https://doi.org/10.20965/jdr.2021.p0607

Survey Report:

Development of Dam Safety Remote Monitoring and Evaluation System

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[Received November 24, 2020; accepted February 2, 2021]

More than 4,000 dams are constructed in Thailand for several purposes, including water supply, flood control, irrigation, and hydropower generation. Among these dams, 14 large dams are operated by the Electricity Generating Authority of Thailand (EGAT). As a dam operator, EGAT is committed to ensuring dam safety by regularly conducting dam inspections and maintenance. This paper presents the development and practical applications of the Dam Safety Remote Monitoring System (DS-RMS). The objective of DS-RMS is to enhance the EGAT's implementation of its dam safety program in terms of dam monitoring by instrumentation to satisfy international recommendations. DS-RMS consists of five subsystems: Dam Behavior, Reservoir Operation, Earthquake Monitoring, Expert System and Public Communication. DS-RMS has been deployed at 14 large EGAT-operated dams across the country since 2016. Results show that the novel features of DS-RMS enable faster and more reliable dam safety monitoring and evaluation processes.

Keywords: remote terminal unit, dam safety evaluation, reservoir operation, expert systems

1. Introduction

Dams are used to manage surface water for irrigation, flood prevention, agriculture, and power generation. More than 4,000 dams are constructed in Thailand, each of which is small, medium, or large in size. The primary owners of these dams are the Royal Irrigation Department, the Department of Water Resources, the Electricity Generating Authority of Thailand (EGAT), the Department of Alternatives Energy Development and Efficiency, and local administrative organizations. A large dam is defined in [1] by International Commission on Large Dams (ICOLD) to be a dam with a height of 15 m or greater from its lowest foundation to its crest, or a dam of height between 5 and 15 m impounding more than 3 million m^3. EGAT currently operates 14 large and important dams located across the country, as illustrated in **Fig. 1**. The dams can be categorized into three major types: 2 concrete dams (circled in grey), 10 embankment dams (circled in brown), and 2 impervious faced rockfill dams (circled in blue).

Fig. 1. Fourteen large dams operated by EGAT.

In 1978, Ubolratana dam was severely affected by a monsoon, which caused significant inflow into its reservoir. As depicted in **Fig. 2**, the crest of the dam was almost overtopped, thereby increasing dam instability. After that incident, EGAT established the Civil Maintenance Division to seriously implement a dam safety program. Furthermore, personnel were appointed at each dam to perform stringent dam inspection and maintenance procedures.

2. Dam Safety Monitoring and Management

To ensure dam safety, a dam's structure should be regularly inspected and maintained throughout its lifetime.

Fig. 2. Ubolratana dam incident in 1978.

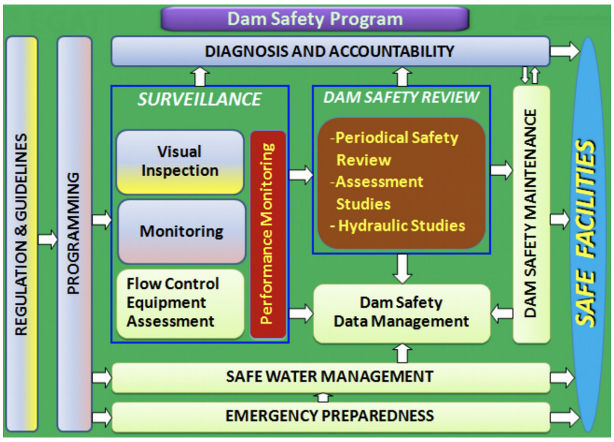

Fig. 3. ICOLD dam safety program.

Most countries have effective regulatory frameworks at the national level, focusing on comprehensive details of dam safety management activities [2]. ICOLD is a non-governmental international organization that provides a forum for the exchange of knowledge and experience in dam engineering [3]. ICOLD also leads the profession in setting standards and guidelines to ensure that dams are built and operated safely. One such standard is the dam safety program, as shown in **Fig. 3**. The program includes routine surveillance (visual inspection, dam behavior monitoring, and flow control equipment assessment), periodic dam safety review, dam safety data management, safe water management, emergency preparedness, and dam safety maintenance. Dam monitoring by instrumentation is crucial for evaluating dam behavior and conditions. Appropriate data obtained from the instruments will result in high-quality interpretations. The data should be communicated to the interpreter as soon as possible to prevent undesired outcomes.

