Evaluating sampling quality and its impact on deformation properties of Coode Island Silt

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Abstract. This study investigates effects of sampling quality on the primary consolidation and secondary (creep) deformation behavior of Coode Island Silt (CIS), a problematic Australian soft soil. Samples collected using Block, BIT (modified fixed piston), and Shelby tube samplers were tested with Incremental Loading (IL) and multi-stage creep oedometer tests. Using the Lunne's criterion, Block samples were assessed as "Good to fair" quality ($\Delta e/e_0 = 0.061$), while BIT ($\Delta e/e_0 = 0.094$) and Shelby tube ($\Delta e/e_0 = 0.13$) were classified as "Poor". Reduced sample quality led to lower compression and creep indices (up to 38% and 26%, respectively, when compared against Block sample) and greater deviation from in-situ cone penetration correlated values. The analysis of a trial embankment demonstrated the significant effect of sample quality on the settlement predictions.

1 Introduction

Coode Island Silt (CIS) is a soft, Quaternary-aged soil that covers large parts of the Yarra Delta in Melbourne, Australia. Although referred to as silt, it is comprised of clays of high plasticity and characterized by high natural water content and low strength, which make construction on it highly challenging. The issues related to construction in CIS have been widely reported in previous studies [1–3]. These studies confirm that the clays of CIS are highly compressible, with settlements on the order of 150 mm under a 1 m fill and long-term settlements of 5–10 mm per year occurring at a nearly constant rate over more than 100 years [4], indicating substantial primary consolidation as well as significant secondary compression (creep). However, local practitioners have struggled to reliably predict the consolidation behaviour of CIS, and this has been speculated to be caused by sampling disturbance [5].

Sampling disturbance has long been recognized as a critical issue in obtaining reliable estimates of the deformation properties of soft soils. During retrieval, soil samples inevitably experience varying degrees of disturbance, which can alter their natural structure and in-situ stress state, resulting in samples of differing quality. Numerous studies have reported that sampling disturbance significantly affects the deformation behaviour of soft soils [6–10]. The effect of sampling quality is often more pronounced on deformation than on strength [11]. Therefore, given the natural sensitivity of CIS to deformation and the well-known construction challenges associated with it, understanding how sampling quality influences both primary consolidation and secondary compression (creep) in CIS is essential.

This study investigates the sampling quality effect on the primary consolidation and creep deformation response of CIS and demonstrates its impact on the settlement assessment of this highly compressible soil.

2 Tested Soil and Methods

The test site is located next to 59 Cook Street in Port Melbourne, Australia. To determine the depth of the CIS, two piezocone penetration tests (CPTu-01 and CPTu-02) were performed. The CPTu test results showed that CIS extends from 10 m to 22 m, which is consistent with previously reported CPTu profiles [2,5]. The similar CPTu results at the two locations confirmed the uniform stratigraphy, allowing for the retrieval of natural soil samples from a depth interval of 16.25–17.5 m in two boreholes (BH-01, BH-02) (Fig. 1a).

Samples were obtained using three types of samplers: a mini-block sampler (Block), a 100 mm diameter modified fixed piston sampler (BIT, named after Black In-situ Testing), and a 63 mm diameter Shelby tube sampler (Fig. 1b). The BIT sampler is designed to provide high-quality samples with a low area ratio (AR = 6%), while the Shelby tube has an AR of 13%.

After sampling, the specimens were properly sealed with wax. Block and Shelby tube samples were placed vertically in plastic drum barrels, while BIT samples were placed in foam boxes to minimize movement and disturbance during transport (Fig. 1c). The samples were then transported to the laboratory and stored in a high relative humidity environment (RH > 97%) for 20 months prior to testing. Literature suggests that the storage duration effects on the deformation

