Research Assessment Exercise 2020
Impact Case Study

University: The Hong Kong University of Science and Technology
Unit of Assessment (UoA): 16 - civil engineering and building
Title of case study: Green technologies for mitigating urban landslide and debris flow risks

(1) Summary of the impact

Landslides are Hong Kong's No. 1 natural hazard. Professor Charles Ng and Professor Limin Zhang have developed a package of green technologies for mitigating landslide risks, including two novel active protection techniques (soil nailing for loose fills and an environmentally friendly three-layer capillary barrier cover applicable to all-weather climate conditions), and a multi-risk assessment protocol for landslide risk management. These have been applied to upgrade about [redacted] slopes annually in Hong Kong; design three major mountain highways in China's Wenchuan earthquake area and a large landfill in Shenzhen; and adopted in an HKSAR design guide and a Chinese national standard.

(2) Underpinning research

Over 30% of the natural terrain in Hong Kong is steeper than 30° and densely populated urban areas extend to the point where the terrain is too steep, making landslides the No. 1 natural hazard. Approximately 57,000 engineered slopes, particularly over 6000 sizeable loose-fill slopes, are at risk of landslides. For example, on 18 June 1972 the Sau Mau Ping and the Po Shan Road landslides killed 138 people. However, internationally widely used landslide mitigation measures, such as large concrete retaining walls and deep recompaction do not meet the public expectation for sustainable development in Hong Kong. Green technologies and holistic landslide risk assessment protocols are required instead.

Supported by the Research Grants Council's Collaboration Research Fund (CRF) [**G1, G2, G3** & **G4**] and industry [**G5**], we developed a package of green techniques to stabilise slopes and mitigate the landslide risk. In particular, soil nails and native-species vegetation granular covers are combined creatively to stabilise slopes, with the former preventing deep-seated slope failures, and the latter preventing shallow-seated slope failures and enhancing ecological value. A multi-risk assessment protocol has also been developed to manage the risk of the large number of slopes.
Soil nail behaviour in saturated and unsaturated strain-softening loose fills under undrained shearing was studied at three scales: extensive element tests in the laboratory, model testing in HKUST's 400 g-ton geotechnical centrifuge, and full-scale field trials at Kadoorie Farm [**G3**]. The flow-like behaviour of the saturated loose fills under both static and dynamic loadings was delineated [**P1** & **P2**]. Fundamental understanding of root-soil-water interactions [**P3**], water infiltration and gas emission in green granular covers, and stability of vegetated green slopes and granular covers [**P4**] was also obtained at three scales [**G1** & **G2**]. According to unsaturated soil mechanics, a novel three-layer capillary barrier landfill cover that uses recycled construction waste materials has been proposed for humid climates. Extensive investigations examined the growth and eco-environment of native species, pullout resistance of various species, and leakage or emission from the novel cover [**P3** & **P4**]. Long-term monitoring of the performance of the green slope scheme and the three-layer cover was conducted at HKUST Eco Park and Shenzhen Xiaping [**P4**].

When facing over 57,000 slopes, achieving a target tolerable risk level relies on quantitative risk assessment and risk-based engineering decisions. We led another CRF project [**G4**] and an industrial project [**G5**], addressing the issue of slope safety under extreme rainstorms within a novel framework of 'stress testing' [**P5** & **P6**]. The scientific tasks included (1) identification of future critical storm scenarios considering climate changes; (2) evaluation of slope system response under extreme

rainstorms; (3) multi-hazard risk assessment; and (4) formulation of a unique stress-testing framework for evaluating the Hong Kong slope safety system. Mechanisms and field evidence of interactive landslide hazard chain effects [**P5**] were discovered and a methodology for multi-risk assessment established for risk management [**P6**].

The underpinning research was internationally recognised with Telford Premium Prize 2016 (Ng), RM Quigley Award 2017 (Ng) and GEOSNet Award 2017 (Zhang).

