Proc. of the 9th International Symposium on Geotechnical Safety and Risk (ISGSR)
Edited by Zhongqiang Liu, Jian Dai and Kate Robinson
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doi: 10.3850/GRF-25280825_isgsr-091-P274-cd

PREDICTING SETTLEMENTS DEVELOPMENT UNDER ROAD EMBANKMENT USING PROBABILISTIC MODELS

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The road infrastructure project E6 Kvithammar-Åsen in the north of Trondheim, Norway, contains several large road embankments on sensitive clay. To improve the properties of such clays to sustain such embankments, lime-cement columns could have been installed, however, this would have led to high CO2 emissions. Therefore, preloading and vertical drains have been used as alternative soil improvement measures to reduce the extent of traditional lime-cement columns. The soil improved areas have been monitored by deformation sensors and piezometers during the 1.5 years since construction of the embankments. During this time, continuous assessments of the settlements have been performed showing that physics-based deterministic models underestimated the final total settlements. In this paper, the settlement measurements have been combined with available site data to gain new insights on how vertical drains affect the sensitive clays. Regression and probabilistic models have been applied on the time series data from the settlement sensors to see whether probabilistic methods can give a good forecast on how large the final settlements will be and when an acceptable rate of settlements will be reached.

Keywords: Vertical drains, embankments, sensitive clay, time series forecasting, settlements, sensor data.

1. Introduction

Several theoretical models can estimate the rate of consolidation and final settlement of a soil body. In addition, there are models developed for prefabricated vertical drains (PVD) to account for both the combination of radial and vertical drainage and potential installation effects (Larsson and Muller 2013). The models require soil material properties typically derived fromlaboratory tests (i.e. oedometer test)such as the compression modulus M and the coefficients of consolidation c_v and c_h. Furthermore, the soil parameters are expected to change with time and degree of consolidation, which requires additional estimates, like the diameter of the disturbed smear zone around the installed PVD, drainage path and soil layering.

Advanced material models in finite element (FE) analysis require fitting several parameters, but both Ayeldeen et al. (2021) and Berre (2017)found that the FE analysis underestimated the measured settlements. See for instance Filippo et al. (2017) for a thorough back-calculation of settlements that require many parameters to be set, estimated or tuned. They conclude that the predictions are noticeably influenced even by small variations in c_h and in the soil layering.

For areas subject to vertical drains, monitoring is recommended (Ayeldeen et al. 2021, Filippo et al. 2017). With monitoring settlement data available, statistical regression methods such as the approaches described in Asaoka (1978) can be applied to the problem to predict the total settlement at the end of the consolidation period. Uncertainty quantification is also obtainable by adopting a Bayesian approach.

This paper applies Bayesian linear autoregression to a vast amount of settlement measurement data spanning more than 1.5 years. The data is from a road infrastructure project located north of Trondheim, Norway where a 14-meter-high embankment with an additional 2-meter preloading has been established on 40 m thick sensitive clay with PVD. The purpose is to support the engineering estimation of final settlements, quantifying the uncertainty in such estimation, and the calculation of the settlement rate which is acceptable acoording to current guidelines for road design.

2. The Asaoka method with Bayesian regression

In his paper from 1978, Asaoka outlined a graphical, statistical approach to settlement predictions based on measurement data(Asaoka 1978). The method is a first order autoregressive method with 2 steps: (i) Interpolating all data points to a constant time interval Δt; (ii) plotting the interpolated data points in a S_i by S_{i-1} plot and do linear regression on them. Then, the fitted curve along with the final settlement value is given by

$$S_i = a + bS_{i-1} + \varepsilon \qquad (1)$$

where ε is the Bayesian error term having the standard normal distribution. The total settlement is found from the asymptote estimation using the assumption that $S_i = S_{i-1}$, which gives

$$\mathrm{S}_\infty = \frac{a}{1-b}, \qquad (2)$$

where a is the fitted intercept and b is the fitted slope. They are either point estimates or posterior distributions.

