Abstract

Influenced by the recent global climate change, extreme rainfall events have become more frequent worldwide and resultant hydro-meteorological hazards are creating more deaths and devastations. One of the most remarkable disasters of rain-induced rapid long-travelling landslides (RRL) in Sri Lanka took place at Aranayake, 70 km east of Colombo in 2016 (JICA Survey Team 2016) (JICA Survey Team in Survey results of Aranayake Disaster, 2016). The fluidized landslide mass ran over an about 2 km distance claiming the lives of 125 people. This tragic event has thus highlighted the importance of sophisticated early warning and disaster management mechanism even more than ever, because the presence of these hidden unstable soil masses as well as their run-out distances are very difficult to predict, and once they start sliding, it is almost impossible to stop them. Both the National Building Research Organisation, Sri Lanka (NBRO) and the International Consortium on Landslides (ICL) have jointly compiled a research proposal within the framework of SATREPS, standing for “Science and Technology Research Partnership for Sustainable Development,” a Japanese government program that promotes international joint researches, and it passed the final round of selection on May 16, 2019. Thus, the new 5-years SATREPS project for Sri Lanka with regard to “Development of early warning technology of Rain-induced Rapid and Long-travelling Landslides (Project RRL)”, starts in 2020. This article reports on the outline of the project including its goals, plans of plots for developing individual technologies for the early warning system, etc.

Keywords

Rain-induced rapid long-travelling landslide • SATREPS • Sri Lanka • Early warning

Introduction

Sri Lanka, being an isolated island in the southern tip of India, usually experiences extreme weather patterns with two peaks of rainfalls in two monsoon seasons (Department of Meteorology, Sri Lanka 2020). Particularly the south-western monsoon from May to September brings rain to the southwest mountainous area of Sri Lanka. Out of 25 administrative districts in Sri Lanka, ten districts, approximately 30% of the total land area of the Island, have been mostly prone to landslides. Landslides had previously been perceived as isolated events, which occurred mainly due to natural causative factors with low vulnerability. However, these areas had long been the major area of tea and cinnamon plantations, being occupied by about 35% of the population of Sri Lanka. Moreover, the post-civil-war Sri Lanka have been attracting tourists with 5 of 7 UNESCO cultural and natural world heritages of Sri Lanka located in the landslide-prone areas. Studies have revealed that nearly 70% of the landslides in Sri Lanka are influenced by human induced interventions in prone areas such as rapid urbanization, population growth, inappropriate land management, development trends, deforestation in steep slopes and degradation of forests and natural resources. One of the most remarkable disasters to be mentioned took place at Aranayake in Kegalle District, 70 km east of Colombo (JICA Survey Team 2016). The fluidized landslide mass ran over a 2 km distance killing 125 people. This tragic event has thus highlighted the importance of sophisticated early warning.
and disaster management mechanism, because the presence of these hidden unstable soil masses as well as their long run-out distances are very difficult to predict, and once they start sliding, it is almost impossible to stop them.

Both the National Building Research Organisation, Sri Lanka (NBRO hereafter) and the International Consortium on Landslides (ICL hereafter) have jointly compiled a research proposal within the framework of SATREPS (Japan Science and Technology Agency 2020); SATREPS, “Science and Technology Research Partnership for Sustainable Development,” is a Japanese government program, with two funding organizations Japan International Cooperation Agency (JICA hereafter) and the Japan Science and Technology Agency (JST hereafter), that promotes international joint researches, and it passed the final round of selection on May 16, 2019 that the new 5-years SATREPS project for Sri Lanka with regard to “Development of early warning technology of Rain-induced Rapid and Long-travelling Landslides (Project RRLL hereafter)”, starts in 2020.

