Engineering Assessment of Aging Degradation for Small Sediment Control Structures

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Landslides and associated debris flow are major natural disasters in Korea. Sediment-related disaster prevention structures, such as erosion control dam (ECD) and check dam, have been practically implemented on forested watersheds to control landslide hazards. After construction, engineering strength of ECDs could be lost partly or completely due to aging degradation. Thus, long-term scale, weaker force than design strength can induce loss of designed function or failure of structure exceptionally. In this study, a numerical approach was applied for performance evaluation to aging concrete ECDs. With finite element technique considering static and dynamic loads, simplified ECD and debris flow as dynamic load were simulated. Age degradation curve of concrete strength was derived from previous studies. Because this research is in progress, numerical analysis will be conducted with results of this paper, and the effect of earthquake will be also considered in future works. This study provides with engineering techniques for an accurate structural performance assessment of landslide disaster mitigation/prevention structures.

Key words: aging degradation, erosion control dam, performance capacity, reliability analysis, finite element method

1. INTRODUCTION

Landslides and associated debris flow are major drivers of natural disasters in Korea, and these disasters seem to occur more frequently due to climate changes [*Kim et al*., 2014; *Jeong et al*., 2015]. To prevent damages from those hazardous events, sediment retention structures, such as erosion control dam and check dam, have been implemented for steep torrents on forested watersheds [*Suda et al*., 2009; *Scheidl et al*., 2013].

In Korea, more than 10,000 erosion control dams (ECDs) have installed to date since ECD project has first employed in 1985 [*Song*, 2013]. There ECDs are structurally small, with typically 5~7 m height and 30~50 m width, and are usually receiving sediment mixture from small forest watersheds (< 300 ha). Although these structures could be varied in construction material and structure type, majority of ECD in Korea is a concrete closed-type dam [*Song*, 2013].

As other field structures, time dependent deterioration of ECDs is random and irreversible phenomenon in nature. Although ECD materials are inherently durable, engineering strength of dam could be lost partly or completely due to aging degradation [*Ellingwood and Tekie*, 2001]. Aging degradation can slowly and progressively change the engineering characteristics of materials over a period [*Mori and Ellingwood*, 1993; *Burman et al*., 2009]. In cases of submerged concrete structures like ECD, water induced aging processes, which include freezing and thawing, leaching, cracking due to temperature variation, corrosion of concrete structures, and cement debonding, are the main sources of aging deterioration [*Kuhl et al*., 2004; *Burman et al*., 2009].

Age-related degradation can lead to changes in structural performance and resistance capacity of ECDs [*Kuhl et al*., 2004; *Burman et al*., 2009]. These degraded structures are more vulnerable to unexpected extreme events, such as earthquake or debris flow. Thus, when structural stability of ECD is examined in landslide or earthquake hazard zone, age degradation on structure strength should be considered.

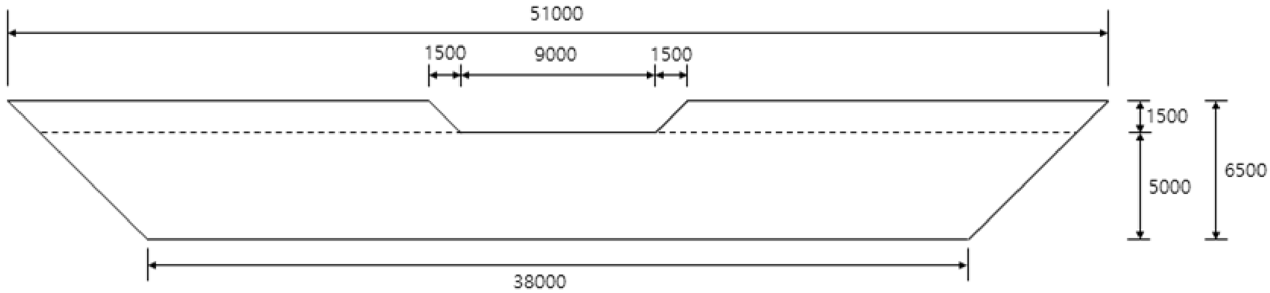

Fig. 1 Dimension of modeled erosion control dam from front-view (unit: millimeter).

In this study, a numerical approach is applied for performance evaluation to aging concrete ECDs. To assess the resistance with static and dynamic loads, such as debris flow impact force and earthquake, numerical analysis of aged ECDs has been done using the finite element method coupling with aging degradation function.

