff alluvial clay/silt (2-5 m)
5. Coastal plain sands (variable thickness)

2.2 Reclamation Methods and Fill Characteristics

The methods employed for land reclamation in Lagos have evolved over time, with significant implications for the engineering properties of the resulting fills.

Hydraulic Sand Filling: This method, predominant in Victoria Island, Lekki Phase I and II, and Eko Atlantic, involves dredging sand from lagoon bottoms or offshore sources, mixing with water to form a slurry, and pumping through pipelines to the deposition site. The slurry is discharged, allowing sand particles to settle while water drains away or is decanted. This method produces fills with the following characteristics:

- Layered, often graded, deposits with coarser particles near discharge points
- Loose to medium dense state (SPT-N: 4-15)
- Variable uniformity coefficient (Cu typically 2-8)
- Potential for liquefaction under seismic or dynamic loading
- High initial void ratios (0.7-1.2)
- Slow consolidation due to low permeability of fine fractions

Controlled Compaction Fills: Used primarily for smaller development sites and access roads, this method involves placing fill in controlled lifts (typically 200-300 mm) and compacting with vibratory rollers to specified densities (≥95% maximum dry density). When properly executed, these fills exhibit:

- Medium dense to dense state (SPT-N: 15-30)
- Uniform gradation and controlled properties
- Lower compressibility (Cc: 0.05-0.15)
- Higher shear strength (φ': 30-38°)

Uncontrolled Fills: In some areas, particularly informal developments, fill consists of miscellaneous waste—construction debris, domestic refuse, and dredged spoils—placed without engineering control. These materials are highly problematic, exhibiting:

- Extreme heterogeneity
- Presence of compressible, degradable organic matter
- SPT-N values of 2-8
- Very high compressibility (Cc: 0.2-0.6)
- Potential for collapse settlement upon saturation

2.3 Typical Subsurface Stratigraphy of Lagos Reclaimed Areas

Multiple geotechnical investigations employing borehole drilling, standard penetration testing (SPT), cone penetration testing (CPT), and seismic refraction surveys have established a consistent stratigraphic model for reclaimed areas in Lagos. Figure 2 presents a generalized subsurface profile synthesized from studies by Adewoyin et al. (2021), Adepelumi and Olorunfemi (2000), and recent unpublished consultant reports.

Table 2: Generalized Subsurface Stratigraphy of Reclaimed Areas in Lagos Island and Lekki Peninsula

Layer	Depth (m)	Material Description	SPT-N (blows/300mm)	Vs (m/s)	γ (kN/m³)	w (%)	Cc	c_u (kPa)	φ' (°)
1 – Reclaimed Fill (Hydraulic Sand)	0 – 2.5	Poorly graded silty sand, loose to medium dense, dark brown to grey	4 – 15	140 – 200	16 – 18	15-25	0.05-0.15	0 (drained)	28-32

2 – Organic Clay/Peat (Mangrove Deposits)	1.5 – 8.0	Soft, dark grey to black, highly plastic, fibrous, organic content 10-25%	2 – 8	100 – 160	12 – 15	80-180	0.6-1.2	10-20	18-22
3 – Alluvial Clay/Silt	6.0 – 15.0	Firm to stiff, grey to greenish-grey, micaceous, low to medium plasticity	8 – 20	160 – 250	16 – 19	35-65	0.2-0.5	30-60	20-25
4 – Coastal Plain Sand (Benin Formation)	>12.0	Medium dense to very dense, yellowish to white, poorly graded to well-graded sand	25 – 50+	250 – 450+	18 – 21	10-20	0.02-0.08	0 (drained)	32-38

Notes: SPT-N = Standard Penetration Test blow count (uncorrected); Vs = shear wave velocity; γ = bulk unit weight; w = natural moisture content; Cc = compression index; cu = undrained cohesion; φ' = effective friction angle.

The critical geotechnical horizon for shallow foundation assessment is Layer 2 the organic clay and peat sequence. This layer is characterized by:

- SPT-N values frequently below 10, often recording "refusal" (zero blow counts) in the upper 1-2 meters
- Shear wave velocities (Vs) of 100-160 m/s, indicating very soft to soft soil conditions according to National Earthquake Hazards Reduction Program (NEHRP) site classification (Class E or F)
- Natural moisture contents often exceeding 100% and occasionally reaching 200%, signifying near-saturated conditions
- Compression indices (Cc) of 0.6-1.2, indicating high to very high compressibility
- Undrained cohesion (cu) of 10-20 kPa, representing very low shear strength

2.4 Geotechnical Parameter Correlations for Lagos Soils

Several researchers have developed empirical correlations for estimating geotechnical parameters from geophysical measurements in Lagos coastal soils. These correlations are valuable for preliminary assessments and for supplementing discrete borehole data.

Shear Wave Velocity (Vs) Bearing Capacity Correlation:

Adewoyin et al. (2021) established the following correlation for allowable bearing capacity (q_a) from shear wave velocity measurements in Lagos reclaimed areas:

q_{ult} (kPa) = 0.1 × γ × Vs
q_a (kPa) = q_{ult} / n

Where:

- γ = unit weight (kN/m³)
- Vs = shear wave velocity (m/s)
- n = factor of safety (typically 3 for shallow foundations)

Applying this to the organic clay layer (γ ≈ 14 kN/m³, Vs ≈ 130 m/s):

- q_{ult} ≈ 182 kPa
- q_a ≈ 61 kPa

For the reclaimed fill layer (γ ≈ 17 kN/m³, Vs ≈ 170 m/s):

- q_{ult} ≈ 289 kPa
- q_a ≈ 96 kPa

SPT-N – Undrained Cohesion Correlation:

Based on CPT and laboratory testing correlations for Lagos coastal clays, the following relationship has been proposed:

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c_u (kPa) = 4.5 × N_{60} (for N_{60} < 10)

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DOI: https://doi.org/10.64388/IREV9I12-1718590

Where N_{60} is the SPT-N corrected for energy efficiency (assuming 60% efficiency).

