Research Assessment Exercise 2020
Impact Case Study

University: The University of Hong Kong (HKU)
Unit of Assessment (UoA): 10 - Earth Sciences (incl. oceanography, meteorology) and other physical sciences (incl. environmental science)

Title of case study:
Defining a new landslide model for hillslopes with confined groundwater, and the resultant impact on slope stability in highly populated areas

(1) Summary of impact

Landslides kill over 3,500 people per year globally and are the leading natural hazard in Hong Kong. Landslides are often caused by groundwater. Hence it can be costly and even fatal to misunderstand groundwater regimes. The Hydrogeology Research Group (HRG) in the Department of Earth Sciences at HKU, led by Prof. Jiao, has pioneered a paradigm shift in understanding the importance of confined groundwater and applying new approaches to slope design, remediation, and risk assessment. This has successfully explained the failure mechanism of landslides worldwide. Hong Kong is now a state-of-the-art exemplar for construction on similarly densely-populated extreme-slope environments. HRG's research has also led to changes in Hong Kong's professional practice and contributions to professional guidance documents in Hong Kong and China.

(2) Underpinning research

Due to limited land availability in Hong Kong, steep slopes must be used for construction, and maintenance of slope safety costs exceeds HKD2 billion annually. Correctly understanding the mechanisms of landslides is the key to preventing slope failures, thereby avoiding the loss of property and, most importantly, life. In the past 70 years, over 470 people have been killed by landslides in Hong Kong; more than 90% of which were caused directly or indirectly by adverse groundwater conditions. It is essential therefore to understand hillslope hydrogeological characteristics. As such, since 1999, HRG has researched this topic [R1–3]. The igneous rocks of Hong Kong are strongly weathered under a sub-tropical climate. In traditional slope-stability studies, the focus was on the resulting saprolite, which was treated as an aquifer with bedrock as an impermeable boundary. It was customary to assume that the permeability of weathered igneous rocks decreased with depth. Such a permeability profile could only lead to an unconfined aquifer, so the regionally influential and internationally cited "Geotechnical Manual for Slopes" (Geotechnical Engineering Office (GEO), Hong Kong, 1994) stated that "In Hong Kong, aquifers are usually unconfined". The HRG has challenged this faulty assumption, leading to a paradigm shift in geotechnical engineering thinking and practice by showing they can be confined.

In many places, a relatively high permeability zone exists around the contact zone between saprolite and bedrock. The clay-rich saprolite has low permeability, behaving as a confining zone for the highly permeable fracture zone in bedrock [R2]. HRG reviewed many of the deep-seated landslides in Hong Kong and found that they have a chair-shaped rockhead profile, and that most involve a high-permeability zone and confined water [Fig 6, R2]. The groundwater in such zones may experience a much higher rise in water pressure after rainfall than might otherwise be expected [R3]. HRG observed that the fractured aquifer in Central District can be so confined that the water level can be almost four metres above the ground surface [Section 5.1.1, R3].

Numerical analysis demonstrates that the confined groundwater zone represents the worst hydraulic condition for slope stability [R2], and stability can be further reduced if the lower part of the zone is

blocked by deep building foundations which retard groundwater discharge [R2]. Such foundations, mainly consisting of impermeable materials, are very common in Hong Kong, and they significantly modify the regional groundwater flow, leading to a build-up of water level and a reduction of slope stability [R4-5]. HRG has systematically investigated the impact of this confined water zone and produced a conceptual model of resultant slope failure [Fig 7, R2]. These findings were first presented as conference papers in 2000, which led to SCI journal papers [R2-R3].

The researchers in the papers cited are Prof. Jimmy Jiao (1997–present), PhD students Dr Subhas Nandy (1998–2002) and Guoping Ding (2001–2006), MPhil student Mr Chiman Leung (2001–2004), and visiting scholars Profs. Jiafa Zhang from the Yangtze River Scientific Research Institute and Xusheng Wang (2004–2005) from China University of Geosciences.

(3) References to the research

[R1] Zhang, J., J. J. Jiao, and Yang, J., 2000, In situ rainfall infiltration studies at a hillside in Hubei Province, China. *Engineering Geology*, v*57* (1–2), 31–38.

[R2] Jiao, J. J., X. S. Wang and S. Nandy, 2005, Confined groundwater zone and slope instability in weathered igneous rocks in Hong Kong, *Engineering Geology*, v80(1-2), p71–92.

[R3] Jiao J. J., G. P. Ding, and C. M. Leung, 2006, Confined groundwater near the rockhead in igneous rocks in the Mid-Levels area, Hong Kong, China, *Engineering Geology*, v84 (3–4), p207–219.

[R4] Jiao, J. J., X. S. Wang, and S. Nandy, 2006, Preliminary assessment of the impacts of deep foundations and land reclamation on groundwater flow in a coastal area in Hong Kong, China, *Hydrogeology Journal*, v14 (1–2), p100–114.

[R5] Ding, G. P., J. J. Jiao, and D. X. Zhang, 2008, Modelling study on the impact of deep building foundations on the groundwater system, *Hydrological Processes*, v22 (12), p1857–1865.