The management of large dams requires complex computing and the involvement of multidisciplinary teams with specialized knowledge. This knowledge is accumulated through learning to understand structural responses that may change occasionally [4]. Previous studies have considered the development of analytical approaches and engineering software related to dam safety, with sub-

Fig. 4. Manual measurements and recording: ground water level (left); pressure gauge (right).

jects including geotechnical engineering, dam design and simulation, and automated dam monitoring [5–10]. The SUT-DAM introduced in [11] is an integrated software environment for the multidisciplinary computational modeling of structural and geotechnical problems such as the large deformation dynamic analysis of saturated and unsaturated soils, as well as the simulation of failure mechanisms along the failure surfaces. As discussed in [4], a knowledge-based dam safety management system supports engineers in performing dam safety assessment, enabling them to make adequate and timely decisions. Two multivariate dam safety monitoring models based on environmental effect extraction were proposed and analyzed in [12]. The first model achieves dam state monitoring using data collected from all instruments, with low computation time and low false alarm rates. It is suitable for a steady dam response with no significant time-varying trends. The second model predicts the future dam state by simulating the relationship between environmental variables and the dam response using least-squares support vector machine models. The results of displacement monitoring of a dam following an earthquake using data from a synthetic aperture radar satellite were reported in [13]. Satellite data collected before and after the Kumamoto earthquake at a rockfill dam located approximately 20 km from the epicenter were analyzed, and dam displacements were estimated. The Kwater Dam Safety Management System (KDSMS) was developed by the Korea Water Resource Corporation for consistent and efficient dam safety management [14]. KDSMS consists of dam and reservoir data, a hydrological information system, a field inspection and data management system, an instrumentation and monitoring system (including earthquake monitoring), a field investigation and safety evaluation system, and a collective information system. Using KDSMS, quick and systematic decisions and safety evaluations can be realized.

EGAT has monitored dam behavior as part of its dam safety activities since 1982 and has improved its processes according to the ICOLD dam safety program mentioned previously. Conventional dam monitoring and data acquisition were carried out periodically. The data were recorded by local operators, as shown in **Fig. 4**, and remotely acquired from automatic instruments. The data were manually screened and checked for validity, correctness and time synchronization. They were then input into stand-alone commercial software that can plot graphs of instrument data and contains statistical modeling func-

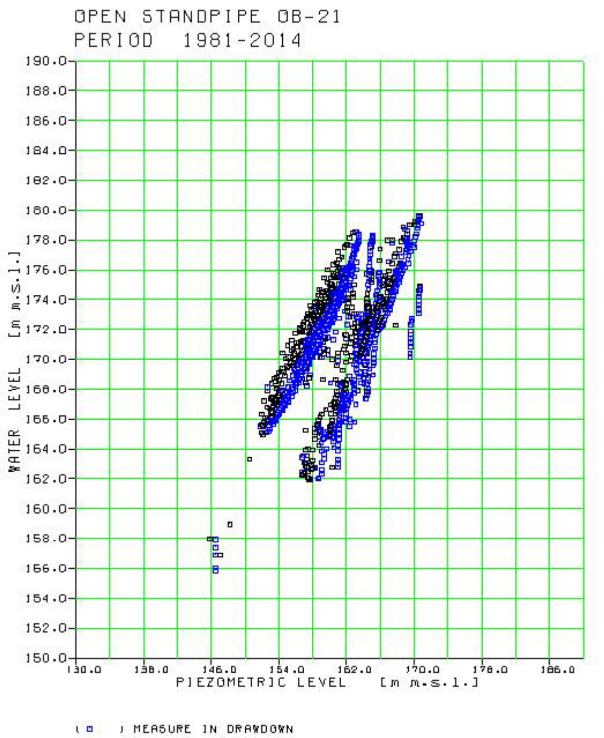

Fig. 5. Correlation between water level and piezometric level plotted by using commercial software.

Table 1. Summary of required time for each process of conventional dam behavior monitoring per dam.

Process	Time (days)
Instrument reading, data verification and formatting	3
Enter the verified and formatted data into the software	0.5
Time history display with additional parameters	0.5
Section View/Profile View/Plan View Display	0.5
Report generation	1

tions. An example of the correlation plot between water level and piezometric level is shown in **Fig. 5**. Subsequently, dam safety was evaluated by experienced officers and reported to local and executive officers. This is a time-consuming and error-prone process, particularly when dealing with a large number and variety of dam data and timestamps. **Table 1** summarizes the time required to complete each process of conventional dam behavior monitoring per dam.

3. EGAT Dam Safety Remote Monitoring System

In 2013, EGAT initiated the Dam Safety Remote Monitoring System (DS-RMS), a collaborative project involving EGAT, the National Electronics and Computer Technology Center (NECTEC), and the Geotechnical Engineering Research and Development Center – Kasetsart University (GERD-KU) as a consultant. The main objective is to enhance the dam monitoring system to reassure the downstream public that the dam conditions are thoroughly monitored. Its major improvement over the conventional system is the automatic acquisition of safety-related measurements such that comprehensive information is remotely obtained in real-time, and dam safety conditions can be evaluated by an expert system in minutes.