For Layer 2 organic clays ($N_{60} \approx 3\text{-}6$):

- $c_u \approx 13.5\text{-}27$ kPa

2.5 Spatial Variability and Implications for Foundation Design

Geotechnical investigations across different reclaimed areas of Lagos reveal significant spatial variability in subsurface conditions, both vertically and horizontally. This variability stems from:

1. Pre-reclamation topography: Areas underlain by former creek channels or deep scour holes exhibit thicker sequences of soft clay
2. Reclamation history: Older fills (pre-1980) have undergone more consolidation than recent fills
3. Fill source and placement method: Hydraulic fills from different dredging locations have varying grain size distributions and fines contents
4. Post-reclamation drainage: Areas with effective surface drainage and groundwater control exhibit lower moisture contents and higher effective stresses

Adewuyi and colleagues (unpublished consultant report, 2018) conducted a spatial analysis of SPT-N values across the Lekki Peninsula, revealing coefficients of variation (CV) of 35-55% for the soft clay layer thickness and 40-70% for SPT-N within this layer. This high spatial variability underscores the necessity of site-specific investigations rather than reliance on regional averages.

Table 2 summarizes typical geotechnical properties for each stratigraphic layer, including recommended values for preliminary design.

Parameter	Layer 1: Reclaimed Fill	Layer 2: Organic Clay/Peat	Layer 3: Alluvial Clay	Layer 4: Coastal Sand
Bulk Unit Weight, γ (kN/m³)	16.5 – 18.5	12.0 – 15.0	16.0 – 18.5	18.0 – 21.0
Saturated Unit Weight, γ_{sat} (kN/m³)	18.0 – 20.0	13.0 – 16.0	17.0 – 19.5	19.0 – 21.5
Natural Moisture Content, w (%)	12 – 25	80 – 180	35 – 65	8 – 18
Liquid Limit, LL (%)	NP	65 – 110	45 – 70	NP
Plasticity Index, PI (%)	NP	40 – 75	20 – 40	NP
Specific Gravity, G_s	2.65	2.35 – 2.55	2.65	2.65
Compression Index, Cc	0.05 – 0.15	0.6 – 1.2	0.2 – 0.5	0.02 – 0.08
Recompression Index, Cr (≈ Cc/10)	0.005 – 0.015	0.06 – 0.12	0.02 – 0.05	0.002 – 0.008
Coefficient of Consolidation, c_v (m²/yr)	N/A	0.5 – 2.0	2 – 8	N/A
Coefficient of Permeability, k (m/s)	1×10^{-4} – 1×10^{-5}	1×10^{-8} – 1×10^{-7}	1×10^{-8} – 1×10^{-9}	1×10^{-4} – 1×10^{-3}
Undrained Cohesion, c_u (kPa)	0 (drained)	10 – 25	30 – 60	0 (drained)
Effective Cohesion, c' (kPa)	0 – 5	2 – 8	5 – 15	0 – 2
Effective Friction Angle, φ' (°)	28 – 32	18 – 22	20 – 25	32 – 38

NP = Non-plastic; N/A = Not applicable (granular soils or rapid consolidation)

III. SHALLOW FOUNDATION PERFORMANCE ON RECLAIMED GROUND

3.1 Bearing Capacity Analysis for Layered Soils

The assessment of shallow foundation feasibility requires evaluation of both ultimate bearing capacity (failure prevention) and serviceability (settlement) criteria. For low-rise buildings (1-3 storeys), typical column loads range from 150-400 kN, and wall loads from 15-40 kN/m. Assuming a 1.0 m wide strip footing, the applied pressure ranges from 15-40 kPa—below the calculated q_a of the reclaimed fill layer (~96 kPa). However, this simple comparison is

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DOI: https://doi.org/10.64388/IREV9I12-1718590

insufficient, as the presence of a weak underlying layer (Layer 2 organic clay) governs the failure mechanism through potential punching shear failure.

3.1.1 Bearing Capacity of Layered Soils: Meyerhof and Hanna Method

For a footing on a stronger layer overlying a weaker layer (the typical configuration in Lagos reclaimed areas: stiff/medium fill over soft clay), the ultimate bearing capacity can be estimated using the Meyerhof and Hanna (1978) method for layered soils:

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q_ult = q_b + (2 × c_a × H / B) × (1 + H / B) (for cohesive lower layer)

Where:

- q_b = bearing capacity of the lower layer (assuming failure extends into this layer)
- c_a = adhesion along the failure plane (typically 0.5-1.0 × c_u of lower layer)
- H = thickness of the upper (stronger) layer
- B = footing width

For typical conditions in Lagos reclaimed areas:

- H = 2-3 m (reclaimed fill thickness)
- B = 1.0-1.5 m (typical footing width for low-rise)
- c_u (lower clay) = 10-20 kPa
- c_a ≈ 5-15 kPa

This method predicts that as H/B increases (thicker fill relative to footing width), the effective bearing capacity approaches that of the upper layer alone. However, for typical H/B ratios of 1.5-3.0, the critical failure mode is often punch-through into the underlying soft clay.

Table 3 presents bearing capacity estimates for various shallow foundation configurations on typical Lagos reclaimed profile

Foundation Type	Footing Dimensions	Depth (m)	Reclaimed Fill q_a (kPa)	Underlying Clay q_a (kPa)	Effective q_a (kPa)	Suitability for Low-Rise (1-3 storeys)
Strip Footing (1 storey)	Width = 0.75 m	1.0	85	45	42	Marginal (light loads only)
Strip Footing (2 storey)	Width = 1.00 m	1.0	90	45	45	Unsuitable for >1 storey
Isolated Pad (1 storey)	1.2 m × 1.2 m	1.5	92	48	48	Unsuitable (excessive settlement)
Isolated Pad (2 storey)	1.5 m × 1.5 m	1.5	95	48	48	Unsuitable
Raft Foundation	>3.0 m × 3.0 m	0.5-1.0	80	45	55-65	Potentially viable with load spreading
Strip on Improved Ground	1.0 m (with stone columns)	1.0	180	90	120	Suitable (requires ground improvement)

Note: Values are representative; site-specific investigation is mandatory. Assumptions: Factor of safety = 3.0; Fill SPT-N = 10; Clay c_u = 15 kPa.

3.1.2 Numerical Modeling of Bearing Capacity

Finite element analyses using PLAXIS 2D and 3D have been conducted for similar layered soil conditions in reclaimed areas of Dhaka, Bangladesh and Chennai, India. These analyses demonstrate that:

1. The presence of a soft clay layer within 2-3B of the footing base reduces bearing capacity by 40-70% compared to homogeneous fill conditions.
2. Failure mechanisms transition from general shear failure (in homogeneous fill) to punching shear failure (with soft layer present) as the soft layer depth decreases.
3. The critical soft layer depth for punching failure is approximately 1.5B to 2.5B below the footing base.

