Application of 3D finite-element analysis to predict ground displacement from horizontal directional drilling in highly compressible organic clays.

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Abstract. Horizontal Directional Drilling (HDD) is a proven trenchless methodology for utilities installation below critical infrastructure that limits predicted ground displacement to 5mm. In very soft, highly compressible organic clays, the option to HDD is discounted as small ground displacements are considered unachievable. Very soft, highly compressible organic clays are problematic due to high water content, low permeability and high compressibility, which cause excess pore pressures and time-dependent consolidation during and after drilling. The resultant effects are settlement and distortion; risks increase if annular pressures approach hydraulic-fracture thresholds or if ground loss occurs. This paper presents an HDD case study to install two high-voltage circuits below a National Railway in Tilbury, where the drill alignment below track is within a very soft, slightly sandy, very silty, organic clay. This study applies Finite-element software PLAXIS 3D to predict; ground displacement, long-term consolidation, and assess bore stability. The benefit of the software is the HDD bore geometry, staged construction (i.e., pilot bore, reaming), and idealised bore pressures can be modelled. PLAXIS has developed Soft Soil model specifically designed for highly compressible clays, and organic soils, similar to the Alluvium deposits recorded either side of the railway. The Soft Soil parameters calibrated from triaxial, 1D oedometer, and in-situ testing are screened to identify the high-influence parameters.

1 Introduction

Horizontal directional drilling (HDD) is a well-established trenchless construction method for installing underground utilities beneath transport infrastructure, particularly in situations where open-cut excavation is impractical or would impose unacceptable operational constraint.

The use of HDD beneath critical transport corridors is controlled by strict ground-movement tolerance. Even minor displacements can introduce unacceptable safety risks and disrupt operations to rail or road infrastructure. Essentially, effective control of drilling-induced ground movement is fundamental to the successful delivery of any trenchless installation.

Ground movements attributed to directional drilling are largely driven by the combined effects of excessive annular pressure, borehole enlargement during reaming, over-excavation, and the migration of drilling fluids into the surrounding strata.

This paper investigates the influence of bore pressure when predicting ground displacement within a highly compressible organic clay. Maximum allowable bore pressures are determined using rheological flow models such as the Bingham Plastic Model and the Delft Geotechnics model, which simulate drilling-fluid behaviour under operational flow conditions. These models are calibrated using project-specific field measurements, including Marsh funnel viscosity data, to ensure that the predicted pressure envelope reflects the actual drilling-fluid characteristics.

In very soft, highly compressible organic clays, controlling bore deformation is particularly challenging. These soils exhibit high compressibility, pronounced time-dependent behaviour such as secondary compression and creep, and characteristically low permeability, which can significantly prolong excess pore-pressure dissipation.

Laboratory studies on highly organic soils have documented distinctive one-dimensional (1D) compression behaviour and substantial compressibility compared with inorganic clays, while more recent experimental work has shown that secondary compression in alluvial organic soils can be stress- and strain-rate dependent [1-2].

These soil characteristics imply that short-term drilling-induced ground movements may evolve into delayed settlements arising from pore-pressure dissipation and the gradual accumulation of creep strains within the soil matrix. This effect is not evaluated in this paper because bores beneath key infrastructure are typically back-grouted upon product-pipe installation, replacing the slurry and mitigating further bore consolidation.

Empirical displacement models that are derived from simple granular or cohesive soil datasets, are

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poorly suited to model very soft, highly compressible organic deposits. The simplified approach does not capture the high compressibility, low permeability, or significant creep behaviour characteristic of such soils, leading to unreliable predictions in ground displacements. Recent publications comparing empirical methods with FEA software based numerical predictions for HDD-induced settlement has shown that numerical models can more accurately represent layered stratigraphy and provide a rational basis for assessing the sensitivity of key soil and construction parameters [3]. The additional benefits of 3D FEM are the option to simulate bore geometry, staged drilling processes, annular-pressure distributions, and soil–structure interaction.

This paper presents a three-dimensional finite-element analysis developed using PLAXIS 3D to model an HDD installation beneath a railway in Tilbury, UK, where the alignment passes through very soft organic clay. The objective is to predict ground displacements while accounting for allowable bore pressures and employing an appropriate soft-soil constitutive model [4] calibrated to the site-specific ground conditions.

