Lin Li · Bora Cetin · Xiaoming Yang
Editors

Proceedings of GeoShanghai 2018 International Conference: Ground Improvement and Geosynthetics

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Preface

The 4th GeoShanghai International Conference was held on May 27–30, 2018, in Shanghai, China. GeoShanghai is a series of international conferences on geotechnical engineering held in Shanghai every four years. The conference was inaugurated in 2006 and was successfully held in 2010 and 2014, with more than 1200 participants in total. The conference offers a platform of sharing recent developments of the state-of-the-art and state-of-the-practice in geotechnical and geoenvironmental engineering. It has been organized by Tongji University in cooperation with the ASCE Geo-Institute, Transportation Research Board, and other cooperating organizations.

The proceedings of the 4th GeoShanghai International Conference include eight volumes of over 560 papers; all were peer-reviewed by at least two reviewers. The proceedings include Volumes 1: Fundamentals of Soil Behavior edited by Dr. Annan Zhou, Dr. Junliang Tao, Dr. Xiaoqiang Gu, and Dr. Liangbo Hu; Volume 2: Multi-physics Processes in Soil Mechanics and Advances in Geotechnical Testing edited by Dr. Liangbo Hu, Dr. Xiaoqiang Gu, Dr. Junliang Tao, and Dr. Annan Zhou; Volume 3: Rock Mechanics and Rock Engineering edited by Dr. Lianyang Zhang, Dr. Bruno Goncalves da Silva, and Dr. Cheng Zhao; Volume 4: Transportation Geotechnics and Pavement Engineering edited by Dr. Xianming Shi, Dr. Zhen Liu, and Dr. Jenny Liu; Volume 5: Tunneling and Underground Construction edited by Dr. Dongmei Zhang and Dr. Xin Huang; Volume 6: Advances in Soil Dynamics and Foundation Engineering edited by Dr. Tong Qiu, Dr. Binod Tiwari, and Dr. Zhen Zhang; Volume 7: Geoenvironment and Geohazards edited by Dr. Arvin Farid and Dr. Hongxin Chen; and Volume 8: Ground Improvement and Geosynthetics edited by Dr. Lin Li, Dr. Bora Cetin, and Dr. Xiaoming Yang. The proceedings also include six keynote papers presented at the conference, including "Tensile Strains in Geomembrane Landfill Liners" by Prof. Kerry Rowe, "Constitutive Modeling of the Cyclic Loading Response of Low Plasticity Fine-Grained Soils" by Prof. Ross Boulanger, "Induced Seismicity and Permeability Evolution in Gas Shales, CO_2 Storage and Deep Geothermal Energy" by Prof. Derek Elsworth, "Effects of Tunneling on Underground Infrastructures" by Prof. Maosong Huang, "Geotechnical Data Visualization and Modeling of Civil

Infrastructure Projects" by Prof. Anand Puppala, and "Probabilistic Assessment and Mapping of Liquefaction Hazard: from Site-specific Analysis to Regional Mapping" by Prof. Hsein Juang. The Technical Committee Chairs, Prof. Wenqi Ding and Prof. Xiong Zhang, the Conference General Secretary, Dr. Xiaoqiang Gu, the 20 editors of the 8 volumes and 422 reviewers, and all the authors contributed to the value and quality of the publications.

The Conference Organizing Committee thanks the members of the host organizations, Tongji University, Chinese Institution of Soil Mechanics and Geotechnical Engineering, and Shanghai Society of Civil Engineering, for their hard work and the members of International Advisory Committee, Conference Steering Committee, Technical Committee, Organizing Committee, and Local Organizing Committee for their strong support. We hope the proceedings will be valuable references to the geotechnical engineering community.

