Assessment of soft clay characteristic after 40 years of treatment using preloading with wick drains

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ABSTRACT: It is not always easy to accurately predict the ongoing improvement of the strength and compressibility of soft clays after preloading, due to lack of long-term field records. A site with up to 10m thick soft clay in Southeast Queensland, Australia, was treated using preloading/surcharge with wick drains in 1980s. In 2020, the site was re-investigated after 40 years of treatment as a part of the motorway upgrade project. The soil strength and compressibility were studied based on results of a comprehensive geotechnical investigation, including SPTs, CPTs, FVS and oedometer tests. Test results were compared to the previous results obtained in 1980s and analysed using Hansbo's method in which smear zone and construction staging was taken into account. The 1979 and 2020 geotechnical investigation results indicated that wick drains with preloading improved the soil strength from soft to firm. Pre-consolidation pressure was increased due to the embankment fill, while no significant change was identified in compression index (C_c), re-compression index (C_r) and OCR. A change of coefficient of consolidation was also observed. Comparison of calculated and actual settlement values demonstrated that the initial design intention of the ground improvement had been achieved. The correlation between unified undrained shear strength (S_u/σ'_{v0}) and OCR was also studied for future design practice.

KEYWORDS: Road embankment; ground improvement; soft soil; preloading; wick drains

1 INTRODUCTION

Geotechnical design for road widening projects in soft soil areas needs to take into account the historical ground improvement and in-service loading, as part of its stress history, to establish a realistic ground model. For this purpose, the strength and compressibility of soft soil under an embankment after years of in-service life were studied based on a road project in Southeast Queensland, Australia.

As a classical topic in geotechnical engineering, soft soil properties and associated ground improvement technologies (e.g., preloading with wick drains) have been studied for decades (Sharma et al, 2001; Indraratna et al, 2005). Some recent research included a performance monitoring and numerical assessment of a 2.8 m high test embankment with vertical drains on soft highly compressible clays in Mexico (Lopez-Acosta et al, 2019; Espinosa-Santiago and Lopez-Acosta, 2020). The monitoring data during a four year and two-month observation period (1525 days) were analysed and compared to a long-term numerical analysis. In some cases, field vane shear tests were performed before and after ground improvement to study the strength gain (Shibuya and Hanhh, 2001; Oh et al, 2004), however these tests were usually carried out at about one year after the treatment (i.e. when >90% consolidation degree has been achieved) rather than after 40-year service life. Although it is a common and reasonable approach to focus on soil properties prior to ground improvement to estimate the stability and deformation during and post construction, to accurately interpret the geotechnical model under an existing embankment is difficult. This is mainly due to the segregated nature of the investigation data and limited knowledge of the site. However, as the demand for road upgrade projects increases, a more comprehensive understanding on the evolvement of ground behaviour under existing embankment is required, to support an economical future design and reduce engineering risks.

The case study presented in this paper is based on a project which required widening a motorway to a minimum of three (3 no.) lanes in both directions. The alignment traverses a creek and its associated flood plain, where a highly compressible estuarine alluvium of up to 10m thick was previously treated using preload with wick drains in 1980s. This provided a great opportunity to examine the soft soil properties after 40 years of ground treatment. The improved soft soil stratum in the critical section (i.e. with the thickest and most compressible soft soil) at the creek was investigated prior to the ground improvement design in 1979. Investigation results and available historical documentation at Department of Transport and Main Roads (TMR) were re-examined. Additional analyses were also performed to better understand the strength and compressibility properties of the previously treated soft soil over 40-year service life.

2 HISTORICAL GROUND IMPROVEMENT

The existing motorway was constructed along the former railway corridor in the 1980s. The soil profile at the site was presented mainly as three strata: approximately 3m thick very loose to loose sand, followed by an up to 10m thick soft to firm clay or silty clay, overlying residual soil or weathered rock.