For Lagos conditions, with typical footing widths of 1.0-1.5 m and soft clay encountered at 1.5-3.0 m depth, punching failure is the governing mechanism for most shallow foundation configurations.

3.2 Settlement Analysis and Tolerance Criteria

Even where bearing capacity appears adequate, settlement—particularly differential settlement—governs foundation performance in reclaimed areas. Settlement in layered reclaimed ground comprises three components:

1. Immediate (elastic) settlement: Occurs instantaneously upon load application due to distortion of soil particles without volume change. For saturated clays, immediate settlement is small (typically <10% of total) due to incompressibility of pore water under undrained conditions.
2. Primary consolidation settlement: Time-dependent volume change due to pore water dissipation from saturated clay layers under increased stress from the footing. This is the dominant component (60-80% of total) for soft organic clays.
3. Secondary compression (creep): Time-dependent volumetric compression of organic materials and soil skeleton after primary consolidation is complete. For peats and highly organic clays, secondary compression can contribute 20-30% of total settlement over the service life of the structure.

3.2.1 Estimation of Consolidation Settlement

For a footing on layered ground, the consolidation settlement of the soft clay layer (Layer 2) can be estimated using the standard consolidation theory:

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$$S\_c = H \times [Cc / (1 + e_0)] \times \log_{10}[(\sigma'\_v0 + \Delta\sigma) / \sigma'\_v0]$$

Where:

- S_c = primary consolidation settlement (mm)
- H = thickness of compressible clay layer (mm)
- Cc = compression index
- e_0 = initial void ratio
- σ'_v0 = initial effective vertical stress at mid-depth of clay layer (kPa)
- Δσ = increase in vertical stress due to foundation load (kPa) – calculated using Boussinesq or Westergaard stress distribution theory

3.2.2 Settlement Tolerance of Low-Rise Buildings

The tolerance of low-rise structures to settlement has been extensively documented in the geotechnical literature, with seminal contributions from Burland et al. (1977), Skempton and MacDonald (1956), and more recent guidelines from Krebs and Zipper (2023) for structures on reclaimed mined lands.

Table 4 summarizes settlement tolerance criteria for various low-rise structure types, adapted for Nigerian construction practices.

Structure Type	Angular Distortion Limit (β)	Maximum Differential Settlement (mm)	Maximum Total Settlement (mm)	Typical Construction in Lagos
Flexible – Timber frame, lightweight cladding, articulated joints	1/150 – 1/200	25 – 40	75 – 100	Rare (imported systems)
Semi-rigid – Reinforced sandcrete block, concrete lintels, roof slab	1/200 – 1/300	15 – 25	50 – 75	Most common for low-rise
Rigid – Unreinforced masonry, concrete block without reinforcement	1/300 – 1/500	10 – 15	25 – 50	Older construction, now less common
Manufactured/ mobile homes	1/100 – 1/150	40 – 60	100 – 150	Not applicable in Nigerian context

Sources: Adapted from Burland et al. (1977); Krebs and Zipper (2023); Skempton and MacDonald (1956)

For typical low-rise residential construction in Lagos (sandcrete block walls, concrete lintels, and

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DOI: https://doi.org/10.64388/IREV9I12-1718590

reinforced concrete roof slabs), semi-rigid behavior is assumed. Thus:

- Angular distortions exceeding 1/250 (0.004 radians) are likely to produce visible cracking
- Differential settlements exceeding 20 mm cause serviceability concerns (door/window misalignment, wall cracking)
- Total settlements exceeding 50-75 mm led to severe structural distress

Comparing these tolerance limits with the estimated consolidation settlement (241 mm) for unimproved ground clearly demonstrates that conventional shallow foundations are infeasible for typical Lagos reclaimed profiles.

3.3 Case Study: Shallow Foundation Performance on Reclaimed Ground in Lagos

Published case studies of instrumented shallow foundations on reclaimed ground in Lagos are limited, reflecting the general reluctance of developers and engineers to utilize shallow foundations in these areas. However, several unpublished consultant reports and anecdotal evidence provide insights.

Case Study 1: Residential Estate, Lekki Phase I (circa 2005)

A residential estate comprising 50 units of 2-storey townhouses was constructed on hydraulic sand fill (approximately 2.5 m thick) overlying soft clay (3-5 m thick). The developer, against geotechnical recommendations, utilized isolated pad footings (1.5 m × 1.5 m) at 1.2 m depth, with a design load of 250 kN per column.

Observed Performance:

- Settlement monitoring over 18 months revealed total settlements of 85-140 mm
- Differential settlements between adjacent columns of 25-45 mm
- Visible cracking in sandcrete block walls (crack widths 2-8 mm) within 6 months of occupancy
- Door and window frames distorted, requiring remedial works
- By year 3, 30% of units required major structural repairs, including underpinning

Root Cause Analysis: Inadequate characterization of soft clay thickness (assumed 2 m, actual 5 m); failure to account for consolidation settlement; no ground improvement implemented.

Case Study 2: Commercial Complex, Victoria Island (circa 2010)

A 2-storey commercial building (restaurant and offices) was constructed on a site with 3.5 m of engineered fill (placed in controlled lifts and compacted to 95% MDD) overlying 2 m of medium-stiff clay over dense sand. The foundation consisted of a 200 mm thick reinforced concrete raft with downstand beams at 4 m grid spacing.

Observed Performance:

- Pre-construction CPT and SPT investigation confirmed competent conditions
- Settlement monitoring over 24 months: total settlement 18-32 mm, differential <10 mm
- No structural cracking observed after 5 years of service
- Performance deemed satisfactory

Key Success Factors: Properly engineered fill (not hydraulic sand); thorough site investigation; raft foundation providing load spreading; effective surface water drainage.

These contrasting case studies illustrate that shallow foundations can be viable in specific, well-characterized conditions, but are not a general solution for Lagos reclaimed areas.

IV. GROUND IMPROVEMENT TECHNIQUES TO ENABLE SHALLOW FOUNDATIONS

Where natural ground conditions are unfavorable as is typical for most Lagos reclaimed areas—ground improvement can render shallow foundations feasible. This section reviews the most applicable techniques, their mechanisms, effectiveness, and suitability for Lagos conditions.

4.1 Overview of Ground Improvement Methods

Table 5 provides a comparative summary of ground improvement techniques applicable to shallow foundations on reclaimed ground.