Outline of Project RRLL

The technologies to stabilize reactivated and creeping landslide masses have much progressed because their locations can be easily identified. However, recent tragic events in Sri Lanka, showing a soaring trend in general with some remarkable spikes in 2014, 2016 and 2017 as shown in Figs. 1 and 2, highlighted the difficulty in coping with devastations caused by RRLLs. Neither their locations nor early signs of movement can be easily identified in advance. Therefore, implementation of advanced and feasible technologies for early warnings of RRLLs are extremely crucial.

There has been a remarkable development reported in the international world of academy with the ICL as the core organization; they include forecasting of localized precipitation events, early detection of ground movements and relaying timely early warning to the last mile, namely, residents at landslide risk. Among them, the key technologies for the success of Project RRLL are:

1. Time prediction of heavy rainfalls and pore water pressure build-ups,
2. Site prediction of landslide initiations and motions, and
3. Effective risk communication and public education.

Fig. 1 Number of landslides and deaths from 2003 to 2017 (credit: NBRO)

Fig. 2 Locations of landslides from 2003 to 2017 (credit: NBRO)
This project is implemented by the NBRO of the Ministry of Defence (Formerly, Ministry of Irrigation and Water Resources Management and Disaster Management) with support from Department of Meteorology (DOM) and Disaster Management Centre (DMC), which are coming under the purview of Ministry of Defense and the Department of Irrigation (DOI) under the purview of Ministry of Mahaweli, Agriculture, Irrigation and Rural Development (Fig. 3). It is noteworthy that this project is complementary with the other ongoing JICA projects such as Project SABO for implementing some intangible measures including refining the current hazard maps and public educations.

Main Implementing Agency and Collaborating Entities in Sri Lanka

National Building Research Organization (NBRO), Ministry of Defence

Main Implementing Agency in Sri Lanka is National Building Research Organisation (NBRO), which has long been the national focal point for landslide risk management in Sri Lanka. NBRO is an autonomous institution established in 1984 and as assigned by the Government of Sri Lanka, NBRO has been carrying out landslide investigation

![Implementation structure for project RRLL (as of April 2020)](image-url)
and studies since 1985. NBRO is a multi-disciplinary research and consultancy institution having its Head Office in Colombo and ten branch offices in landslide-prone districts of the country to implement landslide-disaster risk management activities. Real-time rainfall data from about 250 automated rain-gauges are currently being collected and used to issue early warning to vulnerable communities when rainfall intensities reach to certain threshold values.

Department of Meteorology (DOM), Ministry of Defence

DOM is the mandated national body for the provision of meteorological and climatological services as well as early warning services on weather related disasters and tsunami. It assists in the proposed project in giving inputs on weather forecasting, rainfall monitoring and prediction, thus strengthening the sediment disaster early warning process.

Disaster Management Centre (DMC), Ministry of Defence

DMC is the leading agency for disaster management in Sri Lanka. It is the coordinating body for disaster management in the country, mandated with the responsibility of implementing and coordinating national and sub-national level programs for reducing the risk of disasters with the participation of all relevant stakeholders. The main activities of the DMC are disaster mitigation, preparedness, public awareness, dissemination of early warning to vulnerable populations, emergency operations, and coordination of relief and post disaster activities in collaboration with other key agencies. District Disaster Management Coordination Units (DDMCUs) have been established in all districts to coordinate and carry out Disaster Risk Reduction (DRR) activities at the sub national levels.

In this project, DMC provides necessary inputs and support in the early warning communication process, especially in the liaison with local government bodies and community-based organisations in the line of relaying early warning communication from the Emergency Operation Centre of the DMC to communities at large, in the villages.

Department of Irrigation (DOI), Ministry of Mahaweli, Agriculture, Irrigation and Rural Development

DOI, with over a century of experience as a pioneer organization, takes responsibility for most of the development works in the irrigation sector. In this project, DOI plays an important role, as one of the most important stakeholders, to help develop a strategy for social implementation of the RRLL early warning system.

