Geoenvironmental Disasters

CASE REPORT

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A community-operated landslide early warning approach: Myanmar case study

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Abstract

A landslide early warning system based on monitoring acoustic emission (AE) generated by slope movements has been developed that can deliver alerts direct to a community at risk, with relevance to low- and middle-income countries. The Community Slope SAFE (Sensors for Acoustic Failure Early-warning) (CSS) approach uses steel waveguides driven into the slope to transmit detected high frequency noise (AE) to a sensor at the ground surface. CSS gives a measure of slope displacement rate. Continuously measured AE is compared to a pre-defined trigger level that is indicative of decreasing slope stability (i.e., landslide initiation), and a visual and audible alert automatically generated so that a community can follow a pre-defined course of action (e.g., evacuation). This paper describes the CSS approach and details a field trial of the system at two sites in Hakha, Chin Sate, Myanmar. The trial, which included training a group of youth Landslide Response Volunteers to install and operate the CSS system, increased landslide awareness and knowledge in the Hakha community, delivered the required real-time continuous operation, and demonstrated the practicality of using the CSS system for community landslide protection.

Keywords: Acoustic emission, Community preparedness/Resilience, Early warning, Geohazards, Landslides, Monitoring

Introduction

Problem and requirements

Rainfall-induced landslides cause tens of thousands of deaths annually. They also damage critical infrastructure, impacting on quality of life and costing millions of dollars to repair (Froude & Petley 2018). Climate change, coupled with growing populations and urbanisation, is increasing the prevalence of landsliding and their impacts (Kjekstad & Highland 2009). Despite the availability of well-established monitoring approaches (e.g., Stähli et al. 2015), communities experiencing the largest impacts from landslides are often amongst the poorest and include those that do not have access to bespoke monitoring solutions (e.g., Liu et al. 2016; de Assis Dias et al. 2020). UNISDR (2007, 2015) has called for development of early warning systems (EWS) that can be deployed in low-income economies. EWS have been defined by UNISDR (2009) as '*the set of capacities needed to generate and disseminate timely and meaningful warning information to enable individuals, communities and organizations threatened by a hazard to prepare and to act appropriately and in sufficient time to reduce the possibility of harm or loss*'.

EWS can be classified as *alarm*, *warning* and *forecasting* systems (Stähli et al. 2015). This paper focusses on an *alarm* system to provide alerts direct to a community in the immediate vicinity of a landslide. The goal is to provide sufficient time for implementation of a predetermined action plan to protect people at risk (e.g., evacuation). This *alarm* approach is distinct to a *warning system* whereby experts analyse a situation, or a *forecasting system* whereby regional-scale danger levels are produced by experts (e.g., based on rainfall thresholds; Nam and Wang 2020; Ngandam Mfondoum et al. 2021; Kalubowila et al. 2021). As noted by Dixon et al. (2018) amongst others, a landslide *alarm* EWS for use

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by vulnerable communities in low- and middle-income countries must fulfil the following criteria:

- be affordable (i.e., sufficiently low cost)
- easy to install and use
- operate in a range of site conditions
- monitor at appropriate spatio-temporal resolutions
- quantify slope deformations (rates) that can pose a risk
- be self-sustaining and require minimal human intervention
- transfer information direct to the user (i.e., the alert)
- operate in real-time; and
- be robust (i.e., minimal false alerts).

It must also be recognised (UNEP 2012) that an EWS is not solely about technology, and must comprise all four following elements:

- A comprehensive assessment of the risks
- A sensor-based monitoring and warning system
- A plan for the dissemination of alerts
- A strategy for the response of the people at risk

It can be concluded that there is an urgent need for affordable sensor-based EWS that can be operated by communities in low- and middle-income countries.

Landslide early warning approach

Research has established acoustic emission (AE) slope monitoring as a viable alternative to traditional deformation-based measurement techniques (Berg et al. 2018; Dixon et al. 2015a, 2015b; Smith and Dixon 2015; Smith et al. 2014, 2017a, b). It uses detection and quantification of super-audible noise (i.e., high frequency) generated by particle-to-particle contacts during deformation of soil in a failure event to derive slope displacement rates. AE can be used to provide an early warning of slope instability by detecting both the development of shear surfaces and accelerating deformation behaviour (Chichibu et al. 1989; Fujiwara et al. 1999; Koerner et al. 1981; Michlmayr et al. 2017; Nakajima et al. 1991; Smith et al. 2017a). This significant body of research has proven AE rates are indicative of slope displacement rates, and hence, AE instrumentation can be defined as a slope displacement rate sensor. Activity status of a slope can be obtained (e.g., stable, accelerating and decelerating trends). Also, critical AE rate thresholds (i.e., related to slope velocities) can be established to trigger alerts. Dixon et al. (2018) detail development and laboratory testing of an AE monitoring approach for use by communities called Community Slope SAFE (Sensors for Acoustic Failure Early-warning) (CSS). A key motivation for developing the CSS approach was to establish a cost effective, subsurface monitoring system that can provide alerts of movements continuously and in real-time direct to those in danger. The expectation is that following training, non-specialist community members can install and set up the system, maintain it and use the EWS. The CSS approach used and evaluated in the Myanmar case study is described in "Community slope SAFE (CSS) monitoring system" section.

Myanmar case study

In June 2015, parts of Myanmar were devastated by cyclone Komen and Chin State was one of the most severely affected, with housing and infrastructure damaged and destroyed. Even before the disaster, Chin State was the poorest region of the country and is geographically isolated. Although a mountainous sparsely populated region (Fig. 1), it is estimated that over 20,000 people were temporarily displaced in Chin State by extensive flooding and landsliding caused by the cyclone (Cuai 2017). Reasons for the high number of people impacted include: higher than expected rainfall (potentially exacerbated by climate change), changes in vegetation cover (including deforestation), unplanned development, an absence of regulations, and a lack of experience and professionals to provide guidance for construction activities. After the event, due to concern of potential future impacts from landslides, 4,000 people from Hakha were moved to temporary displacement camps and consideration was given to relocate Hakha, the state capital with a population of 50,000.

