Probabilistic Approach for Dam Safety Evaluation of Mae Mao Hydropower Project

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Abstract

Dam Risk Assessment is a tool to measure dam efficiency by assessing the degradation of filling materials, concrete, other materials, and also external factors. External factors particularly natural disasters that occur more frequently and intensively nowadays are considered as a key influence to dam efficiency. Moreover Dam Risk Assessment is also a tool to develop suitable maintenance plan and schedule within limited budget and acceptable safety standards both during pre-construction and post-construction phases. Hence Dam Risk Assessment is applied and integrated between Soil Engineering and Statistic. This study evaluates concrete dam safety of Mae Mao Hydropower Project in Fang District, Chiang Mai Province during 1987 – 2012. Most of the parameters were executed from dam instrumentation such as reservoir water level and ground water level, and mostly analyzed in probabilistic aspect for probability of failure of dam. The safety factors and probabilities of failure changes were resulted from deterioration of grouting material that was leached by water over time. However, it is recommended to conduct more analysis in other Statistical aspects and collect more data for evaluation.

Keywords: probabilistic analysis, dam safety, concrete dam, hydropower dam

1. Introduction

History shows that the loss of life from dam failure in the United States has diminished with the passage of time. In the late 1800's and early 1900's, there were several dam failures with considerable loss of life. (USBR 1999). In the last 4,000 year, dam design and dam construction were not considering about the principle of geotechnical engineering such as seepage through the dam, separation of filling material, inadequate filter drain and also differences of geological characteristics. Thus, there were many dam failures occurred in the past e.g. Proserpina Dam in Spain that was constructed by Roman trooper (Jansen 1983).

Nowadays, dam design and construction have taken dam risk into account which can occur from several factors such as topography and construction time. Dam designer has to think about influencing factors such as slope and foundation stability, dam seepage, differential settlement, seismic force, erosion, and other major impacts.

Dams and reservoirs create liabilities as well as benefits. Earthquakes, floods, landslides, and volcanic activities have resulted in catastrophic dam failures in a variety of environments (Gupta and Rastogi 1976). In the US, 318 people have been killed by dam failures between 1960 – 1997 (FEMA 1999). In other instances, reservoirs such as Lake Nasser (behind the Aswan High Dam on the Nile River) have resulted in evaporative water loss, salinization, loss to groundwater recharge, and the spread of human disease via vectors that established habitat in the reservoir (Waddy 1975)

This paper endeavors to evaluate probabilistic conditions of concrete dam from instrumentation aspect at a certain time by examining some of uncertainties and apply to design, construction, and maintaining the dam performance.

2. General Concept for Concrete Dam

2.1 Seepage of Water through Rock Foundation

In the past, major cause of dam failure is seepage through dam body, dam foundation and dam abutment that depends on geology in dam site. If seepage flow is continuous, it will develop erosion which can be severe and destroy larger areas. Thus, ones must realize about modes of failure and probabilities of failure.

Seepage of water in rock foundations are distinguished with low porosity, so that seepage take place through fissures and fractures, created as a result of various tectonic processes, and further due to erosion and excavation of foundation pits by means of blasting. (Tancev L. 2005)

Fissures and fractures can have very different dimensions, ranging from parts of a millimeter up to a number of tens centimeters. If they are filled up with fine fractions from weathered minerals, then they will be poorly water-permeable, but they could also remain partially filled, i.e. open. By moving through fissures of rock, seepage flow loses a part of its potential, the same as seepage in a porous earth medium. In such a case, it is not possible to apply the theory of potential flow of underground water, so that the law according to which reduction of the potential take place (Tancev L. 2005).

2.2 Uncertainty in Dam Safety

Dam safety serves to fulfill the public trust responsibility associated with agency/department exposure as a result of dam failures (dams should not fail frequently even if the consequences are low). Maybe multiple fatalities are possible due to dam failure. Protection of human life is of primary importance to public agencies constructing, maintaining, or regulating public works. There are two views to explain dam failure:

1) *Rainy day failure* involves periods of excessive precipitation leading to an unusually high runoff. This high runoff increases the reservoir of the dam and if not controlled, the overtopping of the dam or excessive water pressure can lead to dam failure. Normal storm events can also lead to rainy day failures if water outlets are plugged with debris or otherwise made inoperable (USBR 2011).