2 Project overview

This study is based on the installation of two 11 kV electrical circuits beneath National Rail infrastructure in Tilbury. The project consists of two HDD under-track crossings, each approximately 146 m in length, installed beneath a twin-track railway with a minimum vertical cover of 8.7 m and a minimum horizontal bore separation set at 11.5 m. The crossings consist of 610 mm (HDD1) and 508 mm (HDD2) diameter bores constructed using a Midi-class HDD rig configured to support a gyro-based guidance tool. HDD1 will receive two 225 mm OD and two 110 mm OD SDR11 ducts during pullback, while HDD2 will install one of each size.

Fig. 1 presents the layout of the twin HDD installations, and their position relative to the track and principle lineside infrastructure i.e. Overhead Line equipment gantries.

Fig. 2 depicts the minimum cover below track ballast, and the corresponding offsets to the OHLE foundations, both of which govern the principal geometric inputs specified in the FE model.

3 Ground conditions

3.1 Ground investigation

The ground model for the HDD crossing was developed from a targeted ground investigation comprising two Cable-percussive boreholes (BH1 and BH2) advanced to 15.45 mbgl, in-situ standard penetration testing (SPT) and laboratory testing, including Atterberg limits, particle size distribution (PSD), consolidated undrained (CU) triaxial tests, and incremental loading oedometer tests (ILOT).

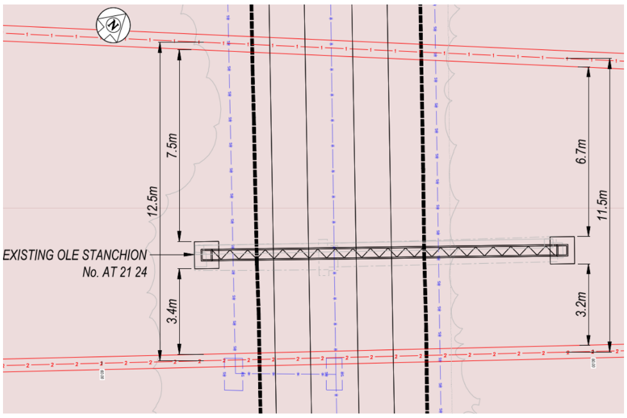

Fig. 1. Twin bore horizontal alignment.

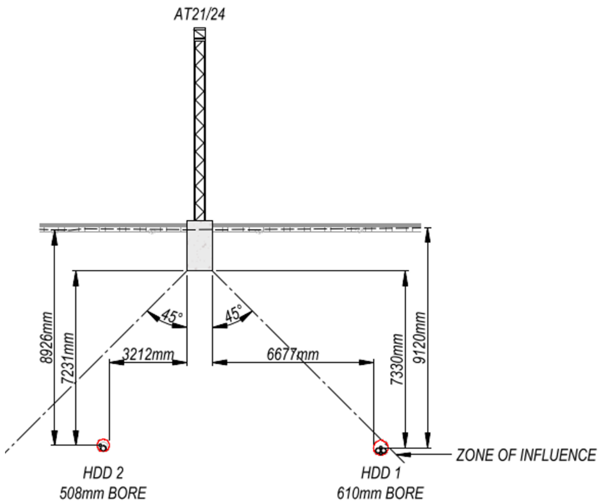

Fig. 2. Twin bore section at undertrack crossing.

3.2 Groundwater

No groundwater strikes were recorded during drilling; however, a standing groundwater level of approximately 3.0 mbgl was observed in BH2 upon completion. This indicates a saturated, low-permeability Alluvial unit, where slow dissipation of excess pore pressures can lead to creep-related settlement.

3.3 Stratigraphy and geological model

The interpreted stratigraphy at Tilbury comprises a thin Made Ground layer overlying Alluvium described as very soft to soft organic clay and silt with intermittent peat bands. The Alluvium was encountered in both boreholes to depths of approximately 10.5–15 m below ground level, beneath which lie the River Terrace Deposits, comprising medium dense to dense sandy gravel.

Fig. 3 depicts the interpreted ground model and confirms that the HDD drilling horizon beneath the railway is located entirely within the Alluvium Deposits.

