Engineering Research Journal
journal homepage: https://erj.journals.ekb.eg/

Reliability Analysis Methodology and Review on Design of Wick Drains in Soft Clay

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Abstract. This study outlines the current advancements in designing soil improvement systems utilizing preloading and prefabricated vertical drains (PVDs) in large soft soil deposits. Settlement values often exhibit significant variability due to uncertainties, particularly those associated with over-consolidation, compressibility characteristics, and the stratification of clay layers. Accurately quantifying these uncertainties poses a considerable challenge because of the typically limited and inconsistent data available.
To address these uncertainties, reliability analysis can be employed, allowing the estimation of the probability distribution of consolidation settlement rather than relying on a single deterministic value. This probabilistic approach provides valuable insights and a more comprehensive understanding of the outcomes. Stochastic methods, such as Monte Carlo simulations (MC), are commonly utilized in reliability analysis. These simulations involve selecting random values for input variables by constructing models that represent potential outcomes. By doing so, Monte Carlo simulations assess the impact of uncertainty and risk on predictions, thereby enhancing accuracy.
This paper provides state of the art for design of wick drains. In addition, this paper proposes a detailed methodology for conducting reliability analysis in the design of wick drains. The methodology incorporates soil variability and settlement monitoring data to improve the precision of settlement predictions for structures.

Keywords: Prefabricated vertical drains, Monitoring, Monte Carlo simulation.

1 Introduction

Soft clay soils are found across the globe, posing significant challenges due to their high compressibility and low bearing capacity [11, 39, 44, 45]. To address these challenges, various soil improvement techniques can be explored to mitigate the unfavorable properties of soft clay [3]. The primary objective of soil improvement is to manage structural deformations on soft clay foundations. The preloading technique is commonly employed in conjunction with vertical drains to expedite the consolidation process. This is particularly important because the low permeability of soft clay results in extended consolidation periods when preloading is used without drains.

DOI: 10.21608/erj.2025.341583.1151
Received 03 December 2024; Received in revised form 03 December 2024; Accepted 16 February 2025

Vertical drains can be constructed by drilling and backfilling with materials such as gravel, sand, or stones, or by using prefabricated synthetic drains (PVDs) [7, 12, 14, 16, 19, 20, 22, 23, 25, 28, 34, 43]. The integration of preloading with prefabricated vertical drains has recently emerged as one of the most efficient and cost-effective methods for improving soft clay soil [18]. The primary purpose of installing vertical drains is to shorten the drainage paths, enabling water in the clay to flow laterally towards the drains rather than vertically over the full thickness of the clay layer. When single drainage is applied, the water must travel the entire thickness of the clay layer, while with double drainage, the path is halved [17]. Essentially, the combination of preloading and prefabricated vertical drains accelerates the consolidation of the soft clay layer prior to construction, thereby reducing post-construction settlement. The degree of consolidation at time t is estimated using Carrillo's equation [10]:

$$\mathrm{U(t)} = 1 - [1 - \mathrm{U_v(t)}][1 - \mathrm{U_h(t)}] \qquad (1)$$

Where U_t is the degree of consolidation, U_v is the degree of vertical consolidation and U_h is the degree of horizontal consolidation.

The degree of vertical consolidation U_v at time t is estimated using Terzaghi's equation [42]:

$$\mathrm{U_v(t)} = 1 - 8\sum_{i=0}^{\infty} \frac{exp\{-[\pi(2i-1)]^2\, C_v t/(2h_{dr})^2\}}{[\pi\,(2i-1)]^2} \qquad (2)$$

Where C_v is the vertical coefficient of consolidation and h_{dr} is the length of drainage path.

The degree of horizontal consolidation U_h at time t is estimated using the radial consolidation equation [40]:

$$\mathrm{U_h(t)} = 1 - \exp\left(-\frac{2\mathrm{C_h t}}{\mathrm{r_e^2 F_{(r)}}}\right) \qquad (3)$$

Where C_h is the horizontal coefficient of consolidation, re is the radius of influence of wick drains and $F_{(r)}$ is the soil disturbance coefficient during installation.

The installation process of wick drains using a steel mandrel often results in the remolding of the surrounding soil, which reduces the permeability of the clay and slows down the consolidation process. The smear zone refers to the area around the vertical drains where the soil has been disturbed during installation, leading to a decrease in soil permeability [5]. Accounting for the smear zone effect is essential for accurately predicting the performance and behavior of wick drains.

Both numerical and analytical approaches are capable of producing realistic results. However, the evaluation of soil parameters plays a pivotal role in influencing the outcomes of the analysis [33]. Due to the inherent variability and randomness of soil profiles, deterministic methods are often insufficient for accurately predicting settlement behavior of structures [23]. Therefore, it is essential to account for uncertainties in soil parameters, as these uncertainties significantly impact the calculated settlements. A clear understanding of these uncertainties enables the development of methods to quantify and address them effectively [4]. When predicted values deviate significantly—whether higher or lower—from the calculated outcomes, this information aids clients in decision-making by assessing the level of risk and the associated economic implications of implementing appropriate corrective measures. Taking suitable actions minimizes risks, reduces associated costs, and maximizes benefits [9, 46].

In geotechnical engineering analysis and design, terms such as risk, uncertainty, and safety are widely recognized and frequently utilized. While comprehensive site investigations and field monitoring are often conducted, especially for large-scale projects, to ensure reliable input for geotechnical analyses, it is also crucial to evaluate and quantify uncertainties alongside these studies [30]. Reliability analysis is an effective tool to account for the impact of uncertainties on the results. Such analyses are based on statistical and probabilistic principles, which allow for the quantification of the mean (most probable) values and the range of variability in input soil parameters, thereby influencing the output results accordingly [36]. In essence, statistical and probabilistic methods provide a framework for quantifying uncertainties, enabling a rational and consistent consideration of variable randomness in geotechnical assessments.