The preliminary investigation in 1979 indicated that additional treatment was required for a two-year construction program and a maximum tolerable in-service settlement of 100mm (settlement criteria adopted in 1979). A special performance criterion was defined within the limits of the creek cross-drainage, where nominated consolidation degree needed to be achieved within one year to facilitate the installation of the permanent drainage structure. As floating culvert was adopted in the historical design, the timing of the culvert installation was verified based on the observation of differential settlement on the embankment cross-section during the first year.

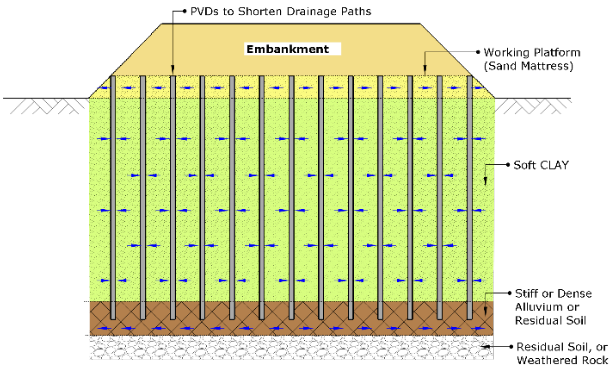


Figure 1. Drainage path with vertical drains installed under embankments

To accelerate soil consolidation, preloading with wick drains was proposed to provide horizontal drainage thus the drainage path could be significantly reduced, as illustrated in Figure 1. With the granular working platform at top, the pore water could be drained to the outside of the embankment efficiently.

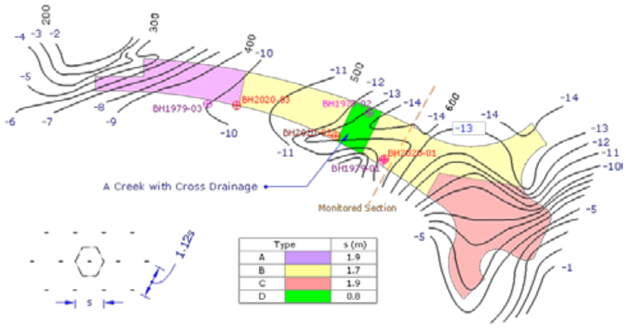


Figure 2. Wick drains pattern, spacing and base level of installation in 1980s

The Franki Wick Drain (100 mm wide and 3 mm thick), with a corrugated PVC core covered with a non-woven filter fabric was used in 1979. In total 9000 drains with the lengths ranging from 5 m to 16 m were installed. The reduced level (RL) of the base of treatment, the installation pattern, and spacing of wick drains are shown in Figure 2. The ground improvement was intended to reduce post-construction settlement to no greater than 100mm, and the target of the degree of consolidation was 90% prior to the installation of pavement, with estimated settlement of up to 1m. The construction of the existing embankment was completed in 1981.

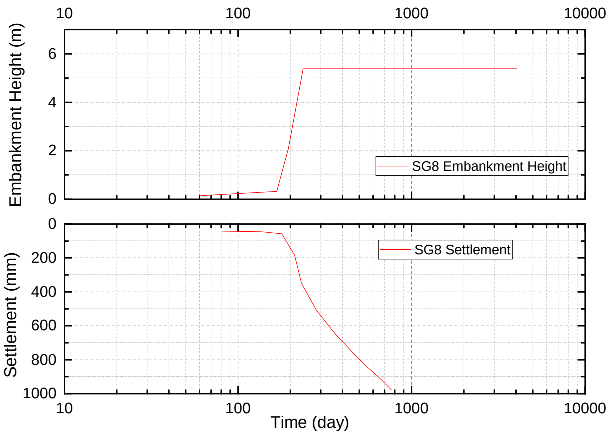


Figure 3. Settlement monitoring data compared to embankment height

The performance of the wick drains was assessed by instrumentation monitoring (14 no. water overflow settlement gauges, 15 pneumatic piezometers, 4 inclinometers and 3 settlement profile gauges) installed under the roadway embankment. One settlement gauge (SG8) was installed below the central line of the cross section at RL +2m, on 24th November 1980. The settlement monitoring data were obtained from a published paper and TMR reports. The results from the settlement gauge SG8 compared to embankment (fill) height were plotted as shown in Figure 3.

