Ageing Evaluation Model of Dams and Case Studies

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Abstract
While many dams around the world are still under construction or planning, existing dams are ageing and becoming more degraded over time since their completion. Due to the relatively higher probability of failure during their remaining lifetime, ageing dams need to be properly maintained based on well-established inspection and evaluation systems. However, at present, it is not easy to know how seriously aged or degraded they are and when to take the action required to secure their safety at rational cost. In this paper, an ageing evaluation model (AEM) is suggested as a simple assessment method for dam ageing which can be used to determine the time for adequate maintenance work to extend the lifetime of dams. For the development of the AEM for existing dams, a variety of data showing any changes in integrity of the dam body since its completion were collected and analyzed. Some examples of ageing evaluation using the newly proposed AEM are presented here. It is expected that the proposed method may be useful to estimate the time for the opportune maintenance of existing dam facilities.
Keywords: Ageing, Evaluation Model, Deterioration, Existing Dams, Lifetime of Dam.

1. INTRODUCTION

Dams provide us with a variety of benefits such as hydropower, flood control, drinking water, irrigation, and recreation. However, as our population grows, their development continues and natural disasters are increasing due to climate change, thus they are sometimes a great threat to the public in respect of their hazard potential. Once a dam has been successfully built so that reservoir water can be safely stored (note that many dam failures occur either during construction or during or shortly after reservoir filling), its structure and component parts will begin to age with each structure ageing at a different rate in a different way. Some dams may remain safe for more than a thousand years, while others may start to be severely degraded and/or leak after less than a decade and consequently cause devastating damage and loss of property and life.

The Republic of Korea has around 15,000 facilities classified as “critical infrastructures” by the Korean government, and 9.3% of them are more than 30 years old. In the case of water infrastructure, around 56% of the classified dams are more than 30 years old (Kim, 2013). Around the world, some 5,000 large dams are now more than 50 years old, and the number and size of the dams have rapidly increased in the last half century. The average age of the 90,580 dams in the US is, as of 2016, around 56 years old. Around 80,000 of 98,000 dams in China were built in the 30 years between 1950 and the end of the 1970s, and among them, many have been identified as having a “high hazard potential” (Wang, 2017). In relation to the ageing issue of dams, it seems that every country is trying to develop technologies to identify defects or the possibility of dam failure at any age and to establish a number of institutional systems to maintain those ageing dams systemically.

In this paper, a theory or model developed to evaluate the degree of aging of dams is introduced and examples of the ageing evaluation of dams using it are described. It should be noted that while the newly propose evaluation model is one of a number of simple models by which quantitative evaluation can be made for ageing dams, a more generalized evaluation model should be developed to consider the more varied conditions that can be encountered during the ordinary operation of dams. Note that in this paper, according to the definition of the International Commission on Large Dams (ICOLD) Bulletin 93 (1994), the ageing of dams is defined as deterioration that occurs more than 5 years after the beginning of its operation and is a class of deterioration associated with time-related changes in the properties of the materials with which the structure and its foundations are constructed. Excluded are the effects of exceptional events. Under normal conditions during dam operation, structural ageing will usually affect the performance requirements and then later affect safety if corrective measures are not taken. However, in this paper, the author would like to use the term ‘degradation’ instead of ‘deterioration’, because it is considered that ‘degradation’ can more properly explain the cause-effect relationships regarding the reduction of performance or safety instigated by the results of ageing.

2. AN AGEING EVALUATION MODEL (AEM) FOR DAMS

Ageing as a cumulative degradation process occurring over time. It usually leads to degradation of materials subjected to service conditions and can cause a reduction in component and/or system safety margins if the degradation phase continues, eventually resulting in failure of the structure or else abandoning and demolishing it.

2.1. THE RELATIONSHIP BETWEEN PERFORMANCE (OR SAFETY) AND AGE

From the above perception of the ageing process of dams, the AEM can be expressed as a relationship between performance (or safety) and age (time), as shown in Figure 1.

