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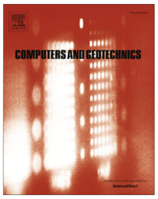

Research Paper

Embankment prediction using testing data and monitored behaviour: A Bayesian updating approach

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ABSTRACT

Settlement prediction is critical for soft ground projects. Traditional predictions using laboratory and field test data, however, can suffer from a lack of accuracy, which results in a lack of confidence by the designer. This paper employs the Bayesian approach with laboratory data, field test data, and monitoring data to yield accurate predictions during the construction and consolidation periods for the test embankment built at Ballina, New South Wales, Australia. We show that surface settlement can be well predicted using 116 days of observed settlements, while the pore pressure can be predicted using 292 days of pore pressure measurements. The predictions are shown to converge to the field measurements, regardless of some assumptions about the measurement errors. Finally, it is demonstrated that incorporating more monitoring data into the Bayesian updating process enables more accurate predictions.

1. Introduction

The Australian Research Council Centre of Excellence for Geotechnical Science and Engineering (CGSE) established the Australia's National Soft Soil Field Testing Facility at Ballina, New South Wales (NSW), Australia in 2013 [1]. To study the settlement behaviour of soft ground in the coastal areas in Australia, an instrumented embankment with prefabricated vertical drains (PVDs) was constructed. Before the construction of the test embankment, geotechnical investigations such as oedometer test and triaxial test were conducted [2,3]. To monitor the settlements and pore water pressure dissipations, 2 Magnetic extensometers, 20 Vibrating Wire Piezometers and 12 Push-in Pressure Cells were installed across three sections in the embankment. The predictions based on data from field and laboratory tests usually deviate from the observed behaviour, and thus the trial and error approach is commonly used to adjust the soil parameters to obtain better fits. This technique can be time-consuming and provides no information regarding the potential variation and degree of certainty [4]. How to take full advantage of the limited data to obtain accurate long-term predictions, in a time frame where decisions can be made during construction, is of great practical importance. Generally speaking, embankments constructed on soft soils in NSW have settled more than expected during and after construction. The implications of this are that costs are higher during construction than otherwise expected or maintenance costs post construction of the embankments (and associated culverts, structures, etc.) are increased. Occasionally, the predictions are too conservative, leading to too higher costs of surcharge, stripping and spoiling during construction.

Monitoring data can be used to predict future embankment behaviour [5,6]. Back-analyses, based on the observational method [7,8] for embankment consolidation, have been reported previously [9–11]. By using the measured settlements and pore pressures to update the soil parameters [4], the future embankment response can be predicted with improved fidelity [12]. The soil parameters updated using the field observations are not necessarily the true soil properties because: (1) a theoretical model is used to capture the physical mechanism of the complex consolidation process [13,14], and (2) the monitored embankment response during consolidation may be affected by the monitoring equipment, human error, and environmental factors (such as temperature variation). Nevertheless, using back analysis to update the soil parameters may allow for more accurate predictions of the long-term embankment response, which is critical for developing rational strategies for accelerating consolidation in projects.

There are several methods which can be used for back analysis, e.g., the maximum likelihood method [15], artificial intelligence [16–18], Extended Kalman Filter techniques [19,20] and the

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Bayesian method [12,21–23]. Among these, the Bayesian approach has proved to be a rational and robust means of updating the probability distribution function (PDF) of the input parameters and accurately predicting the long-term behaviour, provided that reliable observations are available [4,12,21,24,25]. It is also a consistent and effective approach for combining new monitored information within an existing model. Because of the uncertainties in the parameters, updating them is best tackled as a Bayesian statistical inference problem [24]. Many successful applications of the Bayesian updating approach in geotechnical engineering have been reported, e.g., pile capacity analysis [26], inverse analysis of consolidation of soft clay [5], updating bearing pressure of jack-up penetrations [27], serviceability assessment of braced excavations [28] and slope stability [21,22,29,30].

Moreover, the insights from practice are that a strong business case can be made for adopting probabilistic methods, e.g., the Bayesian approach, during design and construction. A probabilistic analysis during design allows the constructors to assign risk and opportunity money to soft ground engineering prior to construction. The use of Bayesian methods during construction provides updates on performance and uncertainty at, say, monthly intervals that can be used to update the financial risk model. Bayesian methods are able to demonstrate what the actual performance of the system will be in a relatively short time relative to the project construction period, and allow the constructor to either take early action to manage risks or realise opportunity. Early action minimises costs and maximises profits.

To accurately predict the long-term behaviour of the Ballina embankment using Bayesian updating, several important issues must be considered and require further investigation. Several sources of errors, such as uncertainties associated with the input soil properties [31] and the monitored data, should be rationally considered and incorporated into the predictions. In a previous study, an analytical model was used in conjunction with Bayesian method for predicting settlement and pore pressure [4]. The conditions in the Ballina embankment, however, are more complex, and the mechanism of consolidation cannot be captured adequately by an analytical model. An advanced numerical model for consolidation analysis is therefore required.