Pilot Study Sites

Geologically, the island of Sri Lanka is an extension of Peninsular India and forms part of the Indian Shield, one of the oldest and most stable parts of the earth’s crust. Previous studies have suggested that the greater part of the landslide-prone areas is draped thick with weathered gneiss metamorphosed during Precambrian Era. The tropical climate has favoured deep weathering of these metamorphic rocks reaching tens of meters in these mountains with thick tropical vegetation drapes. Two pilot study sites, Aranayake and Athwelthota, are selected as representatives of two major types of RRLL (Fig. 4).

Aranayake Landslide Area

Aranayake landslide was triggered on May 17, 2016, by exceptional rainfall associated with a slow-moving tropical cyclone. The fluidized landslide mass from the relative elevation of about 600 m ran over an about 2 km distance claiming the lives of 125 people. This landslide is unique in that it is much bigger in size and its runout distance than the others. Though this type of landslides rarely occurs, a large RRLL can surely cause a big disaster. This landslide mass ran across two local communities, Elagipitiya and Debathgama Pallebage, having populations of about 1,500 and 1,100, respectively. Summing up populations of the neighbouring communities with similar risks of this type of RRLL expected, the number of beneficiaries of this project will be at least several thousands.

Athwelthota Landslide Area

This landslide, which occurred in Athwelthota area, Badoraliya District on May 26, 2017, destroyed 9 houses, killed 9 people and stopped traffic on a national highway. Each individual landslide of Athwelthota type will not cause surprisingly large disaster, but the number of landslides of this type can be very large causing extensive losses of human lives and properties.

During heavy rain of 2017, 37 RRLLs reportedly took place all at once claiming the lives of 262 people. In the above two pilot study sites, there remain unstable soil masses perching in and around atop of the exposed bare earth. Necessary pieces of equipment will be installed on/in these soil masses to measure causal factors of landslides and...
creeping deformations of these soil masses; these pieces of equipment include pore pressure sensors, inclinometers, borehole extensometers, etc. Furthermore, the movements of these soil masses will be monitored with Persistent Scatterer Interferometric Synthetic Aperture Radar (PSInSAR), a remote sensing technique that uses radar signals from a satellite to accurately measure ground displacement. Using this technique, the motion of each scatterer structure can be very precisely tracked and ground deformation can be determined. These measurements will help develop infiltration models for the weathered gneiss in these areas.

Technologies to Be Developed

This project has the following three groups, G1, G2 and G3:

- **G1** works as a hub for this joint research, and integrates individual technologies developed at two pilot sites by Groups 2 and 3. Capacities of scientists/researchers of Sri Lanka are strengthened through this activity.

- **G2** develops technologies for (1) 24 h in-advance prediction of heavy rainfalls, and (2) assessing groundwater pressure build-up, initiation of an RRLL and its flowing dynamics.

- **G3** strengthens RRLL risk communication protocol, developing an augmented reality system for shearing predicted risk information and providing public education to develop capacities of the communities.

As said before, key technologies that will be developed in the above-mentioned three groups are for (1) precise weather forecast in mountain regions, (2) predicting groundwater pressure build-up, identifying locations of RRLLs and their moving areas, and (3) effective risk communication and public education. Here follow their details.

**Precise Weather Forecast in Mountain Regions**

Though the south-west region of Sri Lanka, where the south-western monsoon brings heavy rain between May to September, is our target region for precise weather forecast, it is desirable for the technology to be flexibly applied to wherever we need it, focusing on its future applications worldwide. From this perspective, we use MSSG as our generic platform for precise weather forecast. MSSG, standing for Multi-Scale Simulator for the Geo-Environment, is a coupled non-hydrostatic atmosphere–ocean–land model developed at the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) (e.g., Takahashi et al. 2007, 2013; Onishi and Takahashi 2012). The developers of this MSSG join the research activity of G2 to help develop the rainfall prediction system suitable for Sri Lanka. The Yin-Yang grid system (Fig. 5) is used in both atmospheric and ocean components of MSSG. This grid model looks exactly like a tennis ball with two identical skins stitched together, thus the grid spacing becomes quasi-uniform allowing seamless zoom-in and zoom-out to be made anywhere on earth. On this MSSG, precise topographic effect and boundary-layer turbulence effect (Seifert and Onishi 2016) on the cumulonimbus clouds development particularly over upwind slopes can be taken into account for the better 24 h-in-advance prediction of heavy rainfalls in Sri Lanka.