In a response to this event, Family Health International (FHI) 360, an international not-for-profit organization with offices in Myanmar working to improve the health and well-being of its people, decided that it should be part of their mission to help protect communities from landslides. In 2016, they instigated a search for innovative technological solutions and potential partners to deliver landslide EWS for communities in remote areas of Myanmar. This led to a collaboration between FHI 360 and Loughborough University (LU) to develop a monitoring approach that vulnerable communities can afford and use. From inception, it was considered essential that the end-user community should be engaged with the maintenance and use of the system, and therefore the interface between technology and users was of critical importance. With funding from FHI 360, the authors undertook a trial of the CSS approach at two sites in Hakha.

Study aim

The research reported in this paper was designed to have an impact on the landslide resilience of communities in Chin State, Myanmar, by:

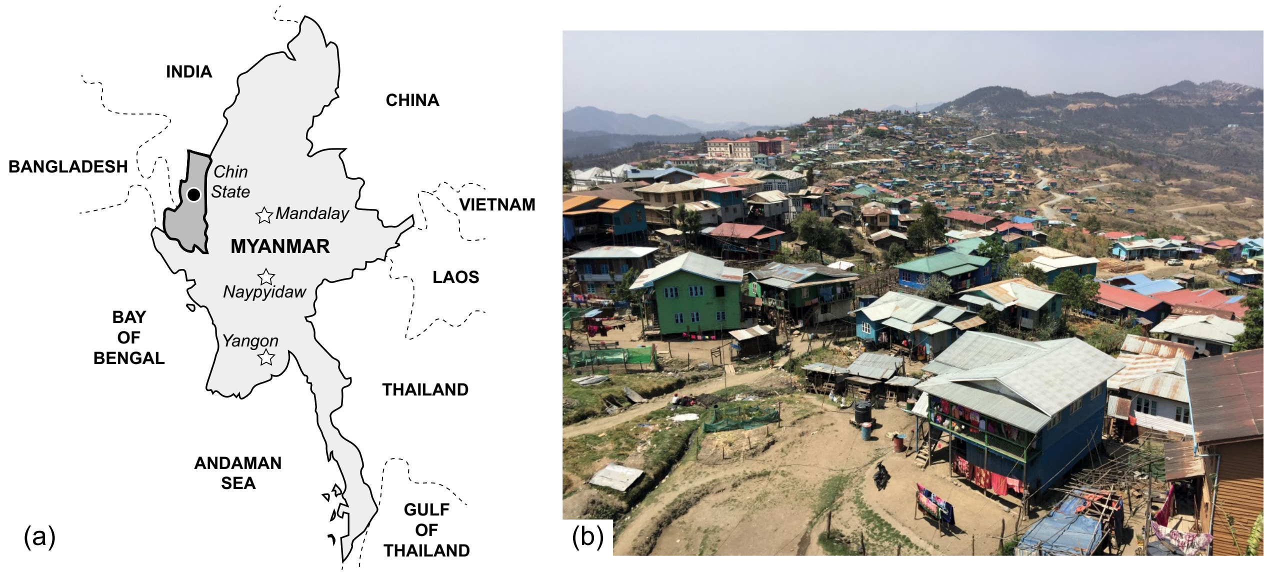

Fig. 1 **a** Diagram of Myanmar showing the location of Chin State (the black circle shows the location of Hakha), and **b** photograph of Hakha

- increasing landslide awareness and knowledge in the community via a trial of the CSS approach
- training a group of youth Landslide Response Volunteers (LRV) to install and operate the CSS *alarm* system and to act as ambassadors within the community; and
- evaluating the performance and practicality of using the CSS specifically, and EWS in general, for community landslide protection.

The paper describes the CSS system and details the Myanmar case study. Performance of the system and lessons learned are also addressed. The original contributions of this study include the installation and trial of the landslide EWS in the field environment and operation by the community in Myanmar.

Community slope SAFE (CSS) monitoring system

Figure 2 a) shows a schematic of the CSS system used in this trial, Fig. 2 d) details the main components and operating architecture, Fig. 2 b) shows photographs of the sensor and base station components and Fig. 2 c) shows the method of sensor connection on a waveguide. A full description of the CSS approach, including details of a laboratory study to validate operation of the system and interpret detected AE, is given by Dixon et al. (2018), with a summary provided below.

The AE sensor is attached to a steel tube waveguide driven into the slope (Fig. 2a, c). The waveguide both intercepts AE generated by soil deformation if the slope starts to move (it can also generate AE as the tube is deformed as described below) and it also provides a low attenuation propagation pathway for AE produced in the slope to travel to the ground surface where they can be detected and quantified by the sensor. Use of driven waveguides simplifies the installation process by using readily available low-cost equipment (e.g., hand operated post rammers), and this also reduces costs, although the depths to which they can be driven depends on the strength and stiffness properties of the host soil. Installation of a waveguide by driving, results in the steel tube being in intimate contact with the in-situ ground forming the slope, which ensures it is sensitive to slope deformations by minimising AE transmission losses at the soil/tube boundary. 'Noisy' material is placed inside the waveguide as proposed by Nakajima et al. (1991) such that as the tube is deformed, straining of the infill also generate AE. Sand is an ideal material to use as the 'noisy' infill material as it is cheap and universally available, and it was used in this study. The CSS system comprises the following functions (Fig. 2 d):

- Conversion of AE (i.e., stress waves) propagating along the waveguide to voltages using a piezoelectric transducer
- Signal amplification and filtering to remove noise at both low (< 15 kHz) and high (> 40 kHz) frequencies that can be generated by the electronics and/or environment
- calculation of the signal RMS (root mean square, a measure of signal energy)

