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Decision Support System in Thailand's Dam Safety With a Mobile Application for Public Relations:
DS-RMS (Dam Safety Remote Monitoring System)

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ABSTRACT

This paper describes the decision-making based on civil engineering expertise of the dam safety remote monitoring system (DS-RMS), which decides on action-based advice depending on everyday scenarios and special occurrences such as earthquakes and floods. The system has been in full operation since 2016 and automatically evaluates 35 failure modes for three major dam types 24 hours a day. Key benefits include quick and reliable access to current information about the dams and being a reliever to dam executives in critical situations. In further development, parts of the real-time dam information were selected and made available to the public together with dam safety evaluation results automatically and continuously via a mobile application.

KEYWORDS

Dam Safety, Decision Support System, Remote Monitoring

INTRODUCTION

The Electricity Generating Authority of Thailand (EGAT) is currently operating fourteen large dams constructed for irrigation, flood prevention, power generation and so forth. In order to ensure dam safety, EGAT has analyzed and monitored dam behavior through its dam safety program since 1982 and has been improving the processes according to international standards and guidelines, one of which was to initiate an automated Dam Safety Remote Monitoring System (DS-RMS) in 2013. The first objective is to automate the conventional acquisition of safety-related measurements by using remote-monitoring technology like dam safety management systems named KDSMS from Korea introduced by Jeon et al. (2009), MISTRAL Italy Lazzari and Salvaneschi (1923), ESMHS Egypt

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Abd-Elhamid et al. (2008), or PAEWEB Brazil Leone-Filho et al. (2014). Existing dam instruments were connected to reliable remote terminal units (RTUs), communication links and computer servers running advanced information software so that comprehensive information can be remotely obtained in real time.

SCADA (Supervisory Control And Data Acquisition) high functions: dam behavior visualization showed by Nuntawattanasirichai et al. (2019), earthquake monitoring, flood routing simulation, safety evaluation and warning system are the goals objectives. DS-RMS is designed to support three major dam types: concrete, embankment and impervious faced rockfill dams, with special requirements for the Bhumibol Dam and the Lamtakong Jolabha Vadhana Power Plant, presented in Figure 1 with detailed information in Table 1.

BACKGROUND

Sander-Kessels & Straßer (2016) have published experience of Uniper, the international operator of 185 hydropower plants and the associated 225 dams, in the implementation of Dam-Safety-Management-System (DSMS), whose principle of DSMS came from §2 ICOLD-Bulletins Nr. 154 published in 2010. The Dam Safety Policy is implemented in three steps according to the BowTie method as part of Standard IEC/ISO 31 010: risk management – Risk assessment techniques published in 2009. DSMS uses a risk management process named AERO (Asset Engineering Risk and Opportunities) with the Swedish hazard classification RIDAS (Hydropower Industry Dam Safety Guidelines) published in 2012. Early results showed that the transfer of proven, best practice (e.g. in thermal plant) BowTies procedures to dams is difficult: "This is mainly due to the fact that dams are unique in every way and that the different hazard potentials do not automatically derive from the dam parameters, but must be determined individually." (Freely translated from German into English).

Hence, EGAT in cooperation with Geotechnical Engineering Research and Development Center (GERD) – Kasetsart University (KU) has been endeavoring to define criteria for several dam instruments in order to identify the safety of the dams listed in Table 1. GERD (2014) reported the analysis of historical data for each dam individually. Examples of the results with evaluation flowchart are presented in the next section. Subsequently, the National Electronics and Computer Technology Center (NECTEC) – National Science and Technology Development Agency (NSTDA)

Figure 1. Locations of the fourteen large[1] dams operated with DS-RMS. Dams in Northeastern Thailand are outside of earthquake hazard. Adapted from (National Electronics and Computer Technology Center [NECTEC], 2019)

Table 1. Details of dams numbered in Figure 1

No.	Name Location: River, District, Province	Type Reservoir's storage capacity
1	Bhumibol Dam Ping, Sam Ngao, Tak	Concrete arch gravity 13,462.00 million cubic meters
2	Sirikit Dam Nan, Tha Pla, Uttaradit	Earth dam with clay core 9,510.00 million cubic meters
3	Mae Chang Dam Mae Chang, Mae Moh, Lampang	Rockfill dam with clay core 105.78 million cubic meters
4	Nam Pung Dam Phung, Kut Bak, Sakon Nakhon	Rockfill dam with clay core 165.48 million cubic meters
5	Sirindhorn Dam Lam Dome Noi, Sirindhorn, Ubon Ratchathani	Rockfill dam with clay core 1,966.47 million cubic meters
6	Pak Mun Dam Mun, Khong Chiam, Ubon Ratchathani	Diversion dam of compacted concrete 225.00 million cubic meters
7	Ubol Ratana Dam Phong, Ubol Ratana, Khon Kaen	Rockfill dam with clay core 2,434.30 million cubic meters
8	Chulaphorn Dam Phrom, Khon San, Chaiyaphum	Rockfill dam with clay core 193.75 million cubic meters
9	Huai Kum Dam Nam Phrom, Kaset Sombun, Chaiyaphum	Rockfill dam with clay core 22.80 million cubic meters
10	Bang Lang Dam Pattani, Bannang Sata, Yala	Rockfill dam with clay core 1,454.36 million cubic meters
11	Rajjaprabha Dam Klong Saeng, Ban Ta Khun, Surat Thani	Rockfill dam with clay core 5,638.80 million cubic meters
12	Lamtakong Jolabha Vadhana Power Plant is a pumped-storage hydropower plant located between Sikhio and Pak Chong, Nakhon Ratchasima	Rockfill dam 10.30 million cubic meters
13	Srinagarind Dam Kwai Yai, Si Sawat, Kanchanaburi	Rockfill dam with clay core 17,745.00 million cubic meters
14	Vajiralongkorn Dam Kwai Noi, Thong Pha Phum, Kanchanaburi	Rockfill dam with concrete facing slab 8,860.00 million cubic meters

(Data Source: Geotechnical Engineering Research and Development Center [GERD], 2014)

developed a knowledge-based automated web application by splitting GERD's evaluation methods into smaller flowcharts and sort them into three operational situations: normal operation, earthquake events and flood events. The evaluation results and some supporting data were finally transferred for publication in form of a Dam Safety mobile application. In comparison to Sanders and Kim (2016), Wang et al. (2013), Gu et al. (2013), Kassa (2010), Alliard et al. (2008), Marengo (2006), Rutledge et al. (2006), and Hartford and Baecher (2004), the method and implementation presented here is a holistic innovation, which includes support for operators until dam safety status is easily accessible for the public.

CONCERNED ISSUES FOR ESTABLISHING THE SAFETY CRITERIA

DS-RMS is primarily responsible for dam safety assessments, display and alarms. The main data used in the dam safety assessment are measurement values from dam instruments, meteorological-hydrological instruments, earthquake detection instruments and accelerometers.

An RTU can receive signals from three types of dam instruments as follows:

- Measurement head with 4-20 mA output signal
- Vibrating wire measurement head, no more than 32 channels
- Data provided by a Campbell scientific device: Measurement and control data-logger: Model CR800 or CR1000

At the Bhumibol Dam for example, EGAT has installed two tilt meters and three 3D joint meters. The two types of measurement heads are connected to two units of Campbell scientific CR1000 models classified by the type of head measurement. And at the Lamtakong Jolabha Vadhana Power Plant, an only one pumped-storage hydropower plant, EGAT has installed SAA1-4 and ISG1-4 measurement heads, which are connected to two Campbell scientific CR800 models data-loggers.

From a meteorological-hydrological instrument an RTU receives two types of signals:

- Pulse receiving type, two channels including rain measuring tank and anemometer. The data collected in the RTU and the data sent to the dam server are divided into two parts:
  - Rainwater tank as pulse counting data and
  - wind speed as frequency data.
- 4-20 mA signal from the measuring instruments receiving type, three channels such as thermometers, air humidity meters and barometric pressure gauges (barometer). The data stored in the RTU and the data sent to the dam server will be 4-20 mA data.

Reading values from a seismograph will display earthquake epicenter information covering Thailand, such as longitude, latitude, epicenter area (sub-district, district, and province), date, time, size, depth, and distance from the dam. EGAT's automatic earthquake detection system will send earthquake data in form of a text file consisting of magnitude, latitude, hypocenter, epicenter, and time stamp to the central server.

An accelerometer provides information about ground acceleration from earthquakes that occur towards the dam and sends the acceleration value (g) and time as text file and in wave form in the seed file format to the dam server.

http://water.egat.co.th is a source of daily and hourly data such as the amount of inflow, water level, amount of water, storage in reservoirs, drainage rates through spillway discharge and drainage rates via electricity generators (release).

For detecting backward erosion in embankment, EGAT installed piezometers at the interface between the clay core and the filter where exit points are expected to form. An additional piezometer is installed within the clay core, which although it cannot instantly detect an initiation of backward erosion, it can detect backward erosion after the erosion enlarges and the pore pressure in that area has decreased. Thongthamchart and Brohmsubha (2014) presents the manner of introducing the internal erosion process for the dam interpretation by geotechnical instruments in order to evaluate the safety of an embankment dam based on International Commission on Large Dams [ICOLD] (2017). In order to understand the derivation of the security criteria developed by GERD, a short extract is given here.

At a certain RWL, the piezometric head during the impounding may differ from the piezometric head during lowering as shown in Figure 2 and Figure 3. An important factor influencing the properties mentioned is the elapsed time in which the RWL is maintained. Another factor that affects the relationship between the piezometric pressure and RWL is the position of the piezometer. The piezometric head in the piezometer near the abutment can be raised by groundwater level. However, the piezometric head downstream of the clay core, next to the filters and behind the cutoff wall or grout curtain is controlled. In addition, the piezometric head can vary due to the accuracy of the measuring instruments and the human influence.

Figure 2. Relationship between piezometric head at the abutment and reservoir water level (RWL) Source: Thongthamchart and Brohmsubha, 2014.

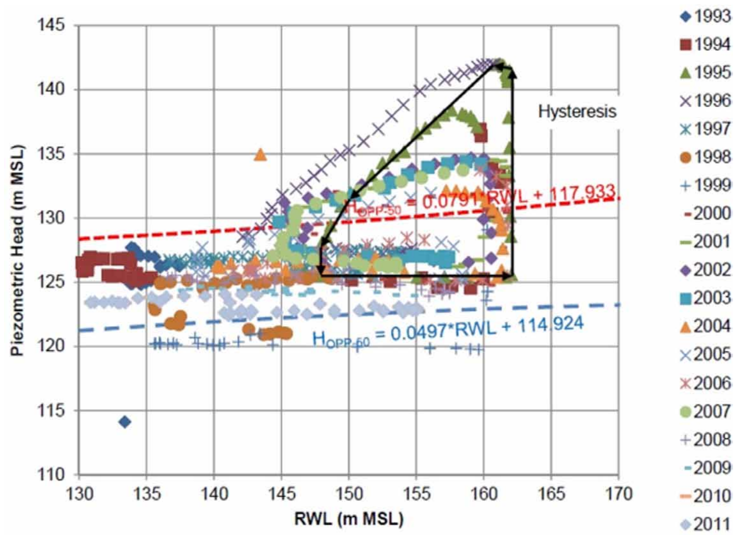
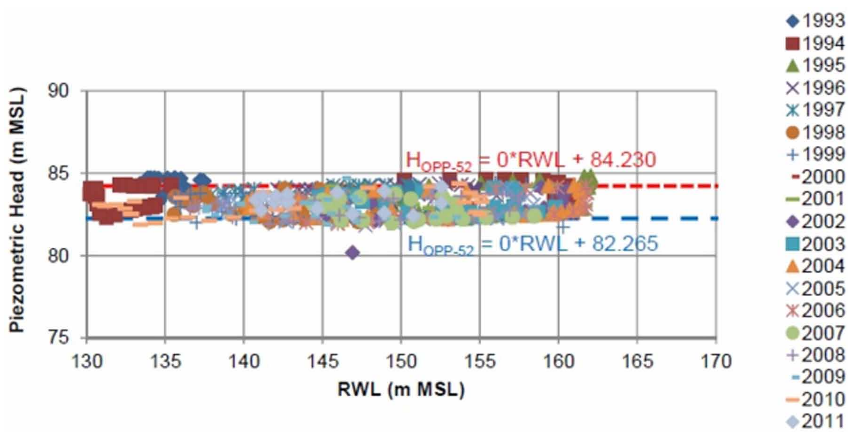


Figure 3. Relationship between piezometric head within the embankment and reservoir water level. Source: Thongthamchart and Brohmsubha, 2014



In practice, the piezometers are installed in pairs. If one of them fails, the other cannot be used to determine the hydraulic gradient. The safety criterion is simplified by introducing the relationship between RWL and piezometric head using the individual piezometer.

ICOLD (2010), and Fell et al. (2005) recommend two warning levels, which represent abnormal behavior of the dam for surveillance as follows:

- **Alert:** The measured data is out of the expected range, considering common changes due to cyclic or stationary loads.
- **Alarm:** The maximum level of safety coefficients for the dam, forecast by the engineering board are being surpassed.

