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Can DDCs Tolerate Cracking? A New Design Paradigm with Case Study Insights

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ABSTRACT: This paper proposes a performance-based design paradigm for Drilled Displacement Columns (DDCs) that integrates flexural cracking as a deliberate and essential aspect of their behaviour. This study recommends treating DDCs explicitly as geotechnical elements in which column/flexural cracking is an intrinsic aspect of their performance rather than representing a failure condition. The Causeway Pedestrian and Cyclist Bridges (Boorloo Bridges) project in Perth, Western Australia, illustrates this approach. Faced with tight schedule demands and challenging geotechnical conditions of soft Swan River Alluvium overlying the complex Kings Park Formation, a cracking-tolerant DDC design enabled optimized construction sequencing, reduced differential settlement risks, and minimized conservatism without compromising structural integrity. Field assessments confirmed that flexural cracks did not affect the settlement-reduction function of the columns. This paradigm shift demonstrates the benefits of performance-driven designs that enhance efficiency, resilience, and cost-effectiveness in complex ground conditions.

KEYWORDS: Drilled Displacement Columns (DDCs), 3D FEM, flexural cracking, geotechnical elements, settlement control.

1 INTRODUCTION

Drilled Displacement Columns (DDCs) – also marketed as Controlled Modulus Columns (CMCs) and more broadly classified as rigid inclusions (RIs) – have become a mainstream ground improvement solution for soft and variable soils. A recent survey reports that over 1,000 RI projects have completed in the US alone (Masse et al., 2020). Owing to their rapid installation, high axial resistance, and adequate flexural stiffness, DDCs serve both capacity-governed foundations (e.g., storage tanks, onshore wind turbines; Sahyouni et al., 2021) and flexure-governed embankments for road, railways, and bridge approaches (Burtin and Racinais, 2016; Coghlan et al., 2016).

Despite widespread adoption, significant challenges remain regarding long-term performance, particularly due to column cracking under lateral loading conditions. Previous studies have identified two coupled mechanisms: (i) stiffness degradation leading to differential settlements and (ii) reduced bending capacity affecting overall stability (Han, 2015; Yu et al., 2021). Yet, these cracking-related issues are often overlooked or underestimated by designers, despite their substantial impact on long-term performance. Current capacity-based design methods do not explicitly address these mechanisms, and major codes (e.g., FHWA (2017); BS 8006 (2010); EBGEO (2011); CUR (2016)) typically treat columns as uncracked homogeneous elements, providing no guidance on crack-width limits, residual stiffness, or life-cycle performance assessments. This disconnect between observed behaviour and design assumptions has created a critical knowledge-to-practice gap.

To bridge this gap, this paper proposes a performance-based design principle that treats column cracking as inherent rather than accidental. By explicitly accounting for cracking – whether due to lateral soil movements during installation or operational loading – and quantifying their effects on residual stiffness, realistic long-term performance prediction can be achieved. A full-scale Boorloo Bridges case study illustrates this principle in practice, demonstrating how acknowledging and designing for cracking facilitates more efficient construction sequencing under tight schedule while reducing costs and satisfying serviceability requirements.

2 FROM STRUCTURAL ANALOGY TO CRACK-TOLERANT DESIGN

DDCs are a subset of auger cast-in-place / drilled-displacement piles that range from partial to full soil displacement (Prezzi, 2005). DDCs, CMCs, and other RIs were originally developed as ground improvement elements working in combined action with surrounding soils to enhance bearing capacity and control settlements in soft and compressible deposits. Unlike traditional piles that transfer loads directly to deeper competent strata, DDCs function as part of a composite soil–inclusion systems rather than as isolated structural elements (Briançon and Simon, 2012; Masse et al., 2020). Because of this interaction, flexural cracking is essentially inevitable – during curing (thermal or shrinkage strains), installation (from lateral soil pressure) and service (under traffic, seismic, or differential movements). Consequently, eliminating cracking is impractical; the rational approach is to quantify and manage it within a performance-based design framework.

Design codes for column-supported embankments such as BS 8006 (2010), EBGEO (2011), CUR (2016), reflect this geotechnical perspective. While they emphasize global stability, settlement control, and load transfer platform (LTP) efficiency, none prescribes crack-width limits or residual flexural capacity once columns crack, despite field evidence that such cracking is commonplace (King et al., 2018).