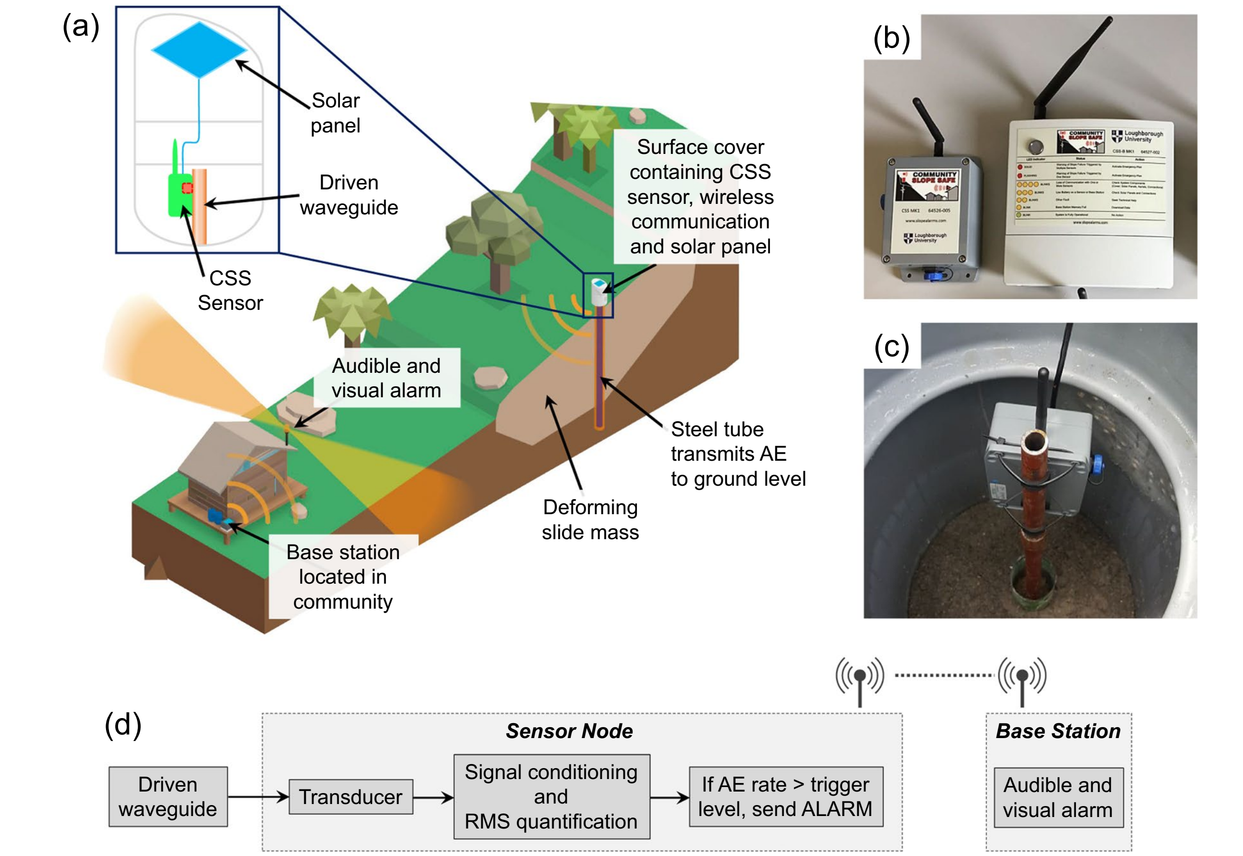

Fig. 2 **a** Community Slope SAFE (CSS) AE monitoring approach incorporating a driven waveguide, **b** CSS sensor and base station components, **c** a view of a sensor located on the waveguide inside a cover, and **d** system architecture of the Community Slope SAFE approach (modified after Dixon et al. 2018)

- averaging AE activity over a defined period (e.g., 30 s) by aggregating the RMS values
- comparison of the AE RMS rate over the aggregation period with a pre-determined threshold value; and
- generation of an alert message to the community via the base station if the threshold is exceeded, which sets off an audible and visual *alert*.

A community can use the alert to initiate a pre-agreed action plan such as evacuation of a specified area using agreed routes, inspecting the slope if safe to do so and informing nominated authorities and professionals.

Series of physical model experiments were conducted to evaluate performance of the CSS approach by comparing applied deformation behaviour of active waveguides with the measured AE response. The waveguides were subjected to accelerating deformations to replicate known behaviour in first-time landslides, which accelerate as progressive failure occurs and post-peak strengths are mobilised. Figure 3 a) shows the experimental setup, and full details of the test procedure are reported in Smith et al. (2017a) and Dixon et al. (2018). The large-scale direct shear device has a central column filled with stiff clay. An active waveguide and a ShapeAccelArray (SAA) in-place inclinometer were installed through the clay column. Displacement of the top block relative to the bottom block was by a pulley system controlled by a hydraulic actuator, which generated shearing in the clay column. The excellent agreement between AE and displacement trends (i.e. cumulative and rate) shown in Figs. 3 b) and c) provides conclusive evidence that AE rates are indicative of 'slope' displacement rates, and hence that AE monitoring can be used to provide information on the stability status of a slope.

Myanmar case study

CSS trial permission

Following extensive discussions, permission was obtained in 2017 from the Director General of the *Department for Disaster Response and Resettlement* to undertake a trial of the CSS landslide early warning system in Chin State.

