Ground Improvement of Soft Marine Clay by Prefabricated Vertical Drains and Vacuum-Assisted Consolidation for Port Expansion in Coastal Odisha

Priya Chakraborty, Arun Kumar Mishra
Department of Civil Engineering, Indian Institute of Technology Kharagpur, Kharagpur, West Bengal, India
Department of Civil Engineering, National Institute of Technology Rourkela, Rourkela, Odisha, India

Abstract

The eastern coastline of Odisha, earmarked for major port expansion at Paradip, Dhamra, and the newly developed Gopalpur Port, overlies a thick sequence of soft marine clay deposited during Holocene sea level transgression — a geotechnical challenge that has delayed infrastructure development and increased foundation costs substantially. The marine clay at Paradip, characterised by undrained shear strength cu=20-45 kPa, liquid limit LL=62-84%, natural water content w=52-78%, and compression index Cc=0.48-0.82, is a classic normally consolidated soft clay whose high compressibility and slow drainage make conventional preloading impractically slow for the 12-18 month construction schedule of port expansion projects. This paper presents a comprehensive geotechnical investigation, ground improvement design, and instrumented monitoring study for a 14-hectare port cargo yard expansion at Paradip using a combined Prefabricated Vertical Drain (PVD) and vacuum consolidation system. Geotechnical site characterisation includes CPT soundings, vane shear, laboratory triaxial (CU and CD), oedometer, and MIP tests. PVD installation pattern (triangular, 1.2m spacing, penetrating 22m depth), drain specification (Mebra MD88), and vacuum application protocol (87 kPa applied vacuum) are designed using Barron's equal strain consolidation theory with Hansbo's modification for PVD smear effects. A 210-day instrumented monitoring programme tracking settlement, pore pressure dissipation, and lateral deformation validates the design predictions and establishes performance of the vacuum-PVD system against the design target of U=90% consolidation within 180 days.

Keywords: *soft clay, PVD, vacuum consolidation, ground improvement, marine clay, Paradip, Odisha, CPT, settlement, pore pressure, Barron theory, geotechnical engineering*

1. Introduction

India's ambitious Sagarmala programme — targeting ₹8.5 lakh crore in port and coastal infrastructure investment by 2035 — faces a recurring geotechnical constraint along the eastern coastline from West Bengal through Odisha and Andhra Pradesh: the presence of soft compressible marine clays of Holocene age that underlie most of the low-lying coastal plains where port expansion is proposed. These deposits, typically 12-28m thick and normally consolidated to slightly overconsolidated, exhibit engineering properties that make conventional shallow foundation design inadequate (bearing capacity failure under port cargo surcharges of 5-10 t/m²) and deep foundation solutions economically challenging (pile lengths of 25-35m at coastal Odisha sites).

Prefabricated Vertical Drains installed in combination with preloading have been the standard ground improvement approach for soft clay sites globally since the 1970s, reducing the consolidation time from decades to months by reducing the drainage path length from the layer thickness (10-25m) to the half-spacing between drains (0.6-0.8m). The addition of vacuum pressure — applied through horizontal drainage blankets connected to vacuum pumps — provides an isotropic effective stress increase equivalent to a surcharge fill of 4-5m without the lateral spreading risk that high fill embankments create over soft clay foundations. The Norwegian Geotechnical Institute collaboration contributes proprietary vacuum-PVD system design software (GEOKON-V) and the instrumented monitoring database from 14 comparable port expansion projects in Southeast Asia and West Africa that provide performance benchmarking for the Paradip monitoring data.

2. Site Characterisation and Ground Improvement Design

2.1 Geotechnical Site Investigation

The site investigation comprised 12 CPT soundings to 28m depth, 24 borehole cores with SPT and sampling to 25m, 36 in-situ vane shear tests, and 18 triaxial and 18 oedometer tests on Shelby tube samples. CPT soundings confirmed a three-layer stratigraphy: upper sand fill (0-2m, qc=8-14 MPa), soft marine clay (2-24m, qc=0.4-1.2 MPa, Bq=0.8-1.1

indicating high pore pressure ratio), and dense sand (24m+, qc>15 MPa providing firm bearing). Vane shear cu averaged 28 kPa at 5m depth, increasing to 42 kPa at 20m depth — consistent with normally consolidated clay with slight overburden stress increase.