2 Soil Parameters Estimation

For large soft clay layers, CPTu testing is widely preferred over boreholes due to the high sensitivity of unit weight and over-consolidation ratio (OCR) to sample disturbances, which are difficult to avoid in soft clay [1, 13, 27]. Additionally, CPTu tests offer detailed and accurate profiling through the clay layer. One critical factor in estimating clay parameters from CPTu is the soil unit weight (γ), as it directly influences the total vertical stress (σ_{vo}), effective vertical stress (σ_{vo}'), and other geotechnical parameters.
The soil unit weight (γ) can be estimated from CPTu data using Lengkeek's equation [26]:

$$\gamma_{sat} = \gamma_{sat,ref} - \beta . \frac{\log\frac{q_{t,ref}}{q_t}}{\log\frac{R_{f,ref}}{R_f}} \qquad (4)$$

Where:
γ_{sat} is the saturated unit weight of soil,
q_t is the total cone resistance,
R_f is the friction ratio,
$\gamma_{sat,ref}$ is the reference unit weight where cone resistance is constant irrespective of R_f,
$q_{t,ref}$ is the reference cone resistance where the unit weight remains constant irrespective of friction ratio,
$R_{f,ref}$ is the reference friction ratio where the apex of all equal unit weight lines is located,
β indicates the inclination of the equal unit weight contours.
The OCR can be determined from CPTu data using Kulhawy's equation [24]:

$$\mathrm{OCR} = K.\left(\frac{q_t - \sigma_{vo}}{\sigma_{vo}'}\right) \qquad (5)$$

The parameter K_{ocr} can be calculated using the following relation:

$$K_{ocr} = \left[\frac{Q_{tn}^{0.2}}{0.25.(10.5+7.\log(F_r))}\right]^{1.25} \qquad (6)$$

Where:
Q_{tn} is the normalized cone resistance,
F_r is the normalized friction ratio.
If OCR varies significantly with depth, the clay layer may be subdivided into thinner sub-layers to ensure a more precise analysis.
The undrained shear strength (C_u) can be estimated using Mayne's formula [32]:

$$C_u = \frac{q_t - \sigma_{vo}}{N_{kt}} \qquad (7)$$

Where N_{kt} is a factor dependent on clay plasticity and OCR. This value increases with higher clay plasticity and decreases with lower OCR, typically ranging from 10 to 18. Robertson's equation [38] can be used to estimate N_{kt}:

$$N_{kt} = 10.5 + 7\log(F_r) \qquad (8)$$

The horizontal hydraulic conductivity (K_h) of clay can be assessed through dissipation tests performed during CPTu investigations. Using Parez's equation [35], K_h can be calculated as:

$$K_h(\mathrm{cm/s}) = \left(\frac{1}{251.t_{50}(\mathrm{sec})}\right)^{1.25} \qquad (9)$$

The vertical hydraulic conductivity (K_v) can then be estimated from K_h. Typically, the ratio of horizontal to vertical permeability ranges from 2 to 5 [15]. It can also be estimated from consolidation tests. Both horizontal and vertical permeability values should be verified through back-analysis, comparing the observed degree of site consolidation to predictions from finite element models at the end of the preloading phase.

3 Field instrumentation and Construction stages

The primary objective of the instrumentation program is to monitor soil improvement and validate the design through site-specific readings. The instrumentation setup includes deep settlement plates (DSP), surface settlement plates (SSP), and inclinometers. DSPs are positioned at the base of the preloading embankment, while SSPs are located on the top surface of the preloading embankment. Fig. 1 presents an illustrative cross-section of the preloading embankment and the associated instrumentation techniques applied in the project.

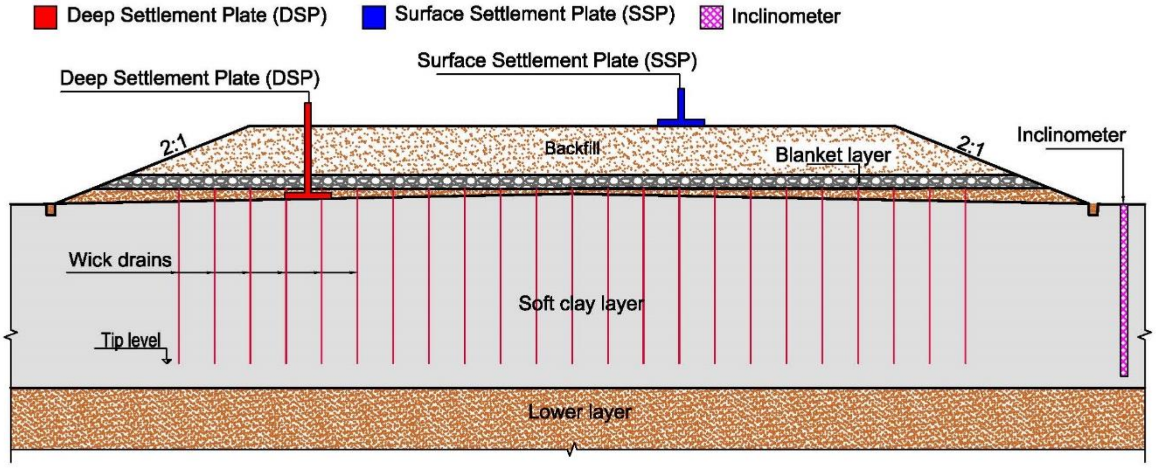

Fig. 1. General section for the preloading embankment

3.1 Monitoring Program Objectives

The monitoring program aims to document and evaluate the improvement process over time by focusing on the following aspects:

1. Tracking settlement progression over time, comparing in-situ measurements with theoretical calculations, and predicting the time required to achieve a specific settlement value based on observed results.
2. Monitoring lateral soil deformation at the boundaries of the preloading embankment.
3. Assessing improvements in the treated soil properties.

