Project number: T22-603/15N

RESEARCH GRANTS COUNCIL
THEME-BASED RESEARCH SCHEME (TRS)

Completion Report on Funded Project

Project start date: 1 Jan. 2016
Project completion date: 31 Dec. 2020

1. Project Title: Understanding Debris Flow Mechanisms and Mitigating Risks for a Sustainable Hong Kong

2. Names and Academic Affiliations of Project Team Members[#]

Project team member	Name / Post	Unit / Department / Institution	Average number of hours per week spent on this project in the whole project period
Project Coordinator (PC)	Charles W.W. NG / Chair Professor, Vice President of HKUST (Guangzhou Campus) & Dean of HKUST Fok Ying Tung Graduate School [#a]	Civil and Environmental Engineering / HKUST	20
Co-principal Investigators (Co-PI)	Peng CUI / Academician of Chinese Academy of Sciences (CAS) & Vice-Director of IMHE	Institute of Mountain Hazards and Environment (IMHE) / CAS	12
	Wai-Keung PUN / Chairman	R&D Group for Flexible Barriers of the Geotechnical Division of the Hong Kong Institution of Engineers (HKIE)	12
	Long QUAN / Professor	Computer Sciences and Engineering / HKUST	12
	Limin ZHANG / Chair Professor	Civil and Environmental	12

	& Head of Department [#b]	Engineering / HKUST	
	Yu WANG / Professor [#c]	Department of Architecture and Civil Engineering / City University of Hong Kong	10
External Co-principal Investigators (Co-PI)	Matthew COOP / Professor of Geotechnics [#d]	Civil, Environmental & Geomatic Engineering / University College London (UCL)	5
Co-Investigators (Co-I)	Konstantinos SENETAKIS / Associate Professor [#e]	Department of Architecture and Civil Engineering / City University of Hong Kong	10
	Sergio LOURENÇO / Associate Professor [#f]	Civil Engineering / The University of Hong Kong	10
	Malcolm BOLTON / Fellow of Royal Academy of Engineering, UK, Professor Emeritus	Civil Engineering / The University of Cambridge	5
	Billy HAU / Principal Lecturer	School of Biological Sciences / The University of Hong Kong	10
	Julian Shun-Hang KWAN / Secretary	R&D Group of Flexible Barriers of the Geotechnical Division of the Hong Kong Institution of Engineers (HKIE)	10
	Suzanne LACASSE / Member of US National Academy of Engineering, former Director of NGI	Norwegian Geotechnical Institute (NGI)	5
	Gang WANG / Professor [#g]	Civil and Environmental Engineering / HKUST	10
	Yu-Hsing WANG / Professor [#h]	Civil and Environmental Engineering / HKUST	10
	Jidong ZHAO / Professor [#i]	Civil and Environmental Engineering / HKUST	10
	Gordon G.D. ZHOU / Professor [#j]	Institute of Mountain Hazards and Environmental (IMHE) / CAS	10
External co-Investigator (Ex Co-I)	Beatrice Baudet / Lecturer [#d]	Civil, Environmental & Geomatic Engineering / UCL	5
	Jui-Pin WANG / Assistant Professor [#k]	Civil and Environmental Engineering / HKUST	10
Collaborators	C. K. LAU / Managing Director	Fong On Geotechnics	N.A.
	Ringo YU / Managing Director	Frazer Construction Company Ltd.	N.A.

 # Please highlight the approved changes in the project team composition and quote the date when the RGC granted approval of such changes. For changes in the project team composition, please submit a separate request, together with the justification and the curriculum vitae of the new member(s), to the RGC three months prior to the intended effective date of the change.

[#a] Prof Charles W. W. Ng (PC) was promoted to Dean of HKUST Fok Ying Tung Graduate School on 8 Sept. 2020 and the Vice-President of HKUST (GZ) on 12 Apr. 2021.

[#b] Prof Zhang Limin (Co-PI) was promoted to the Head of Department on 1 Jul. 2021.

[#c] Prof Yu Wang (Co-PI) was promoted from Associate Professor to Professor on 1 Jul.2020.

[#d] The change of project team composition was approved by RGC on 10 Aug. 2016.

[#e] An additional request to add Dr Kostantinos Senetakis from City University of Hong Kong to the project was made on 28 July 2017. He was promoted from Assistant Professor to Associate Professor on 01 July 2019.

[#f] *Prof Sergio Lourenço (Co-I) was promoted from Assistant Professor to Associate Professor on 1 Jul. 2020.*
[#g] *Prof Gang Wang (Co-I) was promoted from Associate Professor to Professor on 1 Jul. 2020.*
[#h] *Prof Yu-Hsing Wang (Co-I) was promoted from Associate Professor to Professor on 1 Jul. 2016.*
[#i] *Prof Jidong Zhao (Co-I) was promoted from Associate Professor to Professor on 1 Jul. 2020.*
[#j] *Prof Gordon Zhou (Co-I) was promoted from Associate Professor to Professor on 1 Oct. 2017.*
[#k] *Prof J.P. Wang left HKUST effective from 1 July 2017 and remains as an external Co-I for the project (letter to RGC on 16 June 2017 refers)*

3. Project Objectives

Summary of objectives addressed/achieved:

Objectives for the whole project (5-year project)*	Percentage achieved	Remarks **
1. To characterise debris flows relevant to Hong Kong at both particulate and continuum levels	100%	
2. To understand the dynamics of debris flows by carrying out field monitoring of natural debris flows, and developing and conducting large-scale flume testing	100%	
3. To develop new monitoring techniques for debris flow processes using high-resolution image processes and Smart Soil Particles	100%	
4. To formulate a novel multi-scale and multi-physics computational platform that can simulate a wide variety of debris flows	100%	
5. To develop novel vulnerability models for areas potentially affected by debris flows	100%	
6. To understand the interaction between debris flow and multiple flexible barriers, and develop world-leading guidelines with consideration of ecological restoration	100%	
7. To educate the public and practitioners about debris flow mechanisms and mitigation measures for the sustainable development of Hong Kong	100%	

* *Please highlight the approved changes in objectives and quote the date when the RGC granted approval of such changes.*
****** *Please provide reasons for significantly slower rate of progress than originally planned.*

6. Research Highlights and Outputs

6.1 What are the most exciting research accomplishments of the project?
(Please list five or more of the team's best research accomplishments, such as journal and conference papers, software codes, research infrastructure, etc. For each item, please clearly justify how it has achieved international excellence (e.g. best paper award, invited presentation, citations, product licensed to industry, etc.))

The most exciting research accomplishments of the project are as follows:

1. Based on the research outcomes from this TRS project and in collaboration with the Geotechnical Engineering Office (GEO) of the HKSAR government, the publication of new state-of-the-art technical guidelines (not available elsewhere in the world):
    a. Technical Guidance Note (TGN 52) entitled, "Enhanced Technical Guidance on Design of Rigid Debris-resisting Barriers", which is a legal design document, published in 2020. A copy of the TGN 52 is provided in Appendix D8.
    b. GEO Report 319 entitled, "A Pilot Study on the Design of Multiple Debris-resisting Barriers" published in 2016. This report is the first of its kind in the world to provide practitioners with guidance on how to design multiple debris resisting barrier systems. GEO Report 319 is provided in Appendix D9.