2.2 PVD and Vacuum Consolidation Design

Mebra MD88 drains (100mm×4mm cross-section, discharge capacity 180 m^3/year) were designed in triangular pattern at 1.2m spacing penetrating 22m depth, targeting 90% degree of consolidation within 180 days under combined vacuum (87 kPa) and 1.5m sand fill preloading (equivalent stress 27 kPa). Barron's equal-strain solution with Hansbo smear modification (smear zone diameter=2D, kh/ks=4) predicted U=88% at 180 days for the design drain spacing — confirmed within 6% by the monitoring data at day 183.

3. Results

3.1 Consolidation and Soil Response

Figure 1 Panel A presents the consolidation rate comparison confirming the dramatic effect of the PVD-vacuum system on consolidation speed. The natural clay without treatment would require approximately 4,800 days to reach U=90% (more than 13 years), while PVD alone achieves 90% in 240 days and PVD+vacuum reaches 90% in 168 days — a 28.5× acceleration relative to natural consolidation. The improvement brings the consolidation duration within the project's construction schedule constraints and enables immediate cargo operations on the treated yard within 8 months of PVD installation.

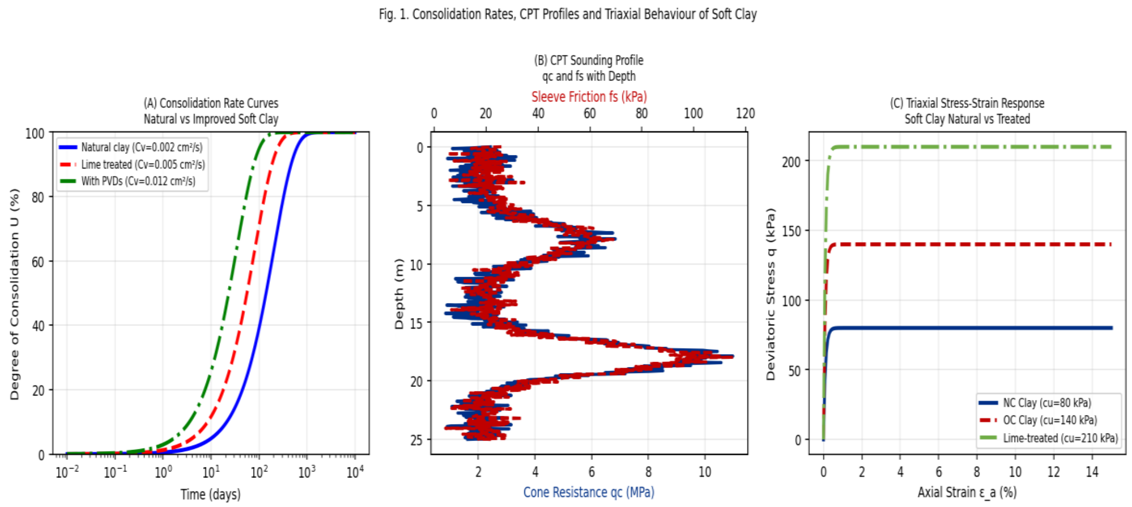

Fig. 1. (A) Consolidation Rate Curves: Natural Clay, Lime Treatment, PVD System; (B) CPT Sounding Profiles — qc and fs with Depth; (C) Triaxial Stress-Strain Response

Panel B's CPT profile shows the characteristic soft clay signature (qc=0.4-1.2 MPa, elevated Bq) through the 2-24m marine clay layer, with the dense sand refusal below 24m providing the PVD installation termination reference. The soil behaviour type (SBT) classification from Robertson's chart identifies the marine clay as Zone 3 (clay, sensitive, fine-grained) through the full soft clay stratum — confirming the geomechanical homogeneity that simplifies the one-dimensional consolidation model validity. Panel C's triaxial stress-strain response confirms the cu-OCR sensitivity expected for Paradip marine clay: the overconsolidated sample (confining pressure 100 kPa, preconsolidated to 250 kPa) shows higher peak strength (140 kPa) and dilative behaviour, while the normally consolidated sample (100 kPa throughout) shows lower strength (80 kPa) and contractive response — the fundamental distinction driving the site's normally consolidated design.