The continuous measurement and back-analysis of these factors will facilitate a comprehensive evaluation of the soil improvement process.

3.2 Instrumentation and Monitoring Tools

The monitoring program employs various tools to measure key parameters, as detailed below:

1. Deep Settlement Plates (DSP)

DSPs are installed at the ground surface within the loaded area prior to placing the preloading backfill. Settlement measurements are conducted using survey equipment, capturing the total settlement, which includes both immediate settlement and consolidation settlement induced by the preloading surcharge. Fig. 2 shows typical section of deep settlement plates

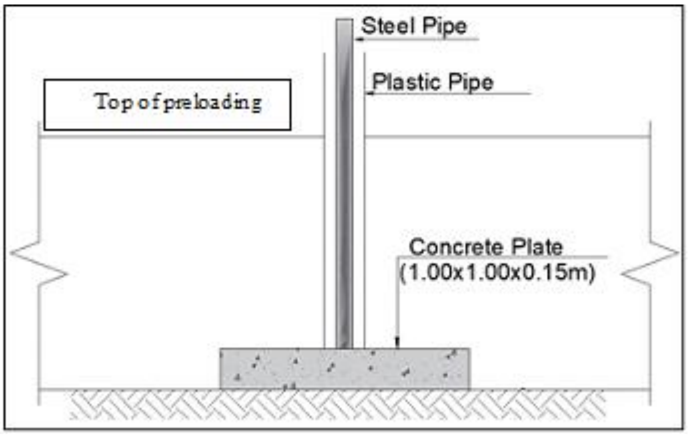

Fig. 2. Typical section of deep settlement plates

2. Surface Settlement Plates (SSP)

SSPs are placed on top of the preloading backfill after its completion. Measurements, also conducted with survey equipment, are focused solely on consolidation settlement. Notably, settlement data collected during the preloading phase can be utilized to predict the final settlement using methods such as Asaoka's procedure [2] or similar approaches. Fig. 3 shows typical section of surface settlement plates

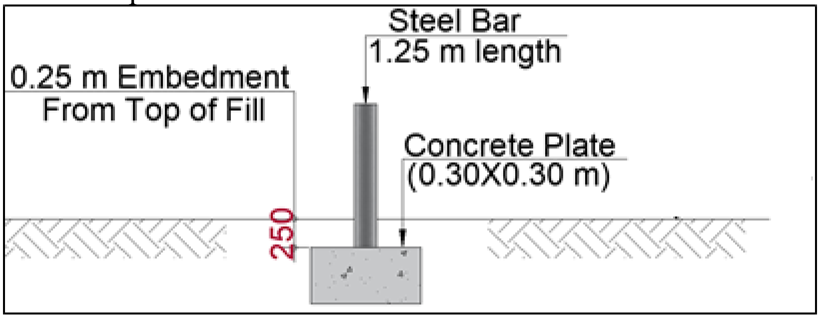

Fig. 3. Typical section of surface settlement plates

3. Inclinometers

Inclinometers are employed to measure lateral ground deformation adjacent to the loaded area. They are installed in boreholes near the embankment prior to backfill placement. Periodic measurements during the backfill placement and the subsequent loading period provide insights into the lateral deformation and ground squeeze during the soil improvement process.

3.3 Evaluation of Treated Soil

The improvement of treated soil maybe assessed through CPTu tests conducted at various stages:

1. Pre-Improvement Phase: CPTu tests are performed at the existing ground level before any soil improvement activities commence.
2. Post-Preloading Phase: CPTu tests are carried out at the top surface of the completed preloading backfill.
3. Results from these tests are analyzed to quantify improvements in shear strength and over-consolidation ratio (OCR), thereby providing a clear indication of the soil enhancement achieved.

3.4 Construction Stages

The construction sequence usually proposed for using preloading and wick drains besides the installing of monitoring system can be summarized as per Fig. 4.

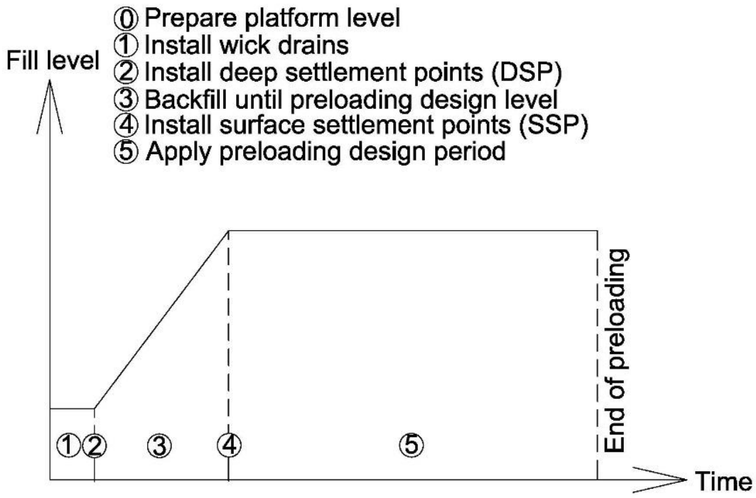

Fig. 4. The construction sequence used for preloading and wick drains

4 Prediction of Final Consolidation Settlement from Monitoring Results

Final settlement values can be determined through field monitoring data. Several observational methods use measured settlement values to predict the final settlement, with Asaoka's observational approach [2] and the hyperbolic curve method [41] being widely employed for this purpose. These methods also facilitate the calculation of the degree of consolidation, which can be compared with results obtained through finite element analysis.

