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Benchmarking the Extra-Trees and Hybrid Physics–Informed Models against Classical CPT-Based Methods for Shallow Foundation Settlements on Lateritic Soils

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Abstract

Terzaghi's consolidation theory, Janbu's tangent-modulus approach, and the CPT-based correlations proposed by Meyerhof and Schmertmann remain widely used for estimating foundation settlement. Their original calibrations, however, were based largely on temperate soils or clean granular deposits, so their performance in tropical lateritic soils needs to be examined rather than assumed. This study evaluates six approaches: a tuned Extra Trees ensemble (the XT-Settlement Model), the closed-form Hybrid Physics–Informed Settlement Model (HPISM), and four classical methods. The comparison uses three CPT parameter sets representing typical, favourable, and adverse lateritic ground conditions. On the independent test set of 2,681 records, the tuned ensemble achieved R^2 = 0.9950; the other data-driven formulations recorded R^2 values between 0.44 and 0.99. The worked examples show increasing disagreement among the methods as the conditions depart from the database mean. Meyerhof's correlation, developed for clean sands, returned settlements of only 2–7 mm at the low cone resistances considered, while the data-driven models predicted 38–309 mm. Schmertmann's method gave the largest estimate under heavy loading (359 mm). Terzaghi's and Janbu's estimates were of a more comparable order, but both required parameters—such as void ratio and a constrained-modulus coefficient—not available from CPT measurements alone. These results indicate that methods calibrated on temperate granular soils should not be transferred to lateritic ground without independent validation. They also provide a documented basis for selecting a method for preliminary assessment and design.

Keywords: Classical settlement methods; Comparative validation; Cone penetration test; Lateritic soils; Shallow foundation settlement

1. Introduction

For many shallow foundations, settlement rather than bearing-capacity failure governs serviceability design (Burland & Burbidge, 1985; Bowles, 1996; Terzaghi et al., 1996). Commonly used approaches include Terzaghi's one-dimensional consolidation theory (Terzaghi, 1943), Janbu's tangent-modulus method (Janbu, 1967), and the CPT correlations developed by Meyerhof (1974) and Schmertmann (1970, 1978). These methods were developed from a limited set of regional case histories, often involving temperate soils, clean granular deposits, or normally consolidated materials. Their assumptions include relatively uniform soil profiles, elastic response, or predictable drainage, and several depend on a simplified relationship between stiffness and a single parameter. Lateritic soils may depart from these conditions: they can be layered, partly saturated, and variably cemented. Settlement calibrations specifically established for such soils remain limited (Das & Sobhan, 2018; Mayne, 2014).

A related study assembled 8,934 CPT-derived settlement observations for lateritic soils and evaluated twelve algorithms. The tuned Extra Trees ensemble, referred to as the XT-Settlement Model, gave the strongest test performance (R^2 = 0.9950). SHapley Additive exPlanations (SHAP) was used to rank predictor importance, after which SHAP-guided symbolic regression and a Gradient Boosting residual correction were combined to develop the Hybrid Physics–Informed Settlement Model (HPISM). The HPISM achieved R^2 = 0.9901 in semi-closed form and 0.9725 in fully closed form. The earlier analysis did not, however, compare these models directly with the classical methods still used by practitioners, or show how the predictions diverge under different ground conditions. The present study addresses that comparison.

1.1 Classical Settlement Prediction Methods

Terzaghi's consolidation theory describes settlement as compression associated with the dissipation of excess pore pressure. Its usual assumptions include a homogeneous, fully saturated soil, one-dimensional deformation, and constant compressibility (Terzaghi, 1943; Terzaghi et al., 1996). In lateritic deposits, variable cementation, partial saturation, and anisotropy can limit how directly those assumptions apply.

$$S = \frac{qB(1-\nu^2)I_s}{E_s} \qquad (1)$$

In this expression, q denotes applied pressure, B is foundation width, ν is Poisson's ratio, Is is the influence factor, and Es is the soil modulus. Soil stiffness is not generally constant: it changes with stress level, stress history, and strain. Elastic calculations therefore often need empirical adjustments (CEN, 2004).

