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Site-specific consolidation analysis for Newtown (Kolkata) using the Soft Soil Model calibrated with Flat Dilatometer (DMT) test results

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Abstract. Kolkata (22.5744° N, 88.3629° E), the capital city of West Bengal, is undergoing rapid urbanization at an annual rate of 4.7%. This growth has intensified challenges related to the city's soft subsoil conditions, as much of Kolkata lies along the banks of the Ganges and is predominantly underlain by alluvial deposits rich in fine soil particles. These fines govern the time-dependent response of the ground, leading to consolidation settlement. However, in practice, many projects in Kolkata tend to underestimate this issue, often resulting in premature structural damage due to excessive settlement of foundations before the end of their design service life. This study addresses the problem through advanced in-situ geotechnical investigations using the Dilatometer Test (DMT). Complementary in-situ dissipation tests (DMT-A) were also performed to estimate the in-situ coefficient of permeability of the subsoil at a project site in Newtown, Kolkata. The derived soil parameters were then used to calibrate soft soil constitutive models for the site. These models were implemented in PLAXIS 3D (V20) to perform consolidation analyses of a pile-raft foundation system. The results effectively capture the time-dependent behavior of the system under structural loading, providing valuable insights for developing more sustainable and reliable foundation designs in such challenging ground conditions.

1 Introduction

Kolkata is situated within the Bengal Basin and is underlain by Quaternary fluvio-deltaic deposits, predominantly composed of clay and silt, which form the primary foundation soils of the city. Based on lithological characteristics and radiocarbon dating, the Holocene subsurface sediments of Kolkata have been categorized into three lithofacies—clay, sandy clay, and sand [1, 2]. Rapid urbanization and population growth have driven eastward expansion beyond the Hooghly River into areas such as Salt Lake, Rajarhat, and Newtown, where large tracts of low-lying land were reclaimed using dredged alluvial material from the Ganges River [3].

Subsurface investigation data indicate that soil layers up to depths of approximately 12–13 m are largely unconsolidated, exhibiting abrupt variations in engineering properties and very low Standard Penetration Test (SPT) N-values, generally not exceeding 5. Below this depth, a marked increase in N-values, typically ranging from 16 to 18, is observed across the city, signifying the transition from Holocene to denser Pleistocene deposits [3,4]. The shallow Holocene strata play a critical role in foundation performance and, owing to their nature, are particularly susceptible to long-term consolidation settlement.

Conventional settlement assessments are often reliant on empirical correlations and high-quality laboratory data such as oedometer test results, which are frequently absent in routine geotechnical investigation reports [5 – 7]. In contrast, advanced finite-element software such as PLAXIS enables time-dependent consolidation analysis using constitutive models like the Soft Soil (SS) model. The SS model is primarily defined by the modified compression index (λ*) and modified swelling index (κ*), where λ* can be derived from the oedometer modulus (E_{oed}), and κ* can subsequently be estimated from λ* using established mathematical relationships within the PLAXIS framework.

$$E_{oed}^{ref} = \frac{p^{ref}}{\lambda^*} \quad (1)$$

where, E_{oed}^{ref} = tangent stiffness for primary oedometer loading, p^{ref} = atmospheric pressure = 101.3 kPa

This limitation can be effectively addressed through advanced in-situ testing techniques such as the Flat Dilatometer Test (DMT). Originally developed by Prof. Silvano Marchetti in the late 1970s, DMT has since evolved into a widely accepted in-situ testing method and is incorporated within major international standards and geotechnical design guidelines [8–10]. Comprehensive descriptions of the equipment, testing procedure, and interpretation methods are provided in the ISSMGE monograph [11], with further

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methodological enhancements documented in subsequent studies [12]. As a direct-push test, DMT does not require borehole drilling and induces minimal disturbance to the surrounding soil. Unlike penetration-based tests that primarily capture strength or failure characteristics, DMT operates as a load–displacement device, enabling direct assessment of in-situ stiffness, stress history, and deformability. These attributes make DMT particularly well suited for settlement and consolidation analyses. In geologically complex settings such as Kolkata, the use of advanced in-situ techniques like DMT is therefore critical for reliable estimation of in-situ stress state, stiffness, and compressibility parameters [5–13], which fundamentally control consolidation settlement behavior in cohesive and fine-grained soils. Di Mariano et al. [14] proposed a systematic approach for deriving Hardening Soil (HS) model parameters directly from in-situ test data, with subsequent transformation to Soft Soil (SS) model parameters using relationships implemented in the PLAXIS material module.