3.1. System Requirements and Description

DS-RMS software is used to manage the information necessary for the safety monitoring and evaluation process of the three different dam types mentioned above. The software currently supports the monitoring of 14 dams, although it is designed to allow for more dams to be added to the system if required. The main features of the software are summarized as follows:

- Web application operating on EGAT intranet to allow all authorized staff to easily access from anywhere.
- Instant dam behavior displays in different graph views: Time History, Cause and Effect, Plan View, Section View, and Profile View.
- Earthquake incident report: magnitude, location, acceleration at the dam body.
- Reservoir operation: reservoir water level (RWL), rule curves, inflow, rainfall, flood routing simulation.
- Dam safety evaluation in static, earthquake and flood conditions.
- Real-time closed-circuit television (CCTV).
- Executive summary.
- Document and report management.

3.2. Design and Development

At each dam, various types of dam behavior, seismic, and hydrometeorological sensors are installed around the reservoir, at the dam body, and at the foundation. The measured data from the sensors are collected by remote terminal units (RTUs) and then transmitted to the dam server using MODBUS TCP/IP via wired or wireless networks [15, 16]. Since the sensors and related cables at the dam body are sensitive to electromagnetic interference, the sensors and the inputs of the RTUs are equipped with high-performance surge protection devices to minimize possible damages. In addition, the RTUs are installed as close to groups of sensors as possible to minimize signal loss and interference.

Three communication configurations between RTUs and the dam server are used, based on distance and geographical obstacles: i) fiber optics, ii) fiber optics and wireless, and iii) fiber optics and mobile data transmission. Although the fiber optics are costly, they are used because of their insusceptibility to the environment and surges. **Fig. 6** illustrates examples of the configurations in detail. The top figure shows the configuration at Srinagarind Dam, where only fiber-optic links (red lines) are

Fig. 6. Examples of RTU and dam server connections.

Fig. 7. DS-RMS on EGAT communication network.

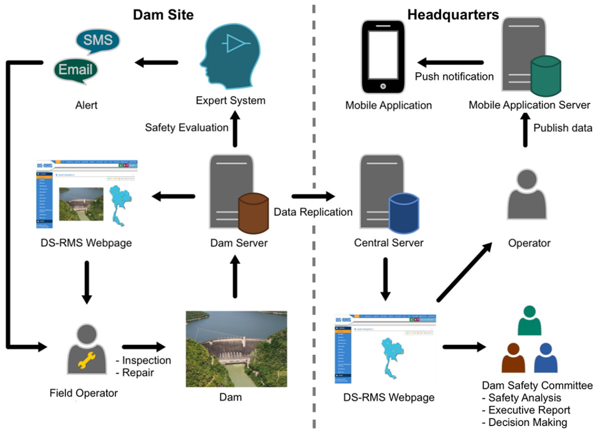

Fig. 8. DS-RMS system diagram.

used (since the RTUs are located around the dam crest and not distant from the server). The middle and bottom figures show the configurations at Mae Chang and Sirikit dams respectively, where wireless and mobile data transmissions are used. In these cases, the measurement points are spread out and distant from the servers; therefore, it is not economical to install fiber-optic cables. All dam servers are connected to the headquarters by the existing EGAT nationwide network for data back-up and replication, as shown in **Fig. 7**.

Figure 8 shows the DS-RMS system diagram, illustrating how the collected raw data is stored in a dam-site database. The engineering data can be selected and graphically displayed to analyze the dam behavior. Additionally, the engineering data is the input of an expert system in the safety evaluation and warning processes. Responsible staff are promptly informed of the updated instrument status and dam safety conditions via short message service (SMS) and email so that they can take appropriate actions rapidly. All configurations, corrections, data analysis, and updates are conducted at the local servers and then replicated and sent to the central server at the EGAT headquarters for monitoring purposes. To ensure system connectivity, the resumable replication service of the database system is used, and the connection is regularly checked by the administrator. This means that the local or field operators and dam safety experts can obtain synchronized data. The executives and civil maintenance staff at the headquarters can view the overall safety status of all dams. The safety status of each dam is summarized on the headquarters' DS-RMS homepage and can be clearly viewed in different colors on the country map, as illustrated in **Fig. 9**. Furthermore, some information is made available to the public via mobile applications. This information includes dam safety status, RWL, earthquake magnitude and location, real-time CCTV, and announcements. Details regarding the evaluation method of the status will be discussed in the next section.

The data flow is illustrated in **Fig. 10**. The raw data collected from various sensors and manually recorded by local staff is automatically screened and converted to engineering data by the software before being stored in a database. The vital data for safety evaluation comprises dam behavior data, reservoir operation data, and earthquake data.