GERD and EGAT considered a system that is able to support the decision-making in three areas:

1. dam behavior monitoring using special equipment, further called ‘dam instruments’,
2. tracking flood and
3. tracking the effects of earthquakes and aftershocks on the dam.

In practice, dam instruments are of the utmost importance since they indicate critical dam behavior even in normal operation as well as in crisis e.g. due to flood or earthquake events. The established safety criteria indicate a dam status in three stages/levels, which consist of normal (background color: green), alert (yellow) and alarm (orange).

The whole frame of safety criteria for internal erosion can be illustrated as in Figure 4. Piezometric head values from all locations are used to determine the possible seepage path and to identify the mechanism, while the measured seepage discharge classifies erosion as an alert or alarm level. If the seepage discharge is above upper bound, the alarm level is displayed. However, this must be confirmed by a manual visual inspection in the downstream area of the embankment.

The alert and the alarm statuses can be reverted if no anomalies of the embankment are found and the upper and lower bounds are revised or if a dam rehabilitation is performed.

DEVELOPING A KNOWLEDGE-BASED AUTOMATED WEB APPLICATION

Since the whole frame of safety criteria, as shown exemplary in Figure 4, is so complex, NECTEC starts by grouping dams into five types and splitting GERD’s flowcharts into 35 modes of failure to sort them into three conditions:

1. Static condition is normal operation where neither flood nor earthquake events happen;
2. Flood condition; and
3. Earthquake condition.

Figure 5 shows an example for a rockfill dam with a clay core.

At the lowest level, all modes of failure for this dam are evaluated separately and the computer programming will output exactly one of the three mentioned statuses. The worst of those statuses is being inherited by the condition levels. Then again, the worst status at the condition level is inherited as the dam’s full status.

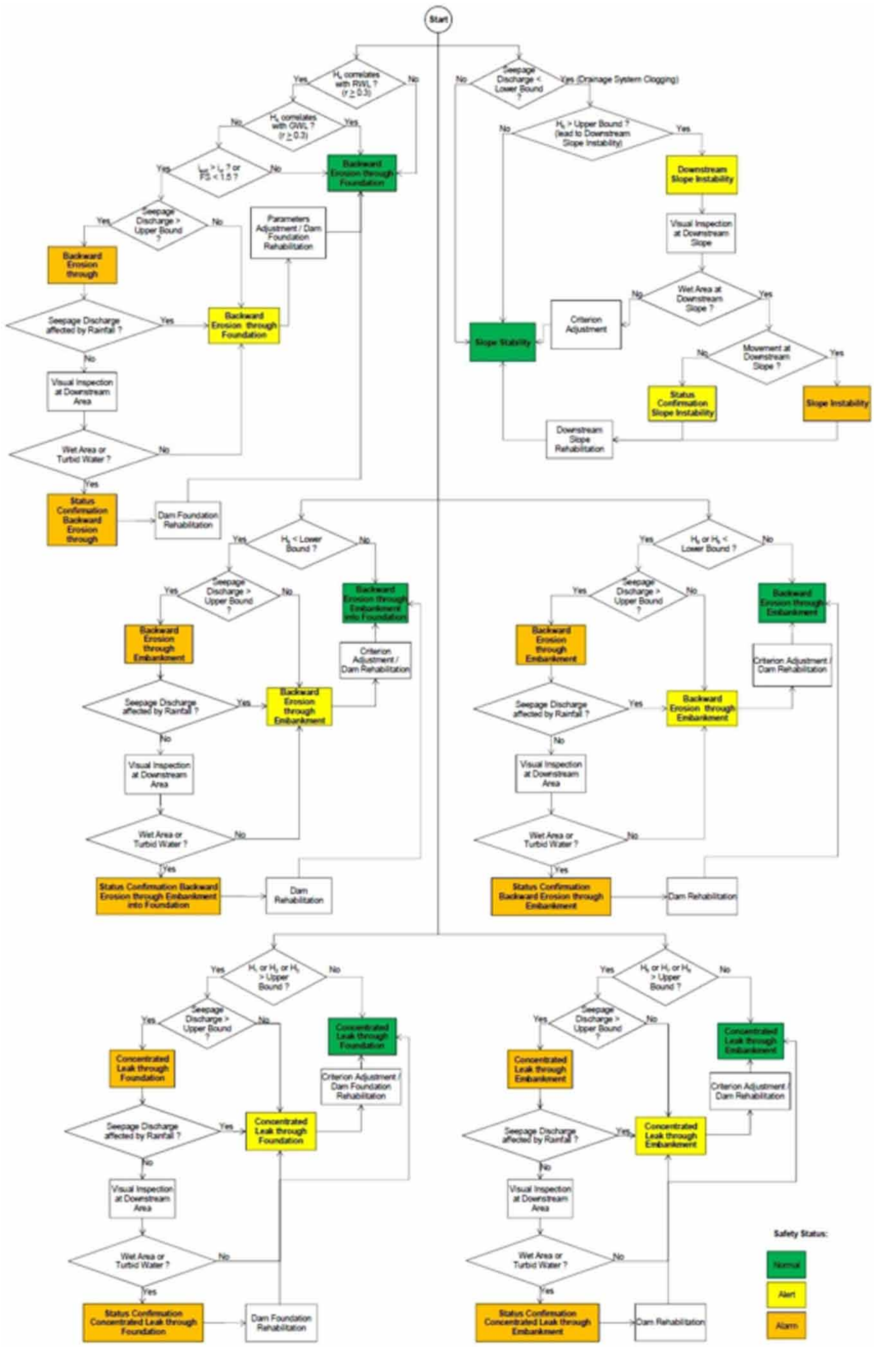
There are two critical differences to a classic expert system for example to the system proposed by Fell et al. (2005):

1. DS-RMS will never decide on its own and will only issue action-based advice to dam officials, e.g. NOT give out an evacuation command and therefore red is not being used here as status/level color.
2. EGAT wants to know if an unexpected scenario occurs, that is not covered by any of the developed flowcharts. Therefore, an additional color is defined: grey.

For instance, a mode of failure is introduced in Figure 6. The stored procedure in the SQL Server checks whether the thresholds in Table 2 and Table 3 are being exceeded and appoints suggestion(s).

After logging in with a single sign-on account, also used for e.g. the email server, EGAT staffs are greeted by a summary for executives with the real-time evaluated dam safety status of all dams on the map of Thailand as in Figure 7. This main page is obviously leaned on Figure 1 and contains common user experience design. For clarity and redundancy reasons, the overall system is also designed in a way, that users can decide to log-in to the central server or remotely to one of the 14

Figure 4. Example of a flowchart for evaluating internal erosion in embankment dam (Source: Thongthamchart and Brohmsubha, 2014)



servers located at each dam. A summary in text form can be opened as well as latest events of the three conditions. More detailed information regarding every single dam can be found by selecting the left menu panel. Both Thai and English are normally used in tandem on the user interface. In this paper, figures of UI have been translated into English and convert to grayscale.

Figure 5. Hierarchy in evaluating dam safety status for a rockfill dam with a clay core

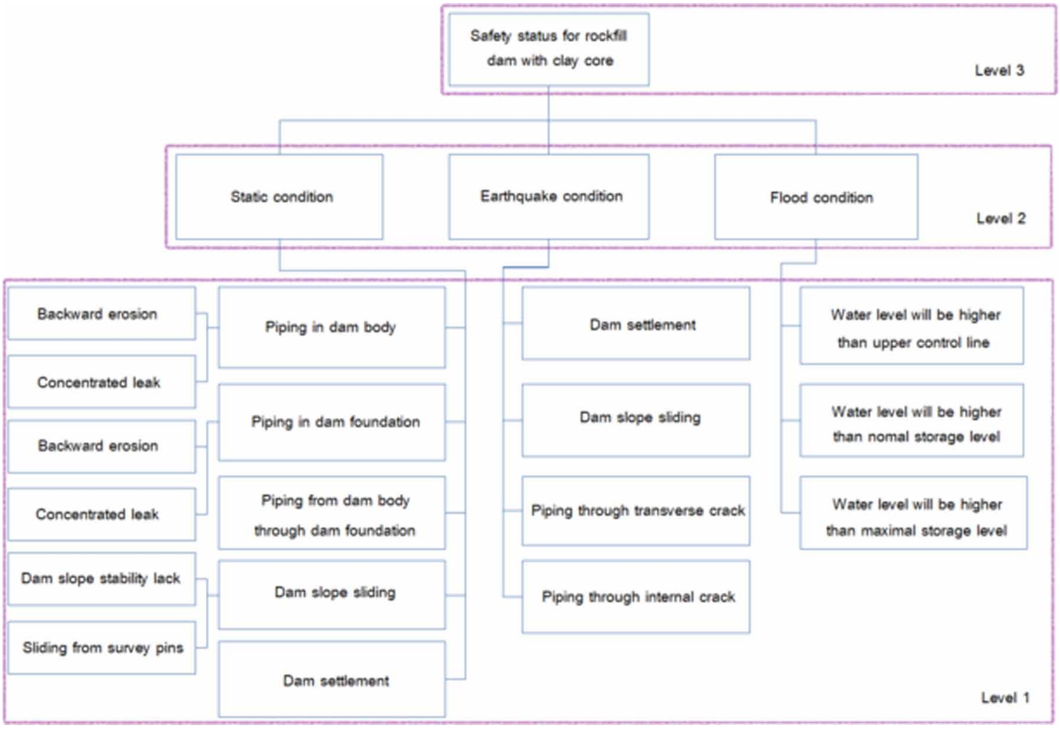


Figure 8 presents sample evaluation[2] results divided into static conditions by rows with five modes of failure in this dam as a subset of all feasibility listed in Figure 5 for this dam type. The middle row is the earthquake condition and contains modes of failure only for all dams located in earthquake-prone areas. Finally, the flood condition row contains three modes of failure for all dams.

Clicking on an evaluation result shows more detailed information as in Figure 9. The system suggests checking for seepage from the weir effected by rainfall and sends this to the assigned operators via SMS to their mobile phones and via email. After the operators finish checking for seepage, they input their newly gained information into the system by answering a set of questions. Then the system immediately reevaluates following the stored expert knowledge.

Dam behavior visualization[3] was developed with features such as an automatic data mapping mechanism and multi-dimensional displays, including cause and effect (correlation), section, plan, and profile views to ease data interpretation. The data mapping mechanism is designed to help map data from two concerned instrument types which may have different sampling rates, but selected to be plotted together as ‘cause and effect’ display e.g. to find out whether the piezometric head is affected by the reservoirs water level. The mapping mechanism searches and maps two values with the nearest timestamps by considering an acceptable time gap.

The multi-dimensional displays provide users with various data plots overlaid on the graphical dam structure drawing in the background. Cause and effect plots show the relationship between two variables (or two instrument types). Section/plan/profile views display the various graph types on different dam drawings where instruments or sensors are installed. For example, displacement vectors can be shown on a plan view to indicate how much and in which direction the dam body moves. The settlement profile view can illustrate the settlement of the dam crest in the vertical direction. This allows EGAT operators to easily identify problems and take appropriate actions promptly.