Some typical types of ageing process encountered in practice are classified into **4 Types**. **Type 1** is the most common pattern in which ageing is detected after the first 5 years of operation. **Type 2** shows ageing at a slightly faster rate which begins within the first 5 years of operation (from the literature, it is well known that many dam failures occur during this period). **Type 3** is an unwanted case in which a dam shows anomalous behaviors such as excessive deformations or leakage during the first reservoir filling due to defects in design and construction, and in addition does not meet the design safety requirements. If the amount and rate of degradation are so big and rapid respectively, they may eventually result in catastrophic failure of the dam. **Type 4** is one of the worst cases in that a dam fails due to congenitally critical defects in design and construction.

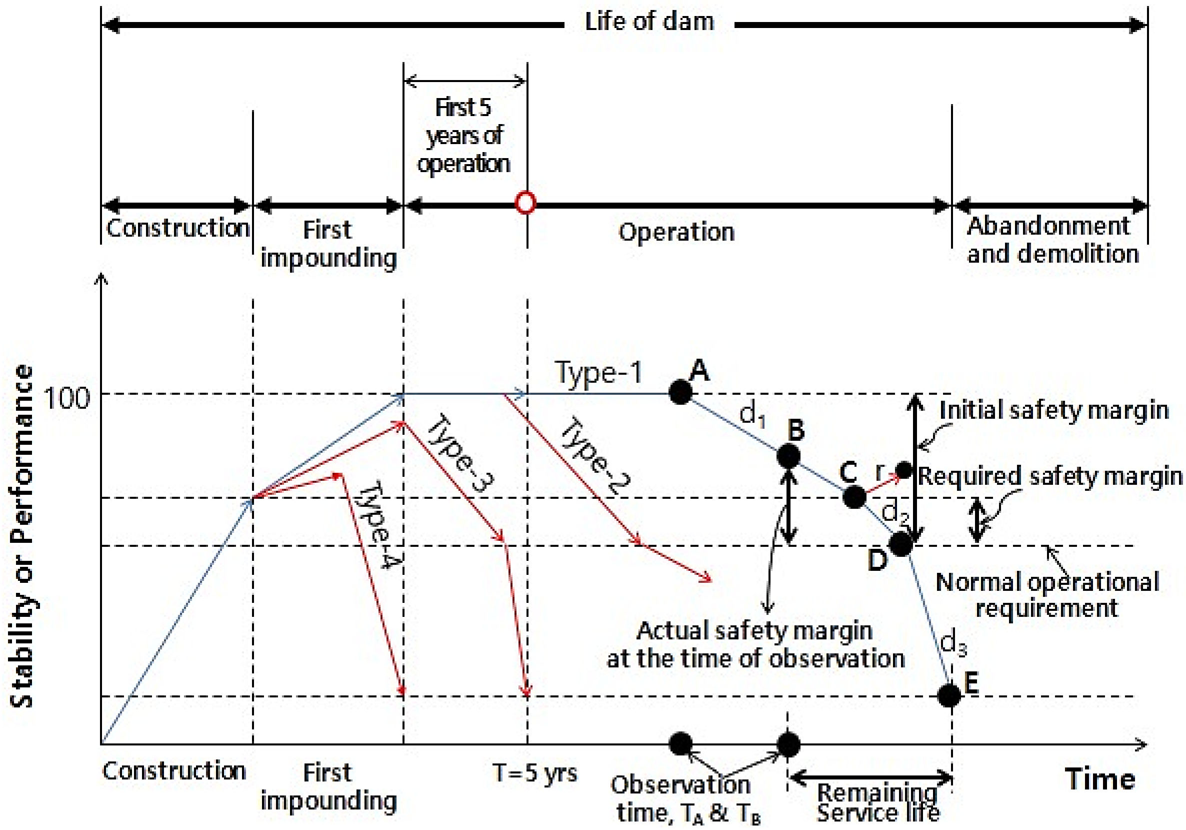

Figure 1. The relationship between performance and ageing of dams with time passage