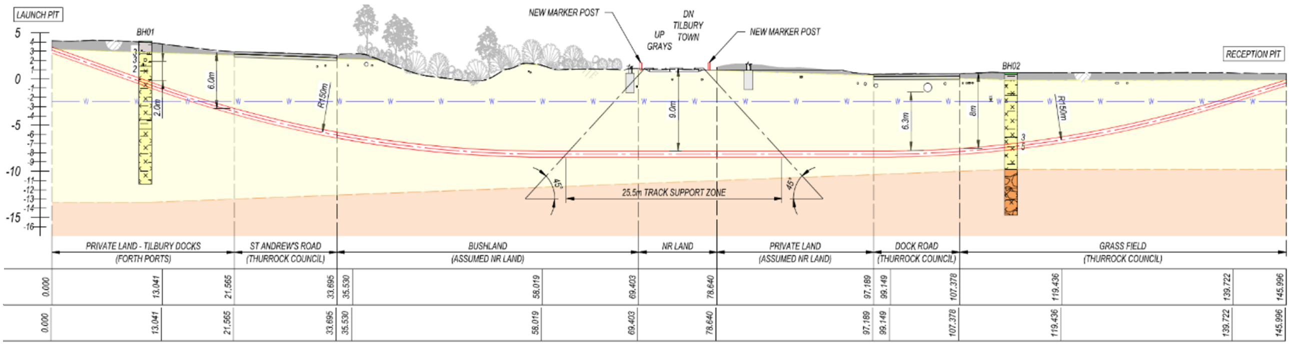

Fig. *3*. Interpreted geological model along HDD alignment.

3.4 Compressibility and consolidation characteristics of the Alluvium

The deformation behaviour of the trenchless crossing is governed by the highly plastic, organic, fine-grained Alluvium that forms the drilling horizon beneath the railway.

Laboratory classification testing classified the soil as fine-grained (54% silt and 41% clay), and yielded water contents of 54-85% (mean 70%), liquid limits of 78-103% (mean 92%), and plasticity indices of 46-66% (mean 57%). These results indicate a highly compressible soil, hence both construction-induced ground displacements and time-dependent consolidation settlement is to be assessed.

3.4.1 Compression index and consistency verification from liquid limit

Using empirical correlations between the compression index (Cc) and liquid limit (LL) proposed by Terzaghi and Peck [5], a first-order estimate of the 1D compressibility for undisturbed, inactive clays of medium sensitivity can be obtained from:

$$Cc = 0.009(LL - 10) \tag{1}$$

Substituting the representative value LL = 92% into Eq. (1) yields Cc = 0.738, which aligns closely with the adopted value of Cc = 0.75 derived from ILOT results. This agreement provides confidence in the selected compressibility parameter.

3.4.2 Modified compression index for Soft Soil modelling

Using the Soft Soil formulation described by Carter and Bentley [6], the modified compression index (λ*) required for constitutive modelling can be obtained from the relationship:

$$\lambda^* = \frac{Cc}{2.3(1 + e_0)} \tag{2}$$

Based on interpretation of ILOT results, an initial void ratio of e_0 = 1.0 was considered, generating a characteristic value of λ* = 0.16. This value agreed with the range (0.15-0.18) obtained directly from laboratory test data.

3.4.3 Organic/ peat horizons (localised high compressibility zones)

Localised peat horizons within the Alluvium exhibit markedly higher compressibility, reflected in water contents ranging from 164% to 466% (mean 315%) and very high plasticity (PI = 124%). These index properties correspond to an estimated compression index of Cc = 1.61, indicating that such horizons represent the 'worst-case' geotechnical conditions for evaluating compressibility and predicting consolidation settlement.

3.5 Characteristic geotechnical design Parameters

Characteristic parameters for each stratum were interpreted from the ground investigation using a combination of in-situ SPT correlations, laboratory derived effective strength relationships, and index-based empirical methods.

For the cohesive Alluvium, effective strength parameters (c', φ') were obtained from consolidated undrained triaxial testing, while the over-consolidation ratio (OCR) was estimated from the undrained shear strength profile, with the coefficient of earth pressure at rest (K_0) subsequently derived from the resulting OCR.

The Made Ground and River Terrace Deposits exert limited influence on the predicted HDD response, as the drilling horizon is located entirely within the Alluvium. Mohr-Coulomb parameters for these strata were derived from SPT-based correlations for drained stiffness [7] and effective friction angle [8,9], with unit weight densities assigned in accordance with BS 8004:2015.