(4) Details of the impact

HRG works on real sites, using research findings to address complex practical problems. Four inter-related impact-types are:

Contribution to professional guidance documents in Hong Kong and China. HRG's conceptual model [Fig 7, R2] of the impact of a confined groundwater zone on slope stability is included in the GEO guidance document "*Engineering Geological Practice in Hong Kong*" [S1] [Fig 4.6.6, P83] (2007). This document was published before 2013 but remains the key source for practitioners, and is freely downloadable. In 2018, it was viewed/downloaded 54,357 times from domains in Hong Kong and beyond.

The China Association of Geological Hazard Prevention was commissioned by the Ministry of Natural Resources of China to form an editorial board to compile the *National Guide of Geohazard Prevention* to be used as official standards of practice for the prevention and mitigation of various geological hazards across all of China. Prof. Jiao was appointed on July 28, 2018 as a member of the board [S2&S3]. He is responsible for two chapters: 1) groundwater design for slope stability, providing a reference for practising engineering geologists to improve awareness of groundwater conditions in slope design and stability assessment; 2) lessons learned from landslide prevention and mitigation in Hong Kong, including failure of slopes when a confined aquifer was not recognized.

Changes in Hong Kong professional practice. Hong Kong has a geotechnical community of over 4,000 practitioners to maintain slope stability. Generally, a slope affected by confined water has much lower stability than otherwise, and Prof. Jiao's failure model with confined groundwater has

important implications for slope design and remediation. The Head of the GEO says [S4]: "…*His studies have identified some shortcomings in the current engineering practice and formulated insightful approaches to assessing the implications of groundwater regime for engineering projects… Jiao has shown the common occurrence of confined aquifers in slopes… in Hong Kong, and revealed the adverse effects of these confined aquifers on slope stability [R2]. He pointed out that the most effective solution to drain a slope with a confined aquifer... would be intercepting the aquifer in a more permeable zone in the bedrock… His recommendations are … followed by local geotechnical practitioners… Jiao's work has rightly identified some areas for improvement in engineering practices. For instance, it was a common practice previously to record the groundwater level at ground surface when there was groundwater overflow from piezometers due to artesian conditions. Professor Jiao warned that [R3] such adverse artesian groundwater conditions must be allowed for in engineering design. As the result of his study, more attention is now paid to the overflowing piezometers for more accurate valuation of water head.*"

Influencing landslide investigation worldwide. Although the RAE assessment of research impact does not consider evidence from journal papers, internal reports on landslides are generally confidential because they may involve loss of life and property, and the interpretation of failure mechanisms has implications for insurance claims. However, papers like those below are usually not purely academic and are often developed from site investigation reports. R2 has been cited over 80 times, showing that Prof. Jiao's confined water concept and failure model has been used to interpret landslides worldwide, e.g., Kyushu Island, Japan (2014); Itaipu, Brazil (Patias et al. 2015); Zhejiang and Shenzhen, China (Sun et al. 2013; Chao et al. 2016); Calabria, Italy (Letto and Cella 2016). Prof. Jiao has identified the original Chinese site investigation report [S6] of a failure at Meilin Port, Shenzhen in 2002 which killed five people and injured 31. The site investigation was led by the Shenzhen Geotechnical Investigation and Surveying Institute Co. Ltd, and the internal report was completed in 2013, with the detailed analysis of the failure mechanism in 2016 [S6a]. Both the original report and the paper extensively cited Prof. Jiao's research. This site has a high-permeability zone, confined groundwater, and chair-shaped bedrock profile [Fig 3.32 and 5.13 in S6, or Fig 7, 11, and 15 in S6a] which fit Prof. Jiao's model almost perfectly [Fig 7, R2]. The model simplification, hydraulic parameters, and initial and boundary condition selection [S6a] were entirely based on Prof. Jiao's research [R2]. Prof. Jiao's research provided not only the theory to understand the failure mechanism but also the most effective approach to remediate the slope. Again, a major measure to stabilize the slope was to dewater the confined aquifer.

(5) Sources to corroborate the impact

[S1] Engineering Geological Practice in Hong Kong (GEO Publication 1/2007)

[S2] Certificate of Appointment of Prof. Jiao by China Association of Geological Hazard Prevention as a member of the editorial board to compile the National Guide of Geohazard Prevention (in Chinese). 2018.

[S3] Letter from Chairman of the Editorial Board, the National Guide of Geohazard Prevention, 2019.

[S4] Letter from the Head of the GEO, Civil Engineering and Development Department, HKSAR, 2018.

[S6] Shenzhen Geotechnical Investigation and Surveying Institute Co. Ltd: Site investigation report on landslide at Meilin Port, Shenzhen, 2013 (in Chinese) ([S6a]: see for English summary of report published in Li, W. C., Dai, F. C., Wei, Y.Q., Wang, M. L., Min, H., and Lee, L. M., 2016, Implication of subsurface flow on rainfall-induced landslide: a case study. Landslides, 13(5), 1109–1123)