Probabilistic Cost Optimisation of Soil Improvement Strategies

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Abstract

In this paper a short overview is presented on the use of probabilistic calculations in order to increase the insight in the anticipated costs involved in a soil improvement strategy and to provide a useful tool for an economical optimisation.

1 Introduction

In Singapore, large-scale land reclamations for industrial purposes are executed by, among else, Van Oord ACZ. The subsoil of these reclamations often consists of soft, compressible materials such as marine clay. Depending on the clay properties, the thickness of the soft layer and the thickness of the placed sand layer, a certain settlement will occur within a certain consolidation time. In the specifications for reclamation works conditions are usually included, which restrict the remaining settlement after completion or which demand a minimum percentage of consolidation to be reached on a certain date.
To control the occurring settlement and/or to shorten the consolidation time different measures are available, such as prefabricated vertical drains and surcharge. These measures are recapitulated called "soil improvement".
During the tender procedure as well as during the actual execution of the reclamation works, it is of great importance to predict the settlement and consolidation time (possibly including a soil improvement) as accurate as possible. A probabilistic analysis is used to gain insight into the accuracy of settlement and consolidation calculations and to point out those parameters that have the largest influence on the degree of accuracy.

2 One-dimensional and Radial Consolidation

The compressibility of soils is almost entirely the result of a reduction of the void volume. This occurs as the applied stresses distort or break down the existing soil-skeleton structure locally, forcing the particles to form a denser structure with a lower void ratio. When a soil layer, saturated with water, is subject to a stress

increase, initially the pore water pressure is increased. In sandy soils, which are highly permeable, the drainage caused by the increase in the pore water pressure is completed immediately. When a saturated clay layer is subject to a stress increase the excess pore water pressure generated gradually dissipates over a long period. The settlement process, which takes place over a longer period of time caused by the slow drainage of pore water, is called consolidation.
A vertical drainage system relies in principle on the fact that the drainage path for the excess pore water from a layer of low permeability to a free surface is shortened. Along with the drainage path, the consolidation time is shortened as well. Equally spaced vertical drains are installed in the ground. These drains must offer insignificant resistance to the influx of excess pore water and channel it away vertically.

3 Errors and their Consequences

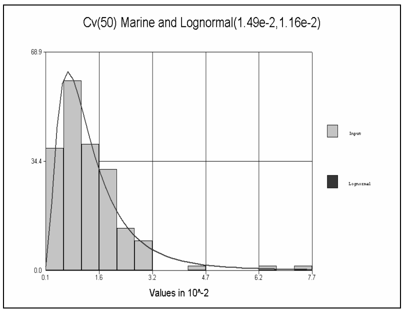
The natural heterogeneity of the subsoil plus the random nature of soil investigations introduces uncertainties with respect to the soil characteristics into the consolidation and settlement calculations. Furthermore the currently used calculation methods themselves are a simplification of reality. Due to the deviations in soil parameters and the simplifications in the methods used, the calculated consolidation time, as well as the predicted settlement, are subject to a certain error.
This has the following consequences:

- If the consolidation time and/or the final settlement appear to be less than predicted, then there are no negative effects, unless possible soil improvement actions appear to be unnecessary. Making a sharp first assessment can save costs.
- A more inconvenient situation arises when the consolidation time appears to be underestimated. Especially when the occurring consolidation time exceeds the date of completion. In this case, generally two actions can be taken:
    - execution of additional soil improvement, in order to reach the required consolidation percentage on the date of completion,
    - accept the consequences of not reaching the required consolidation percentage by the date of completion.

  Both actions have their own financial consequences.
- If the final settlement appears to be larger than the estimated settlement during the tender phase, more sand is needed to reach the design level. This can induce enormous additional costs. (e.g. remobilisation of trailing suction hopper dredgers)

4 Data Analysis

The soil data derived from the project is analysed in order to make the dataset suitable for further processing in the probabilistic calculations. First a multiple layer approach is performed and outliers are removed. Next, statistical distribution functions are fitted. See Figure 1.