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Monte-Carlo Simulation of Post-construction Settlement After Vacuum Consolidation and Design Criterion Calibration

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Abstract. Reliability-based design is required to minimise risk induced by soil properties variation and laboratory tests discrepancy in geotechnical engineering. A procedure was proposed to analyse probability of post-construction settlement (PCS) after vacuum consolidation, and to calibrate the design criteria to achieve a target reliability index. A Monte-Carlo simulation based on analytical solution of vacuum consolidation was developed to incorporate both primary and secondary consolidation settlement. The reduction of secondary consolidation coefficient during construction was considered in the method. This design and analysis approach were applied in the design review of Kalibaru port, Indonesia. Statistical analysis on soil properties was performed based on comprehensive investigations. The original design was reviewed by using both deterministic analysis with FEM and reliability-based analysis with the proposed method. Lastly, the coefficient of variation (COV) of 1.164 was found for PCS, and design criteria were calibrated to target different levels of P_e, from 6.7% to 25%.

Keywords: Reliability-based geotechnical design · Reclamation
Post-construction settlement (PCS) · Monte-Carlo simulation

1 Introduction

In a geotechnical design, significant uncertainties exist in the process of defining geomaterial properties, which need to be evaluated via reliability analysis. In Kalibaru port, Indonesia, prefabricated vertical drains (PVDs) with preloading and vacuum is proposed to improve the soft ground at a 900 $\times$ 2600 m site. Comprehensive investigations were performed to mitigate potential risk. However, there was no similar case using reliability-based design (RBD) could be found in literature. Therefore, a RBD procedure and analysis method need to be developed.

Several reliability-based analysis approaches have been developed for geotechnical structures [1], such as the first-order reliability method (FOSM), the second-order reliability method (SORM), and numerical simulations. Monte-Carlo simulation is a numerical process of repeatedly calculating a performance function, in which the variables within the function are random or contain uncertainty with prescribed probability distributions. A large number of outputs can be obtained and used in statistical analysis for directly estimating the probability of failure (P_f), or the

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probability of exceedance (P_e). In this way, conventional deterministic modelling can be extended to reliability analysis without complex concept and algorithms.

In this paper, RBD procedure based on Monte-Carlo simulation was developed and applied in the Kalibaru port. The mean value of PCS and COV were obtained, then the design criterion was calibrated to achieve reliability index of 1.5. This also provides a detailed case study for future engineering practice.

2 Analytical Solution of Vacuum Consolidation Combined with Preloading

PVDs with vacuum and preloading have been widely applied to accelerate the consolidation of soft ground all over the world. The successful applications include Port of Brisbane, Ballina Bypass, and Sunshine Coast Motorway, in Australia [2, 3]; Tianjin Port and Wenzhou Reclamation, in China [4, 5]; Philadelphia International Airport, in USA [6]; North South Expressway, in Malaysia [7]; Second Bangkok International Airport, in Thailand [8]; Shin-Moji Oki Disposal Pond, in Japan [9]. In these projects, fill preloading was combined with vacuum to avoid excessively high embankment and a lengthy preloading period to achieve the same amount of consolidation degree.

A typical cylindrical element of a PVD with preloading and vacuum is shown in Fig. 1. The PVD has the equivalent radius of r_w, and the influence radius of r_e. A smear zone with the radius of r_s is formed during vertical drains installation with a steel mandrel which significantly remoulds its immediate vicinity. Studies showed that, the radius of the smear zone is about 2.5 times the equivalent radius of the mandrel, and the lateral permeability within the smear zone is 61%–92% of the outer undisturbed zone [10]. Preloading, p_0, is applied on the ground surface, and vacuum pressure, p_s, is applied via pump connected to PVDs. Experience has shown that the vacuum pressure applied in field through PVDs may decrease with depth. Let the decreasing rate is λ, then the suction propagated to the toe is p_s- λl when the length of PVDs, l, is not sufficient to reduce the suction down to zero. This pressure loss rate, λ, was found up to 3 kPa/m in experiments [11].