The detection of significant indicators of structural behavior poses a constant challenge for engineers involved in large dam safety control [17]. Large dams interact significantly with environmental, hydraulic, and geomechanical factors such as air and water temperature, water level, pore pressure and uplift, and rock deformability. Dam behavior data in DS-RMS includes, for instance, seepage

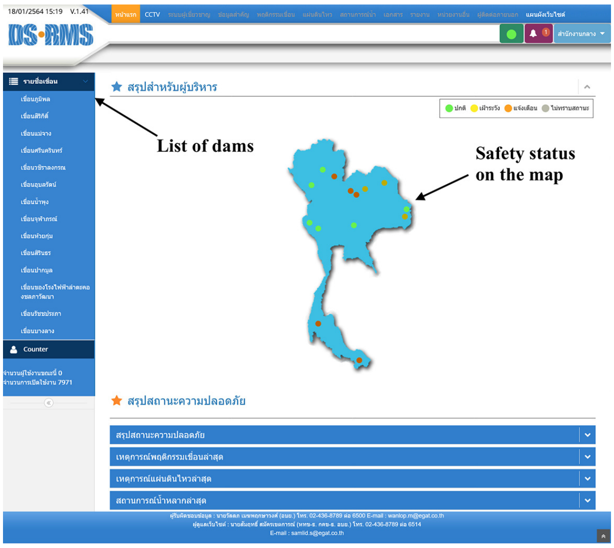

Fig. 9. Headquarters' homepage.

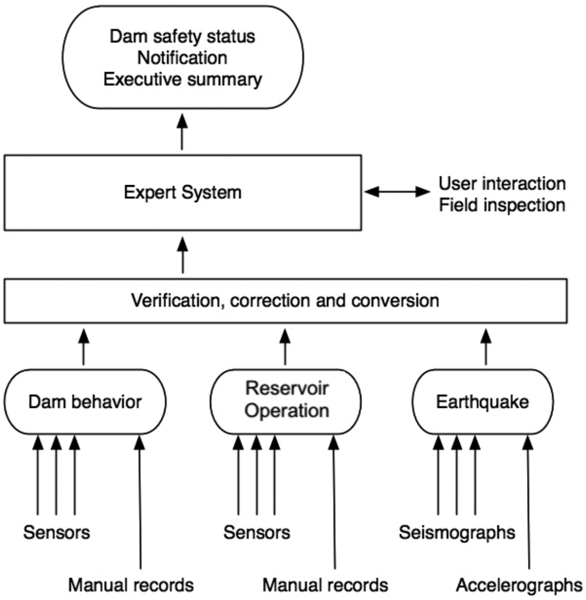

Fig. 10. DS-RMS data flow.

in weirs, tilt angles and joint movements, settlement and displacement, and piezometric pressure.

The major causes of dam failures are crest overtopping during extreme flooding and internal erosion. It was estimated that overtopping constituted more than 40% of dam failures worldwide, and observed that the time for creating and widening a breach varied with the dam's material [18–20]. The reservoir operation data includes RWL, rainfall, ambient temperature and humidity, wind speed, atmospheric pressure, and calculated inflow. This enables engineers to maintain dam safety during floods and to manage the amount of water in the reservoir to comply with the rule curves for various uses and interests.

Earthquake data is obtained from a network of seismographs installed around reservoirs. Instant and historic magnitudes and locations are reported in DS-RMS. Additionally, accelerations at the dam body, a key safety indicator, are also measured. If the detected magnitude, location and accelerations exceed the criteria, then the safety evaluation process begins, and warning messages are sent to the relevant staff to perform further inspections of the dam.

Subsequently, the engineering data is then used by the expert system in the safety evaluation and warning processes. This is carried out using evaluation flows developed in this project, based on knowledge obtained from dam safety experts, academics and experienced staff. Different dam types have different evaluation flows and, in some situations, the expert system requires more field data to proceed with the safety analysis. In this case, the user is prompted to provide explicit answers to questions in order to facilitate an accurate analysis.

3.3. Key Subsystems

3.3.1. Dam Behavior

Dam behavior instruments are connected to the RTUs, which then transmit data to the dam server. The data is processed by the dam behavior monitoring software and displayed in various views and axis combinations, such as Plan View, Section View, Time History, and Cause and Effect. For easy interpretation and analysis, an as-built dam drawing is imported into the system and rescaled to be used as a background. Plot areas are created and placed on the background by referencing coordinates with the measurement positions. A display example, "Radial Displacement on Dam Profile" is shown in **Fig. 11**, where dam behavior is observed through a plot of displacements inside the concrete blocks on a graphical dam profile. The lines show the dam movements over time with reference to gravity. An illustration of the behavior of an impervious faced rockfill dam is given in **Fig. 12**. Displacements of the dam body are represented as vectors such that engineers can observe both magnitudes and directions of the displacements on an actual graphical plan view. Using the dam behavior subsystem, the time required to complete each process is significantly reduced, as summarized in **Table 2**. The conventional instrument reading time may take one or two days for each dam. The reading time begins when the operator leaves the office to measure the first sensor and stops when all data of the dam are recorded. In DS-RMS, the instrument reading time requires less than 5 minutes on average. The measuring time starts counting when the RTUs begin reading data and stops counting when all data are stored in the database of each dam. Dam operators process the manual reading by collecting data from the instruments, filtering out the unacceptable data, formatting the data into correct forms, and manually picking up or aggregating some data such as rainfall with the nearest timestamp to plot several instruments into the same chart. Some charts are plotted as overlays on drawing pictures. These procedures are time-consuming but can be completed rapidly by DS-RMS.