In response, current best practices have evolved along two complementary directions:

1. *Mitigating during construction:* “Hit-and-miss” installation sequencing combined with low-pressure grout injection reduces lateral soil movements and necking issues, understanding that these effects typically confined within ~2–3D from the shaft (Plomteux et al., 2004; Suleiman et al., 2016).
2. *Designing for cracks in service:* Wong and Muttuvel (2011) introduced a reduced-stiffness model that remains satisfactory if lateral deflection is below D/6. Gniel and Haberfield (2014) showed that crack-tolerant columns retained axial capacity in a tied-wall embankment, and Larisch et al. (2015) confirmed that targeted reinforcement limits lateral dislocation.

These studies demonstrate that cracking cannot be avoided, so design should pivot from prevention to control. “Crack-tolerant” (or “controlled cracking”) does not mean cracks can be adjusted in the field; rather it means that impacts associated with column cracking, such as embankment settlement and differential movement, are controlled (or designed) so that overall embankment performance is not impaired. By clearly setting residual-stiffness and deformation thresholds designers can manage cracking and its adverse impacts, shorten construction sequencing and cut costs while satisfying serviceability requirements – an evolution toward performance-based geotechnical design.

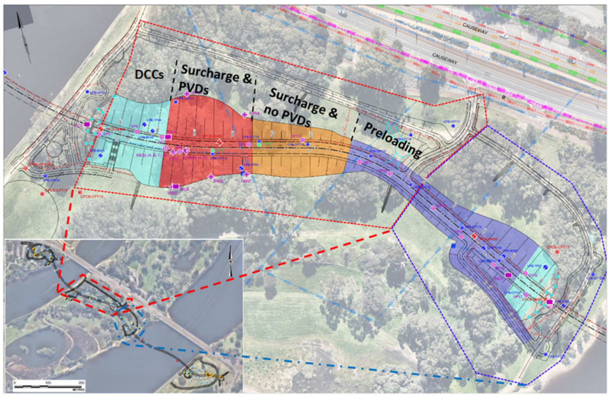

Figure 1. Ground improvement schematic for the Perth Boorloo Bridges; red dashed line indicates focus area.

3 PERFORMANCE OF CRACKING-TOLERANT DDCS: A CASE STUDY

3.1 *Project Background*

The Boorloo Bridges project, comprising two bridges linking Point Fraser, Heirisson Island, and Victoria Park, serves as a significant case study highlighting the implementation of this crack-tolerant design approach in practice. This infrastructure enhances connectivity across the Swan River in Perth, Australia, accommodating approximately 1,400 cyclists and 1,900 pedestrians daily (as shown in Figure 1). Positioned about 80 m downstream of the existing Causeway bridge, the bridge integrates seamlessly with its surroundings, respecting the cultural significance of the Swan River (Derbal Yerrigan) to Perth's First Nations peoples.

The bridge's design features two six-meter-wide cable-stayed spans with a modern S-shaped alignment inspired by the Wagyl, a serpent central to Noongar mythology. Cultural symbols, such as pylons shaped like digging sticks and boomerangs, further emphasize the blend of cultural heritage with engineering innovation.

3.2 *Site Challenges*

The challenges at the site are complex and include geotechnical uncertainties relating to settlement control, differential settlement mitigation, and load transfer mechanisms, among others as described further by Duong et al., (2026).

The site presented significant challenges due to the presence of Swan River Alluvium (SRA), a highly compressible layer of soft soil with variable sand and clay densities, interspersed with up to 0.2-meter-thick oyster shell beds (Gozzard, 2007). This layer can reach up to 10 meters in thickness with an undrained shear strength of less than 20 kPa (Figure 2). The site's fluvial and estuarine depositional history further complicated stratification and drainage, increasing susceptibility to erosion.

Strict settlement criteria were specified to ensure approach-embankment performance: post-construction settlement was limited to 200 mm over five years and 400 mm over forty years for general embankments, and to less than 50 mm within DDC-treated zones, with differential settlement not exceeding a 1:100 ratio. The up-to-5.5 m-high approach embankments required combined ground improvement techniques, including DDCs with a Load Transfer Platform and preloading/surcharging with Prefabricated Vertical Drains, to control settlement and lateral movement while protecting the heritage-listed Causeway Bridge from new loading impacts.