3 SOIL PROPERTIES COMPARISON

In 2020, comprehensive geotechnical investigations were conducted prior to the upgrade of this section. Boreholes and Cone Penetration Tests (CPTs) were carried out on the shoulder of motorway.

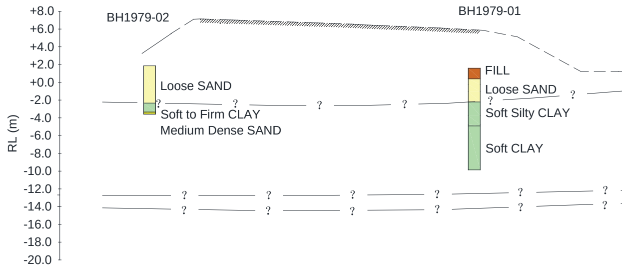
3.1 *Investigation locations*

The approximate borehole locations are illustrated in Figure 2. BH1979-01 and BH2020-01 were conducted in close proximity to each other, while other boreholes and CPTs were scattered throughout the section.

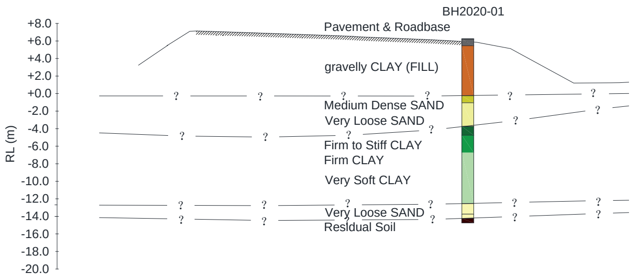
Three boreholes in 2020 (i.e., BH2020-01, BH2020-02 and BH2020-03) were drilled immediately after the CPTs had been completed, at the same locations to depths beyond where the CPTS were terminated.

The interpreted soil profiles across the creek, based on geotechnical investigation in 1979 and 2020, are illustrated in Figure 4. The base of BH1979-01 and BH1979-02 were at RL -9.9m and RL -3.6m, respectively, which did not reach the bottom of alluvium. A comparison of 1979 and 2020 results indicated that the site consist of soft clay up to 10 m and it becomes thinner and interbedded with more sandy material towards the northern end of the site.

The interpreted soil profiles are reasonably consistent between 1979 and 2020. The pavement and embankment fill identified in BH2020-01 was constructed in 1980s. No borehole was conducted outside the embankment zone in 1979.



(a) 1979 investigation



(b) 2020 investigation

Figure 4. Soil profile interpreted based on 1979 and 2020 investigations

3.2 *Strength*

Three types of field test results were available for assessment of soil strength / consistency: Cone Penetration Tests (CPTs), Standard Penetration Tests (SPTs), and Field Vane Shear (FVS) tests. Among all the available information, CPT tests carried out in 2020 prior to boreholes were considered more reliable, as SPTs and FVS might have been impacted by soil disturbance associated with CPTs.

The CPT test result at BH2020-01 was used to assess the undrained shear strength (S_u) by using the formula proposed by Robertson et al (2022) below

$$S_u = \frac{q_t - \delta_v}{N_{kt}} \quad (1)$$

where, N_{kt} = 16 according to Robertson et al (2022) and local experience.

The S_u assessed by CPTs and by FVS were plotted against the elevation in Figure 5. The CPT test results were reasonably consistent compared with the FVS, with noticeable discrepancy at two points. Based on test results, the S_u of soft clay had been improved from around 15kPa to 45kPa, due to the action of the preloading/wick drains.