Janbu (1967) proposed the tangent-modulus concept to represent changes in stiffness with stress, although its parameters commonly need to be established through laboratory testing. Meyerhof (1974) related cone resistance to settlement using empirical correlations developed mainly from clean-sand data. Schmertmann's strain-influence method (1970, 1978) estimates settlement by integrating vertical strain, derived from cone resistance, over an influence depth. It remains an important CPT-based reference method, but its validation has largely involved sands (Robertson & Cabal, 2022). Robertson's framework (Robertson, 2010; Robertson & Cabal, 2022) provides normalized CPT parameters, including corrected cone resistance and the soil behaviour type index used in this study; it does not, by itself, calculate settlement.

Three difficulties recur in the use of these methods: their constitutive assumptions simplify actual soil behaviour; their calibration datasets are often small and region-specific; and their closed-form equations cannot readily capture the interacting effects of cone resistance, stress history, cementation, foundation geometry, and applied pressure (Janbu, 1967; Meyerhof, 1974; Mayne, 2014). These limitations provide a rationale for examining machine-learning methods for settlement prediction (Breiman, 2001; Chen & Guestrin, 2016; Willard et al., 2022) and for comparing their estimates with those from established methods.

1.2 Aim and Objectives

The aim of this study is to compare two recently developed approaches—the Extra Trees Settlement Model (XT-Settlement Model) and the Hybrid Physics–Informed Settlement Model (HPISM)—with classical CPT-based methods for predicting settlement in lateritic soils. The specific objectives are to:

(i) assess the accuracy, interpretability, and practical engineering use of classical, symbolic, and hybrid approaches;

(ii) compare the tuned ensemble, HPISM, and four classical methods using three CPT parameter sets representing typical, favourable, and adverse lateritic ground conditions;

(iii) examine, while stating the assumptions used, why the classical methods may depart from the data-driven predictions outside their original calibration domains; and

(iv) set out a practical basis for choosing among classical, symbolic, and hybrid approaches.

2. Materials and Methods

2.1 Database and Machine Learning Benchmark

The analysis uses a database containing 8,934 settlement observations for lateritic soils. The eight input variables are embedment depth (z), unit weight (γ), foundation width (B), foundation length (L), applied pressure (q), corrected cone resistance (qt), soil behaviour type index (Ic), and overconsolidation ratio (OCR). Measured settlement is the target variable. Twelve algorithms were evaluated using a 70:30 split, comprising 6,253 training records and 2,681 test records (random_state = 42). The tuned Extra Trees ensemble achieved the best performance, with test R^2 = 0.9950 and RMSE = 6.13 mm, and was therefore used as the main data-driven benchmark.

2.2 The Hybrid Physics–Informed Settlement Model

The HPISM combines an explicit symbolic base equation with a Gradient Boosting Regressor trained to model the base equation's residual errors. The symbolic equation was obtained through SHAP-guided symbolic regression and achieved a test R^2 of 0.9133 (Njah, 2026c):

$$S = S_{base}(X) + f_{GBR}(X) \qquad (2)$$

When the residual-correction procedure is applied to the power-law base equation, the result is Hybrid B (R^2 = 0.9853). Applying it to the symbolic base produces Hybrid C, referred to here as the HPISM (R^2 = 0.9901). Approximating the correction with a second-degree polynomial yields fully closed-form versions with R^2 values of 0.8930 and 0.9725, respectively. The present comparison uses the closed-form HPISM and the tuned ensemble as the two data-driven approaches.

2.3 Worked-Example Design

The classical methods require inputs specific to the site rather than a model-training dataset. They were therefore compared with the data-driven approaches through three worked examples, each defined by the eight predictors listed in Table 1. In Example 1, the inputs were set to their database means to represent typical conditions. Example 2 represents more favourable ground: relatively firm, strongly overconsolidated soil (OCR = 10.0; qt = 0.68 MPa) under a light applied pressure (q = 0.10 MPa). Example 3 represents less favourable conditions, with softer, lightly overconsolidated soil (OCR = 6.0; qt = 0.45 MPa) beneath a wider footing carrying a heavier load (B = 2.7 m; q = 0.18 MPa). All three parameter sets fall within the range represented in the database.