In the present study, an extensive field investigation comprising three Standard Penetration Tests (SPT), three DMT, and one in-situ dissipation tests (DMT-A) was carried out at a site in Newtown, Kolkata. DMT-derived in-situ stress and compressibility parameters were employed for calibration of the SS constitutive model, while consolidation-related parameters, such as the horizontal coefficient of permeability (k_h), obtained from DMT-A, were used for time-dependent consolidation analysis.

2 Geotechnical characterization

The study area is located at 22°35'14.86"N longitude and 88°29'15.48"E latitude as shown in Fig. 1, which demonstrates the rate of urbanization of this area in last ten years.

Extensive geotechnical investigations suggest that the subsoil is clayey in nature throughout the test depths. Fig. 2 shows the DMT interpreted results of the study area.

3 Constitutive modelling

The primary input parameters for the Soft Soil (SS) constitutive model are the modified compression index (λ*), modified swelling index (κ*), drained cohesion (c′), and drained friction angle (φ′). This section describes the derivation of λ* and κ* from DMT results, while the estimation of c′ and φ′ from DMT-A data is addressed in the subsequent section.

Following the methodology proposed by [14], it has been demonstrated that for silty and clayey soils, constrained moduli measured in laboratory oedometer tests show good agreement with the constrained modulus obtained from the DMT (M_{DMT}). Accordingly, the oedometer modulus is assumed to be adequately represented by the DMT-derived modulus, i.e., $E_{oed} \approx M_{DMT}$. On this basis, M_{DMT} is adopted as the reference stiffness parameter, consistent with recommendations from previous studies [15,16]. This approach allows stiffness characterization directly from in-situ measurements, thereby minimizing reliance on laboratory data that may be affected by sampling disturbance.

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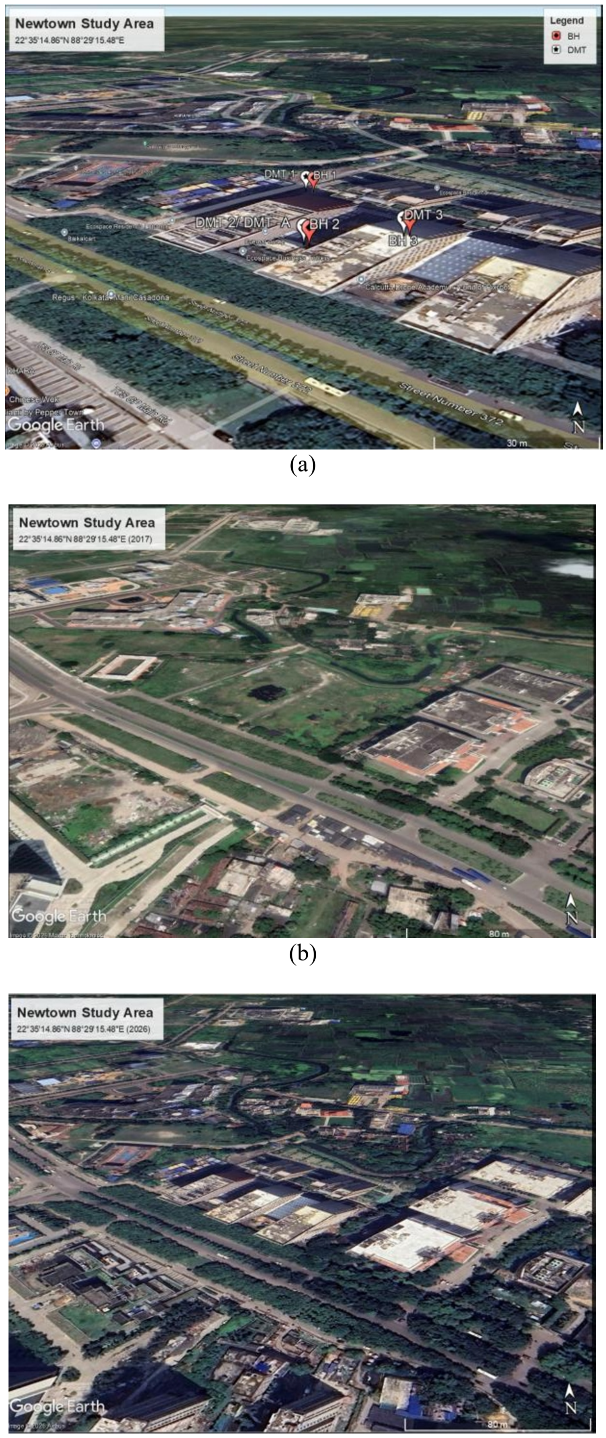

