Proc. of the 8th International Symposium on Geotechnical Safety and Risk (ISGSR)
Edited by Jinsong Huang, D.V. Griffiths, Shui-Hua Jiang, Anna Giacomini and Richard Kelly

doi: 10.3850/978-981-18-5182-7_10-009-cd

ISGSR 2022

Settlement Prediction of Teven Road Trial Embankment Using Back Analysis Methods

Shan Huang[1], Jinsong Huang[2], Richard Kelly[3] and Ahm Kamruzzaman[4]

[1]Discipline of Civil, Surveying and Environmental Engineering, The University of Newcastle, Callaghan, NSW 2308, Australia.
E-mail: SHuang2@uon.edu.au
[2]Discipline of Civil, Surveying and Environmental Engineering, The University of Newcastle, Callaghan, NSW 2308, Australia.
E-mail: jinsong.huang@newcastle.edu.au
[3]SMEC, Australia & New Zealand Division, Australia.
E-mail: DrRichard.Kelly@smec.com
[3]Transport for NSW, NSW 2308, Australia.
E-mail: Zaman.AHMK@transport.nsw.gov.au

Abstract: The Teven Road trial embankment is located adjacent to the existing Pacific Highway which is in the south of the National Field Testing Facility (NFTF) at Ballina, New South Wales, Australia. The construction of the trial embankment took over 7 years (2826 days). A sharp increase of the monitored ground settlement behavior was observed from 1940 to 2160 days, which makes it difficult to predict the settlement at early stages. To investigate how back analysis methods can be used to predict future settlement for Teven Road trial embankment, this study applied Asaoka method, Hyperbolic method and Bayesian back analysis method to predict settlement based on the monitored settlements. The results show that the prediction obtained by Asaoka and Hyperbolic methods are similar. The prediction made by Asaoka method is not stable due to the limited available records after the final loading. The predictions made by Bayesian back analysis agree with the measurements using 2400 days monitored data and the predictions can be further improved by incorporating creep.

Keywords: Settlement prediction; back analysis; embankment; soft soil creep.

1 Introduction

In coastal areas, embankments for supporting transportation infrastructures are inevitable to be constructed over soft soils, marine clays. Settlement prediction allows for more accurate predictions of the long-term embankment response, which is critical for developing rational strategies for accelerating consolidation in projects.

Considering the available monitored settlement in situ during and after the construction ages, back analysis may be a good choice to make settlement predictions. The data-based back analysis methods, Asaoka and Hyperbolic methods, were widely applied as the two methods are easy to be applied. Asaoka method was proposed by Asaoka (1978), and is a useful tool for interpreting and extrapolating field settlement observations (Jamiolkowski 1985; Mesri and Huvaj-Sarihan 2009). The Hyperbolic method originates from the rectangular hyperbola fitting method established and refined by (Sridharan and Rao 1981; Sridharan, Murthy, and Prakash 1987; Tan 1993). Tan (1994) extended this work to cover the case of finite strain consolidation with nonhomogeneous initial conditions and nonlinear compression property and permeability in clay sand mixes. The limits of Asaoka and Hyperbolic methods are that the two methods lack of solid mechanic background, which means that the accuracy of these two methods significantly rely on the quality of the measurements. However, due to the nature of the site investigation, soil sampling, and soil tests, inaccuracies exist inevitably in the monitored data. Model-based prediction methods use the mathematics of the physical model to simulate and usually require the recording of multivariate data. The accuracy of the prediction depends on the validity of the physical assumptions soil variables. Bayesian back analysis provides an effective tool to improve the understanding on the uncertain soil properties by combining prior knowledge with sparse site specific information in a consistent way (Straub and Papaioannou 2015; Papaioannou and Straub 2017; Zhang et al. 2017). It has been proved to be a rational and robust means of updating the input parameters and accurately predicting the long term behavior based on reliable observations (Kelly and Huang 2015; Hsein Juang et al. 2013; Zhang, Tang, and Zhang 2010; Miranda, Correia, and e Sousa 2009; Honjo, Wen-Tsung, and Guha 1994; Huang et al. 2021).

In this study, the settlement prediction of the Teven Road trial embankment is performed by the data-based Asaoka and Hyperbolic methods, and the model-based Bayesian back analysis methods based on a period of more than 3 years field monitored data and results from laboratory tests. This work aims at providing a complete case study by comparing the settlement predicted by Asaoka and Hyperbolic methods, and Bayesian back analysis method with field data from the instrumented embankment. The results can provide a reference for the geotechnical design, and improve the confidence for the engineers to make decisions in time.