- Asaoka's Observational Method

Asaoka [2] introduced a technique for predicting the final consolidation settlement using measured settlement data, grounded in one-dimensional consolidation theory. In this method, the relationship between settlements at successive equal time intervals, S_n and S_{n-1}, is modeled as a first-order approximation:

$$S_n = \beta_o + \beta_1 S_{n-1} \qquad (10)$$

Here, $S_1, S_2, \ldots, S_n$ represent settlement measurements at times $t_1, t_2, \ldots, t_n$, with a constant time interval $\Delta t = t_n - t_{n-1}$. The parameters β_o and β_1 are the intercept and slope of the linear trend in the S_n versus S_{n-1} plot, respectively. At the end of primary consolidation, $S_n = S_{n-1} = S_{ult}$, and the ultimate settlement S_{ult} is calculated as:

$$S_{ult} = \frac{\beta_o}{(1-\beta_1)} \qquad (11)$$

To apply Asaoka's method, the measured settlement data are plotted as S_n versus S_{n-1}. A linear trend line is then fitted to the data, and its intersection with the 45° line represents the final consolidation settlement.

- Hyperbolic Curve Method

The hyperbolic curve method [41] assumes that the settlement-time relationship during preloading follows a hyperbolic trend. The settlement equation is expressed as:

$$S_t = S_o + \frac{t-t_o}{\alpha + \beta(t-t_o)} \qquad (12)$$

Here, S_t is the settlement at time t, S_o is the initial settlement at time t_o, and α and β are the intercept and slope of the fitted line in the plot of $(t-t_o)/(S_t-S_o)$ versus $(t-t_o)$. For parameter estimation, the equation is rewritten as:

$$\frac{t-t_o}{S_t-S_o} = \alpha + \beta(t-t_o) \qquad (13)$$

The final consolidation settlement, S_{ult}, can be determined using the relation:

$$S_{ult} = S_o + \frac{1}{\beta} \qquad (14)$$

Degree of Consolidation (U_t) is an essential parameter for assessing the effectiveness of soil improvement, U_t, which is calculated as:

$$U_t = \frac{S_t}{S_{ult}} \qquad (15)$$

In this equation, S_t is the settlement at time t, and S_{ult} is the final consolidation settlement. This metric provides a measure of the progress of consolidation over time.

5 Settlement Analysis Tool

Finite element analyses maybe performed using 2D and 3D simulations. The finite element analyses can be conducted using PLAXIS software. The construction stages are usually considered in the finite element analysis to simulate exactly the works adopted in the site. Table 1 summarizes the construction sequence to be adopted in modelling.

Table 1. Construction sequence for modelling

Stage No.	Description	Notes
1	Backfilling to prepare platform	The platform can be simulated as surcharge load
2	Installing the wick drains	This can be simulated as line drains
3	Backfilling to reach preloading level	The backfill can be simulated as surcharge load
4	Applying Preloading period	Apply consolidation analysis
5	Final consolidation settlement of preloading	100% consolidation
6	Removing preloading load, excavate and add replacement under foundations.	This stage starts from end of stage 4
7	Applying structure loads	The structure can be simulated as surcharge load
8	Final consolidation settlement due structure loads	100% consolidation

The consolidation phase (Stage 5) is considered in the analysis after the end of preloading phase. This stage considers final consolidation due to the preloading loads. The aim of this phase is to verify the finite element analysis with the final settlement predicted by Asaoka and Hyperbolic results

6 Constitutive Models and Material Properties

The soft soil model [8] can be adopted for analyzing the soft clay layers. This model requires input parameters such as C_c, C_r, e_o and OCR, which are typically obtained through soil investigations. Due to the availability of these parameters through site investigations, the soft soil model is particularly suitable for settlement analysis. For the sand layers, the Mohr-Coulomb model or hardening soil model can be applied. Additionally, simulations for soft clay maybe conducted using undrained analysis with Method A [37], which incorporates drained shear parameters while simulating undrained soil behavior.

For clay layers improved with wick drains, the smear effect caused by drain installation can be taken into account. The equivalent soil parameter method, as proposed by [29], was utilized to model this effect. In this approach, both the disturbed and undisturbed soil surrounding the vertical drains are replaced by an equivalent soil cluster. This equivalent cluster retains the same parameters as the undisturbed soil, except for permeability. The permeability of the equivalent cluster can be determined using Lin's equation [29]:

$$\mathrm{K_e} = \frac{\mathrm{K_h} \ln\left(\frac{\mathrm{r_e}}{\mathrm{r_w}}\right)}{\ln\left(\frac{\mathrm{r_e}}{\mathrm{r_s}}\right) + \frac{\mathrm{K_h}}{\mathrm{K_s}} \ln\left(\frac{\mathrm{r_s}}{\mathrm{r_w}}\right)} \qquad (4)$$

Where r_w is the equivalent radius of the vertical drain, r_e is the radius of the influence zone, r_s is the radius of the smear zone, K_e is the equivalent soil permeability, K_s is the permeability within the smear zone, and K_h is the horizontal permeability of undisturbed soil.

In studies conducted on soft Bangkok clay [6], the smear zone diameter was observed to be approximately two to three times the cross-sectional area of the mandrel, while the smear zone permeability ranged between one-third and one-half of that of the undisturbed soil. Accordingly, the equivalent permeability can be estimated.

The drains can be modeled as line drains, and surface loads can be employed to represent the backfilling of the platform and preloading activities.

7 Reliability Analysis

Reliability analysis can be conducted using the Monte Carlo (MC) simulation method, an advanced numerical technique for estimating statistical characteristics of random input data and corresponding response variables. This method is particularly effective for solving stochastic problems, as it generates random samples from the distribution of each variable to produce a series of values. MC simulations can be applied to both linear and non-linear problems and require a significant number of iterations to ensure a reliable response distribution.

