Research Assessment Exercise 2020
Impact Case Study

University: City University of Hong Kong
Unit of Assessment (UoA): 16- Civil Engineering (inc. Construction Engineering & Management) and Building Technology

Title of case study: Quantification of uncertainties in geotechnical properties and their impact on international geotechnical practices

(1) Summary of the impact

Soils and rocks are underground natural geo-materials, and their occurrence and properties vary spatially. Due to difficulty in access to underground and the technical, resource, and time constraints, only a small portion of geo-materials (e.g., a few boreholes) is examined during site investigation. This leads to a long-standing challenge in geotechnical practice: how to properly determine design values of soil and rock properties from limited measurements in a specific site? Dr Wang has developed Bayesian methods to effectively tackle this challenge and generated widespread impact on billion-dollar engineering practice globally (e.g., ISO2394 and design codes in Europe and USA).

(2) Underpinning research

Unlike steel or concrete, soils and rocks are natural geo-materials, and they are affected by many spatially varying factors during the geological processes they have undergone, such as their parent materials, weathering and erosion processes, transportation agents, and sedimentation conditions. The occurrence of soils and rocks and their properties therefore vary spatially. Furthermore, soils are rocks are often underground and invisible at ground surface. Subsurface site investigation is therefore necessary before construction of any geotechnical project can commence. However, due to the difficulty in obtaining access to subsurface geo-materials and the constraints of investigation costs, manpower, and time, it is impossible to test subsurface geo-materials at every location within a site. Only a small portion of geo-materials at a few locations can be examined during site investigation. This leads to a long-standing challenge in geotechnical engineering practice: how to rationally determine design or characteristic values of soil and rock properties from a limited number (e.g., often only a few) of data points from a specific site? In many other engineering disciplines (e.g., structural engineering), characteristic values of material properties (e.g., steel or concrete strength) are determined using statistical methods. In geotechnical engineering, however, it is difficult to use conventional statistical methods for determination of soil or rock property characteristic values, because of the curse of small sample size (i.e., the number of site-specific measured data obtained during site investigation is generally too sparse to generate meaningful statistics). Dr Wang has developed a Bayesian equivalent sample method (Wang and Cao 2013) to generate meaningful statistics from limited data for geotechnical reliability-based design and analysis (e.g., Wang 2011) and effectively tackled this challenge.

Bayesian equivalent sample method integrates limited measurement data from geotechnical investigation of a specific site with prior knowledge [e.g., previous engineering experience and judgment, soil and rock properties from similar sites (Cao et al. 2016)] under a Bayesian framework and transforms the integrated knowledge into many numerical data points simulated by Markov chain Monte Carlo simulation (Wang et al. 2016). A user-friendly Microsoft Excel-based software package, called Bayesian Equivalent Sample Toolkit (BEST), was also developed to facilitate application of the method by practitioners, and it can be downloaded from Dr. Wang's webpage (https://sites.google.com/site/yuwangcityu/best/1).

The method has been applied to various soil and rock properties [e.g., undrained shear strength of clay (Cao and Wang 2014) and uniaxial compressive strength rock (Wang and Aladejare 2015)]

and generated significant impact on both geotechnical research and engineering practice worldwide. Dr Wang has earned several international awards and recognitions for research on this topic, including the GEOSNet Young Researcher Award by the Geotechnical Safety Network (GEOSNet) during the 5th International Symposium on Geotechnical Safety and Risk (ISGSR), 13-16 October 2015, Rotterdam, The Netherlands, the Highly Cited Research Award by Engineering Geology, an international journal, in 2017, the First-Class Award of the Natural Science Award by Hubei Provincial Government in China.

(3) References to the research

[1] Wang, Y. (2011). "Reliability-based design of spread foundations by Monte Carlo Simulations." *Geotechnique*, 61(8), 677-685.

[2] Wang, Y. and Cao, Z. (2013). "Probabilistic characterization of Young's modulus of soil using equivalent samples." *Engineering Geology*, 159, 106-118.

[3] Cao, Z. and Wang, Y. (2014). "Bayesian model comparison and characterization of undrained shear strength." *Journal of Geotechnical and Geoenvironmental Engineering*, 140(6), 04014018, 1-9.

[4] Wang, Y. and Aladejare, A. E. (2015). "Selection of site-specific regression model for characterization of uniaxial compressive strength of rock." *International Journal of Rock Mechanics & Mining Sciences*, 75, 73-81.

[5] Wang, Y., Cao, Z., and Li, D. (2016). "Bayesian perspective on geotechnical variability and site characterization." *Engineering Geology*, 203, 117-125.

[6] Cao, Z., Wang, Y., and Li, D. (2016). "Quantification of prior knowledge in geotechnical site characterization." *Engineering Geology*, 203, 107-116.