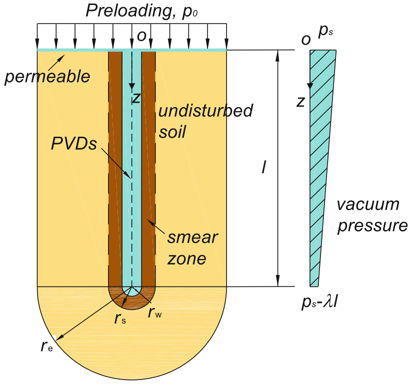

Fig. 1. Illustration of PVDs with preloading and vacuum pressure [2]

Settlement development by using PVDs with preloading and vacuum incorporates both primary and secondary consolidation.

Primary consolidation. The primary consolidation of soil with PVDs is dominated by radial drainage. The theory of radial drainage and consolidation has been developed by many researchers [12, 13]. Consider a thin layer with ΔH in thickness, the excess pore pressure during vacuum consolidation can be solved by:

$$\frac{\bar{u}_{h,t}}{u_0} = \left(1 + \frac{p_s}{u_0}\right) e^{\left(\frac{-8c_h t}{\mu d_e^2}\right)} - \frac{p_s}{u_0} \tag{1}$$

where, $\bar{u}_{h,t}$ is excessive pore pressure at depth of h and time of t; u_0 is the initial excessive pore pressure induced by preloading, p_0; c_h is the coefficient of consolidation; d_e is the diameter of the influencing zone, and $d_e = 2r_e$; μ is a factor as follow:

$$\begin{aligned} \mu = & \frac{n^2}{n^2-1}\left[\ln\left(\frac{n}{s}\right) + \frac{k_h}{k_s}\ln(s) - \frac{3}{4}\right] \\ & + \frac{s^2}{n^2-1}\left(1 - \frac{s^2}{4n^2}\right) + \frac{k_h}{k_s}\frac{1}{n^2-1}\left(\frac{s^4-1}{4n^2} - s^2 + 1\right) \end{aligned} \tag{2}$$

where, $n = r_e/r_w$, $s = r_s/r_w$.

The degree of consolidation is:

$$U_{h,t} = \frac{1 - \bar{u}_t/u_0}{1 - u_\infty/u_0} = \frac{u_0 - \bar{u}_t}{u_0 - p_s} \tag{3}$$

Thus, primary consolidation can be obtained by:

$$s_t = s_p U_{h,t} \tag{4}$$

where, s_p is the ultimate primary consolidation computed by,

$$s_p = \frac{C_c}{1 + e_0}\Delta H \log\left(\frac{\sigma'_{z,t}}{\sigma'_{z,0}}\right) \tag{5}$$

where, C_c is compression index; e_0 is initial void ratio; $\sigma'_{z,t}$ is vertical effective stress at time t; $\sigma'_{z,0}$ is initial vertical effective stress at time 0.

Except for loading process, the recompression index, C_r, is smaller than C_c.

Secondary consolidation. Secondary consolidation plays an important role in long-term settlement. If the time to reach the end of primary consolidation is relatively short which benefits from vacuum consolidation and reloading, the time-dependent settlement is basically controlled by the secondary consolidation [14].

Secondary consolidation, s_s, is given by the formula:

$$s_s = \frac{\Delta H}{1 + e_0} C_\alpha \log\left(\frac{t}{t_{95}}\right) \tag{6}$$

where, C_α is the coefficient of secondary consolidation; t_{95} is the time when primary consolidation reaches 95% consolidation degree.

For simplification, the time at the end of construction was taken as t_{95} in this paper.

A number of authors [15–17] have reported the significant reduction of secondary consolidation when the soil is over-consolidated even to a modest degree. Laboratory and field experiments results indicated a decreasing exponential relationship between over-consolidation ratio (OCR) and C_α. The uniform expression is [16]:

$$C_\alpha = 10^{(A + B \cdot OCR)} + C \tag{7}$$

where, A, B, and C are fitting parameters, as recommended in papers [14, 16].

Kosaka [17] proposed the formula to determine OCR as follow:

$$OCR = \frac{\sigma'_{z,0} + \left(\Delta\sigma'_1 + \Delta\sigma'_s\right) \times U}{\sigma_{z,0} + \Delta\sigma'} \tag{8}$$

where, $\sigma_{z,0}$ is initial effective stress; $\Delta\sigma'$ is effective stress induced by design load; $\Delta\sigma'_1$ is effective stress induced by preloading; $\Delta\sigma'_s$ is effective stress induced by vacuum pressure; U is the consolidation degree at the time of preloading and vacuum removal.