   The PC and his project team were invited by the International Consortium of Landslides (ICL) of UNESCO to deliver a plenary forum lecture at the Fifth World Landslide Forum in Kyoto, Japan in Nov., 2021 (postponed from Oct 2020 due to the COVID19). Furthermore, the PC was also invited to deliver a keynote lecture at the 13th International Symposium of Landslides (ISL) in Cartegena, Colombia in 2021. The forum and keynote lectures promulgated the design recommendations for the design of rigid and flexible barriers, especially, the newly developed design framework for multiple barriers. The contents of the forum and keynote lectures were published in the conference proceedings and are provided as C64 and K82, respectively, in Appendix A1.

2. The PC and his project team developed a new state-of-the-art flexible barrier system for resisting debris flow impact. The system consists of a novel bi-linear energy-dissipating and shock-absorbing device. To transfer the new technology to practice, key components of the barrier were patented (i.e., United States patent no. US 20180274618A1; Chinese invention patent nos. PCT/CN2017/070127 and PCT/CN201711317935.2). Details of the patents are provided in Appendices I1-I3.

3. The PC and his project team were awarded five best paper awards by leading journals in the geotechnical engineering field. Most notably, the Telford Premium Prize for the best paper, entitled "Coarse granular flow interaction with slit structures" in Géotechnique Letters in 2016. The award was given by the Institution of Civil Engineers; U.K. Géotechnique Letters is one of the top five journals in the geotechnical engineering field. Similarly, the PC and his project team were awarded the R.M. Quigley Award in Ottawa by the Canadian Geotechnical Society in 2016. Their paper entitled "Large-scale successive boulder impacts on a rigid barrier shielded by gabions" was nominated and voted as one of the top 3 papers out of a total of 296 published in the Canadian Geotechnical Journal in 2016; about 30 editorial board members of the journal voted. Please refer to Appendix A2 for details of all awards received by the PC and his project team.

4. One of the world's largest flumes for modelling debris flows was developed as a result of this project. The flume is 28-m in length and it can model up to 10 m^3 of debris materials. The

flume is equipped with novel instrumentation, capable of simultaneously measuring the mechanical and kinematic parameters of debris flow. A Chinese invention patent (CN201810614916) was obtained for the novel instrumentation used in the flume. Additionally, two generations of novel self-standing smart soil particles (FSSPs) were developed and used to monitor the debris flow processes as well as distributed debris impact sensors in the 28-m flume tests. The flume was instrumental in evaluating the proposed design criteria for single and multiple barriers. International collaborations (i.e., Norway; Korea; Italy; and Switzerland) were successfully seen through using this flume. Please refer to appendices D3, D6 and I4 for details of the 28-m long flume and the patent, appendix D4 for details of the FSSPs and appendices C8, C9 and C11 for details of international collaborations.

5. Based on the research findings from this TRS project, the PC led and launched a state-of-the-art postgraduate course on "Landslides and mitigation" in the open-source Virtual University (VU) platform of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE). This online course is freely available for practicing geotechnical engineers and researchers worldwide through the link: http://virtualuniversity.issmge.org/courses/course-v1:ISSMGE+LM101+2021/about.
   Furthermore, a unique graduate-level course entitled "Debris flow mechanisms and mitigation (CIVL6100)" was developed and delivered to train the next generation of engineers at The Hong Kong University of Science and Technology. The details of this course are provided in Appendix F.

6. The outstanding theoretical work carried out in this project led to the development of a world-leading fully coupled computational fluid dynamics / discrete element method (CFD-DEM) computational platform to simulate debris flow runout and impact on resisting barriers. The capabilities of this multi-scale and multi-physics computational platform have been recognised, evidenced by invited keynote lectures in leading conferences (K37, K62; Appendix A1) and a journal paper (J90; Appendix A1). The details of the CFD-DEM model are provided in Appendix D3.

7. A reliability-based debris flow vulnerability model and a multi-hazard assessment procedure for debris flow impact have been developed and evaluated for Hong Kong. The newly developed model was presented in the 5th ISSMGE Suzanne Lacasse Lecture (K80; Appendix A1), which recognises world-leading scholars and practitioners in the practice of engineering risk assessment and management.

8. A novel unmanned aerial vehicle (UAV)-integrated system for high-resolution area reconstruction has been built, and a software copyright has been obtained for the use of a UAV-based particle grading identification system (Chinese Copyright of Computer software; Classification Codes: 30200-8000; Appendix I7).

9. The project team developed the world's first-of-its-kind dynamic inter-particle testing apparatus for micromechanical studies of grain-contact behaviour. The device capabilities are featured in the invited international keynote lecture (K56; Appendix A1). The contents of the keynote lecture are published in the conference proceedings (C29; Appendix A1).

To provide further detailed information about the stated most exciting research accomplishments above, **Table 1** below summarises each of the project objectives in connection of our key research accomplishments stated above. A list of the research outputs is provided in Appendix A1 that best highlights the project achievements for the entire project (A for Awards; J for journal paper; C for conference paper; K for keynote or invited talk)

Table 1: A summary of project objectives and research accomplishments

Objectives for the whole project (5-year project)	**Research accomplishments**
To characterise debris flows relevant to Hong Kong at both particulate and continuum levels	• The project team developed the world's first-of-its-kind dynamic inter-particle testing apparatus for micromechanical studies of grain-contact behaviour. Unique software was developed for advanced high-quality testing. Damage mechanisms of grains during dynamic inter-particle loading were characterised using the novel apparatus (Appendix D1; J1, J8, J10, J12, J27-J29, J31, J32, J35, J37, J38, J41-J43, J45, J56, J58, J65, J73-J77, J80, J81, J84, J85, J86-J88, J93, J97, J105-J113, J124, J125, J127, J128, J136, J146-J152, J169, J170, J180-J184, J186, J187; C28, C29, C36, C55; K17-K19; K56, K78; Appendix A1).
To understand the dynamics of debris flows by carrying out field monitoring of natural debris flows, and developing and conducting large-scale flume testing	• A new state-of-the-art 28-m long flume has been developed with testing capacity of up to 10 m^3 and equipped with unique instrumentation to assist in advancing scientific knowledge. High-quality data from large-scale flume tests were used to calibrate our new theories and develop world-leading design guidelines (Appendix D6, pages 8 to 17; J158, J162; C25, C64; K44, K45, K52, K54, K81, K82; Appendix A1, Appendices I1-I4). • A new large-scale pendulum impact facility was developed and used to investigate the cushioning performance of different materials for attenuating debris flow impact force (Appendix D6, pages 29-33; J6, J50, J53, J54, J79, J161, J163; C12; Appendix A1). • New instrumentations were installed in the Dongchuan Debris Flow Observation and Research Station (DDFORS) to capture high-quality data of natural debris flows. The new instrumentation includes novel moisture and temperature sensors and a relay station (Appendix D2). Field monitoring data have been interpreted to understand natural debris flow dynamics (J61-J63, J115, J122; K20; Appendix A1).
To formulate a novel multi-scale and multi-physics computational platform that can simulate a wide variety of debris flows	• A world-leading fully coupled computational fluid dynamics / discrete element method (CFD-DEM) computational platform was developed to simulate debris flow runout and impact at resisting barriers. The novel computational platform was benchmarked with existing international state-of-the-art models for debris flow runout and entrainment predictions (Appendix D3; J4, J5, J9, J11, J18, J33, J46, 57, J64, J69, J77, J82, J89, J90, J96, J99, J118- J120, J139-J146, J172-J179, J188, J189; C4, C14-C17, C24, C30, C32-C35, C38, C49-54, C65-C67; K4-K6, K23-K25, K36-K38, K57-K77; Appendix A1).