2 Bayesian back analysis

Considering the uncertainties existing in some of the soil parameters, those uncertain parameters are thus modelled as random variables $\boldsymbol{x}$. A measurement error $\boldsymbol{e}$ is defined as the difference between the actual performance $\boldsymbol{d}$ and the model prediction $\boldsymbol{F}(\boldsymbol{x})$. We then have

$$\boldsymbol{d} = F(\boldsymbol{x}) + \boldsymbol{e} \tag{1}$$

Based on the Bayesian theorem, the posterior information is inferred by updating prior probability distribution with monitored data. This process can be expressed with

$$P(\boldsymbol{x}|\boldsymbol{d}) = cL(\boldsymbol{x}|\boldsymbol{d})\,P(\boldsymbol{x}) \tag{2}$$

where c is a normalized constant and $L(\boldsymbol{x}|\boldsymbol{d})$ is the likelihood function; $P(\boldsymbol{x})$ is the prior distribution reflecting the knowledge about $\boldsymbol{x}$ before obtaining the field-monitored data and $P(\boldsymbol{x}|\boldsymbol{d})$ represents the posterior information.

The prior information is usually obtained from site investigation, engineering judgement and experience. The posterior information $P(\boldsymbol{x}|\boldsymbol{d})$ is obtained by updating $\boldsymbol{x}$ which incorporates both the prior information and the field monitored behaviors. In this study, a multi-chain MCMC program, DREAM(ZS), proposed by (Vrugt et al. 2009) is used to obtain the posterior probability distribution function (PDF) of the model parameters $\boldsymbol{x}$.

3 Case study

3.1 Model description

The Teven Road as a proportion of the Ballina Bypass, is constructed by the Roads and Traffic Authority (RTA) of New South Wales. The soil deposit of the Teven Road embankment is overlain by 1.1 m crust clay, followed by 11.4 m estuarine soft clay and 8.6 m transition clayey sand layer with increasing sand content with depth. Permeable boundary conditions are imposed on both the top and the bottom the soil model. To increase the accuracy of the consolidation analysis, the estuarine clay layer is further divided into two sublayers. Therefore, there are 4 layers in total. The scheme diagram the soil profile and the drainage condition of the Teven Road trial embankment is shown in Figure 1. The vertical loading history and the monitored settlement are presented in Figure 2.

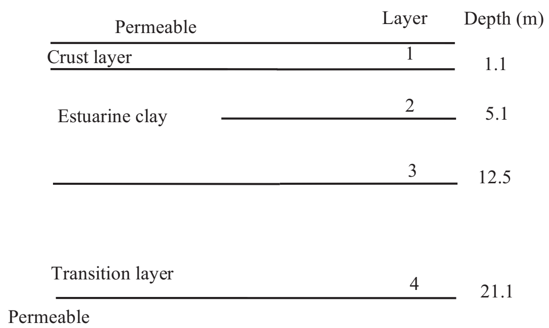


Figure 1. The schematic diagram of the Teven Road trial embankment.

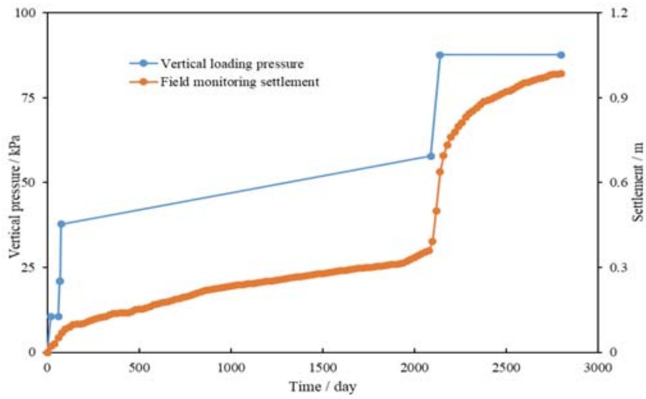


Figure 2. The vertical loading history and the monitored surface settlement of the Teven Road embankment.