4 Bore design and hydrofracturing assessment

Maintaining drilling-fluid circulation while regulating annular pressure is a primary control for any HDD beneath sensitive infrastructure. Annular pressure influences borehole stability and cuttings suspension, while excessive pressures elevate the risk of hydraulic fracturing or inadvertent returns, potentially causing ground heave and loss of circulation.

Thus, HDD bore planning is undertaken alongside the development of a project-specific drilling-fluid specification and an annular-pressure model. This approach allows for the estimation of the required circulating pressure and the determination of the maximum allowable bore pressure to ensure that operating pressures do not exceed the formation-limit threshold along the alignment [10-13].

4.1 Drilling fluid specification and rheology

The drilling-fluid specification was developed for drilling through Alluvium deposits, using a bentonite-based system with additives to promote rapid viscosity build-up and filtration control. The recommended mix consisted of Soda Ash 1.0 kg/m³, Tunnel-Gel Max 40.0 kg/m³, and PAC-L 1.0 kg/m³.

The drilling-fluid rheology was determined from viscometer measurements (600 rpm = 61; 300 rpm = 48) and interpreted using the Bingham–Plastic model, yielding a plastic viscosity of 13 cP and a yield point of 35 lb/100 ft². The resultant PV–YP presents a drilling fluid with sufficient viscosity for cuttings transport and adequate gel strength to maintain borehole stability, especially within low-permeability, fine-grained alluvial soils.

The adopted fluid properties for annular pressure modelling incorporated a flow rate of Q = 870.60 L/min and a drill fluid density γ = 10.80 kN/m³. These parameters define the hydrostatic component and the frictional pressure losses within the annulus, which together define the annular-pressure envelope and the pump rates required along the bore [10,11].

4.2 Circulating pressure and pressure-control rationale

The bore path and pressure envelope were evaluated using an industry HDD bore-planning tool that estimates annular pressure along the alignment (including frictional losses) based on the ground model and drilling-fluid rheology.

The analysis indicated that the required circulating pressures within the track influence zone would remain below 2.74 bar for both bores. Hence, to minimise the risk of hydrofracture, it is essential that operating pressures are maintained below the local allowable formation-limit pressures.

4.3 Selection of bore pressures for FE analysis use

Since annular pressure can vary during drilling, a range of bore pressures were modelled in the 3D FE analysis to assess the influence of bore-pressure variation on ground response:

- 2.0 bar represents the minimum circulating pressure.
- 5.0 bar represents an upper bound allowable bore pressure for the drilling horizon.

Higher pressures were excluded, since in very soft soils they could produce ground-response predictions of reduced reliability.

5 3D finite-element model

PLAXIS 3D was selected for this study because it provides the advanced soil–structure interaction capabilities required to model the very soft, highly compressible organic clay encountered along the HDD alignment at Tilbury. PLAXIS 3D incorporates advanced constitutive models, such as the Soft Soil model that capture the non-linear stiffness, anisotropic consolidation behaviour, low permeability, and time-dependent deformation that govern ground response in such deposits.

In addition, a 3D modelling approach is necessary to reflect the curved bore geometry, staged construction sequence, and variation in the annular-pressure envelope. PLAXIS 3D facilitates this by allowing explicit definition of the bore path and construction stages, enabling realistic simulation of the planned drill.

5.1 Ground model

The FE ground model in Figure 4 incorporates three soil layers—Made Ground (MG), Alluvium Deposits (AD), and River Terrace Deposits (RTD), consistent with the interpreted ground model.

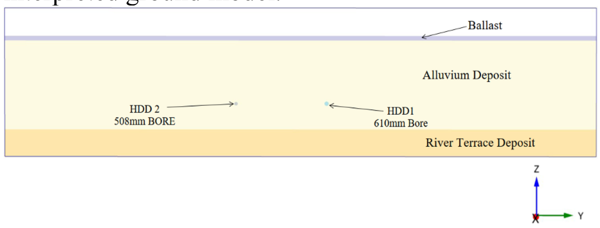

Fig. 4. FE Ground Model below the Track.

The elevation (mAOD) and thickness of the three soil layers are presented in Table 1, with the RTD layer extended in the FE domain to mitigate boundary effects.

Table 1. Soil Model Used for FEM Model.