To develop new monitoring techniques for debris flow processes using high-resolution image processes and Smart Soil Particles	• Novel instrumentation for monitoring debris flow processes such as self-standing smart soil particles (FSSPs) were developed and subjected to large-scale flume tests. The 2nd generation of smart soil particles were also modified for use as distributed debris impact sensors on barriers to aid in impact detection and maintenance planning (Appendices D4, pages 1 to 11; J15, J17, J22, J26, J39, J67, J68, J101-J104, J137, J168, J185; C3, C6, C7; K26-K35, Appendix A1). • A novel unmanned aerial vehicle (UAV)-integrated system for high-resolution area reconstruction has been built. A new 3D surface reconstruction algorithm was developed and successfully applied to generate high-fidelity 3D models of barriers impacted by debris flows in large-scale flume tests (Appendix D4, pages 12 to 19; J44; C8, C10, C11, C18, C23, C37, C39-C48, C56-C63; K13-K16; Appendix A1, Appendix I7).
To develop novel vulnerability models for areas potentially affected by debris flows	• Geographic information system (GIS)-based databases containing elements at risk in Hong Kong were compiled and built for catchment-scale numerical simulations considering initiation mechanisms and debris flow interactions. A new reliability-based debris flow vulnerability model and a multi-hazard assessment procedure for debris flow impact have been developed and evaluated for Hong Kong (Appendix D5; J2, J3, J13, J16, J21, J34, J36, J83, J85, J95, J100, J121, J138, J134-J156, J157, J168; C26; K7-K11, K39-K43, K79, K80; Appendix A1).
To understand the interaction between debris flow and multiple flexible barriers, and develop world-leading guidelines with consideration of ecological restoration	• A geotechnical centrifuge flexible barrier impact model was developed with a novel bilinear energy-dissipating brake element (United States Patent No.: US 20180274618A1; Chinese Patent Application No.: PCT/CN2017/070127) (Appendices I1, I2). Centrifuge tests were conducted to evaluate our new theories of flow barrier interaction and to propose design guidelines (Appendix D6, pages 1 to 7). • A new generation of flexible barriers were developed with Kevlar mesh, equipped with our novel bi-linear energy-dissipating brake element and tested in the large-scale 28-m long flume (Appendix D6, pages 16 to 28). • A modernised 6-m long flume was developed to investigate flow barrier interaction and evaluate existing design guidelines (Appendix D3, pages 20 to 26; J24, J123, J132, J134, J164, J165, J167; C1, C2). • Research findings from this project have been successfully translated into world-leading design guidelines for debris-resisting, dual rigid and flexible barriers (Appendices D8, D9) (J6, J7, J13, J14, J19, J20, J23-J25, J30, J47-J55, J59-J63, J66, J70, J78, J79, J91, J92, J94, J114-J117, J123, J126, J129-J137, J158-J167; C5, C9, C12, C19-C22, C25, C27; K1-K3, K21, K22, K44-K55, K81, K82; Appendix A1, Appendices I1-I6). • Technical guidelines on ecological restoration for landslide trails and landscape treatment for flexible barriers have been developed (J71, J72; Appendix A1, Appendices D7-D9).

To educate the public and practitioners about debris flow mechanisms and mitigation measures for the sustainable development of Hong Kong	• A new postgraduate-level course on debris flows was developed and delivered (Appendix F). • Two issues of a thematic newsletter on debris flow mechanics and mitigation measures were published and promulgated at local and international conferences (Appendices E1 and E2). • A total of 82 keynotes and invited talks have been delivered worldwide by members of the project team (Appendix A1). • A new partnership has been established with the Hong Kong Jockey Club Disaster Preparedness and Response Institute (HKJCDPRI) to enhance public education (Appendix C15).

6.2 What was the added value of the TRS funding, rather than standard project grant funding?
(For example, could this work have been achieved with other funding scheme, such as the General Research Fund or Collaborative Research Fund? If not, why?)

This TRS project addressed a topic of major strategic importance to Hong Kong, specifically in the context of sustainable development against debris flow hazards via a comprehensive micro to macro approach. This unique approach could not have been implemented through schemes such as the GRF (max. HK$1.2M) and CRF (max. HK$10M) due to their funding limitations and shorter project durations of three years, respectively. Unique expertise and equipment were required to achieve the project outcomes, and substantial resources were needed to ensure that this project made an international impact via collaborations and public engagement. For instance, experts in large-scale physical modelling were required to develop and use the world-leading 28-m long flume and pendulum apparatus, and micromechanics experts were required to develop and use static and dynamic inter-particle apparatuses. To bridge the two scales, each newly developed technological advance such as the CFD-DEM model, state-of-the-art smart soil particles, and 3D reconstruction using UAVs required unique expertise. Evidently, the success of this project hinged upon a much larger scale of resources in terms of research staff (refer to Appendix B for staff trained), equipment (refer to Appendices D1-D6), collaboration efforts (refer to Appendices C1-C15), and public engagements (refer to Appendices C15, E1, E2, G, H6) compared with the scale of resources and time limited by a typical GRF or CRF project.

6.3 If the project has not met its original objectives, why?

<u>The project has successfully met all its original objectives.</u>

6.4 (a) Peer-reviewed journal publication(s) arising <u>directly</u> from this project:
(Please attach a copy of the publication and/or the letter of acceptance if not yet submitted in the previous progress report(s). All listed publications must acknowledge RGC's funding support by quoting the specific grant reference. Please mark the symbol "#" next to the publications involving inter-institutional collaborations)

A total of 186 papers have been published and 3 have been accepted for publication. The list of journal papers that have been published, accepted and currently under review are shown in Appendix A1.

(b) Recognised international conference(s) in which paper(s) related to this project was/were delivered:
<u>(Please attach a copy of each conference abstract)</u>

A total of 67 conference papers have been accepted and published over the project duration. The list of published and accepted conference papers are provided in Appendix A1.

(c) RGC funding should have been acknowledged in all publication(s)/conference papers listed in (a) and (b) above. If no acknowledgement has been made in any of the publications/ papers, please indicate and provide explanations.