Fig. 1. (a) Location of DMT and SPT at the study location, (b) urbanization rate in the study area 2017 and (c) urbanization rate in the study area 2026.

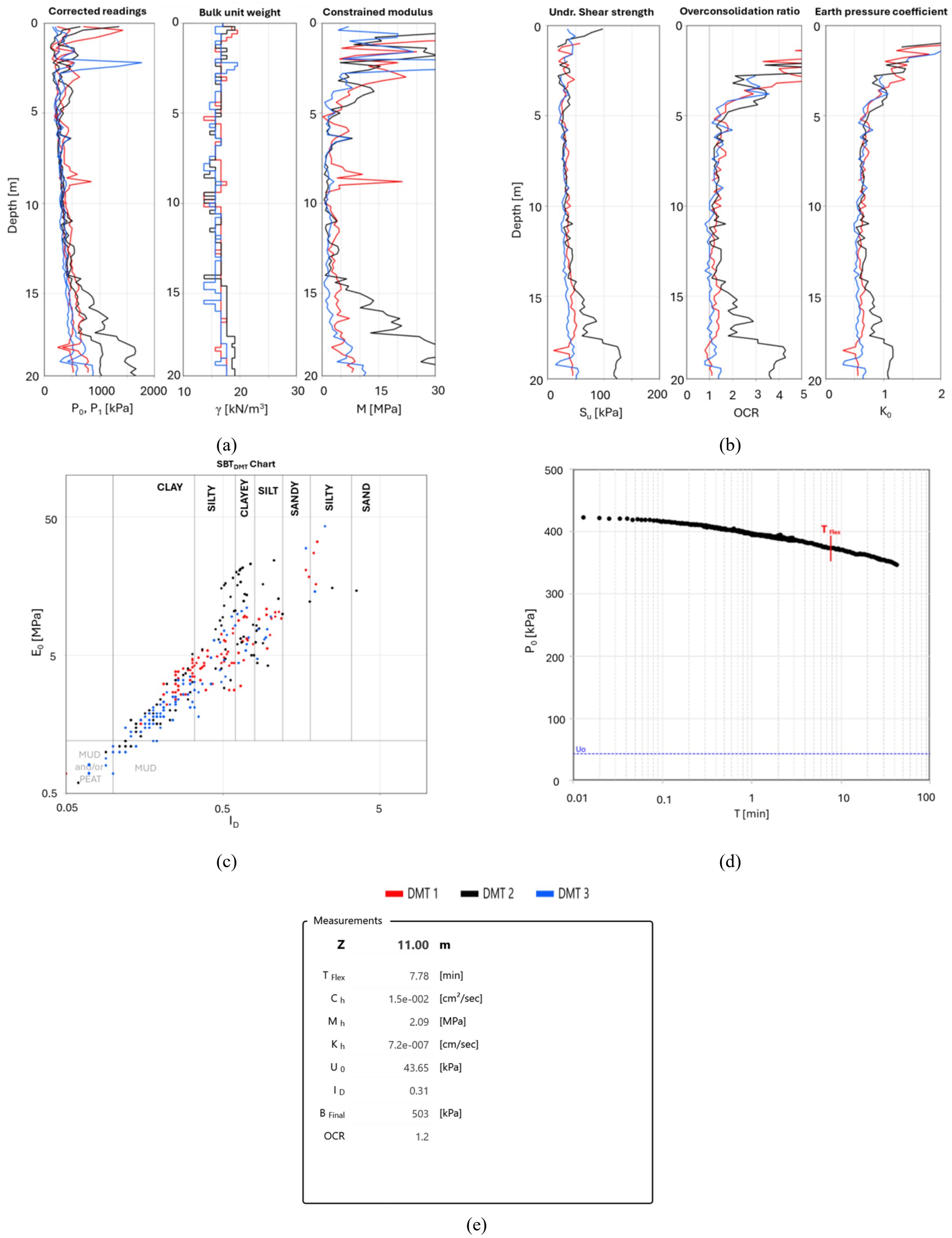

Fig. 2. DMT and DMT - dissipation interpreted results of the study area: (a) DMT raw data, (b) geotechnical design parameters obtained from DMT, (c) SBT index from DMT, (d), (e) DMT – dissipation test results.

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For calibration of the Hardening Soil model (HS), stiffness relationships suggested by [17] are employed. Specifically, the reference tangent stiffness for primary oedometer loading is assumed equal to the secant stiffness at 50% of the failure stress in drained triaxial compression, such that

$$E_{oed}^{ref} = E_{50}^{ref} \tag{2}$$

The unloading–reloading stiffness modulus is taken as four times the reference oedometer modulus, i.e.,

$$E_{ur}^{ref} = 4E_{oed}^{ref} \tag{3}$$

These stiffness parameters respectively represent the tangent modulus governing one-dimensional compression, the secant modulus mobilized in drained triaxial loading, and the unloading–reloading modulus relevant at operative strain levels in numerical analyses.

The reference oedometer modulus E_{oed}^{ref} is evaluated using the empirical formulation proposed by Di Mariano et al. [14], which directly links E_{oed}^{ref} to DMT-derived parameters:

$$E_{oed} = E_{oed}^{ref}\left(\frac{c'\cot\phi' + \sigma_1'}{c'\cot\phi' + p_{ref}}\right)^m \tag{4}$$