2. METHODOLOGY

2.1 Dam structure modeling

We chose a test dam that constructed at 2012 in the Hyungchon watershed in Seoul, Korea. This young ECD was installed as part of restoration project of debris flow disaster in 2011. [*Jeong et al*., 2015]. **Fig. 1, 2** are the schematic design of front-view and side-view of modeled ECD, respectively, and the dimension of the dam is summarized in **Table 1**. When the structure dimension was drawn from ECD in the Hyungchon watershed, we simplified the dam structure by omitting some components, such as drainage hole and fishway, for convenience of numerical analysis of desired structure.

2.2 Debris flow impact force modeling

When an ECD is constructed, strength of structure against destruction and resistance against momentum is evaluated by several engineering methods. However, in many cases of ECD in Korea, only static pressure induced by water and deposited sediment have been considered to calculate the structural stability, regardless unexpected dynamic force, i.e. seismic wave or debris flow. The design process of the modeled dam was also considered only static pressure although it aimed to endure debris flow hazard. Therefore, to analyze behavior of structure under dynamic force condition, we simulated debris flow impact force derived from debris flow events on the Hyungchon watershed in 2011.

2.2.1 Debris flow simulation

To simulate debris flow behavior, we employed debris flow simulator "Kanako 2D" [*Nakatani et al*., 2008]. Kanako 2D is a GUI-equipped simulator that has the combined model of 1D-channel flow and 2D-deposition in alluvial fan. To simulate debris flow event, several conditions should be assumed as follows. First, stream channel has no branch, and is a rectangular-shape open channel. Second, soil particles in debris flow have uniform in size, and evenly distributed in any part of flow. These

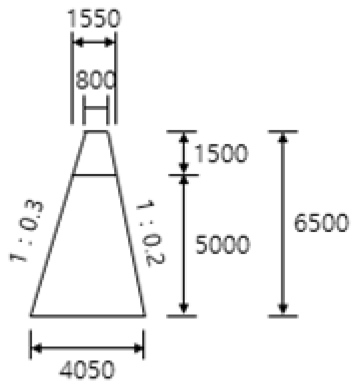

Fig. 2 Dimension of modeled erosion control dam from side -view (unit: millimeter).

Table 1 Summary of dimension of front and side-view of modeled ECD.

View of section	Elements	Size [m]
Front-view	Length at top of dam	51
	Length at base of dam	38
	Height to crest	5
	Total height	6.5
	Spillway width	9
Side-view	Base width	4.05
	Width at the crest	1.55
	Top width	0.8
	Slope of upstream face	1:0.2
	Slope of downstream face	1:0.3

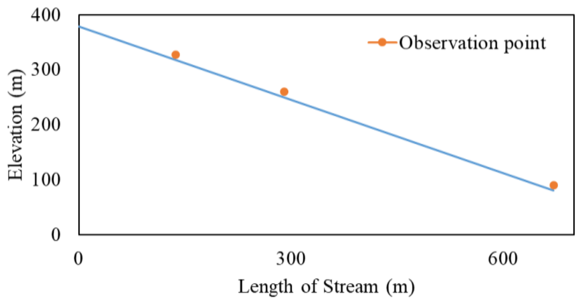

Fig. 3 Schematic design of stream channel input data for Kanako 2D.

assumptions does not exactly correspond to debris flow event in 2011. Despite this disagreement, we chose Kanako 2D and operated it due to convenience of handling input data.

We designed stream channel as shown in **Fig. 3**. According to *Jeong et al*., [2015], mean slope of the watershed was 24° and length of stream channel from top of stream to ECD was 671.32 m. In case of hydrograph for input data, simplified hydrograph (**Fig. 4**) was applied referring to rainfall data when debris flow at 2011 occurred [*Jeong et al*., 2015].

Other initial condition for Kanako 2D simulation, such as material properties, was derived from field examination of debris flow, which includes geological data, soil test, and survey of channel morphology [*Jeong et al*., 2015]. However, some parameters required for Kanako 2D was not directly obtained from field data, i.e. Manning's coefficient. In those cases, we applied commonly used value. Initial input data for Kanako 2D, including time scale of simulation and material properties, was summarized in **Table 2**.