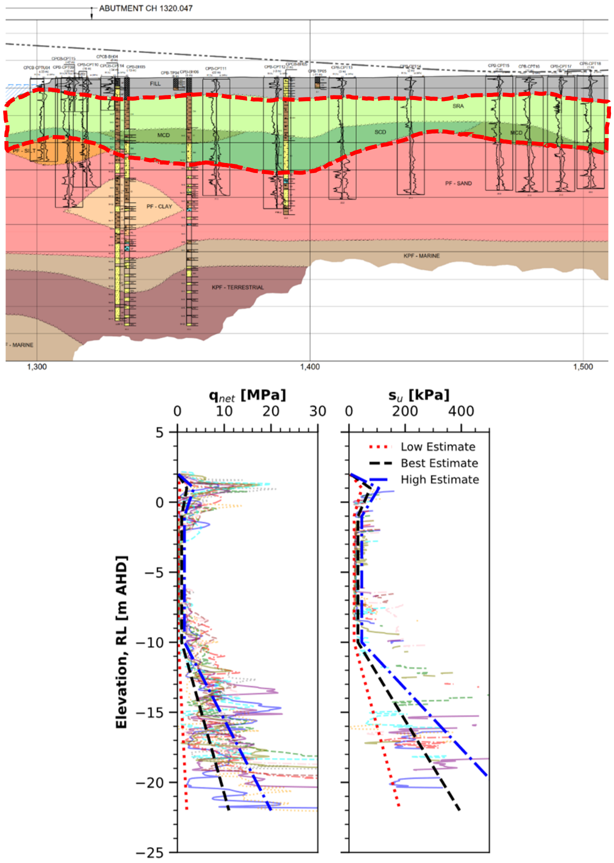

Figure 2. Geological long section (top), and typical undrained shear strength profile for the SRA layer (bottom).

3.3 *Engineering Strategy and Rationale for Tolerant Cracking*

Ground improvement at the Boorloo Bridges involved preloading/surcharging with PVDs accelerated primary consolidation so that total and differential settlements remained within the tight tolerances. DDCs were then installed between the abutment and the surcharge footprint, carrying vertical loads to competent strata while shielding abutment piles from lateral soil movements induced by the surcharge. Finally, a crushed-limestone LTP, reinforced with high-tensile geotextile, distributed stresses uniformly across the embankment.

The need to construct the abutment and approach embankment concurrently left no time for staged dissipation of excess pore pressures; bending moments in the columns were therefore expected to peak during surcharging. Designing DDCs as geotechnical elements, cracking was permitted to occur without compromising their axial bearing capacity. Residual stiffness and deformation limits ensured that cracking remained serviceable. Where analyses predicted localised exceedance of the bending moment–axial force envelope, a single N32 reinforcing bar was added to selected columns to prevent lateral shear (or dislocation) while still permitting crack formation.

Accepting – and explicitly designing for – controlled flexural cracking thus resolved schedule constraints, complex ground conditions, and settlement-performance requirements, and it establishes the crack-tolerant, performance-based framework developed further in the following numerical-modelling section.

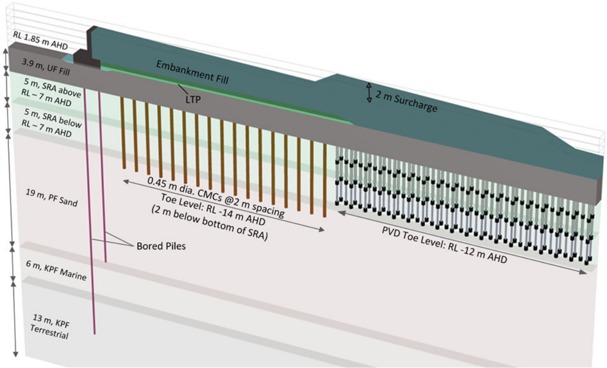

Figure 3. Numerical model setup with ground improvement techniques and boundary conditions.

3.4 *Numerical Modelling*

Finite element analysis in PLAXIS 3D was adopted to capture staged loading, crack-tolerant behaviour, and soil–structure interaction beyond the reach of empirical/analytical methods. A 2 m-wide strip model along the bridge alignment (≈140,000 ten-noded tetrahedral elements) incorporated the soft SRA, DDCs, PVDs, and LTP (Figure 3).