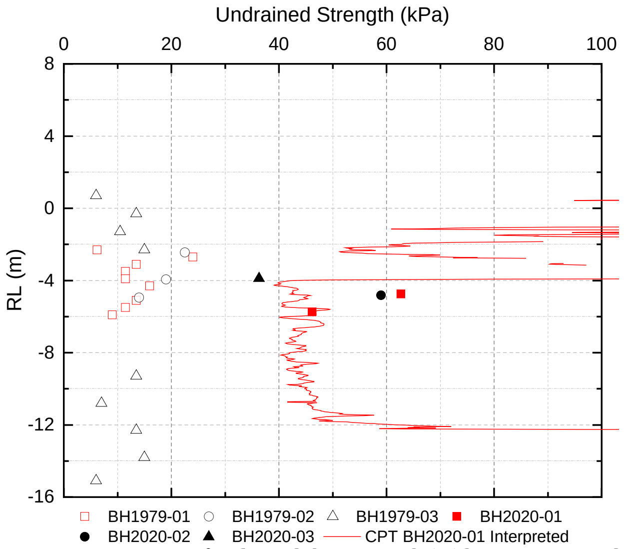


Figure 5. Comparison of undrained shear strength (S_u) between 1979 and 2020 investigations

3.3 *Compressibility*

Oedometer tests were carried out in both 1979 and 2020 investigations. The raw data of all available test results were processed using Boone's method (Boone, 2010). The obtained compression index (C_c) and re-compression index (C_r) are plotted in Figure 6.

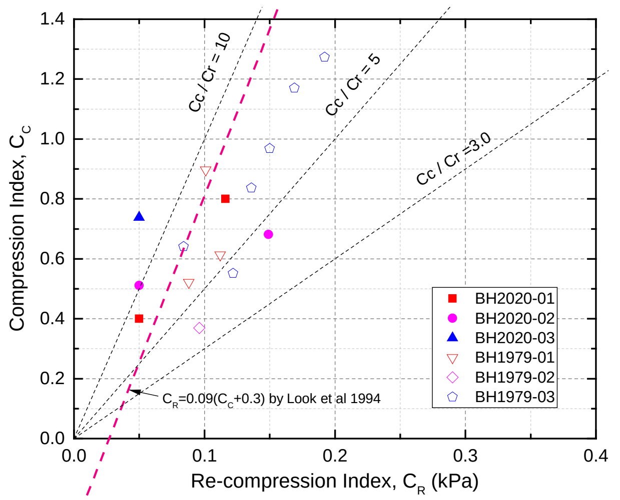


Figure 6. Compression / re-compression index comparison between 1979 and 2020

Based on test results, the range of compression index values was 0.37-1.27 in 1979, compared to 0.40-0.80 in 2020. The highest four values (0.84-1.27) were obtained at shallow depth (RL -2.4m to RL -3.3m) of BH1979-03, where localized waterlogged material might be encountered. The compression index values for BH2020-01 and BH2020-02 were observed to be in a similar range with BH1979-01 and BH1979-02. Negligible change in C_c is deemed reasonable, as C_c represents the slope of virgin compression that may be linear within a normal stress range (Mitchell, 2005), except for highly sensitive clay (Boone, 2010). This departs from the general practice that corelate C_c to soil consistency. Therefore, it is suggested that this type of correlation should be assessed on a case-by-case basis.

Re-compression index values were observed to be 0.08 - 0.19 in 1979, and 0.05-0.15 in 2020. The tested values fall into a similar range based on two site investigations. The ratios of C_c to C_r in both site investigations were mostly in the range of 5 – 10. A correlation between C_c and C_R for Queensland soils proposed by Look and Williams in 1994 was plotted against the data and demonstrated a good agreement.

No significant changes were observed in C_c and C_r, while it is reasonable that minor discrepancy was encountered due to sampling and testing procedure (Bilgin and Tsimbelman, 2017). The change in soil compressibility is mainly dependent on its stress history (pre-consolidation pressure and/or OCR), which is discussed below.