where m is the stress-level dependency parameter ($0.5 < m < 1.0$); for soft clays, $m = 1.0$ is recommended [18], while values around 0.5 are suggested for sands and silts [19]. Here, σ_1', the major principal effective stress, is substituted in this study with the mean effective confining stress $\sigma_m = \frac{1+2K_0}{3}\sigma_1'$; c' is the drained cohesion; φ' is the drained friction angle; and p_{ref} is the reference pressure, equal to atmospheric pressure (101.3 kPa).

Once E_{oed}^{ref} is determined from Eq. (2), the mathematical relationships provided in the PLAXIS material manual (Eq. 1) are used to compute the SS model parameters, namely the modified compression index (λ*) and the modified swelling index (κ*), with κ* commonly taken as λ*/2.5.

4 Finite Element Analysis (FEA)

In this study, three FEA were conducted to identify the most effective foundation solution for the study area. All analyses consider a raft foundation with plan dimensions of 28 m × 62 m and a thickness of 0.5 m, subjected to a uniform distributed load of 88 kPa.

The first analysis involves a 50-year time-dependent consolidation settlement assessment of the raft foundation alone. The second analysis evaluates a pile–raft foundation system under the same loading and duration, incorporating piles of 500 mm diameter and 18 m embedment depth, spaced at 1.5 m c/c. The third analysis considers an alternative pile–raft configuration with 600 mm diameter piles of 18 m length, spaced at 1.8 m c/c, and includes coupled time-dependent behavior comprising 40 years of consolidation followed by an additional 10 years of creep analysis.