3 Reliability-Based Analysis and Design Approach

3.1 Monte-Carlo Simulation Based on Analytical Solution

The analytical solution of vacuum consolidation and preloading can be incorporated into reliability procedure by using Monte-Carlo simulation (MCS), as indicated within the dashed box in Fig. 2. Comparing to deterministic analysis, MCS computes PCS repeatedly (usually > 5000 times) based on randomly generated samples of soil parameters, and perform statistical analysis on output to extract its probabilistic characteristics. MCS has been widely used in probabilistic analysis of geotechnical engineering problems, such as slope stability analysis, retaining structures, and foundations [1]. However, no study was found in vacuum consolidation combined with preloading.

For soil consolidation, obvious correlations exist among soil parameters such as C_c, and C_r. Thus, these correlations need to be considered in random samples generation.

In this paper, MCS based on the analytical solution was programmed with GNU software, Octave 4.0.

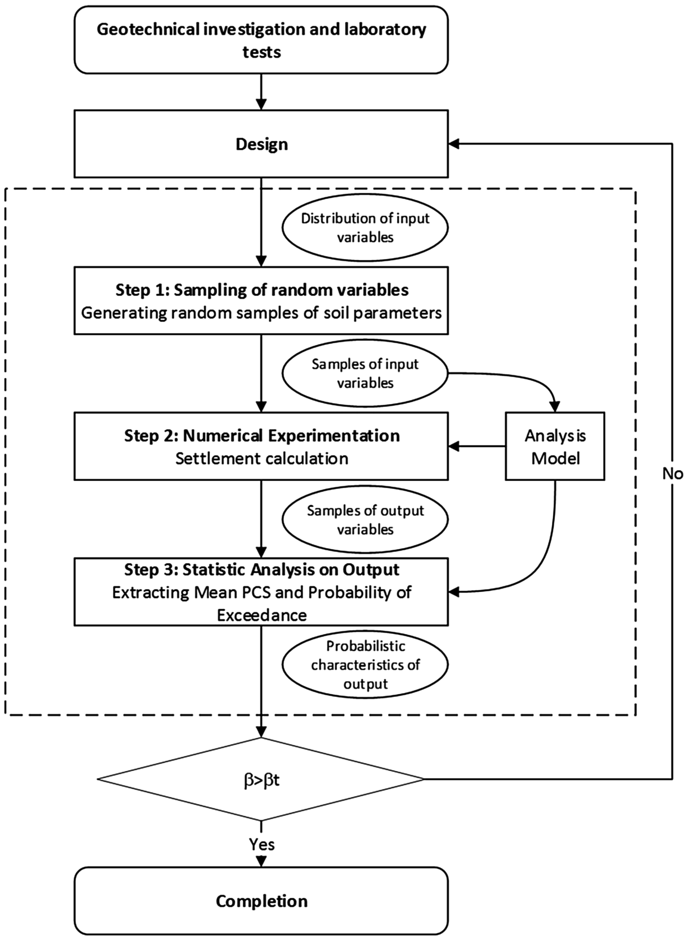

Fig. 2. Flowchart of RBD based on MCS

3.2 Reliability-Based Design Approach

Geotechnical design codes have been migrating towards RBD concepts for several decades [18]. The latest International Standard, ISO2394-2015 [19], has differentiated and related three levels of approach: risk-informed decision making, reliability-based design (RBD), and semi-probabilistic approaches. Comparing to semi-probabilistic approaches such as the load and resistance factor design (LRFD) approach in North American [20], and the characteristic values and partial factors used in the limit state design approach in Eurocode 7 [21] and AS 5100.3-2004 [22], RBD is based on a target reliability index that explicitly reflect the uncertainty of the parameters and their correlation structure, thus more suitable for large scale projects.