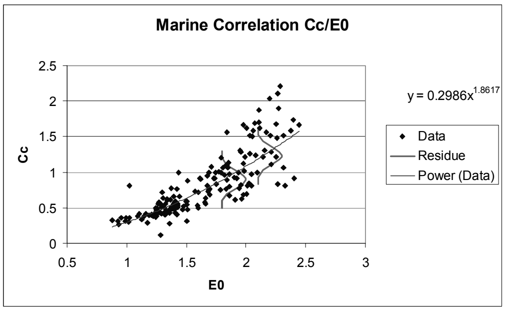


Figure 1 Distribution Function

Figure 2 Correlation

Finally, correlations between the different soil parameters are analysed. See Figure 2. The correlation between two stochastic parameters can be taken into account by means of Equation 1.

$$Y = A \cdot X^{B} + N(0,\sigma) \tag{1}$$

In which:

A, B = Variables
X = Base parameter
Y = Correlated parameter
N(0,σ) = Normally distributed residue

5 Probabilistic Calculations

The conventional method to calculate the consolidation time and the settlement is a deterministic one. In reality, the variables are stochastic, with a certain mean and standard deviation. In order to calculate the settlement and consolidation time, with stochastic variables, a Monte Carlo simulation is performed, using a computer model. The basic outline of this computer model, programmed in Visual Basic, is visualised in Figure 3. The figure visualises the different types of input, the position of the actual calculation module and the output of the calculation model. The output consists of distribution

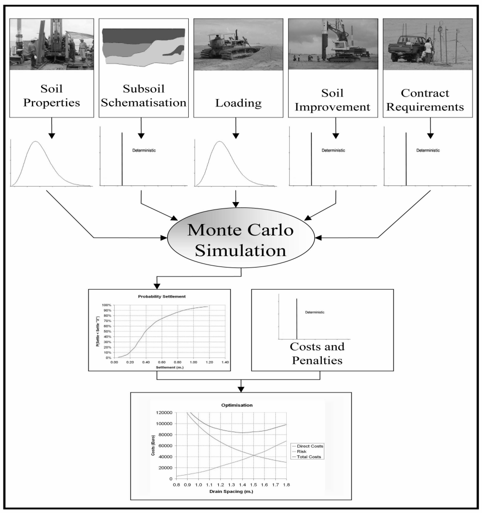


Figure 3 Basic outline calculation model

and probability density functions of the settlement and consolidation time.

In Figure 4 an example of a probability density function of the consolidation time is shown.

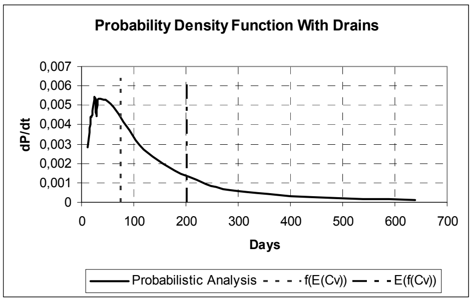


Figure 4 Probability density function consolidation time

6 Cost Optimisation

Risk can be defined as the product of the probability of a failure and the results of that failure, expressed in a financial value (costs and liquidated damages). The risk involved in estimating the consolidation time is expressed by Equation 2.

$$Risk = B\int_{t_{\lim}}^{\infty}\left(t - t_{\lim}\right)\cdot f\left(t\right)\cdot dt \qquad (2)$$

In which:

B = Penalty per day (Liquidated damages)

t_{lim} = Days at which the penalty procedure starts

f(t) = Probability density function

This empirical solution can also be derived analytically [1]. The total costs are the sum of the direct costs and the risk. In general one should minimise the total costs to obtain an optimal design. In this optimisation, vertical drains as well as surcharge are included. An example of this optimisation is visualised in Figure 5. The minimum total costs represent the optimum combination of surcharge and vertical drainage.

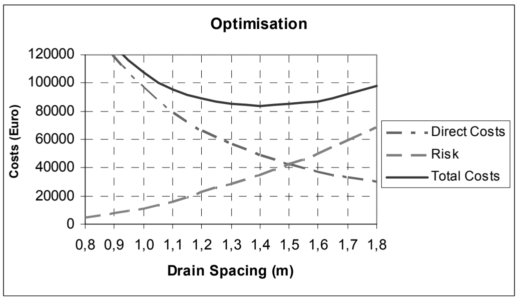


Figure 5 Cost optimisation

7 Voluntary versus Involuntary Risks

The risks as calculated by the probabilistic model form a significant part of the total costs. However, the risks can be separated in a voluntary and an involuntary part. The voluntary part is defined as that part of the risk, which is chosen simply because it is cheaper to accept the penalty, than to execute more soil improvement.