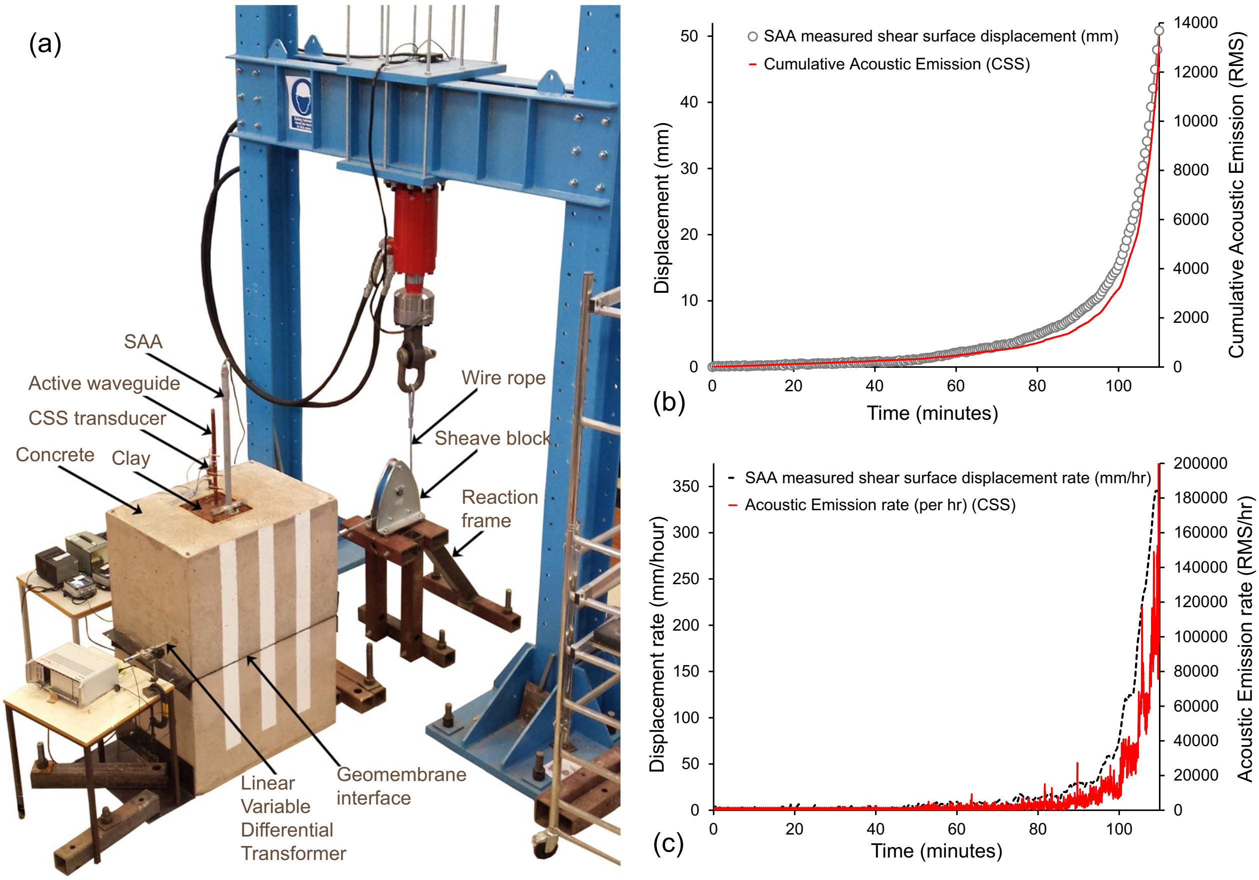

Fig. 3 Large-scale slope failure physical model used to accelerate the top box relative to the bottom and to compare displacement behaviour with AE measured using the CSS system: **a** annotated photograph of the apparatus; **b** CSS cumulative AE and SAA measured displacement time series; and **c** CSS AE rate and SAA measured velocity time series (modified after Smith et al. 2017a and Dixon et al. 2018)

Community engagement strategy

A critical element of project delivery was the need to establish collaboration with a local Chin State organisation to lead engagement with the community and hence facilitate delivery of the landslide monitoring program and associated training. An agreement was made between FHI 360, LU and the local collaboration partnership *Chin Committee for Emergency Response and Rehabilitation* (CCERR). CCERR is a community organization that was already coordinating relief efforts and supporting communities to recover from the 2015 cyclone event and was working to build capacity and resilience to future events. With assistance from CCERR, agreement and support were obtained from both the Chin State government *Department of Disaster Management*, and *Department of Meteorology and Hydrology* to conduct a trial in Hakha. CCERR were responsible for engagement activities with the community for the duration of the trial. As a first step, they canvased the local community, including town elders, and confirmed a desire to participate in the project. Community representatives were thankful for the interest shown in helping them to address risks from landslides, which they live with every day. All parties demonstrated real interest, were happy to collaborate and provided enthusiastic support.

A key element of the trial design was to engage with the community, provide training on landslide causes and monitoring, and hence increase awareness and resilience to these catastrophic events. Core to this aim was a plan to engage with young people to act as *Landslide Response Volunteers* (LRVs), who would be trained to install and maintain CSS. This was accomplished by the Director of CCERR making a request for participants that was broadcast on local radio, which led to recruitment of 20 LRV in the age range 18 to mid-20 s, with 60% of LRV female. A member of CCERR staff acted as translator (between English and Burmese), enabling the LU team to explain activities on site and during training presentations, and production of translated CSS instructions and operation manuals.

Site selection

The 2015 Komen cyclone triggered large deep seated slope failures and many tens of relatively shallow small-scale landslides in the Hakha area of Chin State; both types caused destruction to property and infrastructure (Ministry of Mining and Myanmar Geo-Science Society 2015). When planning the project in 2017 there was limited information available on landslide hazards in the Hakha area to guide the selection of trial sites, other than the work of Thein (2016), which indicated that most of the Hakha area has a high to very high hazard designation. A study by Mon et al. (2018), which was published after the CSS trial commenced, details the geological setting and response to the landslide disaster in 2015.

The trial of CSS focussed on shallow failures that typically occur in the residual soils formed by weathering of the bedrock immediately beneath (mudstones and sandstones) and with a thickness in the order of 1 to 3 m. In places, these are overlain by thick layers of soil debris and colluvial from historical landslide activity. The dearth of local professionals who could advise on site selection meant the first step was to develop a selection procedure that employed local project representatives from CCERR and town elders, supported by FHI 360 project staff. The procedure was based on criteria established by the LU authors, who are experienced in studying landslide mechanisms. A site selection checklist (Table 1) was produced for use in Hakha by the local non-specialists. Based on seven criteria, it defined sets of questions written in non-technical language, most requiring either yes or no answers, that would provide the details required to rank and select sites with a risk of future shallow slope failure. Additional requirements and comments were provided to the assessors as context for the questions, and site photographs and GPS coordinates were also requested. This information was then used by LU to select the most promising sites for the installation and trial of CSS.

In November 2017, FHI 360 working with CCERR, state government and town elders held a workshop in Hakha to explain the planned trial and, based on collective knowledge and experience of the area, to produce a short-list of six candidate sites. These sites were then visited by the team of local representatives, and the checklist (Table 1) completed for each site and provided to LU. Feedback from the site review team indicated that the checklist was logical and easy to follow. LU selected two sites that best met the criteria, with two others designated as backups. Planning was progressed based on the two primary sites but with the proviso that their suitability would be reviewed and confirmed by LU as the first activity of the CSS installation campaign. The two selected sites were both in the Hakha urban area. The near surface geological materials at both sites comprise residual soils comprising fine sandy clayey SILT with some fine to coarse gravel.

1. Site 1 Keisi-Titawwin is in the middle of a slope that comprises an area of gardens, including a plant nursery, and scrub land hosting livestock (Fig. 4), bounded by an access track at one side, and houses and workshops at the other side and at the toe. The general undulating topography and cracking on the lower part of the site indicates previous shallow slope movements, which was confirmed by discussions with locals. The concern at this location is that during periods of heavy rainfall, movements could be reactivated, impacting on the properties at the toe and damaging the communal garden area.
2. Site 2 Keisi-Khaikam is at the top of a steep slope that has previously experienced landslides, as evidenced by the undulating slope profile and cracking. These failures damaged properties at the slope toe. The concern at this location is that retrogressive failures in the top of the slope would damage government buildings located close to the crest (Fig. 5).