3.4 *Over-Consolidation Ratio (OCR)*

Pre-consolidation pressures were interpreted by using Boone's method based on the available oedometer test results. The pre-consolidation pressure (P'_c) versus depth, and P'_c versus vertical effective stress (σ'_{v0}) are plotted in Figure 7(a) and 7(b), respectively.

As shown in Figure 7(a), the pre-consolidation pressure was increased from 57-79kPa to 123-196kPa at various depths. Due to load from the embankment fill, the vertical effective stresses of all samples were increased from 29-54kPa to 53-147kPa, according to Figure 7(b). It can be also observed from Figure 7(b) that the OCR values ranged between 1.1 to 2.9, and no significant increase was observed. This is reasonable, as both the pre-consolidation pressure and the effective vertical stress of the soft clay layer have been increased simultaneously.

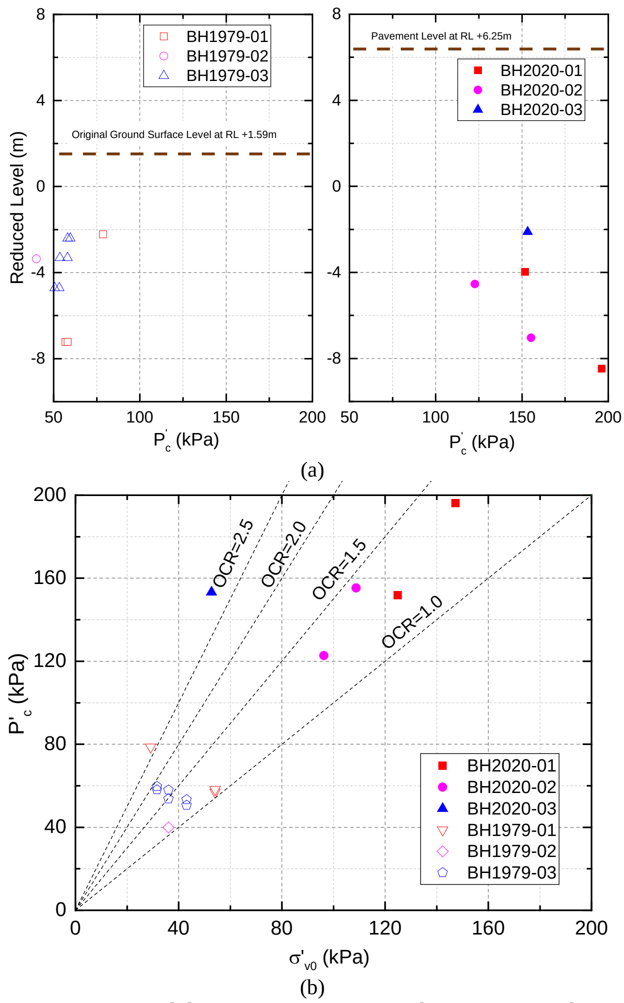


Figure 7. Pre-consolidation pressure comparison between 1979 and 2020 investigation

3.5 Coefficient of Consolidation (C_v)

The coefficient of consolidation (C_v) was determined from oedometer testing in both 1979 and 2020. The samples were prepared with various specimen diameters (generally about 50mm or 76.2mm) in 1979. No description of sampling diameter was provided in 2020 test results; however, the specimen diameter can be back calculated to about 50mm. All C_v results from oedometer testing are plotted in Figure 8.

A series of in-situ pore pressure dissipation tests were conducted during CPT tests in 2020, and the results indicated C_h between 16 to 49 m^2/year. The C_h from CPT tests are not included in this analysis as no CPT tests were carried out in 1979 for comparison.

In general, the C_v values obtained from oedometer test in 2020 (average 2.0 m^2/yr) are higher than those determined in 1979 (average 1.2 m^2/yr). Theoretically, this is unlikely as C_v decreases with reducing permeability when void ratio becomes smaller. Possible reasons of this discrepancy are:

- Change of the soil properties due to wick drains installation in 1980s.
- Variability of soil properties, as these boreholes were not drilled at the same location.
- Soil disturbance during sampling.