Table 1: *Input parameters for the three worked examples*

Variable (unit)	Ex. 1 Typical	Ex. 2 Favourable	Ex. 3 Adverse
Embedment depth, z (m)	2.26	2.30	1.80
Cone resistance, q_t (MPa)	0.554	0.68	0.45
Soil behaviour type index, I_c (–)	3.04	2.75	3.35
Unit weight, γ (kN/m^3)	16.5	17.2	15.7
Overconsolidation ratio, OCR (–)	8.26	10.0	6.0
Foundation width, B (m)	2.3	1.8	2.7
Foundation length, L (m)	1.82	1.6	2.1
Applied pressure, q (MPa)	0.135	0.10	0.18

2.4 Implementation of the Classical Methods

For each case, the classical methods were assigned one representative value for each CPT parameter, matching the database structure, which records a single qt, Ic, γ, and OCR value for each site rather than a full depth profile. A square footing (L = B) and the absence of a water table were assumed; effective stress was therefore taken as equal to total stress, consistent with the unsaturated residual soils represented in the database. Terzaghi's consolidation settlement was calculated as follows:

$$S_c = \frac{C_c H}{1+e_0} \log_{10} \frac{\sigma'_0 + \Delta\sigma}{\sigma'_0} \qquad (3)$$

The stress increase at the centre of the compressible layer (Δσ) was estimated using the 2:1 method. The compressible thickness was set to H = 2B, and q was treated as net pressure. For a typical silty-clayey soil with Ic ≈ 3, the initial void ratio was assumed to be e_0 = 0.75 because it was not available in the CPT dataset. The compression index was estimated from the Terzaghi–Peck relationship (Terzaghi et al., 1996), Cc = 0.30(e_0 − 0.27).

$$\varepsilon = \frac{\Delta\sigma}{M}, \qquad S = \varepsilon H \qquad (4)$$

Janbu's settlement was calculated in the linear case (j = 1), using the same H and Δσ. The constrained modulus was estimated as M = αMqt, with αM = 5, using Robertson's cone-factor relationship for clayey silt (Robertson & Cabal, 2022). Meyerhof's settlement expression for B > 1.2 m was then applied:

$$S\ (\text{mm}) = \frac{2\bar{q}}{q_t}\left(\frac{B}{B+0.3}\right)^2 \qquad (5)$$

In the original Meyerhof formulation for clean sand, both q̄ and qt are expressed in kg/cm^2. Schmertmann's method was calculated as follows:

$$S = C_1 C_2\, \bar{q} \sum \frac{I_z}{E_s}\, \Delta z \qquad (6)$$

The strain-influence integral was evaluated from 0 to 2B, with Es = 2.5qt held constant. A creep factor C2 corresponding to a 10-year period was included, and the strain-influence diagram was taken as triangular, with its peak at z = B/2 (Schmertmann, 1970). The reported classical estimates follow these equations and the assumptions stated above.

3. Results and Discussion

3.1 Qualitative Comparison of Modelling Approaches

The results in Table 2 show that no single approach performs best in accuracy, interpretability, and practical applicability at the same time. The tuned Extra Trees ensemble provides the highest predictive accuracy, but its internal decision process is comparatively difficult to interpret. Schmertmann's method and elastic theory are easier to follow, although their accuracy is more moderate. The symbolic-regression equation and HPISM sit between these extremes: they retain a clearer mathematical form while delivering good to very good predictive performance.

Table 2: *Qualitative comparison of settlement-prediction approaches*

Model	Accuracy	Interpretability	Applicability
Schmertmann method	Moderate	High	High
Elastic theory	Moderate	High	High
Symbolic-regression equation	Good	Very high	Very high
XT-Settlement Model (Extra Trees)	Excellent	Low	Moderate
HPISM	Excellent	High	Excellent

3.2 Quantitative Worked Comparison

Table 3 summarises the six methods' estimates for each worked example; Figure 1 displays the results on a logarithmic scale. In all three cases, the XT-Settlement Model and HPISM predict greater settlement than Terzaghi's and Janbu's methods, and considerably more than Meyerhof's correlation. Their relationship with Schmertmann's estimates varies by case. For Example 1, Schmertmann predicts 132.4 mm, close to the XT model (135.1 mm) and HPISM (135.3 mm). In Example 3, however, Schmertmann gives the highest estimate, 359.4 mm. Agreement is closest for Example 2, while the results spread apart in Examples 1 and 3. The pattern suggests that the methods respond differently to nonlinear interactions among the input variables.