Both sites had easy and safe access, were covered in grass, small shrubs and occasional trees thus allowing good access and safe working conditions, permissions were in place from the local government, and they were located close to the homes of the LRV, thus giving short travel distances.

Description of monitoring system and installation process

The LU authors and staff from the FHI 360 Myanmar mission, visited Hakha in March 2018 to install the CSS systems and deliver training to CCERR and LRV members. Firstly, visits to the two selected sites ("Site selection" section) confirmed that both were suitable. Equipment and materials were in part delivered from the UK (e.g., CSS sensors, base station, and protective covers), with the remainder supplied locally based on specifications produced by LU (e.g., steel tubing for waveguides, post rammer, granular soil to infill the waveguides and laptop for system setup and data download).

The CSS systems were installed during a five-day period. The installation team comprised the LU authors, three project staff from FHI 360, two project officers of CCERR, the 20 youth LRV and ad hoc community engagement (e.g., a local carpenter made fences). During the works, many locals visited the sites to offer help and show interest. Local government representatives also visited the sites to observe the works and confirm their support. The LRV were trained by the LU authors to create and infill the waveguides, construct the cover systems,

Table 1 Trial site selection check list

Criteria	Requirements and comments	Questions	Yes/No[x]
Geology/soil Presence of superficial deposits (fill or natural soil): Soil type Thickness (estimate) Presence of ground water	Materials that could develop a shear surface leading to mass movement during a failure event Must be able to drive a steel waveguide to required depth (i.e., typically at least 2 to 3 m)	**S1**—Is the slope covered in loose soil/dirt?	Yes/No
		S2—What is the size of the largest soil particle in metres?	m
		S3—Is the slope manmade from tipping of rubble?	Yes/No
		If yes, was the slope made in the last few years?	Yes/No
		S4—Is there evidence of water flowing out of the slope or ponding at the toe?	Yes/No
		S5—Do you think it would be possible to drive a steel tube/rod 2 to 3 m into the slope?	Yes/No
Geometry of slope Height Slope angle Profile (i.e., steps)	Safe conditions for manual installation of waveguide, cover and sensor (e.g., not too steep)	**G1**—How high is the slope?	
		Less than 10 m	Yes/No
		10 to 20 m	Yes/No
		Greater than 20 m (if so, how high)	Yes/No
		G2—How steep is the slope, could you walk up it:	
		Easily?	Yes/No
		With difficulty?	Yes/No
		Not at all?	Yes/No
		G3—What would you estimate the angle of the slope to be?	°
Vegetation Type Coverage	No restrictions on activities Unrestricted wireless connection and solar radiation	**V1**—What type of vegetation covers the slope?	
		None	Yes/No
		Grass	Yes/No
		Small bushes	Yes/No
		Trees	Yes/No
		V2—Does the vegetation obstruct the view across the slope when standing at the toe or top?	Yes/No
Location and access Vehicle access to vicinity of slope Access for people and materials	Safety of access to site and onto the slope for installation and maintenance	**L1**—Is the slope close to a road or track for vehicles?	
		Near top of slope	Yes/No
		Near toe of slope	Yes/No
		L2—Will it be easy to carry materials onto the slope?	Yes/No
Stability of slope Evidence of historical instability Potential for future instability Likely mechanism(s) of failure	Reasonable expectations that a slope failure could occur in the next 1 year, with assessment based on failure frequency of comparable slopes in the vicinity	**St1**—Does it look like there have been any recent movements of material on the slope?	
		Is there any soil debris at the toe of the slope?	Yes/No
		Is the slope profile uneven, indicating local slumps of material?	Yes/No
		Are there any cracks behind the top of the slope or on the slope?	Yes/No
		Are there any steep steps in the slope profile?	Yes/No
		St2—Does the slope look more uneven and/or disturbed compared to similar slopes nearby?	Yes/No
Community interest Permissions for slope access Potential interest and engagement Management of system Hosting of base station Receipt and use of alarm information Site for location for base station	Government permissions in place A community that could be affected by a slope failure Focus on risk to infrastructure rather than directly on people Willing to host, operate and maintain the system Willing to share experiences and provide feedback	**C1**—Is there any infrastructure (e.g., housing, roads, water supply pipes) that could be damaged by failure of the slope (record the type of infrastructure and provide a sketch of its location relative to the slope):	
		At the toe?	Yes/No
		At the crest?	Yes/No
		On the slope?	Yes/No
		C2—Is it likely that government permission will be granted to work at the location of the slope?	Yes/No
		C3—Is there a youth group living near the slope that could be trained to operate the sensors?	Yes/No

Table 1 (continued)

Criteria	Requirements and comments	Questions	Yes/No[x]
Health & Safety considerations Risk assessments required Safety of staff Constraints on installation and operation	Permissions for travel to site obtained from employers Site geometry/ conditions must not put site operatives at risk	**H1**—Is it safe to visit the site and surrounding area?	Yes/No
		H2—Is it safe to walk to and work on the site?	Yes/No
		x Support your answers with photographs and video clips of the slope and surrounding area, and provide additional comments and sketches to help explain answers you have given	

Fig. 4 General views of the slope at Keisi-Titawwin **a** the middle part of the slope and **b** the lower part of the slope

Fig. 5 General view of the slope at Keisi-Khaikam, the buildings on the left would be impacted by any retrogressive slope failure in the slope to the right (i.e., the chain fence in the centre of the photo is located at the slope crest)

install sensors and base stations and then to set up, operate and maintain the monitoring system.