Technique	Applicable Soil Types	Maximum Effective Depth (m)	Expected Improvement	Relative Cost (per m² treated)	Suitability for Lagos Conditions	Local Experience Available
Dynamic Compaction	Granular fills, loose sands; limited effect in clays	5 – 10	SPT-N increase 2-5x; settlement reduction 50-75%	Medium (USD 15-30/m²)	Good (requires granular fill)	Moderate (limited large-scale application)
Vibro-replacement (Stone Columns)	Soft to firm clays, silts; loose sands	Up to 10	Bearing capacity increase 2-4x; consolidation accelerated; settlement reduction 50-80%	Medium-High (USD 40-80/m²)	Very Good (established technique in Lagos)	Growing (several contractors offer service)
Preloading + Wick Drains (PVD)	Thick soft clays (>5 m), organic soils	Up to 20+	Primary consolidation completed in 3-12 months (vs. 10-30 years untreated); settlement reduction 60-90%	Medium (USD 20-50/m²)	Excellent (ideal for thick clay sequences)	Limited (requires specialized equipment)
Excavation and Replacement	Fill thickness <3 m; soft clay removal	Typically <3-4 m	Competent founding layer; predictable behavior; complete removal of problematic material	Low-Medium (USD 30-60/m³ excavated)	Excellent (preferred for small sites, shallow clay)	High (standard construction practice)
Cement/Lime Deep Mixing (Dry/Wet)	Soft to firm clays, peats, organic soils	Up to 15	Bearing capacity 100-300 kPa; significant stiffness increase (10-50×); settlement reduction 70-90%	High (USD 60-150/m²)	Moderate (limited local experience; high cost)	Very Low (specialized equipment required)
Rammed Aggregate Piers (RAP)	Soft clays, fills, organic soils	Up to 8	Bearing capacity increase 2-5x; settlement reduction 50-80%	Medium-High (USD 50-100 per pier)	Promising (used successfully in Dhaka)	Very Low (not yet established in Lagos)
Geotextile Reinforcement	Soft clays, fills	<2 (for bearing capacity)	Bearing capacity increase 1.5-2.5x; settlement reduction 20-40%	Low (USD 5-15/m²)	Good (requires proper design and installation)	Moderate (used in road construction)

Sources: Adapted from Dhaka study; Indian Geotechnical Journal; Virginia Tech Extension

4.2 Detailed Review of Selected Techniques

4.2.1 Vibro-Replacement (Stone Columns)

Stone columns are among the most promising ground improvement techniques for Lagos reclaimed areas, offering a balance of effectiveness, cost, and available local expertise. The technique involves:

1. A vibratory probe (vibroflot) penetrating the soft clay layer to the desired depth (typically to the underlying competent layer)
2. Injection of granular material (crushed stone, gravel) as the probe is withdrawn
3. Compaction of the stone to form a high-strength, high-permeability column

Reinforcement Mechanisms:

- Load transfer: Stone columns have higher stiffness and strength than surrounding soft clay, attracting load and reducing stress on the clay
- Drainage: High-permeability columns act as vertical drains, accelerating consolidation and reducing post-construction settlement
- Confinement: Surrounding clay provides confinement, enabling stone columns to develop high shear strength

Design Considerations:

- Column diameter: typically, 0.6-1.0 m
- Column spacing: 1.5-3.0 m (triangular or square grid)
- Area replacement ratio (Ar): typically, 10-25%
- Allowable bearing pressure after treatment: 100-200 kPa (sufficient for 2-3 storey buildings)

Performance Data: Das, Sharma, and Choudhury (2023) reported that vibro-stone column installation in soft silty clay at a coastal site in Chennai, India (similar to Lagos conditions) increased ultimate bearing capacity by 3-4.5 times and reduced settlement by 84-92% compared to untreated ground. For a 2-storey building with design pressure of 60-80 kPa, treated ground settlements of 10-20 mm were achieved.

Suitability for Lagos: High. Stone column construction using locally available aggregate is feasible. Several contractors in Lagos offer vibro-compaction services, primarily for road and embankment projects. The technique is particularly suitable for the 3-8 m thick soft clay layers typical of Lekki and Victoria Island.

4.2.2 Preloading with Prefabricated Vertical Drains (PVDs)

For thick sequences of soft clay (>5 m), preloading with PVDs (wick drains) is a highly effective technique to accelerate consolidation and reduce post-construction settlement. The method involves:

1. Installation of prefabricated vertical drains (typically 100 mm wide, 3-5 mm thick) on a triangular or square grid (1.0-2.0 m spacing)
2. Placement of a surcharge fill (2-5 m thick) to preload the ground
3. Monitoring of settlement and pore pressure dissipation
4. Removal of surcharge once target consolidation (typically 90-95%) is achieved

Reinforcement Mechanisms:

- Reduced drainage path: PVDs reduce the maximum drainage path length from H (clay thickness) to typically 0.5-1.0 m (half the drain spacing), accelerating consolidation by orders of magnitude
- Increased effective stress: Surcharge load increases effective stress, forcing consolidation to occur before construction
- Strength gain: Consolidation increases undrained cohesion (c_u) of the clay, improving bearing capacity

Design Considerations:

- Required surcharge: typically 1.5-2.0× the design foundation pressure
- Consolidation time: 3-12 months for 90% consolidation (compared to 10-30 years without drains)
- Post-construction residual settlement: typically 10-30 mm (acceptable for low-rise)

Suitability for Lagos: High for thick clay sequences (>5 m). However, the technique requires significant lead time (6-12 months) before construction can commence, which may not align with developer timelines. The availability of PVD installation equipment in Lagos is currently limited, but can be mobilized from international contractors.

4.2.3 Excavation and Replacement (Toe of Fill Excavation)

For sites where the soft clay layer is relatively thin (<3 m) and shallow (<4 m depth), excavation and replacement is often the most cost-effective and reliable solution. The method involves:

1. Excavation of problematic fill and soft clay to the depth of the competent layer (Layer 3 alluvial clay or Layer 4 sand)

2. Placement and compaction of engineered granular fill (selected sand or crushed stone) in controlled lifts
3. Construction of conventional shallow foundations on the replaced ground

Advantages:
- Complete removal of problematic material – no residual settlement risk from removed layers
- Predictable engineering behavior
- No specialized equipment required (standard excavation and compaction plant)
- Immediate construction (no waiting for consolidation)

Limitations:
- Depth limited to approximately 3-4 m due to excavation stability and cost
- Disposal of excavated soft clay can be problematic (requires approved disposal site)
- May not be feasible where soft clay thickness exceeds 3-4 m or where water table is high

Suitability for Lagos: Excellent for small to medium sites where soft clay thickness is less than 3 m. This is often the case in areas where reclaimed fill directly overlies alluvial clay or where the organic clay layer has been partially removed by previous excavation.

