Technical Note

Landslides (2018) 15:1889–1899
DOI 10.1007/s10346-018-1034-9
Received: 30 January 2018
Accepted: 22 June 2018

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Utilizing crowdsourcing to enhance the mitigation and management of landslides

Abstract Landslides are mainly triggered by earthquakes and rainfall and have poor temporal predictability. Landslides pose significant threats to settlements and infrastructure in mountainous regions around the world. To mitigate this natural hazard, a new paradigm of landslide mitigation and management is required. Increasing smartphone ownership around the world, especially in developing countries, offers scientists an opportunity to embrace crowdsourcing so as to improve landslide research. This paper presents a new landslide information system (LIS) comprising a smartphone app and an administrative interface and database. The mobile app has been published for both iPhone and Android platforms. The interface of the smartphone app is powered by the highly-customizable Google Maps platform, which is overlaid with real-time landslide data. Users can choose between visualizing “known sites” and “contribution” of landslide data. The visualization option shows published landslides and areas that are susceptible. Users can contribute their GPS coordinates and multimedia to enhance landslide reports. A comparison with similar systems, potential applications, and challenges of using smartphone technology for mitigating landslides are also discussed.

Keywords Smartphones · Crowdsourcing · Geo-fencing · Early-warning · Disaster-management

Background

Landslides are mainly triggered by earthquakes (Keefer 1984; Yin et al. 2009; Zhang et al. 2017; Wang et al. 2018) and rainfall (Iverson 2000; Wang and Sassa 2003; Zhang et al. 2010; Cui et al. 2017), and a difficult to predict natural hazard (Jakob and Hungr 2005). As human development encroaches hillsides and as extreme rainfall events occur with increasing frequency due to climate change (IPCC 2012), the threat posed by landslides will inevitably increase. The seriousness of this threat is reflected by recent disasters in Sichuan, China, resulting in the destruction of houses and fatalities (Qiu et al. 2017; Chen and Cui 2017), and in Hiroshima, Japan, where a landslide killed 74 people and destroyed 133 homes in 2014 (Wang et al. 2015). Much research has been carried out on enhancing early-warning systems (Baum and Godt 2010; Intrieri et al. 2012, 2013), improving risk and consequence analysis (Fell et al. 2005; Van Westen et al. 2006; Dai et al. 2002; Choi et al. 2018), and installing structural countermeasures (VanDine 1996; Kwan 2012; Choi et al. 2014; Takahashi 2014; Cui et al. 2018) to mitigate landslides. Despite ongoing efforts by the research community, as many as 2250 deaths have resulted from 444 fatal landslides occurred in 2016 around the world (Petley 2017). Clearly, a new paradigm of landslide mitigation and management is required.

With the increasing availability and the decreasing costs of smartphone technology (Bosomworth 2015; Poushter 2016), especially in developing countries, scientists and practitioners need to explore and embrace smartphone technology so as to better mitigate and manage landslide disasters. Figure 1 shows trends of smartphone ownership in developed and in-transition economies (Fig. 1a), and developing economies (Fig. 1b) as estimated by Statista (2018). Although, trends show that an increase in smartphone ownership for developed and in-transition economies have slowed down compared to developing economies, the sheer magnitude of smartphone ownership around the globe is astonishing.

Crowdsourcing (Zhu et al. 2014) is one of the approaches that scientists use to collect data for early-warning and post-disaster management systems (Frommberger and Schmid 2013b). This approach relies on the vast number of smartphones available on this planet. Mobile applications are then developed to acquire measurements from sensors from these smartphones, including acceleration, temperature (Overeem et al. 2013), and GPS coordinates. Crowdsourcing is particularly useful in developing countries where early-warning and disaster management systems are not yet mature. For example, an earthquake-prone region, like Nepal, does not have any seismic stations or real-time rain gauges to serve as early-warning against landslides. However, Nepal is estimated to have more than six million smartphones. Clearly, the multitude of smartphones in the world can be used to form a vast network for landslide early-warning or post-landslide reporting.

Aside from collecting data from smartphones for early-warning, data can also be used to assist scientists to better understand landslides mechanisms at an entirely different scale. A pertinent example of a large-scale landslide disaster where crowdsourcing may have been useful is the 7.8 magnitude earthquake that hit Kaikoura New Zealand in November 2016 (Bradley et al. 2017; Gorum and Yildirim 2017). This earthquake triggered more than 100,000 landslides (Villeneuve et al. 2017; Shi et al. 2017). Some landslides blocked off entire towns, for instance Kaikoura, with a population of about 2000 people, was completely cut-off. In addition, some landslides were responsible for forming quake-dams (Woods et al. 2017; Stahl et al. 2017; Choi et al. 2018), which posed significant flooding threats to downstream facilities. Furthermore, numerous landslides could have been remobilized as debris flows and debris floods (Villeneuve et al. 2017). Furthermore, large boulders were left in a meta-stable state as a result of the earthquake (Dizhur et al. 2017), and many large tension cracks, which indicate progressive failure (Tiande et al. 1999), were reported on hillsides all over the country. Evidently, a wide-range of landslide types and threats were presented (Woods et al. 2017), and smartphone technology that utilizes crowdsourcing could have helped equipped authorities to better manage and prioritize these threats.