Figure 6. An example for a mode of failure in earthquake events. Source: Dowrueng et al., 2019

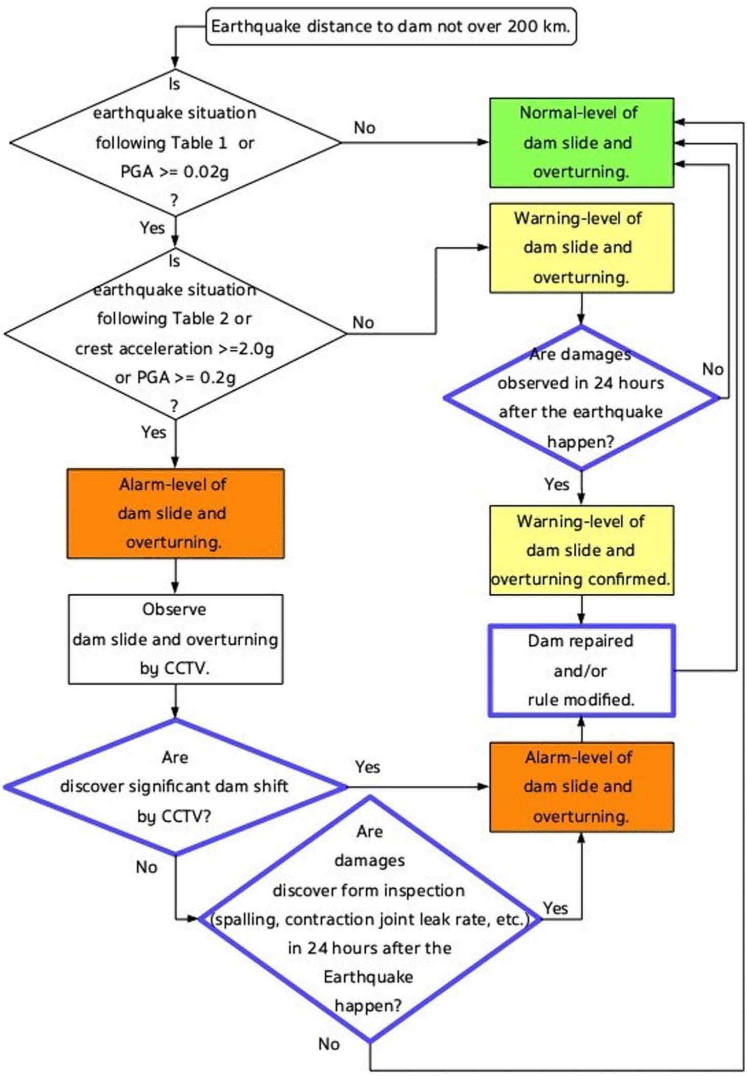


Table 2. Earthquake magnitude in relation to the distance of earthquake epicenter to the dam which induced a PGA of more than 0.02g (acceleration on the foundation of the dam)

Earthquake magnitude	Distance of earthquake epicenter to dam (km)
≥ 4	≤ 25
≥ 5	≤ 50
≥ 6	≤ 80
≥ 7	≤ 125
≥ 8	≤ 200

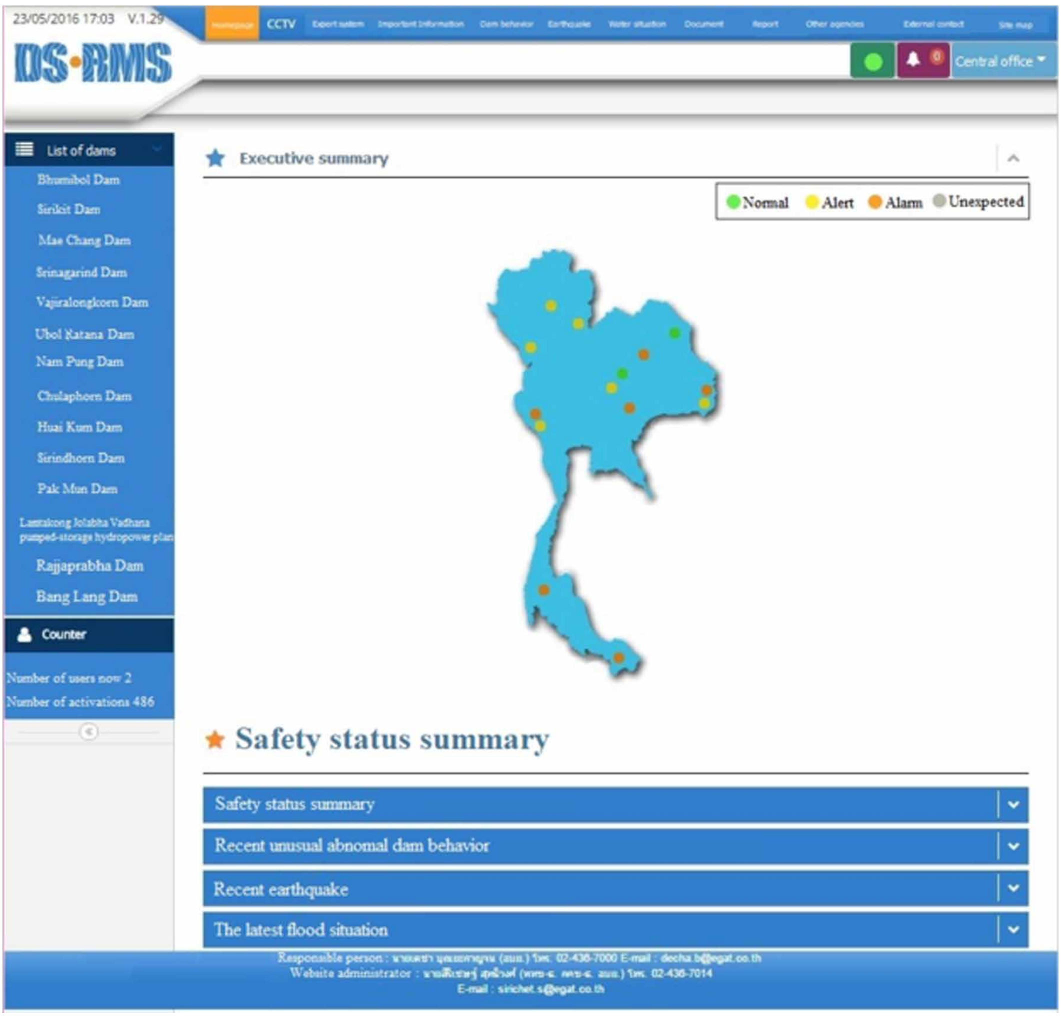
Source: (Dowrueng et al., 2019)

Table 3. Earthquake magnitude in relation to the distance of earthquake epicenter to the dam which induced a PGA of more than 0.2g

Earthquake magnitude	Distance of earthquake epicenter to dam (km)
≥ 6	≤ 12
≥ 6.5	≤ 18
≥ 7	≤ 24

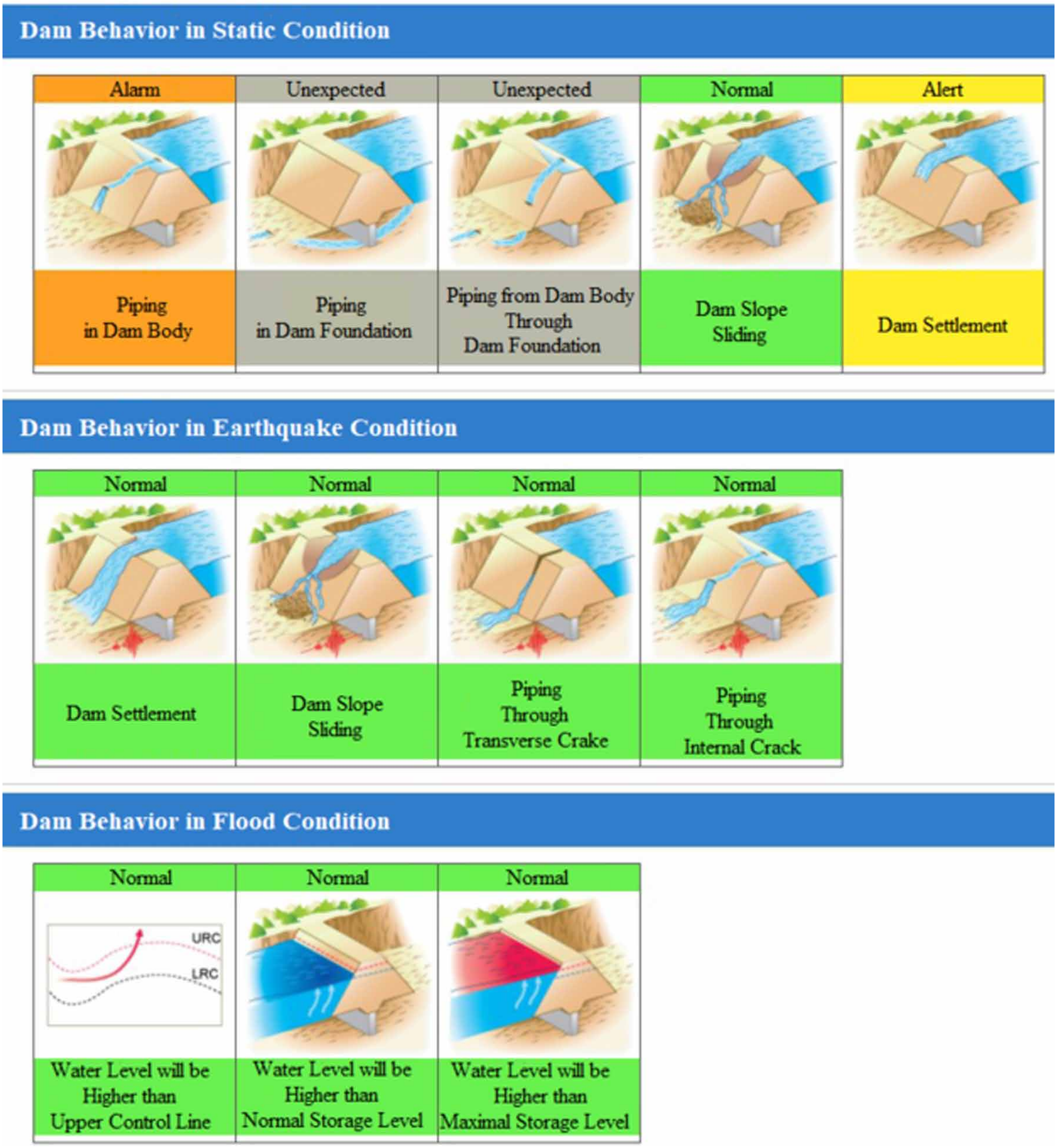
Source: (Dowrueng et al., 2019)

Figure 7. DS-RMS User Interface (UI): Summary for executives on central server. Adapted from (Dowrueng et al., 2019)



If an earthquake affects the dam e.g. detected accelerators, those are displayed with red dots as in Figure 11. The system will adjust the evaluation frequency and may give out visual inspection instructions. DS-RMS also has many UIs for tracking flood and water situation at a dam both in graphical and table form as shown in Figure 12. MSL in Figure 12 is abbreviated from Mean Sea-

Figure 8. An example of evaluation results



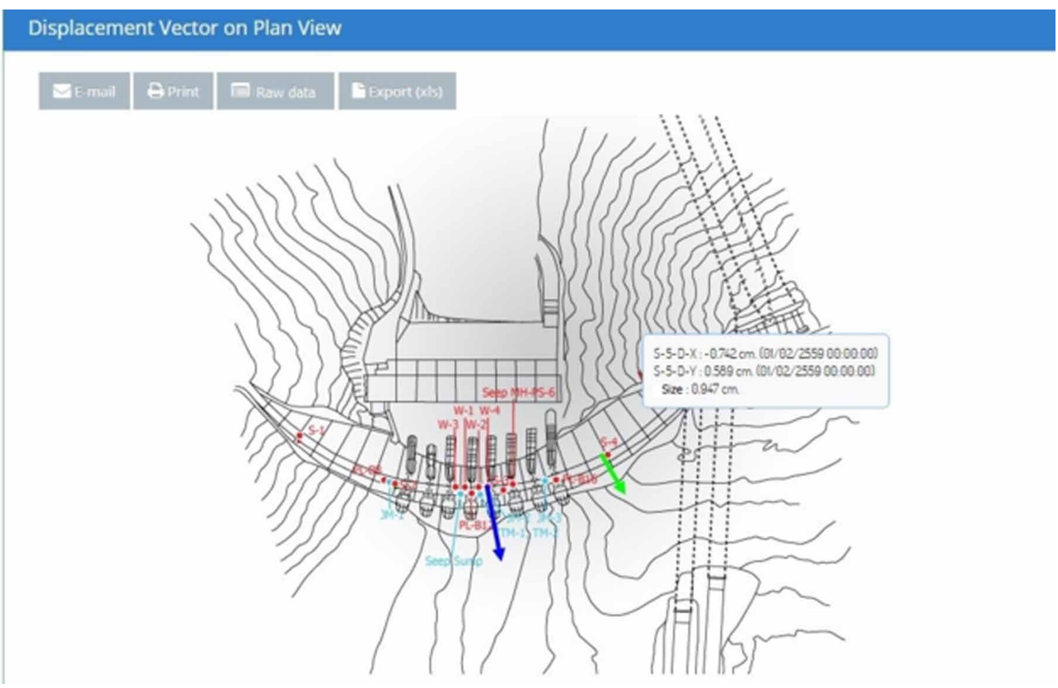
Level and indicates the height above sea level. MCM is SI (abbreviated from the French Système international (d'unités)) unit million cubic meters. A publication on this specific topic is in preparation.

DAM SAFETY MOBILE APPLICATION

Humans (and cars) undergo a health check regularly once every one or two years. Under this background a mobile application was designed and developed as a health check for dams so the people in Thailand can look up the current security status of these fourteen dams at any time and easily accessible from anywhere. Seismic data from earthquake events, water (level) situations and CCTV cameras are collateral, which boosts the confidence of the public living near those dams, in

Figure 9. An example of detailed information. Adapted from (Supakchukul et al., 2019)

Figure 10. Displacement Vectors on Plan View can indicate how much and in which direction the dam body of the Bhumibol Dam moves. Adapted from (Nuntawattanasirichai et al., 2019)



that they are tended properly and can determine the strength of their local dam. The Dam Safety mobile app is completed with modern notification functions in the event of a malfunction of a dam in Thai language. Figure 13 shows the original screenshot and Figure 14-19 were modified with some translations into English. Duplicates remain in Thai for conservative reasons.