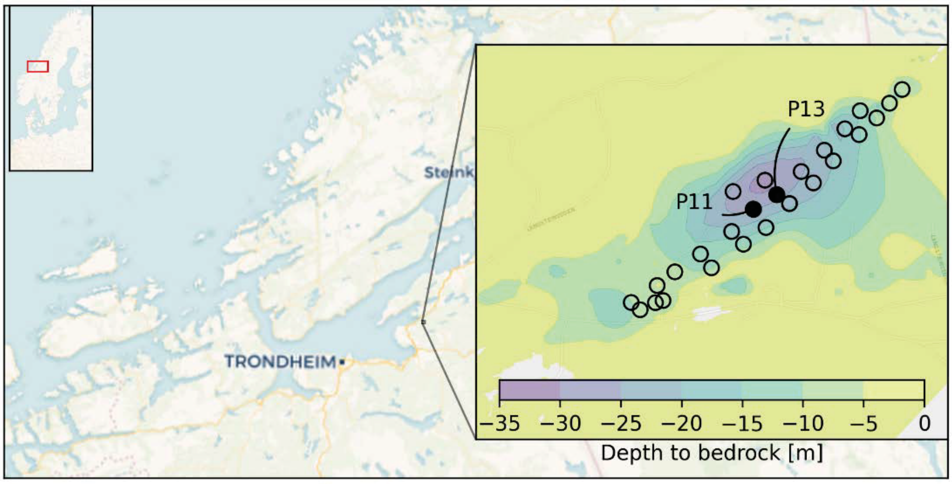

Figure 1. Location of sensors with P11 and P13 marked. The sensors are shown on a contour map of depths to bedrock.

3. Approach

3.1 *Dataset*

Historical settlement data from the area Langsteindalen along the road infrastructure project E6 Kvithammar-Åsen was utilized in the analyses, see location in Figure 1. The data is gathered from the deformations created by a 14-meter-high embankment with an additional 2 meters of pre-loading, on top of a roughly 40-meter-thick layer of sensitive clay. PVD are installed to improve the soil strength and increase the rate of consolidation to minimize future settlements of the finished road. There are 25deformation sensors installed in the area.For the present study, only sensors P11 and P13 are considered since they show the largest settlement development, being placed in an area with the largest soil thickness, as shown in Figure 1.

The Norwegian Public Roads Administration (NPRA) requires that the road does not exceed 40 cm of total settlements after 40 years of construction (Statens Vegvesen 2024). The aim of the geotechnical design was to allow for primary consolidation to be finished during construction period, leaving only secondary consolidation settlements for the operation phase. In the design, the estimate was to allow 6 months to up to a year for the consolidation.

3.2 *Data processing*

The data from each deformation sensor is fitted independently. Then, by means of the fitted curve parameters, a and b, whether they are point predicted or a distribution, the settlement curve is progressed into the future. The total settlement or asymptote is found from Eq. (2). Following recommendations from (Asaoka 1978), the initial settlement measurements are not included in the regression.

3.3 *Scoring*

To quantify the accuracy of the regression model, we employ two different metrics: *mean signed difference* or *deviation* (MSD) for the point predictions and *continuous ranked probability score* (CRPS) for the probabilistic predictions. Both scores have the same unit as the measurements, which make them easier to interpret in the context of the real-world application. MSD also has the benefit of showing whether the model underestimates settlements or overestimates.

4. Results and discussion

4.1 *Probability of fulfilling the settlement requirement*

The posterior distribution of the Bayesian regression gives an estimate of the probability that the final settlements (at infinite time) will be larger than 40 cm. To address this, Figure 2 presents the posterior distribution of sensors P11 and P13 with the final measured values and the value 40 cm larger than the final measured values are both marked with lines. This is on the conservative side because (a) more settlements are expected to occur before road finalization, and (b) the results are shown for infinite time, which is considerablymore than the required 40 years.Neither the posterior distributions of P11 and P13 crosses the limit at all.

