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METHOD UNCERTAINTY FOR SLOPE STABILITY ANALYSIS BASED ON ACTUAL LANDSLIDE CASES IN HONG KONG

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Method uncertainty is one of the uncertainties to consider under reliability analysis. The method uncertainty for slope stability analysis using the 2D Morgenstern-Price method, which is a commonly employed limit equilibrium method, was evaluated based on landslide cases in Hong Kong. Model factors were established by considering the responses in terms of factor of safety. Ten notable landslide cases with detailed landslide investigation information were investigated in this study, which enabled the calculation of the analytical factor of safety at the time of the failure, with minimal uncertainty about the landslide conditions. The model factors determined from the best-estimate model parameters have a mean of approximately 1.0 with coefficient of variation of 0.1. A sensitivity analysis considering the uncertainties in groundwater conditions at failure was also conducted to assess the lower and higher bound estimates of model factors based on these cases. The findings align with the range of model factors established in the literature and encourage practitioners to consider the uncertainties associated with analytical methods in their calculations.

Keywords: Method Uncertainty; Model Factor; Slope Stability; Actual Landslide Cases; Hong Kong.

1. Introduction

The uncertainty associated with the analytical method used to predict engineering behaviors, also known as method uncertainty, is one of the uncertainties to consider in reliability analysis. The method uncertainty can be quantified by a model factor (M), which is defined as the ratio of the measured or observed response (X_m) to the calculated response (X_c).

In conventional soil slope engineering, the 2D plane strain limit equilibrium method (LEM) is usually adopted to analyze slope stability in terms of the factor of safety (FOS). This analytical method, which involves simplifications of the actual equilibrium conditions, 3D effect, etc., introduces uncertainties into the calculated results. The response for evaluating method uncertainty for slope stability can be defined in terms of FOS. It is assumed that when a slope fails, the observed FOS (i.e. X_m) is unity. This assumption enables the evaluation of method uncertainty by comparing the observed FOS of unity for failed cases with the calculated FOS (i.e. X_c) by modelling the slope under the observed conditions at failure.

The Probabilistic Model Code by the Joint Committee on Structural Safety (Baker and Calle 2006) provides indicative figures of the expected means and standard deviations of M for common geotechnical computation models. For embankment slope stability assessed using failure arc analysis (e.g. Bishop, Spencer, etc.), the expected mean of M is 1.1 and the standard deviations are 0.05 and 0.10 for homogeneous and non-homogeneous soils, respectively.

In the literature, studies of method uncertainty of slope stability analysis have mainly been based on the observed response from centrifuge tests and actual landslide cases. Centrifuge tests are carried out in relatively controlled conditions in which the uncertainties related to material parameters and hydraulic conditions are minimized. Zhang et al. (2009) adopted the Morgenstern-Price method to calculate the FOS of slopes corresponding to a series of centrifuge tests conducted on sandy soils without slope reinforcement by Kim and Ko (1982). The mean and coefficient of variation (COV) of the corresponding M are 0.999 and 0.043 respectively. It is considered that the M evaluated based on centrifuge tests can reflect effectively the uncertainty pertaining to the calculation method for idealized, laboratory-prepared slope models; however, the centrifuge idealization could not address certain aspects of uncertainty of the actual slopes including the representativeness of the conditions in-situ.

Evaluation of M based on actual slope failure cases can reflect also the uncertainty due to modelling assumptions made about the representativeness to the in-situ slope conditions at failure. Detailed landslide investigations reveal the slope conditions at failure and provide valuable information for constructing reliable analysis models. For example, ground investigation conducted near the slip surface can reduce the uncertainty of stratigraphy and soil shear strength. Continuous groundwater monitoring during progressive failure provides valuable information on the failure groundwater conditions. The global database of landslide cases from Travis et al. (2011a) and Bahsan et al. (2014) show that the mean of M for man-made slopes is between 0.89 and 1.19 while the COV is between 0.15 and 0.28 for various LEMs.