No.	Soil Layers	Top (mAoD)	Base (mAoD)
1.	MG	4.210	2.960
2.	AD	-2.960	-11.50
3.	RTD	-11.50	-15.00

5.2 Constitutive models adopted and material parameters

To replicate the contrasting behaviour of the strata, a mixed constitutive approach was adopted:

- Made Ground and River Terrace Deposits parameters were simulated using the Mohr–Coulomb (MC) model, appropriate where a first-order linear elastic–perfectly plastic representation is sufficient for strength and stiffness response.
- The Alluvium Deposits (including a separate parameter set for peat horizons) were simulated using the Soft Soil (SS) model to better capture high compressibility and stress-dependent stiffness, while supporting time-dependent consolidation responses in soft fine-grained soils.

In PLAXIS, the Soft Soil (SS) formulation is expressed using modified compression and swelling indices (λ* and κ*) and related state parameters (e.g., OCR and K_0), enabling the prediction of more realistic volumetric straining behaviour of normally consolidated to lightly over-consolidated clays compared with simple linear-elastic models.

The design parameters for each stratigraphic unit, as inputted in PLAXIS 3D, are summarised in Table 2 for MG and RTD, and Table 3 for AD. To account for the observed variability in organic content two soft soil parameters sets (cohesive alluvium, & peat) are provided in Table 3.

The Soft Soil parameters listed in Table 3 differ in certain respects from the characteristic estimates presented in Section 3.4. The modified compression index (λ* = 0.2171) was calculated using Eq. (2) with Cc = 0.75 and a void ratio of e_0 = 0.50 representative of the soil state at the drilling horizon, whereas the characteristic value of λ* = 0.16 was derived using a general initial void ratio of e_0 = 1.0 for the broader Alluvium stratum. For the peat horizons, a compression index of Cc = 1.50 was adopted as a characteristic design value, marginally below the Cc ≈ 1.61 estimated from index property correlations. The compression index range [0.35, 0.75] presented in Table 3 for the cohesive Alluvium denotes the bounds evaluated in the compressibility sensitivity analysis described in Section 5.3 (C2) and does not supersede the adopted characteristic value of Cc = 0.75.

Table 2. MC Model – MG & RTD Soil Parameters.

Model parameter	MG	RTD
Model type	MC (Undrained B)	MC (Drained)
γ_{unsat} (kN/m³)	17	17
γ_{sat} (kN/m³)	19	19
E′ (kPa)	15000	25000
ν	0.3	0.3
S_u (kPa)	17.0	-
ϕ' (°)	-	35.0
c′ (kPa)	-	5.0
OCR	-	-
K_0	-	-

The defined ground model and soil parameters form the basis for all subsequent construction-stage simulations in PLAXIS, including bore excavation, pressure application, and consolidation analyses. The model also facilitates targeted sensitivity analyses, including variations in compressibility parameters and circulating pressure while maintaining a consistent ground model.

Table 3. SS Model – AD Soil Parameters.

Model parameter	AD	AD (Peat)
Model type	SS(Drained)	SS (Drained)
γ_{unsat} (kN/m³)	14	11
γ_{sat} (kN/m³)	15	12
E′ (kPa)	4,921	700
ν	0.2	0.2
λ*	0.2171	0.43
κ*	0.0559	0.388
Cc	[0.35, 0.75]	1.5
ϕ′ (°)	20	16
c′ (kPa)	5.0	1.0
OCR	1.0	1.0
K_0	0.7	0.8

5.3 Structural model & construction

The model domain was set as 143 × 80 × 20 m (x, y, z) to position the mechanical boundaries well outside the anticipated zone of influence of the HDD beneath the railway crossing. This ensures that potential deformation and collapse mechanisms can develop freely and are not constrained by the model limits.

The FE process that replicates the HDD construction stages can be divided into the following steps:

1. The in-situ stress state, topography, stratigraphy, and groundwater conditions were established to represent the existing site conditions, as depicted in Fig 5. Due to the sensitivity of OHLE assets, the 2.0m deep concrete foundations are included in the initial phase.
2. To represent the operational railway, a uniform surcharge of 52 kPa was applied at the ground surface above the HDD alignment. The displacement field resulting from this surcharge was reset to zero to simulate pre-existing consolidation prior to the HDD. The surcharge was re-applied as an initial load condition for subsequent analysis stages.
3. The HDD1 alignment depicted in Fig. 3, is modelled by excavating the final 610mm bore diameter in 4.5 m advancements, resulting in a total of 32 modelling phases.
4. For each excavation stage, a distributed load was applied to the bore surface to represent the drilling-fluid pressure detailed in Fig. 6. In this

study, bore pressures ranging from 2.0 to 5.0 bar were assessed.