None

6.5 To what extent this project has strengthened inter-institutional collaborations and other partnerships?

Frequent collaborations between the project's different task groups were essential in the facilitation of activities and the delivery of output. Details of the collaborations between the different task groups from participating institutions are provided in appendices C1-C7.

In addition to the inter-institutional collaborations between participating institutions, the following international collaborations with research institutions were nurtured to research geohazard mitigation.

6.5.1 A new international collaboration has been established between ISAN Corporation of Korea (representing the Korean government) and HKUST to use the large-scale flume in Task A3 to test debris flow baffles (Appendix C8). The first set of international guidelines for the design of debris flow baffles will result from this collaboration.

6.5.2 A new international collaboration has also been set up between the Politecnico Di Torino, Italy and HKUST. The collaborative scheme is a research grant to jointly supervise a PhD student to build on the strengths of the two partnering institutions. The topic is closely aligned with the mission of this project and is entitled "*multi-scale modelling strategies for debris-flow; a new technique for hazard assessment combining numerical modelling and physical experiments*" (Appendix C9).

6.5.3 HKUST collaborated with the International Consortium on Landslides (ICL) of UNESCO to promote landslide research, education, and risk evaluation and reduction by disseminating key project research output in a forum lecture (see section 6.1; item 1, Appendix C10).

6.5.4 A tripartite international collaboration between Norwegian University of Science and Technology (NTNU), HKUST and HKU has been established to investigate the fundamental mechanisms of debris flow-erodible bed-barrier interactions by carrying out tests in the 28-m flume facility. The Norwegian research council has awarded a collaborative research project entitled "Landslide mitigation of Urbanized Slopes for Sustainable Growth (LIFELONG)" from 2020 to 2023 with a sum of NOK 5.400M (HK$ 4.760M).
This collaborative project focuses on combining the research efforts and strengths of partner institutions to support impactful research and education on (a) innovative and environmentally sustainable methods for landslide mitigation, (b) early warning of landslides and (c) gamification of landslide risk management. The research project envisions collaborative research through student and research staff mobility between partner institutions.
In developing innovative solutions for landslide mitigation in urban slopes, the mechanisms of debris flow-erodible bed-barrier interactions will be investigated in the 28-m long flume. To address the objective of identifying the key mechanisms of bed entrainment by debris flows and subsequent impact on resisting barriers, a series of tests will be conducted using rigid and

flexible barriers installed in the section of the erodible bed. The dual barriers will be installed 1 m and 5 m from the start of the erodible bed to gauge the influence of multiple barriers on limiting bed entrainment and downstream impact. The planned tests will also allow a unique opportunity to evaluate the recently proposed multiple barrier design criteria (see section 6.1) for erodible bed conditions.
Preliminary tests of a 6-m^3 debris flow entraining erodible bed have been carried out. Tests with flow volumes of 10 m^3 and multiple barrier configurations are planned. The details of the preliminary tests as well as the proposed test plans are provided in Appendix C11.

Furthermore, collaborations with industry have been established to translate research findings from this project into world-leading design guidelines by commissioning the unique physical modelling facilities as follows:

6.5.5 The 28-m long flume model (see Appendix D6) located at the Kadoorie Centre was commissioned by the Geotechnical Engineering Office of the HKSAR government for debris flow impact tests against rigid and flexible barriers. The test results were used to evaluate existing design guidelines and to propose new design recommendations in Hong Kong for sustainable and robust barrier designs (see Appendices C12, D8, D9).

6.5.6 Collaboration within the project team was required for Tasks C1 and C2. The Hong Kong Institution of Engineers (HKIE) provided input for designing the large-scale pendulum setup (Appendix C13), including cushioning material, foundations and required impact energy. The collaborative effort facilitated the development of design guidelines for rigid barriers in Hong Kong. Furthermore, several novel and sustainable cushioning materials were tested. Details of the large-scale pendulum setup can be found in Appendix D4.

6.5.7 Project members from Tasks A3, C1, and C2 participated in a technical visit to Chengdu, China on 8 – 10 December, 2016 to learn how flexible barriers are manufactured and tested under full-scale conditions. Furthermore, the delegation utilised the opportunity to share research findings with project members from Task A1 to seek technical advice from one another at the Institute of Mountain Hazard and Environment of the Chinese Academy of Sciences. Details of the visit can be found in Appendix C13.

6.5.8 The full-scale pendulum impact apparatus developed in this project was commissioned by industry to study a wide-range of sustainable cushion layers for absorbing boulder impact force. Full-scale test results were directly translatable into design guidelines in Hong Kong to ensure sustainable and economic barrier designs (see Appendix C13).

6.5.9 The centrifuge model developed in this project (Appendix D6) was commissioned by the GEO to study fundamental debris flow impact mechanisms on debris flow barriers (Appendix C12). The results have been used to reveal previously unknown impact mechanisms and enable the evaluation of existing design guidelines. Furthermore, a patent has been successfully obtained for one of the key components of the centrifuge model, namely the bi-linear energy-dissipating and shock-absorbing device for cables subjected to tension (see Appendices I1 and I2).

6.5.10 To investigate debris flow interaction with flexible barriers, a collaboration with GEOBRUGG (Swiss company) was established. Tests were carried out in the 28-m flume facility using GEOBRUGG Tecco® G45 mesh (Appendix C14) to understand the debris straining mechanisms of a flexible barrier.

6.5.11 A collaboration has been established between HKJCDPRI and HKUST in a new project called Smart Landslide Barriers (Appendix C15). The smart barrier serves as an early warning

system to enhance the resilience of the community against landslides. The barrier was assessed for practical use. The collaboration has resulted in obvious social and economic implications for sustainable development in Hong Kong.

6.6 Research students trained (registration/awards):

In this collaborative project, a total of 135 students (80 PhD, 25 MPhil, 8 MSc and 22 BEng students) and 20 research staff (14 postdocs and 6 RAPs) were trained at HKUST, CityU, and HKU. A list of trained students and research staff is provided in Appendix B.

6.7 Specific products (e.g. software or netware, instruments or equipment developed):

- A monotonic and dynamic inter-particle loading apparatus was developed (Appendix D1).
- A Coupled Computational Fluid Dynamics (CFD) and Discrete Element Method (DEM) computational platform was developed for analysing debris-barrier interaction to support the formulation of design guidelines (Appendix D3).
- Two generations of self-stand smart soil particles (FSSPs) were developed (Appendix D4).
- A novel UAV-based data capturing system was developed (Appendix D4) and used in an image-based particle grading identification system (Chinese Copyright of Computer software; Classification Codes: 30200-8000, Appendix I7).
- A state-of-the-art flexible barrier system and design approach has been developed (Chinese patent no. PCT/CN201711317935.2). A US patent (US 20180274618A1) and a Chinese patent (PCT/CN2017/070127) have been successfully obtained for the key component of this flexible barrier (Appendix I1-I3).
- A large-scale pendulum impact facility was built (Appendix D6).
- A new state-of-the-art 28-m long flume facility was built at the Kadoorie Centre in Hong Kong (Appendix D6). The flume facility is equipped with unique instrumentation to capture debris flow mechanical parameters (Chinese patent, application no. CN201810614916, Appendix I4).