2.2.2 Impact force modeling

Unfortunately, few debris flow simulators calculate impact force of debris flow directly. Thus, it is necessary to estimate impact force from the flow behavior of debris flow. Many researchers have been suggested various estimation methods with flume experiences or real time measurements [*Hungr et al*., 1984; *Hübl et al*., 2009; *Suda et al*., 2009; *Scheidl et al*., 2013]. Although some equations have been suggested based on hydrostatic model or hydrodynamic model [*Armanini*, 1997; *Scheidl et al*., 2013; *Koo et al*., 2017], *Proske et al*. [2011] pointed out that those models show reliable estimation under only limited Froude number. On the other hand, hybrid model suggested by *Hübl et al*. [2009] and *Suda et al*. [2009] estimated impact force regardless of range of Froude number. Thus, we estimated debris flow impact force using a hybrid model as shown as Eq (1).

$$p_{max} = 4.5\rho v^{0.8}(gh)^{0.6} \qquad (1)$$

Table 2 Summary of values used in simulations.

Parameter/variables [unit]	Value
Stream channel length [m]	671.32
Mean slope of channel [degree]	24
Simulation continuance time [sec]	600
Time interval of calculation [sec]	0.01
Diameter of material [m]	0.005
Mass density of bed material [kg m^{-3}]	2665
Mass density of fluid phase [kg m^{-3}]	1000
Internal friction angle [°]	29.3
Concentration of movable bed	0.606
Coefficient of erosion rate	0.0007
Coefficient of accumulation rate	0.05
Manning's roughness coefficient	0.03
Interval of calculation point in 1D [m]	15.26

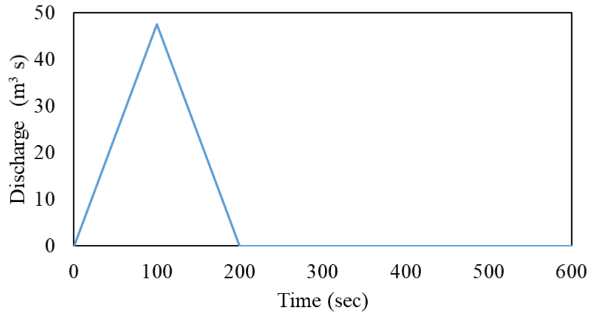

Fig. 4 Simplified hydrograph for initial input data of Kanako 2D

where p_{max} is maximum impact force per unit area [N m^{-2}], ρ is density of debris flow [kg m^{-3}], v is flow velocity [m s^{-1}], g is gravitational acceleration [9.807 m s^{-2}], and h is flow depth [m]. Impact force calculated by Eq (1) is maximum value acting on the base part of ECD near by channel bed. To analyze behavior of structure against impact force accurately, force distribution on dam surface should be considered. *Suda et al*. [2009] considered the distribution of impact force based on results of HüBl and *Holzinger* [2003]. According to *Suda et al*. [2009], distribution of impact force is different whether type of debris flow is granular flow or mudflow. In case of debris flow in the Hyungchon watershed in 2011, it seems to be similar to mudflow type from *Suda et al*. [2009]. Therefore, we used mudflow-type impact force distribution (**Fig. 5**) on numerical analysis.

2.3 Age degradation modeling

Age-related degradation of structural materials is a complicated process. Various approaches have been conducted to quantitatively examine the

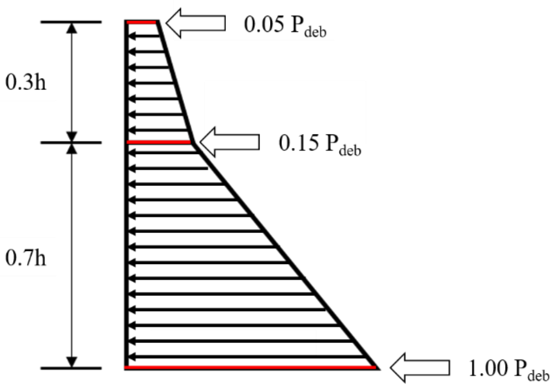

Fig. 5 Debris flow impact force distribution (mudflow type). h means height of dam surface and p_{max} is maximum impact force per unit calculated from hybrid model from *Suda et al.* [2009].