(3) References to the research

Key outputs:

[P1] Cheuk, CY, Ng, CWW and Sun, HW. (2005). Numerical experiments of soil nails in loose fill slopes subjected to rainfall infiltration effects. Computers and Geotechnics, 32(4), 290–303

[P2] Ng, CWW, Li, XS, van Laak, PA and Hou, YJ. (2005). Centrifuge modelling of loose fill embankment subjected to uniaxial and biaxial earthquakes. Soil Dynamics and Earthquake Engineering, 24(4), 305–318

[P3] Ng, CWW, Leung, AK and Ni, J. (2019a). Plant-Soil slope Interaction. Taylor & Francis, London and NY. 182 pages

[P4] Charles W.W. Ng, R. Chen, J.L. Coo, J. Liu, J.J. Ni, Y.M. Chen, T.L.T. Zhan, H.W. Guo and B.W. Lu (2019b). A novel vegetated three-layer landfill cover system using recycled construction wastes without geomembrane. Canadian Geotechnical Journal, https://doi.org/10.1139/cgj-2017-0728

[P5] Zhang, S, Zhang, LM, Nadim, F and Lacasse, S. (2016). Evolution of mass movement near epicentre of Wenchuan earthquake, the first eight years. Scientific Reports, 6, 36154

[P6] Shuai Zhang, Limin Zhang, Suzanne Lacasse & Farrokh Nadim (2017). Stress testing framework for managing landslide risks under extreme storms. World Landslide Forum 2017: Advancing Culture of Living with Landslides, Springer, 17–32

Key grants:

[G1] Green slope engineering: bioengineered, live cover systems for man-made fill slopes and landfill capillary barriers in Hong Kong. RGC Collaborative Research Fund; Funding: [redacted]; Period: 2013–2016

[G2] Green slope engineering for Hong Kong. RGC Collaborative Research Fund; Funding: [redacted]; Period: 2010–2013

[G3] Behaviour of loose fill slopes and its stabilization with soil nails. RGC Central Allocation; Funding: [redacted]; Period: 2000–2003

[G4] Coping with landslide risks in Hong Kong under extreme storms: Storm scenarios, cascading landslide hazards and multi-hazard risk assessment. RGC Collaborative Research Fund; Funding: [redacted]; Period: 2016–2019

[G5] Theory and technologies for warning against earthquake-induced geohazards. Sichuan Department of Transportation; Funding: [redacted]; Period: 2010–2018

(4) Details of the impact

The impact of our research is demonstrated by the inclusion of our environmental friendly soil nail technology and green three-layer capillary barrier system in HKSAR's design guideline and a Chinese national design standard, as well as the use of HKUST's multi-hazard risk protocol to solve landslide risk management problems during the reconstruction of three major highways near the epicentre of the Wenchuan earthquake.

Design of soil nails for upgrading loose-fill slopes

There are more than 7000 loose-fill slopes in Hong Kong, which were formed before the establishment of the Geotechnical Control Office (GEO) in 1977. The failures of loose-fill slopes in Sau Mau Ping in 1972 and again in 1976 demonstrated the devastation that failure of a loose-fill slope could cause. Loose-fill materials may 'collapse' during undrained shearing, leading to flow-like behaviour. While soil nails are the most common method for stabilising cut slopes in Hong Kong, there was no established method for the design of soil nails in loose fills. We developed a method for designing soils nails for upgrading loose-fill slopes, including clauses on failure modes, stability analysis, shear strength parameters and nail configurations. The method is environmental friendly as it does not require the removal of native vegetation as the traditional recompaction method does. This proposed method was first synthesized in a Hong Kong Institution of Engineers (HKIE) report in 2003 [**E1**], and finally adopted as a GEO standard design method [**E2**]. [redacted] The overall risk to life posed by substandard man-made slopes had been reduced to less than 25% of the 1977 level, showing the great contribution from our developments.

Innovative bioengineered three-layer cover system for landfills

Building on RGC CRF projects [**G1** & **G2**], a bioengineered live cover system has been developed, which utilises native species and is self-regenerative [**P3**]. The live cover is underlain by a novel three-layer capillary barrier for all climate conditions [**P4**, **E4, E5** & **E6**], which prevents both water infiltration into the wastes during the wet season and gas emission into the atmosphere during the dry season. This cover has been extended to utilising construction waste as cover materials [**E4**]. No artificial materials such as geomembranes are needed and interface failure of a traditional landfill cover system is prevented. A US invention patent and a Chinese invention patent have been granted [**E4**]. A full-scale production trial on the new cover has been completed at Xiaping Landfill, Shenzhen. In the 985 days of monitoring period from June 2016 to February 2019, the average annual infiltration was only 23mm (lower than the allowable value of 30mm/year specified by the US Environmental Protection Agency), and further reduced to 19.6mm when the surface of the capillary cover was vegetated [**E5**]. The environmental friendly cover system has been adopted in the new Chinese National Standard GB51220 'Specifications of Geotechnical Techniques for Municipal Waste Disposal', and will be used extensively over the whole of China [**E6**].