As shown in Fig. 2, the reliability index, β, need to be checked in RBD rather than overall factor of safety. EN1990-2002 [23] recommends the target reliability index, β_t,.

For PCS, β_t for serviceability (irreversible) limit state in 50 years is 1.5. The Chinese Standard GB 50068-2001 [24] states that, β_t is between 0 to 1.5 for serviceability limit state, depending on the reversibility. The target reliability index of 0 and 1.5 are equivalent to failure probability of 50% and 6.7%, respectively.

In contrast to probability of failure for ultimate limit state, a low probability of exceedance needs to achieve for PCS. The concept of probability of exceedance and design consideration are illustrated in Fig. 3. Assume that settlement conforms reasonable well to a normal or log normal distribution. The probability density function (PDF) 1 has the same mean value μ_1, but smaller standard deviation than PDF 2, namely $\sigma_1 > \sigma_2$. The area under each PDF in the excessive settlement zone indicates probability of exceedance, P_e. Although PDF2 has the same mean value, which is usually the criterion in design, its P_e is obviously higher than that of PDF 1. This indicates that, the same design criterion does not necessarily mean the same level of P_e.

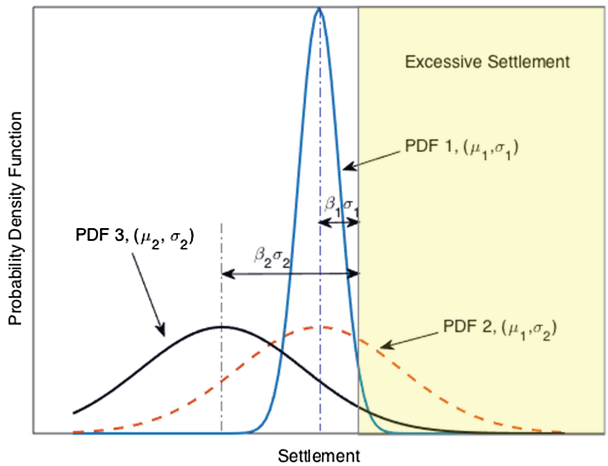

Fig. 3. The concept of P_e and design strategy

With the larger variation level (larger standard deviation) such as in PDF 2, the design needs to be offset to solution represented by PDF 3, which has the same standard deviation σ_2, but stringent design criterion (smaller mean value μ_2). Each P_e can be related to a reliability index, β, as indicated in Fig. 3.

Therefore, the variation of settlement can be considered in design criteria to achieve a specific level of P_e. When the settlement conforms to log normal distribution, Settlement Ratio (SR) can be applied in design according to the COV of settlement and a target exceedance probability from 6.7% to 25.0%, which is plotted in Fig. 4.

Given the maximum allowable settlement is S_{allow}, and the COV of settlement is 0.3, if the target P_e is 6.7%, then SR = 1.489 can be obtained from Fig. 4. This means the design criterion needs to be set at S_{allow}/1.489 to achieve the P_e of 6.7%, which has a reliability index of 1.5.

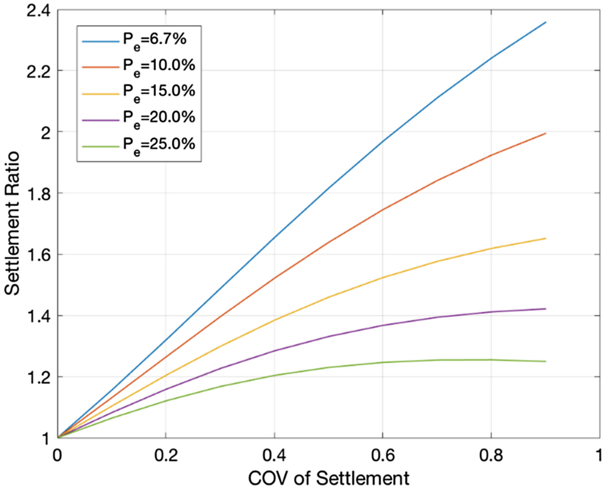

Fig. 4. Settlement ratio vs. COV for P_e of 6.7%–25.0%

4 Application in Design Review of the Reclamation of Kalibaru Port

4.1 Project Summary

The Kalibaru port development is located in the Jakarta bay, and will be constructed from dredged clay and sand materials, as indicated in Fig. 5. The proposed offshore development includes container terminals (CT2 and CT3), product terminals north of CT2 and CT3 and reserve area. In total, the area being constructed is approximately rectangular with dimensions of 2600 m by 900 m.