Figure 11a. Example of UI displaying earthquake information

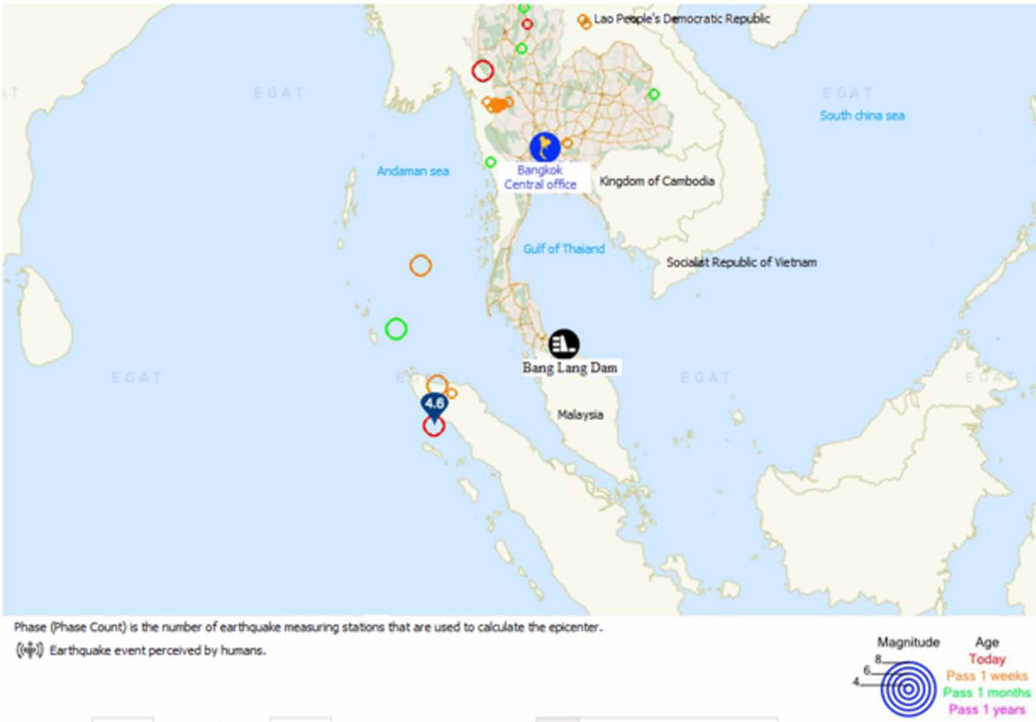


Figure 11b. Example of UI displaying acceleration graph

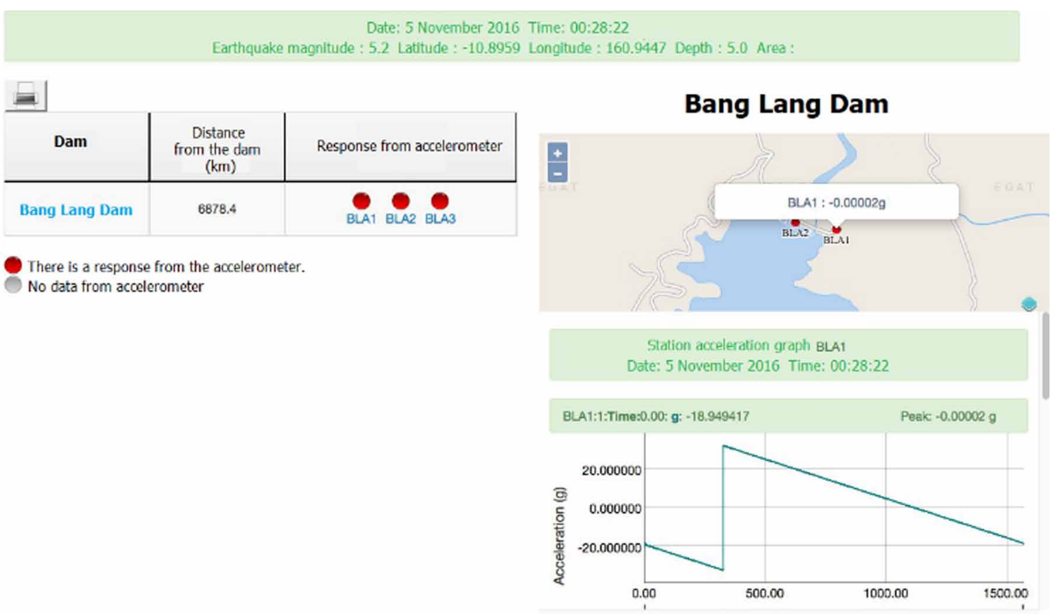
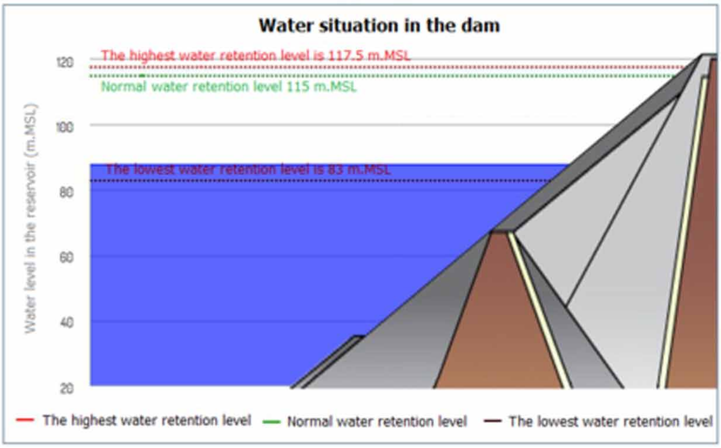


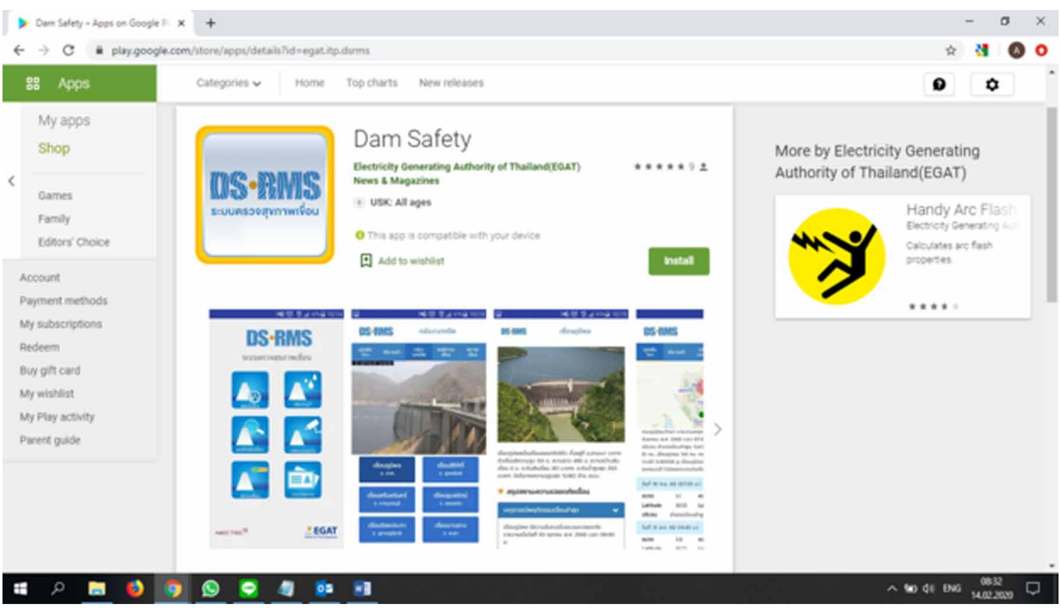
Figure 12. A part of the UI for tracking water level, inflow, and spillway



Bang Lang Dam
5 November 2016 13:00:00
The current water level is 87.65 m.MSL, equivalent to the amout of water 379.67 MCM.
Daily inflow 2.99 MCM (data from http://water.egat.co.th)

Dam	Current water level (m.MSL)	Current water retention amount (MCM)	The amount of water flowing into the basin (MCM)			Water level through the machine (MCM)			Water level through the spillway (MCM)			Most recent date (dd/mm/yyyy) and time Measured every 1 hour
			Last hour	00:00-now	Yesterday	Last hour	00:00-now	Yesterday	Last hour	00:00-now	Yesterday	
Bang Lang Dam	87.65	379.67	0.25	2.99	2.17	0	0	1.13	0	0	0	05/11/2016 13:00:00

Figure 13. As a health check system for dams selected DS-RMS data is publicly accessible via a mobile app for Android at https://play.google.com/store/apps/ details?id= egat.itp.dsrms



After successful installation, launching the Dam Safety mobile application offers six main functions as translated on the left of Figure 14. New / Announcement shown on the right contained on February 14, 2020 only earthquake announcements, the first three of which have been translated into English. The official announcement in Portable Document Format (PDF) can be downloaded with one click on the announcement text.

Earthquake data in Figure 15 is compared with the Meteorological Department of Thailand, Ministry of Digital Economy and Society before being published on this page.

Figure 16 shows due to page limitation an example of the amount of water in the dams.

Figure 14a. Main page with six functions and "News / Announcement" that can only be accessed from this main page. The other five functions on the main page are also reachable from the menu bar on the top of following pages.

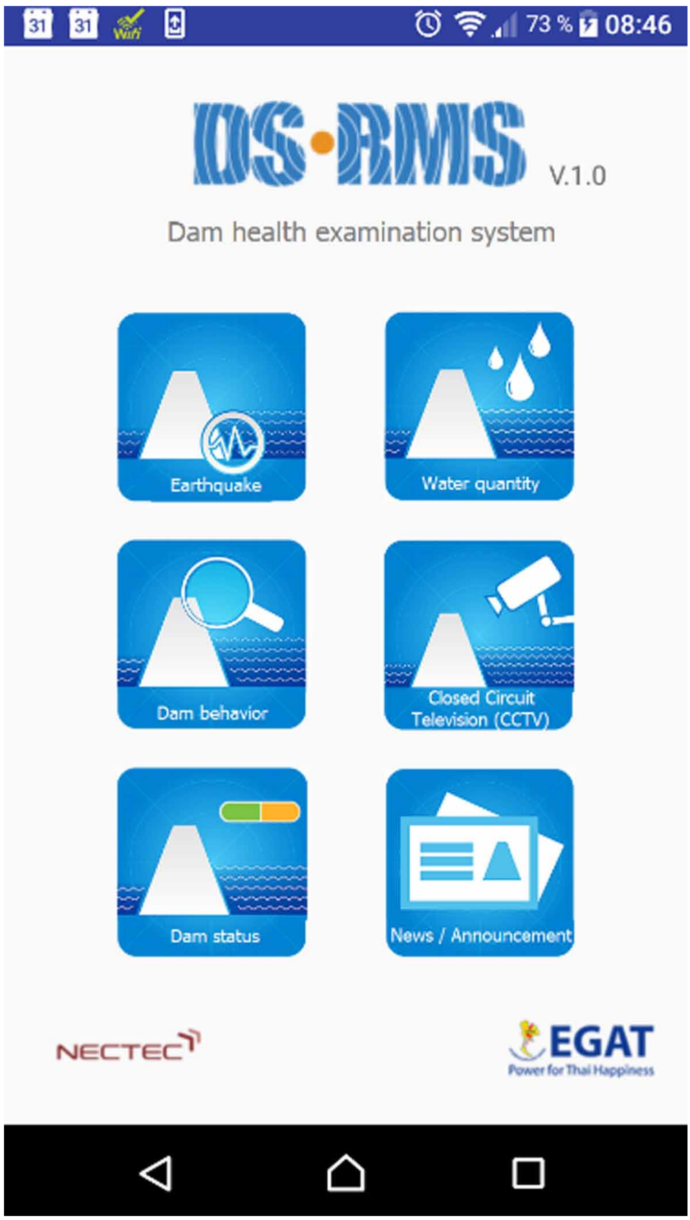


Figure 14b. Main page with six functions and "News / Announcement" that can only be accessed from this main page. The other five functions on the main page are also reachable from the menu bar on the top of following pages.

