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BARRIERDT: A DIGITAL TWIN OF RIGID DEBRIS-RESISTING BARRIERS FOR GEOHAZARD EVENT MONITORING AND RISK ASSESSMENT

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Rigid debris-resisting barriers are one of the most commonly adopted structural countermeasures for landslides and debris flows from natural terrain slope failures on natural hillsides in Hong Kong[1]. As urban development gradually encroaches toward natural hillsides and weather patterns become erratic from climate change effects, the risks associated with landslide debris hazards will undoubtedly increase. It is therefore essential that the barriers are designed, constructed and maintained with an adaptation to changing conditions of geohazard events driven by climate change. One emerging area of research which focuses on addressing this challenge is the creation of 'digital twins' for rigid barriers. A digital twin serves as a virtual representation of the physical infrastructure (i.e. the physical twin), which can be updated in near real time as new data is collected, provide feedback into the physical twin and perform 'what-if' scenarios for assessing asset risks and predicting asset performance.

This paper presents our exploratory study towards creating a digital twin of rigid barriers for geohazard event monitoring and risk assessment purposes. In particular, it is an interdisciplinary study involving modelling, monitoring and simulation, using rigid barriers in Hong Kong as case studies. Four areas of research were investigated: (i) 3D reconstruction of rigid barriers using UAVs and Structure-from-Motion (SfM) methods, (ii) BIM modelling of rigid barrier with Scan-to-BIM methods and parametric modelling, (iii) near-real-time monitoring of rigid barrier, and (iv) prompt landslide and debris flow event simulation with consideration of risk mitigation effects of rigid barriers in place using fast simulation approaches. The rigid barrier's performance of resisting large dynamic impact loads imposed by landslides and debris flows are simulated and evaluated with the BIM model modelled as-built of real site barrier structure, and real-time monitoring IoT sensor data. A new framework for creating a digital twin of rigid barriers for event monitoring and risk assessment, is proposed and briefly discussed. Since impacts of debris-resisting barriers by landslide debris are rare events in Hong Kong, this study also sets out a new outlook on assisting the implementation of the performance-based approach in the design of rigid debris-resisting barriers.

Keywords: rigid barrier; digital twin; scan-to-BIM; parametric modelling; fast simulation.

1. Introduction

Rainfall-triggered landslides are devastating natural disasters that can lead to considerable human and economic losses.Rigid debris-resisting barriers are frequently employed as a primary defense against landslides and debris flows resulting from natural slope failures in places with high risks of rainfall-induced landslides such as Hong Kong.However, in the context of climate change, there is a growing necessity to enhance the understanding of the design, construction and maintenance of rigid barriers, which is essential for effectively adjusting to the evolving conditions of geohazard events driven by climate change.

Digital Twin (DT) is emerging as one of the most promising digital technologies being developed at present to support digital transformation and decision making in multiple disciplines, By creating a digital replica that mirrors the real world, digital twins are showing great potential in hazard assessment, emergency decisionmaking and risk mitigation[2]. Here we conduct the exploratory study on constructing a digital twin for the rigid barriers in Hong Kong, named as BarrierDT, with more details laid out in the following sections.

2.Investigation of constructing a BarrierDT

2.1.*3D Reconstruction of rigid barriers with drones*

There are about 300 rigid barriers in place in Hong Kong, and each rigid barrier has complex and unique geometries due to the various geographical conditions of the surrounding area. Thus, the first step to construct a BarrierDT is to reconstruct the geometries of rigid barriers. Considering the complex geography, dense vegetation and inaccessible terrain,utilizing drones to capture images for photogrammetric 3D reconstruction is more suitable than LiDAR scanning. Several field trips are conducted to obtain the 3D reconstructed point cloud data of rigid barriers.Subsequently, Structure-from-Motion (SfM) methods are used to conduct the 3D reconstruction of the righd barrier from photos to 3D point clouds.Fig. 1 illustrates the 3D reconstruction process and reconstructed point cloud model of a typical rigid barrier (slope number in Slope Information System (SIS): 11SW-C ND/29).

Fig. 1.(a) Data collection with UAV for 3D reconstruction and (b) reconstructed point cloud model of a rigid barrier.

2.2.*BIM modelling of rigid barriers with scan-to-BIM methods*

After 3D reconstruction,the next step is to construct the Building Information Model(BIM model) of rigid barrierbased on the point cloud data to better facilitate the downstream applications.BIM model stands for the3D digital representation of infrastructure that integrates detailed information about its physical and functional characteristics, which serves as an important step in thephysical-to-virtual side of development of digital twin and provides various advantages, such as interoperability between various visualization and simulation platforms and support of lifecycle management. Considering the regularized geometry of the rigid barrierswith main components being walls and baffles, PlaneSlam[2] method, a Simultaneous Localization and Mapping (SLAM) algorithm that extracts planar featuresfrom point clouds was used to extract the lightweight geometry of rigid barriers to facilitate the downstream BIM modelling.Fig. 2 shows the extracted planes from the point cloud data of the same rigid barrier in the previous section (slope No.11SW-C ND/29). The dimension of the extracted planes are further processed to construct the BIM model of such rigid barrier using parametric modeling technique.