While the global database provides a general indication of the distribution of M, the model representativeness to the in-situ slope conditions at failure may be related to the ground and hydrogeological conditions and the practice of data collection in a local region. Therefore, it is of interest to establish the distribution of M for Hong Kong, by leveraging the database of well-documented assessments of field conditions at the time of landslide and in-depth landslide investigation, and compare with the literature. This paper presents the method uncertainty assessed using ten selected landslide cases in Hong Kong with high-quality field observations and landslide investigation conducted by the Geotechnical Engineering Office (GEO).

2. GEO Systematic Landslide Investigation

The GEO launched the systematic landslide investigation program in 1997. All landslides reported to the GEO were investigated, and selected cases were studied in detail on the basis either of their serious nature or for the purposes of advancing the understanding of landslides in Hong Kong. In some landslide studies, when deemed necessary, ground investigations with continuous retrieval of undisturbed soil samples from drillholes near the failure surface were carried out, which confirmed the stratigraphy of the ground. Laboratory tests were also conducted on the retrieved soil samples or failure materials, allowing for a refined estimation of shear strength of the materials along the failure surface. To approximate the groundwater conditions at failure, post-landslide groundwater monitoring was conducted if pre-landslide measurement was not available. Site observations of seepage conditions during landslide inspection, which was usually conducted within a few hours after a landslide case was reported to the GEO, were also useful in estimating the groundwater conditions at failure. To delineate the failure surface, advanced remote sensing technology using laser scanning was applied to landslide scars and surroundings for high-resolution topography surveys. In the case where a slope underwent progressive failure, although less common in Hong Kong, subsurface movement monitoring through instrumentations such as inclinometers was carried out, which provided information on the location of the slip surface.

These landslide studies and findings were documented in reports systematically, which are available on the Civil Engineering and Development Department website (https://www.cedd.gov.hk) as GEO Reports. All the above information assists in constructing analytical models with the best-estimate failure conditions, reducing the uncertainties from other sources during the evaluation of the model factor in this study.

3. The Selected Landslide Cases in Hong Kong

In this study, ten landslide cases were selected based on the availability of detailed investigation information, which facilitated the calculation of the analytical FOS of the slopes at the failure condition. Table 1 summarizes the information about the ten selected landslide cases. All of the landslides occurred in cut slopes. Various sources of information pertaining to the ground model, laboratory test results of soil properties, slip surface geometry, groundwater conditions and field observations shortly after the landslide had been elaborated in the respective landslide study reports.

In each landslide case, a best-estimate model factor was obtained by adopting the best knowledge of the landslide conditions as the input parameters of the 2D slope stability model and computing the FOS using the Morgenstern-Price LEM. For example, the ground profile, ground model and failure slip geometry as depicted in the landslide investigation reports were directly employed. The best-fit shear strength parameters of soils derived from site-specific laboratory test data within the relevant stress range were adopted. The best-estimate groundwater conditions based on the information provided in the study reports were considered in the calculation model. This approach of presenting the method uncertainty using the best knowledge of the landslide case aligns with the methodology employed in the literature such as Travis et al. (2011a & 2011b). The best-estimate model factors for the ten selected landslide cases are presented in Table 1. The distribution of these best-estimate model factors has a mean value and COV of 1.0 and 0.1, respectively. Compared with the M distribution established in Zhang et al. (2009), which was based on centrifuge tests, the best-estimate M distribution based on actual landslide cases in Hong Kong has essentially the same mean but more dispersed.

It is well known that the accuracy of model factors determined based on actual landslide cases is closely related to the uncertainty of input parameters in the slope stability model, which arises from various information sources potentially containing measurement errors, bias and randomness. The best-estimate model factor therefore consists of not only the calculation method uncertainty but also the uncertainty in representing the field conditions to varying degrees. In particular, the information on the groundwater profile at failure is usually not exact for slopes without real-time groundwater monitoring along the failure sections coupled with the knowledge of the precise failure time. For this reason, the landslide study reports often provide a range of probable groundwater levels at the time of failure. In this study, a sensitivity analysis of model factors considering the uncertainties in groundwater conditions at failure was conducted.