6.8 Other education activities and/or training programmes developed:

The PC of this project, as the president of the International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE), launched ISSMGE's virtual university (VU). The VU platform provides open-source, high-quality technical and educational content for practicing engineers and graduate students. In order to disseminate the project findings and contribute not only to Hong Kong but also to the global geotechnical community, the PC developed and published the "Landslides and Mitigation" course in the VU of ISSMGE. The course is freely accessible via the link (http://virtualuniversity.issmge.org/courses/course-v1:ISSMGE+LM101+2021/about).

Furthermore, the PC and his project team also developed Hong Kong's first course on debris flow mechanics and mitigation measures. The postgraduate course was delivered during the 2016 Fall semester at HKUST (see Appendix F). The new course provides students and practitioners with the necessary training to identify and characterise debris flows, understand their fundamental flow mechanisms, and apply mitigation measures. In addition, this course focuses on approaches to reduce the environmental impacts and the cost of mitigation measures against debris flows for the safe and sustainable development of Hong Kong.

To further enhance public education, the PC established a partnership with the HKJCDPRI (Appendix C15). The HKJCDPRI specialises in providing comprehensive training, research,

policy exchange and platforms to enhance resilience in the community. The project team attended their Annual Conference on Disaster Preparedness and Response in 2018 and 2019 (13 January, 2018 and 29 June, 2019) to disseminate details of the TRS project to the public.

To disseminate the project's research output to the public, the project team published two thematic newsletters (Appendices E1 and E2) about ongoing research on debris flow mechanisms and mitigation measures. The newsletters were promulgated at different local and international conferences and exhibitions. Research students involved in the project participated in the Safer Living 2.0 kick-off exhibition in Hong Kong on 10 June 2019 to disseminate the knowledge and research outputs of the TRS project (Appendix H6) as well as the 7th International Conference on Debris Flow Hazards Mitigation (7th DFHM) in Colorado, USA from 10-12 June 2019 (Appendix H5).

6.9 Please highlight any deliverables indicated in the project implementation timetable endorsed by the RGC which have not been covered or achieved as per sections 6.1 to 6.8 above, and explain/ elaborate.

None

Project Management

6.10 Please elaborate how the PC has played his/her role in coordinating and managing the project.

To manage the project, the PC assembled a management committee consisting of project members representing each of the institutions involved (see Table 2). The key responsibilities of the appointed management team members were to work with the PC to direct the project and manage resources, raise concerns or report challenges encountered during the project to the PC, request support from the PC, and ensure research progress is on schedule.

Moreover, regular inter-task group meetings were held regularly by the relevant Task teams. The outcomes of the meetings were reported to the management committee. Details of management committee meetings and other regular progress meeting notes are provided in Appendices A3 and A4, respectively.

Importantly, the PC and the management committee recognised that the substantial budget cut from the original requested amount of HK$73M to an awarded amount of HK$33.25M would compromise the impact made by the project. To mitigate the effects of the budget cut, the PC actively secured the following private donations:

- Donation of HK$1M from Ir. Mr. Ringo Yu (Frazer Construction Company Ltd.).
- Donation of HK$0.36M/year over the five-year project duration (total HK$1.8M) from Mr. W.K. Cheung (Geotech. Engineering).
- Donation of HK$0.2M from the Geotechnical Division Committee (GDC) of the Hong Kong Institution of Engineers.

The donations demonstrate the industry's commitment to the project team and their confidence in the expected benefits from the TRS project in the contribution toward the sustainable development of Hong Kong.

Table 2. Appointed management team committee members

Institution/Department	Appointed leader
Hong Kong Institute of Engineers / Task force on physical testing of flexible debris-resisting barriers	Julian KWAN
City University of Hong Kong / Department of Architecture and Civil Engineering	Yu WANG
The University of Hong Kong / Department of Civil Engineering	Sergio LOURENÇO
The University of Hong Kong / School of Biological Sciences	Billy HAU
Institute of Mountain Hazards and Environment / Chinese Academy of Sciences	Gordon ZHOU
The Hong Kong University of Science and Technology / Department of Civil and Environmental Engineering	Charles W. W. NG

In addition to the management committee, an external advisory committee was also appointed by the PC (Table 3). The committee consisted of both international and local experts on debris flows. The committee's responsibilities included providing advice, identifying and raising technical concerns in the project, recommending improvements, and assessing the overall performance of the project.

Table 3. Members of the international advisory committee

Project role	Name / Post	Unit / Department / Institution
Co-Investigator	Malcolm BOLTON / Fellow of the Royal Academy of Engineering, UK, Professor Emeritus	Civil Engineering / University of Cambridge
	Suzanne LACASSE / Member of US National Academy of Engineering, former Director of NGI	Norwegian Geotechnical Institute (NGI)
Industrial collaborator	C. K. LAU / Managing Director	Fong On Geotechnics
	Ringo YU / Managing Director	Frazer Construction Company Ltd.
Local advisor	James W. C. SZE / Director	Ove Arup and Partners
	Rupert LEUNG / Director	Hong Kong Institute of Engineers; Hyder Consulting Limited
	Andrew MALONE / Adjunct Professor	Department of Earth Science / The University of Hong Kong
	Raymond CHAN / Director	Meinhardt Limited
	Patrick CHAO / Director	AECOM Asia Ltd.
	H. N. WONG / Former Head	The Geotechnical Engineering Office of the Civil Engineering and Development Department
	Jack PAPPIN / Fellow	Ove Arup and Partners
	John ENDICOTT / Fellow	AECOM Asia Ltd.
	T. K. CHEUNG / Director	GeoTech Engineering
Overseas advisor	Oldrich HUNGR / Professor Emeritus[#a]	The University of British Columbia
	David PETLEY / Vice-President for Innovation	University of Sheffield
	Kenichi SOGA/ Chancellor's Professor[#b]	Civil and Environmental Engineering / University of California, Berkeley

[#a] Prof Oldrich Hungr passed away in 2017 and no longer serves on the international external advisory committee.
[#b] Prof Kenichi Soga was invited to succeed Prof Oldrich Hungr.

The minutes of the external international advisory committee meetings are provided in Appendix A5.

7. Awards and Recognition

7.1 Have any research grants been awarded that are directly attributable to the results obtained from this project?

The PC of this project has been awarded an Areas of Excellence (AoE) grant to investigate a much broader range of landslide types and to predict landslides caused by extreme weather events using artificial intelligence. The project, entitled Centre for Slope Safety (AoE/E-603/18), was awarded a total sum of HK$91.852M (budget approved by RGC).

7.2 Have any project team members participated as invited speakers in or organisers of international conferences as a result of this project?

A total of 82 keynote talks were delivered by team members at international conferences over the project duration (Appendix A1).