The MC simulations employed Latin hypercube sampling from the Python library pyDOE. Latin hypercube sampling is a form of stratified sampling, where the cumulative probability distribution is divided into equal intervals, and samples are randomly drawn from each interval. This approach ensures that all sections of the input distribution are represented in the samples.

PLAXIS 2D scripting tools, integrated with Python coding, can be utilized to automate the reliability analysis using the MC simulation method. The number of simulations used is a critical parameter that should be explicitly defined during the analysis to achieve accurate results.

Statistical properties of random variables, including the mean (μ), standard deviation (σ), and coefficient of variation (CoV), were considered. The CoV, which expresses the relative dispersion of data as a ratio of the standard deviation to the mean, provides insight into the confidence level of the input soil parameters. Lower CoV values indicate higher confidence in the parameters and vice versa. These statistical parameters were derived from extensive site investigation data to capture variability in soil properties accurately. For this analysis, the compressibility parameters of the soft clay layers were emphasized, as they are the most influential factors affecting consolidation settlement.

The standard deviation for a dataset X with n data points is calculated using the following formula:

$$standard\ deviation\ = \sqrt{\frac{\sum(Xi-\bar{X})}{n}} \qquad (5)$$

Where X_i represents individual data points and $\bar{X}$ is the mean value.

The Coefficient of Variation (CoV) is then computed as:

$$CoV = \frac{standard\ deviation}{mean\ value} \qquad (6)$$

8 Proposed Methodology For Reliability Analysis

A methodology for reliability analysis for wick drains design is proposed. The proposed methodology can be clarified as below:

Step 1: Planning of wide site investigations with preferring the use of CPTu tests due to the expected soil disturbance that arise in large soft clays during boreholes sampling. The CPTu provides a detailed profile through the whole depth. Fig. 5 shows a typical CPTu example results showing the detailed variations of cone resistance, sleeve friction and pore pressure through the whole depth of soil.

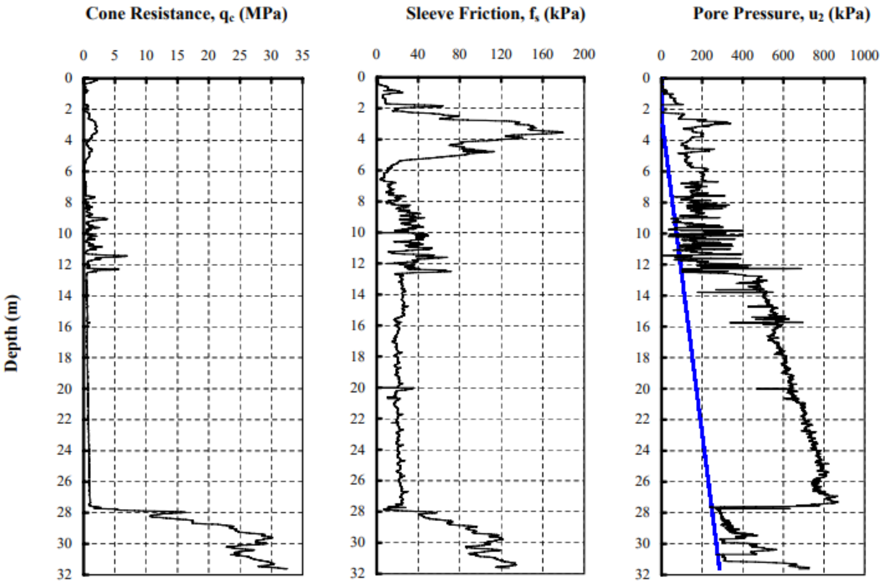

Fig. 5. Typical CPTu example showing variations of cone resistance, sleeve friction and pore pressure

Step 2: Analysis of the site investigations. The analysis may consider dividing the clay layer to many sublayers due to consolidation parameters variation versus depth especially OCR. Such sub layering can be provided accurately using CPTu compared to boreholes. Fig. 6 shows typical soft clay sub layering example due to variation of OCR versus depth.

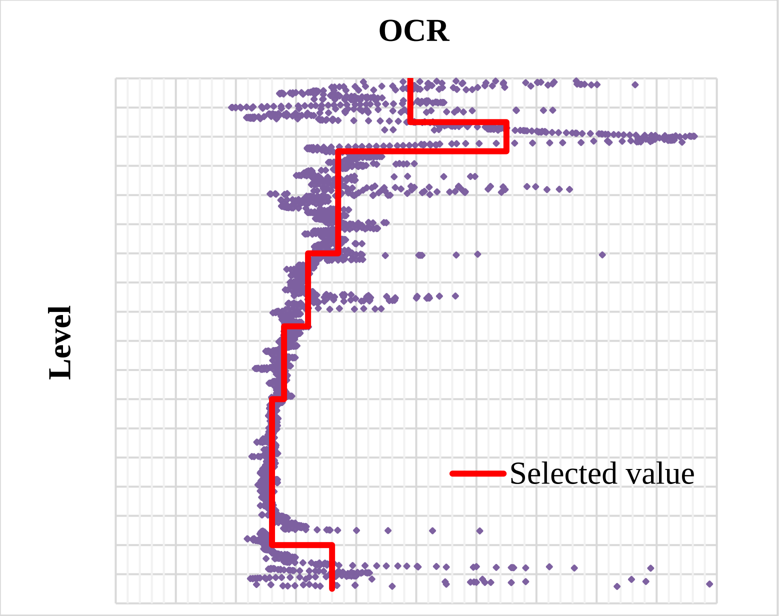

Fig. 6. Typical soft clay sub layering example due to variation of OCR versus depth.

Step 3: Determining the statistical factors (μ, σ, CoV) for the soft clay consolidation parameters according to the site investigations. The statistical factors to be estimated for the consolidation parameters are the mean value, standard deviation and coefficient of variance.