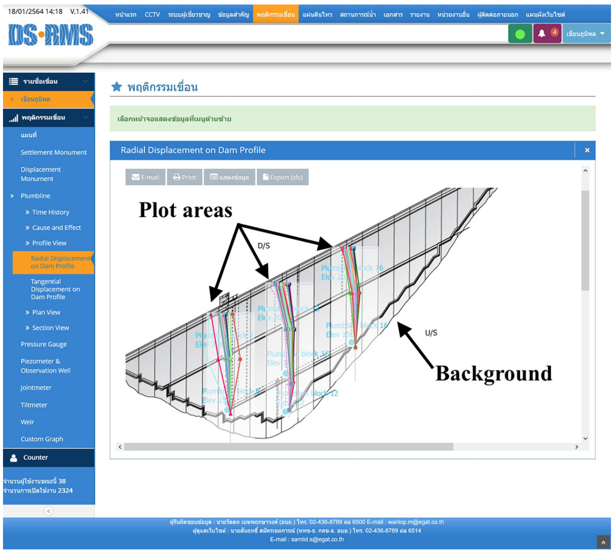

Fig. 11. Movement behavior of a concrete dam.

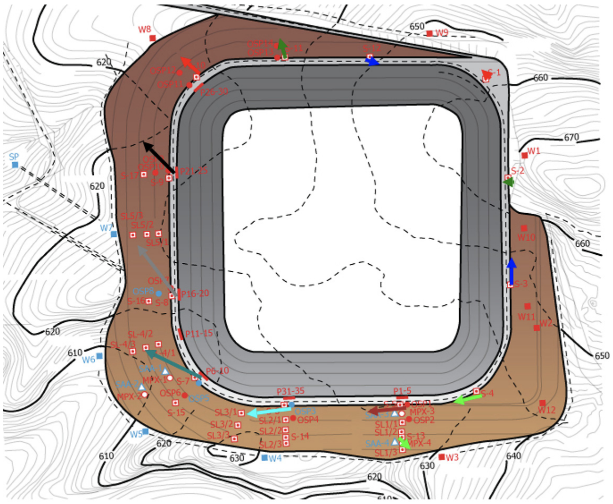

Fig. 12. Displacement vectors of an impervious faced rock-fill dam.

3.3.2. Reservoir Operation

Hydrometeorology data play an extremely important role in safety evaluation during floods. As mentioned previously, the relevant data are collected from instruments installed at the dam crest and around the reservoir. The user interface displays historical and current RWL values along with the dam cross-section, thereby enabling engineers to evaluate the possibility of an overtopping failure. The subsystem can predict flood frequency by comparing the current inflow with an inflow at any selected return period using a flood frequency hydrograph. To calculate the current inflow (hourly or daily), the outflow, RWL, and evaporation rate of the reservoir are used for each period of the calculation. **Fig. 13** shows a graphical plot that can predict the possibility of flooding, where the blue solid line is the inflow of Bhumibol Dam in 2011 (when the great flood occurred in Thailand), and the movable red dotted line is the inflow of the 20-year return period inflow. By comparing these two datasets, it was obvious that the inflow in early October was higher than that in the 20-year flood return period, indicating a high possibility of flooding and that preventative steps and preparation for potential disaster were necessary.

Table 2. Comparison of average time required for each process of conventional dam behavior monitoring per one dam and DS-RMS.

Process	Conventional	DS-RMS
Instrument reading, data verification and formatting	3 days	5 mins
Enter the verified and formatted data into the software	0.5 days	5 mins
Time history display with additional parameters	0.5 days	Instant
Section View/Profile View/Plan View Display	0.5 days	Instant
Report generation	1 day	Instant

In addition, an advanced feature of this subsystem is the newly developed flood routing simulation that can provide the local staff with reservoir operation guidance. Flood routing is a mathematical procedure that predicts the changing magnitude, speed, and shape of a flood wave at one or more points in a stream channel. One type of flood routing that we focus on is reservoir flood routing, based on the assumption of a slow-rising flood wave, where acceleration terms of the flood are relatively low. This type of flood routing requires the following information:

- Elevation-storage relation: the relation between RWL and storage volume.
- Elevation-outflow relation: the relation between RWL and outflow rate.
- Inflow hydrograph to reservoirs.