5. The advancement sequence proceeds rod-by-rod until the full drill length is reached. Once the bore is completed, the applied drilling-fluid pressure is removed along the entire excavation, and the cavity is subsequently backfilled by activating a linear elastic material representing a low-strength cementitious grout (≈ 3.5 kPa), as shown in Fig. 7.
6. The modelling procedure described above was repeated for HDD2.

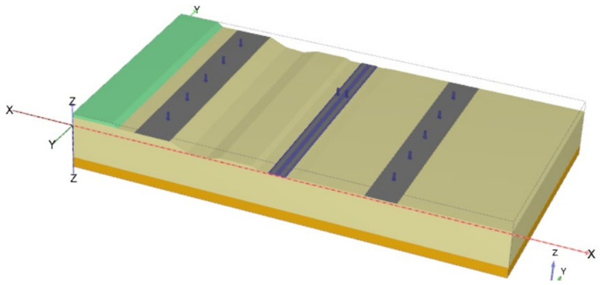

Fig. 5. Existing Site Conditions.

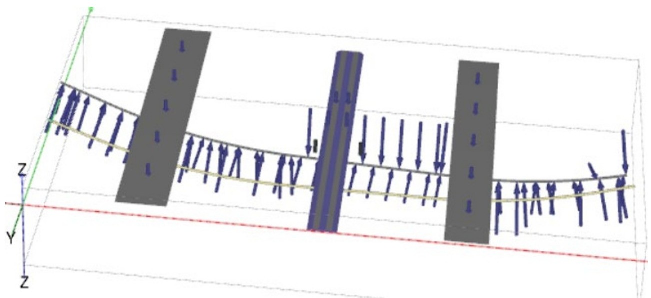

Fig. 6. HDD 1 alignment with activated bore pressure.

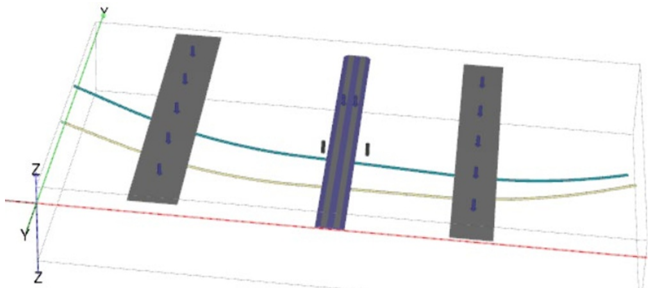

Fig. 7. HDD1 Completed and Grouted.

In addition to the bore-pressure evaluation, a compressibility-sensitivity analysis was conducted with the bore pressure fixed at 3.0 bar. The compression index of the cohesive Alluvium was systematically varied (Cc = 0.35, 0.75, and 1.50) to assess the influence of material compressibility on the predicted ground response.

6 Ground displacement results

This section presents the predicted ground-displacement results obtained from the PLAXIS 3D analysis for two sensitivity cases: (i) variation in annular bore pressure, and (ii) variation in the compressibility index of the cohesive Alluvium. Ground displacements are evaluated directly beneath the railway and compared against the allowable ground displacement thresholds specified by National Rail.

6.1 C1: Annular bore pressure (2.0-5.0 bar)

Annular bore pressure is a key operational variable, as it directly influences the local effective stress state around the excavation and governs both deformation response and the potential for pressure-driven instability in soft ground.

The sensitivity-assessment results for HDD1 and HDD2 are presented in Fig. 8, which plots the predicted displacement profiles parallel to the railway for bore pressures ranging from 2 to 5 bar.

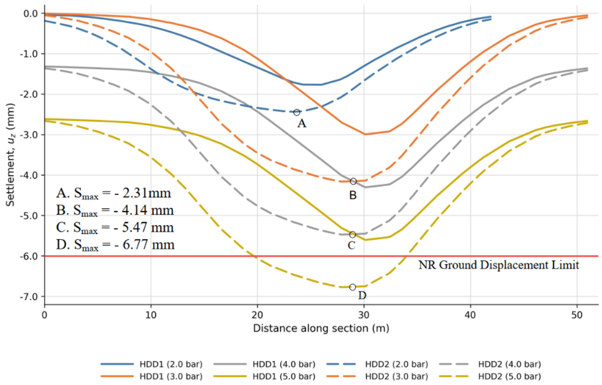

Fig. 8. Summary of HDD1, HDD2 predicted displacement results.

