DAM SAFETY RISK ASSESSMENT FOR KIU KHO MA AND KIU LOM DAMS

Sahaphol TIMPONG
Dam Engineer, ASDECON Corporation Co., Ltd., THAILAND

Sompop SUCHARIT
Director of Dam Safety Division, Royal Irrigation Department, THAILAND

Aphichat SRAMOON
Senior Dam Engineer, Geotechnical & Foundation Engineering Co., Ltd., THAILAND

Amnarj YANUVIRIYAKUL
Geotechnical Engineer, Geotechnical & Foundation Engineering Co., Ltd., THAILAND

1. INTRODUCTION

Dams are usually categorized as high-hazard, low risk structures. That is, even though, the probability of dam failure is extremely low, but dam failure can cause catastrophic consequences downstream, including loss of life and property damage, economic loss as well as social and environmental impacts. Dam failure can be caused by overtopping a dam due to insufficient spillway capacity, internal erosion or piping through the embankment dam, instability of slope embankment, earthquake, equipment malfunction, foundation and abutment failure, landslide or by sabotage.

The International Commission on Large Dams (ICOLD) estimated that by the end of the last century there were over 45,000 large dams, and another 1,600 large dams are under construction worldwide. Thus, the subjects of dam safety and risk assessment become an important basis for emergency action planning to minimize potential loss of life and property damage in areas that could be flooded as a result of dam failure or operation.

In Thailand, almost 5000 dams have been constructed by several government agencies, mostly for irrigation and hydropower generation. Royal Irrigation Department (RID) who responsible for more than 4,000 dams in Thailand realized the important of dam safety and established the dam safety division in 1992 for dam inspection and evaluation [1]. The study of dam break analysis for setting up the Emergency Preparedness Plan (EPP) has been carried out since 2000 for many large dam projects such as Klong Tha Dan dam and Kwainoi dam. As a part of the recent study of dam break analysis for Kiu Kho Ma and Kiu Lom dams, this paper presents the application of Failure Modes, Effects and Criticality Analysis (FMECA) approach and the use of LCI diagrams for dam safety risk assessment. This consists of identifying the most likely modes of failure for the dams, foundation, abutments, and appurtenant structures, with consideration of the consequences of failure, so that appropriate preventive or remedial actions can be developed.

2. KIU KHO MA AND KIU LOM DAMS

Kiu Kho Ma dam is located in Pong-Don Sub-district about 13 km northeast of Jae Hom District, Lampang Province. It consists of a main dam, an embankamnt zoned type dam with 43.5 m height, 500 m crest length and a saddle dam, homogenous earthfill dam with 15.5 m height and 300 m long. The construction was started in 2005 and completed in 2009. The dam create a reservoir of about 209 million cubic meter retention capacity for multipurpose such as irrigation water supply for cultivated areas, raw water supply for the water works of Lampang Province as well as flood alleviation in the provincial areas.

Kiu Lom Dam is located downstream along the Wang River approximately 38 km from Kiu Kho Ma dam at Ban Laeng Sub-district, Mueng Lampang District, Lampang Province. The dam is a gravity concrete dam with 26.5 m height and 135 crest length. After completion of its distribution system in 1981, the dam has yielded benefits in many aspects including irrigation for agriculture, flood control, fisheries and tourist spot for Lampang Province. Both of the dams are under the administration of the Royal Irrigation Department. Table 1 shows the information of Kiu Kho Ma and Kiu Lom dams, the location map are shown in Fig. 1.

Table 1
Geometrical characteristics of Kiu Kho Ma and Kiu Lom dams

Description	Kiu Kho Ma Dam		Kiu Lom Dam
	Main Dam	Saddle Dam	Main Dam
Dam type	Zoned type	Homogenous	Concrete gravity
Crest level (m asl)	+355.50	+355.50	+277.40
Crest width (m)	8.00	6.00	5.35
Length (m)	500.00	300.00	135.00
Maximum height (m)	43.50	15.50	
Maximum width at base	275.00	102.00	
Height from dam foundation (m)			42.00

Height from river bed (m)			26.50
Upstream slope	1:2.5 / 1:3.0	1:3.0	
Downstream slope	1:2.0 / 1:2.5	1:2.5	
Maximum level (m asl)	+352.90		+285.00
Normal storage level (m asl)	+350.60	+350.60	
Minimum storage level (m asl)	+325.00		+270.00
Maximum storage volume (x10^6 m^3)	208.60		112
Normal storage volume (x10^6 m^3)	170		
Spillway	Radial gate 12.50 m x 7.00 m (3 gates)		Radial gate 13.00 m x 8.00 m (5 gates)
Maximum drainage capacity (m^3/s)	1,209		3,000