Construction sequencing drove the modelling stages. Figure 4 contrasts the tender sequence (PVD surcharge → DDC installation → abutment → backfill) with the revised scheme that installs PVDs, DDCs, and abutment piles first, then surcharges and builds the abutment concurrently. This optimisation trimmed roughly three months from the programme but pushed bending moments to their peak during surcharging (i.e., Stage 2), making cracking integral to the analysis.

Soil constitutive models were assigned as follows: the soft SRA (as marked in Figure 2) employed the Soft Soil Creep (SSC) model, calibrated from field and laboratory data (Table 1) to reproduce primary consolidation and long-term creep; above fill layers used the Hardening Soil (HS) formulation; and competent founding units followed the Mohr–Coulomb (MC) elastic–perfectly plastic behaviour. Together they provided a realistic stiffness profile through depth.

DDCs representation used 0.45 m-diameter concrete volume elements extending 16 m to terminate 2 m below the SRA base (reduced level at RL -14 m AHD). Volume elements were selected rather than axisymmetric or plane-strain simplifications, to capture three-dimensional interaction that governs differential settlement and flexural response. This was essential for evaluating the performance of column-supported embankments, where DDCs act as geotechnical inclusions subject to cracking. Soil–column interaction was captured with MC interface elements that allow slip and gapping. Two material states for DDCs were defined:

- Uncracked: linear-elastic (LE) properties.
- Cracked: Mohr-Coulomb parameters with flexural stiffness (Ec) reduced to 2 % of the intact modulus and strength set to c' = 500 kPa, φ′ = 40°, reflecting residual capacity when cracking occurs, after Wong and Muttuvel (2011). The full cracked and uncracked parameters are listed in Table 2.

A *wished-in-place* installation assumption was adopted to avoid added uncertainty of modelling large-strains, soil remoulding, and installation-induced disturbance (Amarathunga et al., 2024; King et al., 2018); realistically capturing those effect would require high-overhead techniques such as Coupled Eulerian–Lagrangian or mesh-free methods (Bui et al., 2008; Więckowski, 2004). For the same reason, continuum FEM with standard MC or HS models cannot fully reproduce the progressive soil arching and load recovery that develop in a geosynthetic load-transfer platform (LTP); it tends to over-predict arching and under-predict surface settlement because strain-softening and mesh-distortion effects are not represented (Smith et al., 2022).

The model outputs – total and differential settlements, lateral deflection of columns, and moment–axial-force (MN) envelopes – were used to track serviceability limits, predict crack initiation, and identify locations where a single N32 reinforcing bar was required for robustness. This unified numerical framework and underpinned the tolerant-cracking design strategy evaluated in the subsequent results section.

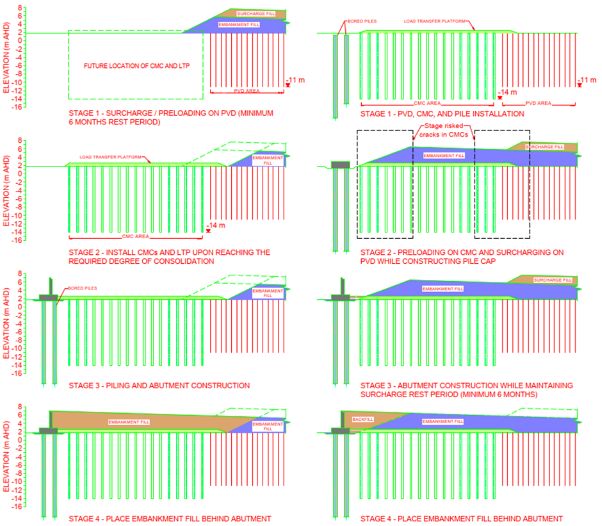

Figure 4. Comparison of construction sequences: tender phase (left) vs. optimized sequence with cracking in DDCs (right).

Table 1. Material properties for soil layers used in numerical analysis.