3.2 Results and discussions

3.2.1 Settlement prediction based on Asaoka method

In this section, Asaoka and Hypobolic methods are applied to make settlement predictions of the Teven Road trial embankment. The obtained results based on all of the monitored settlements with Δt=10 days are shown in Figure 3 where the round points are measurements and the straight line is the linear fitting of the measurements.

As shown in Figure 3, the slope of the linear trend line, β, is 1.0042 and the intercept β_0 is 0.0019. A negative ultimate settlement, δ_f, is then obtained. To obtain a reasonable final settlement, the monitored data is divided into two parts. The first part includes the monitored data from 0 to 2000 days, and the second part includes the monitored data from 2000 days to the end. The monitored data for the two parts and the corresponding linear fitting straight lines when Δt=100 and 200 days are all presented in Figure 4.

As shown in Figure 4(a), Δt=100 days, the ultimate settlement can be obtained by the second part monitoring data, which is 0.5947 / (1-0.3774) = 0.95519 m. However, if less than 2000 days monitoring data is applied, the ultimate settlement cannot be used to make the prediction as the slope of linear fitting line is larger than 1.0, which would lead to a negative ultimate settlement. In Figure 4 (b), when Δt=200 days, the ultimate can be obtained from the two parts of the monitored data. For the first part, the ultimate settlement is 0.043 / (1-0.9216) = 0.544 m. For the second part, the ultimate settlement is 0.6372 / (1-0.3544) = 0.987 m which is closer to the settlement monitored at 2700th day (0.97 m). It can be concluded that the reasonable prediction of ultimate settlement can only be obtained if the monitoring data after 2100 days (the start of the last loading stage) is used.

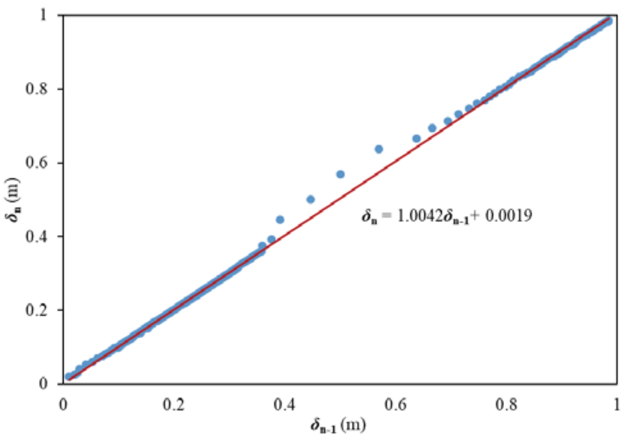
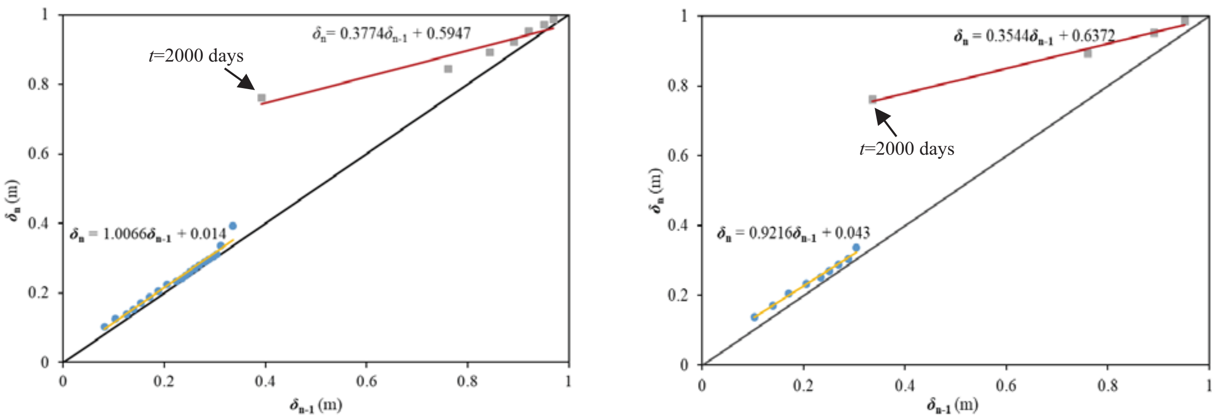


Figure 3. Predictions obtained using Asaoka method with Δt=10 days



(a) Δt=100 days (b) Δt=200 days

Figure 4. Predictions obtained using Asaoka method with Δt=100 and 200 days

3.2.2 Settlement prediction based on Hyperbolic method

In this section, the Hyperbolic method is applied to make the prediction based on the monitored settlement of the Teven Road trial embankment. Any settlement data before loading was completed cannot be used in Hyperbolic method. Therefore, according to the loading history shown in Figure 2, the last loading ends at 2160 days and the settlement was 0.695m. The hyperbolic plot based on the monitored data after 2160 days is shown in Figure 5.