To enhance the dissemination of project findings and to benchmark our performance against others, the PC (co-)organised the following events:

- The 1st International Symposium on Debris Flow Mechanisms and Mitigation for Sustainable Development on 2 December, 2018 at HKUST, HKSAR (organiser) (Appendix H1).
- The 2nd JTC1 workshop on triggering and propagation of rapid flow-like landslides from 3 – 5 December, 2018 at HKUST, HKSAR (co-organiser) (Appendix H1).
- The 5th International Debris Flow Workshop & Symposium on Silk Roads Disaster Mitigation from 5 – 6 November, 2018 at Xinjiang Plaza, Beijing, China (supporting institution) (Appendix H2).
- International Conference on Silk Roads Risk Reduction and Sustainable Development (SiDRR) from 11 – 12 May, 2019 in Beijing, China (co-organiser) (Appendix H3).
- Climate Adaptation and Resilience Conference 2018 from 27 – 29 October, 2018 at HKUST, HKSAR (organiser) (Appendix H7).

For other activities organised during the project period, please refer to Appendices H1—H9.

7.3 Have any project team members taken leadership positions in editorial boards, scientific and professional organisations?

- Charles W. W. Ng (PC) is Editor-In-Chief of the *Canadian Geotechnical Journal* (July 2021 to date)
- Charles W. W. Ng (PC) is an Associate Editor of *Landslides Journal* (2003 to date)
- Charles W. W. Ng (PC) is an Editorial Board Member of the *Chinese Journal of Geotechnical Engineering* (2003 to date)
- Charles W. W. Ng (PC) is an Editorial Board Member of *Journal of Zhejiang University-Science A* (applied physics and engineering) (2014 to date)
- Charles W. W. Ng (PC) is an Editorial Board Member of *Geomechanics for Energy and Environment* (2014 to date)
- Charles W. W. Ng (PC) is an Editorial Board Member of *Computers and Geotechnics* (2015

to date)

- Limin Zhang (Co-PI): Editor-in-Chief of *International Journal Georisk*, Taylor & Francis (2014 to date)
- Limin Zhang (Co-PI): Associate Editor of *Journal of Geotechnical and Geoenvironmental Engineering American Society of Civil Engineers* (ASCE) (2009 to date)
- Limin Zhang (Co-PI): Associate Editor of *Environmental Geotechnics*, ICE, UK (2013 to 2016)
- Limin Zhang (Co-PI): Member of Editorial Board of *Soils and Foundations*, Elsevier & Japanese Geotechnical Society (2013 to 2016)
- Limin Zhang (Co-PI): Member of Editorial Board of *Computers and Geotechnics*, Elsevier (2012 to date)
- Limin Zhang (Co-PI): Member of Editorial Board of *Geomechanics and Geoengineering* (2012 to date)
- Limin Zhang (Co-PI): Member of Editorial Board of *Journal of Mountain Science*, Springer and Chinese Academy of Sciences (2013 to date)
- Jidong Zhao (Co-I) is an Editorial Board Member of *Computers and Geotechnics* (2013 to date)
- Jidong Zhao (Co-I) was a Leading Guest Editor for *Granular Matter* (Springer) (2015 to 2016)
- Gang Wang (Co-I) is an Associate Editor of *Journal of Micromechanics and Molecular Physics* (2015 to date)
- Sérgio D. N. Lourenço (Co-I) is an Editorial Board Member of the *Canadian Geotechnical Journal* (2016 to date)
- Sérgio D. N. Lourenço (Co-I) is a Member of the Editorial Board of the *Journal of Rock Mechanics and Geotechnical Engineering* (Chinese Academy of Sciences) (2014 to date)
- Sérgio D. N. Lourenço (Co-I) is a Member of the Editorial Board, *Geotechnical Research* (Institution of Civil Engineers, UK) (2013 to date)

Project team members took up the following leadership positions in scientific and professional organisations:

- Charles W. W. Ng (PC) was elected as the 17th President of the International Society of Soil Mechanics and Geotechnical Engineering (ISSMGE) in September 2017 for four years. The ISSMGE was established in 1936 and governs and directs 92 member societies and special regions worldwide. More details are provided on the website: https://www.issmge.org/
- Charles W. W. Ng (PC): Board Representative of the International Consortium of Landslides (ICL), The United Nations Educational, Scientific and Cultural Organization (UNESCO) (April 2019 to date)
- Charles W. W. Ng (PC): Chair of Awards Committee of International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) (2013 to 2017)
- Charles W. W. Ng (PC): Editor-in-Chief of the *Bulletin for the International Society for Soil Mechanics and Geotechnical Engineering* (2014 to date)
- Charles W. W. Ng (PC): Member of Technical Committee (TC106) on *Unsaturated Soils* of the ISSMGE (2013 to 2017)
- Charles W. W. Ng (PC): Member of Technical Committee (TC308) on *Energy Geotechnics* of the ISSMGE (2013 to 2017)
- Charles W. W. Ng (PC): Member of American Society of Civil Engineers' Earth Retaining Structures Committee, USA (2000 to date)
- Charles W. W. Ng (PC): Member of American Society of Civil Engineers' Deep Foundation Committee, USA (2001 to date)

- Charles W. W. Ng (PC): President of the Hong Kong Geotechnical Society (HKGES) under the ISSMGE (2014 to 2017)
- Jidong Zhao (Co-I): Secretary for ISSMGE TC103 *Numerical Methods in Geomechanics* (2011 to 2017)
- Jidong Zhao (Co-I) Member of the Hong Kong Institute of Engineers (HKIE), Geotechnical Division: Task Force on Numerical Modelling of Debris Flow (2014 to date)
- Jidong Zhao (Co-I): Member of ISSMGE TC105 Micro Geomechanics Committee (2011 to date)
- Jidong Zhao (Co-I): Member of the Engineering Mechanics Institute (EMI) Granular Materials Committee (2013 to date)
- Gang Wang (Co-I): President of the American Society of Civil Engineers Hong Kong Section (2015 to 2016)
- Gang Wang (Co-I): Council Member of the Chinese Society of Theoretical and Applied Mechanics (2014 to date)
- Gang Wang (Co-I): Member of Technical Committee (TC203) on *Earthquake Geotechnical Engineering* of the ISSMGE (2014 to date)
- Gang Wang (Co-I): Secretary of Technical Committee (TC210) on *Dams* of the ISSMGE (2010 to date)
- Sérgio D. N. Lourenço (Co-I) is a Full Member of the Peer Review College, Engineering and Physical Sciences Research Council (United Kingdom) (2017 to date)
- Sérgio D. N. Lourenço (Co-I) is a Member of the Physical Sciences Board of the Royal Society (United Kingdom) (2013 to date)
- Sérgio D. N. Lourenço (Co-I) is a Member of the Technical Committee 211 Ground Improvement & Affiliate Technical Committee 106 Unsaturated Soils, (2015 to date)
- Sérgio D. N. Lourenço (Co-I) is a Member of the Association of Geotechnical Specialists (Hong Kong) (2017 to date)

7.4 Any documentary proof of the application of technologies arising directly from this project?

A total of seven patent applications have been filed in China and the United States for technologies arising from this project (Table 4).