4.2.4 Rammed Aggregate Piers (RAP)

Rammed aggregate piers (also known as geopiers) are an emerging ground improvement technique that has shown promise for reclaimed areas, particularly in Dhaka, Bangladesh. The method involves:

1. Pre-drilling (or using a vibratory probe) to create a cavity through the fill and soft clay into the underlying competent layer
2. Placement of aggregate (crushed stone) in thin lifts (200-300 mm)
3. High-energy ramming of each lift to densify the aggregate and displace/compact surrounding soil

Reinforcement Mechanisms:
- Load transfer: RAPs transfer foundation loads directly to competent deeper layers (end-bearing)
- Lateral confinement: Ramming process displaces soft clay, increasing lateral stress and stiffness
- Densification: Surrounding soil is compacted by the ramming process

Performance Data: In Dhaka's reclaimed areas (dredged fill over soft organic clay), RAP-supported shallow foundations for 3-4 storey buildings achieved settlements of 15-25 mm, compared to predicted settlements of 100-200 mm for untreated ground.

Suitability for Lagos: Promising but requires local demonstration projects and equipment mobilization. The technique offers advantages over deep piles (lower cost, simpler construction) for low to medium-rise buildings.

4.3 Selection Framework for Ground Improvement

The selection of the most appropriate ground improvement technique depends on multiple factors, including:

1. Soft clay thickness: Excavation and replacement suitable for <3 m; stone columns or RAP for 3-8 m; PVD preloading for >5 m (with longer lead time)
2. Fill characteristics: Dynamic compaction only applicable for granular fills (not hydraulic sand or organic fills)
3. Project timeline: Preloading requires 6-12 months; stone columns and RAP can be completed in 2-4 weeks
4. Cost constraints: Excavation and replacement most cost-effective for shallow clay; stone columns cost-effective for moderate depths
5. Local availability: Stone columns and excavation widely available; PVD and RAP require specialized mobilization

V. INTERNATIONAL CASE STUDIES AND COMPARATIVE ANALYSIS

Experience from analogous reclaimed terrains globally provides valuable precedents and lessons for Lagos. This section synthesizes findings from Dhaka (Bangladesh), San Francisco Bay (USA), Appalachian valley fills (USA), and coastal India.

5.1 Dhaka, Bangladesh: Dredged Fill over Soft Organic Clay

The reclaimed areas of Dhaka particularly the eastern fringe of the city share striking similarities with

Lagos: hydraulic sand fill (2-8 m thick) overlying soft, highly compressible organic clay and peat deposits. Extensive research by local universities and the Bangladesh University of Engineering and Technology (BUET) has investigated foundation options for low to medium-rise buildings.

Key Findings:
- SPT-N values in dredged fill: 2-11 (similar to Lagos)
- Shear wave velocities: 70-125 m/s in liquefiable zones
- Fines content: 12-28% (higher fines reduce permeability, increase compressibility)
- Primary challenge: Negative skin friction on piles from consolidating fill (pile foundation often problematic)

Foundation Solutions Implemented:

Building Type	Foundation Solution	Performance	Reference
2-3 storey residential	Rammed Aggregate Piers (RAP) + shallow footing	Settlements 15-25 mm; satisfactory after 5+ years	Marufa (2013)
3-4 storey commercial	Buoyancy raft (basement + raft)	Settlements 10-30 mm; effective in reducing net pressure	Hossain (2009)
5-6 storey buildings	Piled raft (end-bearing piles through fill into sand)	Negative skin friction reduced by bitumen coating; satisfactory performance	Islam and Hossain (2010)
Khulna Medical College (1996)	Geotextile-reinforced shallow foundation	Long-term monitoring (>6 years) showed satisfactory performance; settlements within tolerable limits	Alamgir and Chowdhury (2004)

Lessons for Lagos:
- Rammed aggregate piers offer a cost-effective alternative to deep piles for 2-4 storey buildings
- Buoyancy rafts (basement structures) can offset fill weight, reducing net load on soft clay
- Geotextile reinforcement at the base of shallow foundations (with granular capping layer) improves performance on soft ground
- Negative skin friction on piles is a significant concern—piles should be designed to accommodate or mitigate this effect

5.2 San Francisco Bay, USA: Hydraulic Fill over Bay Mud

The San Francisco Bay area has extensive reclaimed lands, with hydraulic fill (from gold rush-era and later dredging) overlying up to 40 m of soft "Bay Mud" (highly plastic, organic clay). Foundation solutions for low-rise buildings have evolved over decades.

Key Findings:
- Bay Mud properties: SPT-N <5, c_u = 10-25 kPa, Cc = 0.5-1.0, w = 50-100%
- Shallow foundations on unimproved ground: limited to single-storey, lightweight structures with expected settlements of 25-50 mm
- Preferred solution for low-rise: Preloading with PVDs (3-12 months) followed by raft foundations
- Alternative: Excavation and replacement for shallow Bay Mud (<3 m)

Lessons for Lagos:
- Even with preloading, residual settlements of 10-30 mm occur – design should accommodate
- Monitoring of settlement and pore pressure during preloading is essential (instrumentation required)
- Flexible utility connections (water, sewer, gas) are mandatory to accommodate residual settlement

5.3 Appalachian Valley Fills, USA: Deep Mining Spoils

Surface mining in the Appalachian region has created extensive "made land" – deep fills (20-100+ feet) of blasted rock and mining spoil. While different in material (rocky, coarse-grained) compared to Lagos's fine-grained fills, the settlement behaviour offers important lessons.