Step 4: Design of the soil improvement system using the preloading and wick drains. The design shall consider the selection of spacing of wick drains, preloading loads and preloading periods. Indeed, settlement analysis shall be performed for designing the preloading and wick drains system. Stochastic analysis using Monte Carlo simulations can be performed using finite element analysis with PLAXIS 2D and 3D. The Monte Carlo simulations can be performed by the automation of the settlement analysis to perform large number of models to achieve the required accuracy. The Monte Carlo simulation shall consider the statistical factors (μ, σ, CoV) estimated for the clay consolidation parameters from the conducted site investigations. Sensitivity analysis can be performed in order to determine the accuracy versus the proposed number of simulations. Fig. 7 shows the typical settlement analysis example results using Monte Carlo simulation.

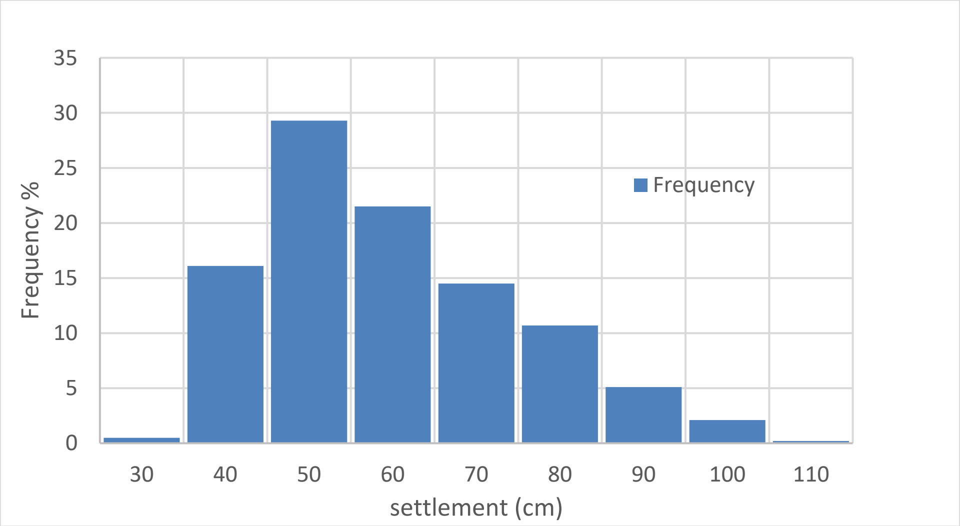

Fig. 7. Typical settlement analysis example results using Monte Carlo simulation

Step 5: Planning of extensive monitoring program for the preloading embankment. The main monitoring components necessary for the proposed reliability analysis methodology are the deep settlement plates to provide settlement measurements since the start of backfilling and surface settlement plates to provide settlement measurements since reaching the final backfilling level. Fig. 8 shows typical settlement measurements example for surface / deep settlement plates.

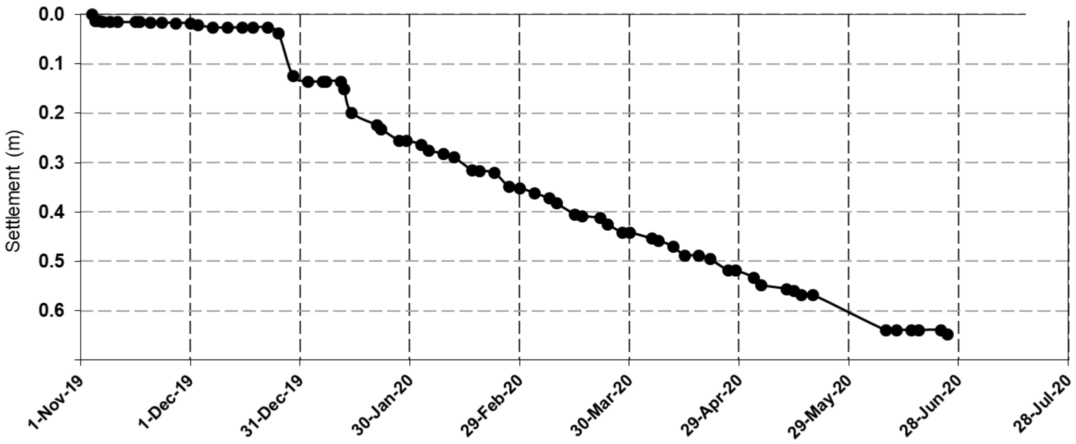

Fig. 8. Typical settlement measurements example for surface / deep settlement plates.

Step 6: Obtain the final settlement using both Asaoka and Hyperbolic methods based on the recorded field measurements from the deep and surface settlement plates. Figs. 9 and 10 shows typical application example of Asaoka and Hyperbolic methods respectively.