Figure 6 shows the system configurations and reference notation used at the two sites. Time and resources prohibited a detailed survey necessary to produce detailed plans or cross-sections. At Site 1, Keisi-Titawwin, Sensor 1 is in the upper part of the slope, and is closest to Base station 1, and Sensor 2 is in the lower part of the slope. Waveguides at each of the two locations were installed using the post rammer to drive the steel tubes to depths of 3 m below ground level. Sand infill was placed inside the tubes to form active 'noisy' waveguides ("Community Slope SAFE (CSS) monitoring system" section) and purpose-designed covers with pre-mounted solar panels were concreted in place to enclose and protect the waveguide and sensor. The sensors were attached to the

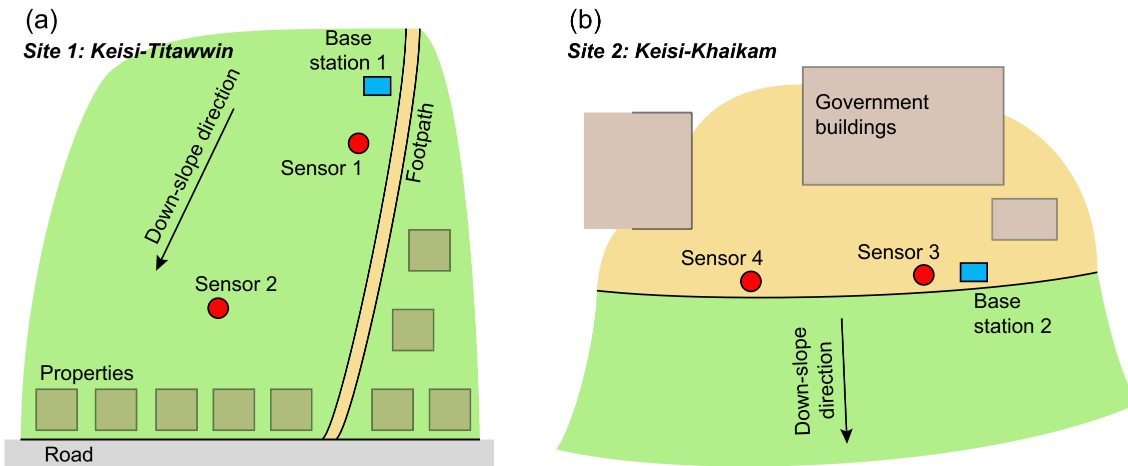

Fig. 6 CSS installation plans for Sites 1 and 2

waveguides using cable ties so that the piezoelectric elements were in good contact. The base station was housed in a lidded plastic container, with a solar panel positioned on top. All solar panels were orientated (i.e., rotated and tilted) to maximise solar gain. Figure 7 shows photos depicting the key stages of installation taken at the two sites.

At Site 2, Keisi-Khaikam, both sensor nodes were installed behind the slope crest on horizontal ground, approximately 1.5 m from the top of the slope (Figs. 5 and 6). Sensor 3 is installed on a 5.5-m-deep waveguide and is closest to Base station 2, and Sensor 4 is installed on a waveguide 4-m-deep and is furthest away from the base station.

Before leaving Hakha, the LU authors commissioned the CSS system at each site and trained the CCERR liaison officer and LRV to operate the system and download data. Subsequently, the data was downloaded and emailed to LU by CCERR every two weeks for review. CCERR continued to act as a mentor to the LRV, providing support and training.

Operation and maintenance

Supported by LU, the LRV members and CCERR staff maintained and operated the CSS systems at the two sites from March 2018 until December 2019, when responsibility was passed to the Chin State government. However, the situation in Myanmar meant that the government department was not able to continue the monitoring. During that period, two-weekly site visits were made by CCERR and LRV to download data from each base station onto the laptop. In addition, operation of the system was checked by artificially generating AE on the waveguides to trigger a warning (i.e., by tapping a metal object on the top of the steel tube). The systems were re-initialised if communication between the sensors and base station had been lost (see below).

The data and reports sent by CCERR allowed LU to propose modifications to upgrade the system and improve robustness and performance for operation in the field environment. Upgrades planned by LU and implemented by CCERR/LRV in 2018/19 were carried out to:

- Decrease background AE noise (i.e., interference)
- Upgrade the wireless communication system, and
- Improve battery charging.

Generally, the background levels of AE detected were well below the thresholds defined to trigger an alert of slope movement. However, there were periods when either general background levels increased or when peaks of AE were detected. After collecting data for a few months, analysis of the AE trends indicated that these increases were caused by electronic interference due to the waveguide acting as an antenna. Placing a thin strip of plastic tape between each piezoelectric transducer and steel tube isolated the sensor electronics from the waveguide and successfully eliminated this spurious AE.

The sensor nodes communicate with the base station at each site using a wireless system. This requires line of sight between the antenna at each sensor location and the base station. At both sites, adequate communication was checked before finalising the locations of the sensors and base station. However, an unforeseen government condition for permission to install CSS was that all elements (i.e., sensors and base station) must be protected by fences; once the wooden fences had been built around each installation, the wireless

Fig. 7 Key stages of works by the authors, LRV and CCERR to install CSS at Sites 1 and 2: **a** driving the steel waveguide, **b** concreting the base for the cover, **c** placing the cover with help from interested children, **d** placing 'noisy' sand inside the steel waveguide, **e** the CSS sensor attached to the waveguide, **f** a completed sensor installation with integrated solar panel to charge the sensor battery, **g** set up of the base station and flashing light/siren alert system, **h** completed base station with solar panel to charge the battery

signal in all cases was reduced and communication was regularly lost. The wireless communication system was improved by CCERR/LRV installing new directional antennas (sent from the UK). In all cases, communication was improved and on the rare occasions it was lost, it could be re-established by artificially generating AE to trigger an alarm from the sensor to the base station. The upgraded antenna made CSS more reliable and resilient.

During prolonged periods of overcast weather in October/November 2018, the solar panels were unable to generate enough power to keep the sensors operational. These low battery levels were exacerbated by the communication issues detailed above, which used additional power as the sensors tried repeatedly to re-connect to the base station. This issue was overcome by upgrading the wireless antennas to reduce power consumption and repositioning the solar panels to optimise efficiency. No further losses of power occurred in 2019 after these modifications. Work by CCERR and the LRV to clear vegetation every few months from around the installations also aided performance of the system. Dense vegetation can shade the solar panels and interfere with wireless signals.

In 2019, following completion of the above system upgrades, the CSS monitoring systems at the two sites operated as designed, with only small numbers of sensor/base station communication issues experienced.

Example measured AE data is presented in Fig. 8 a) for Site 2, Sensor 3. It shows very low levels of AE detected throughout the monitoring period. This is indicative of stable ground. The peaks in AE at the start and end were artificially generated by tests conducted during LRV visits. Because no slope instability events occurred at the sites during the trial, there was not an opportunity to detect ground movements using CSS and hence test triggering of the visual/audible alert system. However, the trial was still able to provide useful learning as discussed in "CSS performance" section. Figure 8 b) presents example data for operation of the solar panel (voltage level) and charging of the battery (percent). This shows the system operating continuously over a period of 5 months.