Table 3: *Predicted settlement (mm) from all six methods for the three worked examples*

Case	XT Model (Extra Trees)	HPISM (Hybrid C)	Terzaghi (1943)	Janbu (1967)	Meyerhof (1974)	Schmertmann (1970)
Example 1: typical site	135.1	135.3	55.1	49.6	3.8	132.4
Example 2: firm ground, light load	38.4	43.5	37.0	24.9	2.2	41.2
Example 3: soft ground, heavy load	263.4	308.7	85.5	94.5	6.5	359.4

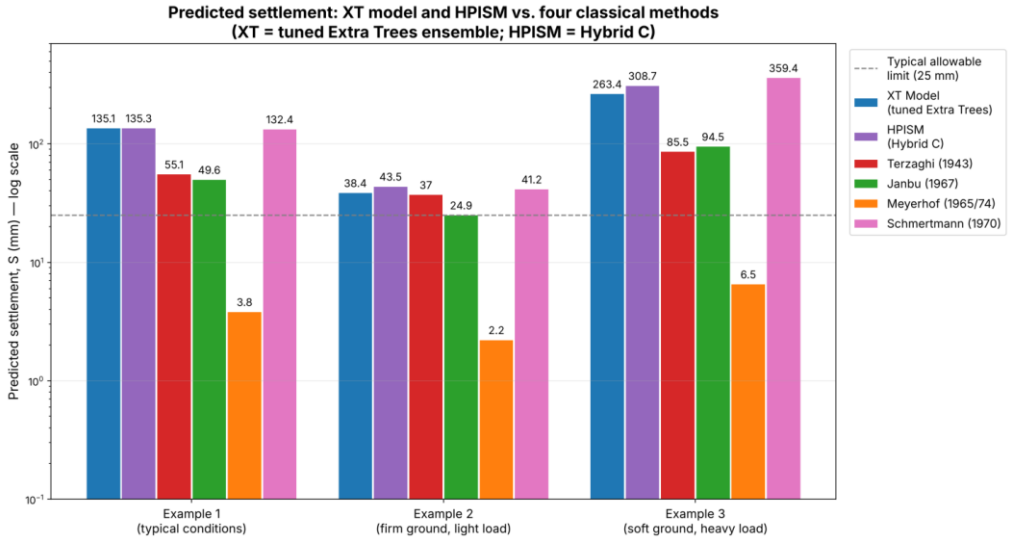


Figure 1: *Predicted settlement of the XT-Settlement Model and the HPISM versus four classical methods for the three worked examples (logarithmic axis; dashed line: 25 mm allowable limit)*

3.3 Domain Mismatch in the Meyerhof and Schmertmann Methods

Both Meyerhof's and Schmertmann's methods were developed from load tests on clean sands, where cone resistance commonly reaches several to tens of megapascals. In the examples examined here, qt ranges from 0.45 to 0.68 MPa—roughly one to two orders of magnitude lower—and represents soft, fine-grained, lightly cemented lateritic soil. Meyerhof's correlation assumes a substantially stiffer material and consequently predicts only 2.2–6.5 mm of settlement in these cases. Schmertmann's estimate of stiffness (Es = 2.5qt) is also low; combined with the strain-influence calculation, this can produce a large settlement estimate for a wide footing under heavy loading, as in Example 3 (359.4 mm). The results indicate that clean-sand correlations may be unreliable for lateritic soils with this level of cone resistance. Depending on how the low resistance enters a particular equation, the resulting error may be an underestimate or an overestimate.

3.4 Behaviour of the Terzaghi and Janbu Methods

Terzaghi's and Janbu's predictions are of a broadly comparable order to those from the data-driven models and do not change erratically in the examples considered. However, their application requires assumptions about parameters such as void ratio, compression index, or modulus coefficient that are not supplied by the CPT dataset. Their estimates are also generally below those of the XT-Settlement Model and HPISM, which may reflect the simplified way these methods represent nonlinear stress–strain response.

3.5 Engineering Implications

The classical methods should not be treated as direct replacements for the tuned ensemble, HPISM, or a site load test, particularly near the limits of the input range. The XT-Settlement Model was evaluated against 2,681 held-out observations, and its predictions cluster closely around the line of equality (Figure 2). The classical methods do not have equivalent validation against this dataset; their performance here is illustrated through only three cases. Under the relatively favourable conditions of Example 2, all six methods give similar estimates, suggesting that they may provide a useful cross-check in comparable circumstances. For more demanding conditions, the tuned ensemble is the stronger predictive reference, while the closed-form HPISM

offers a more transparent check. Classical methods should be used with attention to the limits of their original calibration. If one is selected for design, assumed parameters such as void ratio, compression index, and modulus coefficient should be established from site-specific testing. None of the six methods should be presumed valid for soil profiles substantially different from those examined here.