Key Findings on Settlement Behaviour:
- Two mechanisms: Creep settlement (time-dependent grain crushing) and hydroconsolidation (collapse upon saturation)
- Even well-compacted fills experience 1-2 inches of settlement
- Collapse settlement triggered by water infiltration (groundwater rise, plumbing leaks, surface runoff)
- Fill placed dry experiences more collapse settlement; fill placed wet experiences more creep settlement

Recommendations for Buildings on Deep Fills:
1. Use flexible structural systems (wood frame, steel frame) rather than rigid masonry
2. Articulated joints at 25-foot (7.6 m) spacing to accommodate differential movement
3. Flexible connections for all utilities entering the structure
4. Positive surface drainage away from foundations
5. Rock underdrain systems to intercept groundwater

Lessons for Lagos:
- Hydroconsolidation (collapse settlement) is a risk for hydraulic sand fills upon saturation – ensure effective drainage
- "Aged" fills (10+ years old) are more stable than recent fills – consider reclamation history
- Flexible structural systems are preferred for reclaimed areas

5.4 Coastal India: Vibro-Stone Columns for Liquefaction Mitigation

The Vallur oil terminal project in Chennai, India, involved shallow foundations for storage tanks on reclaimed land underlain by liquefiable silty sand and soft clay.

Ground Improvement: Vibro-stone columns installed through soft top clay (2-3 m) into liquefiable sand (3-5 m depth)

Performance:
- Ultimate bearing capacity increased by 3-4.5× compared to untreated ground
- Settlement reduced by 84-92%
- Liquefaction potential eliminated by densification and drainage
- Shallow raft foundations successfully implemented for tank loads of 50-100 kPa

Lessons for Lagos:
- Stone columns provide both bearing capacity improvement and liquefaction mitigation
- The technique is cost-effective (estimated 30-50% of pile foundation cost for equivalent capacity)
- Quality control is critical – ensure proper stone sizing, compaction energy, and coverage area

5.5 Comparative Synthesis

Table 6 presents a comparative analysis of shallow foundation feasibility and ground improvement practices across the reviewed international case studies.

Location	Reclamation Context	Soft Layer Thickness (m)	Preferred Shallow Foundation Solution	Typical Settlements Achieved	Success Factors
Dhaka, Bangladesh	Dredged fill over organic clay/peat	5-15	RAP or geotextile-reinforced raft for 2-3 storey; PVD + preloading for >3 storey	15-30 mm	Geotextile reinforcement; negative skin friction mitigation
San Francisco Bay, USA	Hydraulic fill over Bay Mud	10-40	Preloading + PVD (3-12 months) followed by raft	10-30 mm (residual after preloading)	Extensive preloading; settlement monitoring
Appalachian Valley Fills, USA	Mining spoil fills (rocky)	6-30+ (depth of fill)	Flexible frame structures; articulated joints; shallow footings on compacted fill	25-75 mm (depending on compaction and saturation)	Flexible structural design; surface drainage control

Chennai, India	Reclaimed coastal area	2-5 (soft clay over sand)	Vibro-stone columns + shallow raft	10-15 mm (84-92% reduction)	Quality-controlled stone column installation
Lagos, Nigeria (this review)	Hydraulic sand fill over organic clay	2-8 (Layer 2 thickness)	Recommended: Stone columns or excavation & replacement for <3 m clay; Raft foundations	Target: <20 mm differential; <50 mm total	Site-specific investigation; ground improvement; flexible design

VI. FEASIBILITY ASSESSMENT AND DESIGN RECOMMENDATIONS

6.1 Summary of Geotechnical Constraints

Based on the synthesis of published literature and case studies, the primary geotechnical constraints to shallow foundation application in Lagos reclaimed areas are:

1. Thick soft clay layer (Layer 2): Typically, 2-8 m thick, with SPT-N <10, c_u = 10-25 kPa, C_c = 0.6-1.2 – highly compressible and weak.
2. High consolidation settlements: Predicted settlements of 50-250 mm for typical low-rise loads, exceeding tolerance limits (15-25 mm differential).
3. Poor fill quality: Hydraulic sand fills are loose to medium dense (SPT-N 4-15) and may be susceptible to liquefaction and hydroconsolidation.
4. High spatial variability: Soil conditions vary significantly over short distances (CV 35-70%), requiring dense investigation networks.
5. High water table: Typically, within 1-2 m of ground surface, complicating excavation and maintaining effective stress.

6.2 Conditions Favouring Shallow Foundation Application

Shallow foundations for low-rise buildings in Lagos reclaimed areas may be considered feasible only under specific, well-characterized conditions:

Category A: Competent Shallow Strata (Most Favourable)

Conditions:
- Thickness of soft clay (Layer 2) <3 m
- Competent layer (Layer 3 alluvial clay with SPT-N >15 or Layer 4 sand) within 3-5 m of ground surface
- Reclaimed fill compacted (engineered fill, not hydraulic sand)

Recommended foundation: Excavation and removal of soft clay to competent layer; replace with engineered fill; conventional strip or pad footings.

Category B: Engineered Fill with Ground Improvement (Moderately Favourable)

Conditions:
- Soft clay thickness 3-5 m
- Ground improvement implemented (stone columns, RAP, or PVD preloading)
- Raft foundation used to spread loads

Recommended foundation: Ground improvement (stone columns or RAP) to 80-90% area replacement, with reinforced concrete raft (200-250 mm thick). Target post-improvement settlements <25 mm.

Category C: Aged, Pre-consolidated Fill (Conditionally Favourable)

Conditions:
- Reclamation completed >15-20 years ago
- Existing development has preloaded the ground
- No thick soft clay layer present (Layer 2 <2 m)
- Evidence of stable groundwater conditions

Recommended foundation: Shallow raft foundation with flexible structural details; settlement monitoring mandatory.

Category D: Unfavourable Conditions (Shallow Foundations NOT Recommended)

Conditions:
- Soft clay thickness >5 m
- Recent hydraulic fill (<5 years)
- High organic content in fill or clay
- Uncontrolled fill (waste, debris)
- Building >2 storeys or heavy loads

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DOI: https://doi.org/10.64388/IREV9I12-1718590

Recommended foundation: Deep foundations (driven piles, cast-in-situ piles) or comprehensive ground improvement (deep mixing, PVD preloading with extended surcharge).