The input parameters for the Soft Soil (SS) model used in the consolidation analyses are summarized in Table 1, while the parameters for the Soft Soil Creep (SSC) model are presented in Table 2. The SSC model parameters were calibrated following the methodologies proposed by [22, 23]. Work done by [22] reported that fully drained clayey soils typically exhibit effective friction angles in the range of 30°–34°, which was adopted as a reference for strength parameter selection. Another work by [23] demonstrated that soil permeability decreases with increasing aging time, with the most pronounced reduction occurring within the first five months, after which permeability tends to stabilize (see Fig. 3). This time-dependent reduction in permeability was explicitly considered in the creep analysis with OCR 1.5 as per DMT to ensure realistic simulation of long-term settlement behaviour.

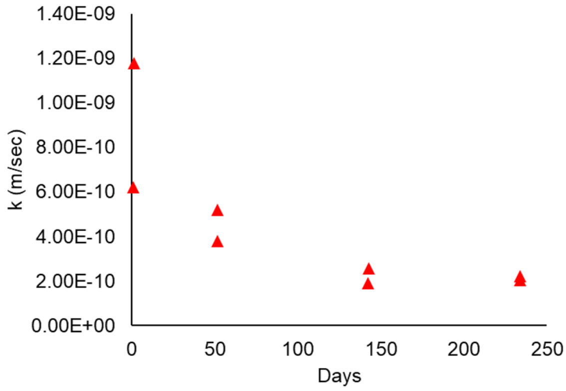

Fig. 3. Permeability versus aging time [23].

Table 1. SS Model input parameters.

Layer Depth (m)	MDMT (MPa)	λ*	κ*
0 – 4	7.00	0.00703	0.0028
4 – 6	5.00	0.02003	0.0080
6 – 9	4.23	0.02397	0.0095
9 – 17	3.94	0.02631	0.0105
17 – 20	7.33	0.01421	0.0056

Table 2. SSC Model input parameters.

Layer Depth (m)	λ*	κ*	μ*
0 – 4	0.00385	0.00154	0.00025
4 – 6	0.01485	0.00594	0.00099
6 – 9	0.02039	0.00815	0.00135
9 – 17	0.02820	0.01128	0.00188
17 – 20	0.01698	0.00679	0.00113

5 Results and discussion

The three-dimensional finite element model was developed in PLAXIS 3D based on the raft foundation geometry. To reduce boundary effects to a large extent, the model extents were set to x = ±62.0 m and y = ±62.0 m.

Results from Case Study (i), involving a raft foundation subjected to a uniform load of 88 kPa over a 50-year consolidation period, indicate that the foundation does not satisfy serviceability requirements. The computed total settlement at the end of 50 years is

329 mm (Fig. 4), which significantly exceeds the maximum allowable settlement of 125 mm prescribed by IS 1904, thereby indicating failure under settlement criteria.

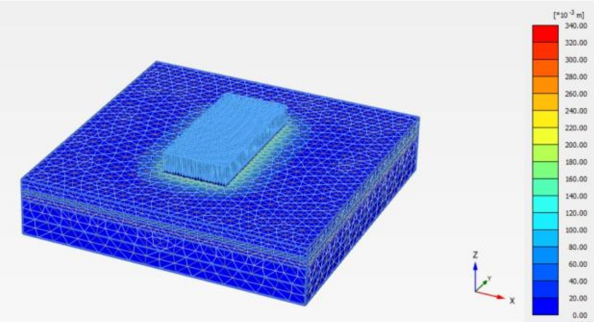

Fig. 4. Total settlement of the raft foundation at the end of 50 years 319 mm.

To improve performance, a pile–raft foundation system comprising piles of 500 mm diameter and 18 m embedment depth, spaced at 1.5 m c/c, was analysed under identical loading and consolidation conditions. The results show a substantial reduction in settlement to 38 mm after 50 years (see Fig. 5), demonstrating the effectiveness of pile inclusion in controlling primary consolidation settlement.