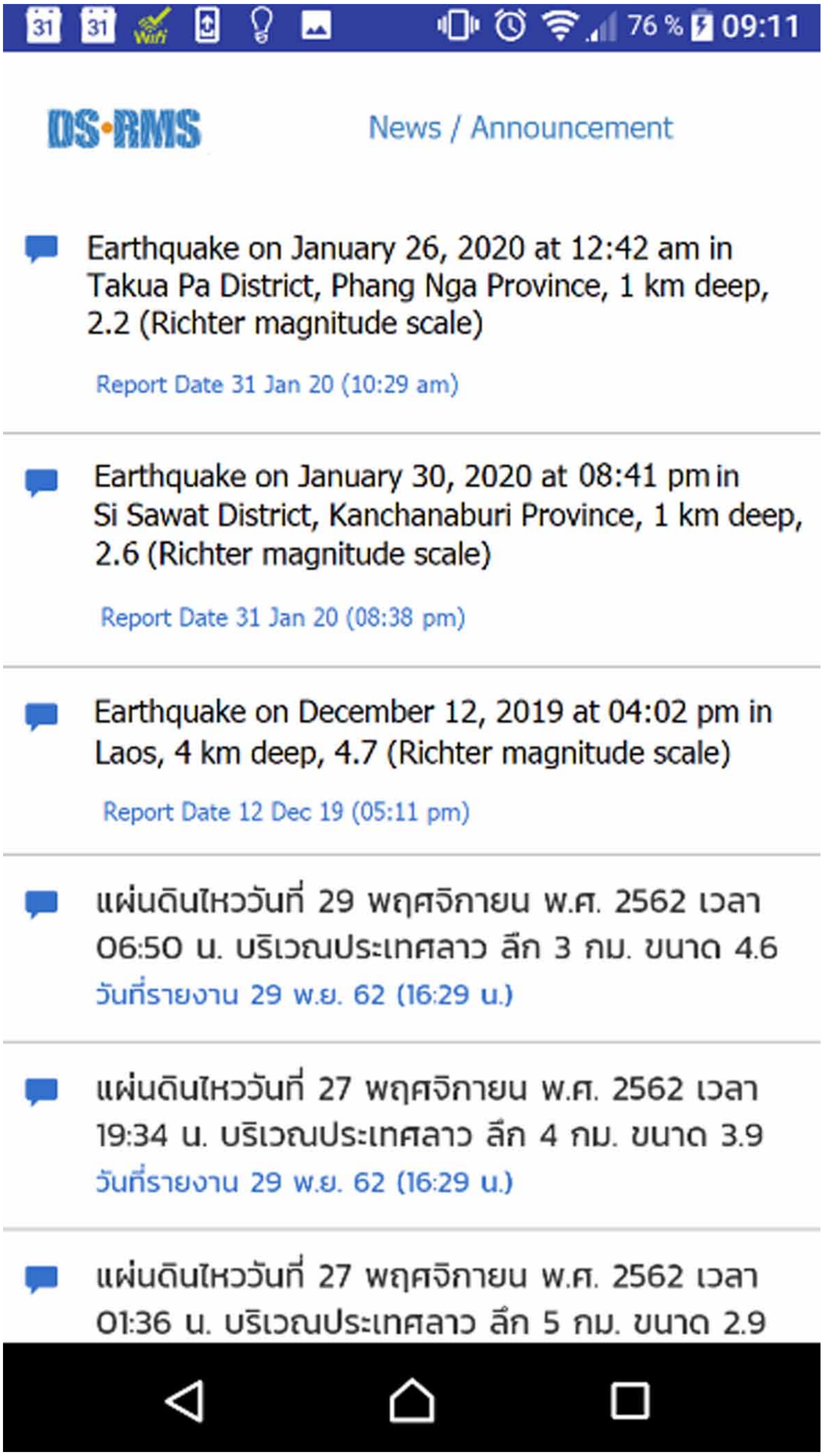


Figure 15a. Earthquake reports with detected accelerations on the six dam foundations in earthquake-prone areas

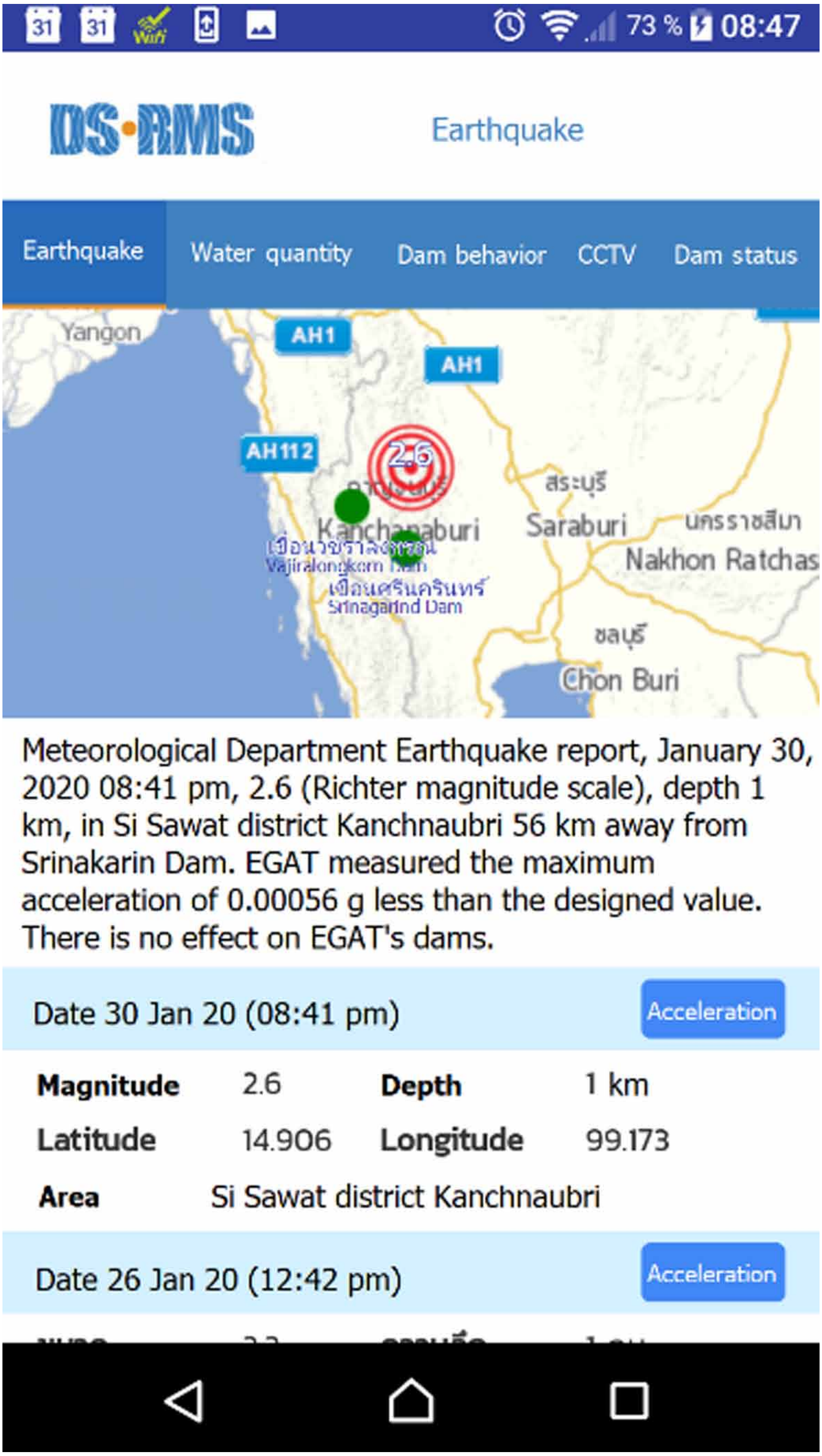


Figure 15b. Earthquake reports with detected accelerations on the six dam foundations in earthquake-prone areas

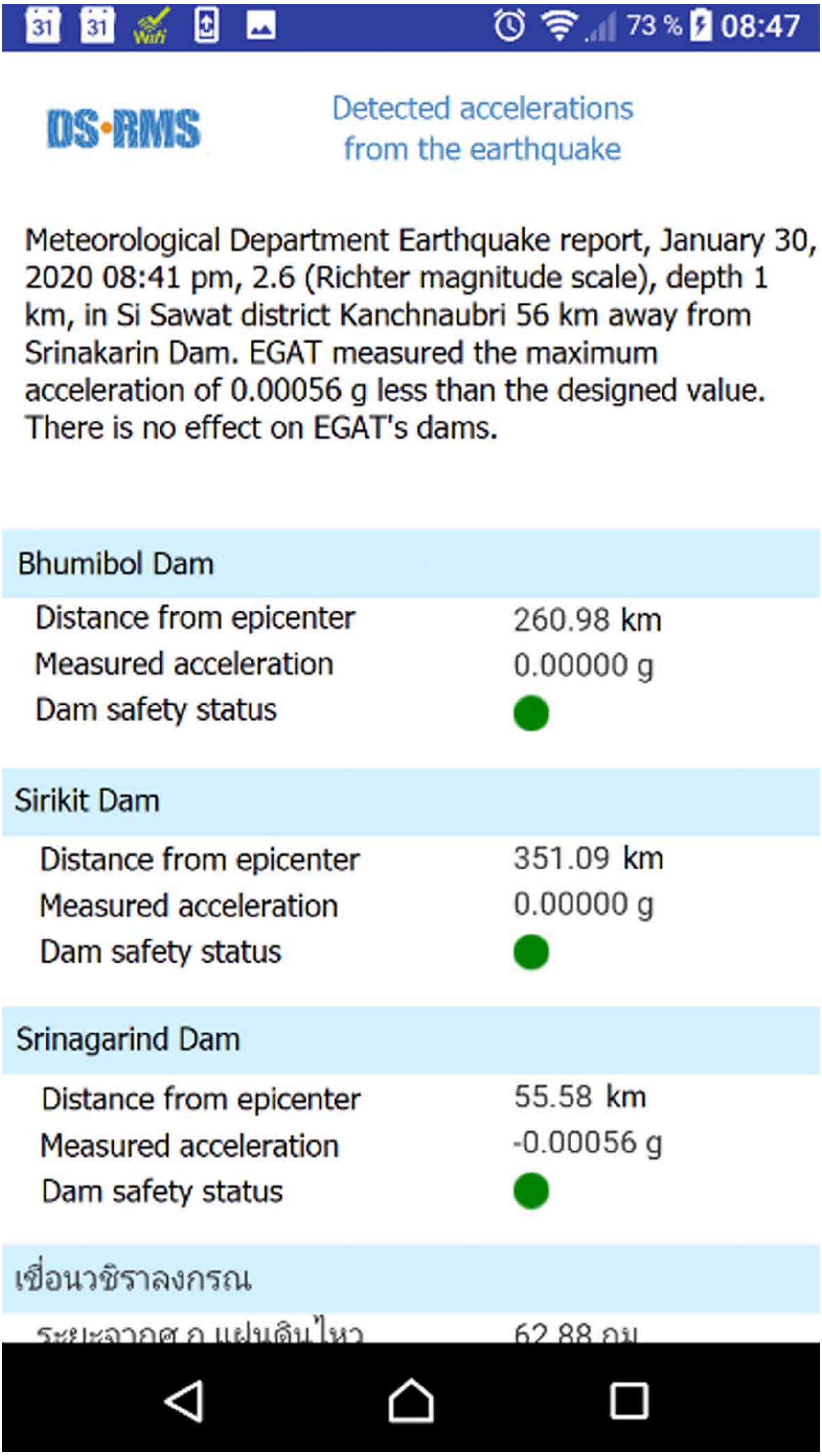


Figure 15c. Earthquake reports with detected accelerations on the six dam foundations in earthquake-prone areas