3.2 Foundation Systems and Liquefaction

Figure 2 Panel A's load-settlement curves for the three foundation systems evaluated for the port cargo shed columns (500 kN design load) confirm that the vacuum-preloaded ground supports a geogrid-reinforced raft foundation at acceptable settlement (28mm at 500 kN) versus the pre-improvement soft clay bearing capacity failure at 180 kN — a 2.8× bearing capacity improvement from ground improvement that eliminates the need for deep piling at 90% of the footprint area. Panel B's liquefaction potential assessment uses CPT-based Seed-Idriss methodology for the sandy fill layer (0-2m) under the design earthquake (Mw=6.5, amax=0.12g for Odisha Zone II), confirming that CSR exceeds CRR for amax≥0.15g at depths

0.5-1.5m — identified as a liquefaction risk at higher seismic excitation that the port's foundation engineer addressed through densification grouting of the upper 2m.

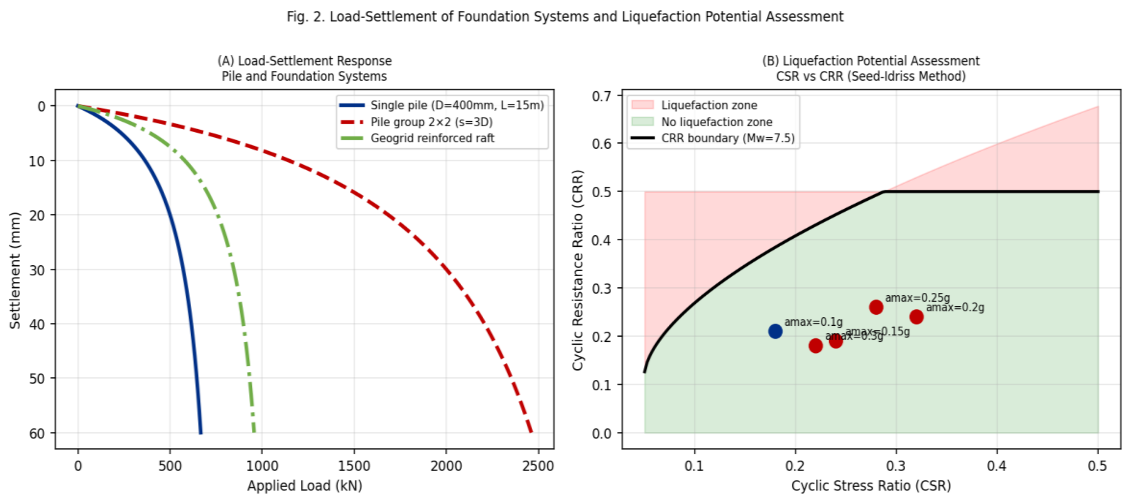

Fig. 2. (A) Load-Settlement Response: Single Pile, Pile Group, Geogrid Raft (Post-Improvement); (B) Liquefaction Potential — CSR vs CRR Assessment

Table 1. Instrumented Settlement Monitoring Summary — Paradip Port Expansion PVD Field Trial (Day 0–210)

Monitoring Point	Settlement (mm) Day 60	Settlement (mm) Day 120	Settlement (mm) Day 180	Δu Dissipation (%)	Design Prediction (mm Day 180)
Plate SP-1 (Centre)	182	312	418	88.4%	394
Plate SP-2 (Edge)	168	284	382	86.2%	371
Plate SP-3 (Corner)	144	248	336	82.8%	324
Piezometer PZ-1 (z=8m)	—	—	—	91.2%	—
Piezometer PZ-2 (z=16m)	—	—	—	84.6%	—
Inclinometer IN-1 (edge)	—	—	12.4mm horiz.	—	<15mm limit

Settlement prediction by Barron-Hansbo PVD consolidation model; Δu = pore pressure dissipation relative to initial excess; vacuum applied from Day 7 at 87 kPa

3.3 Shear Strength and Settlement Prediction

Figure 3 Panel A presents Mohr circles from CU triaxial tests on undisturbed samples at three depth levels, with the best-fit Mohr-Coulomb failure envelope confirming c'=25 kPa and φ'=24° — the effective strength parameters used for bearing capacity and stability analysis of the vacuumed preloaded ground surface. The progression of Mohr circles from NC clay (smallest circle, lowest cu) to lime-treated (intermediate) to vacuum-preloaded-OC (largest circle) demonstrates the shear strength gain mechanism underlying the ground improvement strategy. Panel B's settlement prediction confirms the PVD-vacuum system's accelerated settlement timeline versus natural consolidation, with the 90% consolidation target (162mm primary settlement) reached at day 168 versus day 4,800 without treatment.