For both alignments, a uniform increase in settlement is observed with increasing circulating pressure, and the location of maximum displacement is consistently observed near the midpoint of both drills. HDD2 exhibits slightly greater settlement magnitudes than HDD1 for all pressure levels. Across the pressure range considered, the maximum settlements vary from approximately 1 mm to 3 mm for HDD1 and from 2 mm to 6 mm for HDD2, with the settlement trough becoming progressively deeper and wider as circulating pressure increases.

The predicted settlement results indicate that bore pressures exceeding 3 bar would exceed the allowable displacement limit of 5mm set in National Rail's UTX standard NR/L2/CIV/044 [14]. This statement discounts additional settlement contributions associated with Alluvium layers containing peat that could reduce the allowable bore pressure below 3 bar.

6.2 C2: Compressibility Index (0.35,0.75,1.50)

This case evaluates the effect of drilling through a very soft highly compressible organic clay by varying the compression index (Cc) at a fixed bore pressure of 3 bar, with predicted settlements taken at centrally located node representing the maximum ground movement beneath the railway.

When modelling Cc as a variable, it is appropriate to present the corresponding implied oedometer (constrained) modulus, $Eoed$ using the standard 1D relationship $Eoed = 1/mv$. This correlation, commonly used in settlement assessment, allows the FE sensitivity output to be interpreted consistently with laboratory oedometer behaviour. [15]

Fig. 9 presents the results of the compressibility sensitivity analysis, showing how variations in the AD compression index (Cc = 0.35, 0.75, 1.50) influence both the Oedometric modulus ($E_{oe}d$) and the predicted vertical displacement (uz).

As Cc increases, the corresponding oedometric modulus decreases significantly from values exceeding 1,000 kPa at Cc = 0.35 to approximately 250 kPa at Cc = 1.50 indicating the significant reduction in stiffness associated with higher organic content.

A consistent trend is observed in the displacement results: increasing Cc leads to progressively larger settlements, with uz values ranging from approximately 2 mm at Cc = 0.35 to ~7 mm at Cc = 1.50. Best fit lines are included to illustrate the overall trend across the discrete PLAXIS outputs and are not intended to represent a constitutive relationship.

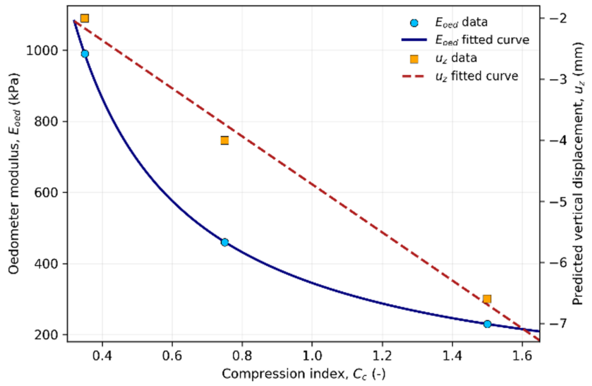

Fig. 9. (Cc), vs ($E_{oe}d$), predicted displacement.

7 Discussion

The integrated design process adopted for this study which models bore pressures, soil behaviour, and staged construction within a single 3D FE model provides a robust platform for predicting HDD induced ground displacement. As illustrated in Fig. 10a, and Fig. 10b, the PLAXIS model captures the full spatial distribution of displacement around the drill path, resolving the localised and asymmetric deformation patterns, that empirical methods are unable to calculate.

The results from the 3D finite-element modelling suggests that HDD-induced deformation in very soft organic alluvium is influenced by the combined interaction of (i) the imposed annular pressure envelope and (ii) the compressibility/stiffness characteristics of the alluvial cohesive stratum.

The bore pressure sensitivity case demonstrates a near-linear increase in predicted settlement beneath the railway corridor as circulating pressure increases from 2 bar to 5 bar (Fig. 8). This trend aligns with the established understanding that annular pressure affects both stress redistribution around the bore and excess pore-pressure generation in low-permeability soils and therefore remains a principal control on deformation and frac-out risk management in HDD design.