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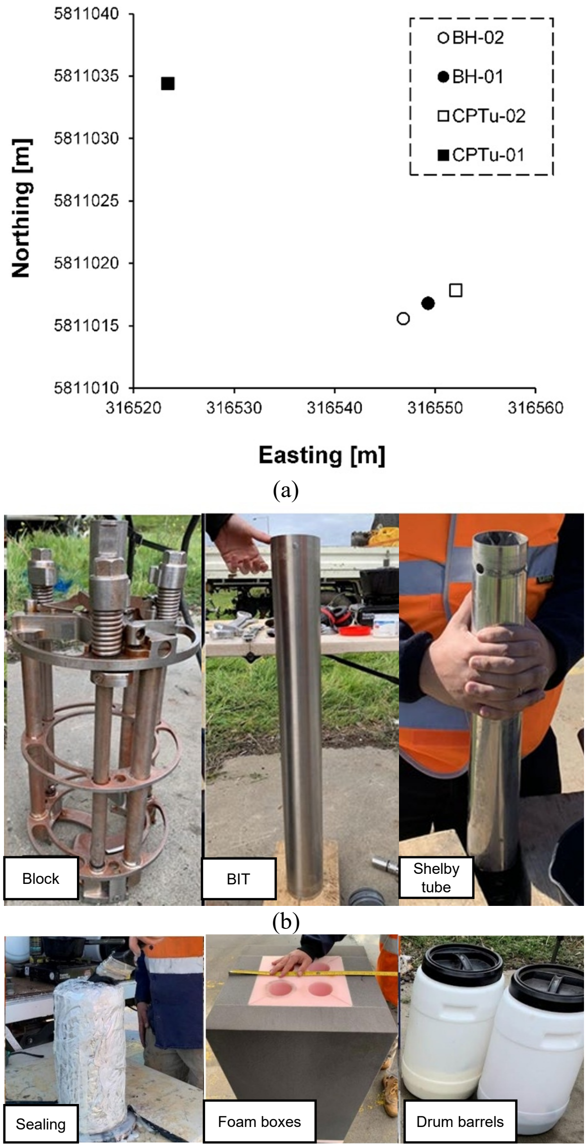
characteristics of soft soils depend on soil sensitivity and plasticity [12,13]. For low-plasticity soils, these effects can be significant; however, for high-plasticity clays, Ouyang and Pineda [14] reported that storage duration has minimal impact unless the samples are mechanically disturbed during penetration or extraction. Although not explicitly evaluated in this study, given the relatively poor quality of the BIT and Shelby tube samples (discussed in Section 3.2), incorporating storage effects could be an important aspect to address in future investigations.



(a)
(b)
(c)

Fig. 1. In-situ testing campaign: CPTu and borehole locations (a), sampling methods (b), and sample handling [15] (c).

To identify the suitable zones of relatively intact and disturbed soil within the samples, X-ray scans were conducted. The soil from disturbed zones was used for determining index properties while relatively intact soil was used for element tests to quantify sample disturbance effects.

The index properties of CIS were determined following relevant Australian and ASTM standards. The natural water content ranges from 57–65%, with a plasticity index (PI) of 56.6–58.4%, classifying the soil as a high-plasticity clay (CH) under the Unified Soil Classification System.

To quantify the sample disturbance effects on primary consolidation and creep deformation, two types of element tests were conducted on 63 mm diameter samples trimmed from the intact zones of the Block, BIT, and Shelby tube samplers: (1) incremental loading (IL) oedometer tests and (2) stepwise multistage creep (MSC) loading tests. For IL tests, a loading increment ratio (LIR) of 1 was adopted from 6.25 kPa up to 50 kPa, followed by an LIR of 0.3 up to 896 kPa. Unloading and reloading were then performed with an LIR of 0.5. The duration of each load increment was 2.5 hours, with the stress held constant overnight after every third increment. On the other hand, three MSC tests, were conducted at stresses of 0.9 to 2.2 (ratio of consolidation stress to in-situ vertical stress) and then unloaded to 263 kPa followed by recompression up to 1792 kPa. The loading durations were selected to allow for calculation of creep index over 1 log cycle.

3 Results and analysis

3.1 Compressibility response

Table 1 summarizes the deformation parameters determined from IL (peak compression index, $C_{c\text{-}peak}$; preconsolidation pressure, σ'_p; constrained modulus, M) and MSC (peak creep index, $C_{\alpha\text{-}peak}$) tests. The σ'_p is determined based on the work-based method [16].