Units	Soil model	γ_{sat} [kN/m^3]	c' [kPa]	ϕ' [^{0}]	$C_c/(1+e_0)$ [-]	$C_r/(1+e_0)$ [-]	C_α [-]	k_v [m/s]	c_v [m^2/year]	OCR [-]	E_{50}^{ref} [MPa]	E' [MPa]	ν [-]
Engineering Fill	HS	19	-	34	-	-	-	-	-	-	35	-	0.2
Existing Fill	HS	18	-	32	-	-	-	-	-	-	20	-	0.2
Upper SRA	SSC	15	5	30	0.3	0.05	0.01	1e-8	2.0	1.5		-	-
Lower SRA	SSC	15	5	30	0.25	0.05	0.01	1e-9	1.0	1.0	-	-	-
PF Sand	MC	18	-	33	-	-	-	-	-	-	-	30	0.25
KPF Marine	MC	19	-	40	-	-	-	-	-	-	-	150	0.25

Table 2. Material properties of cracked and uncracked concrete columns used in numerical analysis.

Properties	Unit	Uncracked Concrete	Cracked Concrete
Behaviour model	–	LE	MC
Drainage type	–	Non-porous	Non-porous
γ_{unsat}	kN/m^3	22	22
E	kN/m^2	3.10^7	6.10^3
$\nu(nu)$	-	0.2	0.2
c'	kN/m^2	–	500
φ'	o	–	40
R_{inter}	–	1.0	1.0
Initial K_0	–	Automatic	Automatic

Notes: LE = Linear Elastic model; MC = Mohr-Coulomb model.

3.5 *Analysis Results*

FE outputs confirmed that the revised crack-tolerant sequencing met serviceability targets. As shown in Figure 5, total post-construction settlement is calculated as approximately 50 mm at 5 years and 100 mm at 40 years, both comfortably within the project limits of 200 mm and 400 mm, respectively. Within the DDC zone, final settlements ranged from 15 mm to 20 mm, validating the load-sharing efficiency of the columns and the geosynthetic-reinforced LTP, which also kept differential movement between the embankment and abutment within tolerance.

The critical surcharge stage (Stage 2) produced the highest bending moments. Figure 6 shows that columns L1–L3 (behind the abutment) and L13–L17 (rear of the grid) exceeded the unreinforced capacity envelope, whereas L4–L12 remained below threshold. Maximum compressive stresses in the DDCs reached 4.0 MPa, with maximum tensile stresses being around 0.5 MPa. During this stage, lateral displacements were limited to 5-10 mm, well within the project serviceability threshold. These responses imply that cracking occurred within the columns, but the overall integrity of the DDCs was maintained. Adding single N32 bar in selected DDCs was therefore to mitigate dislocation risks (for robustness purpose) without delaying the programme.

All subsequent calculations adopted the "cracked stiffness" model: flexural stiffness is reduced once cracking initiates, yet axial stiffness remained so long as the line of action stays within the middle third of the column (i.e., lateral deflection < 75 mm). The analysis demonstrates that cracking, supplemented by selective reinforcement where required, achieves long-term settlement control and maintains axial capacity. These outcomes highlight the practical value – and necessity – of a crack-tolerant, performance-based design for DDC-supported embankments such as the Boorloo Bridges.

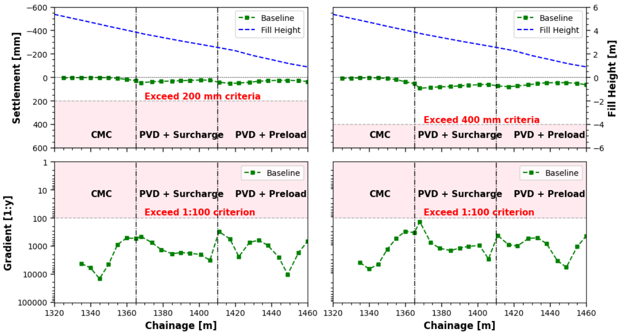

Figure 5. Post-construction settlement and differential settlement at 5 years (left) and 40 years (right).

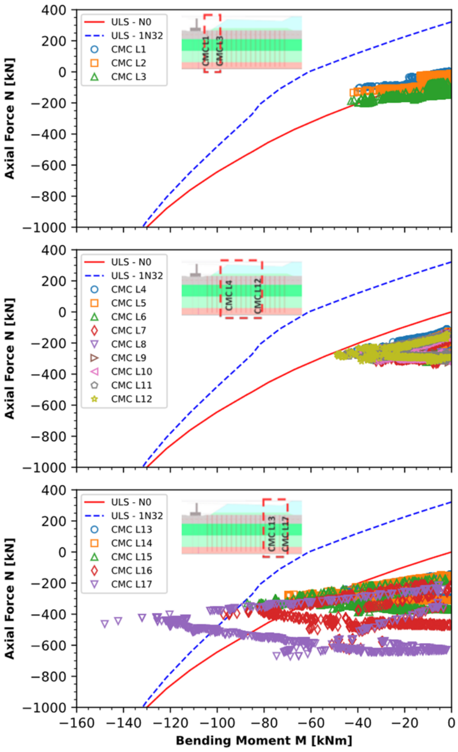

Figure 6. Structural capacity analysis during Stage 2 surcharge.