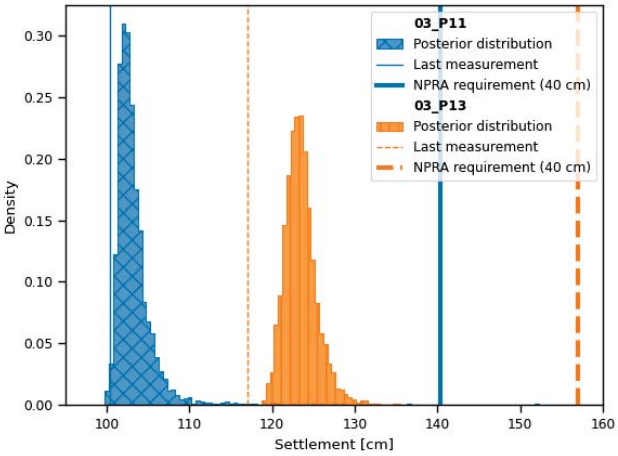

Figure 2Probability distribution for the posterior final settlement for sensors P11 (blue) and P13 (orange). The distribution is shown as a histogram. The NPRA requirement not exceeding 40 cm since road finalization is marked by a vertical line, but conservatively marked as 40 cm (thick line) from the last measurement (thin line).

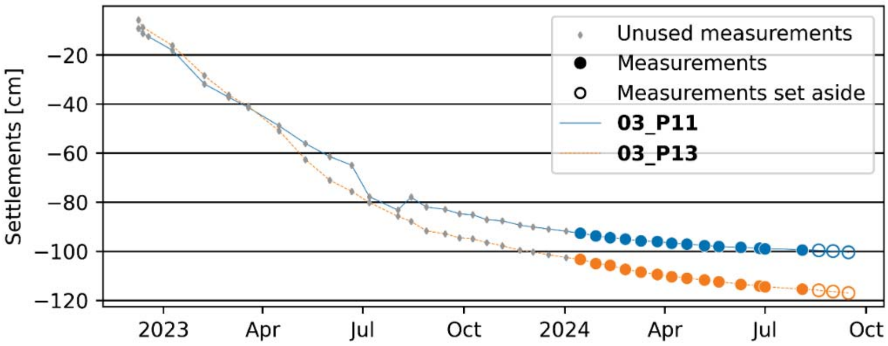

Figure 3 Visualization of the training and testing measurement data for sensors P11 (blue) and P13 (orange, dashed). All markers are measurements, with the gray diamonds being measurements unused in analysis, filled circles are measurements used for fitting the regression, and unfilled circles are measurements that are set aside to be the true answer to verify the model against.

4.2 *Model performance*

To judge how well the model performs, the 3rd and 10th most recent measurement data points have been set aside before applying the Asaoka Bayesian method on parts of the remaining measurement history, see Figure 3for an illustration of using a test set of 3 points and a training set of 14 points. The posterior results are progressed into the future, as illustrated inFigure 4 with all the most recent measurements included.After the regression model has been fitted to the sensor history, we have predicted the settlements at the time of the test datapoints.Then we compare the predicted distribution at that time point with the actual measurement to obtain the scores.

The MSD and CRPS scores for P11 and P13 are summarized in Table 1, averaged over the test points.Predictions get worse when the forecasting horizon is longer using most of the history (10 test points, 24 historic points), and the MSD shows they are less than the actual measured values. Most scores are less than 1 cm off, which are good results for our use case.

Table 1 Summary of CRPS and MSD scores for sensors P11 and P13. Worst results per sensor and metric are *italicized*, while best results are **bold**.