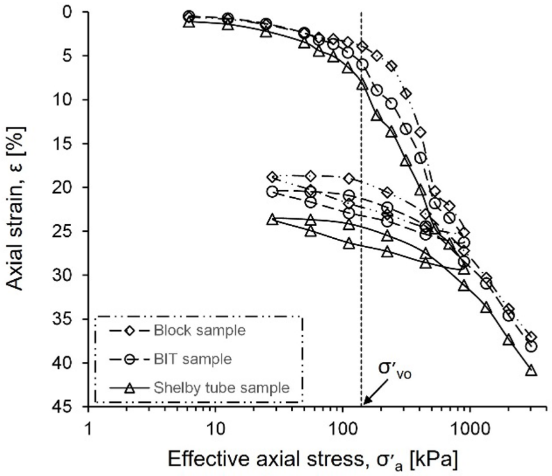
Table 1. Summary of measured deformation parameters.

Sample	$C_{c\text{-}peak}$	σ'_p [kPa]	M [MPa]	$C_{\alpha\text{-}peak}$
Block	1.59	263	6.7	0.046
BIT	1.19	214.9	2.42	0.036
Shelby tube	0.99	184.7	1.75	0.034

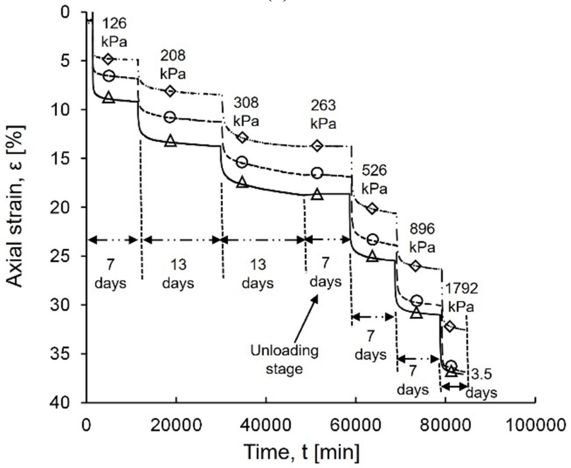
Fig. 2 compares the compressibility response of samples from the Block, BIT, and Shelby tube samplers based on the IL and MSC tests. In Fig. 2a, the Block sample exhibits a more rounded compression curve in the ε–log σ'_a space, whereas the curves for the BIT and Shelby tube samples are relatively flattened, indicating the effects of sampling disturbance. As highlighted in previous studies, the compression curve in the ε–log σ'_a space tends to move downward and flatten as sample quality decreases [16,17], affecting critical stress history estimates such as the overconsolidation ratio (OCR), defined as the ratio of σ'_p to in-situ effective stress σ'_{vo}, and oedometer stiffness (M). The OCR decreases from 1.84 for Block samples to 1.31 for Shelby tube samples (28.8% reduction). Similarly, M decreases from 6.7 MPa to 1.75 MPa (73.9% reduction).

Fig. 2b shows the accumulated strain for each creep stress (σ'_{cr}) over different durations. The σ'_{cr} of 126 kPa, 526 kPa, and 896 kPa were applied for 7 days, while 208 kPa and 308 kPa were applied for 13 days. In addition, an initial stress of 6.2 kPa was applied for 24 hours to allow for saturation, and 1792 kPa was applied for 3.5 days only. The results show that, for a given σ'_{cr}, the Shelby tube sample accumulates more strain, while the Block sample exhibits the lowest accumulated strain under the same conditions.

Overall, these observations qualitatively indicate that the Block sample has the highest sample quality, followed by the BIT and then the Shelby tube samples. This is further confirmed through quantification of sample quality by Lunne et al. [6] criterion in Section 3.2.