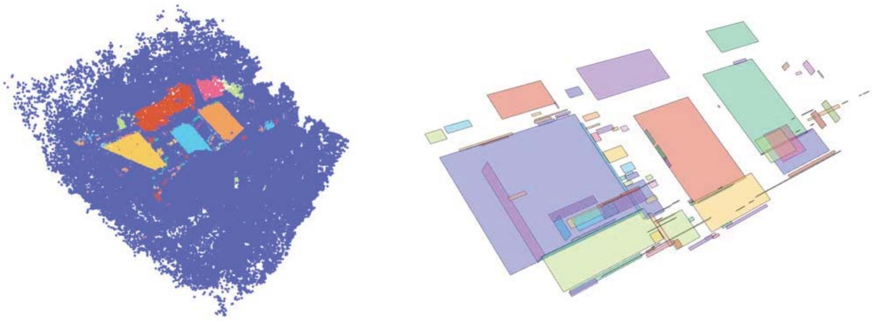

Fig. 2.(a) Planes highlighted in point clouds and (b) extracted planes in the selected rigid barrier with PlaneSlam.

2.3.*Near-real-time monitoring of rigid barriers with remote sensing*

Recently there have been great advancements in remote sensing technologies, and subsequently the application of remote sensing technologies in building digital twins of geohazard risk mitigation infrastructures to help manage geohazard risks. The advancements in remote sensing technologies are two folds: the increase in the spatial and temporal resolution of satellite imagery with the advancement of instruments mounted on remote sensing satellites (payloads), and theadvancement of the downstream analytic algorithms of the remote sensing imagery. For example, on August 25th 2023, HKUST successfully launched a high-resolution optical satellite "HKUST-FYBB#1" for research on regional environmental and disaster monitoring. HKUST-FYBB#1 has 0.5m spatial resolution and 150km swath, which allows it to monitorall rigid barriers across the entire Hong Kong region with one take while preserving the refined details on the status of major components of each rigid barrier.Meanwhile, recent advancements in AI-driven analysison remote sensing imagery, includingrecently emerging large foundation models such as Satlas[4] and Prithvi-EO-2.0[5], increases the accessibility and accuracy of the tasks such as object detection and instance segmentation with potential of integrating with multi-modal prompts such as natural language prompt.

Utilizing such high-resolution imagery and downstream AI-driven analysis,near-real-time monitoring of rigid barriers at a regional scale can be achieved to promptly detect potential damage, assess structural integrity, and assist in emergency management. Fig (a)(b) gives the example of a prompt assessment of the status of a typical rigid barrier (slope number in SIS: 11SE-B/ND 14) located in Tseung Kwan O, New Territories, Hong Kong before and after a major rainstorm occurred on 7th September 2023 with data retrieved from HKUST-FYBB#1 and Satlas model. From the side-by-side comparison we can verify there is no debris flow impacting thisparticular rigid barrier during this rainstorm and the structure of main components of remainsundamaged. Such analysis can extend to all rigid barriers in Hong Kong and potentially in other regions.

Fig. 3.Near-real-time monitoring of a typical rigid barrier (a) before the rainstorm and (b) after the rainstorm.

2.4.*Fast simulation of landslides and the interaction withrigid barriers*

Efficient and cost-effective numerical simulation of landslides, such as mobility analysis, is essential for understanding their process and impacts on risk mitigation measures to enable timely disaster assessment and decision-making in the digital twin. Traditional numerical approaches like the Discrete Element Method (DEM) and Material Point Method (MPM) are commonly used to evaluate landslide runouts and their interactions. However, these methods are computationally intensive when applied to large-scale problems, limiting the feasibility of conducting multiple full-scale simulations needed for a thorough evaluation of runout hazard scenarios at regional scale. Thus, various methodologies to increase simulation speed to achieve fast numerical simulation are explored. This section highlights an attempt to deploy a new class of simulatorsable to utilize the parallel computational power of modern GPUs to accelerate the computation speed. GeoTaichi[6], a high-performance numerical simulator which maximizes the utilization of modern computer resources on multicore CPU and GPU architectures by leveraging the power of the Taichi[7] parallel language, was selected.

We present a landslide mobility analysis and impact analysis test to showcase the feasibility of this approachalong with the constructed BIM model in the previous sections.The rigid barrier located at near Queen Mary Hospital with slope No. 11SW-C ND/29 is selected. The digital elevation model (DEM)of the surrounding area are constructed, and the recently emerging material point-discrete element method (MPDEM) method is selected as the simulation method of the case.

Fig. 4illustrates the preliminary results of the landslide simulation. The simulator successfully simulates the runout process of landslidewith MPDEM method utilizing the GPU acceleration feature and produced plausible runout results. According to [6], the new method can achieve 337%-493% calculation speed improvement against benchmark traditional methods even with less strong GPUs. The next step is to run more benchmark tests on the same case and compare the calculation speed performance.