Example:
To reach 90% consolidation within 30 days, a drain spacing of 0.97 meter is necessary, determined by a deterministic calculation. The optimum drain spacing, determined by means of a probabilistic calculation, is 1.30 meter. The risks for the drain spacing of 0.97 and 1.30 meter are respectively 17000 and 37000 Euro. One could say that the split in voluntary and involuntary risks is 31% against 69%. The assumption is made that the risk in case of the deterministic calculation is the involuntary risk, the difference with the risk in case of the probabilistic optimisation is therefore the voluntary risk.
The possible penalty suffered following the probabilistic approach is lognormally distributed, as visualised in Figure 7.

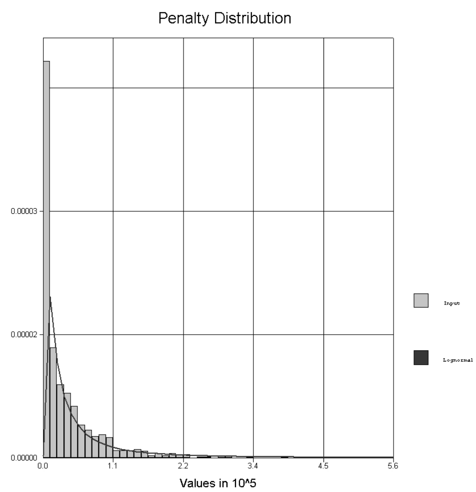


Figure 7 Penalty distribution

8 Conclusions and Discussion

Probabilistic calculations increase the insight in the costs involved in a soil improvement and make an economically optimal design possible.

Some of the most important conclusions and points of discussion are summarised below:

- Probabilistic calculations give a detailed insight into the costs involved in a soil improvement. The total costs for a soil improvement calculated in a deterministic manner usually comprise the direct costs plus a mark-up of approximately ten percent risk. Probabilistic calculations show that the direct costs are often slightly underestimated. Furthermore, probabilistic calculations indicate that the risk is likely to be approximately forty percent, depending on the input parameters. If one realises, however, that the deterministic calculations are accompanied by a certain “underestimated” risk and that this risk should be covered, a more beneficial configuration of direct costs and risk can be calculated using probabilistic methods. For more detailed information on this subject and other conclusions presented in this paper, see [2].
- Using probabilistic calculations, the total costs of a soil improvement can be minimised. By doing this a certain risk is often accepted. Increasing the amount of drains might prove to be more expensive than accepting the risk. The management perspective of this optimisation has not been assessed. Liquidated damages are often not the only negative effect caused by exceeding the penalty limit, also keywords like reliability and publicity can play an important role.
- Designers should recognise that soil properties contain large uncertainties, and should adopt design strategies that are effective in coping with such uncertainties.
- It is important to make the effort to obtain a robust subsoil model, in which not only several different soil layers are distinguished, if present, but in which surface deviations within the same layer are also assessed. This in order to minimise the standard deviation within a cluster of data used for calculation.
- The relative standard deviation in the consolidation coefficient determines for a significant part the magnitude of the risks involved in a soil improvement. See also [3]. This standard deviation can for example be reduced by narrowing the area of subsoil investigation. This can be done by subdividing the total area of interest into smaller calculation units.
- To lower the costs, direct as well as risk, additional soil investigation with the aim to decrease the relative standard deviation in the consolidation coefficient can be a lucrative option.
- Predictions of consolidation time and settlement made during the design can be expected to be approximate at best. Therefore a back analysis and monitoring of the settlements during construction are of high priority. The results of monitoring and observational methods should be used to update the design. The necessity of observational methods is also highlighted in [4].

- A good geotechnical design should allow for deviations in the soil properties and should be cost-effective.
- Soil improvement by means of drains is, in general, an economically more attractive option than the use of surcharge. Surcharge however is necessary in case a part of the expected creep has to be dealt with.

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