(a)



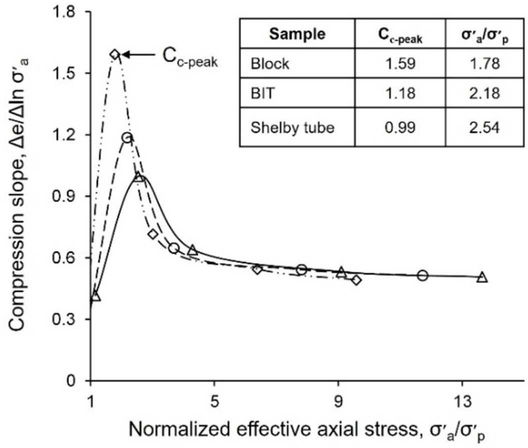
(b)

Fig. 2. Compression response of CIS under IL and MSC tests: ε vs σ′a (a), and t (b).

whereas Shelby tube samples, being the most disturbed, show the lowest $C_{c\text{-}peak}$ (0.99) and $C_{\alpha\text{-}peak}$ (0.034).

3.2 Sampling quality assessment

Different criteria have been proposed to evaluate sample quality, but the method by Lunne et al. [6] remains the most widely accepted [20,21]. According to this criterion, sample quality is quantified based on the change in void ratio required to reconsolidate the sample.



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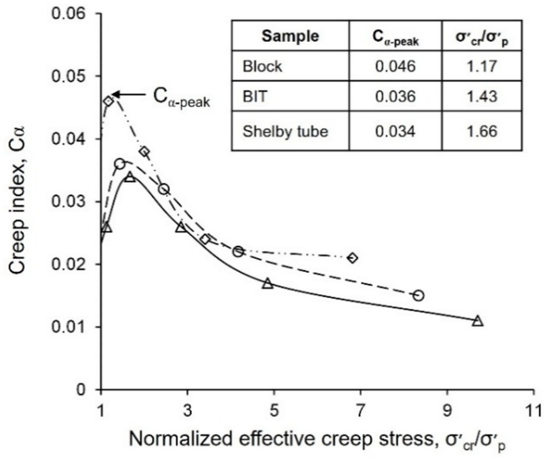


(b)

Fig. 3. Stress dependent response of CIS: $\Delta e/\Delta \ln \sigma'_a$ vs σ'_a/σ'_p (a), and C_α vs σ'_a/σ'_p (b).

Fig. 3 shows the stress-dependent compression response of CIS under IL and MSC tests, with the compression slope ($\Delta e/\Delta \ln \sigma'_a$) and creep index ($C_\alpha = \Delta e/\Delta \log t$) plotted against the normalized stresses σ'_a/σ'_p and σ'_{cr}/σ'_p, respectively. Both parameters increase sharply in the post-yield region ($\sigma'_a/\sigma'_p > 1$ and $\sigma'_{cr}/\sigma'_p > 1$), reach a peak at certain stress levels, and then decrease due to bond degradation and fabric rearrangement [19].

Peak compression slopes ($C_{c\text{-}peak}$) occur at σ'_a/σ'_p values of 1.78, 2.18, and 2.54 for Block, BIT, and Shelby tube samples, respectively [Figure 3(a)], while peak creep indices ($C_{\alpha\text{-}peak}$) occur at 1.17, 1.43, and 1.66 (Fig. 3b). Block samples, being the least disturbed, exhibit the highest $C_{c\text{-}peak}$ (1.59) and $C_{\alpha\text{-}peak}$ (0.046),

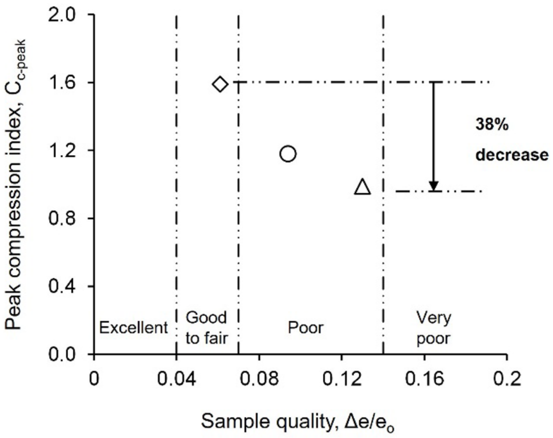
to its in-situ vertical effective stress, normalized by the initial void ratio ($\Delta e/e_o$). For soils with an OCR less than 2, the sample quality is classified into four categories: Excellent ($\Delta e/e_o < 0.04$), Good to fair ($\Delta e/e_o = 0.04$-0.07), Poor ($\Delta e/e_o = 0.07$-0.14), and Very poor ($\Delta e/e_o > 0.14$).