Another pertinent example of how crowdsourcing could be used to enhance the resilience of an urban community can be highlighted using the 2008 rainstorm in Hong Kong. Hong Kong has a population of about seven million and a small area of only 1100 km^2, of which 70% is hilly terrain. This terrain is subjected to torrential rainfalls during the wet season (Geotechnical Engineering Office 2016a), which present ideal conditions for

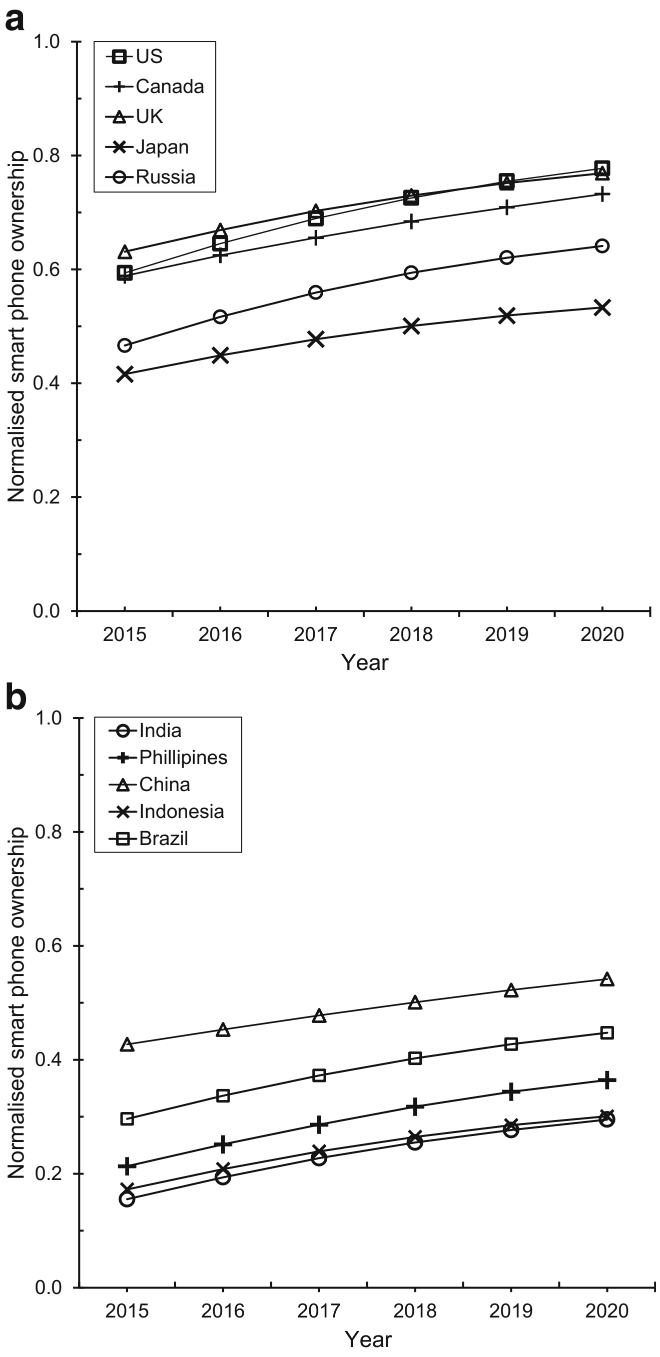


Fig. 1 Normalized smartphone ownership by total population. **a** Developed and in-transition economies. **b** Developing economies

landslides. On average, 300 landslides occur every year (Geotechnical Engineering Office 2015). With the advent of climate change, the number, scale, spatial extent, and frequency of landslides are expected to be unprecedented.

A glimpse into the potential consequences of intense rainfall in an urban setting is best illustrated by a severe rainstorm that bombarded Hong Kong in June 2008. This storm triggered over 2400 landslides on Lantau Island (Geotechnical Engineering Office 2016a), culminating in the loss of life, the blockage of roads, and the temporary evacuation of homes. In particular, a landslide at Cafeteria Old Beach in Tuen Mun resulted in two fatalities (Lam et al. 2012), and a landslide on Lantau Island blocked the sole access to the Hong Kong International Airport for up to 16 h (AECOM 2012) resulting in severe economic repercussions (Fig. 2a). Also, a landslide blocked Keung Shan Road (Lam et al. 2012), the only access to Tai O (Fig. 2b), with regular traffic restored after days of emergency repair (Lam et al. 2012). The maximum rolling 4-h rainfall recorded was equivalent to a rainstorm with a return period of about 1000 years. Had the rainstorm hit a more densely-populated area in Hong Kong, the consequences would have been immeasurable.

As demonstrated by the Kaikoura earthquake in 2016 and the rainstorm in Hong Kong in 2018, large-scale disasters can be challenging for authorities and emergency responders to cope. Therefore, crowdsourcing can play a crucial role to enhance the scale and resolution of landslide data available to better mitigate and manage landslides. During intense storms or ongoing earthquakes, engineers, scientists, and emergency responders may have limited capacity and require more time to mobilize. In light of these challenges, the general public can help to identify landslide hazards and to aid authorities in prioritizing rescue efforts.

In this paper, a new landslide information system (LIS), with an aim to enhance mitigation and management of landslides is presented. A comparison with similar systems, details of the working principle, features, prospects, and challenges are discussed in this paper.