Figure 16a. Example of water quantity function

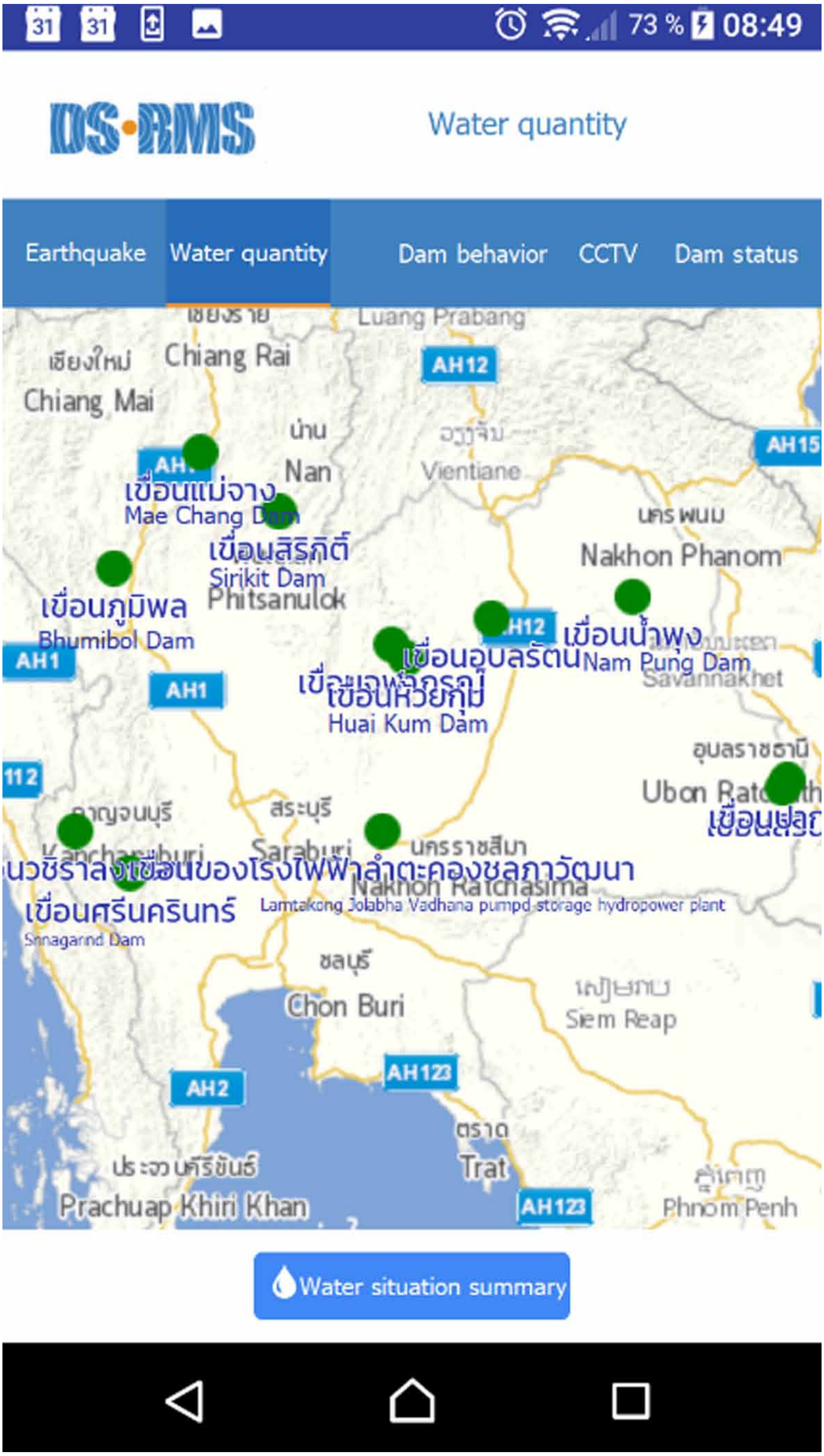


Figure 16b. Example of water quantity function

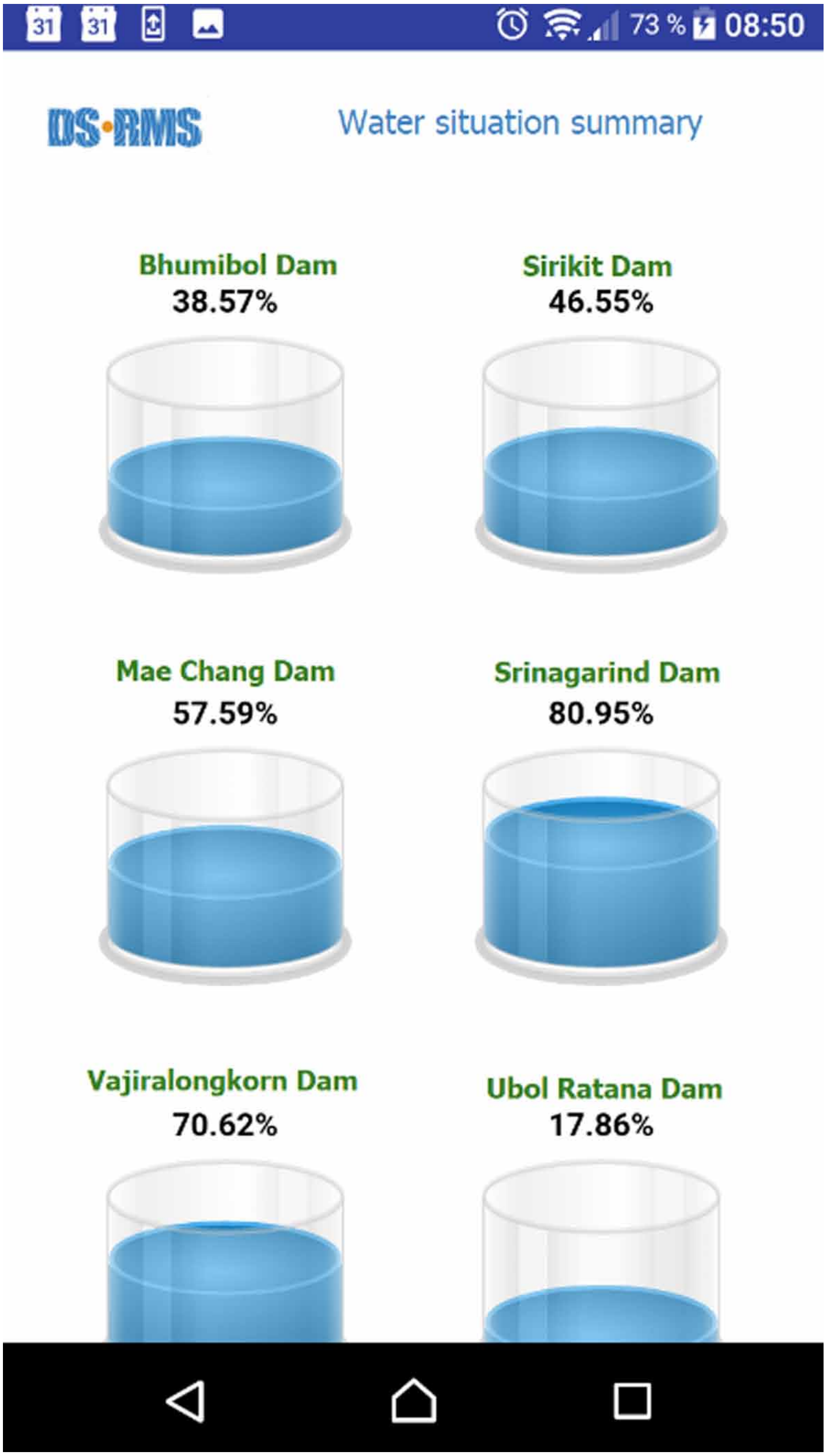


Figure 16c. Example of water quantity function

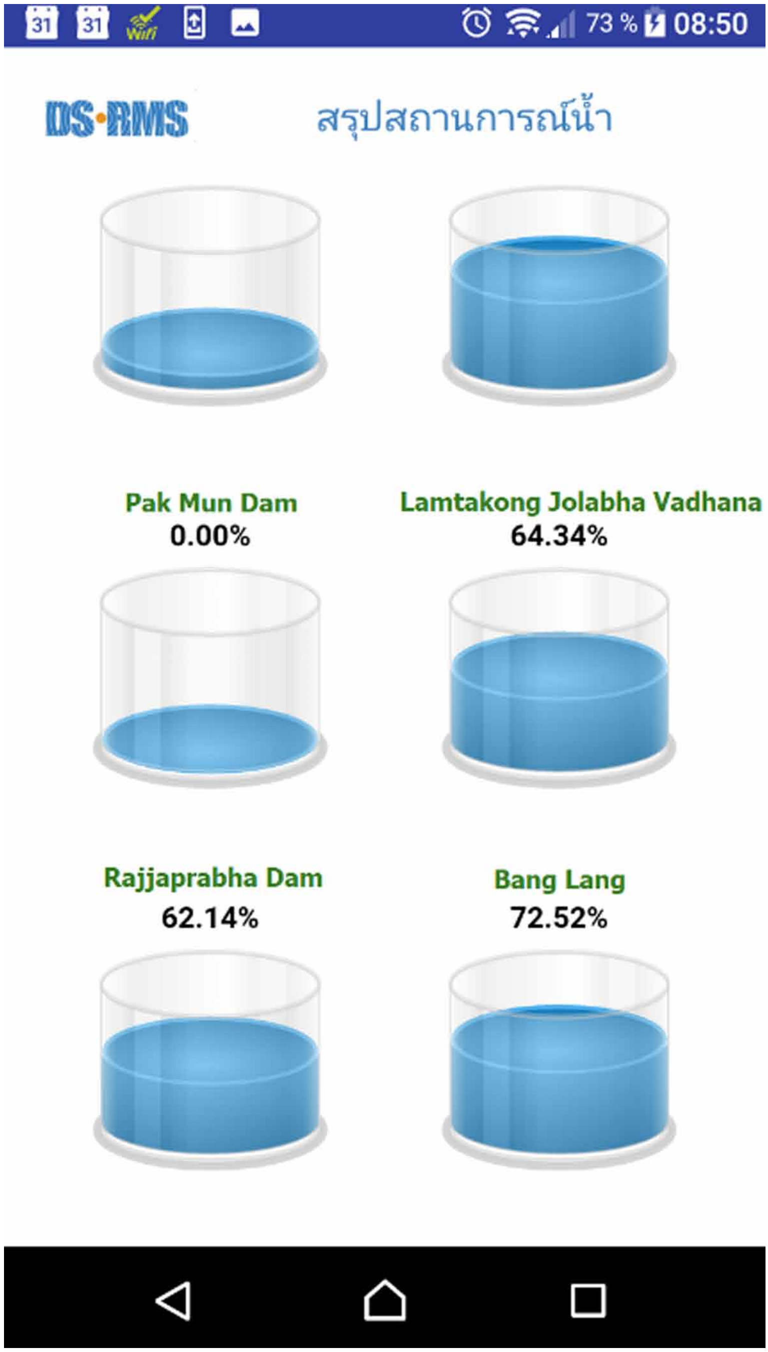


Figure 17 shows examples of Closed-Circuit Television (CCTV) fixated at the Vajiralongkorn Dam and with pan–tilt–zoom function at the Srinagarind Dam.

Dam Safety operates semi-automatic. In case of an error, the public continues to be informed with the latest data and corresponding notice, such as in Figure 18, middle.