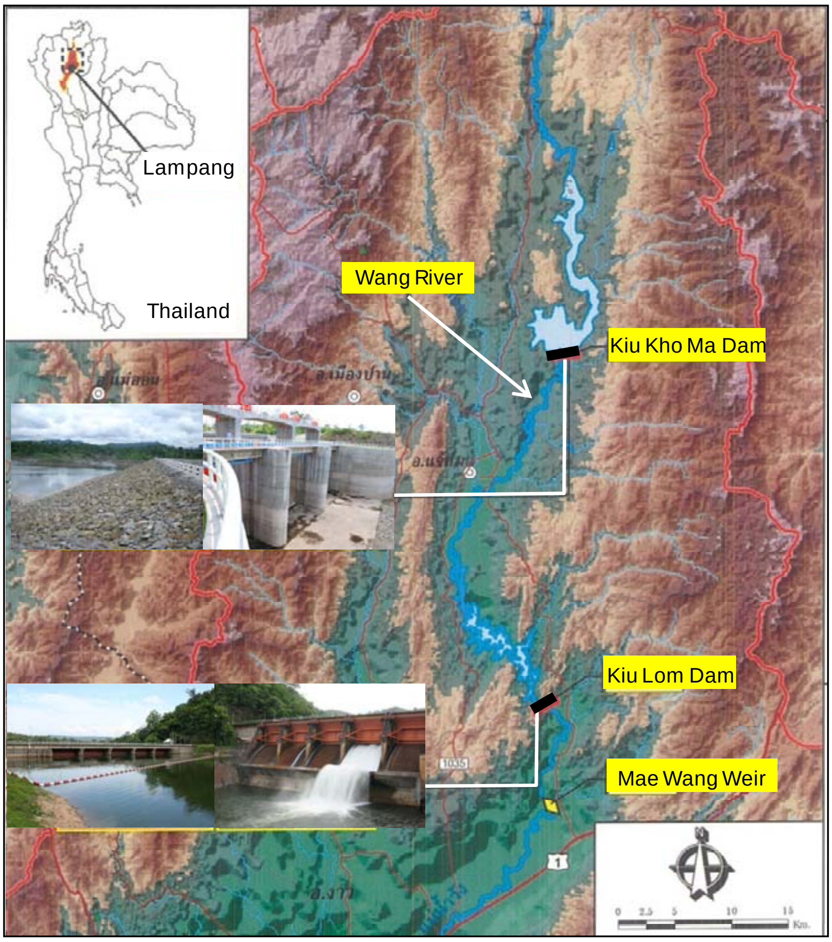

Fig. 1
Location map of Kiu Kho Ma and Kiu Lom dams

3. DAM SAFETY RISK ASSESSMENT

Failure Modes, Effects and Criticality Analysis (FMECA) is a systematic approach to analyzing how parts of a considered system might fail. It provides a structured framework for considering risk of the system, while avoiding the pitfalls of undertaking excessive probabilistic analysis. It uses a common calculation system for all elements, which allows the risks from all elements to be compared directly against each other and hence prioritized. It combines qualitative and quantitative approaches in a way that utilizes the strengths of both approaches.

The application of FMECA approach has been used as a risk assessment tool in dam industry [2]. The approach involves development and analysis of an LCI diagram (Location, Cause, Indicator) for each dam component such as dam body, spillway, foundation and abutment. Failure through a range of possible causes (overtopping, piping, instability) and with different indicators (blocked drains, seepage, cracking) is considered by means of indicator-cause pathways.

3.1 DEVELOPMENT OF LCI DIAGRAM

The steps in developing an LCI diagram are as follows:

1) All available information for Kiu Kho Ma and Kiu Lom dams including geotechnical investigation and design reports, design and as-built drawings, photographs, repair and maintenance records, instrumentation data and other relevant data were collected and analyzed. Historic causes of dam failures and their respective probabilities for the dams similar to Kiu Kho Ma and Kiu Lom dams were also reviewed.

2) Identify situations or initial events that can cause dam failures such as static condition, flood condition, earthquake condition and cascade failure due to the upstream dam failure, and develop a draft of the LCI diagram based on the analyzed data.

3) Site visit and inspection were carried out by experienced dam and geotechnical engineers and geologist to examine the existing condition of the dams and their appurtenant structures. Any significant indicators of an unsafe condition such as cracking, water seepage through dam body or abutment and erosion damage should be indentified and evaluated.

4) Coordination meetings with all relevant parties were held for review and comment on the draft LCI diagram, make any revisions, and finalize the LCI diagram. Fig. 2 and Fig. 3 show some parts of the LCI diagrams of Kiu Kho Ma and Kiu Lom dam, respectively.