A continuity equation, based on the conservation of mass, can then be used to predict the storage and outflow for each subsequent time step. One has

$$\frac{(I_t + I_{t+1})}{2} - \frac{(O_t + O_{t+1})}{2} = \frac{(S_{t+1} - S_t)}{\Delta t}, \quad . \quad . \quad (1)$$

where I_t and I_{t+1} are the inflows (in cubic meters per second, cms) for time t and $t+1$, respectively; O_t and O_{t+1} are the corresponding outflows (in cms); S_t and S_{t+1} are the corresponding storage volumes (in million cubic meters, MCM); and Δt is the difference between $t+1$ and t, which was 1 hour in this study.

For the simulation, RWL for the next hour is calculated based on the information of the current hour. One can rearrange Eq. (1) and obtain

$$\frac{(S_{t+1} - S_t)}{\Delta t} + \frac{O_{t+1}}{2} = \frac{(I_t + I_{t+1})}{2} - \frac{O_t}{2}. \quad . \quad . \quad . \quad (2)$$

Therefore, the terms on the left contain all of the information regarding the next hour, i.e., S_{t+1} and O_{t+1}. It is noteworthy that I_{t+1} is already known in the current hour

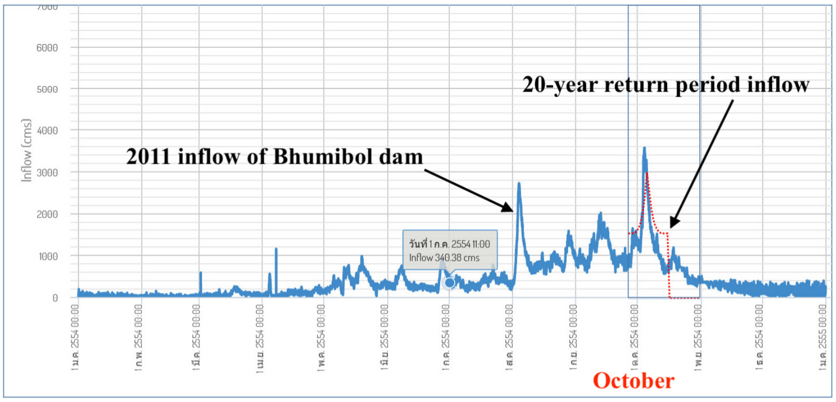

Fig. 13. Flood prediction.

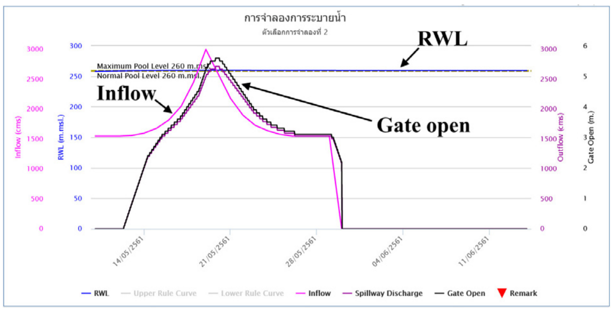

Fig. 14. Reservoir flood routing simulation.

because every time step of the inflow is known in advance as the input of the simulation.

Reservoir flood routing simulation allows dam staff to simulate situations with different scenarios of inflow hydrographs and an initial RWL. Consequently, the outflow hydrograph and RWL can be observed as a function of time. Moreover, the spillway gates in the simulation can be controlled based on the operation manual. The manual describes how high the gates should be opened depending on the situation (as described based on data including current RWL and inflow). Therefore, reservoir flood routing simulation in DS-RMS can be used to assess various situations by using several inflow hydrographs and spillway gate open rules as the inputs. One example of the simulation result is shown in **Fig. 14**, where one can observe that the inflow is increased and decreased according to 20-year return period inflow data. Then, the spillway gates are gradually opened to a maximum height of 5.5 m before closing down, and RWL is controlled around the maximum pool level (dashed line). The simulation is conducted weekly especially during monsoon. The result can be used to consider whether normal operation rules are sufficient to maintain the situation under control or whether flood control operation is required.

3.3.3. Earthquake Monitoring

Currently, earthquake data are obtained from 21 seismic stations installed around the reservoirs of dams located in seismic areas. Users can view the dam locations (black circle icons) and instant and historic earthquake magnitudes (circles in different colors), as shown in **Fig. 15**. The circles vary in size and color, which indicate different magnitudes and times. In addition, accelerations at the dam body are monitored as an important factor in safety evaluation. Equipment status and locations, as well as acceleration waveforms, can be observed from the subsystem, as depicted in **Fig. 16**.