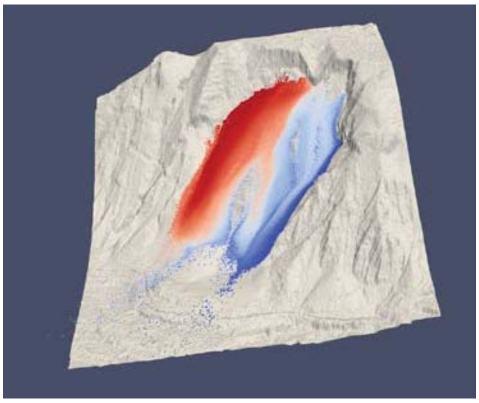

Fig. 4.Preliminary simulation results of the landslide simulation with GPU-parallel computing.

3. New framework for creating a digital twin of rigid barriers

Based on the exploratory work presented in the previous chapter,we propose a new framework for creating a digital twin of rigid barriers for in-time event monitoring and accurate science-backed risk assessment,including 3 main modules: modelling module, monitoring module and simulation module.Fig. 5illustrates the design of the digital twin framework.

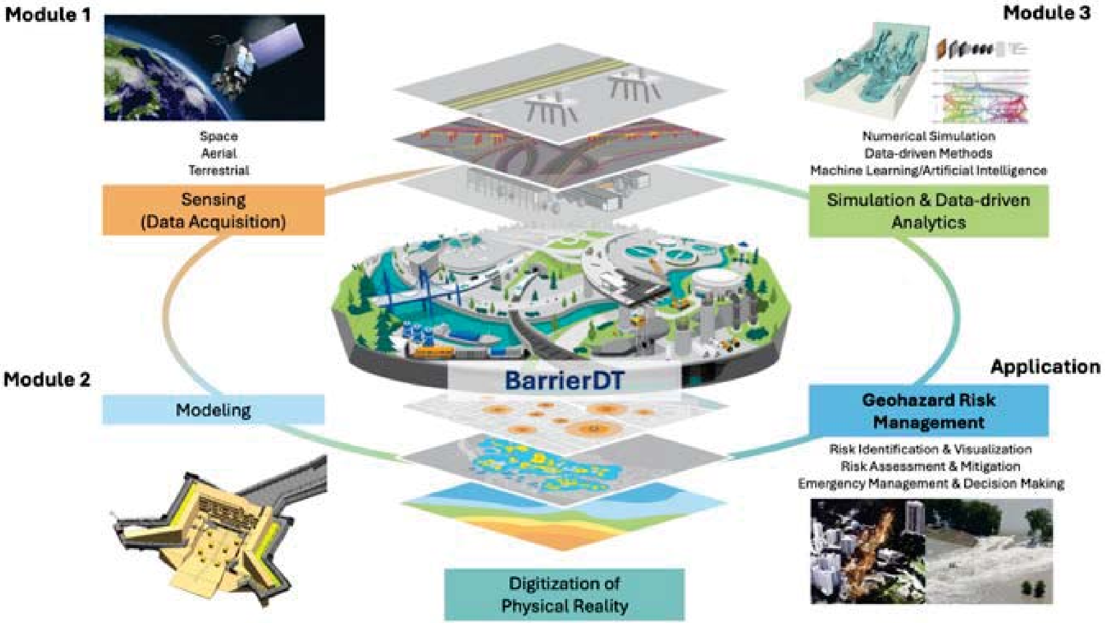

Fig. 5.The proposed new framework for creating a digital twin of rigid barriers.

4. Conclusions and discussions

This paper presents our exploratory study towards creating BarrierDT, a digital twin of rigid barriers in Hong Kong, for geohazard event monitoring and risk assessment purposes. In particular, 4 exploratory works are covered: (i) 3D reconstruction of rigid barriers using UAVs and Structure-from-Motion (SfM) methods, (ii) BIM modelling of rigid barrier withPlaneSlam, (iii) near-real-time event monitoring of rigid barrier with remote sensing satellite imagery, and (iv) prompt landslide event simulation with consideration of risk mitigation effects of rigid barriers using GPU parallel computing-enabled fast simulation approaches. Subsequently, a new framework for creating a digital twin of rigid barriers is proposed, including 3 main modules: modelling module, monitoring module and simulation module.

As impacts of debris-resisting barriers by landslide debris are rare events in Hong Kong, one of the major challenges arethe scarcity of data for verification of the result against the actual recorded spreading and deposition of the landslide, and the impact of the landslide to the particular rigid barrier.By constructing such BarrierDT, we expect to contribute to this particular problem with more data collected during major rainfall events.Moreover, as communication networks continue to develop and expand, the intrinsic complementary characteristics of spaceborne, aerial and ground-based sensors enable the effective integration of data acquired from these sensors. In the future, with more in-situ IoT sensors installed for rigid barriers, the real-time monitoring can be achieved withsuch space-air-ground sensing network to enhancegeohazard resilience and ensuring public safety in the wake of extreme weather events.

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