Fig. 4 compares the sample quality index ($\Delta e/e_o$) of the tested specimens against the peak compression index ($C_{c\text{-}peak}$) and peak creep index ($C_{\alpha\text{-}peak}$). Results show that the Block sample falls in the Good to fair category ($\Delta e/e_o = 0.061$), while the BIT ($\Delta e/e_o = 0.094$) and Shelby tube ($\Delta e/e_o = 0.13$) samples fall in the Poor category. When the sample quality decreases from 0.061 to 0.13, $C_{c\text{-}peak}$ decreases by 38% and $C_{\alpha\text{-}peak}$ by 26%.

These findings highlight the significant influence of sampling quality on both primary consolidation and creep deformation in CIS.

4 Implications of sampling quality

In this section, the implications of sampling quality are examined by comparing deformation properties obtained from different samplers with their corresponding in-situ values estimated from CPTu correlations. The influence of sampling quality on geotechnical design is illustrated through a trial embankment, by comparing settlement predictions using deformation parameters obtained from three samples of varying quality.



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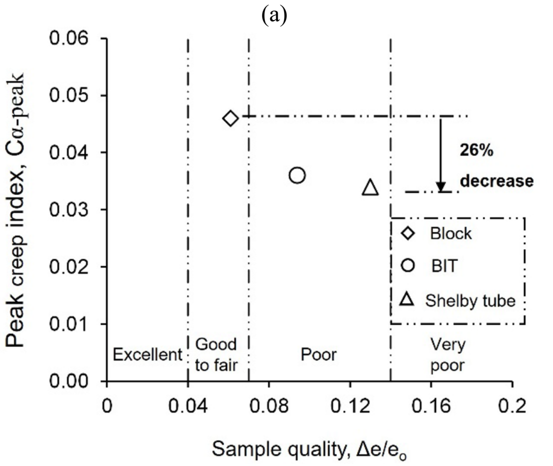


(b)

Fig. 4. Effect of sample quality: $\Delta e/e_o$ vs $C_{c\text{-peak}}$ (a), and $C_{\alpha\text{-peak}}$ (b).

4.1 Comparison with in-situ data

The values of σ'_p and M obtained from Block, BIT, and Shelby tube samples are compared with those estimated from CPTu-based correlations using Eqs. (1-2) [2,22].

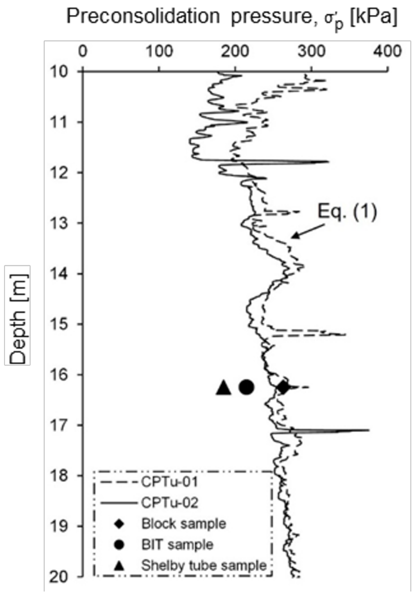
$$\sigma'_p = 0.33(q_t - \sigma'_{vo}) \quad (1)$$

$$M = \alpha q_t \quad (2)$$

Where q_t is corrected cone tip resistance, σ'_{vo} is effective in-situ stress, α is a factor typically ranging between 10 and 15 for clays. Herein, α is taken as 10 for CIS [23].