2) *Sunny day failures* occur due to poor dam maintenance, damage/obstruction of outlet systems, or vandalism. This is the worst type of failure and can be catastrophic because the breach is unexpected and there may be insufficient time to properly warn downstream residents (USBR 2011).

The profession's current ability to demonstrate failure probabilities to very low levels, less than 1 in 1,000,000 per year, is limited. This does not mean that these risks should be ignored or that an attempt should not be made to obtain the best information possible in these cases. The opposite is true, although the costs of obtaining the information should be carefully weighed against the potential to gain useful information that could be used to support a decision. As-low-as-reasonably-practicable (ALARP) principles should be considered and weighed against the residual risks posed by the structure. (USBR 2011)

3. Project Description

3.1 Background

Mae Mao Hydropower project is operated by the Department of Alternative Energy Development and Efficiency (DEDE), Ministry of Energy. This project is located about 870 kilometers north of Bangkok in Fang district, Chiang Mai Province.

The project comprises of a concrete gravity dam 73 meters high and a 4.6 Megawatts. The hydropower is supplied from the reservoir via a 1.5-kilometer long power tunnel. It is about 705 meters MSL at the crest of dam. The dam has full supply level at 700 meters MSL, which the reservoir impounds 20.8 million cubic meters with surface area of 100 Hectare (Fig. 1 – 2).

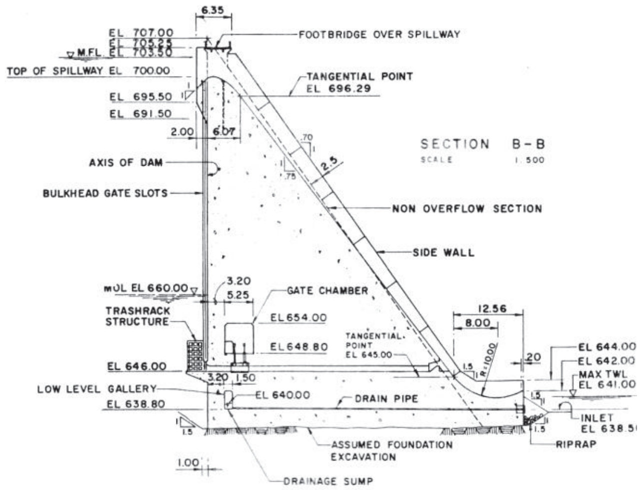

Fig. 1 Cross section of Mae Mao Dam

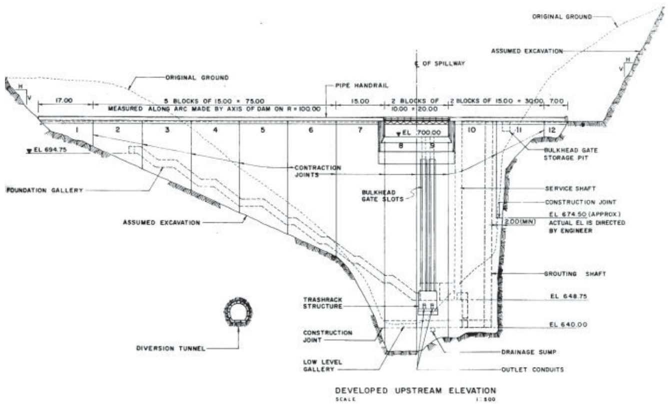

Fig. 2 Longitudinal section of Mae Mao Dam

3.2 Local Geology

Geological condition in the dam site is underlain by several rock units. The dam abutments and shallow foundations are composed of quartzitic sandstone which is of high strength and is closely fractured. This rock on the abutments within 45 meters of ground surface has a high rock mass permeability. In the dam foundation, the quartzite rock mass has a low permeability composing of grouting curtain and 10-meter deep drainage hole for seepage flow and uplift pressure reduction.