Given the initial condition of weather variables such as winds, temperatures, atmospheric pressures, etc., three days before the Aranayake Landslide of May 2016 in Sri Lanka, MSSG simulated cumulated rain falls at Aranayake satisfactory in a decent manner as shown in Fig. 6. The blue line in this figure is the measured cumulative rainfall, while the red one shows what MSSG simulated. This simulation in
Fig. 6 requires huge computer resources, and thus was conducted on a super-computer at JAMSTEC with the upper-level computation nest covering a 200 km by 200 km area of the island and the lower-level nest at resolution of 500 m by 500 m. To make this simulation possible even on a workstation, parameters for the MSSG climate model are to be adjusted for better interpolation of weather at resolution of 2 km by 2 km. The obtained prediction at 2 km resolution will be spatially interpolated into 500 m resolution prediction with the aid of the super-resolution mapping technology based on the deep convolutional neural network (Onishi et al. 2019). This will realize the 24 h-in-advance reliable prediction of heavy rainfalls on a common workstation.

Predicting Groundwater Pressure Build-Up, Identifying Locations of RRLLs and Their Moving Areas

This may not be an easy task given a basic question about how the surface cover-soil profile can vary over space in the vicinity of our pilot study sites. Though we are aware that this is a difficult task, we need at least to begin with the fundamental data that we will obtain from the two pilot sites. It is also worth verifying the feasibility of currently available numerical tools for evaluating how persistent rains would trigger a RRLL and how the fluidized soil mass of the RRLL would run out. Therefore, soil samples were taken from the source area of the Aranayake landslide (Fig. 7) for a series of undrained ring shear tests (Fig. 8). Given the parameters from the undrained ring shear test, a numerical tool, SLIDE (Liao et al. 2010) was first employed to reproduce the porewater-pressure buildup in the time domain, and then LS Rapid model (Sassa et al. 2010) was used to simulate how the landslide soil mass at Aranayake was detached and how the fluidized soil mass did run over that long distance of about 2 km (Fig. 9). These models for simulating infiltrations and fluidized soil dynamics need to be refined as we obtain much more pieces of information on site to be sure. However, the good agreement between the simulated and the observed runouts suggests that these tools will potentially be helpful for pursuing this project.

Effective Risk Communication and Public Education

It will take several hours to make one-day-in-advance forecast of the occurrence of RRLLs using the above-mentioned computer programs on high-performance workstations. The obtained results will then be relayed timely to the last mile as augmented reality dioramas of the predicted rains and
However, we need to take the followings into account for better implementation strategies:

1. In Sri Lanka, districts are the second level administrative divisions under provinces (Statoids 2015). Each district, administered under a District Secretary, is divided into several Divisional Secretary's (DS) divisions, which are further subdivided into extremely many local communities called “Grama Niladhari (GN)” divisions.

2. The number of local GN divisions in RRL-prone areas is increasing year by year reflecting human interventions.

3. Though the Disaster Management Centre (DMC) of the Ministry of Defense has sole authority in terms of the issuance of evacuation alerts and evacuation orders, each Divisional Secretary (DS) can use his/her discretion in taking necessary actions in case of urgency.

4. NBRO has been helping their decisions providing them with alerting information of landslides.

5. In this regard, both NBRO and JICA has started a joint project “Project SABO” (NBRO and JICA 2020), for capacity strengthening on development of non-structural measures for landslide risk reduction. The goals include: (a) strengthening of hazard mapping and risk assessment capacity, and (b) revision of regional-level early warning issuance criteria, etc. Thus, Project RRLL is expected to play a complementary role vis-à-vis Project SABO, providing proactive information allowing people to take a precaution against RRLs (Fig. 11).