4 MODEL VALIDATION AND FIELD VERIFICATION

Design-stage predictions were checked against field data from a full-scale static load test (SLT) and construction monitoring of lateral movement and settlement. These comparisons tested the key assumption that cracked-stiffness parameters accurately represent in-service DDC behaviour.

Figure 7 illustrates the load–settlement response from the full-scale static-load test (SLT). A single column was jacked in five 20 % increments to full design load while four nearby reaction columns provided tension. The uncalibrated PLAXIS model overpredicted 35 mm of settlement versus the 8 mm recorded. Calibrating Young's modulus and undrained shear strength of the top fill and PF sand to 1.5–2.0 × initial design values narrowed the gap to less than 3 mm, indicating that the design parameters was deliberately conservative.

Figure 8 plots monitored lateral displacements at the DDC–PVD interface during Stage 2 surcharging. Recorded movements of 50–90 mm correspond closely with the calibrated model, demonstrating that the FEM captures lateral-pressure redistribution and validating the cracked-stiffness assumption for columns L1–L3 and L13–L17.

Figure 9 presents the settlement history of ground surface within the DDC zone over the six-month period. Field data of 20–30 mm lie slightly below the predicted 25–35 mm because several columns penetrated 1–2 m into the stiffer PF sand, boosting axial capacity and reducing compressibility. Despite this nuance, the numerical trend mirrors the observed trend, and applying cracked parameters does not compromise settlement control.

Across axial load response, lateral movement, and time-dependent settlement, field measurements align with calibrated FEM predictions. The data confirms that:

- The cracked-stiffness approach provides a robust representation of column behaviour under combined axial and bending action.

- Selective reinforcement (e.g., single N32 bars) is sufficient to maintain stability where bending moments peak.
- Tolerant-cracking DDCs achieve the required settlement and lateral-movement limits without schedule delay.

These findings validate the crack-tolerant, performance-based design framework and support its wider adoption for soft-soil embankment projects.

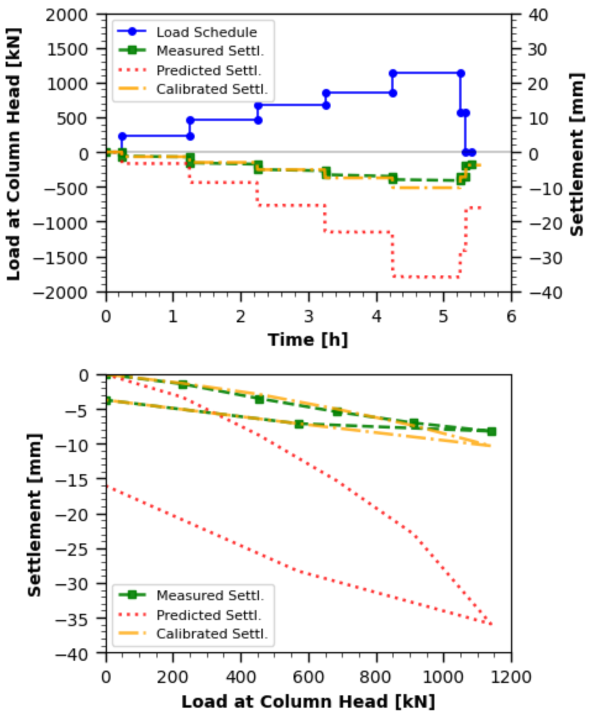

Figure 7. Settlement response of test column during the static-load test.