2.2. A BASIC AEM

In Figure 1, the points ***A, B, C, D***, and ***E*** indicate the level of performance or safety of a dam at a certain time point. Point ***A*** indicates the upper limit of performance and the starting point at which ageing begins. The dam at point ***B*** actually has a larger safety margin than is required and its performance is higher than the normal operational requirements. For the time T_B corresponding to point ***B***, we can estimate the remaining service lifetime if the degradation rate is also known. Points ***C*** and ***D*** (where ageing occurs) are the upper and lower limits of the required safety margin, respectively. Point ***E*** means the lowest performance where the dam should be abandoned or demolished without hesitation. In the same figure, $\mathbf{d_1}$, $\mathbf{d_2}$ and $\mathbf{d_3}$ represent the rates of degradation of the dam. The ordinary ageing process will follow the ***A-B-C-D-E*** path if no mitigating work is taken. If any kind of rehabilitation work is carried out, then the dam's performance may increase along the path **C**-r (r denotes recovery), and consequently its remaining lifetime will be extended.

In order to establish the AEM, we need to essentially know the amount and rate of degradation, and the critical safety requirements such as allowable thresholds for deformation (mandatory), leakage (mandatory), strength (optional), pore pressure (optional), and so on. The amount of degradation and the rate of ageing can be theoretically quantified by long-term monitoring data including the results of surveillance activity. The ageing phenomena to be detected are summarized in Tables 1 and 2. Once we have assessed how far it has developed, then we can decide on appropriate corrective measures to extend the dam's lifetime. The rate of ageing can be calculated by directly monitoring or measuring changes in the dam's structural properties or performance over time:

$$\begin{aligned} P(t) &= 1-F(\text{time}, (\text{deformation, loss of strength, pore pressure increase, permeability change, etc.})) \\ &= 1-\sum(F_{deformation}(t) + F_{leakage}(t) + F_{strength}(t) + F_{pore\ pressure}(t) + F_{permeability}(t) + \bullet\bullet\bullet), \end{aligned} \quad (1)$$

Where P(t) = Performance as a function of time t and $F_{deformation}(t)$ = Reduction of deformation performance in which the rate of degradation is multiplied by the age (period) corresponding to the changes in deformation. The other terms for leakage, strength, pore pressure, and permeability are calculated in the same manner as in the term of deformation. It is assumed for simplicity that each degradation rate varies linearly with time.

Table 1- Major ageing symptoms for earth- and rockfill dams (ICOLD, 1994)

Dam Component	Symptom of Ageing
Foundation (soil or rock mass)	- Deformation - Loss of strength, uplift pressure increase, and change in stress state - Internal erosion - Foundation degradation - Ageing of grout curtains and drainage system*
Dam body (embankment materials)	- Deformation - Loss of strength - Pore pressure increase - Internal erosion - Leakage** - Embankment degradation - Surface erosion
Others	- Seepage through concrete faced rockfill dams - Permeability change - Loss of bond between concrete structures and embankment - Ageing of synthetic polymer materials

* and ** are symptoms added by the author

Table 2- Major ageing symptoms for concrete and masonry dams (ICOLD, 1994)

Dam Component	Symptom of Ageing
Foundation (rock mass)	- Loss of strength under permanent or repeated actions - Erosion and solution - Ageing of grout curtains and drainage system
Dam body (concrete or mortar and stone)	- Chemical reactions resulting in swelling - Shrinkage, creep, and reaction leading to contraction - Degradation due to chemical reactions of materials with the environment - Loss of strength under permanent and repeated actions - Poor resistance to freezing and thawing
Others	- Ageing of structural joints - Ageing of upstream facings - Ageing of pre-stressed structures

3. CASE STUDIES

Using the simplified AEM proposed by the author, the performance-age relationships of two earth and rockfill dams were analyzed.

3.1. THE ANGYE DAM CASE

Completed in 1971 to supply water to the Pohang industry complex located in the south east of Korea, the Angye dam is a 46-year-old center-cored earthfill dam with a height of 32.5 m, a length of 223 m, and a total reservoir capacity of 17 million m^3 (Figure 2).