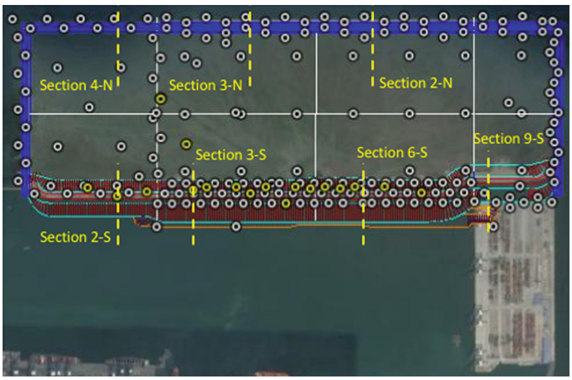

Fig. 5. Kalibaru port, Indonesia

The naturally occuring seabed is a soft Holocene clay material varying from 8 m up to 29 m thickness in some areas. This is followed by a stiff Pleistocene clay, and dense cemented sand. The reclamation works will involve placing grab-bucket dredged mud (GDM) and cutter-suction dredged mud (CSD) to RL 1.5 m. The water level is considered to be equal to the water level in the Jakarta Bay, which is RL 0.

Comprehensive geotechnical investigations have been performed prior to the design. The locations of boreholes and CPT tests are indicated in Fig. 5. Samples were then tested in laboratory to obtain soil parameters. In the original design, mean value of each parameter was adopted to assess the PCS. Generally, 90-day vacuum consolidation combined with preloading was proposed by the specialist contractor to target the criterion of 300 mm in 50 years after construction.

Geoinventions Consulting Services (GCS) was engaged by IPC to review the design, and RBD procedure was implemented to calibrate the design criterion of PCS. Deterministic analysis by using FEM was also carried out to consider the influence of construction stage.

4.2 Deterministic Results by Using FEM

The construction stage of the large-scale reclamation is complex. Preloading and vacuum pressure have to be applied section by section, due to limited volume of fill and quantity of pumps. The construction of filling for preloading and installation of PVDs are time-consuming which also elongate the construction period. To assess PCS under the real construction process, a 2D finite element software, OptumG2 (version 2017.05.20), was used in the deterministic analysis.

To simplify the modelling process, the analysis for each section starts from the stage when GDM/CSD have been built up to RL 1.5. The sections of wick drains/PVDs are modelled using fixed excess pressure lines. These allow the excess pore pressure to be fixed to any value. Pressure loss of 3 kPa/m was considered and average vacuum pressure was applied alone the fixed excess pressure lines. Main soil parameters adopted in the FEM analysis are listed in Table 1. The secondary consolidation coefficient, C_α, was not tested in the investigations. The test results performed at the Belawan Port which is approximately 200 km away from the site were used [25].

Table 1. Parameters adopted in Section 3-N analysis

Parameter	Upper Holocene Clay	Lower Holocene Clay	Stiff Clay	GDM/CDM
γ (kN/m^3)	14.3	14.6	15.8	12.0
C_c	0.96	0.85	0.59	1.08
C_r	0.148	0.108	0.046	0.18
C_v (m^2/year)	1.33	1.37	4.43	3.50
C_α	0.036	0.036	–	0.036
e_0	3.00	2.54	1.68	3.50
OCR	1.00	1.00	2.50	1.00