How the Project has Come Up with Conclusions of Official Agreements

A signing ceremony for the Minutes of Meeting (MM) between NBRO, Sri Lanka and JICA, Japan was held on Oct. 15 at the auditorium of NBRO (Fig. 12). Mr. Satoshi Nakamura, Leader, Detailed Planning Survey Team, JICA, Japan, and Eng. (Dr.) Asiri Karunawardena, Director General, NBRO, Sri Lanka, signed the MM toward the implementation of Project RRLL.

In the same signing ceremony, Collaborative Research Agreement (CRA) between NBRO, Sri Lanka and ICL was also signed by Eng. (Dr.) Asiri Karunawardena, Director General, NBRO, Prof. Kazuo Konagai, Leader on the Japanese side of Project RRLL, Research Director at ICL, Prof. Kyoji Sassa, Secretary General, ICL and Dr. Kaoru Takara, Managing Director, ICL.

Record of Discussions of the Project RRLL was signed by the following officers: Mr. Fusato Tanaka, Chief Representative, JICA Sri Lanka Office, Eng. (Dr.) Asiri Karunawardena, Director General, NBRO, Major General (Retired), Kamal Gunaratne, Secretary, Ministry of Defence and Mr. Ajith Abeysekera, Director General, Department of
Fig. 9 Numerical simulation of the runout of the Aranayake landslide using LS-RAPID (by Tan et al. 2020)

External Resources, Ministry of Finance. This Record of Discussion is an official agreement between both the governments, to confirm implementation of the 05 years Project RRLS starting on Feb. 5, 2020.

Technical Cooperation Agreement for pursuing the Project RRLS over the 5-years period from March 1, 2020 to Feb. 28, 2025 has been implemented between JICA and ICL.

JICA and ICL signed contract for the first year of the Project RRLS with the consent of the both parties. The first year starts on March 1, 2020 and ends up on May 31, 2021.
Influenced by the effects of global climate change, and more seriously, by human-induced interventions in landslide-prone areas, number of tragic RRLL events in Sri Lanka has been on a soaring trend in general with some remarkable spikes in 2014, 2016 and 2017. In this situation, ICL and NBRO are starting this project “Development of early warning technology of rain-induced rapid and long-travelling landslides in Sri Lanka” (Project RRLL). The project is in line with the activities by the Sri Lanka Comprehensive Disaster Management Programme, output 1.3 “National and community level landslide early warning system are in place”. NBRO is currently running one more JICA technical cooperation project, Project SABO for capacity strengthening on development of non-structural measures for landslide risk reduction. Project RRLL is thus complementary with Project SABO providing extra lead time for emergency responses, evacuations, namely, one of the most important missing pieces of the jigsaw puzzle for landslide-hazard mitigation.

**Acknowledgements** In the midst of the currently ongoing coronavirus pandemic, we are now figuring out how we will firmly pursue Project “RRLL” in line with the strategy that we have developed. The good thing is that not only scientists but also all supporters from both governments are united in our common belief that the project will surely contribute to the Sustainable Development Goals (SDGs) of the United...
Nations, especially Goal 11 “Make cities and human settlements inclusive, safe, resilient and sustainable” through the landslide risk reduction for human settlements in mountainous areas and urban areas close to mountains. It would not have been possible for the authors to reach this start-up stage of the project without the support of Mr. Satoshi, Nakamura, Director, Mr. Naoya Orita, Assistant Director at the Disaster Risk Reduction Team, JICA, Prof. Takashi Asaeda, Research Supervisor, Mr. Kazuo Anazawa, Senior Associate Research Supervisor at JST, Mr. Takayuki Nagai, JICA expert, Mr. Kiyofumi Takanashima, JICA Sri Lanka Office. The authors must also thank total 20 officers and scientists from NBRO, DOM, DMC, DMI of the ministry, Central Engineering Consultancy Bureau (CECB), and three major universities in Sri Lanka, who attended the RRL Workshop at the Ministry of Irrigation, Water Resources and Disaster Management (Supervisory authority of NBRO of that time) on June 20, 2018. The authors have largely been inspired by comments from them. Especially, Mr. N.A.S. Kumara, Secretary of the ministry has given valuable comments and useful pieces of information to embody the project were also provided by Mr. Kenichi Sugawara, Ambassador Extraordinary and Plenipotentiary, successive Second Secretaries at the Embassy of Japan in Sri Lanka, and Mr. L.J.M.G. Chandrasiri Bandara, District Secretary of Kegalle. Last but not least, the authors are greatly indebted to Dr. Kiyoharu Hirota, Dr. Kung Dang, Dr. Ms. Kumiko Fujita and Ms. Emi Ueda at ICL, for their ceaseless efforts to support the project.