The dam is an example of ageing by loss of strength, deformation, and internal erosion. There have been two events showing that the dam body has been deteriorating for a long time: in 1985 (14 years after its completion) and 2003 (18 years after the first event) (Korea Water Resources Corp., 2009)

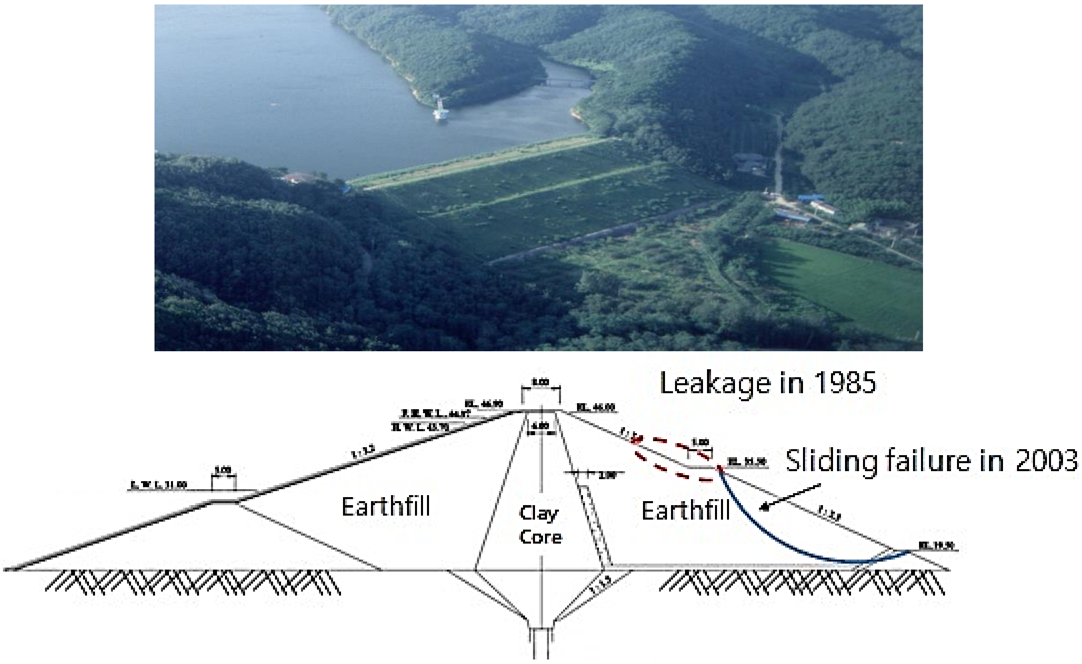

Figure 2. The Angye dam

The first evidence of ageing was detected in June, 1985 when leakage occurred from an area of around 20 m^2 at the downstream slope of the dam body. The amount of leakage was measured at as much as 50~200 ml/min. The results of a series of investigations on the cause of the leakage by drillings at the core zones and an electrical resistivity survey carried out 9 months after the first detection of the leakage implied that some parts of the core zone had loosened and permeability varied irregularly from $k=10^{-2}$ to 10^{-4} cm/s on the right side of the dam body. After that, 223 m-long curtain grouting was carried out as remedial work in 1986. The second event was the collapse of the downstream slope that occurred 8 years later in 2003, which is considered to have been associated with ageing as well as heavy rain at that time.

From the records of the two events and inspections, as shown in Figure 3, an ageing evaluation was carried out based on the performance-age relationship proposed by the author in Figure 1 and Equation (1). As of 2017, the Angye dam is showing sufficient performance above the required performance margin assumed by the author, and this case can be considered as **Type-1** ageing.