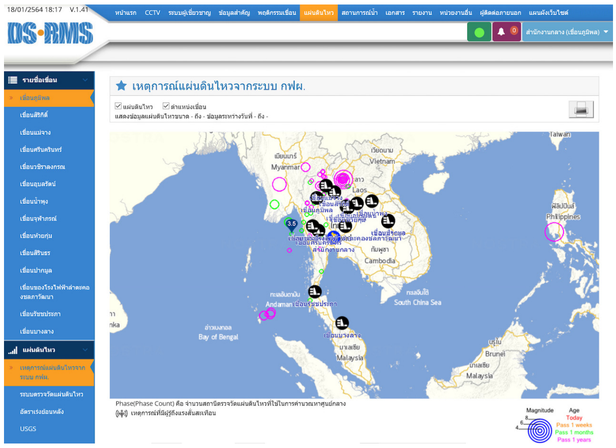

Fig. 15. Earthquake monitoring system.

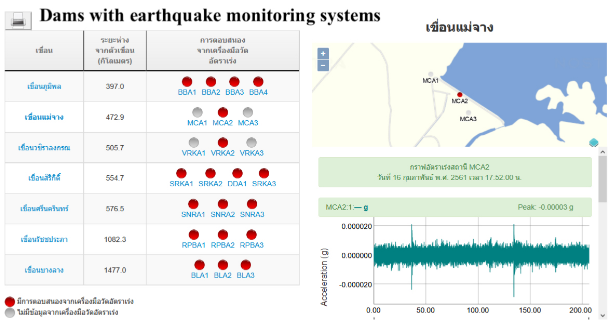

Fig. 16. Acceleration monitoring.

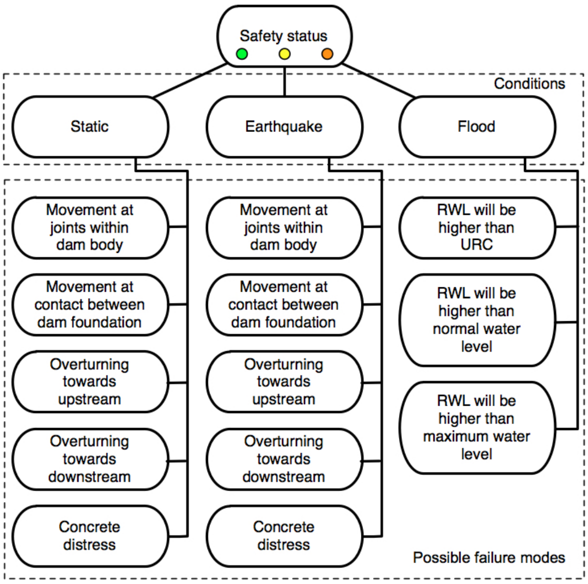

Fig. 17. Expert system for evaluating concrete dam safety status.

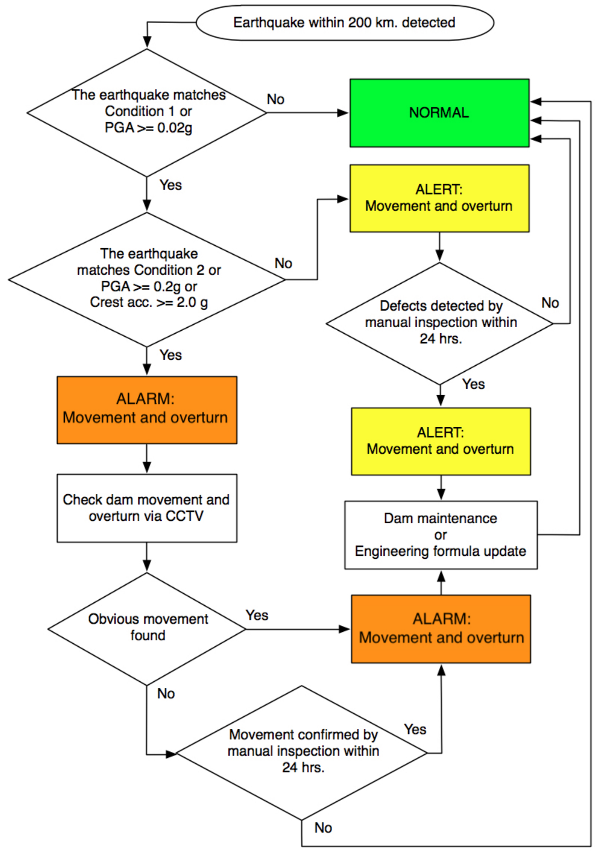

Fig. 18. Rules the earthquake condition of a concrete dam.

3.3.4. Expert System

Dam safety evaluation at EGAT has primarily relied on the expertise of dam engineers and academic specialists. The acquired dam data are analyzed together with additional manual inspections. However, experts are limited in number and not always available when incidents occur. Furthermore, it is an important challenge to accurately maintain the accumulated expertise and knowledge of experts after they retire or are rotated.