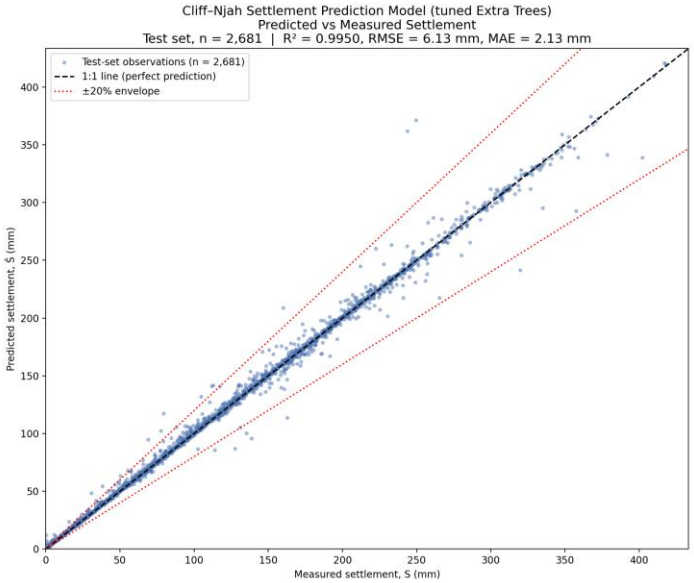


Figure 2: *Predicted versus measured settlement of the XT-Settlement Model (tuned Extra Trees; test set, n = 2,681; R2 = 0.9950, RMSE = 6.13 mm)*

3.6 Limitations

This comparison uses three worked examples rather than a statistical evaluation of every test record. The reason is that several classical methods require parameters that are not consistently available in the database. Although the selected cases represent typical, favourable, and adverse conditions, they do not cover the full range of possible ground and loading conditions. Some inputs required by the classical equations were estimated from standard correlations; accordingly, these results should be interpreted as illustrative estimates rather than exact predictions. Alternative classical formulations or machine-learning architectures may produce different results.

4. CONCLUSION

Six settlement-prediction approaches were compared for lateritic soils: the XT-Settlement Model, HPISM, and the classical methods of Terzaghi, Janbu, Meyerhof, and Schmertmann. The comparison used three sets of CPT parameters representing different ground and loading conditions. The principal findings are as follows:

(i) No approach is strongest in accuracy, interpretability, and practical applicability simultaneously. HPISM provides a compromise between the highly accurate but less transparent ensemble and the more interpretable, but generally less accurate, classical methods.

(ii) Meyerhof's correlation returned very small settlement estimates (2.2–6.5 mm) for the low cone resistances in the lateritic examples. Schmertmann's method produced the largest estimate under heavy loading (359.4 mm).

(iii) Terzaghi's and Janbu's estimates were of a plausible order of magnitude, but their calculations required parameters absent from the CPT dataset. Their predicted settlements were generally lower than those from the data-driven models.

(iv) Classical methods should not be applied to lateritic soils without independent validation. Where input conditions are extreme, the tuned ensemble should be given priority as the predictive reference, with the closed-form HPISM used as a transparent cross-check.

NOMENCLATURE

Symbol	Meaning (unit)
B, L	Foundation width and length (m)
C_1, C_2	Schmertmann embedment and creep factors (–)
C_c	Compression index (–)
e_0	Initial void ratio (–)
E_s	Soil modulus (MPa)
$f_{GBR}(X)$	Gradient Boosting residual correction (mm)
H	Compressible layer thickness (m)
I_c	Soil behaviour type index (–)
I_s	Elastic influence factor (–)
I_z	Strain-influence factor (–)
M, α_M	Constrained modulus (MPa); cone factor (–)
OCR	Overconsolidation ratio (–)
q, $\bar{q}$	Applied (net) foundation pressure (MPa; kg/cm^2 in Eq. 5)
q_t	Corrected cone resistance (MPa)
R^2, RMSE	Coefficient of determination (–); root-mean-square error (mm)
S, S_c	Settlement; consolidation settlement (mm)
$S_{base}(X)$	Base equation of the hybrid model (mm)
z, Δz	Embedment depth; depth increment (m)
γ	Unit weight (kN/m^3)
$\Delta\sigma$	Vertical stress increase (kPa)
ε	Vertical strain (–)
ν	Poisson's ratio (–)
σ'_0	Initial effective vertical stress (kPa)

Declaration of Conflicting Interests

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