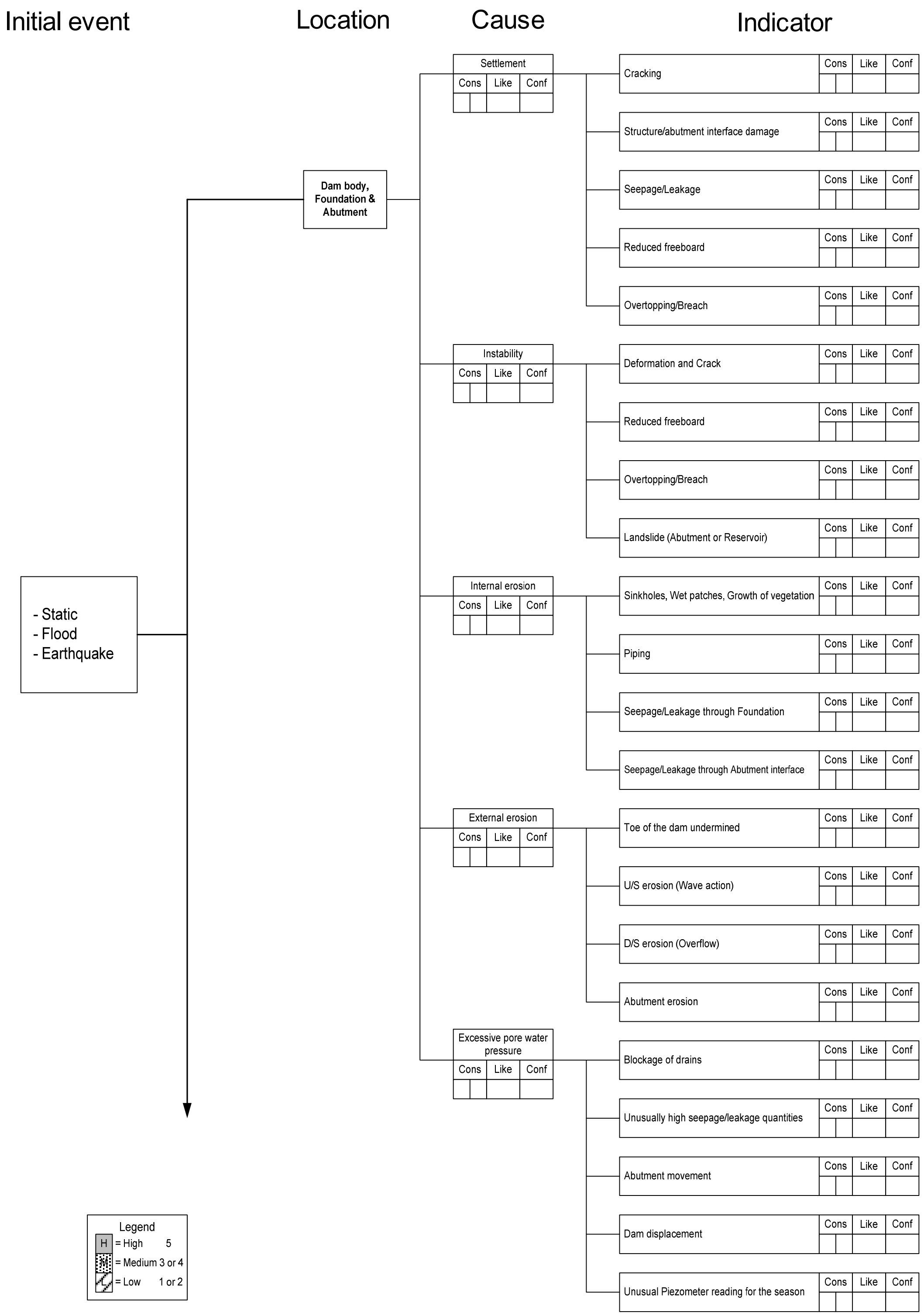

Fig. 2
Part of an LCI diagrams for Kiu Kho Ma dam (main dam)

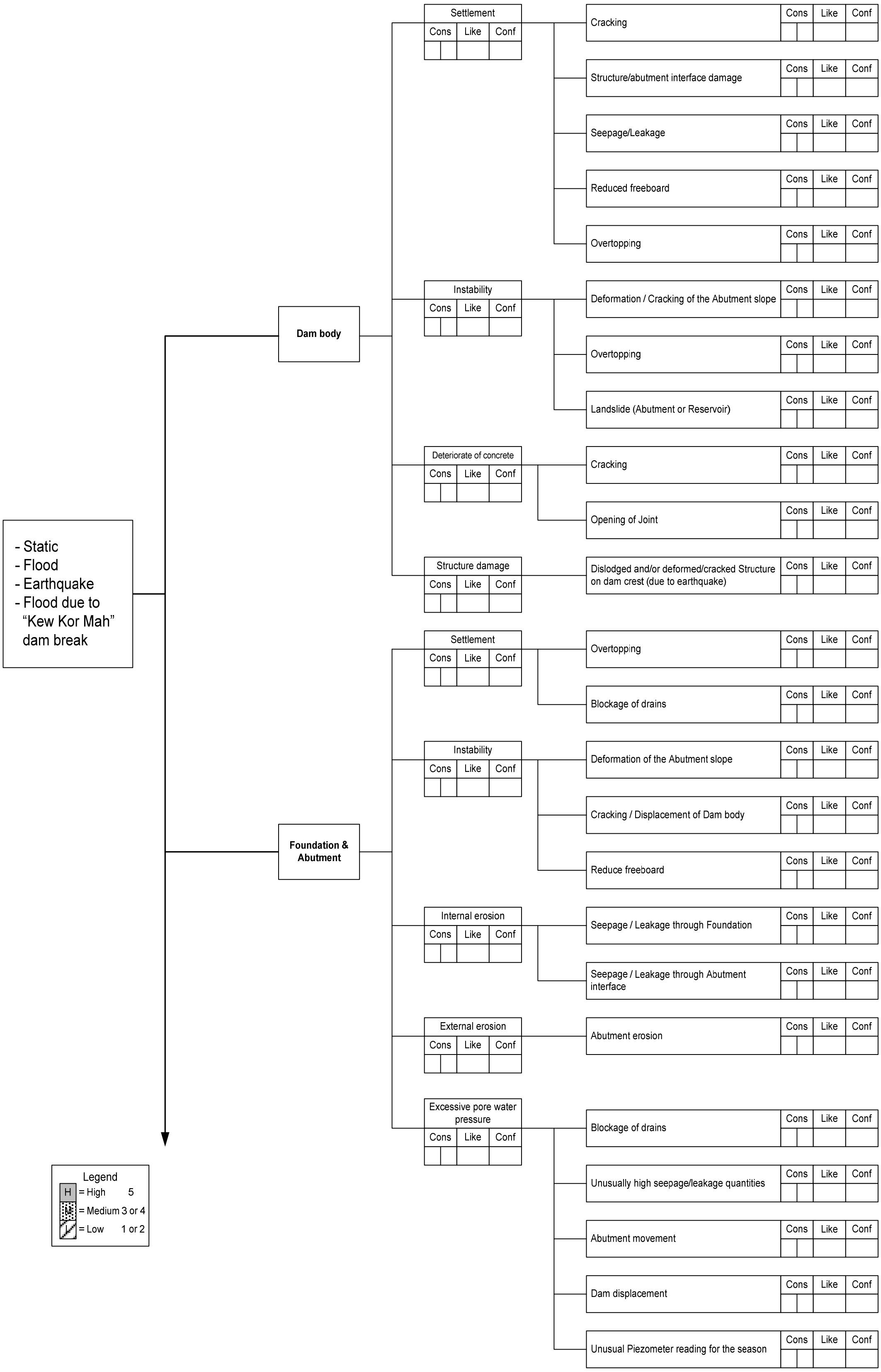

Fig. 3
Part of an LCI diagrams for Kiu Lom dam

3.2 RISK ASSESSMENT PROCEDURE

The risk assessment procedure using the LCI diagrams involves scoring three key factors on a range of 1 to 5, for each indicator-cause pathway. The LCI diagram score categories may be defined as [3]:

Consequence: The consequence expressed in terms of how directly is failure of this element related to complete failure of the dam (1 low, 5 high).