Table 1. Summary of Selected Landslide Cases for Evaluating Method Uncertainty

No.	Landslide Case	Mode of Failure	Failure Volume (m^3)	Predominant Failed Material	Basis of Groundwater Conditions in Slope Stability Models	Best-estimate Model Factor, M
1	1983 Pun Shan Village Tuen Mun Highway (Choot 1984)	Progressive failure of soil mass	34,000	Completely Decomposed Tuff (CDT)	Groundwater Monitoring (GWM) during progressive movement	1.01
2	1992 Siu Sai Wan (GEO 1993)	Progressive failure of soil mass	3,400	CDT	GWM during progressive movement	0.91
3	1994 New Clear Water Bay Road (MGSL 2006)	Landslide through soil mass with effects of relict joints	800	Completely Decomposed Granite (CDG)	GWM before landslide and seepage observed after landslide (one hour after landslide occurred)	1.00
4	1995 Sham Shui Kok CLP Substation (GEO 1995)	Progressive failure of soil mass	40,000	CDT and feldsparphyric rhyolite	GWM during progressive movement	1.08
5	1995 Fei Tsui Road (GEO 1996)	Discontinuity-controlled failure	14,000	Kaolinite-rich altered tuff	GWM before landslide and seepage observed after landslide	1.00
6	1997 Ching Cheung Road (HAPL 1998a)	Landslide through soil mass	1,800	CDG	GWM before landslide and seepage observed after landslide	1.09
7	1997 Hong Tsuen Road (HAPL 1998b)	Landslide through soil mass	250	Clay-rich completely decomposed volcanic	GWM before landslide and seepage observed after landslide	0.88
8	1997 Kau Wa Keng (HAPL 1998c)	Landslide through soil mass	360	CDG	GWM and seepage observed after failure	1.02
9	1997 Ten Thousand Buddhas' Monastery (HAPL 1998d)	Discontinuity-controlled failure	1,500	CDG	GWM and seepage observed after failure	1.03
10	2008 Pak Fuk Road (FSWJV 2009)	Landslide through soil mass	1,270	CDG	GWM before and after landslide and seepage observed after landslide	1.14

4. Sensitivity Analysis of Model Factors Considering Uncertainties in Groundwater Conditions

In some landslide studies, a pair of upper and lower bounds of groundwater conditions at failure were deduced from collected facts and engineering judgment. The probable range of groundwater conditions was usually assessed by considering multiple factors, such as the time and location where seepages were observed, the rainfall pattern before and during the landslide inspection, the potential of upslope recharge and the hydrogeological conditions of the slope, etc. Using the upper and lower bounds of groundwater conditions, a pair of higher and lower bound estimates of M and thus a range of mean and COV of model factor distribution were calculated.

Among the ten selected landslide cases in this study, the best-estimate groundwater conditions at failure for the three cases of progressive failure and the 1994 New Clear Water Bay Road landslide (i.e. No. 1-4 in Table 1), which were either supported by measurement or timely observation, were considered verified, while those for the other six cases (No. 5-10) were less certain and the upper and lower bound groundwater conditions were established. The analytical FOS and its corresponding M were calculated using the upper and lower bound groundwater conditions for these six cases. Table 2 shows the higher and lower estimates of M for the six cases.

To account for the possible occurrence of higher and lower estimates of M of individual landslide cases, a range of mean and COV of model factor distributions was established by considering all possible combinations of the higher and lower estimates of M for Case No. 6-10, and incorporating with the best-estimate M values for Case No. 1-4. The maximum and minimum of the mean value of M are 1.13 and 0.93, respectively; and the maximum and minimum of the COV are 0.22 and 0.12, respectively. While the analytical FOS value is highly sensitive to the groundwater conditions input in the model, the distribution of M of the ten selected cases after considering the probable bounds of groundwater conditions at failure has a narrower range compared to the results based on global database of landslide cases from Travis et al. (2011a) and Bahsan et al. (2014). This may indicate that a local database with detailed landslide investigation is worth establishing for the purposes of refining the distribution of *M.* More case studies covering different site settings are recommended before further conclusions can be drawn.