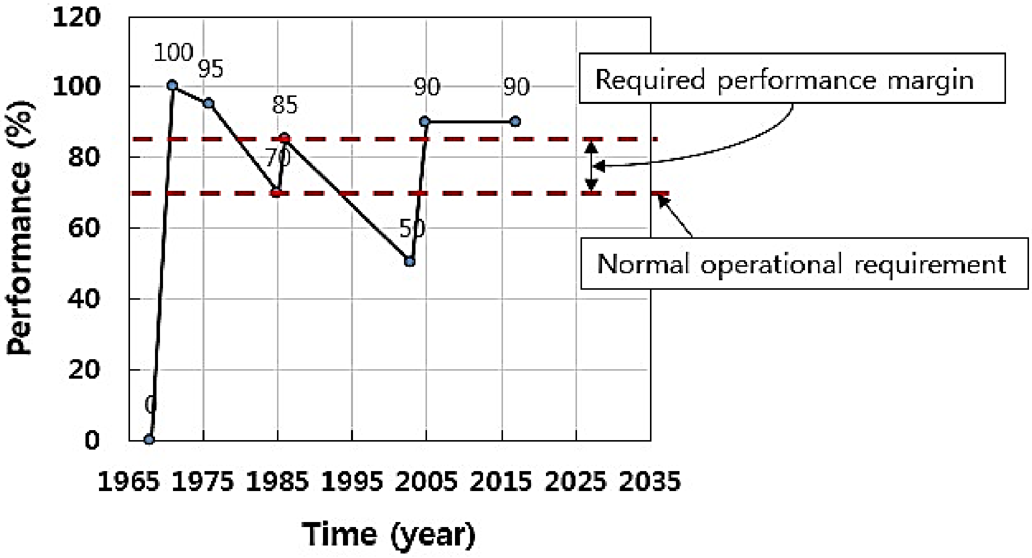

Figure 3. Ageing Evaluation of the Angye Dam

3.2. THE UNMUN DAM CASE

The Unmun dam was completed in September 1994 to supply 376,000 m^3/day of municipal water to neighboring cities in the Kyungsang-bukdo province in Korea. The dam, which is operated by K-water (Korea Water Resources Corporation), is a 23-year-old center-cored rockfill dam as of 2017 with a height of 55 m, a length of 407 m, and total reservoir capacity of 135 million m^3 (Figure 4).

After the Unmun dam was first filled up to its normal high water level in 1998, the first accident of ageing occurred within 5 years after its completion, whereby its safety was seriously threatened by subsidence, sinkholes, and excessive leakage, which are all typical symptoms of ageing of rockfill dams (Korea Water Resources Corporation, 2005). A comprehensive investigation on the causes of such accidents revealed defects in design and construction of the core zone and its materials, and the core materials had been internally eroded due to gap-graded gradation and lead to development of sinkholes and subsidence at the dam crest (Figure 5). Based on the investigation, a compaction grouting method was applied to an 80 m-long strip of the core zone in 2000 as remedial work to extend the lifetime of the dam. However, the second event occurred around 1 year after the first remedial work when an unexpected spike of seepage measurement was recorded by the leakage monitoring system installed at the toe area of the dam. In addition, high turbidity was observed with some blue dye material intentionally mixed with clay materials to detect whether the seepage behavior was normal or not during the compaction grouting work after the first event in 2000. Thus, after more comprehensive investigations were conducted to find all of the defects in the dam safety, a permeation grouting method was applied to the entire length of the dam in 2003.

Using the records of these two important events and other investigations and maintenance, as shown in Figure 6, an ageing evaluation was made based on the performance-age relationship proposed by the author in Figure 1 and Equation (1). The rate of degradation in terms of internal erosion was considered as 'Slow' according to the classification method by Fell et al. (2003). The Unmun dam case is considered as **Type-2** ageing, and as of 2017, the dam is showing sufficiently good performance above the required performance margin assumed by the author.