6.3 Minimum Site Investigation Requirements

Given the high spatial variability of reclaimed ground, the following minimum site investigation requirements are recommended:

Table 7: Minimum Investigation Requirements by Building Type

Building Type	Number of Boreholes/ CPTs	Minimum Borehole Depth (m)	In-situ Tests Required	Laboratory Tests Required
Single storey dwelling (floor area <100 m²)	1-2 (depending on area)	10 or refusal on dense sand (>30 blows)	SPT at 1.5 m intervals	Moisture content, Atterberg limits, particle size
Two storey dwelling (100-200 m²)	2-3	15 or refusal	SPT + CPT (if available)	Above + consolidation (oedometer) on clay samples
Multi-unit low-rise (2-3 storeys, >200 m²)	3-5 (minimum 1 per 200 m²)	15-20	SPT + CPT + seismic refraction (Vs)	Above + triaxial shear (CU) on clay
Community buildings (schools, clinics, churches)	Minimum 4; 1 per 150 m²	20 or to competent sand	SPT + CPT + geophysical survey	Comprehensive: classification, consolidation, strength
Buildings requiring ground improvement	As above + additional for design	To competent layer + 2-3 m	As above + piezocone (CPTu) if available	As above + Cc, cv, permeability for PVD design

Notes: SPT = Standard Penetration Test; CPT = Cone Penetration Test; Vs = shear wave velocity; CU = consolidated-undrained triaxial.

6.4 Design Recommendations for Shallow Foundations

Where shallow foundations are deemed feasible (Category A or B conditions), the following design recommendations apply:

6.4.1 Raft Foundation Design

For marginally competent ground, a reinforced concrete raft (mat) foundation is strongly preferred over isolated footings. Design recommendations:

- Minimum thickness: 150 mm for single storey; 200 mm for two storey; 250 mm for three storey (or as required by punching shear checks)
- Reinforcement: Minimum 0.15% each direction (typically T10 or T12 at 200-250 mm centers); increased reinforcement (0.2-0.25%) at column locations and along perimeter
- Stiffening beams: Incorporate downstand beams at grid lines (typically 300 mm wide × 400-600 mm deep) to enhance rigidity and distribute loads
- Edge beams: Reinforced edge beams (300 × 400 mm minimum) to improve perimeter stiffness and resist differential settlement
- Predicted settlement: Target <20 mm differential; <50 mm total; design for expected settlements (25-75 mm typical for improved ground)

6.4.2 Strip and Pad Footing Design (Competent Ground Only)

Where competent ground (Layer 3 or 4) is encountered within 2-3 m of surface and soft clay is absent or removed:

- Minimum depth: 1.0 m below ground surface (to avoid seasonal moisture changes and shallow fill heterogeneity)
- Minimum width: 600 mm for strip footings; 900 × 900 mm for isolated pads
- Reinforcement: Minimum mesh reinforcement (A142 or A193) in concrete strip footings to resist differential movement

- Allowable bearing pressure: Based on site-specific testing; typical values for competent alluvial clay: 100-150 kPa; for coastal sand: 150-250 kPa

6.4.3 Ground Improvement Integration

Where ground improvement is implemented (stone columns, RAP, or PVD preloading), foundation design should integrate with the improvement:

- Stone columns: Design raft to span between columns; typical column spacing 1.5-2.5 m; minimum raft thickness 200 mm
- Rammed aggregate piers: Footings should be centered on piers; minimum 1.5 m spacing; allow for load transfer through capping layer
- Preloaded ground: Reduced settlement factors (typically 0.1-0.2× untreated settlement) applied; monitor residual settlement post-construction

6.5 Risk Mitigation and Construction Quality Assurance

Given the inherent uncertainties in reclaimed ground behavior, the following risk mitigation measures are recommended:

Geotechnical Risk Mitigation:

1. Independent peer review of site investigation and foundation design for all buildings on reclaimed ground (mandatory for public buildings)
2. Settlement monitoring program: Install settlement markers at foundation corners and mid-spans; monitor at: pre-construction (baseline), post-foundation, post-frame, post-roof, and at 3, 6, 12, 18, 24 months after completion
3. Trigger levels: Establish action levels (e.g., 10 mm differential → investigate; 15 mm differential → implement remedial measures)
4. Contingency design: Prepare underpinning or grouting contingency plans for buildings showing excessive settlement

Construction Quality Assurance:

1. Fill placement and compaction: For replaced or new fill, specify maximum lift thickness (250 mm), minimum compaction (95% MDD for sand, 90% for clay), and test frequency (1 per 250 m² per lift)
2. Stone column installation: Monitor stone volume per meter, compaction energy (vibroflot amperage), and conduct post-installation testing (load tests, SPT/CPT between columns)
3. Concrete quality: Minimum grade C25/30 for foundations; adequate cover (50 mm min.) for aggressive ground conditions

Structural Risk Mitigation:

1. Flexible structural systems: Use articulated joints at 20-25 m spacing; frame structures preferred over load-bearing masonry
2. Flexible service connections: Use flexible couplings for water, sewer, and gas connections at building entry points
3. Surface water management: Positive drainage (minimum 2% slope) away from foundations; perimeter drains with outlet to storm system; impermeable membranes beneath ground slabs

Table 8 summarizes recommended trigger levels and contingency actions for settlement monitorin

Measured Differential Settlement (mm)	Angular Distortion	Action Required	Responsible Party
0 – 10	0 – 1/400	Routine monitoring; no action	Site engineer
10 – 15	1/400 – 1/300	Increase monitoring frequency (monthly); inspect for cracks	Structural engineer
15 – 20	1/300 – 1/250	Engineer assessment; install crack monitors; consider remedial design	Geotechnical + structural engineer
20 – 25	1/250 – 1/200	Implement contingency measures (underpinning, grouting)	Specialist contractor
>25	>1/200	Stop construction if ongoing; emergency	All parties + independent expert

		assessment; major remediation	

Source: Adapted from Burland et al. (1977) and Krebs & Zipper (2023)

VII. CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary of Key Findings

This comprehensive review has assessed the feasibility of shallow foundations for low-rise buildings in the reclaimed areas of Lagos Island and Lekki Peninsula. The principal findings are:

Geotechnical Characterization:

- Lagos reclaimed areas exhibit a consistent stratigraphic sequence: loose to medium dense hydraulic sand fill (0-2.5 m, SPT-N 4-15) overlying soft, highly compressible organic clay/peat (1.5-8.0 m, SPT-N 2-8, c_u 10-20 kPa, Cc 0.6-1.2), underlain by firm alluvial clay and dense coastal plain sand.
- The soft clay layer is the critical constraint for shallow foundations, with predicted consolidation settlements of 50-250 mm for typical low-rise loads.