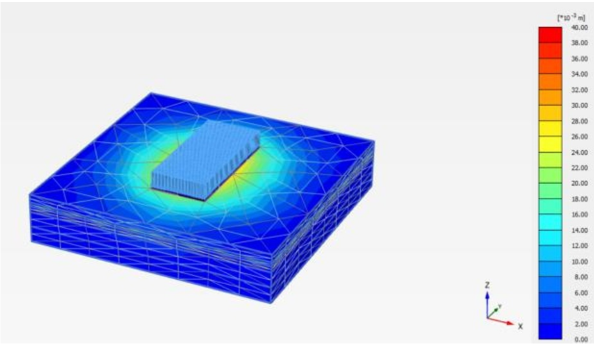

Fig. 5. Total settlement of the pile-raft foundation at the end of 50 years 38 mm.

However, previous studies have highlighted the importance of creep settlement in highly plastic soft soils over the full-service life of infrastructure (Wu et al., 2023).

DMT-based profiling indicates that the subsoil between depths of 5 m and 15 m consists of highly compressible soft clay. Consequently, neglecting creep effects may lead to unconservative serviceability predictions. To address this, an additional analysis (Case Study ii) was performed considering 40 years of consolidation followed by 10 years of creep, with the Soft Soil Creep (SSC) model employed for the latter phase.

The results reveal that the pile–raft system with 500 mm diameter piles is unable to adequately control long-term settlement when creep is accounted for. The total settlement after 50 years increases to 150 mm (see Fig. 6), exceeding the permissible limit of 125 mm specified in IS 1904.

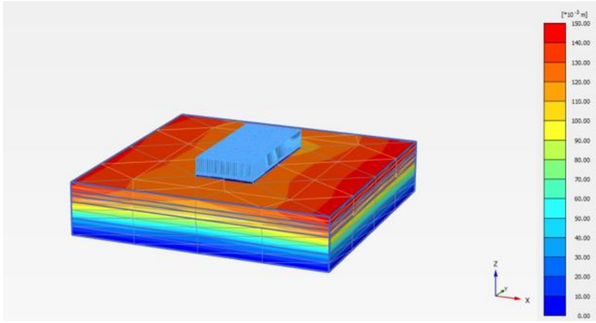

Fig. 6. Total settlement of the pile-raft foundation at the end of 50 years 150 mm including creep.

Based on these findings, a third analysis (Case Study iii) was conducted using an enhanced pile–raft configuration with piles of 600 mm diameter and 18 m embedment depth, spaced at 1.8 m c/c. This analysis also incorporated 40 years of consolidation followed by 10 years of creep. The predicted total settlement at the end of 50 years is 94 mm (see Fig. 7), which lies well within the allowable serviceability limit prescribed by IS 1904, indicating satisfactory long-term performance of the foundation system.

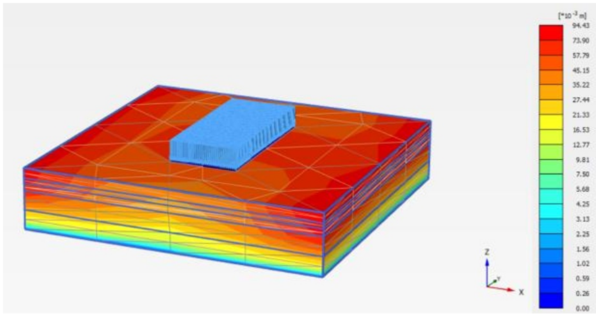

Fig. 7. Total settlement of the pile-raft foundation at the end of 50 years 94 mm including creep.

6 Conclusions

This study demonstrates that accurate long-term settlement prediction for foundations in the soft, compressible soils of Kolkata requires consideration of both consolidation and creep behavior, supported by reliable in-situ characterization.

Finite element analyses show that a raft foundation alone fails to meet serviceability criteria, with settlements far exceeding the permissible limit prescribed by IS 1904. Although a pile–raft system with 500 mm diameter piles effectively controls primary consolidation settlement, it becomes inadequate when creep is incorporated, leading to unacceptable long-term settlements. An enhanced pile–raft configuration with 600 mm diameter piles and increased spacing successfully limits total settlement within allowable limits over a 50-year service life.

The results highlight the necessity of incorporating advanced in-situ testing (DMT/DMT-A), time-dependent constitutive models (SS and SSC), and creep effects in foundation design for highly compressible clayey soils to ensure realistic and safe long-term performance.

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