Enhancing early-warning systems

The use of smartphone-based approaches for mitigating geohazards is a relatively new concept. Smartphone apps have recently been developed to crowdsource accelerometer and GPS data from smartphones for early-warning against earthquakes (Frommberger and Schmid 2013a; Minson et al. 2015; Kong et al. 2016; Finazzi 2016). Based on data collected from smartphones, scientists and authorities can dispatch warnings to smartphones located closest to the epicenter of an earthquake. Aside from taking advantage of built-in accelerometers, smartphone applications can also utilize built-in GPS technology to observe the density of detected earthquake motion within an area to affirm whether an earthquake has occurred. ShakeAlert is a smartphone application that has already shown signs of success (Strauss et al. 2015). This application provided almost 8 s of warning before the arrival of the most intense motion from an earthquake. These additional seconds can be used to allow trains to slow down, surgeons to pause during an operation, or users to exit elevators immediately. In the case of landslides, depending on the type of motion (Hungr et al. 2014) and proximity to infrastructure, warnings can enable people to brace themselves or allow them to evacuate. For very rapid to extremely rapid landslides, a warning in the order of minutes would enable the general public to situate themselves away from weak points of structures, such as doors and windows (Spence et al. 2004). For example, moving to higher floors can help increase the chances of survival against debris flows (Kappes et al. 2012). For slower moving landslides, an early-warning can even allow in the evacuation of buildings. A summary of the landslide velocity scale (Cruden and Varnes 1996) and the recommended response by Hungr (1981) is shown in Table 1.

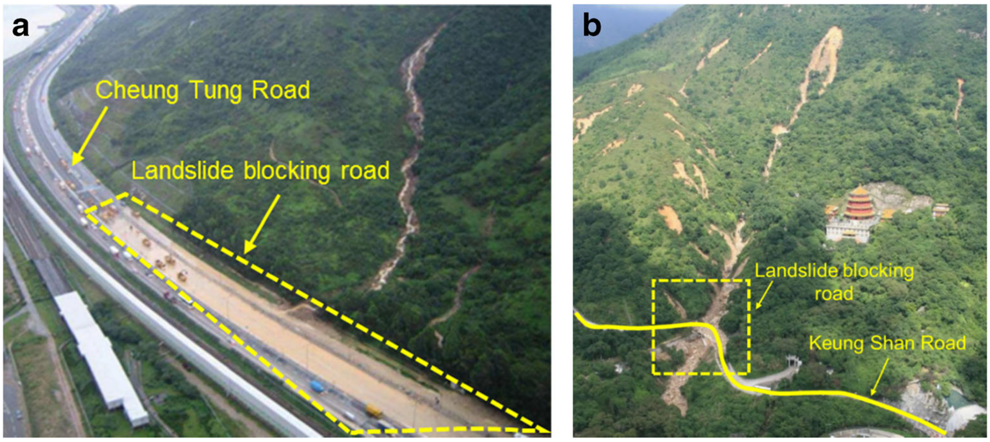


Fig. 2 **a** Cheung Tung Road Landslide, Lantau Island, Hong Kong (Modified from Lam et al. 2012). **b** Keung Shan Road landslides, Tai O, Hong Kong (modified from Lam et al. 2012)

Investigations on the susceptibility of rainfall- and earthquake-induced landslides, at a regional scale, have been carried out (Jibson and Keefer 1993; Jibson et al. 2000; Ko and Lo 2016). Furthermore, building on recent advances of satellite remote-sensing technology, near-real-time ground-shaking prediction system after earthquakes have been proposed by Hong and Adler (2007). Near-real time systems can be further enhanced by adopting data from crowdsourcing to better understand how ground motion, at large-scale, influences landslide initiation. Also accelerometer data from crowdsourcing can help improve susceptibility models for a particular region. Smartphones will unlikely be as effective and as sophisticated as earthquake stations, rainfall gauges, or inclinometers. However, smartphones can certainly enhance predictive tools and early-warning systems based off of a larger scale and resolution of data.

Improving disaster management

Hong Kong implemented the Landslip Warning System (LWS) in 1977 to draw the public's attention to landslide threats and to trigger the government landslide-related emergency services (Geotechnical Engineering Office 2015). The purpose of the LWS is to reduce the public's exposure to the dangers associated with landslides. Since most landslides in Hong Kong are mainly caused by heavy rainfall, the combination of real-time rainfall data, rainfall forecast from the Hong Kong Observatory (HKO), and practical experience on relationships between rainfall and landslides have enabled Hong Kong to identify when landslide danger is high and to issue landslip warnings to the general public. A landslip warning also triggers an emergency response system within government departments, which mobilizes staff and other resources to deal with landslide incidents (Geotechnical Engineering Office 2015).

During intense storms, Hong Kong displays a landslide incident map (LIM) complementary to the LWS. The LIM shows all landslides that have been reported. Currently, the LIM is displayed on the homepage of the Hong Kong slope safety website (Geotechnical Engineering Office 2016b) after a landslip warning has been issued. Each reported landslide is shown as an individual marker based on geographical coordinates. The current LIM has laid a great foundation to inform the general public on areas where landslides have occurred during intense rainstorms. With the prevalence of smartphone technology, the general public may be more inclined to adopt a more convenient map platform that operates on mobile devices, such as Google Maps™, so as to acquire up-to-date and detailed information on where landslides have occurred. More data from smartphones in the form of coordinates, photos, and videos can assist geotechnical engineers to better assess the validity of landslide incident reports.