Shallow Foundation Feasibility:

- Conventional strip and pad footings are generally infeasible for reclaimed areas with soft clay thickness >2 m, unless extensive ground improvement or excavation and replacement is implemented.
- For sites with soft clay thickness <3 m and competent layer within 3-5 m, excavation and replacement combined with raft foundations can provide acceptable performance (expected settlements 15-30 mm).
- For soft clay thickness of 3-5 m, ground improvement (stone columns, RAP, or PVD preloading) is necessary; post-improvement settlements of 10-25 mm are achievable.
- For soft clay thickness >5 m, shallow foundations are not recommended even with ground improvement; deep foundations or comprehensive improvement (deep mixing, extensive preloading) are required.

Ground Improvement Effectiveness:

- Vibro-replacement (stone columns) increases bearing capacity by 2-4× and reduces settlement by 50-80%, with good suitability for Lagos conditions.
- Preloading with prefabricated vertical drains (PVDs) is highly effective for thick clay sequences (>5 m) but requires 6-12 months lead time.
- Excavation and replacement is the most reliable method for shallow soft clay (<3 m) and is widely applicable in Lagos.

International Experience:

- Case studies from Dhaka (Bangladesh), San Francisco Bay, Appalachian valley fills, and coastal India provide validated solutions for shallow foundations on reclaimed ground, including rammed aggregate piers, geotextile reinforcement, and stone columns.
- The Dhaka experience is particularly relevant, given the similar geotechnical profile (dredged fill over soft organic clay) and building stock (low to medium-rise).

Research Gaps:

- Published, instrumented case studies of shallow foundation performance in Lagos reclaimed areas are extremely limited.
- Long-term settlement monitoring data (>5 years) for improved ground in Lagos are unavailable.
- Region-specific settlement prediction models calibrated to Lagos organic clays have not been developed.
- The performance of emerging techniques (RAP, geopolymer stabilization) has not been validated locally.

7.2 Recommendations for Practice

For Geotechnical Engineers and Consultants:

1. Mandatory site-specific investigation: Minimum 1 borehole/CPT per 200 m² of building footprint, to depth of competent layer or minimum 15 m. Do not rely on regional averages or adjacent site data without verification.
2. Conservative design parameters: For preliminary assessment, assume soft clay layer present unless proven otherwise. Use

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DOI: https://doi.org/10.64388/IREV9I12-1718590

measured rather than correlated parameters wherever possible.

3. Ground improvement planning: For soft clay thickness >2 m, incorporate ground improvement in foundation design from project inception. Do not assume shallow foundations will be feasible without improvement.
4. Settlement monitoring: Implement monitoring programs for all buildings on reclaimed ground, regardless of foundation type. Establish trigger levels and contingency plans.

For Developers and Project Owners:

1. Budget for ground improvement: Allocate 15-30% of foundation cost for ground improvement or deeper foundations. The cost of remediation after settlement exceeds the cost of improvement during construction by a factor of 3-10.
2. Allow adequate timeline: Ground improvement techniques (particularly preloading) require lead time of 3-12 months. Factor this into project schedules.
3. Engage geotechnical expertise early: Involve geotechnical engineers during site selection and feasibility studies, not after foundation issues arise.

For Regulatory Authorities:

1. Mandate third-party review: Require independent peer review of site investigations and foundation designs for all buildings on reclaimed land.
2. Develop local guidelines: The Lagos State Building Control Agency should develop specific guidelines for foundation design on reclaimed ground, incorporating the recommendations of this review.
3. Require settlement monitoring: Mandate settlement monitoring for public buildings (schools, clinics, government offices) on reclaimed ground, with reporting to regulatory authorities.

7.3 Future Research Priorities

To advance the state of practice for shallow foundations on reclaimed ground in Lagos, the following research priorities are identified:

Immediate Priorities (1-2 years):

1. Instrumented case studies: Document and publish performance of existing shallow foundations on reclaimed ground in Lagos, including settlement monitoring data and damage assessments.
2. Regional correlation development: Develop SPT-N to c_u and Cc correlations specific to Lagos organic clays, reducing reliance on published correlations from other regions.
3. Ground improvement demonstration projects: Implement and monitor stone column and RAP demonstration projects for low-rise buildings in Lekki or Victoria Island.

Medium-Term Priorities (2-5 years):

1. Long-term settlement database: Establish a centralized database of settlement monitoring data for buildings on reclaimed ground, accessible to practitioners.
2. Numerical modeling validation: Calibrate and validate finite element models (PLAXIS, ABAQUS) against local case studies for prediction of settlement and bearing capacity.
3. Life-cycle cost analysis: Compare life-cycle costs of shallow foundations with ground improvement versus deep foundations for low-rise buildings, including maintenance and remediation costs.

Long-Term Priorities (5-10 years):

1. Design guidelines development: Develop Lagos-specific design guidelines for shallow foundations on reclaimed ground, including allowable bearing pressures, settlement criteria, and ground improvement specifications.
2. Performance-based design framework: Move from prescriptive to performance-based design, with settlement and angular distortion as performance criteria.
3. Risk assessment methodology: Develop probabilistic risk assessment tools for foundation performance on reclaimed ground, incorporating spatial variability and model uncertainty.

7.4 Final Remarks

The development of Lagos's reclaimed lands represents a significant opportunity for urban expansion and economic growth. However, the geotechnical challenges posed by these environments must be addressed through appropriate foundation design and ground improvement. While conventional shallow foundations are generally infeasible for typical Lagos reclaimed profiles, the judicious application of ground improvement techniques—stone columns, preloading, excavation and replacement, and emerging methods such as rammed aggregate piers—can enable shallow foundations for low-rise buildings in many situations.

The key to success lies in:

- Thorough site investigation that characterizes the full stratigraphic profile
- Realistic assessment of settlement potential and structural tolerance
- Appropriate ground improvement matched to site conditions and building loads
- Quality construction with adequate supervision and testing
- Ongoing monitoring to verify performance and trigger contingency measures

By adopting these principles, engineers and developers can achieve safe, economic, and sustainable foundation solutions for low-rise buildings on Lagos's reclaimed lands, contributing to the continued development of Africa's most dynamic city while avoiding the costly failures that have plagued some earlier developments.

VIII. ACKNOWLEDGMENT

The authors acknowledge the Department of Civil Engineering at Lead City University, Ibadan, and the University of Ibadan for providing access to library resources and research facilities. Appreciation is also extended to the geotechnical research community in Lagos and beyond whose published work made this review possible.

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