Likelihood: The likelihood of failure of this element (1 low, 5 high).

Confidence: The assessor's confidence in their predictions of the consequence and likelihood factors (5 no or little confidence, 1 very confidence). This score allows a measure of uncertainty to be included within the assessment.

Based on desk study, literature review and dam inspection, each box in the LCI diagrams was carefully scored according to various initial events (static condition, flood condition, earthquake condition and cascade failure condition). Explanation of the assessor's assumption and judgement was also recorded in the LCI score justification table. This provides a record of the LCI scores and identifying possible failure modes requiring detailed investigation and analysis.

All of the elements are then prioritized by ranking their Criticality score (Consequence x Likelihood x Confidence) and CL score (Consequence x Likelihood). The next stage is to prioritize these elements by selecting the elements with the Criticality score > 12 and the CL score ≥ 16. For the element, which has a low Confidence score of 4 or 5, it can reflect uncertainty in the Consequence and Likelihood scores, highlighting the need for detailed investigation and analysis. Remedial measured may be needed to reduce the risk for the element with a high CL score. Table 2 presents a prioritized list of failure mechanism that pose the highest risk to Kiu Kho Ma and Kiu Lom dams. These failure mechanisms will be investigated in detail in the following sections.

Table 2
A prioritized list of failure mechanism for Kiu Kho Ma and Kiu Lom dams

Dam	Initial event	Cause to failure
Kiu Kho Ma	Static	Piping/Seepage
	Flood	Overtopping, Piping/Seepage
	Earthquake	Instability, Piping/Seepage
Kiu Lom	Static	Instability
	Flood	Overtopping, Instability
	Earthquake	Instability
	Kiu Kho Ma dam failure	Overtopping, Instability

4. RELATIVE LIKELIHOOD OF KIU KHO MA DAM FAILURE BY PIPING

Internal erosion and piping are a significant cause of failure of embankment dams. According to historical frequency of piping failure, about 42% of failures occur on first filling, and 66% on first filling and within the first 5 years of operation. Relative likelihood of failure of Kiu Kho Ma dam due to piping was estimated using the University of New South Wales (UNSW) method [4]. The method is based on an analysis of historic failures in embankment dams. [5]

The historic frequencies of failure by the three modes of piping, namely piping through embankment, piping through foundation, and piping from the embankment into the foundation are adjusted by weighting factors to take account of the dam characteristics, such as dam zoning, filters, core properties, compaction, foundation geology, surveillance and monitoring. The values for each weighting factor were evaluated from existing information obtained from the desk study and the dam inspection. The overall annual likelihood of failure by piping would be obtained by summing the weighted likelihood of each piping failure modes as follows;

$$P = w_E P_e + w_F P_f + w_{EF} P_{ef}$$

where

P = Annual likelihood of failure by piping

P_e = Annual frequencies for piping through embankment

P_f = Annual frequencies for piping through foundation

P_{ef} = Annual frequencies for piping from the embankment into the foundation

w_E = Weighting factors for piping through embankment

w_F = Weighting factors for piping through foundation

w_{EF} = Weighting factors for piping from embankment into the foundation

Table 3 summarized the annual likelihood of failure by piping for the main dam and the saddle dam.

Table 3
The annual likelihood of failure by piping for Kiu Kho Ma dam

Kiu Kho Ma dam	Annual likelihood of failure by piping	
	First 5 years of operation	After 5 years
Main dam	1.03×10^{-4}	1.01×10^{-5}
Saddle dam	5.30×10^{-4}	4.98×10^{-5}

5. STABILITY ANALYSIS OF KIU KHO MA DAM

The slope stability of the main dam and the saddle dam was evaluated using the computer program SLIDE [5] to perform two dimensional limit equilibrium analysis using Simplified Bishop method.

5.1 ANALYSIS CONDITIONS

Dam's zoning configuration and geometry at the representative deepest section of the main dam and the saddle dam are shown in Fig. 4. The following analysis conditions were analyzed:

Normal operation condition: The water remains at normal storage level so that the dams become fully saturated and a condition of steady seepage occurs.

Rapid drawdown condition: The reservoir water level in reservoir decreased rapidly due to piping or spillway damage. This causes the development of excess pore pressure that may result in instability of the upstream slope.

Earthquake condition: The dam is subjected to earthquake motion. Peak ground acceleration (PGA) was obtained from previous seismic study carried out in this area. It is considered that the Operation Basis Earthquake (OBE) with a return period of 500 years is sufficient for the analysis. The PGA (horizontal component) of 0.1g was used for the slope stability analysis of Kiu Kho Ma dam.