Figure 17a. Streaming CCTV

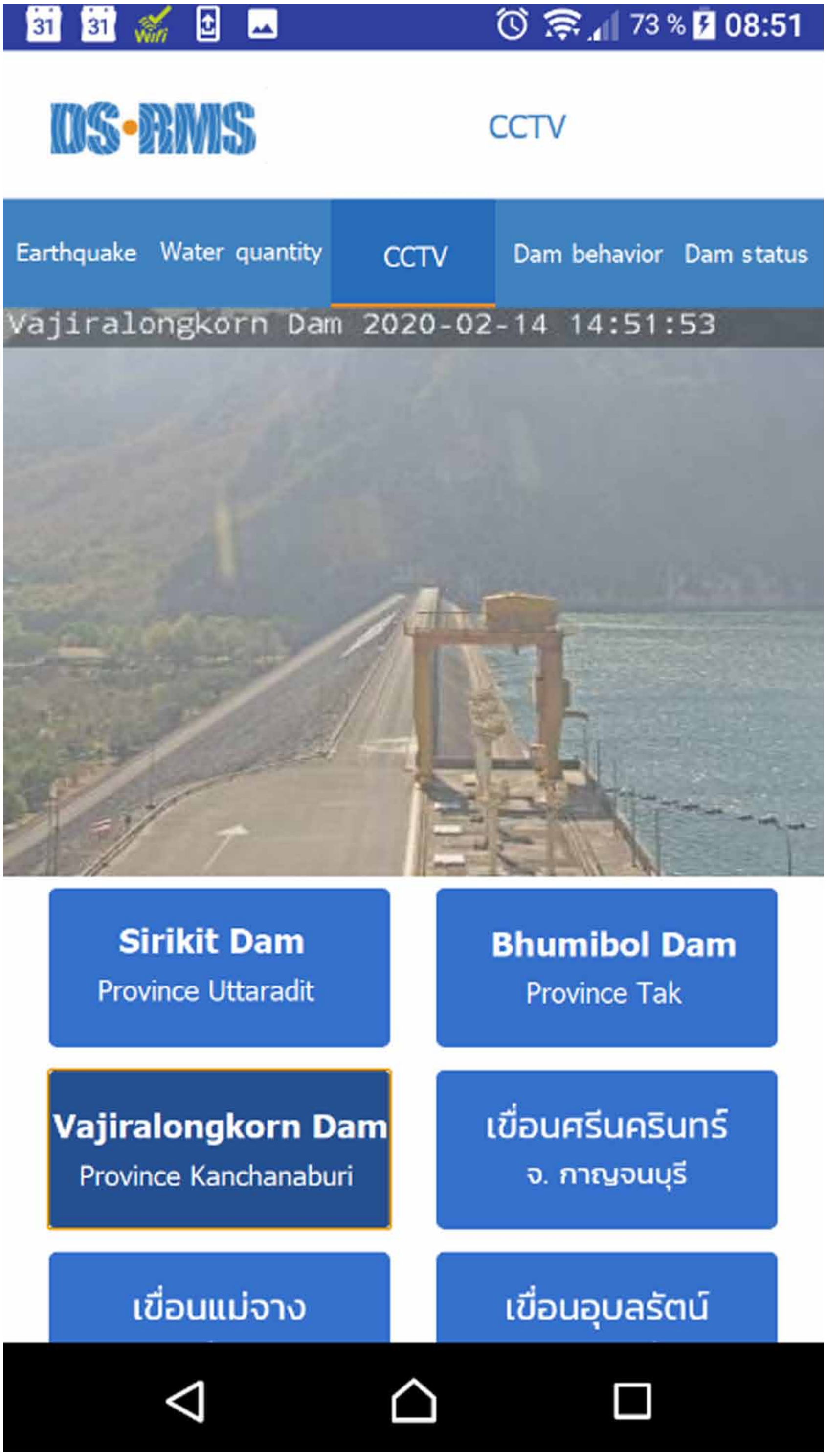


Figure 17b. Streaming CCTV

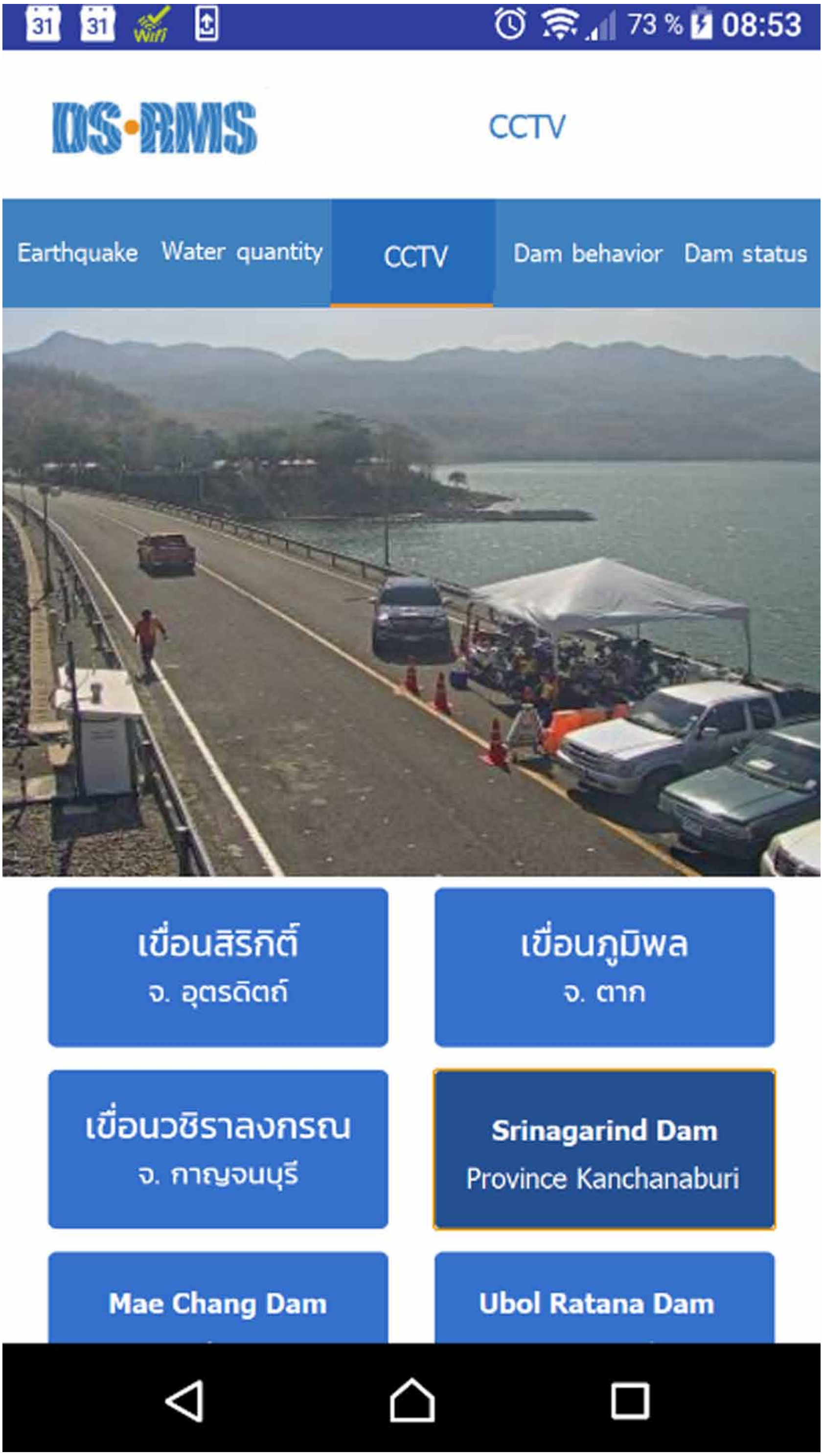


Figure 17c. Streaming CCTV

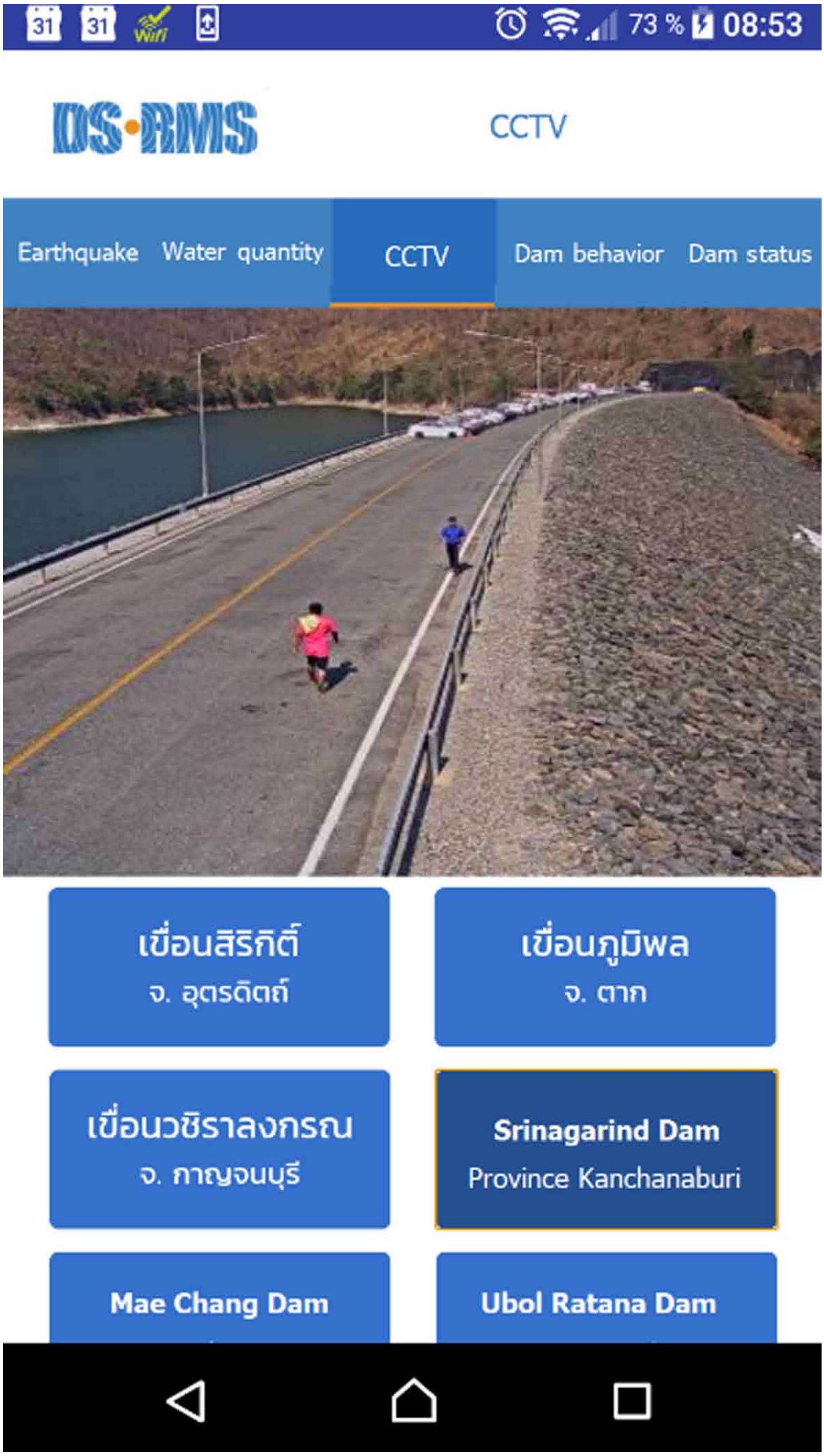


Figure 18a. Dam behavior with special dam instrument installations at the Bhumibol Dam and the Lamtakong Jolabha Vadhana pumped-storage hydropower plant

Figure 18b. Dam behavior with special dam instrument installations at the Bhumibol Dam and the Lamtakong Jolabha Vadhana pumped-storage hydropower plant

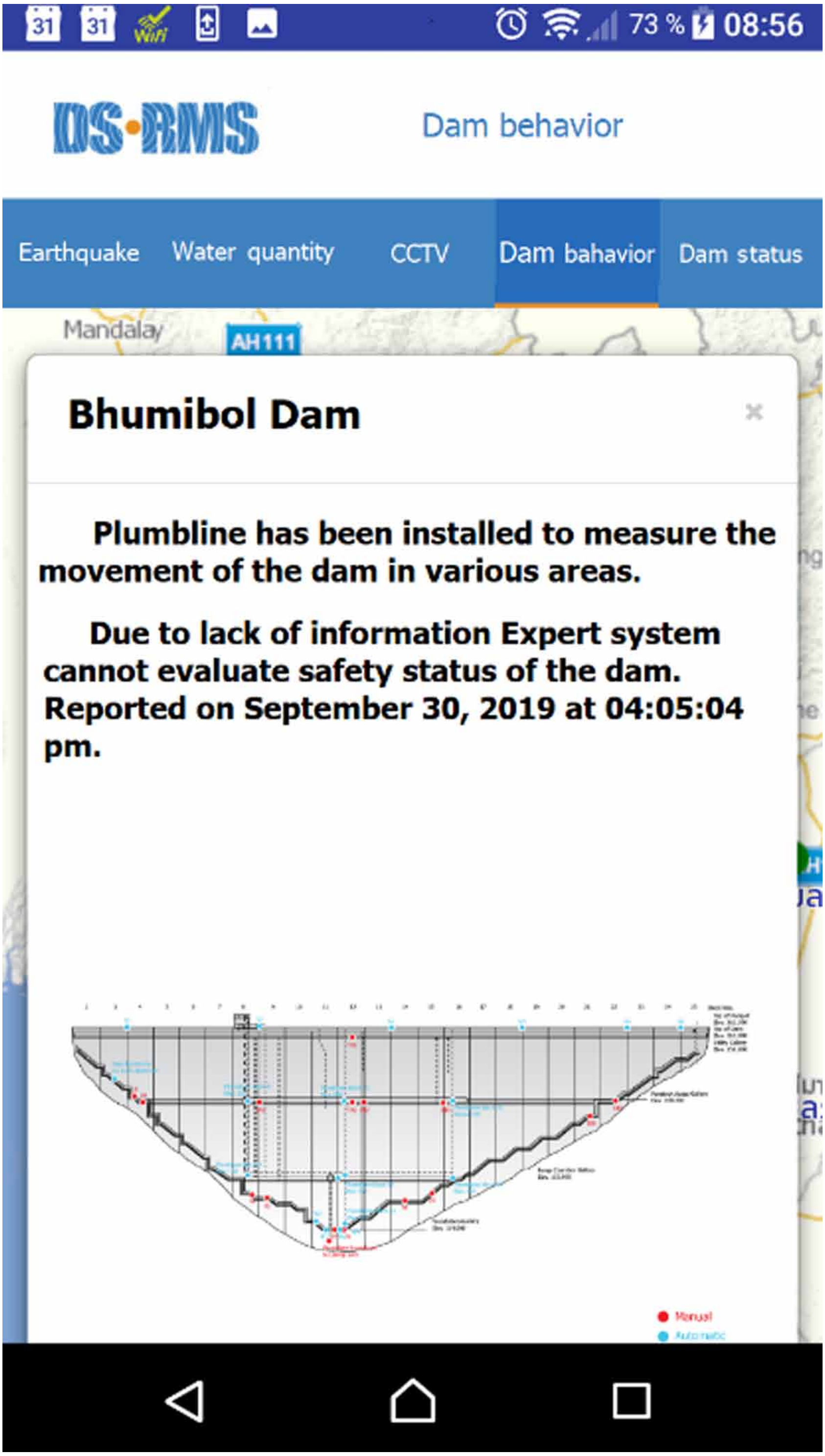


Figure 18c. Dam behavior with special dam instrument installations at the Bhumibol Dam and the Lamtakong Jolabha Vadhana pumped-storage hydropower plant