It can be seen from Figure 5 that the slope for the linear segment of the hyperbolic plot S_i = (620/0.288-280/0.201)/(620-280) = 2.2345. The slope for the 60% consolidation line S_{60} = S_i/0.6/α_i = 2.2345/0.6/0.821 = 4.5362, where α_i is slope of the linear segment for the theoretic Hyperbolic plot based on Terzaghi's consolidation theory and is 0.821 (Tan and Chew 1996). The slope for the 90% consolidation line can be obtained by the same way, which is S_{90} = S_i/0.9/α_i = 2.2345/0.9/0.821= 3.0241. The settlement at 60% consolidation point, δ_{60}, can be determined by 0.6×(α_i/S_i) = 0.6×0.821/2.2345 = 0.22m, based on δ_{60}, t_{60} can be roughly determined as 340 days, the ultimate settlement can also be obtained by 0.22/0.6+0.695=1.062m, where 0.695 is the settlement at t=2160 days. As there is no sufficient monitoring records, as shown in Figure 5, the maximum value for the time from 2160 days is 620 days and t/δ at the maximum time point is 2145.33 day/m which is larger than the one for the 90% consolidation line which is S_{90}×t=3.0241×620=1874.97. Therefore, t_{90} cannot be employed to make the prediction. The estimation of the final settlement based on Hyperbolic method is 1.062 which is quite close to the measurement at 2700th day (0.97 m).

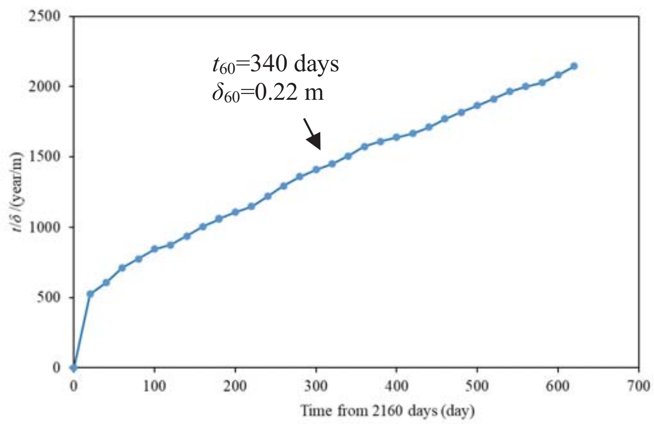


Figure 5. Results of the Hyperbolic method based on the monitored data after 2160 days.

3.2.3 Settlement prediction based on Bayesian back analysis

In this section, Bayesian back analysis approach is used to perform the settlement prediction of the Teven Road trial embankment. A self-developed Visual Basic program based on the simplified hypothesis B method is used to do consolidation analysis in the Bayesian updating process. In the section, the recompression index C_r and the permeability k_v for each soil layer are considered as random variables. In addition, two more factors, R_1 and R_2, are defined as the ratio of the recompression index to the compression index (C_r/C_c), and the ratio of the creep factor to the compression index (C_α/C_c). Therefore, there are 10 random variables for the situation when creep is considered and 9 random variables when creep is ignored. C_r and k_v are considered to obey log-normal distribution to avoid negative values. R_1 and R_2 are deemed to be uniformly distributed with the range of 5-10 and 0.02-0.05 respectively. The basic information and the prior of soil parameters of the Teven Road trial embankment are presented in Table 1. The vertical loading pressure, construction time and the stage duration for the 5 loading stages are shown in Table 2.

Table 1. Parameters of soils for the Teven Road embankment.