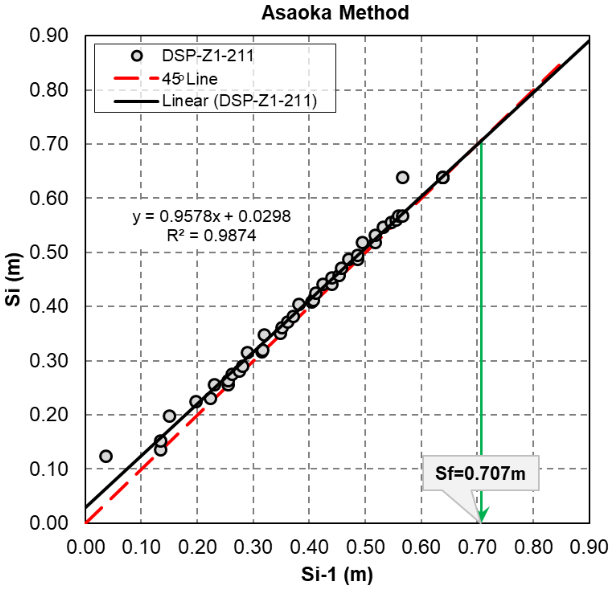

Fig. 9. Typical application example of Asaoka method

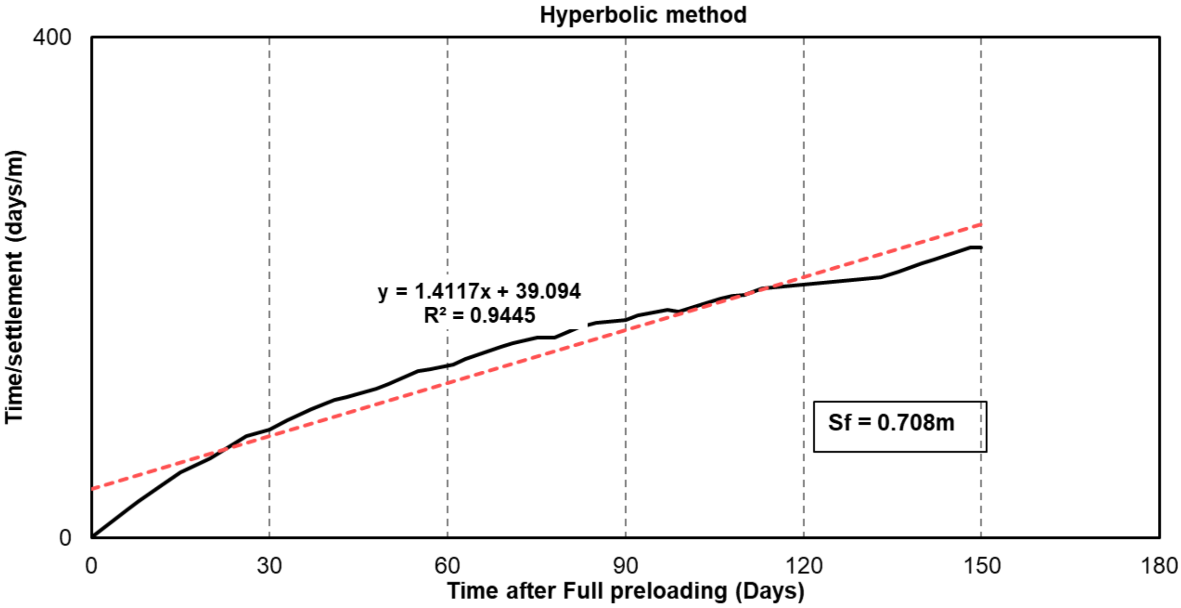

Fig. 10. Typical application example of Hyperbolic method

Step 7: Verify the settlement analysis results. The verification shall include settlement analysis results since start of backfilling until the end of preloading versus deep settlement plates measurements, settlement analysis results since end of backfilling until the end of preloading versus surface settlement plates measurements and finally the final consolidation settlement (100% consolidation) due to the preloading load estimated from settlement analysis versus the estimated final settlement from the monitoring results estimated from both Asaoka and Hyperbolic methods. Fig. 11 shows typical settlement analysis results example obtained from Monte Carlo simulations plotted versus the obtained settlement monitoring results.

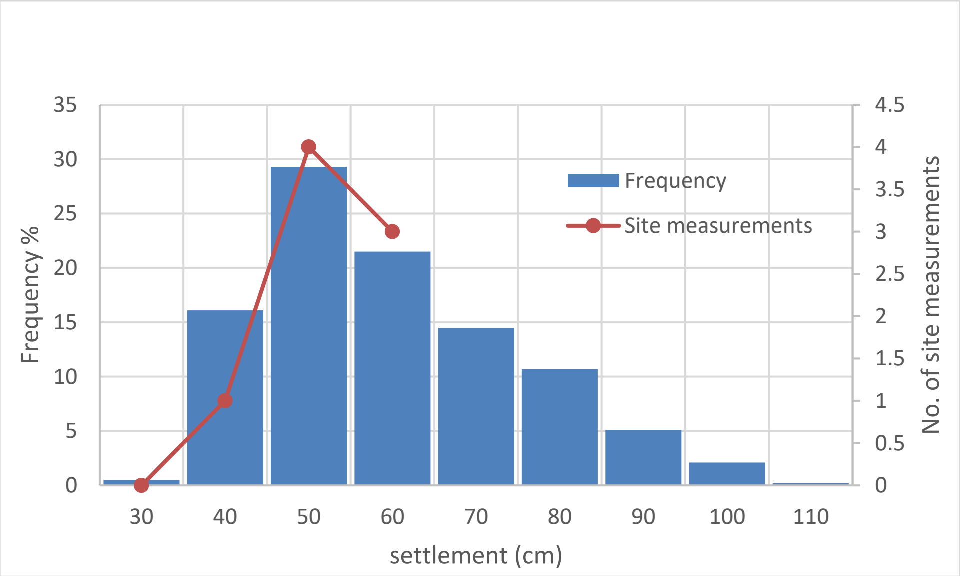

Fig. 11. Typical settlement analysis results example from Monte Carlo simulations plotted versus the settlement monitoring results.

Step 8: After verifying the settlement results and considering the actual preloading period and all the actual construction events, the effective settlement affecting the final structure after the end of preloading and removing of the preloading load can be determined precisely as settlement range with different probabilities for all settlement values instead of single deterministic value. This indeed allows better understanding of the settlement results affecting the structure and accordingly better understanding of the risk that may occur due to the uncertainty of soil parameters. Fig. 12 shows typical results for effective settlement affecting the final structure using reliability analysis.