4. Essential Conception of Concrete Gravity Dam for Dam Safety

4.1 Stability Consideration

4.1.1 Overturning Stability

The overturning stability is calculated by applying all the vertical forces i.e. self-weight of concrete dam and uplift force. (∑V-U) and lateral forces that are composed of hydraulics pressure (∑H) for each loading condition to the dam and, then, summing moments (∑M) caused by the consequent forces about the downstream toe. When the resultant of all forces acting above any horizontal plane through a dam intersects that plane outside the middle third, a non-compression zone will overturn (USACE 1995). The formula of safety factor against overturning (FSO) is shown in equation (1).

$$FSO = \frac{\sum M_{resisting}}{\sum M_{driving}} \qquad (1)$$

Where $\sum M_{resisting}$ is the summation of resisting moment and $\sum M_{driving}$ is the summation of driving moment

4.1.2 Sliding Stability

The sliding stability is based on a factor of safety (FS) as a measure of determining the resistance of the structure against sliding. The multiple-wedge analysis is used for analyzing sliding along the base and within the foundation. For sliding of any surface within the structure and single planes of the base, the analysis will follow the single plane failure surface of analysis. (USACE 1995) After dam stability is checked in cast of overturning, will be determined sliding stability as:

$$FSS = \frac{[(A \times C)+(\sum V\text{-}U) \times \tan\emptyset]}{\sum H} \qquad (2)$$

Where **A** is foundation area of dam, **C** is Cohesion/adhesion of dam foundation with soil/rock strata, **U** is uplift force applying the dam foundation, $\sum V$ is the summation of vertical force concerning the dam, $\sum H$ is the summation horizontal force concerning the dam and $\emptyset$ is the angle internal friction.

From Eq. (1) – (2) the safety factor of Mae Mao Concrete dam indices correlation in reservoir water level (WL), safety factor against overturning (FSO) and safety factor against sliding (FSS) versus time are considerable at same reservoir water level. Pore pressure underneath the dam foundation is measured from the dam piezometer and the pore pressures are used for safety calculation. This is attributed to uncertainty in reservoir water level versus FSO and FSS which the results are plot in Fig. 3

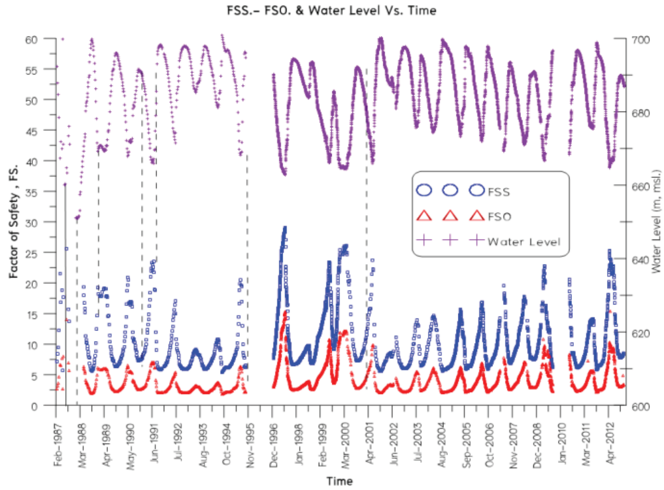

Fig. 3 Reservoir water level and safety factors over time

4.2 Probabilistic Concept

The histograms of the WL, FSO and FSS are plotted in Fig. 4 – 6.