Parameter	Layer	Crust clay	Estuarine clay		Silty transition zone
		1	2	3	4
Layer thickness	H_j (m)	1.1	4.0	7.4	8.6
Over-consolidation ratio	OCR	10.211	3.114	1.712	0.824
Unit weight of soil layer	γ (kN/m^3)	18.7	14.7	14	16
Initial void ratio	e_0	0.62	2.2	2.9	0.5
Recompression index	C_r	0.00989	0.09982	0.09982	0.01978
Factor 1 (C_c/C_r)	R_1	6	6	6	6
Factor 2 (C_α/C_c)	R_2	0.04	0.04	0.04	0.04
Reference time	t_0 (day)	1	1	1	1
Ratio of vertical permeability to the unit weight of water	k_v/γ_w (m/day)	3.52E-03	8.82E-06	4.41E-06	8.82E-06
Coefficient	COV[κ, λ]	0.3536	0.1258	0.1258	0.3
of variation	COV[k_v/γ_w]	3	3	3	3

Table 2. Construction time, stage time, and vertical pressures of the loading history.

	Stage 1			Stage 2			Stage 3		Stage 4		Stage 5		
Time (day)	0	20	60	60	68	70	70	75	75	2091	2091	2140	2800
Pressure (kPa)	0	10.5	10.5	10.5	21	21	21	37.8	37.8	57.8	57.8	87.62	87.62
Construction duration (day)	20			8			5		2016		49		
Stage ending time (day)	60			10			5		2016		709		

In this section, the settlement prediction is performed by using the prior and the monitored data at various days with creep considered and creep ignored. Bayesian back analysis starts with the monitored data prior to 70th day to update the random variables. The results are presented in Figure 6 with creep ignored and in Figure 7 with creep considered. In this two figures, the legend 'measurements' represents the monitored settlement at surface and prior prediction which are obtained by exclusively using prior information is denoted by a legend 'prior'. The legend '70d' means the prediction is based on the monitored data from 0 to 70 days, and the same meaning of '70d' can be extended to the legend '70d', '400d', …, '2800d'.

As presented in Figure 6 and Figure 7, the settlement prediction is improved by incorporating more monitoring data when compared with the settlement prediction based on the prior. It can be seen from Figure 6, when creep is ignored, the settlement after 1940th day can be well predicted when 2400 days monitored data is applied, but the predictions still deviate from the monitored settlement before the last loading (before 1940th day). However, when creep is considered, as shown in Figure 7, the whole monitored settlements agree well with the predictions by using the monitored settlement prior to 2400th day.

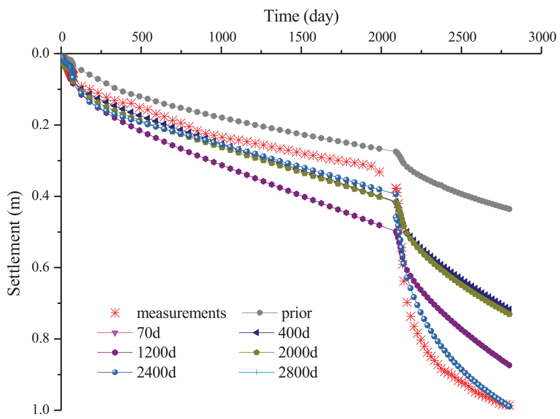


Figure 6. Settlement prediction based on various days monitoring data ignoring creep.

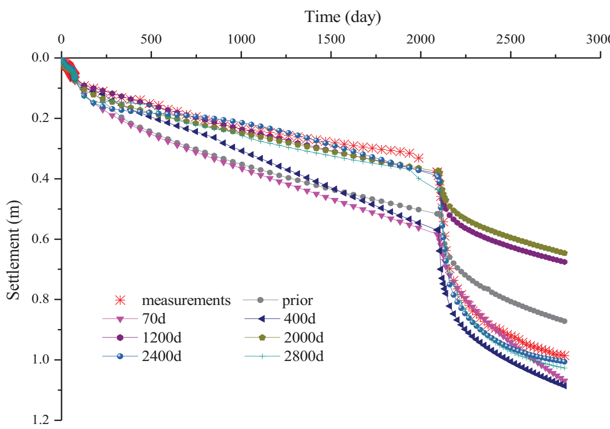


Figure 7. Settlement prediction based on various days monitoring data considering creep.