Number of test points	Number of historic points	CRPS (cm)		MSD (cm)	
		P11	P13	P11	P13
3	14	0.22	**0.23**	-0.29	**-0.35**
3	24	**0.21**	0.35	0.18	0.49
10	14	0.30	0.99	**-0.14**	1.57
10	24	*1.37*	*2.89*	*-1.55*	*-3.90*

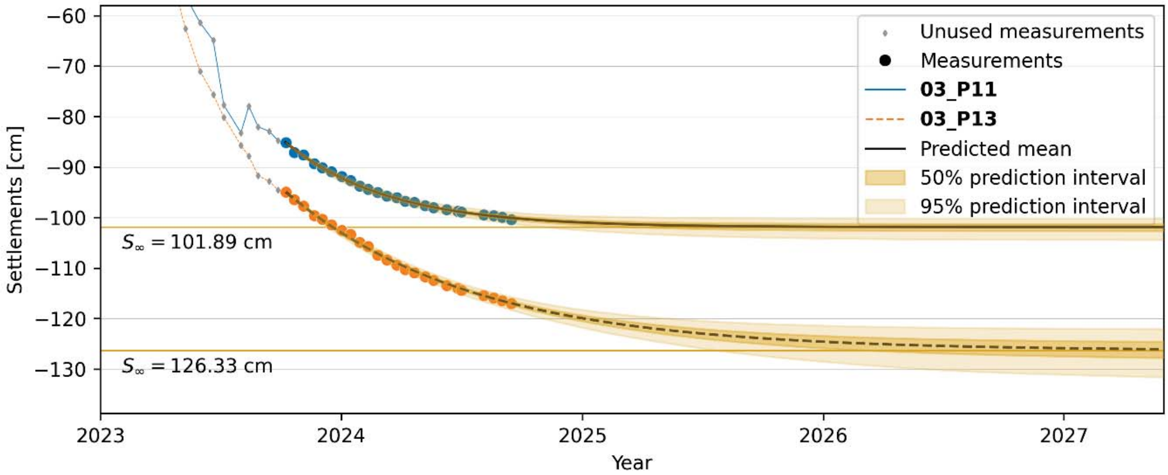

Figure 4 Settlement predictions (black line and shaded areas) for sensors P11 (blue) and P13 (orange, dashed) with final settlement asymptotes (yellow) S = 101.89 cm and S = 121.13 cm, respectively.

4.3 *Discussion*

Previous publications (Filippo, et al. 2017) state some of the limitations in Asaoka's method. Two of the limitations are the dependency of the results on the selected interpolation time interval Δt and the requirement of monitoring data for an extended period with most of the initial consolidation performed.

The Bayesian approach gives accurate enough predictions of the settlements including the entire distribution, as demonstrated by the metrics scores summarized in Table 1.When including the Bayesian regression, the model utilises the complete probability distribution and allows to estimate the deformations with an associated uncertainty (i.e. prediction interval), that can be given per sensor and per project at any given date. Beware that the mean predicted final settlement prediction of the total settlement is less conservative in the beginning of monitoring.

The model can provide predictions at any suitable date. This is helpful for decision making concerning the construction of the embankment. For running assessments of the goodness of fit of the model, the most recent measurements can be left out, as described in Section 4.2 .

5. Conclusion

The paper presented an implementation of the Asaoka Bayesian autoregressive method. The method has been tested and verified on an ongoing large infrastructure project in Trøndelag, Norway, onan embankmentconstructedon thick layers of vertically drained soft clays. The method predictsnear-futurewell, and produces a predicted distribution of the total settlements at infinite time. The implementation is useful for analyzing the monitoring data and making settlement predictions with quantified uncertainties. The geotechnical engineer analizing the data then can judge what settlement estimate to apply for the specific problem.

Further ongoing work will include adapting the second order autoregressive method for Bayesian regression. In this work, creep is not included. While we have implemented the second order autoregression method proposed by Asaoka (1978) to include creep effects, we have not yet extended it for Bayesian regression. Preliminary results show, as expected, that including creep leads to larger final settlements.

Acknowledgements

This work was funded by the basic funding to NGI from The Research Council of Norway.

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