Table 4. List of patents obtained during the project

Item	Author(s) (Last Name, First Name)	Patent name	Patent office
I1	Ng, C.W.W., Choi, C.E., and Song, D.	Bi-linear energy dissipating and shock absorbing device for cable subjected to tension.	United States Patent (US 20180274618A1).
I2	Ng, C.W.W., Choi, C.E., and Song, D.	Bi-linear energy dissipating and shock absorbing device for cable subjected to tension.	Chinese Patent (Application no. PCT/CN2017/070127).
I3	Song, D., Zhou, G.D., Li, S., and Hu, H.S.	Flexible barrier and designing method thereof.	Chinese Patent (Application no. 201711317935.2).
I4	Choi, C.E., Ng, C.W.W., Liu, H., and Cui, Y.F	Device capable of simultaneously measuring multiple mechanics and kinematics parameters of debris flow	Chinese Patent (Application no. CN201810614916).
I5	Xie, Y.X., and Zhou, G.D.	New numerical simulation analysis method and system of debris flow dynamics.	Chinese Patent (Application no. 201710958968.9).

I6	Zhou, G.D., Hu, H.S., and Song, D.	Design method of opening width of comb dam for non-viscous debris flow.	Chinese Patent (Application no. 201810168486.8).
I7	Cui, Y., Yan, Y., and Choi, C.E.	Particle grading identification measurement system for drone aerial data	Chinese Copyright of Computer software. (Classification Codes: 30200-8000)

Please refer to Appendices I1—I7 for details of each patent application.

7.5 Other awards and recognitions as a result of this project (please specify):

- Prof Charles W. W. Ng from HKUST along with Dr Raymond Koo and Dr Julian Kwan from GEO were awarded the HKIE Best Geotechnical Paper Award 2018 for their co-authored paper entitled "Landslide mobility analysis for design of multiple debris-resisting barriers." (Appendix A2)
- Prof Charles W. W. Ng from HKUST was awarded the R.M. Quigley Award 2017 by the Canadian Geotechnical Society for 2nd best paper out of 296 peer-reviewed papers in the *Canadian Geotechnical Journal* entitled "Large-scale successive boulder impacts on a rigid barrier shielded by gabions." (Appendix A2)
- Prof Charles W. W. Ng from HKUST was awarded the Telford Premium Award 2017 by the Institution of Civil Engineers, UK for best paper published in *Géotechnique Letters* entitled "Coarse granular flow interaction with slit structures." (Appendix A2)
- Prof Jidong Zhao from HKUST was honoured with two best paper awards from leading international journals in geotechnical engineering and granular media in 2018 (Appendix A2).
- Dr W. Wang, who graduated from CityU in 2017, Dr Dongri Song, who graduated from HKUST in 2018 and Dr C. S. Sandeep, who graduated from CityU in 2019 won the Ringo Yu Prize for Best PhD Thesis in Geotechnical Studies, organised by the Geotechnical Division Committee of HKIE (Appendix A2).
- Dr Raymond C. H. Koo, who graduated from HKUST, won the Award from the Association of Geotechnical and Geoenvironmental Specialist, Hong Kong, for outstanding research performance (Appendix A2).
- Prof Limin Zhang from HKUST was awarded the Natural Science Award (First Class) 2019 from the Ministry of Education of China (Appendix A2).
- Prof Gang Wang from HKUST received the Mao Yisheng Youth Award for geotechnical earthquake engineering and soil dynamics from the Chinese Institution of Soil Mechanics and Geotechnical Engineering (Appendix A2).

8. Impacts

8.1 What are the current and expected impacts of the project on the long-term development of Hong Kong (social or economic development, e.g., patent, technology transfer, collaboration with external organisations, etc.)?

- The publication of the Technical Guidance Note (TGN 52: Enhanced Technical Guidance on Design of Rigid Debris-resisting Barriers), a legal design document, will enable practitioners to reduce the design impact capacity of rigid barriers by 40%, which will lead to substantial cost savings for future rigid barriers installed on slopes in Hong Kong. This is important to the social and economic development of Hong Kong, as the HKSAR Government has spent a total of HK$23.6 billion (3 billion USD) to date on landslide

mitigation. The spending is expected to increase to combat the effects of extreme rainfalls due to climate change.

- The publication of GEO Report 319: A Pilot Study on the Design of Multiple Debris-resisting Barriers, will for the first time provide local and international practitioners with a framework to design multiple debris resisting barrier systems. There are more than 2,700 landslide catchments that may be suitable for multiple barrier installation in Hong Kong, which will result in smaller individual barriers that are most cost effective and less visually intrusive on the natural hillsides. As many countries such as Canada, Japan and the US, and regions such as Taiwan suffer from debris flow problems, the impact of this design document is clearly significant.
- In recent years, the HKSAR Government has installed 300 flexible barriers, which span a total distance of over 25 km in Hong Kong. There is a genuine and pressing need for research and development that will lead to more cost-effective barrier designs. The development of the state-of-the-art flexible barrier system for resisting debris flow impact provides a unique opportunity for potential technology transfer from research to the industrial practice. Patents obtained in the development of the flexible barrier systems can be used to create marketable products for debris flow hazard mitigation in conjunction with the newly developed design guidelines for multiple debris resisting barriers for Hong Kong.
- In 2010, the HKSAR Government commissioned the Landslip Prevention and Mitigation Program (LPmitP) and shifted its focus towards natural terrain hazards instead of manmade slopes. Thus, conventional slope engineering knowledge is no longer sufficient for mitigating the hazards pertaining to debris flows. The new course on debris flow mechanisms and mitigation that was developed and delivered during this project at HKUST has been instrumental in training the next generation of engineers to tackle debris flow mitigation problems. Moreover, flexible barriers and multiple barriers have seen increasing use internationally in recent years. As such, the Virtual University of ISSMGE launched by the PC aptly provides an open-source platform to increase the outreach of the developed debris flow courses to a much larger audience around the world.
- World-leading research facilities developed in this project such as the 28-m long flume, the geotechnical centrifuge models, pendulum impact apparatus, and novel instrumentation will be used to support future research endeavouring to understand the mechanisms of landslides initiation and interaction with structures under extreme weather conditions. As a successor to this project, the Areas of Excellence project "Centre for Slope Safety" will leverage these unique research facilities to continue exploring slope safety improvement for the sustainable social and economic development of Hong Kong.
- Multiple local and international collaborations were established as a direct result of this project. Most notably, a joint international research collaboration between Norwegian University of Science and Technology (NTNU), HKUST and HKU has been established for landslide mitigation of urbanized slopes for sustainable growth (LIFELONG). The HK$4.760M LIFELONG project will continue to use the 28-m long flume to conduct unique experiments of debris flow-erodible bed-resisting barrier interactions. Locally, a collaboration was set up between HKJCDPRI and HKUST in a new project called Smart Landslide Barriers. This project has obvious social and economic implications for sustainable development in Hong Kong by adopting event-driven early warning systems to protect the general public from landslide hazards. Details of other notable collaborations with direct implications for the technological development of geohazard mitigation measures in Hong Kong are provided in appendices C8-C15.
- Many students have been trained during the course of this project to enhance the supply of human resources both locally and internationally. A total 135 research students (80 PhD, 25 MPhil, 8 MSc and 22 BEng students) and 20 research staff (14 postdocs and 6 RAPs) have been directly trained from this project. Many of them have become assistant

professors in top universities in Hong Kong including the University of Hong Kong and the Hong Kong Polytechnic University and also Tsinghua University in the Mainland, also in École Polytechnique Federale de Lausanne Switzerland etc. The enormous human capital gained from this project is expected to have profound and long-term impacts worldwide.