4 Conclusions

In this study, three different back analysis methods are applied to do settlement prediction of the Teven Road trial embankment. The specific loading history of the Teven Road that the monitored settlement experience a dramatic increase after the last loading, makes it difficult to make long-term predictions. Based on the results obtained, the following conclusions can be drawn:

(1) The predictions obtained by Asaoka and Hyperbolic methods are similar. For Hyperbolic method, to identify the linear portion of the hyperbolic plot, the monitored data after at least 2500 days should be applied. There is no sufficient data recorded to identify 90% consolidation point, which means the Hyperbolic method cannot be employed based on t_{90}. For Asaoka method, unreasonable predictions (negative values) could be obtained if the monitored data before 2000th day is applied. The prediction made by Asaoka method vary with the number of monitored data used as there is no enough monitored data beyond 2000 days.

(2) For Bayesian back analysis, the predictions agree well with the measurements when 2400 days monitoring data is applied;

(3) The settlement predictions can be improved by incorporating creep in the Bayesian back analysis.

References

Asaoka, A. (1978). Observational procedure of settlement prediction. *Soils and foundations*, 18: 87-101.

Honjo, Y., Wen-Tsung, L., and Guha, S. (1994). Inverse analysis of an embankment on soft clay by extended Bayesian method. *International Journal for Numerical and Analytical Methods in Geomechanics*, 18: 709-34.

Hsein Juang, C., Luo, Z., Atamturktur, S., and Huang, H. (2013). Bayesian updating of soil parameters for braced excavations using field observations. *Journal of geotechnical and geoenvironmental engineering*, 139: 395-406.

Huang, S., Huang, J.S., Kelly, R., Zeng, C., and Xie, J.W. (2021). Settlement Predictions of a Trial Embankment on Ballina Clay. *ISSMGE International Journal of Geoengineering Case Histories*, 6: 101-14.

Jamiolkowski, M. (1985). New development in field and laboratory testing of soils. *In Proc. 11th ICSMFE*, 57-153.

Kelly, R., and Huang, J.S. (2015). Bayesian updating for one-dimensional consolidation measurements. *Canadian Geotechnical Journal*, 52: 1318-30.

Mesri, G., and Huvaj-Sarihan, N. (2009). The Asaoka method revisited. *In Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering (Volumes 1, 2, 3 and 4)*, 131-34. IOS Press.

Miranda, T., Correia, A.G., and e Sousa, L. R. (2009). Bayesian methodology for updating geomechanical parameters and uncertainty quantification. *International Journal of Rock Mechanics and Mining Sciences*, 46: 1144-53.

Papaioannou, I., and Straub, D. (2017). Learning soil parameters and updating geotechnical reliability estimates under spatial variability–theory and application to shallow foundations. *Georisk: Assessment and Management of Risk for Engineered Systems and Geohazards*, 11: 116-28.

Sridharan, A., Murthy, N., and Prakash, K. (1987). Rectangular hyperbola method of consolidation analysis. *Geotechnique*, 37: 355-68.

Sridharan, A., and Rao, A. (1981). Rectangular hyperbola fitting method for one dimensional consolidation. *Geotechnical Testing Journal*, 4: 161-68.

Straub, D., and Papaioannou, I. (2015). Bayesian analysis for learning and updating geotechnical parameters and models with measurements. *Risk and reliability in geotechnical engineering*: 221-64.

Tan, S. (1993). Ultimate settlement by hyperbolic plot for clays with vertical drains. *Journal of geotechnical engineering*, 119: 950-56.

Tan, S. (1994). Hyperbolic method for settlements in clays with vertical drains. *Canadian Geotechnical Journal*, 31: 125-31.

Tan, S., and Chew, S. (1996). Comparison of the hyperbolic and Asaoka observational method of monitoring consolidation with vertical drains. *Soils and foundations*, 36: 31-42.

Vrugt, J.A., Ter Braak, C., Diks, C., Robinson, B., Hyman, J., and Higdon, D. (2009). Accelerating Markov chain Monte Carlo simulation by differential evolution with self-adaptive randomized subspace sampling. *International journal of nonlinear sciences and numerical simulation*, 10: 273-90.

Zhang, J., Boothroyd, P., Calvello, M., Eddleston, M., Grimal, A.C., Iason, P., Luo, Z., Wang, Y., and Walter, H. (2017). Bayesian method: A natural tool for processing geotechnical information. *TC205/TC304 Discussion Groups, ISSMGE*.

Zhang, J., Tang, W.H., and Zhang, L.M. (2010). Efficient probabilistic back-analysis of slope stability model parameters. *Journal of geotechnical and geoenvironmental engineering*, 136: 99-109.