Papers [1] – [4] were recognized as "*an impactful series of research papers that advance geotechnical risk and reliability as a distinctive discipline*" by the Geotechnical Safety Network (GEOSNet) and led to Dr Yu Wang's "The GEOSNet Young Researcher Award" by GEOSNet during the 5th International Symposium on Geotechnical Safety and Risk (ISGSR), 13-16 October 2015, Rotterdam, The Netherlands. In addition, Paper [2] was awarded the "Highly Cited Research Award" in 2017 by *Engineering Geology*, an international journal (2018 Impact Factor: 3.909). Paper [3] has been recognized by Web of Science as Highly Cited Paper (top 1%) of the academic field of Engineering. Paper [5] was recognized by Web of Science as Highly Cited Paper (top 1%) of the academic field of Geosciences. Currently (i.e., September 2019), Papers [5] and [6] rank No 1 and 2, respectively, in the list of most cited papers published in *Engineering Geology* since 2016.

(4) Details of the impact

The Bayesian methods and BEST software package developed have been used globally and generated significant impact on geotechnical engineering practice worldwide. The webpage of the BEST software package has attracted a monthly pageview number of more than 80,000 from five different continents (See the last page of corroboration source A). Dr Wang was invited to deliver an online lecture on "*How to Estimate Characteristic Values for Design*" by the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE), and the video posted online in the ISSMGE website (http://virtualuniversity.issmge.org/courses/course-v1:ISSMGE+TC304-101+2019/about) is accessible to geotechnical practitioners all around the world (Corroboration source B). The Bayesian methods developed have impacted the development and revision of international design codes, such as *ISO2394: General principles on reliability for structures*, *Eurocode 7: Geotechnical design* in Europe, Load and Resistance Factor Design (LRFD) in USA, and slope design guidelines in Hong Kong.

ISO 2394

ISO2394: General Principles on Reliability for Structures is an international standard for development of design codes for structures of buildings in general around the world, and it constitutes a risk- and reliability-informed foundation for decision making concerning design and assessment of structures both for the purpose of code making and in the context of specific projects. The 4th edition of ISO2394 was launched in 2015 and included a new Annex D dedicated to the reliability of geotechnical structures. The Annex D recognizes that geotechnical reliability-based design should place site investigation and the interpretation of site conditions/profile/data as the cornerstone of the methodology and that one of the challenges in geotechnical design is scarcity, or small sample size, of geotechnical data from investigation of a specific site. It is recognized in a recent book entitled "*Reliability of Geotechnical Structures in ISO2394*" (See Page 20 of corroboration source C) that "*It is also possible to tackle, at least partially, the difficulty of small sample size using Bayesian methods and prior knowledge (Wang and Cao 2013, Cao and Wang 2014, Wang et al. 2016, Cao et al. 2016).*" Note that the fours papers cited in the previous sentence are Papers [2], [3], [5], and [6] in the previous section and they are all highly cited (See corroboration source D). Because ISO2394 is an international standard for development of national design codes for building structures, it affects the development and revision of national building structure design codes allover the world.

Eurocode 7

Eurocode 7: Geotechnical design is the geotechnical design code in European Union. To build on the new Annex D of ISO2394 for the revision of Eurocode 7, an ISSMGE joint Technical Committee (TC) 205 / TC304 working group on "*Discussion of statistical/reliability methods for Eurocodes*" was formed in 2015. Dr Wang was invited to lead a discussion on "*Selection of characteristic values for rock and soil properties using Bayesian statistics and prior knowledge*" and took the lead to develop Chapter 5 in the final report of the working group (Corroboration source E). The whole report can be downloaded from the TC304 website (http://140.112.12.21/issmge/TC205_304_reports/All%20Chapters%20(TC205_TC304).pdf). The Bayesian methods developed have impact on the revision of Eurocode 7.

Load and resistance factor design (LRFD) in Nevada, USA

The Bayesian equivalent sample method has also been used in the development of resistance factors for LRFD of axially loaded drilled shafts in the Las Vegas Valley, Nevada, USA in 2016. The methods were used to interpreted limited measurement data on soil properties from 41 field pile load tests and to generate meaningful standard deviation and coefficient of variation (See Page 63 of corroboration source F) needed for the development of resistance factors. The Bayesian methods developed have impact on the development of LRFD in USA.

Slope design guidelines in Hong Kong

The Bayesian methods developed also have significant impact on local geotechnical engineering practice, such as slope design, in Hong Kong. [redacted]

(5) Sources to corroborate the impact

[A] Webpage of Bayesian Equivalent Sample Toolkit (BEST) and its internet traffic record.
[B] Webpage of online video hosted by International Society of Soil Mechanics and Geotechnical Engineering.

[C] Phoon, K. K. and Retief, J. V. (2016). *Reliability of Geotechnical Structures in ISO2394*, CRC Press, Taylor & Francis Group, London, UK.
[D] Citation award and records for the selected papers.
[E] TC205 and TC304, (2017). *Final report on Joint TC204/TC304 Working Group on "Discussion of Statistical/Reliability Methods for Eurocodes"*. International Society of Soil Mechanics and Geotechnical Engineering.
[F] Motamed, R., Elfass, S, and Stanton, K. (2016). *LRFD Resistance Factor Calibration for Axially Loaded Drilled Shafts in the Las Vegas Valley*, Nevada Department of Transportation, Report No. 515-13-803.
[G] [redacted]