Notwithstanding the accuracy of the CPTu correlations, results demonstrate that in-situ values of σ'_p and M from CPTu-01 and CPTu-02 are higher than the laboratory measured values, with high-quality Block samples showing closer alignment (Fig. 5).

As the quality of the sample decreases, difference with CPTu data become more pronounced. For σ'_p, the highest quality Block sample produced a value (263 kPa) that is 12% difference from the CPTu estimates, while the lowest quality Shelby tube sample (184.7 kPa) shows a more significant difference of 23% (Fig. 5a). For M, Block sample (6.7 MPa) deviates by 40% from the CPTu-02 value (9.72 MPa), whereas Shelby tube sample differs by 84% (Fig. 5b). These results show that lower-quality Shelby tube samples exhibit large discrepancies with in-situ data, thus caution is required when applying them.



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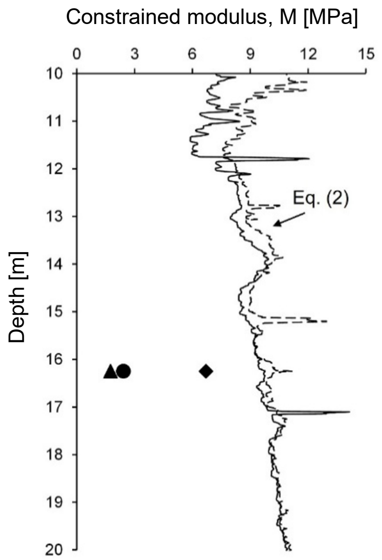

(b)

Fig. 5. Comparison of laboratory measured parameters with in-situ values determined from CPTu correlations: Yield stress (a), and Constrained modulus (b).

4.2 Consequence for geotechnical design

To evaluate the practical implications of sampling quality, a settlement analysis of a trial embankment was performed based on deformation parameters obtained from laboratory tests on samples recovered using the three different samplers (Table 1). The trial embankment has a base length of 22 m, a crest length of 12 m, and a slope of 2H:1V (H is horizontal and V is vertical) (Fig.6). A simplified single-layer soil stratigraphy with a thickness of 10 m was adopted for the analysis. A surcharge loading of 170 kPa, increasing to 310 kPa at the middle of the clay layer, was assumed to represent a lightly overconsolidated case. Note that a similar analysis was previously conducted by Lim et al. [24] for Ballina clay, and the trial embankment geometry in this study is adapted from their design.

The total settlement (S_t) of the soil layer is the sum of primary (S_p) and secondary (S_c) settlements, expressed as Eq. 3. The primary settlement for a lightly OC state ($\sigma'_{vo} < \sigma'_p < \sigma'_{vo} + \Delta\sigma$) can be estimated using Eq. 4, while the secondary settlement can be determined from Eq. 5.

$$S_t = S_p + S_c \tag{3}$$

$$S_p = \frac{\mathrm{H_s C_r}}{1+e_o}\log\left(\frac{\sigma'_p}{\sigma'_{vo}}\right) + \frac{\mathrm{H_s C_c}}{1+e_o}\log\left(\frac{\sigma'_{vo}+\Delta\sigma}{\sigma'_p}\right) \tag{4}$$

$$S_c = \frac{C_\alpha}{1+e_o}\mathrm{H_s}\log(\mathrm{t/t_p}) \tag{5}$$

Where t is time for settlement, t_p is the time at the end of primary consolidation, and H_s is soil layer thickness.

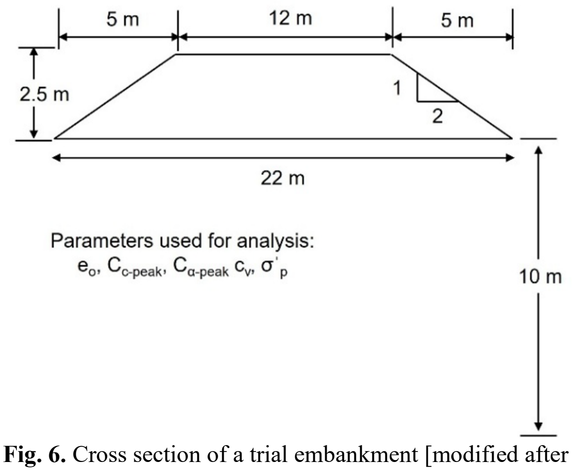

Fig. 6. Cross section of a trial embankment [modified after Lim et al. [24].