The AE warning threshold level shown in Fig. 8 (i.e., the horizontal dashed line) was set such that exceedance would trigger an alert of potential movements. Based on experience from monitoring comparable slopes, an AE threshold was selected to warn of displacement rates in the order of 5 mm per minute. Laboratory calibration for the CSS system by Dixon et al. (2018) was used to define the AE RMS level indicative of this magnitude of displacement rate. Despite no slope failures occurring, the 20 + months of monitoring experience allowed the selected AE trigger level to be reviewed. It was not exceeded during normal operation and no false alerts were generated.

Community training and engagement

An important benefit of the CSS trial in Hakha has been raising awareness in the community to improve resilience to future landslide events. CCERR led this work, aided by the LRVs, by generating publicity about CSS,

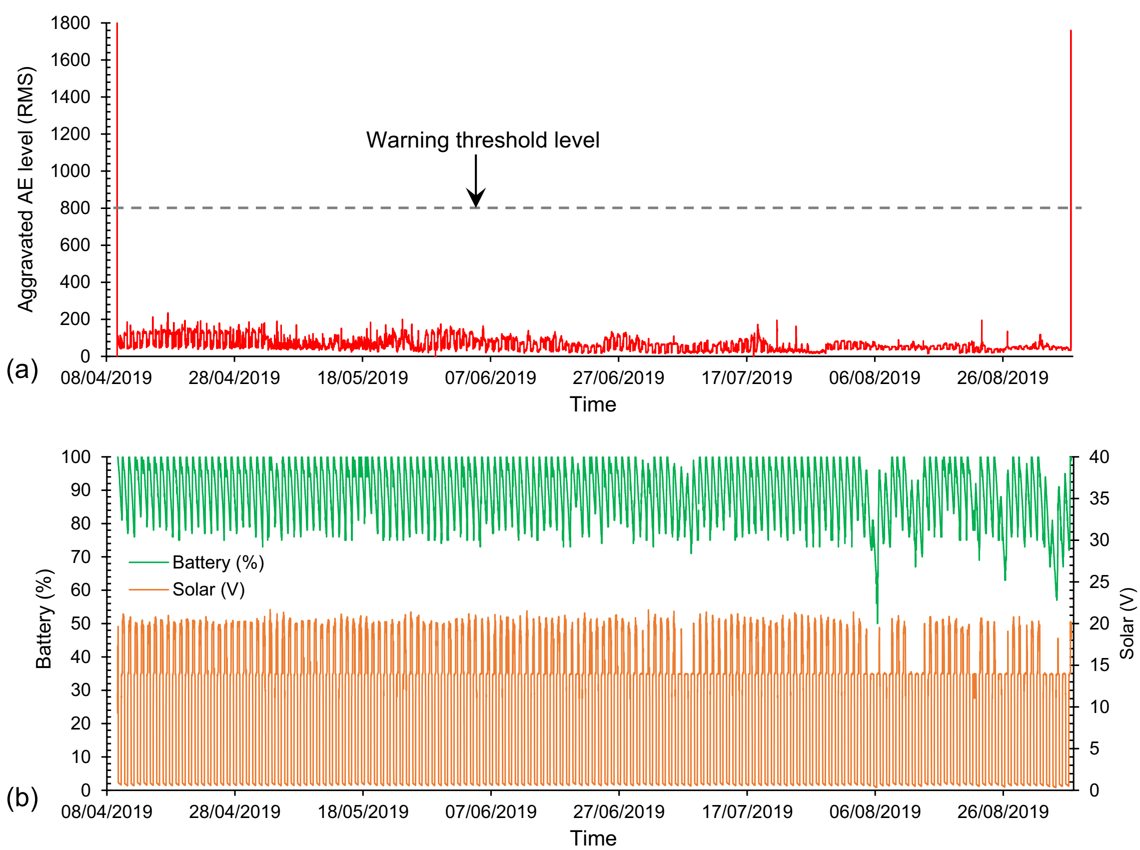

Fig. 8 Site 2, Sensor 3 **a** Example measured AE data showing low level aggregated AE RMS time series measurements indicative of stable ground. The peaks of AE at the start and end of the monitoring period were generated by CCERR/LRV visiting the site to trigger an alert and test operation of the system. **b** shows example solar (V) and battery level (%) data. (Dixon and Smith 2022)

running a series of education events, and holding regular liaison meetings with the partner Chin State government *Departments of Disaster Management, and Meteorology and Hydrology*. Signs were erected at the CSS monitoring sites to highlight the project and to publicize the involvement of the local organizations (Fig. 9). Media organizations reported on the project.

Six open community training events were run in 2018 by CCERR and the LRV who were tasked with championing landslide awareness in the community. The aim was to engage with and educate the community from Hakha township and the municipal ward. About 80 people from Hakha and surrounding communities participated in these events to learn about the CSS sensor programme, discuss landslide risks, consider appropriate community response, and hence improve resilience to landslides. Through these events, CCERR (2018) reported that participants were tasked to '*disseminate about sensors further to the wider community .... during worship service, at churches or houses and other social occasions such as weddings and funerals...*'. These community engagement activities created a large group of trained landslide ambassadors in Hakha and the surrounding region, changing behaviour and delivering improved community awareness and resilience to future landslide events.

The local partners understood that this trial was part of a longer process to learn about the CSS approach, improve sensor performance and hence enable future benefits for the wider Myanmar community. In recognition of the training received and contribution to landslide monitoring and awareness in Hakha, the Landslide Response Volunteers were awarded certificates, which acknowledge and celebrate their valuable contribution to the project under the commendation '*Myanmar Youth use Sensors to Save Lives*'. In a follow up visit by FHI 360 in summer 2018, feedback from CCERR and LRV was that their involvement in the trial was a very positive experience, and they were grateful for the opportunity and proud to play a significant role in what they consider to be an important initiative.

Fig. 9 CCERR with LRV and FHI 360 author publicising the landslide monitoring project via local media coverage

In a follow-up review of the project impacts by LU, CCERR (2020) reported that the project not only allowed the community to overcome a collective psychological panic over landslides, but it also demonstrated the government could take scientific measures to address landslide risks. Community leaders such as the Hakha Town Elders, a committee for Hakha Town's Affairs, came to appreciate and take ownership of the sensors. It is estimated that around 15,000 to 20,000 population in Hakha town benefited from the trial (CCERR 2020).