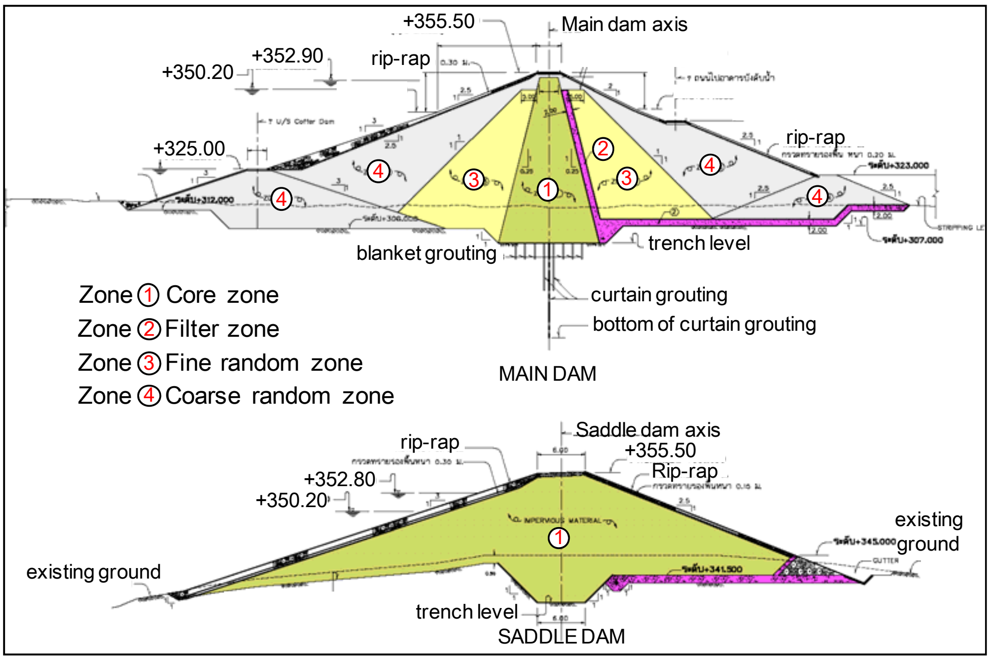

Fig. 4
Representative deepest sections for stability analysis of Kiu Kho Ma dam

Table 4 shows loading conditions for the slope stability analysis, water level in the reservoir and the required minimum factor of safety for upstream and downstream slopes purposed by U.S. Army Corps of Engineers [6] are shown in Table 4.

Table 4
Loading conditions and required minimum factor of safety

Loading conditions	Water level (m asl)		Required Minimum F.S.
	Main dam	Saddle dam	
Usual			
Case 1 Normal operation	+350.60	+350.60	1.50
Unusual			
Case 2 Rapid drawdown	+352.90 to +325.00	+352.90 to +340.00	1.20
Case 3 Normal operation with earthquake	+350.60	+350.60	1.10
Extreme			
Case 4 Rapid drawdown with earthquake	+352.90 to +325.00	+352.90 to +340.00	1.00

5.2 PARAMETER FOR THE ANALYSIS

Typical strength parameters for each zone of Kiu Kho Ma dam (core zone, filter zone, fine random zone and coarse random zone) used for the slope stability analysis were derived from geotechnical investigation and laboratory test, which are summarized in Table 5. It should be noted that the use of minimum factor of safety obtained from the deterministic slope stability analysis as a stability index of the slope does not imply probability of slope failure due to the uncertainty of input parameters used in the analysis, especially the shear strength parameters. This uncertainty can be accounted for by the use of probabilistic slope stability analysis.

Because it is difficult to precisely determine statistical information such as standard deviations (SD) for the shear strength parameters due to the limited data available, the standard deviations of the input parameters that involved uncertainty were estimated from typical value of coefficient of variation (COV) as purposed by many researchers [7] [8] [9] as shown in Table 5. The probability of slope failure was then evaluated by counting the number of analyses with factor of safety less than 1, and then taking this number as a percentage of the total number samples using Monte Carlo sampling method.

Table 5
Shear strength parameters used for slope stability analysis

Material	Mean value			COV (%)			SD*		
	γ (kN/m³)	c (kPa)	ϕ (°)	γ	c	ϕ	γ (kN/m³)	c (kPa)	ϕ (°)
Core zone	21	25	25	3%	40%	12%	0.63	10	3.0
Filter zone	20	0	35	3%	40%	12%	0.60	0	4.2
Fine random zone	21	5	35	3%	40%	12%	0.63	2	4.2
Coarse random zone	21.5	5	38	3%	40%	12%	0.65	2	4.6

*SD = COV x Mean value

5.3 ANALYSIS RESULTS

Fig. 5 and Fig. 6 show example of the typical slope stability results for main dam and saddle dam. The slope stability analysis results of upstream and downstream slopes of Kiu Kho Ma dam are summarized in Table 6 and Table 7. It was found that in most case, the slope stability of main dam and saddle dam satisfy the minimum factor of safety requirements against sliding, except for the case of rapid drawdown with earthquake condition (Case 4).

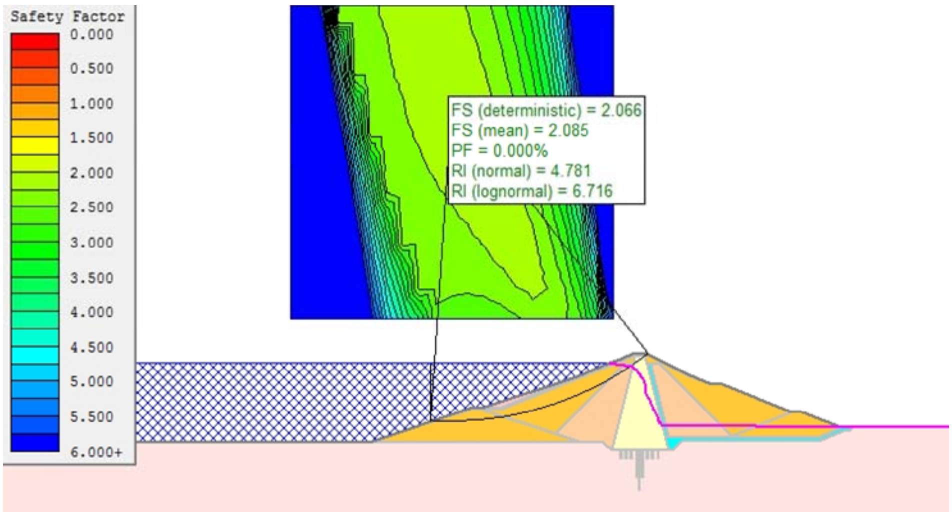

Fig. 5

Slope stability analysis result of the main dam (Case 1 Normal operation)