Table 2. Higher and Lower Estimates of Model Factors considering Probable Range of Groundwater Conditions

No.	Landslide Case	Lower estimate of M	Higher estimate of M
5	1995 Fei Tsui Road	0.93	1.08
6	1997 Ching Cheung Road	0.95	1.27
7	1997 Hong Tsuen Road	0.70	1.35
8	1997 Kau Wa Keng	0.91	1.16
9	1997 Ten Thousand Buddhas' Monastery	0.70	1.12
10	2008 Pak Fuk Road	1.08	1.36

5. Conclusion

The method uncertainty for slope stability analysis using the 2D Morgenstern-Price LEM based on ten notable actual landslide cases in Hong Kong was evaluated. Well-documented detailed landslide investigation information is essential in constructing representative analytical models and assuring the accuracy of the calculated model factors in this study. The findings of this study are useful for practitioners to appreciate the uncertainties associated with the analytical calculations and assumptions made in modeling. The implications of method uncertainty can be considered in a qualitative manner even in conventional deterministic analysis.

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References

Baker, J. and Calle, E. (2006). JCSS Probabilistic Model Code, Section 3.7: Soil Properties. *Joint Committee on Structural Safety*.

Bahsan, E., Liao, H.J., Ching, J., and Lee, S.W. (2014). Statistics for the calculated safety factors of undrained failure slopes. *Engineering Geology*, 172: 85-94.

Choot, E.B. (1984). 1983 Landslide Case Study: Tuen Mun Highway, Chainage 550 (Special Project Report No. 2/84). Geotechnical Engineering Office, Hong Kong, 50 p.

FSWJV (2013). *Detailed Study of The 7 June 2008 Landslide on Slope No. 11SE-A/C502 at Pak Fuk Road, North Point (GEO Report No. 289).* Report to the Geotechnical Engineering Office, Hong Kong, 78 p.

GEO & Knill, J. (1996). *Report on the Fei Tsui Road Landslide of 13 August 1995.* Geotechnical Engineering Office, Hong Kong, 2 Volumes, 156 p.

HAPL (1998a). *Report on the Ching Cheung Road Landslide of 3 August 1997 (GEO Report No. 78).* Report to the Geotechnical Engineering Office, Hong Kong, 142 p.

HAPL (1998b). *Investigation of Some Selected Landslide Incidents in 1997 (Volume 5) (GEO Report No. 91).* Report to the Geotechnical Engineering Office, Hong Kong, 141 p.

HAPL (1998c). *Report on the Landslides at Hut No. 26 Kau Wa Keng Upper Village of 4 June 1997 (GEO Report No. 76).* Report to the Geotechnical Engineering Office, Hong Kong, 100 p.

HAPL (1998d). *Report on the Landslide at Ten Thousand Buddhas' Monastery of 2 July 1997 (GEO Report No. 77).* Report to the Geotechnical Engineering Office, Hong Kong, 96 p.

Ho, K.K.S. & Evans, N.C. (1993). *Interim Report on Investigation of the Failure of Slopes 11SE-D/C182 & 11SE-D/C183 Siu Sai Wan, Hong Kong (Special Project Report No. 3/93).* Geotechnical Engineering Office, Hong Kong, 197 p.

Kim, M.M., and Ko, H.Y. (1982). Centrifugal testing of soil slope models. *Transportation Research Record*, 872: 7-15.

Lau, K.C. & Franks, C.A.M. (1998). *A Study of the Landslide at CLP Substation Site, Sham Shui Kok, Lantau Island (Special Project Report No. 5/98).* Geotechnical Engineering Office, Hong Kong, 54 p.

MGSL (2006). *Review of the 25 July 1994 Landslide on Slope No. 11NE-A/C63 at New Clear Water Bay Road Ngau Chi Wan (Landslide Study Report No. 14/2006).* Report to the Geotechnical Engineering Office, Hong Kong, 58 p.

Travis, Q.B., Schmeeckle, M.W., and Sebert, D.M. (2011a). Meta-analysis of 301 slope failure calculations. I: Database description. *Journal of Geotechnical and Geoenvironmental Engineering*, 137(5): 453-470.

Travis, Q.B., Schmeeckle, M.W., and Sebert, D.M. (2011b). Meta-analysis of 301 slope failure calculations. II: Database analysis. *Journal of Geotechnical and Geoenvironmental Engineering*, 137(5): 471-482.

Zhang, L.L., Tang, W.H., and Zhang, L.M. (2009). Bayesian model calibration using geotechnical centrifuge tests. Journal of Geotechnical and Geoenvironmental Engineering, 135(2): 291-299