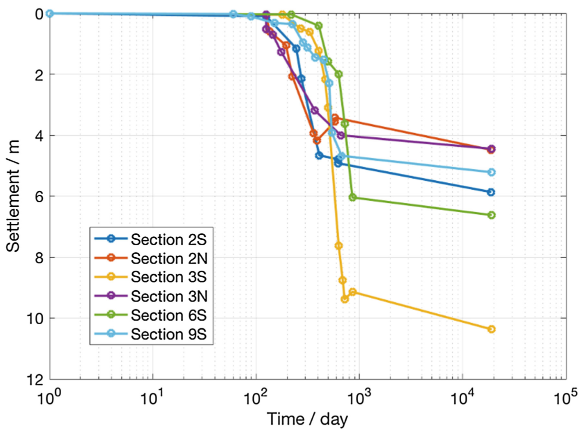

Fig. 6. Settlement development by FEM

A total of six cross sections have been considered across the project – Sections. 2-S, 2-N, 3-S, 3-N, 6-S, and 9-S. These sections are shown in Fig. 1. The settlement results for all six sections is illustrated in Fig. 6. These results indicate that the maximum total settlement occurs for Section 3-S, with a result of 10.4 m. Figure 6 also indicates that Section 2-N and 3-N exhibit very similar settlement profiles. Sections 6-S and 9-S are also similar, but exhibit a 1 m difference in total settlement due to varying soil profile and different construction process. All sections show a similar gradient to the secondary settlement line (after approx. 1000 days), except for Section 3-S which has almost doubled the thickness of soft clay.

4.3 Reliability-Based Design Calibration

According to the FEM analysis results, the soft soil and GDM/CDM are most critical for settlement analysis. GDM/CDM is the dredged layer which can be considered reasonably uniform. Thus, the thick soft soil layer dominates the variation of PCS. Statistical analysis was implemented on soft soil based on gathered test results from the principal geotechnical designer, LAPI. Log normal distribution function was adopted to fit each parameter. Six parameters: unit weight; compression index, C_c; recompression index, C_r; Coefficient of consolidation, C_v; secondary consolidation coefficient, C_α, and

Table 2. Mean Values and Variation of Parameters

Parameter	Mean Value	Standard Deviation	Range
γ (kN/m^3)	14.949	2.516	12.26–19.60
C_c	0.883	0.324	0.110–2.080
C_r	0.124	0.012	0.030–0.300
C_v (m^2/year)	4.068	1.666	0.370–4.248
C_α	0.037	0.003	0.001–0.499
e_0	2.574	2.515	0.040–3.780

initial void ratio, e_0, are considered in MCS. OCR in Table 1 was ignored in RBD because of its estimation in tests were rough thus less meaningful to taken into account.

Correlations exist among parameters listed in Table 2. The most important correlation is between C_c and C_r. Test results shows that the ratio of C_c/C_r is in a range of 2.81–27.60, which can be fitted by log normal PDF with log normal parameters $\mu_{LN} = 2.042$, $\sigma_{LN} = 0.629$, and it is in a range of 3–27. In order to obtain the correlated parameters C_c and C_r, C_c was generated randomly first with parameters listed in Table 3, then the ratio of C_c/C_r was generated and C_r was obtained by C_c and the ratio. The generated samples and test data were shown in Fig. 7. The generated samples conform to the range of test data.