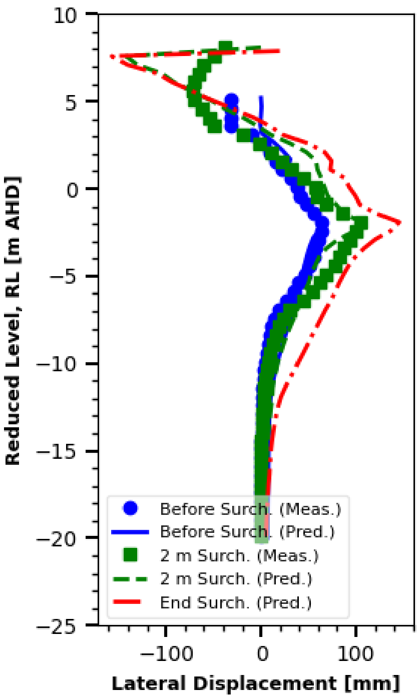

Figure 8. Predicted versus measured lateral soil movement at the boundary between DDC and PVD zones during Stage 2 of construction.

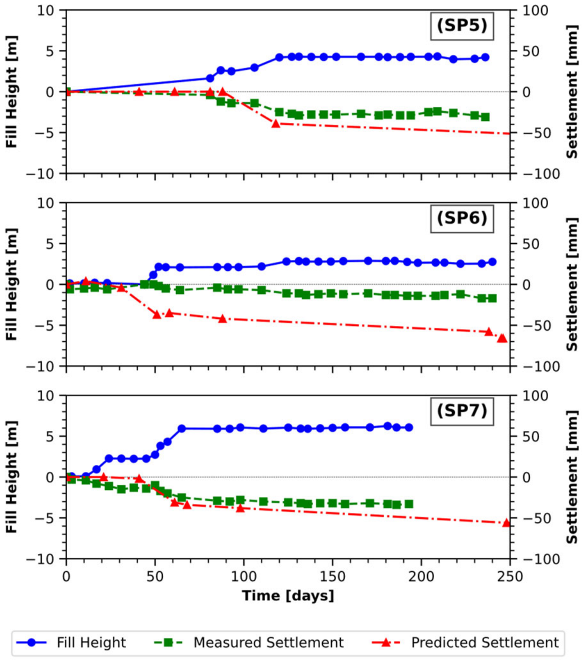

Figure 9. Comparison of measured and predicted settlement within the DDC-supported zone during the six-month preloading period.

5 ECONOMIC AND PRACTICAL IMPLICATIONS

Allowing flexural cracking in the columns supporting an embankment at the Boorloo Bridges turned a traditional linear construction programme into a parallel one: surcharging, abutment piling, and embankment placement progressed simultaneously, trimming the schedule by roughly three months and cutting labour and managing costs. Rather than spending time and material to suppress tensile strain in columns, the design deliberately accepts minor flexural cracks while maintaining axial capacity and satisfying settlement and stability criteria – an explicit trade-off between reduced column stiffness and project savings.

Field data supports the proposed approach. Static-load testing, six-month settlement records, and lateral-movement monitoring tracked the calibrated FEM predictions closely, confirming that crack-tolerant columns perform as intended under combined axial and bending demand. Although minor cracking is permissible, strict QA/QC during installation (e.g., controlling drilling alignment, grout quality, and embedment depth) ensures the as-built column stiffness matches the design specification.

As part of this performance-based approach, a pragmatic design workflow begins with 3-D FEM volume modelling to capture column–soil interaction, followed by structural-capacity checks to identify columns likely to crack, and iterates with reduced flexural stiffness and tuned interface strengths until settlement, lateral-movement, and safety targets converge. When executed in this manner, controlled cracking offers a cost-effective, schedule-optimised approach for the design and construction of soft-soil embankments supported on columns.

6 CONCLUSIONS

Field data from the Boorloo Bridges embankment demonstrates that DDCs can safely accommodate minor, flexural cracking while still limiting total and differential settlement to within stringent serviceability targets. Treating the columns as geotechnical elements – with crack-reduced flexural stiffness, calibrated FEM predictions, and minimal selective reinforcement – shortened the programme by about three months and reduced labour and management costs yet maintained axial capacity and long-term stability.

This outcome reframes DDCs from "crack-free structural piles" to adaptable geotechnical elements whose performance can be optimised through controlled cracking, staged construction, and targeted verification. Wider application will require broader design guidance backed by further experimental and numerical studies, particularly under variable soil profiles, traffic loading, and seismic demand. Adopting this new crack-tolerant, performance-based design paradigm offers the geotechnical profession a practical route to faster, more economical, and reliable foundation solutions in challenging ground conditions.

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