8.2 Others (please specify):

None

9. Sustainability of the Project

9.1 Whether there are new ideas evolved directly from this project?

Yes, new ideas have evolved directly from this project. These ideas include: (i) the realisation that aside from physical barriers, a pressing need exists to enhance predictions of landslide initiation, especially in the face of climate change; (ii) the awareness of the advantages arising from the use of artificial intelligence to study the rich database of available physical experimental and field landslide data generated from this project; (iii) the need to develop green mitigation measures beyond the hard engineered measures recommended in the design guidelines developed in this project; (iv) the potential of data-driven methods for quantifying and managing landslide risks to enhance early warning systems; and (v) a noticeable paradigm shift in the development of immersive education to enhance slope safety awareness for better preparedness and resiliency of the general public. Further research on these ideas is integral to sustainable development against landslide hazards in mountainous regions in Hong Kong and beyond.

9.2 Whether there are new projects evolved directly from this project?

As a result of this project, the PC obtained an Areas of Excellence (AoE) project entitled, Centre for Slope Safety (AoE/E-603/18), to extend the scope of the Theme-based Research project and to address the new ideas discussed in section 9.1.

9.3 Whether there are new collaborations developed directly from this project?

Yes. As a result of this project, a new collaboration was formed with HKJCDPRI. Through this collaboration, two spin-off projects on a smart landslide information system and smart landslide barriers were funded by HKJCDPRI. The collaboration between the PC and HKJCDPRI continued with the abovementioned AoE project, where HKJCDPRI is a collaborator. Additionally, collaborations between the project team and other research institutions have been established in the form of academic exchange, specifically with the University of the Federal University of Paraná in Brazil, Politecnico Di Torino, Italy, Zhejiang University, China and Norwegian University of Science and Technology (NTNU), Norway. The collaboration between the PC and NTNU has continued in the abovementioned AoE project in the form of a collaborative research grant funded by the Research Council of Norway to encourage exchange and workshops between Hong Kong and Norway. Furthermore, collaborations were formed between the project team and industry, specifically ISAN Corporation of Korea (representing the Korean government), and GEOBRUGG. GEOBRUGG, in particular, has expressed interest in future collaborative efforts in the aforementioned AoE project to develop new technologies against landslide hazards.

9.4 Please give details on how much money and from which sources has been obtained/requested for the specific purpose of continuing the work started under this project.

As discussed in section 9.2, the AoE project is funded by the Research Grants Council of Hong Kong. The total project amount is HK$91.852M. The project duration is from 28 March, 2019 to 27 March, 2027.

10. Statistics on Research Outputs

(Please ensure the statistics in this section are consistent with the information presented in other sections of this report.)

	Peer-reviewed journal publications	Conference papers	Scholarly, books, monographs and chapters	Patents awarded	Other research outputs (please specify)	
					Type	No.
No. of outputs arising directly from this research project	189	67	N/A	7	Keynotes and invited talks	82

11. Public Access of Completion Report

(PCs of projects funded in 2010/11 academic year or onwards are required to release the completion reports to the public through the RGC website. Completion reports containing information such as abstracts in non-technical terms, objectives, research output including the list of conference papers / publications / journals and research findings and contact information of PCs should be open to public access.)

Please specify the information, if any, that cannot be provided for public access and give the reasons.

Information that cannot be provided for public access	Reasons

12. The Layman's Summary

(describe in layman's language the abstracts and research impact of the project.)

The risk of rainfall-induced natural terrain landslides in Hong Kong is expected to increase due to urban encroachment on hillsides and more frequent extreme rainfall events caused by the effects of climate change. In fact, the city experiences more than 2,000 mm of rainfall each year, which is expected to increase by 36 mm every 10 years. The city's dense population along with the fact that more than 60% of its area is covered by hilly terrain makes protecting the general public from landslides an even more challenging task. Even a small landslide can have severe consequences. The unique characteristics of Hong Kong limit the use of conventional and empirically based landslide mitigation measures adopted in other parts of the world. Evidently, novel, safe and economical solutions are urgently needed.

Based on the research findings from this project, two new state-of-the-art design guidelines were published with the Geotechnical Engineering Office (GEO) of the HKSAR Government. These guidelines include a legal design document (Technical Guidance Note 52) and a design

recommendation document (GEO Report 319). Technical Guidance Note 52 enables practitioners to reduce the design impact capacity of rigid barriers by 40%, which will result in substantial cost savings. GEO Report 319 is the world's first of its kind design guideline to provide local and international practitioners with a design framework for multiple barrier systems, which will reduce the scale of individual barriers for more cost-effective and sustainable mitigation solutions. Not only will this report have a profound effect on barrier design in Hong Kong, but its impact will also extend to the engineering practices in many countries, such as Canada, Japan, the US and regions such as Taiwan.

The research outcomes of this project have also led to the development of seven new patents, including a new state-of-the-art flexible barrier system for protecting infrastructure against debris flows. With the HKSAR government's plan of installing 40 flexible barriers annually in the coming years, the new technology will offer an alternative to costly proprietary products.

This project directly trained a total of 135 research students and 20 research staff, four of whom landed academic positions in Top 100 universities, according to the 2021 QS Global and Times Higher Education rankings, including the University of Hong Kong, Tsinghua University, École Polytechnique Federale de Lausanne Switzerland and Hong Kong Polytechnic University. Additionally, more than 15 students have joined key positions in academia and industry both locally and internationally.

Key research facilities were developed in this project. The most unique being a 28-m flume facility, which is one of the largest in the world. Numerous international and local collaborative endeavours have been completed using the flume, including those from Norway, Korea, Italy, Switzerland, and the HKSAR Government. The flume will continue to be used by academics and practitioners to investigate local and international landslide-related problems for years to come.

As a way of further extending the impact made locally and internationally by the project, the project team formed a new strategic collaboration with the International Consortium of Landslides of UNESCO to disseminate the key technologies from this project to developing mountainous regions like those along the Belt and Road countries. Finally, a unique course on debris flow mechanisms and mitigation measures was developed and delivered to train the next generation of engineers in Hong Kong. To facilitate global outreach, the course contents are featured on the open-source virtual university platform of the International Society for Soil Mechanics and Geotechnical Engineering.