Another important issue is how to update the prediction in a multi-layered consolidation project with multiple monitoring points. In accordance with site investigation, the soil profile under the Ballina embankment should be divided into several layers, with the corresponding parameters (such as permeability and initial void ratio) being considered as random variables. The number of random variables can be large due to the significant number of soil parameters in the constitutive models associated within each layer. This greatly increases the difficulty in deriving the posterior probabilistic soil parameters. With few exceptions, the posterior distributions should be derived through sampling methods. The Markov chain Monte Carlo (MCMC) method is particularly popular, because it allows direct sampling from the posterior distribution without the need to evaluate a potentially high-dimension integral in the Bayesian formulation [32]. Many researchers have applied MCMC to update model parameters [12,21,22,33].

Taking the above issues into account, Bayes' theorem and an efficient MCMC algorithm are used to update the soil parameters in the multi-layer Ballina embankment, thereby developing updated predictions of its long-term behaviour. The physical mechanism of consolidation is simulated by the finite element method (FEM), in conjunction with the widely used Cam-Clay model [34,35]. The updating starts with an assumption for the prior distribution of the model parameters. The prior distribution may be assumed based on prior knowledge, such as site testing data, published literature, and engineering experience. The monitored behaviour is used to update the prior information, while the updated prediction is based on the posterior distribution of the model parameters. The posterior non-linear high-dimension distributions are obtained by efficient multi-chain MCMC simulation using DREAM$_{(ZS)}$ [36,37].

2. Numerical consolidation analysis using FEM

In this study, all numerical consolidation analyses are carried out using a modified version of the FE code "Program 9.3" from the book by Smith and Griffiths [38] and the paper of Huang and Griffiths [39]. The original Cam-Clay model [34,35] is implemented in this program to calculate embankment settlement and pore pressure, but creep and rate effects are not explicitly included in this numerical model. The validity and accuracy of the modified program will be verified for a one-dimensional (1D) consolidation problem with PVDs, as reported by Walker and Indraratna [36].

PVDs are typically installed in a triangular or square pattern (Fig. 1a), and are usually modelled by equivalent axisymmetric unit cells (Fig. 1b). As shown in Fig. 1b, the pore water in the unit cell flows from a soil cylinder to a single central PVD. The vertical drains are used to accelerate the consolidation of soft soil by providing both horizontal and vertical drainage paths along which excess pore water pressures, caused by a surcharge, can dissipate. Installing PVDs results in disturbance of the soil zone, termed a smear zone, adjacent to the drain. The undisturbed zone is around

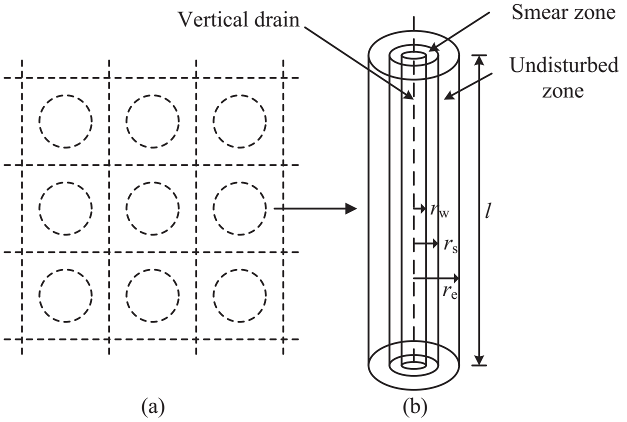

Fig. 1. (a) Drain installation pattern and (b) unit cell.

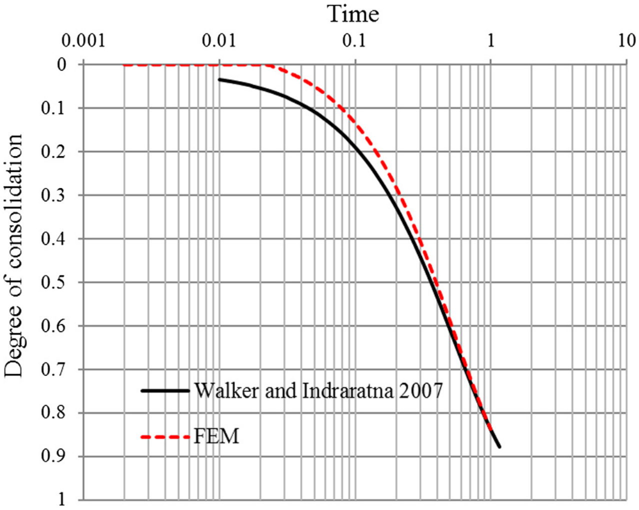

Fig. 2. Comparison between the results from FEM and Walker and Indraratna [40].