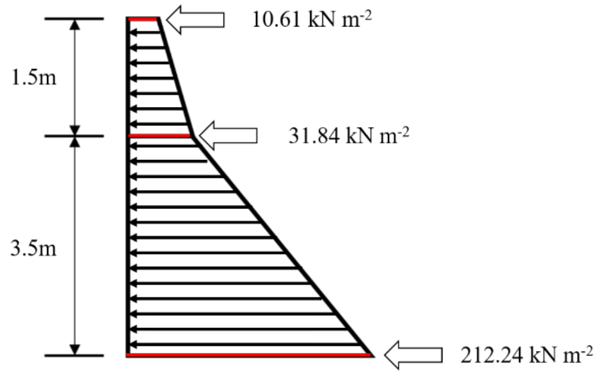

Fig. 6 Simulated impact force distribution on modeled dam surface suggested by *Suda et al.* [2009].

Table 3 Summary of debris flow simulation.

Variables [unit]	Value
Time at maximum velocity and depth [sec]	126
Maximum flow velocity [m s^{-1}]	14.50
Maximum flow depth [m]	0.60

engineering performance for aging concrete structures to avoid catastrophic consequences due to failure of engineering structures [*Mori and Ellingwood*, 1993; *Shinozuka et al*., 2000; *Tekie and Ellingwood*, 2003; *Gogoi and Maity*, 2007; *Burman et al*., 2009]. Time-based reliability analysis was traditionally utilized to evaluate resistance decrease over time [*Mori and Ellingwood*, 1993]. Symptom-based reliability was also employed to predict the safety and performance for existing structural components in future condition [*Gogoi and Maity*, 2007; *Burman et al*., 2009]. Other studies have quantified the degradation effects on stability with fragility curve (or conditional probability of failure) [*Shinozuka et al*., 2000; *Tekie and Ellingwood*, 2003]. Since some parameters in models suggested by those techniques cannot be calculated using visual inspection or non-destructive tests, these methods are hard to apply on field structures that is still functioning.

In this study, time-dependent compressive strength degradation model for concrete material was derived from previous studies [*Koo et al*., 1994; *Kim et al*., 2000; *Song et al*., 2010; *Park et al*., 2013]. It is obvious that the age-related degradation pattern of ECDs is considerably different with general concrete structure/building. ECDs are exposed in natural condition, and many cases of ECDs have reservoir in there upstream side inducing aging process under submerged condition. As *Park et al*. [2013] is the only research that measured compressive strength of ECD in situ until now, there are not enough strength data of ECD for developing time-dependent degradation model. Considering this limitation, we used both general structure [*Koo et al*., 1994; *Kim et al*., 2000; *Song et al*., 2010] and ECD data [*Park et al*., 2013] to produce in this study the age degradation model. Curve fitting analysis was conducted using curve fitting tool package in MATLAB R2017b.

3. RESULTS AND FURTURE WORKS

3.1 Debris flow impact force estimation

Table 3 is summary of debris flow simulation with Kanako 2D. Maximum value of flow velocity and flow depth was 14.50 m s^{-1} and 0.60 m, respectively, and it was occurred at same time. Maximum impact force per unit area was estimated as 212.24 kN m^{-2} from Eq (1). Based on estimated impact force, distribution of impact force for numerical analysis was derived from *Suda et al*. [2009] suggestion (**Fig. 6**).

3.2 Age-dependent strength degradation model

Using least square error method, we made the aging deterioration of concrete strength model (**Fig. 7**). As mentioned above, we made this model using previous results including cases of general structures due to lack of ECD data, but there are different environmental background between them. ECDs studied by *Park et al*. [2013] are constructed in forest watersheds. Most of them have dry reservoir with sediments deposition. Meanwhile, general structures [*Koo et al*., 1994; *Kim et al*., 2000; *Song et al*., 2010] including various type of structures, such as building or bridge, are usually installed in urban area.

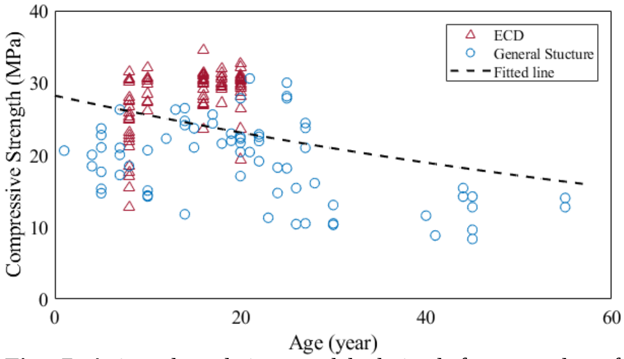

Fig. 7 Aging degradation model derived from results of previous studies [*Koo et al.*, 1994; *Kim et al.*, 2000; *Song et al.*, 2010; *Park et al.*, 2013]. Red triangle means data from ECD measurements [*Park et al.*, 2013]; blue square means general structure researches [*Koo et al.*, 1994; *Kim et al.*, 2000; *Song et al.*, 2010].