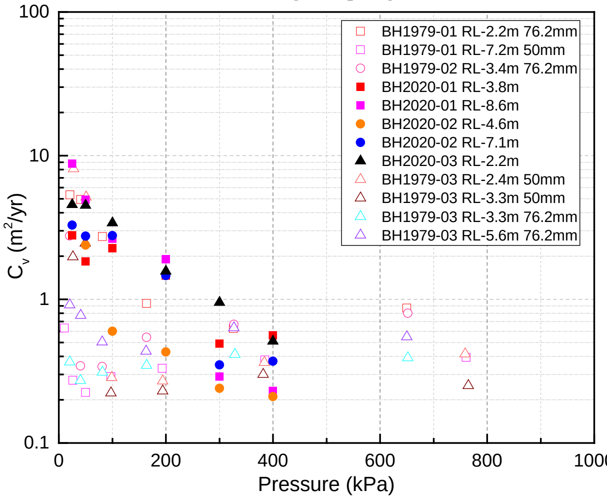


Figure 8. Coefficient of consolidation comparison between 1979 and 2020 investigation

3.6 Statistical Analysis

A statistical analysis was performed on S_u, C_c, C_r, C_v, and OCR values which were obtained from both field and laboratory testing. The mean, median and standard deviation (Std Dev) were calculated and presented in Table 1.

Table 1. Statistical analysis results of key parameters.

Parameters	Mean		Median		Std Dev	
	1979	2020	1979	2020	1979	2020
S_u (kPa)	13.0	47.9	13.5	44.9	4.9	12.2
C_c	0.784	0.626	0.641	0.681	0.295	0.166
C_r	0.125	0.083	0.112	0.050	0.036	0.047
C_v (m^2/yr)	1.16	2.02	0.36	1.57	1.75	1.93
OCR	1.5	1.6	1.2	1.3	0.5	0.7

The results of the statistical analysis confirmed the above-mentioned observations, as summarised below:

- S_u (mean) was improved significantly, from 15kPa to 45kPa.
- No remarkable improvement in compression index and re-compression index (mean value).
- An increase of coefficient of consolidation was observed based on laboratory testing results.
- No significant change was observed in OCR (i.e., pre-consolidation pressure was increased proportionally with increased effective stress under embankment load as expected).

4 ANALYSIS AND RECOMMENDATIONS

The settlement and strength gain within the soft clay layer were analysed at the monitored section (as shown in Figure 2) with geotechnical investigation data and instrument monitoring records. Figure 2 also indicated that BH1979-01 and BH2020-01 were drilled in close proximity to the monitored section.

The wick drains at this section were installed to around 13 to 14m below the ground level, with spacing of 1.7m in triangular pattern, as shown in Figure 2. The maximum embankment height at this location is around 5.4m. Based on the recorded construction staging (Figure 3) and mean values of 1979 investigation (Table 1), the settlement was calculated, using Hansbo's method (using Settle3D). A smear zone with 90% permeability of outer zone, and in diameter of 2 × equivalent diameter of wick drains was assumed in the analysis. The comparison between the measured and calculated values are illustrated in Figure 9. It can be seen that there is generally good agreement between the values.

Although monitoring data after 1983 is not available, to the author's knowledge, there was no settlement issue during the 40 years in-service period. Therefore, it is reasonable to conclude that the initial settlement design intention has been achieved.