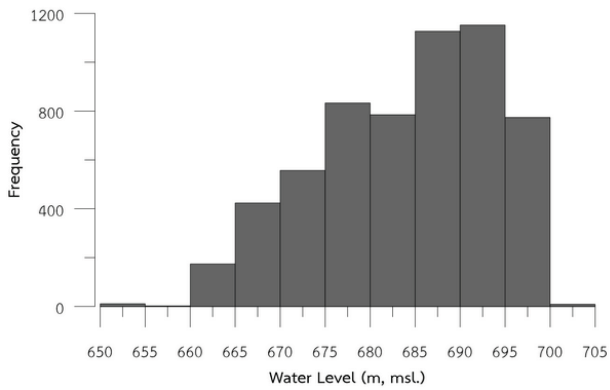

Fig. 4 Histogram of Reservoir Water Level

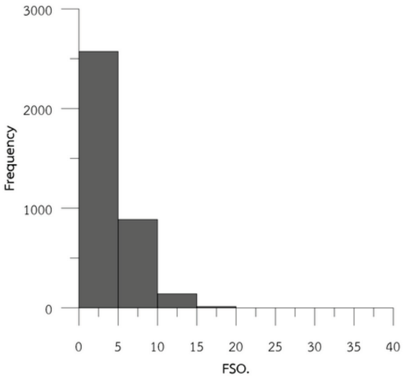

Fig. 5 Histogram of FSO

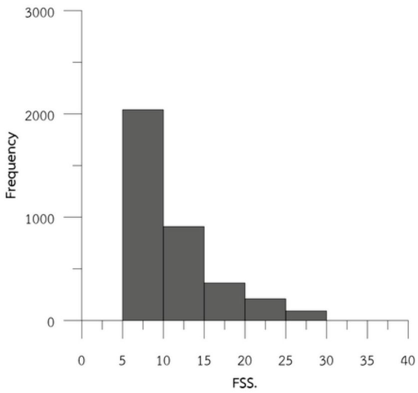

Fig. 6 Histogram of FSS

The characteristic of FSO and FSS versus WL (Fig. 7) varied randomly at a time can attain bivariate distribution to covariance (COV) by applying the following equation.

$$Cov[x,y]= E[xy]-\mu_x \mu_y \quad (3)$$

The mean of covariance between two random variables X and Y are μ_x and μ_y, respectively (Fenton G. A., et al., 2008).

The relation between FSO and FSS versus WL are random variable with joint probability distribution. The correlation coefficient (ρ_{xy}) between FSO and FSS versus WL is defined as

$$\rho_{xy} = \frac{Cov[x,y]}{\sigma_x \sigma_y} \quad (4)$$

The correlation coefficient is a direct measure of degree of linear dependence between X and Y. When the two variables are perfectly linearly related, ρ_{xy} will be either +1 or -1 (+1 if Y increases with X and -1 if Y decreases when X increases) (Fenton G. A., et al., 2008).

Dam materials and dam instrument are modeled as a random variable for different distributions which can be verified with other different patterns of histograms. Mostly, the random variable distributions are close to symmetric bell shapes which are normal distributed. A fundamental result, known as the central limit theorem, implies that the histograms often have this normal distribution curve. Random variables with different means and variances can be modeled by normal probability density functions with appropriate choices of the center and width of the curve. By normal probability density function, mean is μ and variance is σ^2

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{\frac{-(x-\mu)^2}{2\sigma^2}} \quad \text{for } -\infty < x < \infty \quad (5)$$

The probability of dam failure is calculated from generated normal distribution function that is based on the characteristics of linear combination equation of random variables i.e. mean, standard deviation and coefficient of variation. Thus, probability of failure of the two random variables (FSO & FSS) is obtained by extrapolation plot in Fig. 8

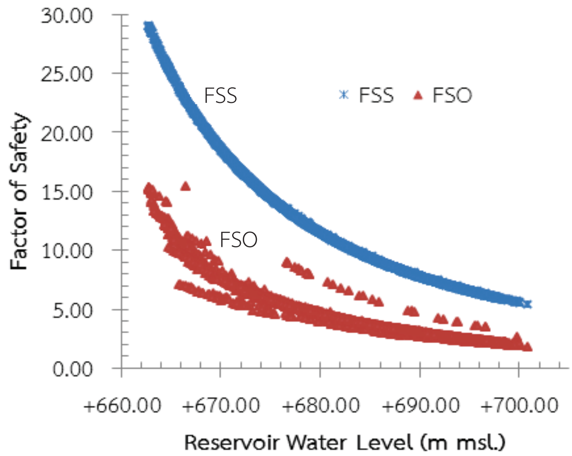

Fig. 7 Correlation of Factor of Safety versus Reservoir Water Level

A safety factor of dam is an index indicating the dam safety performance. It does not imply total actual risk level of dam, due to not including other parameters of dam structure. Probabilistic approach, two useful indices are available to quantify the dam safety or the risk level of dam. These two indices are known as the probability of failure (Pf.) and reliability index.

From Eq. (3) – (4) and Fig. 7, it is resulted that the correlation coefficient equals to -0.879 for FSO and -0.918 for FSS, the dependence between safety factor and reservoir water level is not completely linear; however there could still be a strong nonlinear dependence (Fenton G. A., et al., 2008).

The probability of failure of Mae Mao Dam is obtained from the extrapolation of the probability of safety factor that less than 1.0. The probability of dam failure is determined by counting the number of safety factors below 1.0 and then taking the number as a percentage of the total number of normal distribution. Thus, Mae Mao Dam has condition probability of dam failure of 6% for FSO and 2% FSS (Fig. 9).