References

Dang K, Sassa K, Konagai K, Karunawardena A, Bandara RMS, Hirota K, Tan Q, Ha ND (2019) Recent rainfall-induced rapid and long-traveling landslide on 17 May 2016 in Aranayaka, Kegalle district, Sri Lanka. Landslides 16:155–164

Department of Meteorology (2020) Sri Lanka, Climate of Sri Lanka. https://www.meteo.gov.lk/index.php?option=com_content&view=article&id=594&Itemid=310&lang=en. Last accessed 14 April, 2020

Japan Science and Technology Agency (2020) SATREPS for the earth, for the next generation. https://www.jst.go.jp/global/english/. Last accessed 14 April, 2020

JICA Survey Team (2016) Survey results of Aranayake Disaster, JICA. https://www.jica.go.jp/srilanka/english/office/topics/c8h0vms00006ufwjl-att/160720.pdf. Last accessed 14 April, 2020

Liao ZH, Yang H, Wang J, Fukunaka H, Sassa K, Kamawati D, Fathani F (2010) Prototyping an experimental early warning system for rainfall-induced landslides in Indonesia using satellite remote sensing and geospatial datasets. Landslides 7(3):317–324

National Building Research Organization (NBRO) and Japan International Cooperation Agency (JICA) (2020) Project for capacity strengthening on development of non-structural measures for landslide risk reduction (Project SABO). https://www.nbro.gov.lk/index.php?option=com_content&view=article&id=197&catid=2&Itemid=101&lang=en. Last accessed 14 April, 2020

Onishi R, Takahashi K (2012) A warm-bin-cold-bulk hybrid cloud microphysical model. J Atmos Sci 69:1474–1497

Onishi R, Sugiyama D, Matsuda K (2019) Super-resolution simulation for real-time prediction of urban micrometeorology. SOLA 15:178–182

Sassa K, Nagai O, Solidum R, Yamazaki Y, Ohta H (2010) An integrated model simulating the initiation and motion of earthquake and rain induced rapid landslides and its application to the 2006 Leyte landslide. Landslides 7(3):219–236

Seifert A, Onishi R (2016) Turbulence effects on warm-rain formation in precipitating shallow convection revisited. Atmos Chem Phys 16:12127–12141

Statoids (2015) Divisions of Sri Lanka. https://www.statoids.com/ylk.html. Last accessed 14 April, 2020

Takahashi K, Peng X, Onishi R, Ohdaira M, Goto K (2007) Multi-scale simulator for the geo-environment: MMSG and simulations. Use of high-performance computing in meteorology, pp 36–54

Takahashi K, Onishi R, Baba Y, Kida S, Matsuda K, Goto K, Fuchigami H (2013) Challenge toward the prediction of typhoon behaviour and down pour. J Phys Conf Ser 454:012072

Tan Q, Sassa K, Dang K, Konagai K, Karunawardena A, Bandara R M S, Tang H, Sato G (2020) An attempt to estimate the past and the future landslide hazards based on soil testing and computer simulation around 2016 Aranayake landslide, Sri Lanka, Landslides, Landslides 17:1727–1738