Landslide information system (LIS)

The recently developed landslide information system (LIS) leverages crowdsourcing and location-based GPS technology to provide real-time landslide reporting to the public. The LIS comprises a user smartphone app and an administrative interface and database. The mobile app has been published for both iPhone and Android platforms.

Table 1 Landslide velocity scale and recommended action (Cruden and Varnes 1996; Hungr 1981)

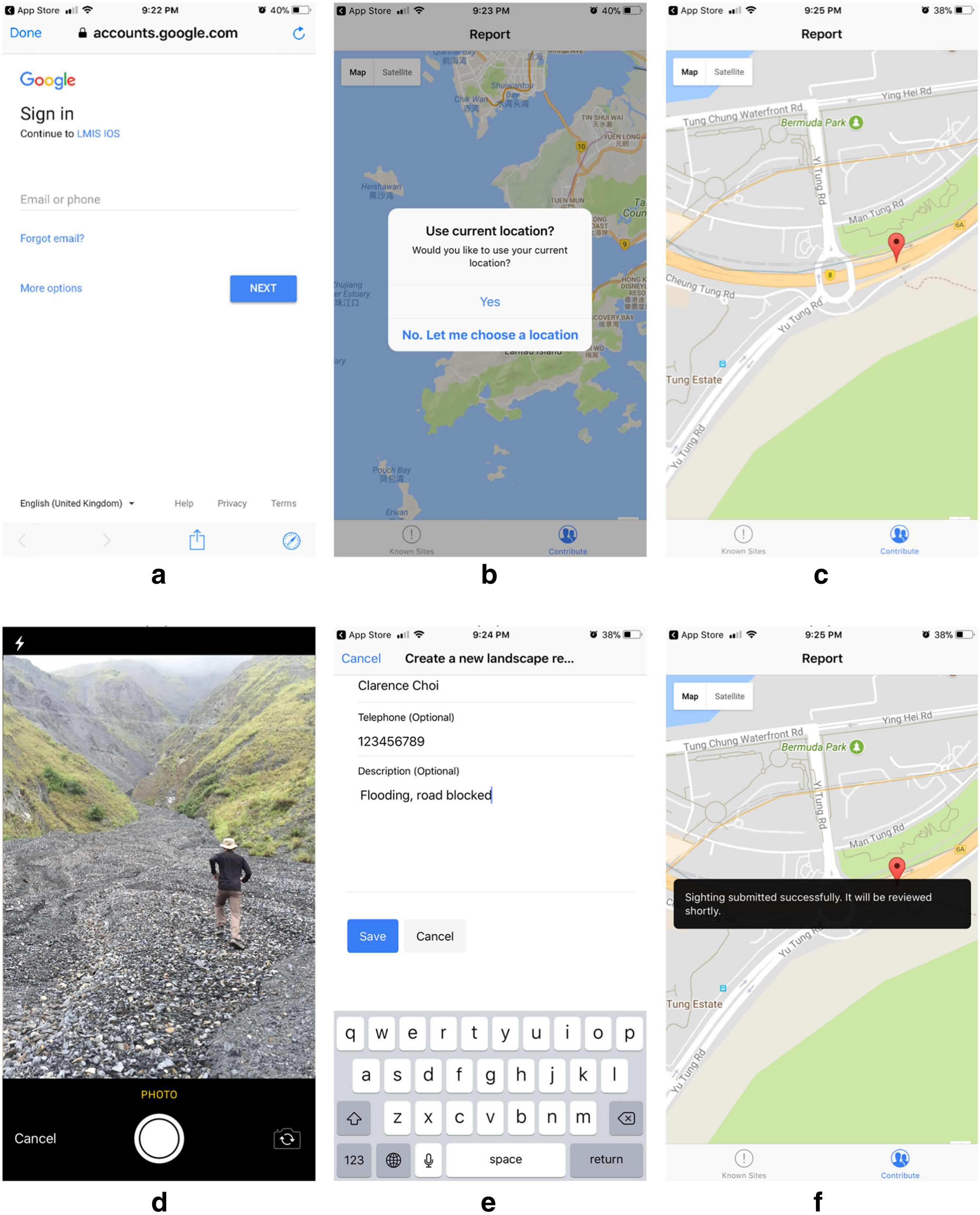
Description	Velocity (mm/s)	Typical velocity	Response
Extremely rapid	5×10^{3}	5 m/s	Nil
Very rapid	5×10^{1}	3 m/min	Nil
Rapid	5×10^{-1}	1.8 m/h	Evacuation
Moderate	5×10^{-3}	13 m/month	Evacuation
Slow	5×10^{-5}	1.6 m/year	Maintenance
Very slow	5×10^{-7}	16 mm/year	Maintenance
Extremely slow	–	–	Nil

Fig. 3 LIS map interface

Smartphone app to report landslide data

The smartphone app interface is powered by a highly-customizable platform, namely Google Maps™ (Fig. 3). Google Maps™ information is overlaid with real-time landslide locations and obstructed transportation lines. The user-interface provides different map types for users to choose. For example, the user can select among normal map, terrain map, and satellite map.

On the main interface, users can choose between visualizing "known sites" and contributing landslide data. The visualization option shows published landslides and susceptible areas to landslides. Both the administrative data base and the susceptibility model will be discussed later. When contributing landslide data, users need to log-in with valid credentials. The existing version requires a Google account (Fig. 4a). After the user logs-in, they have the option to report their



Use current location?