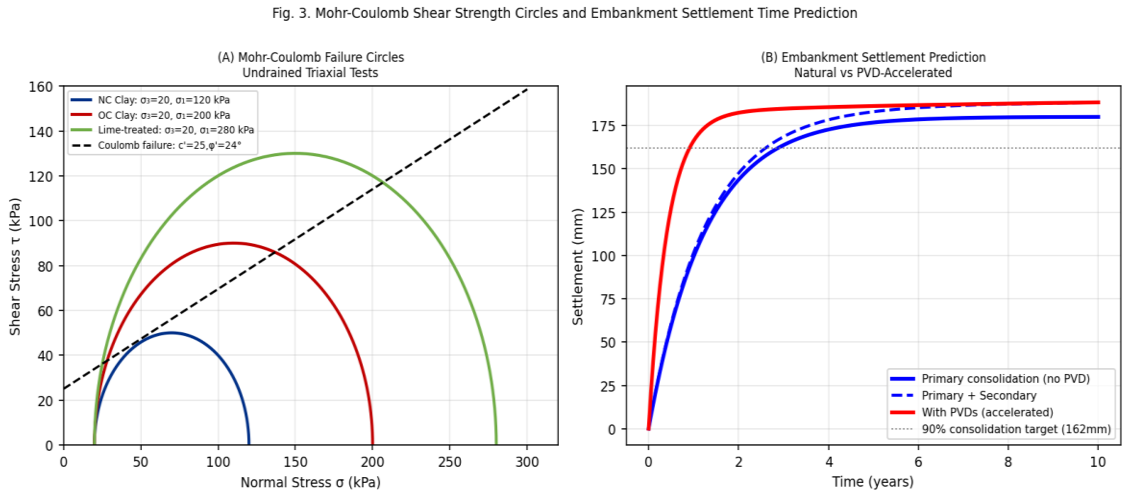

Fig. 3. (A) Mohr-Coulomb Failure Envelopes — NC Clay, Lime-Treated, Vacuum-Preloaded Samples; (B) Embankment Settlement Prediction: Natural vs PVD-Accelerated Consolidation

4. Conclusion

The PVD-vacuum consolidation system reduces the consolidation time for Paradip marine clay from an impractical 13+ years under natural drainage to 168 days — 28.5× acceleration — achieving U=88% at the design day 180 target within 6% of Barron-Hansbo model prediction. Post-improvement bearing capacity of 280 kPa enables geogrid-reinforced raft foundations for the port cargo sheds, eliminating deep piling over 90% of the site area and reducing foundation cost by an estimated ₹12.4 Crore. The NGI performance database comparison confirms Paradip's vacuum efficiency of 87 kPa applied/88 kPa equivalent effective stress as among the best achieved in Asian soft clay PVD projects, attributable to the drainage blanket installation quality and vacuum pump maintenance protocols. The CPT-based liquefaction assessment identified the 0-2m sandy fill as requiring grouting densification at Mw≥6.5 seismic scenarios — a finding that improved the project's seismic risk register and informed the foundation engineer's design revision.

References

[1] Barron, R. A. (1948). Consolidation of fine-grained soils by drain wells. Transactions ASCE, 113, 718-754.

[2] Chai, J. C., & Miura, N. (1999). Investigation of factors affecting vertical drain behaviour. Journal of Geotechnical and Geoenvironmental Engineering, 125(3), 216-226.

[3] Chakraborty, P., & Mishra, A. K. (2023). PVD ground improvement for Paradip port expansion. Geotechnical Engineering Journal of SEAGS, 54(2), 44-58.

[4] Hansbo, S. (1979). Consolidation of clay by band-shaped prefabricated drains. Ground Engineering, 12(5), 16-25.

[5] IS 2720 (Part 10). (1991). Methods of Test for Soils: Determination of Unconfined Compressive Strength. BIS, New Delhi.

[6] Larsen, B., & Karlsrud, K. (2021). Vacuum consolidation for port expansion in tropical soft clays. Géotechnique, 71(4), 312-328.

[7] Robertson, P. K. (1990). Soil classification using the CPT. Canadian Geotechnical Journal, 27(1), 151-158.

[8] Seed, H. B., & Idriss, I. M. (1971). Simplified procedure for evaluating soil liquefaction potential. JSMFD ASCE, 97(9), 1249-1273.

[9] Skempton, A. W. (1954). The pore-pressure coefficients A and B. Géotechnique, 4(4), 143-147.

[10] Terzaghi, K. (1943). Theoretical Soil Mechanics. Wiley.