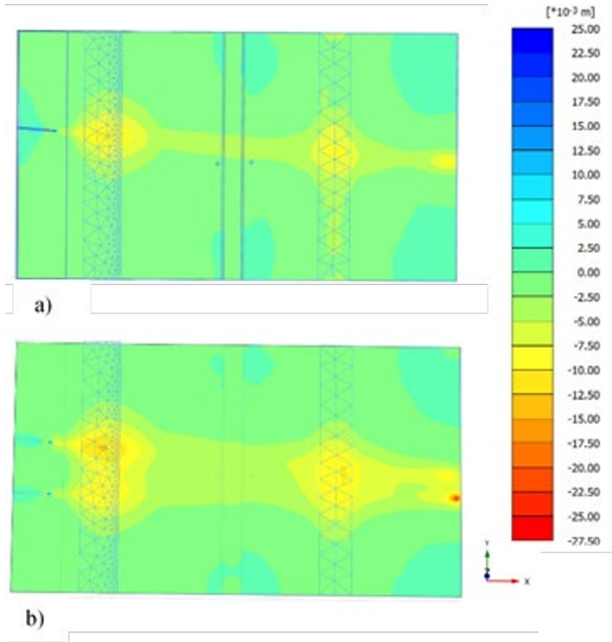

Fig. 10a. Predicted HDD1 surface settlement at a bore pressure of 3.0 bar, **Fig. 10b.** Predicted combined HDD1 & HDD2 surface settlement at a bore pressure of 3.0 bar.

Published HDD research demonstrates that annular-pressure prediction is highly sensitive to bore geometry, drilling-fluid properties, and mud-flow behaviour, emphasising the need for project-specific pressure assessment during design [16,17]. Accurate prediction of bore pressures is essential because actual annular pressures frequently deviate from theoretical estimates, particularly in complex ground conditions such as highly compressible organic clays.

The compressibility-index sensitivity case shows that variability in the compression index (Cc) and the associated oedometer modulus has a first-order influence on predicted settlements. As Cc increases from 0.35 to 1.5, the implied oedometer modulus reduces sharply (Fig. 9), and the calculated settlement increases. This trend is consistent with published evidence that organic clays and peats exhibit high compressibility and significant time-dependent strains relative to inorganic cohesive soils. These results demonstrate that, in highly compressible soils, ground-settlement performance can become the controlling design criterion even when annular bore pressures remain safely below hydrofracture thresholds.

This paper highlights the importance of a comprehensive site investigation and rigorous parameter selection when assessing HDD performance in very soft, highly compressible alluvial soils. The sensitivity analyses demonstrate that key variables governing volumetric behaviour within the adopted constitutive soil model, such as Cc, λ*, OCR, and permeability, can exert a first order influence on predicted ground movements. Published HDD research also confirms that parametric uncertainty, particularly when parameters are inferred from empirical correlations rather than high quality laboratory testing, can lead to substantial variability in allowable annular pressure predictions, which would introduce ground risk to the undertrack crossing.

The modelling approach still includes necessary idealisations; bore pressures are applied through annular-pressure envelopes than full fluid–structure interaction, and excavation and reaming are represented by staged volume removal coupled with boundary pressure application. Potential contributions from; localised ground loss, overbreak, or changes to the slurry remain construction led deviations and excluded from upfront design process.

8 Conclusion

This study demonstrates the value of integrating annular-pressure modelling with three-dimensional finite element analysis to predict HDD-induced ground deformation in highly compressible organic soils beneath critical infrastructure.

Results from the bore pressure sensitivity case confirm that settlement increases steadily with bore pressures, with pressures above 3 bar predicting settlements that exceed the allowable track limits of 5mm set by National Rail. This reinforces that drilling-fluid pressures must be controlled throughout construction, as pressures below the hydrofracture limit can still generate serviceability-critical ground movements.

The compression-index sensitivity analysis highlights an equally important aspect: variations in the compressibility of the Alluvium exert a strong influence on predicted ground movements. As Cc increases, the corresponding oedometer modulus decreases and the predicted settlements increase significantly, demonstrating that deformation is governed as much by intrinsic soil behaviour as by operational pressure control.

This study demonstrates that integrating annular pressure modelling with staged 3D FE simulation constitutes a best practice approach for managing HDD in challenging soft ground conditions. This approach provides a far more reliable basis to protect critical transport infrastructure than traditional empirical methods.

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