Would you like to use your current location?

Yes

No. Let me choose a location

Clarence Choi

Telephone (Optional)

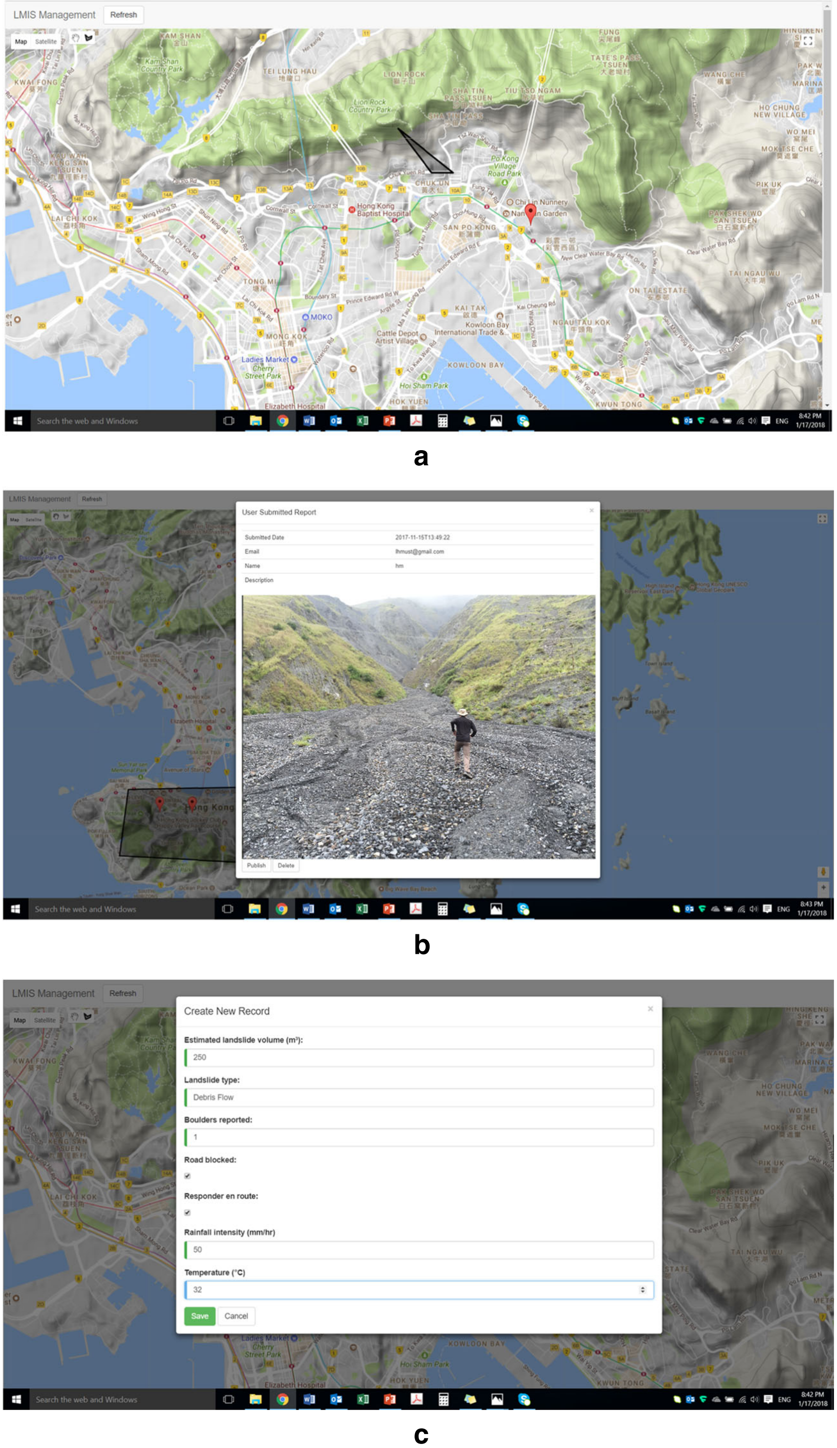
123456789

Description (Optional)

Flooding, road blocked

Sighting submitted successfully. It will be reviewed shortly.

Fig. 4 Landslide reporting. **a** Log in. **b** Provide location. **c** Mark location. **d** Send picture. **e** Enter contact and description. (**f**) Submission confirmation