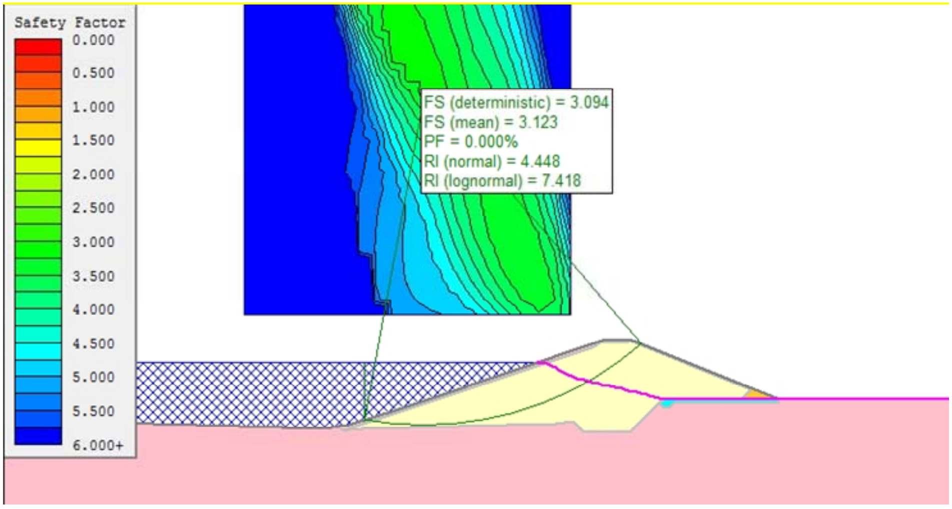

Fig. 6
Slope stability analysis result of the saddle dam (Case 1 Normal operation)

Table 6
Slope stability analysis results of Kiu Kho Ma dam (main dam)

Loading conditions	Location	F.S.	Probability of failure
Case 1 Normal operation	D/S slope U/S slope	1.88 2.07	2.91×10^{-7} 4.15×10^{-9}
Case 2 Rapid drawdown	D/S slope U/S slope	1.88 1.23	2.91×10^{-7} 5.57×10^{-2}
Case 3 Normal operation with earthquake	D/S slope U/S slope	1.44 1.30	5.06×10^{-6} 7.80×10^{-5}
Case 4 Rapid drawdown with earthquake	D/S slope U/S slope	1.44 0.89	5.06×10^{-6} 1.62×10^{-3}

Table 7
Slope stability analysis results of Kiu Kho Ma dam (saddle dam)

Loading conditions	Location	F.S.	Probability of failure
Case 1 Normal operation	D/S slope U/S slope	2.33 3.09	3.09×10^{-6} 2.01×10^{-6}
Case 2 Rapid drawdown	D/S slope U/S slope	2.33 2.04	3.09×10^{-6} 5.10×10^{-4}
Case 3 Normal operation with earthquake	D/S slope U/S slope	1.82 2.02	1.44×10^{-6} 1.03×10^{-6}
Case 4 Rapid drawdown with earthquake	D/S slope U/S slope	1.82 1.45	1.44×10^{-6} 3.41×10^{-5}

By considering the probabilistic slope stability analysis results, the probability of dam failure due to instability is generally low, except for Case 2 and Case 4. It should be noted that the probability of PGA = 0.1g occurrence ($2x10^{-3}$, 500 years return period) was included in the probability of failure for earthquake conditions (Case 3 and Case 4). Because the probability of occurrence for rapid drawdown with earthquake loading is extremely low, therefore, the existing dam geometries and material zoning configurations are acceptable for operation.

6. STABILITY ANALYSIS OF KIU LOM DAM

The stability against sliding and overturning, and stress analyses were conducted for Kiu Lom dam using a computer program CADAM developed by Ecole Polytechnique de Montreal, Canada [10]. CADAM is based on the gravity method (rigid body equilibrium and beam theory). Several modelling options have been included to allow users to explore the structural behaviour of dam (e.g. geometry, uplift pressures, drainage, crack initiation and propagation criteria).

6.1 ANALYSIS CONDITIONS

Because Kiu Lom dam is one of the oldest dams in service in Thailand (more than 40 years old), and the average life span of well designed and well built dams is generally considered to be about 50 to 60 years. In addition, no instrumentation like piezometer, inclinometer and extensometer are in place for monitoring the dam stability, for that reason, conservative assumptions and worse conditions were made for the stability analysis.

The drainage gallery was assumed to be inefficient and silt pressure was also considered in the analysis. The silt depth at the upstream face was estimated by Echo Sounder investigation. Cracking was considered for all loading conditions and was assumed to occur and propagate when the stipulated tensile strength was exceeded.

The water level at the upstream face was calculated according to the initial events (normal operation condition, flood condition and cascade failure due to Kiu Koh Ma dam failure) and operation of the spillway (all gates are closed / all gates are opened) as shown in Table 8. Fig. 7 and Fig. 8 show the critical cross sections of Kiu Lom used for the stability analysis.