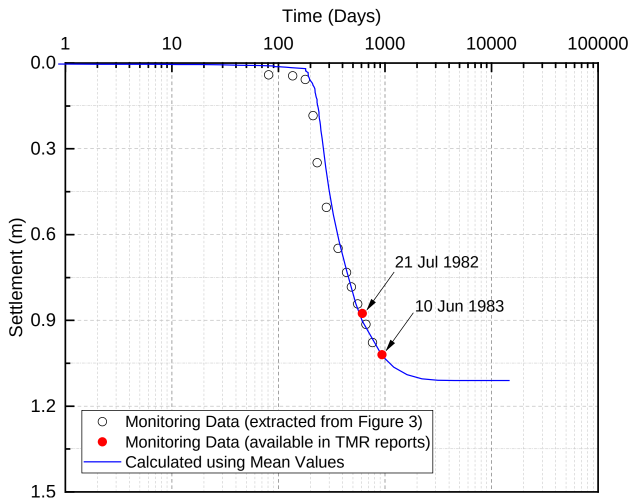


Figure 9. Comparison of calculated and monitored settlement

In addition to settlement, the strength gain during the ground improvement is studied herein with the above-mentioned parameters. One of the accepted methods to estimate S_u under embankment is SHANSEP procedure (Ladd, 1974), which has been verified in a case study from Bangkok (Shibuya, 2001). This method is based on the observation that the results of laboratory tests on clay samples with the same OCR, but different pre-consolidation stress, exhibit very similar strength and stress-strain characteristics when normalised with respect to the consolidation stress. The S_u parameter can be correlated to the effective stress and OCR. This method has been recommended in BS8002, using the following formula:

$$\frac{S_u}{\sigma'_v} = k_1 OCR^{k_2} \tag{2}$$

where, S_u is the characteristic undrained shear strength, σ'_v is effective stress, k_1 and k_2 are constants (may be taken as 0.23±0.04 and 0.8, respectively, according to BS8002)

The results from the laboratory test and CPT test at BH2020-01 are plotted against the unified curves reported in Ladd's paper and BS8002 methods in Figure 10. Most of the test results were enclosed in the reported correlations, with only few points falling outside. It was also observed that BS8002 could provide a reasonably conservative estimation of S_u.

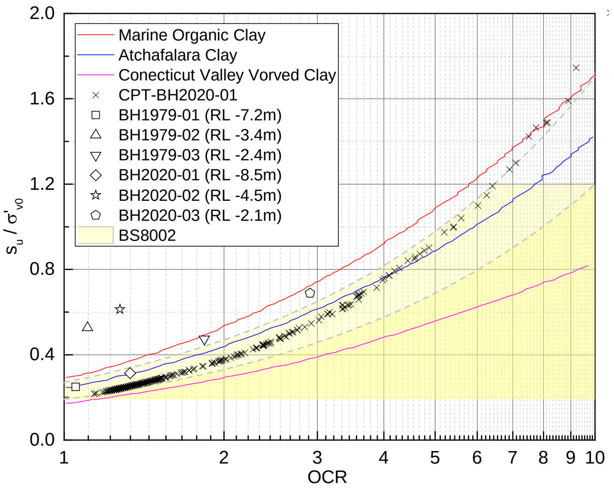


Figure 10. Correlation between unified S_u and OCR

5 CONCLUSIONS

The results of geotechnical investigations carried out at a soft soil site in 1979 and 2020 were reviewed comprehensively to study the improvement of soil properties by wick drains over 40-year in-service load. The following conclusions can be drawn based on a series of analyses:

(1) after ground improvement and 40 years under in-service load: S_u was increased from soft to firm; no significant change was identified in compression index (C_c), re-compression index (C_r) and OCR (pre-consolidation pressure increased proportionally with effective vertical stress); marginal increase of coefficient of consolidation was observed.

(2) the settlement was calculated by using mean parameters obtained in 1979 and compared to available monitoring data. The calculated settlement agrees well with measured value. To the author's knowledge, no detrimental embankment settlement issue has been reported during the 40 years in-service period. It is reasonable to conclude that the initial design intention has been achieved.

(3) the strength gain can be estimated by using reported correlation between unified strength (S_u/σ'_{v0}) and OCR. The comparison in this case study indicated that BS8002 method provided a reasonably conservative estimation.

It should be noted that, the opinions expressed in this paper are those of authors and does not necessarily represent the views of the Department.

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