User Submitted Report

Submitted Date	2017-11-15T13:49:22
Email	lhmust@gmail.com
Name	hm
Description	

Publish Delete

Create New Record

Estimated landslide volume (m³): 250

Landslide type: Debris Flow

Boulders reported: 1

Road blocked: ☑

Responder en route: ☑

Rainfall intensity (mm/hr) 50

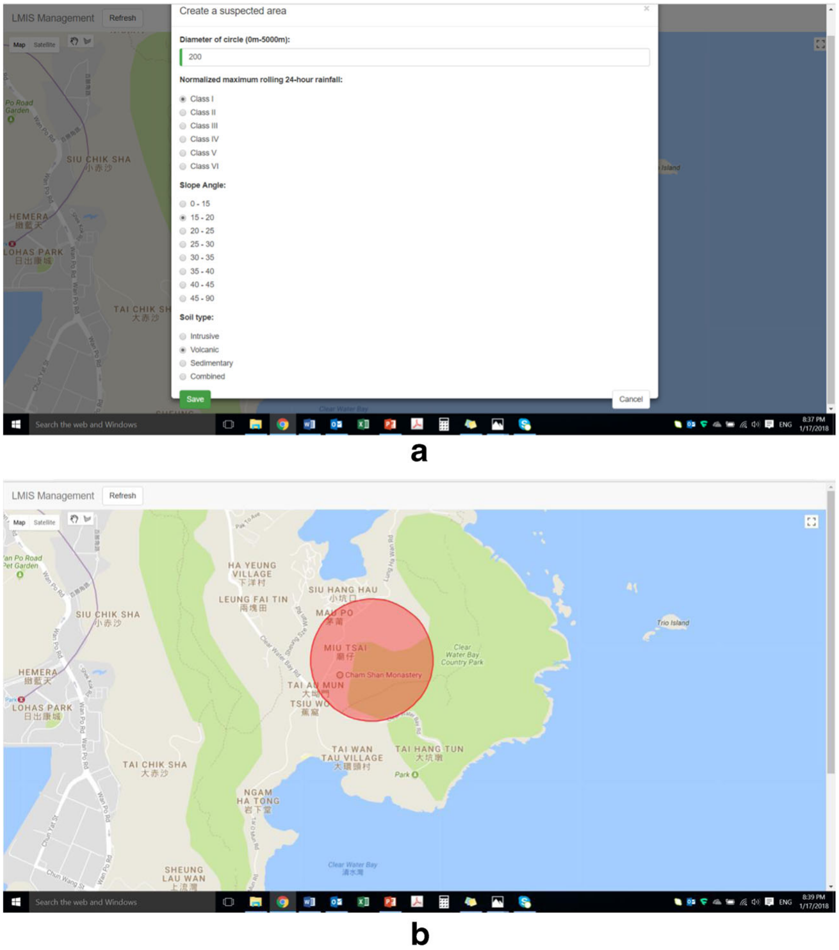
Temperature (°C) 32

Save Cancel

Fig. 5 Administrative interface and database. **a** Interface. **b** Incoming report. **c** Enhanced report and landslide details

current GPS coordinates (Fig. 4b) or manually mark the location on Google Maps™ (Fig. 4c). Furthermore, users can report landslide incidents in the form of photos (Fig. 4d). Compared to phone calls in many existing landslide reporting systems around the world, the multimedia in the LIS enables geotechnical engineers to better assess the validity of landslide reports and deliver a more appropriate response. After a photo has been uploaded, the user can provide additional personal details and technical details on the incident (Fig. 4e). Once the user saves the report, the incident is sent to the administrative database for review (Fig. 4f).

The current version of smartphone app runs silently in the background to utilize geo-fencing and only sends data at the discretion of the user. Settings can be changed so that data is only sent with the phone is connected to a Wi-Fi network. Also, the user can select whether the app accesses the location-tracking device and camera on their smartphone.



Create a suspected area

Diameter of circle (0m-5000m): 200

Normalized maximum rolling 24-hour rainfall:

● Class I
○ Class II
○ Class III
○ Class IV
○ Class V
○ Class VI

Slope Angle:

○ 0 - 15
● 15 - 20
○ 20 - 25
○ 25 - 30
○ 30 - 35
○ 35 - 40
○ 40 - 45
○ 45 - 90

Soil type:

○ Intrusive
● Volcanic
○ Sedimentary
○ Combined

Fig. 6 Built-in adaptive susceptibility model. **a** Characterization of landslide type. **b** Admin defined hazard area

Administrative database to enrich landslide database

The administrative database is where landslide data is collected and reviewed (Fig. 5a). This database enriches the existing landslide data in Hong Kong. Administrators can collect, review, and decide whether to publish and disseminate landslide data to the general public. For example, an administrator can review a report (Fig. 5b), validate a report, and provide more technical details to enrich the database (Fig. 5c).

Aside from publishing the location of a landslide, the LIS also allows an administrator to publish areas that are susceptible to landslides. An existing territory-wide rainfall-based landslide susceptibility model (Ko and Lo 2016) was referenced and implemented into the LIS. This model is based on vast amounts of historic landslide data in Hong Kong. This model correlates rainfall with landslide occurrences, together with the effects of slope angle and bedrock geology. The susceptibility model correlates landslide density with the normalized maximum rolling 24-h rainfall. Terrain units, comprising eight classes of slope angle and four classes of bedrock geology, intrusive, volcanic, sedimentary, and combined, are considered (Fig. 6a). Details of the model are discussed in Ko and Lo (2016).

There are two key developments that were implemented in the LIS. First, the landslide inventory is updated and real-time landslide data is included in the susceptibly model. This enables the LIS to identify susceptible areas based on the real-time rainfall data obtained from rain gauges. Furthermore, the susceptibility model in the LIS captures high-risk areas more accurately and efficiently. Circles are used to represent areas that are susceptible to landslides and also the associated risk level is portrayed using a color scheme (Fig. 6b). As shown earlier, green, blue, and red represent low, medium, and high. The administrator can also input custom shapes to warn the general public of unreported risks. With the implementation of real-time susceptibility analysis, the LIS can warn the general public of potential danger, and emergency responders can enhance their planning for rescues or evacuations. Second, the susceptibility model has the ability to self-integrate, meaning that characterizing the susceptibility of an area will improve with time.