Table 8
Loading conditions for the stability analysis

Loading conditions	Water level (m asl)	
	All gates closed	All gates opened
Usual		
Normal operation	+285.00	+277.40
Unusual		
100 year flood	+290.36	+281.52
1,000 year flood	+290.57	+282.59
10,000 year flood	+290.79	+283.59
Extreme		
PMF flood	+291.00	+284.85
Kiu Kho Ma failure	+291.14	+288.80

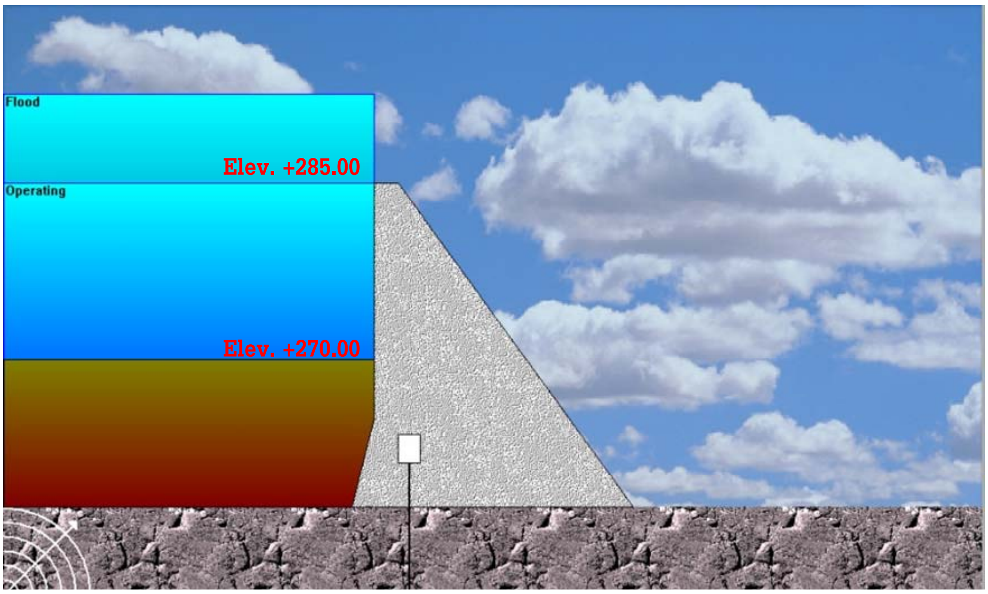

Fig. 7
Kiu Lom dam model in case of all spillway gates are closed

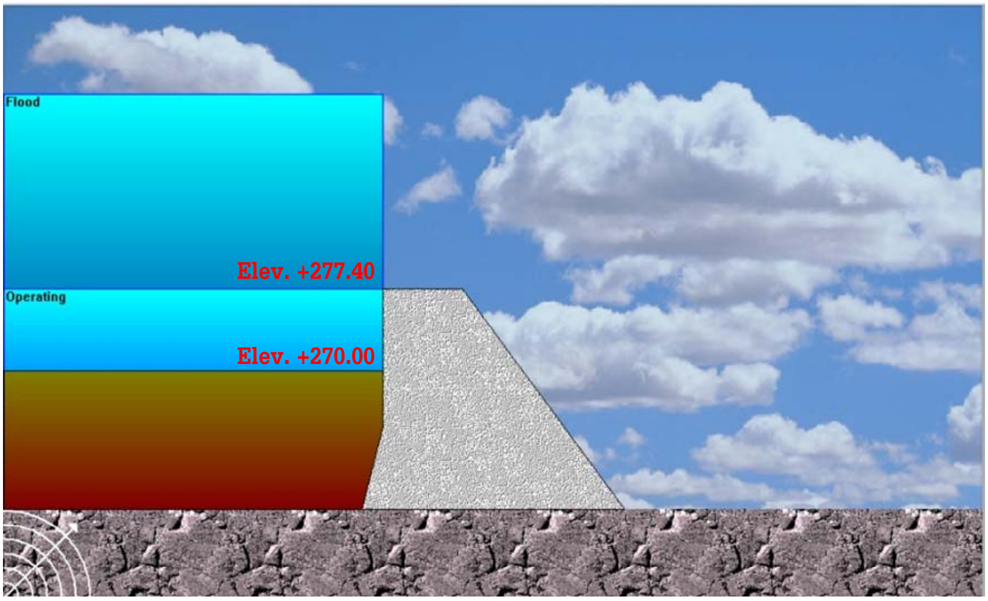

Fig. 8
Kiu Lom dam model in case of all spillway gates are opened

It is noted that before a gravity dam can overturn, other local failures would have to occur (e.g. crushing of the toe or foundation). Therefore, in order to provide adequate safety against overturning, the position of the resultant force must be maintained within the safe ranges, and the allowable stresses at the downstream face of the dam and in the foundation must not be exceeded. The minimum acceptable factors of safety and allowable stress for various loading conditions are adopted based on Federal Energy Regulatory Commission (FERC) [11].

6.2 PARAMETER FOR THE ANALYSIS

Because there is no data available for concrete properties of dam body and rock foundation strength, therefore, all input parameters for the stability and stress analyses were estimated from dam site inspection and geological survey report. According to the geological survey report, the rock formation at the dam site consists of sedimentary rock. It is composed predominantly of quartzite and shale, other inter layered rocks are sandstone.

Shear strength parameters (cohesion and friction angle) for the interface between rock foundation and concrete was estimated from the Unconfined Compressive Strength (UCS) of the rock as proposed in Hydropower Industry Standard of The People's Republic of China [12]. Table 9 shows the estimated material parameters for concrete and shear strength of the interface between rock foundation and concrete.