In DS-RMS, a rule-based expert system was developed to enhance the conventional dam safety evaluation procedures. This is a unique characteristic when compared with KDSMS which only provides dam experts with the data library to evaluate dam safety at a later time. Knowledge bases are built by acquiring knowledge from experienced engineers and experts. Data of a given case are entered into the working memory. The inference engine repeatedly applies the rules to the memory and queries the user for further information, such as manually inspected data, until a goal state is confirmed where safety status is represented in colors: NORMAL (green), ALERT (yellow), and ALARM (orange).

An example of an expert system for a concrete dam is shown in **Fig. 17**, where 13 possible failure modes in static, earthquake, and flood conditions were defined. The inference rules for the earthquake conditions are shown in **Fig. 18** and **Tables 3** and **4**. Earthquake parameters such as magnitude, distance from the epicenter, peak ground acceleration (PGA), and acceleration at the dam crest were obtained from the earthquake monitoring system. If more information is required, the system will provide the user with specific directions to perform actions and questions to answer. For example, if an earthquake with a PGA greater than 0.2 g is detected, the safety status ALARM will be displayed, and an SMS and email will be sent to relevant staff. The staff will manually inspect the dam movements using a CCTV and on-site surveys, and then report the evidence they obtain to the system. If movements are discovered, then dam maintenance must be performed and the result is reported to the system so that the safety status will be changed to NORMAL. The status will remain unchanged until appropriate actions are taken and reported.

Figure 19 shows an image example of the expert system web page at the headquarters. The page summarizes the dam safety status of each dam in three failure condi-

Table 3. Condition 1 of safety evaluation in earthquake condition.

Magnitude	Distance to dam (km)
≥ 4.0	≤ 25
≥ 5.0	≤ 50
≥ 6.0	≤ 80
≥ 7.0	≤ 125
≥ 8.0	≤ 200

Table 4. Condition 2 of safety evaluation in earthquake condition.

Magnitude	Distance to dam (km)
≥ 6.0	≤ 12
≥ 6.5	≤ 18
≥ 7.0	≤ 24

Fig. 19. Safety status summary on expert system page.

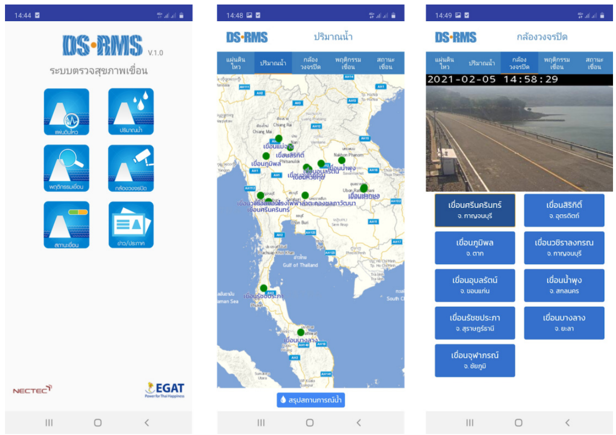

Fig. 20. DS-RMS mobile application – from left to right: Homepage, Dam Status, CCTV.

tions, represented by the graphics of the dam and different colors. Details of each failure mode can be observed by clicking on a failure mode icon.

The current limitation of this automatic evaluation system is that some tasks that require manually collected data, such as settlements and displacements, may not be completely processed because the data is not entered by local staff into the database sufficiently and quickly. A mobile application is being developed to allow staff to input field data into the database as soon as manual data collection is completed.

3.3.5. Public Communication

Public safety is of utmost importance and is the main objective of the EGAT dam safety program. The downstream community should be aware of the correct and updated information of the dam they live nearby. Currently, DS-RMS can only be accessed by authorized staff; however, some information has been selected to be made available to the public via mobile applications. This publicly available data includes dam safety status, RWL, reservoir volume, earthquake magnitude and location, CCTV, and general announcements. The application interfaces are illustrated in **Fig. 20**, from which public users can view dam status, real-time CCTV, and reservoir volume information.

4. Conclusions

In this paper, we described the development of a remote dam safety monitoring and evaluation system, DS-RMS, which has been deployed at the EGAT's fourteen large dams across Thailand. The system was designed to enhance the way EGAT carries out its dam safety program, to better meet international standards. This is achieved through the effective use of instrumentation-based dam monitoring. DS-RMS consists of five key subsystems: Dam Behavior, Reservoir Operation, Earthquake Monitoring, Expert System, and Public Communication. DS-RMS provides staff with a web-based portal such that they can conveniently input manually collected data, and acquire data from automatic instruments via RTUs. The collected data can be visualized rapidly in various graphical illustrations. DS-RMS supports the prediction of flood return period and reservoir management. The newly developed expert system automatically and promptly evaluates dam safety conditions, and sends messages to relevant staff to perform the appropriate actions for further damage prevention. Finally, the system communicates the safety condition to the downstream communities to ensure that the dam conditions are thoroughly monitored.

Acknowledgements

The authors would like to thank the Electricity Generating Authority of Thailand (EGAT) for funding this project.

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