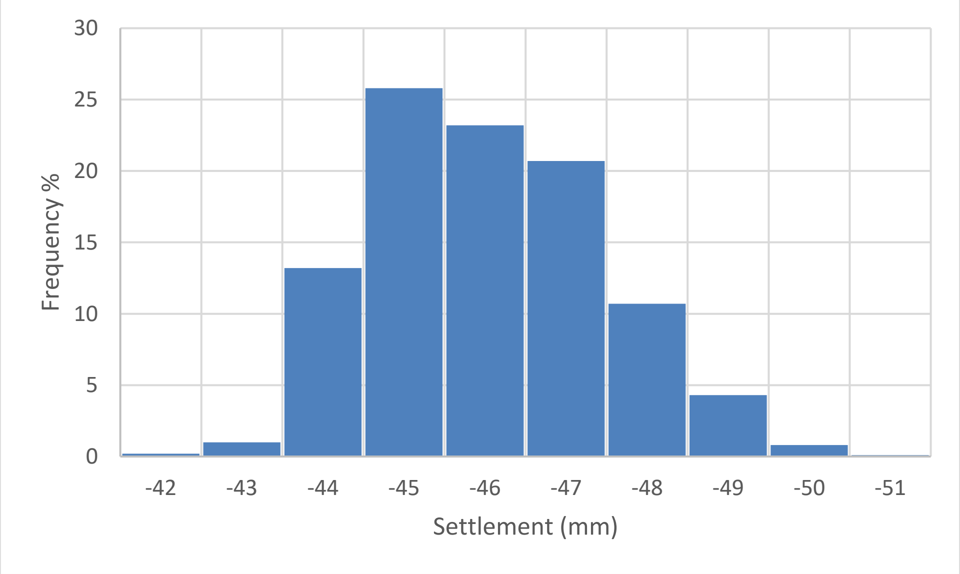

Fig. 12. typical settlement results example for settlement of final structure using reliability analysis

Fig. 13 shows the chart summarizing the proposed reliability analysis methodology for designing of wick drains

Step 1
- Plan extensive site investigation for the soft clay layers.
- CPTu tests are preferred to provide detailed soil profile with parameters variation especially for large soft clay layers.

Step 2
- Analyze the site investigation data.
- Divide the soft clay to sublayers according to variations in consolidation parameters.

Step 3
- Determine the statistical factors (Mean value, standard deviation and coefficient of variance) for the consolidation parameters for each clay layer/sublayer.

Step 4
- Design of the preloading and wick drains and performing settlement analysis models.
- Perform stochastic analysis using Monte Carlo simulations. Preferred by finite element automation to perform large number of models.

Step 5
- Perform extensive monitoring planning during the preloading.
- The monitoring system shall consist of surface settlement plates (SSP) and deep settlement plates (DSP).

Step 6
- Calculate the final consolidation using Asaoka and Hyperbolic methods from monitoring results.

Step 7
- Verify the settlement results. First: calculated settlement since start of backfill until end of preloading vs DSP. Second: calculated settlement since end of backfill until end of preloading vs SSP. Third: calculated 100% consolidation vs Asaoka and Hyperbolic results.

Step 8
- From the verified models and applying construction updates, the effective settlement affecting the final structure can be obtained with different probabilities for settlement ranges instead of single value

Fig. 13. Procedure of flow chart for the proposed reliability analysis methodology for design of wick drains

9 Conclusions

This paper presents the state of the art for design of soil improvement using preloading and wick drains. In addition, the researches presents a methodology for reliability analysis to be adopted for design of soil improvement using preloading and wick drains. The method depends on quantifying uncertainties of consolidation parameters for predicting settlement of soft clay. The reliability analysis may be carried out using Plaxis or any finite element software, automated with python scripting in order to perform stochastic analysis using the Monte Carlo simulations and accounting the uncertainty of the soil consolidation parameters. The settlement analysis results can be verified through the field monitoring results using deep settlement plates and surface settlement plates along with the final settlement estimated using Asaoka and hyperbolic methods. This in turn results in better understanding of the settlement results for the final structure. The conclusions can be summarized as follows:

1. Conducting CPTu tests over extensive soft clay layers is advantageous in estimating the variation of soil parameters with depth, enabling precise calculations for parameters like unit

weight and over-consolidation ratio. This approach allows for the division of the clay layer into multiple sublayers, resulting in more accurate simulation and analysis of the soil profile.

2. Stochastic analysis employing Monte Carlo simulations is a robust and effective tool for performing reliability settlement analysis, offering an advanced understanding of settlement uncertainties.
3. Using Python scripting in Plaxis provides a powerful mechanism for automating reliability analysis in settlement calculations, particularly when modeling preloading scenarios with vertical drains.
4. Conducting extensive site investigations is vital to accurately determine the variability and uncertainty of soil parameters. Estimating statistical factors such as the mean (μ), standard deviation (σ), and coefficient of variation (CoV) for consolidation properties is essential to achieving precise reliability settlement analysis.
5. The number of Monte Carlo simulations required can be adjusted based on the desired accuracy for settlement predictions, which depends on the project's significance and the sensitivity of the structure.
6. Incorporating broad and precise site investigations that minimize soil parameter uncertainties is highly beneficial for reliable settlement analysis. Soil consolidation parameter uncertainty is a critical factor influencing settlement reliability outcomes.
7. Integrating site investigation data with monitoring results facilitates the development of accurate numerical models capable of simulating both short-term and long-term soil behavior. Verified numerical models allow for precise estimations of effective settlements for future structures built on improved clay soils.
8. Combining deep settlement plates (DSP) with surface settlement plates (SSP) yields reliable settlement readings across various construction phases. Utilizing methods such as Asaoka and hyperbolic predictions enables the accurate estimation of final consolidation settlements due to preloading, enhancing the validation of numerical model results through comparisons of settlement versus time, final settlement, and achieved degree of consolidation at the end of preloading.
9. Soil permeability can be confirmed through back analysis, which compares the actual degree of consolidation observed on-site to the degree estimated using finite element calculations at the end of the preloading phase.

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