Table 9
Estimated strength parameters for stability analysis

Parameter	Value
Concrete (dam body)	
Compressive strength	15 Mpa
Unit weight	24 kN/m^3
Rock foundation	
Unconfined compressive strength	20 Mpa
Rock foundation/concrete interface	
Cohesion, C	0.4 Mpa
Friction angle, ϕ	30°

6.3 ANALYSIS RESULTS

Table 10 and Table 11 provide a summary of stability analysis results. In most case, the allowable unit stresses in concrete and foundation material are not exceeded. It is noted that in case of cracking between rock foundation and concrete was considered, the minimum acceptable factor of safety criteria for the unusual and extreme loading conditions has not been met. In contrast, in case of neglecting cracking, all minimum acceptable factors of safety are satisfied for all loading conditions.

From the results, it is clearly found that the operation of spillway gates play an important role to control the dam stability, especially in the case of unusual and extreme loading conditions. Therefore, the spillway gates and their control system should be periodically checked and replaced when needed to ensure that they are working properly for all loading conditions.

In addition, further detailed geotechnical investigation and stress analysis are needed, as well as instrumentation and monitoring program in order to clarify the rock foundation condition and dam stability.

Table 10
Stability analysis results (all spillway gates are closed)

Loading condition	Assumed cracking		Assumed no cracking	
	F.S. Sliding	F.S. Overturning	F.S. Sliding	F.S. Overturning
Usual	2.0*		2.0*	
Normal operation	2.62	1.40	2.62	1.40
Unusual	1.3*		1.3*	
100 year flood	0.72	1.03	1.88	1.17
1,000 year flood	0.65	1.01	1.85	1.16
10,000 year flood	0.57	1.00	1.83	1.15
Extreme	1.0*		1.0*	
PMF flood	0.50	1.00	1.80	1.14
Kiu Kho Ma dam failure	0.23	1.00	1.76	1.14

*Allowable factor of safety (Federal Energy Regulatory Commission, FERC)

Table 11
Stability analysis results (all spillway gates are opened)

Loading condition	Assumed cracking		Assumed no cracking	
	F.S. Sliding	F.S. Overturning	F.S. Sliding	F.S. Overturning
Usual	2.0*		2.0*	
Normal operation	3.92	1.71	3.92	1.71
Unusual	1.3*		1.3*	
100 year flood	3.36	1.52	3.37	1.55
1,000 year flood	3.15	1.47	3.23	1.51
10,000 year flood	2.95	1.43	3.09	1.47
Extreme	1.0*		1.0*	
PMF flood	2.70	1.37	2.92	1.42
Kiu Kho Ma dam failure	2.04	1.19	2.38	1.26

*Allowable factor of safety (Federal Energy Regulatory Commission, FERC)

7. CONCLUSION

Dam failure can cause loss of life, economic loss, environmental damage, disruption of lifeline facilities as well as social impacts. To ensure the dam safety and to reduce the downstream damages, risk assessment using Failure Modes, Effects and Criticality Analysis (FMECA) approach was conducted for Kiu Kor Ma dam (zoned type embankment dam with 43.5 m height and 500 crest length) and Kiu Lom dam (concrete gravity dam with 26.5 m height and 135 crest length) located downstream of Kiu Lom dam.

The approach involved the development and analysis of the LCI diagram (Location, Cause, Indicator) for the individual structure components of each dam under various initiating event such as normal operation, flood, earthquake and cascade failure due to Kiu Kor Ma dam failure.

Potential failures modes were indentified based on the historic dam failures records, desk study and site inspection of the dams and their appurtenant structures. Dam stability was evaluated for all possible loading conditions.

High priority failure modes and potential risk reduction measures were selected and presented for strengthening many aspects of a dam safety program such as dam monitoring and surveillance. Quantitative risk assessment using even tree methods and numerical simulation of dam break will be conducted to provide the information for emergency preparedness planning to minimize potential loss of life and property damage in areas that could be flooded as a result of dam failure or operation.

REFERENCES

[1] MAIRAING W. Dam safety evaluation by condition index system. *The 6th national convention on civil engineering*, 2000.

[2] HUGHES A. K., HEWLETT H.M., MORRIS M., SAYERS P., MOFFAT A.B., HARDING A., TEDD P. Risk management for UK reservoirs. *Report C542. CIRIA*, 2000.

[3] CIRIA. Risk management and UK reservoirs. *Construction Industry Research and Information Association (CIRIA) Report C542*, 2000.

[4] FOSTER M., FELL R., SPANNAGLE M. A method for assessing the relative likelihood of failure of embankment dams by piping. *Canadian geotechnical journal, No 37*, 2000.

[5] FOSTER M., FELL R., SPANNAGLE M. The statistics of embankment dam failures and accidents. *Canadian geotechnical journal, No 37*, 2000.

[6] ROCSCIENCE INC. SLIDE user manual.

[7] US ARMY CORPS OF ENGINEERS. Engineering and design for slope stability, EM 1110-2-1902, 2003.

[8] FREDLUND D.G., DAHLMAN A.E. Statistical geotechnical properties of glacial lake Edmonton sediments. *Statistics and probability in civil engineering*, 1972.

[9] HAMMITT G.M. Statistical analysis of data from a comparative laboratory test program sponsored by ACIL. Miscellaneous paper 4-785, U.S. army engineering waterways experiment station, Corps of Engineers, 1966.

[10] SCHULTZE E. Frequency distributions and corrections of soil properties. *Statistics and probability in Civil engineering*, 1972.

[11] ECOLE POLYTECHNIQUE DE MONTREAL. CADAM user manual.

[12] FEDERAL ENERGY REGULATORY COMMISSION (FERC). Engineering Guidelines for Evaluation of Hydroelectric Projects.

[13] HYDROPOWER INDUSTRY STANDARD OF THE PEOPLE'S REPUBLIC OF CHINA. The design specification for concrete gravity dam, DL 5108-1999, 2000.