Multi-risk assessment protocol for landslide risk management

Our team has successfully developed and applied a novel stress-testing and multi-risk assessment framework to the reconstruction of four major highways near the epicentre of the Wenchuan earthquake [**E7** & **E8**]. Reconstruction of the 45km Yingxiu–Wolong highway, started in 2009, was the largest aid project financed by the HKSAR Government. In 2010, 2011 and 2013, the reconstructed highway was repeatedly buried by rain-induced massive landslides and debris flows. From 2010 onwards, we mapped likely landslide hazard chains along the highway; ranked the risks of the landslide deposits; assessed the risk profiles of several possible highway alignments; and evaluated the feasibility of using long tunnels to reduce landslide risks. These were adopted in the final design [**E7**]. The new highway project was completed in June 2016. A risk-based landslide warning system was also installed to reduce the operational risk. Our risk-based methodologies were covered by Xinhua News Agency, Sichuan Daily and Wen Wei Bo, and recognised both by the Sichuan Provincial Government [**E8**] and with a GEOSNet Award [**E9**]. Recently, our methodologies have been extended to the reconstruction of the 50km Yingxiu–Wenchuan highway, the 135km Yaan–Kangding highway (Sichuan-Tibet Expressway South), and the 172km Wenchuan–Markang highway (Sichuan-Tibet Expressway North) [**E7** & **E8**]. Our risk-based methodologies have fundamentally changed the practice of highway design and construction, leading to safer and more robust infrastructures [**E8**]. The understanding of cascading natural hazards forms part of an HKSAR government policy report **[E10]**.

(5) Sources to corroborate the impact

[E1] Hong Kong Institution of Engineers Geotechnical Division. 2003. Soil Nails in Loose Fill Slopes - A Preliminary Study. http://hkieged.org/download/soilnailsloosefillslopes.pdf

[E2] Geotechnical Engineering Office (GEO) and Hong Kong Institution of Engineers (HKIE). 2011. Design of Soil Nails for Upgrading Loose Fill Slopes. 96pp.

[E3] Testimonial from [redacted]

[E4] Ng, CWW, Xu, J and Chen, R. All-weather landfill soil cover system for preventing water infiltration and landfill gas emission. US Patent No. US 9,101,968 B2; Granted on 11 August 2015. Chinese invention patent – CN103572785A; Granted on 2 March 2016

[E5] Testimonial from Shenzhen Xiaping Waste Solid Landfill Management Office on completion of full-scale production test on HKUST's granular capillary barrier

[E6] Adoption of HKUST's environmental friendly three-layer capillary barrier in the new Chinese National Standard GB51220 'Specifications of Geotechnical Techniques for Municipal Waste Disposal'

[E7] Testimonial from Chief Engineer of Sichuan Department of Transportation's Highway Planning, Investigation and Design Institute on contribution to the reconstruction of three major highways near the epicentre of the Wenchuan earthquake

[E8] Sichuan Province Science and Technology Award 2018: Geohazard evolution and risk mitigation technology package for mountain highways stricken by strong earthquakes, Sichuan Provincial Government.

[E9] GEOSNet Award to Professor Limin Zhang in Denver in June 2017 over ASCE Georisk 2017. The award recognizes an individual who has made impactful contributions to geotechnical reliability, or an individual who has made impactful contributions to geotechnical risk assessment and management.

[E10] CARe2018 HK Conference: Summary Report and Policy Recommendations, 21 Dec. 2018 (https://issuu.com/praise-hk/docs/care2018policyrecommendation). This report is for HKSAR Government's Steering Committee on Climate Change, which is the body that coordinates climate change related actions within the Hong Kong SAR government.