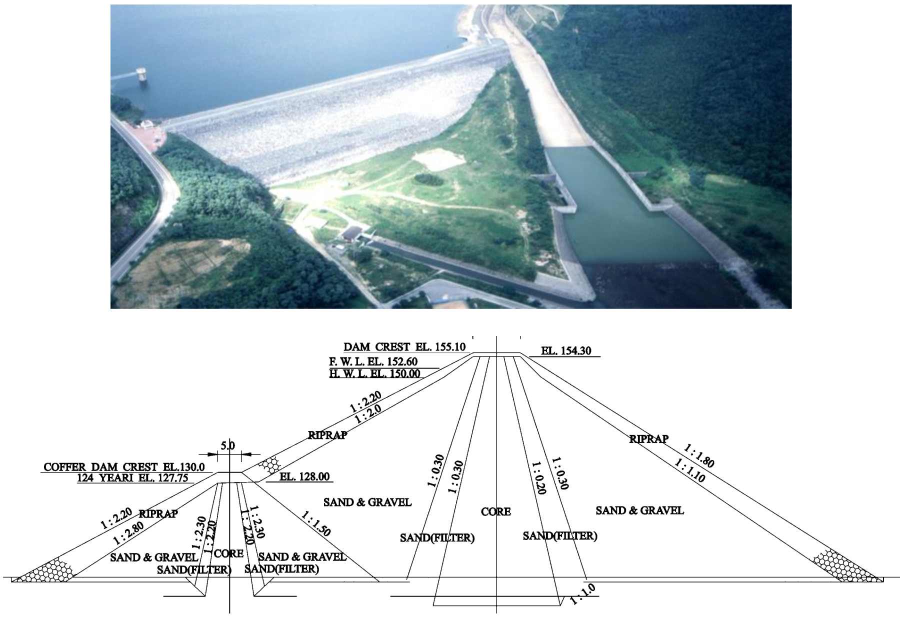

Figure 4. The **Unmun dam before the sinkholes and excessive leakage accidents in 1998**

Figure 5. A sinkhole as a consequence of ageing that developed on the crest of the Unmun dam in 1998

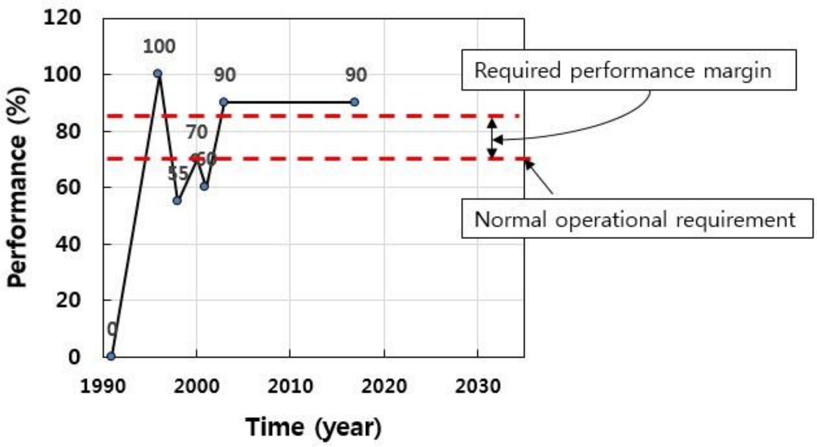

Figure 6. Ageing Evaluation of the Unmun Dam

5. CONCLUSIONS

In this paper, an AEM to assess the degree of aging of dams is introduced and two examples of the ageing evaluation of dams using the proposed model are described. According to the AEM, the ageing patterns of the Angye and Unmun dams are **Type-1** and **Type-2**, respectively, and with a more precise evaluation using data and information collected from all kinds of investigations, inspections, and analyses, then the remaining lifetime of the dams could be more accurately estimated.

Therefore, it was confirmed that the AEM can well describe the entire lifetime of ageing dams. However, it should be noted that while the newly propose evaluation model is one of the simple and basic models by which quantitative evaluation of ageing dams can be made, a more generalized evaluation model should be developed to consider a wider variety of conditions encountered during the ordinary operation of dams. In a rational assessment of the ageing of dams, the realistic determination on a number of important criteria in dam performance such as the normal operational requirements and the required performance margin needs to be made based on the judgements by sufficiently experienced dam engineers.

6. ACKNOWLEDGMENT

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