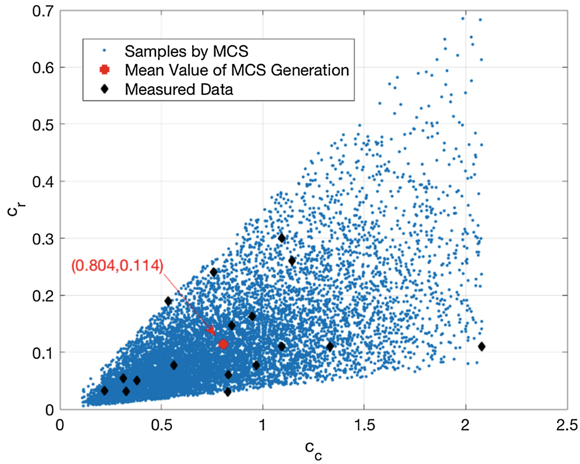

Fig. 7. Random generation of correlated parameters in MCS

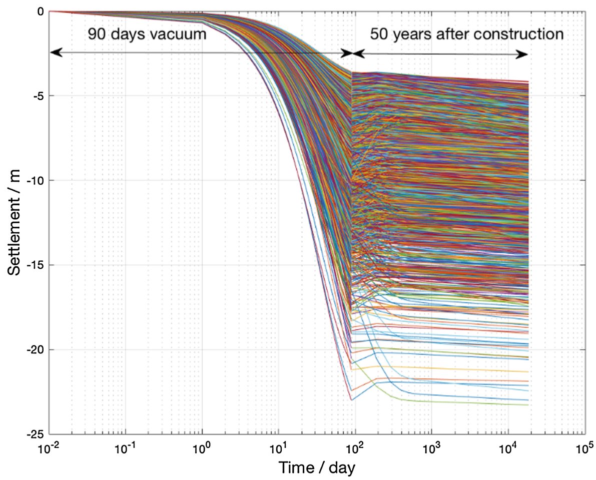

Fig. 8. Repeatedly settlement calculation in MCS

Figure 8 illustrated 10,000 times calculated settlement procession results. The settlement during vacuum and preloading is between 4–23 m depending on parameters generated in MCS. This is a reasonable result with a mean settlement close to FEM result. The settlement development shows different patterns due to combination of parameters.

In total, 10,000 PCS can be obtained in MCS. The absolute value of the output was statistically analysed with log normal PDF, and the result is shown by histogram in Fig. 9. The mean PCS is 917 mm, and the coefficient of variation is 1.164. This indicated a large variation exists because of the variation of soil properties. According to Fig. 4, the settlement ratio is 2.6, 2.1, 1.7, 1.4, 1.2 when target P_e is 6.7%, 10%, 15%, 20%, 25%, respectively. Taking the target P_e is 20%, GCS sets the design criterion at 300 mm/1.4 = 214 mm.

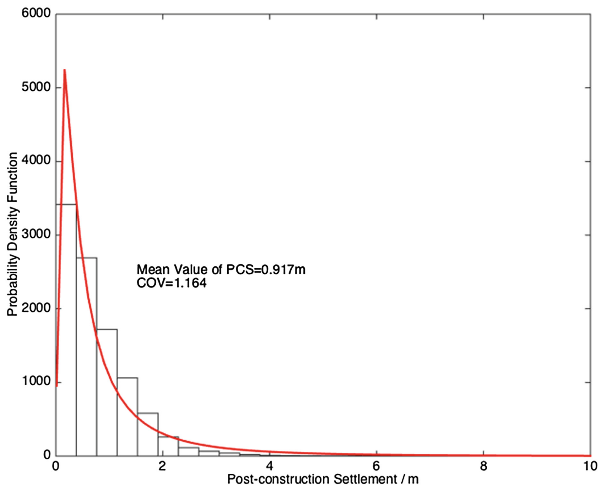

Fig. 9. Probabilistic analysis of MCS outputs

5 Conclusions

A reliability-based geotechnical design procedure with analysis approach was proposed in this paper. And this method was applied in the design review of Kalibaru port, Indonesia. Based on the practice, conclusions can be drawn as follow:

(1) A design criterion requires to be calibrated by using reliability-based design method in large scale projects to mitigate potential risk. This guarantees that a target probability of exceedance can be achieved for PCS in design;

(2) The settlement ratio diagram was developed to determine a settlement criterion based on the COV of PCS and a target exceedance probability, which is straightforward in the design process;

(3) The Monte-Carlo simulation based on analytical solution of vacuum consolidation and preloading was coded and incorporated in the RBD of Kalibaru port.

The COV was found to be 1.164, and the settlement ratios were recommended to target exceedance probabilities of 6.7%–25%. This RBD strategy can take into account the uncertainty induced by soil properties variation, and provide a reasonable criterion for engineering purpose.

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