One of the benefits of having a database, which is systematically updated, is being able to identify landslide patterns. This is especially important with the advent of climate change, which is expected to change the intensity and frequency of rainfall (IPCC 2012). To show an example, Fig. 7 reveals the relationship between the number of landslides in Hong Kong, from 1990 to 2010, and the maximum rainfall. The number of landslides reported, from the enhanced natural terrain landslide inventory as presented by Gao et al. (2017), include both open-hillside failures and channelized debris flows. A system like the LIS can help municipalities understand any obvious relationships between number of landslides and changes in rainfall pattern and help decision-makers enhance infrastructure to accommodate these changes.

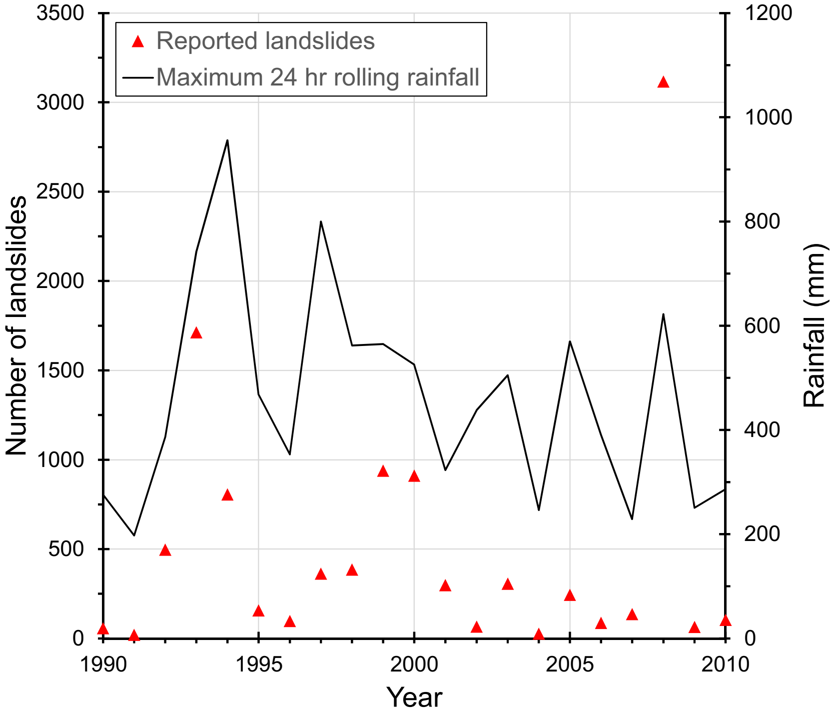


Fig. 7 Number of reported landslides reported and maximum 24-h rolling rainfall in Hong Kong (data from Hong Kong Enhanced Natural Terrain Landslide Inventory (Gao et al. 2017)

An extension of geo-fencing is using GPS technology to record, based on email accounts or phone numbers, who enters or leaves a landslide area. This information may be useful during rescue operations. Furthermore, LIS is designed to alert users with real-time push messages (sound and vibration alert) when they are close to landslides or close to areas identified as high-susceptibility (Fig. 8).

Landslide databases around the world

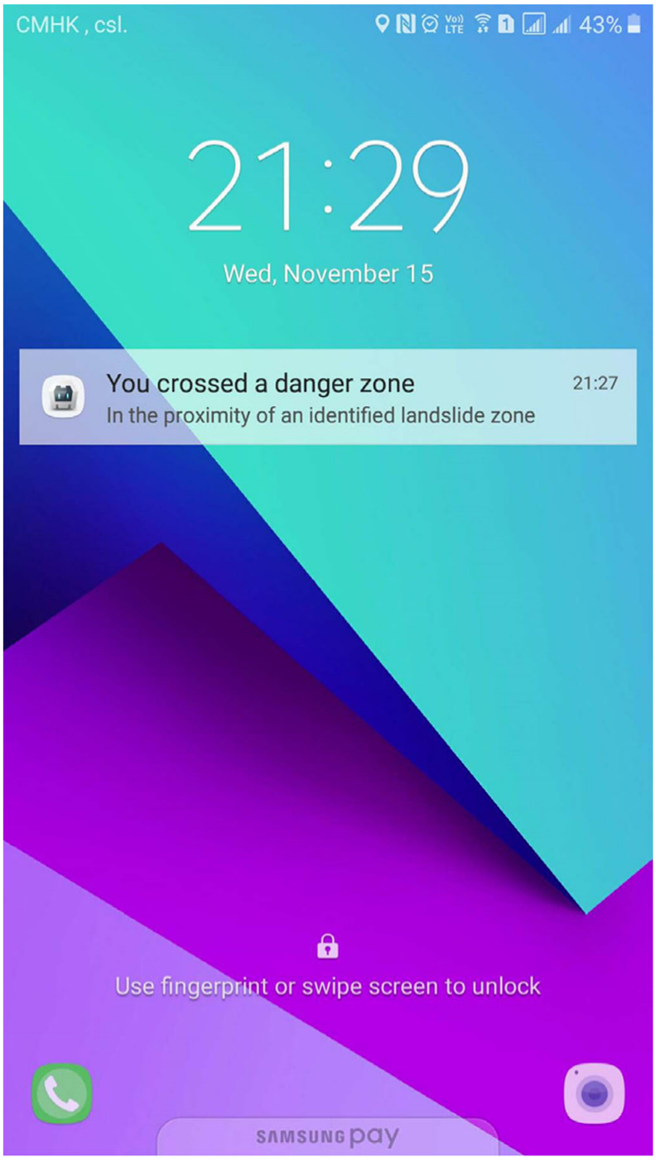
Novelties of the LIS compared to existing landslide databases are given as follows: (i) geo-fencing technology that enables the general public to instantaneously share their location, (ii) geo-fencing technology that warns the general public if they are in the vicinity of a recently reported landslide, (iii) built-in and real-time susceptibility model to warn the general public, and (iv) Google Maps™ application programming interface, which allows new features published by Google Maps™ to be incorporated into LIS with convenience, including rerouting traffic to bypass obstructed roads, and interactive maps for back-analysis of landslides. Other relevant landslide databases are discussed below.