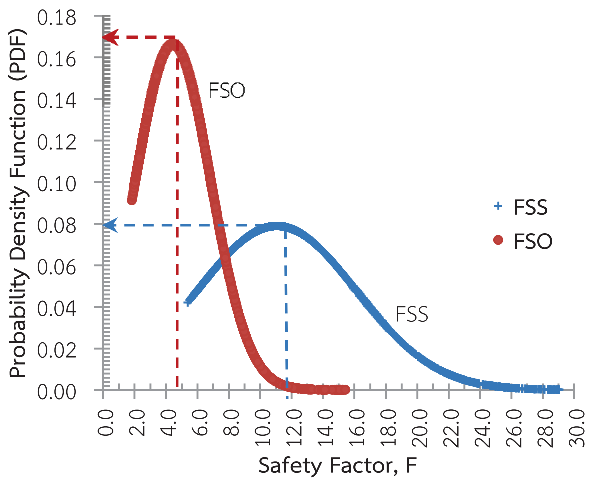

Fig. 8 Normal Probability Density Function

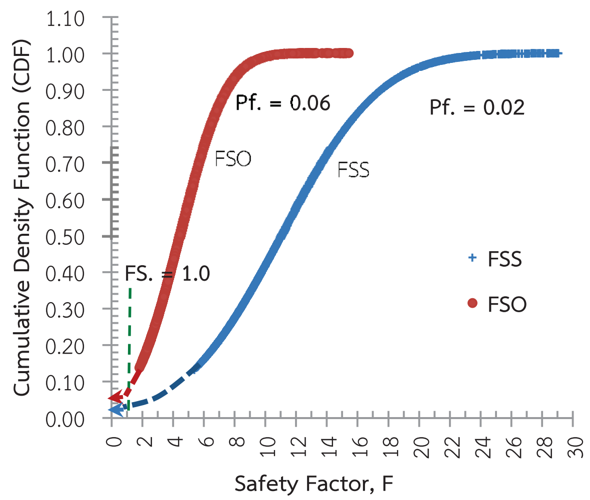

Fig. 9 Normal Cumulative Distribution Function

5. Conclusion

The result of this study is a tool to improve dam instrumentation by testing the correlation of reservoir water level versus factor of safety and determining the tendency of preventive maintenance of concrete dam. This is useful for probabilistic approach in estimating probability. Mae Mao Dam correlation coefficient equals to -0.879 for safety factor against overturning (FSO) and -0.918 safety factor against sliding (FSS). In average, the computed probabilities of Mae Mao Dam for FSO equals to 4.50 for Probability at 16.6%, FSS equals to 11.0 for Probability at 7.8% in normal probability density function. The summation of probabilities less than 1.0 is probabilities of failure (Pf.). The condition Pf. equals to 6% for FSO and 2% for FSS for Mae Mao dam as a result of the calculation.

6. Acknowledgement

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References

[1] Gordon A. Fenton and D.V. Griffiths, *Risk Assessment in Geotechnical Engineering*. John Wiley & Son, Inc., 2008

[2] H. El-Ramly, N. R. Morgenstern and D.M. Cruden. “Probabilistic assessment of stability of a cut slope in residual soil”. *Gèotechnique,* 55, No. 1, 77-84, 2005

[3] James E. Evans, Scudder D. Mackey, Johan F. Gottgens and Wilfrid M. Gill. “Lessons from a Dam Failure” *Ohio Journal of Science*, 100 (5):121-131,2000

[4] Jery R. Stedinger, David C. Heath, and Kay Thompson, Cornell University, *Risk Analysis For Dam Safety Evaluation: Hydrologic Risk*, U.S.Army Corps of Engineers Institute for Water Resources, 1996

[5] Kyoto University GCOE HSE. *Geotechnical Infrastructure Asset Management*

[6] Negede Abate Kassa. “Probabilistic Safety Analysis of Dams Methods and Applications”. Technische Universität Dresden, 2009

[7] R. W. M. Cheung and W. H. Tang. “Realistic assessment of slope reliability for effective landslide hazard management”. *Gèotechnique*, 55, No. 1, 85-94, 2005

[8] Tancev, Ljubomir. *Dams and Appurtenant Hydraulic Structures.* The A. A. Balkema Publishers, 2005

[9] U.S. Department of the Interior, Bureau of Reclamation Dam Safety Office, Denver, Colorado. *A Risk Framework to Support Dam Safety Decision-Making, Dam Safety Public Protection Guidelines*, Interim, 2011