Fig. 7 compares the predicted settlement beneath the embankment using parameters obtained from IL and MSC tests for each sampler (Table 1) for a time period up to 10 years. The results show that the largest total settlement is predicted when using the parameters from the Block sample, which was classified as having "Good to fair" quality, The predicted settlements for the BIT and Shelby tube samples show little difference between them, yet both are significantly lower than the settlement predicted from the Block sample, which is consistent with their "Poor" sample quality classification. Compared to the Block sample, the predicted settlement after 10 years from the Shelby tube sample is 31% lower. Lim et al. [24] reported similar findings for Ballina clay and highlighted that the underestimation of settlement beneath embankments on soft clay is often observed in Australia due to poor sampling practices, particularly when using Shelby tube samples.

The higher predicted settlement from the Block sample is mainly due to its higher coefficient of consolidation (c_v) and $C_{c\text{-peak}}$, both of which increase settlement. Although the Block sample also has a higher σ'_p, which would normally reduce settlement, the overall settlement behavior is controlled by the combined effects of c_v, $C_{c\text{-peak}}$, and σ'_p. In this case, the influence of σ'_p is less significant within the analyzed time period. Its effect may become more significant for soils with different stress histories or over longer durations.

Overall, the results indicate that total settlement predictions are highly influenced by sampling quality. Although the present analysis is based on a simplified trial embankment geometry and soil stratigraphy, the reliability of these predictions should ideally be validated using field settlement measurements from field embankments. Such field data would provide valuable insight into the reliability of laboratory-derived parameters.

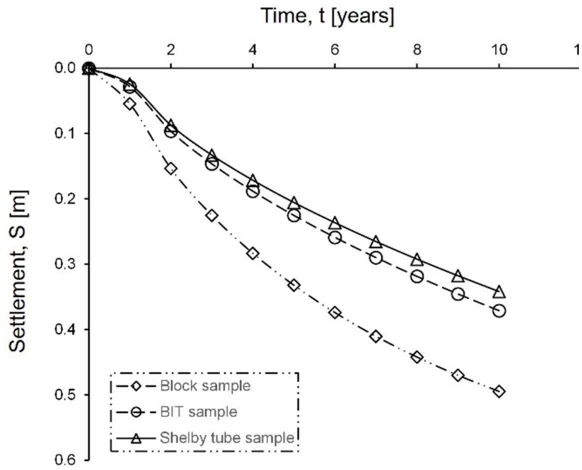

Fig. 7. Predicted embankment settlement.

5 Conclusions

This study investigates the impact of sampling quality on the primary consolidation and creep deformation response of Coode Island Silt (CIS), a problematic soft soil in Melbourne, Australia. Samples from the same depth range were collected using three sampling methods: Block, Fixed piston (BIT), and Shelby tube. The effect of sampling quality on deformation response was evaluated through incremental loading (IL) and multi-stage creep oedometer tests conducted on specimens taken from relatively intact regions identified via X-ray scans, with sample quality determined using Lunne's $\Delta e/e_o$ criterion based on IL tests. Results show that the Block sample had the highest quality ($\Delta e/e_o$ =

0.061, good to fair), while BIT ($\Delta e/e_o$ = 0.094, poor) and Shelby Tube ($\Delta e/e_o$ = 0.13, poor) samples were of lower quality. Reduction in sample quality from Block to Shelby tube specimens led to a significant decrease in peak compression index (up to 38%) and peak creep index (up to 26%). The laboratory measured parameters from specimens of varying quality were compared with in-situ cone penetration test correlated values, revealing greater difference with decreasing sample quality. The implications of sampling quality in geotechnical design are illustrated through settlement analysis of a trial embankment, with the lower quality BIT and Shelby Tube samples underestimate the settlement of CIS.

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