There are several web-based data bases, which do not leverage smartphone technology. For example, Crawford (2014) reported a landslide inventory database, which provides open-access to landslide information in Kentucky, USA. Also, a website was commissioned by the United States Geological Survey, entitled “report a landslide” (Baum et al. 2014), which encourages the general public to report landslide incidents. Furthermore, the British Geological Survey (Foster et al. 2012) has a national landslide database with over 17,000 landslide records. The data base was populated from geological surveys, research studies, data inherited from other departments, and the general public. Information include the location, size, movement type, trigger mechanism, and damage caused. Each landslide report is shown as a data point on a GIS. More importantly, the British Geological Survey recently developed a smartphone version for both onshore and offshore applications. Similarly, this smart phone app utilizes instruments in smartphones to maximize the potential of the national database.

Foreseeable challenges

Varying degrees of success have been reported by Crawford (2014), Baum et al. (2014), Mazengarb et al. (2010), and Foster et al. (2012). Generally, these database rely on data from other engineering or government departments. Contributions from the general public is less than 2% (Crawford 2014). The United States Geological Survey (Radbruch-Hall et al. 1976, 1982) compiled a landslide overview map of the USA, which summarized geologic, hydro-geologic, and topographic data to help delineate areas susceptible to landslides. Other pertinent information included the type of rock, geological structure, precipitation, and landslide motion type. This map was eventually digitized by Godt (1997). The United States Geological Survey further initiated project entitled, “U.S. Geological Survey Landslide Inventory Project”. However, this project was decommissioned after several years of operation due to low usage despite efforts to promote it during and shortly after landslide emergencies. Furthermore, the Washington State Geological Survey (Sarikhan and Stanton 2008) also terminated its online landslide report form and now refers people to their county emergency managers to report landslides. All of these past experiences do suggest that the new LIS will face an uphill climb and may end up being a system primarily used by authorities.

Aside from the challenge of sparking interest from the general public to contribute to the LIS, the costs associated with running such a system can be quite onerous. On average, based on data



You crossed a danger zone

In the proximity of an identified landslide zone

Use fingerprint or swipe screen to unlock

Fig. 8 Real-time push notification

from 1981 to 2010 as reported by the Hong Kong Observatory, an average of 140 rainy days occur per year. Correspondingly, it is estimated that at least 3400 man hours per year would be required to run such a system efficiently for such conditions. Furthermore, based on data collected from 1961 to 2010 from the Hong Kong Observatory, typically 1.3 cyclones occur between July and October, implying that man power would need to operate the LIS continuously around the clock during cyclones. Aside from operational demands, man power is also required to continuously update both the user and administrative interfaces to support advances in iOS and Android platforms. For example, McIlroy et al. (2016) conducted a survey of the Google Play Store and reported that 34% of the apps need to be required at least once a month. Furthermore, data storage on a cloud and physically are required. Based on the past experiences by Crawford (2014), and Foster et al. (2012), there must be a clear objective before establishing such landslide databases, otherwise the overall costs may not be comparable to the expected benefits. For example, Hong Kong has spent about $2.7 billion USD on landslide mitigation to date, the effectiveness and contributions from a system such as the LIS compared to physical countermeasures or public education need to be carefully assessed.

Discussion and summary

This paper impresses upon the readership the potential of crowdsourcing for landslide mitigation. More importantly, this paper presents the development of a new mobile application called the landslide information system (LIS). More importantly, smartphones already have built-in environmental sensors that can be utilized. For example, crowdsourcing is already used to collect battery temperature to measure the temperature of the environment to study global warming (Overeem et al. 2013). The prospects for crowdsourcing for geo-hazard is only limited but what smartphones can do in the future. The application of new technology will entail challenges. For example, the LIS is a "citizen-project," meaning that participation from the general public will be necessary to gain any traction. However, the notion that the general public is willing to download the smartphone app and contribute data remains a practical challenge. Other pertinent problems include data privacy and whether smartphone users want to disclose their personal information, or whether decision-makers and government organization are willing to get involved. Without a strong backing from authorities, the success of landslide mitigation and management using crowdsourcing will only be limited to citizen-scientists.

Funding information This project was supported by the Hong Kong Jockey Club Charities Trust, the Hong Kong Jockey Club Disaster Preparedness and Response Institute (HKJCDPRI17EG04) and the HKUST Jockey Club Institute for Advanced Study, the Hong Kong Research Grants Council (16209717 and T22-603/15 N), and the National Natural Science Foundation of China (5170091039).

Compliance with ethical standards

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