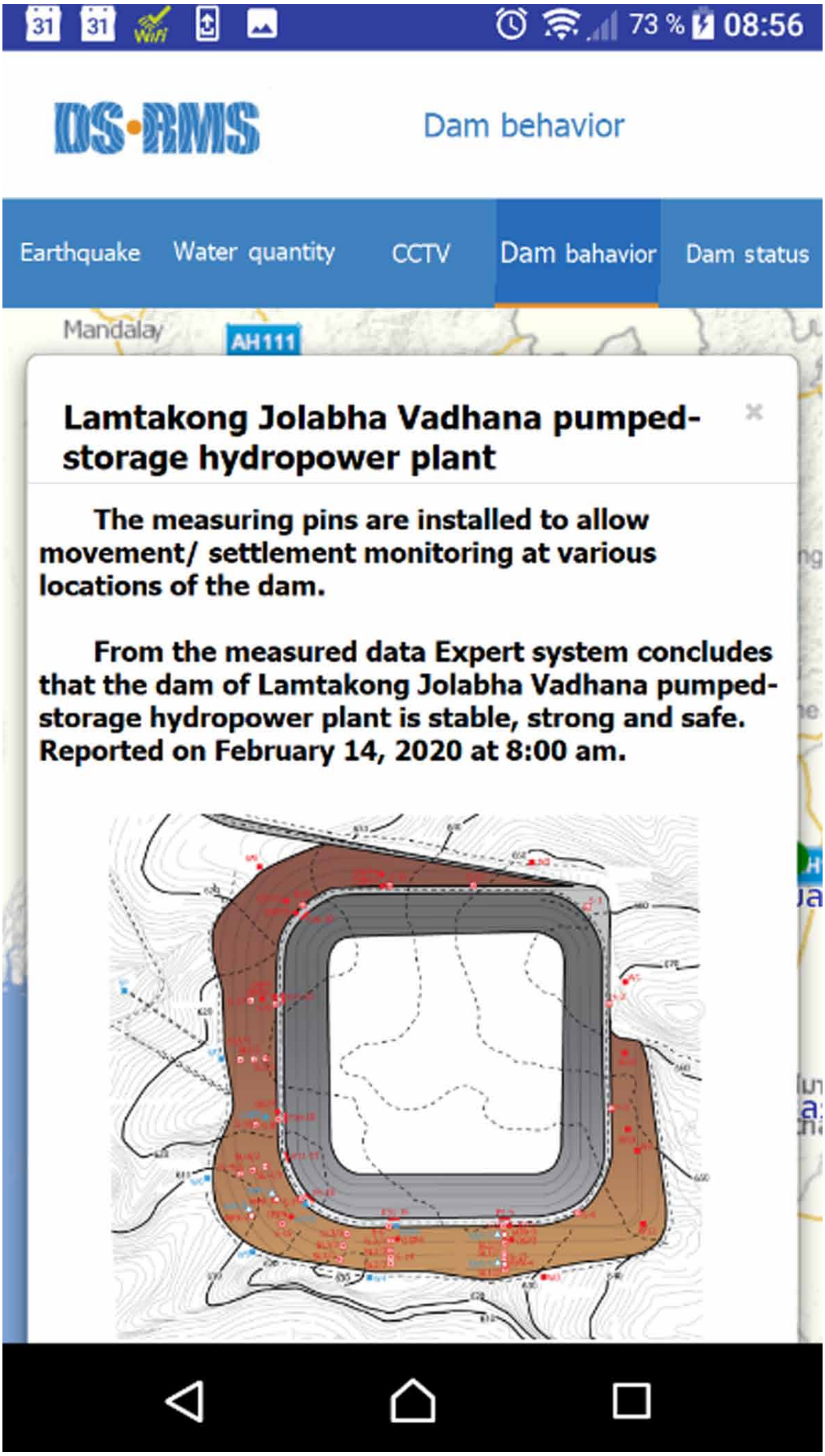


Figure 19 shows example of dam status at a single pumped-storage hydropower plant.

CONCLUSION

DS-RMS is specially designed to support three major dam types: concrete, embankment, and impervious-faced rockfill dams. The main objective is to automate the conventional acquisition of safety-related measurement data by hand, so that comprehensive information can be remotely obtained

Figure 19a. Examples of dam status with a "Recent dam behavior event" as in Figure 18 and notification that this dam is outside of earthquake hazard in the "Recent earthquake event"

Figure 19b. Examples of dam status with a "Recent dam behavior event" as in Figure 18 and notification that this dam is outside of earthquake hazard in the "Recent earthquake event"

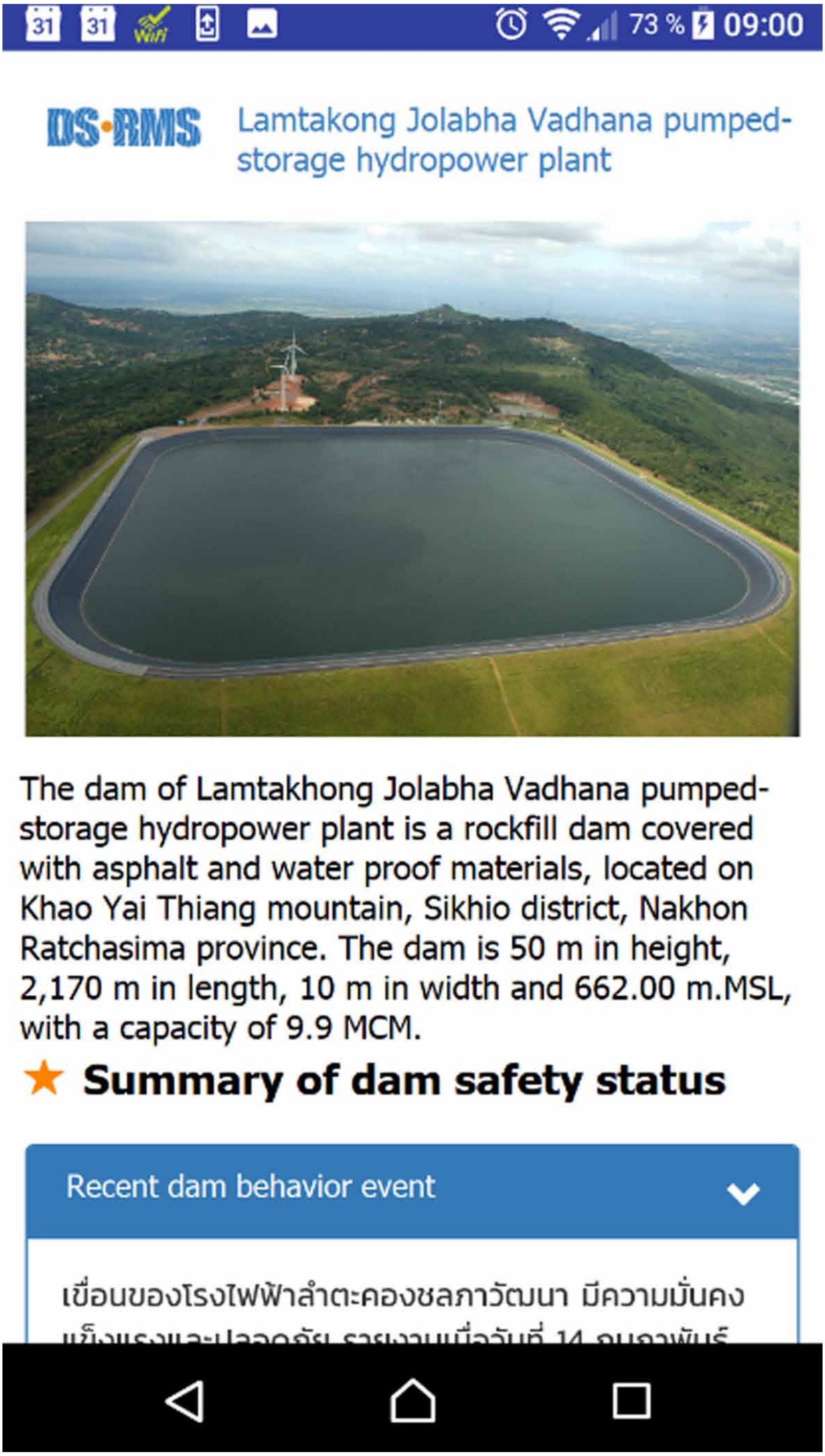


Figure 19c. Examples of dam status with a "Recent dam behavior event" as in Figure 18 and notification that this dam is outside of earthquake hazard in the "Recent earthquake event"

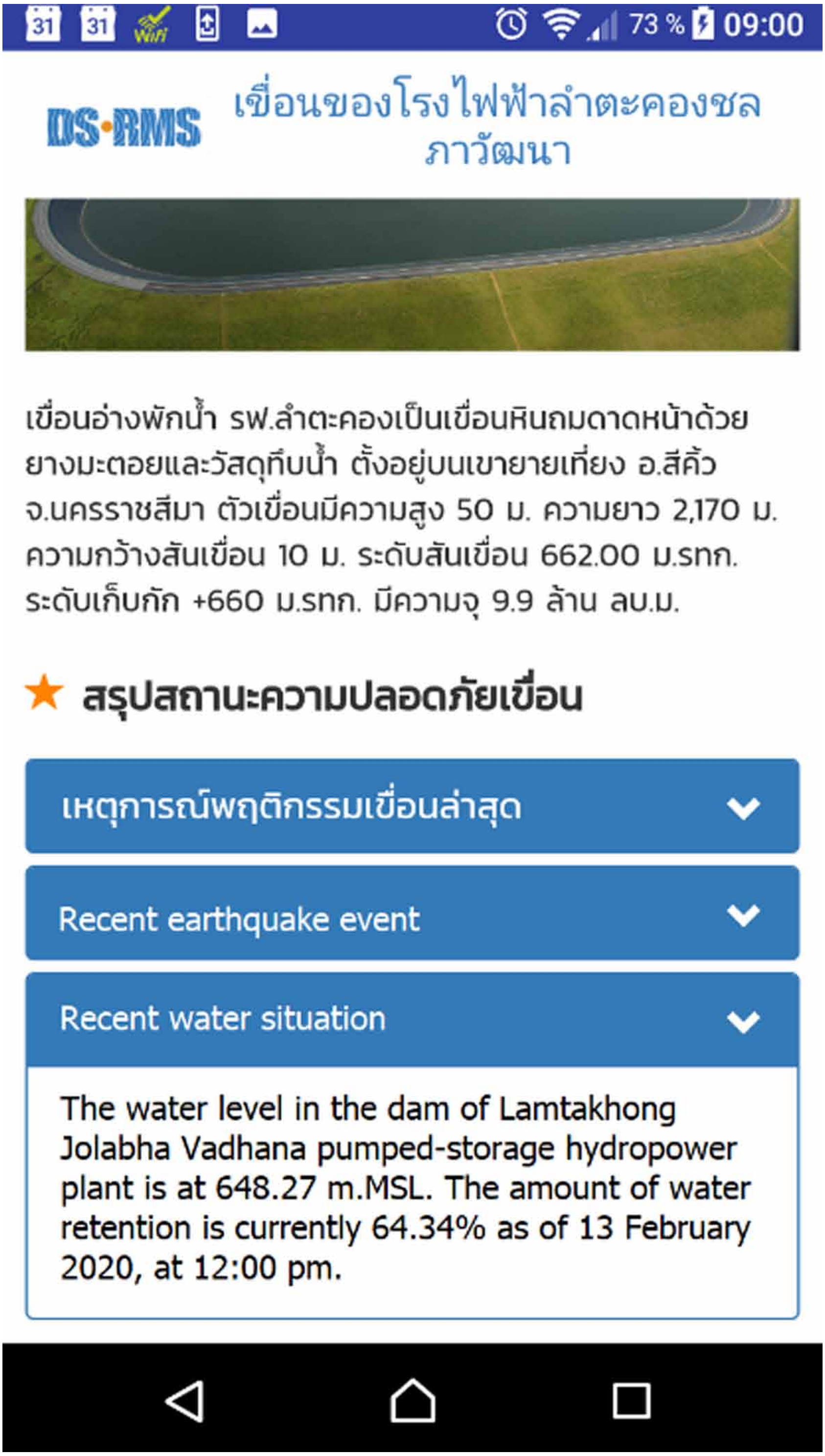


Figure 20. Group photo of EGAT's Dam Safety team during DS-RMS users training in Thailand Science Park Convention Center, NSTDA on 25th-29th April 2016 Source: Dowrueng et al., 2019

in real-time. To reach this goal, the fourteen dams located across Thailand are equipped with reliable RTUs, communication links, and local dam servers.

The safety criteria are established based on behaviors of the dam. Two examples are shown in this paper due to internal erosion and earthquake situation. These criteria will be used to detect abnormalities and to support EGAT staff in the field carrying out visual inspections. On the one hand, limitations are observed in the initial phase of development, in which the safety criteria can only identify internal erosion initiated by concentrated leak and backward erosion. On the other hand, statistical methods are applied to determine the expected range that indicate the usual behavior of the dams, so that the abnormal behavior needs to be confirmed by visual inspection. However, this method can also separate fluctuations in historical data caused by other factors.

SCADA high functions as advanced information software are developed to include dam behavior visualization, earthquake monitoring, flood routing simulation and a safety evaluation and warning system. The Dam Safety Mobile Application reassures EGAT and the public nearby, especially downstream communities, that the safety of the dams is always thoroughly analyzed and monitored.

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ENDNOTES

1 Jeon et al. (2009) alludes icold for definition of a large dam as a dam with a height of 15 m or more from the foundation. Alternatively, dams with a height between 5 and 15 m and a reservoir volume of more than 3 million cubic meters are also classified as large dams. Tungpimolrut (2015) numbers off other 21 large dams operated by royal irrigation department and a total of 422 dams and reservoirs in the Kingdom of Thailand.

2 Supakchukul et al. (2019) describes technical details of evaluation process and discuss thoroughly the example in Figure 6.

3 Nuntawattanasirichai et al. (2019) elaborates this another complex part of ds-rms. only one examples is introduced here in Figure 10.

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