However, because monitoring was discontinued by the state government department, the system has not reached full operational status (i.e., with the alert system live), and therefore a local action plan is yet to be established detailing how the community should respond to an alert (e.g., communication and evacuation plan). Despite this, the evidence is that landslide awareness and knowledge in the community was increased by the trial. It has also been demonstrated that non-specialist local groups (e.g., CCERR and LRV) can be trained to install and operate the CSSsystem and to act as landslide ambassadors within the community.

This has raised interest and provided a positive example of how it is possible to undertake programs that deliver benefits via scientific (e.g., LU) and development (e.g., FHI 360 and CCERR) sectors working together to improve the lives of communities in low-income countries. A unique impact of this collaboration was being able to align engagement of the central government of Myanmar all the way through the state government and CCERR agency to the youth volunteers and ultimately the community. This project called national government attention to the fact that there are ways the local communities can help make significant positive impacts on a major issue such as reducing landslide risk.

CSS performance

The trial of CSS slope monitoring in a remote part of the world using inexperienced local groups to install and then operate the system for 20 + months was a significant achievement by the partners. In addition to the community benefits detailed in "Community training and engagement" section, there have also been useful learning on a range of practical aspects associated with planning, installing, and operating the system. It is important to recognise the very different physical operational conditions between the UK, where CSS was devised and initially tested, and Hakha (e.g., higher maximum temperatures, different solar radiation patterns and faster vegetation growth rates). Key learning from the trial includes:

- The imperative to ensure the community has access to relevant information on landslide risks so that priority sites for monitoring can be identified. In this trial, availability of limited hazard mapping for Hakha was supplemented by input from the LU landslide experts in the form of a pro-forma check list for site assessment.
- Gaining the approval and conditions of all parties to undertake the work is obvious, but a complex task that will vary according to the local social norms and governance. Slope monitoring cannot be achieved without engagement of local organisations from the initial proposal stage. It cannot be 'imposed' by an external party, even if they have the best intentions. For this trial, it took FHI 360 and CCERR many months to gain permissions from the national and regional governments.
- Location of sensors on a given site requires considerable experience and knowledge of landslide processes. Local groups will require this level of landslide expertise/support to establish slope monitoring projects, even if they have the knowledge to install and operate a system. Local and national government agencies should have the expertise available and processes in place to support the community.
- Local people were able to quickly learn the skills required to install the waveguides and covers. Driving the steel tube waveguides to depth was physically demanding using post rammers and it is recommended that manually operated tripod drop weight systems are employed in the future. Account must also be made for local norms and practices when considering what is acceptable health and safety practices.
- The knowledge and skills to operate the CSS system (i.e., set up, download data and trouble shoot problems) was achieved by the local partners through the formal training sessions coupled with on-site instruction provided by LU. Given that the LU authors were only on site for a week, it is encouraging that CCERR with LRV were able to operate the system for 20 + months, including helping to diagnose faults and install upgrade components.
- Following completion of the upgrades detailed in "Operation and maintenance" section, the system operated as designed:
    - AE was measured continuously by the sensors
    - Low levels of AE were synonymous with stable slope conditions
    - Measured AE was automatically compared to predefined trigger thresholds
    - Experiments to artificially generate high levels of AE that exceeded the trigger threshold resulted in automatic communication between sensor and base station to generate an alert
    - No false alarms were generated during normal operation, demonstrating robustness
    - Solar panels were able to charge the sensor and base station batteries to achieve continuous operation
    - Daily health messages (e.g., battery charge level) were generated automatically by the sensors and communicated to the base station where they were logged.
- No cases of damage or interference with the sensors were reported, which is a testament to the community engagement and collective guardianship of the monitoring system.

The project demonstrated that installation and operation of a slope EWS such as CSS is both achievable and beneficial for the education, protection and wellbeing of a community.

Conclusions

A low-cost landslide early warning system that monitors acoustic emission (AE) generated by subsurface slope movements has been developed, called Community Slope SAFE. This paper described the CSS approach and detailed a field trial of the system at two sites in Hakha, Chin State, Myanmar. The trial was delivered via a partnership between the developers of CSS at Loughborough University (LU) who are landslide experts, FHI 360 an international organization working to improve the health and well-being of people in Myanmar, the Chin Committee for Emergency Response and Rehabilitation (CCERR) and both state and national government departments in Myanmar. The following are the principal conclusions:

- A site selection check list produced by LU enabled local non landslide specialists to identify candidate sites, which led to the successful selection of two sites for installation of the CSS system.
- During a one-week period in March 2018, the LU team were able to train representatives from CCERR and a group of 20 youth Landslide Response Volunteers (LRVs) to install and operate the CSS systems.

- CCERR and LRV successfully operated the monitoring system, including sending data to LU for review, from March 2018 until December 2019.
- The specific CSS operating conditions in Hakha meant that modifications to key elements of the system were required. These included upgrading the wireless communication and optimising the solar panel charging of batteries. Key learning from this process is that local non-specialist CCERR and LRV personnel were capable of undertaking modifications and maintenance to the system, guided via instructions from LU.
- Performance of the monitoring system was demonstrated by its operation for months as designed and without problems. There were no slope movements at the monitoring sites during the trial and therefore the system did not experience full operational conditions. However, consistently low levels of detected AE were recorded, indicative of stable slopes, and no false alarms were triggered.
- A key benefit, which is independent of the type of monitoring system employed, has been using this demonstration project to engage with the Hakha community and significantly enhance awareness of landslide risks.
- Training provided by LU to CCERR and the LVR created a group of landslide champions who engaged with multiple community groups and energised awareness and discussion of landslide risks and monitoring.
- AE sensors for monitoring slopes are now commercially available and therefore an opportunity exists to replicate the community slope monitoring approach globally. However, this will require sponsors to fund purchase of the monitoring instruments and provide expertise to select sites, and to train communities to install and operate the system.

The project partnership delivered the Community Slope SAFE trial and demonstrated technical advances in slope monitoring for communities, but potentially more important, the trial has delivered positive impact on lives in the Hakha community and shown that this could be replicated in other communities.

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Author contributions
ND and AS conceived the CSS system and carried out the laboratory and field work, and analysis and interpretation of the data. MP coordinated the field trial locally from Myanmar. All authors secured funding. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets presented in Fig. 8 can be found at https://doi.org/10.17028/rd.lboro.19382939, an open-source online data repository hosted at Loughborough University (Dixon and Smith 2022).

Declarations

Competing interests
The authors declare that they have no competing interests.

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