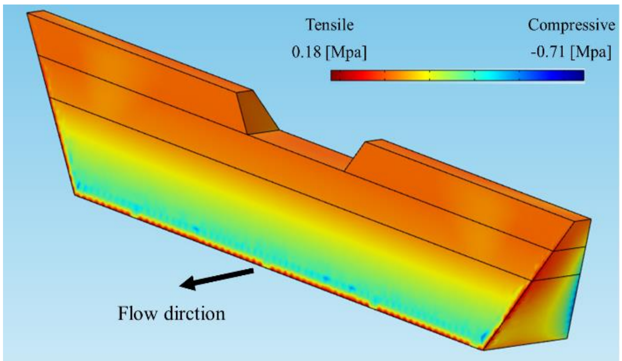

Fig. 8 The result of numerical analysis of ECD under debris flow impact force. Blue color means compressive stress, and red color represents tensile stress.

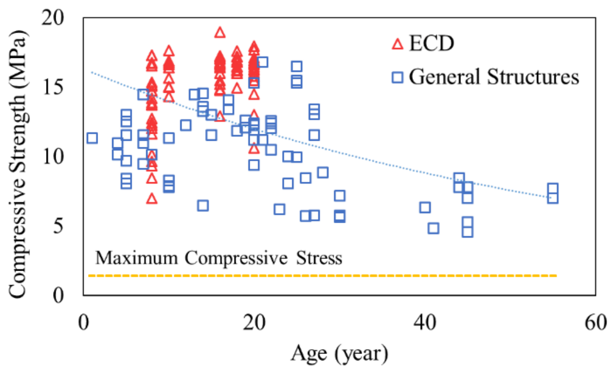

Fig. 9 The result of comparison between compressive strength regarding strength reduction factor (0.55) and maximum compressive stress multiplied by safety factor (2.0). In addition to same symbol to **Fig. 7**, yellow dash line means maximum compressive stress.

As shown in **Fig. 7**, compressive strength of ECD, represented as red triangle, seems to be higher than that of general structures, and ECD strength changed little as becoming older. However, this tendency cannot be explain clearly because of several reasons. First, all of cited previous researches [*Koo et al.*, 1994; *Kim et al.*, 2000; *Song et al.*, 2010; *Park et al.*, 2013] did not mentioned specific location or long-time environmental condition of concrete structures. Thus, it is hard to compare those structures on same conditions. Second, due to sampling methods of *Park et al.* [2013], it is hard to conclude that strength pattern of ECDs can be generalized. According to *Park et al.* [2013], ECD samples were selected by their appearance regardless random sampling. However, as mentioned by *Park et al*. [2013], some ECDs that were regarded as poor condition had enough strength despite their surface damage.

Considering those limitations, we cannot derive different aging degradation model from each groups, Thus, in this study, we made aging degradation model regardless the difference of strength tendency between ECDs and general structures. This model composed of an exponential equation, as shown as Eq (2),

$$Fc = 28.22e^{-0.01t} \qquad (2)$$

where Fc is compressive strength of concrete [MPa], and t means age of ECD [year]. As Statistical parameters, SSE, R^2, and RMSE of this model were 5,924, 0.1426, and 6.202, respectively.

3.3 Numerical analysis of ECD under debris flow impact force

With distribution of impact force and modeled ECD, numerical analysis of ECD was conducted. We conducted Finite Element Analysis (FEA) using COMSOL Multiphysics. Before numerical analysis, we applied several factors based on structure design guideline of Korea. As results, we multiplied safety factor, set up as 2.0, by debris flow impact force. As strength reduction factor, which is regarded as uncertainty of the structure stability, we applied 0.55 that standard factor for structure under compressive strength.

As a result, **Fig. 8** represents the response of ECD structure under designed impact force condition. Blue colored area with negative pressure value shows structural elements under compressive stress, while red colored elements with positive value are under tensile stress. Maximum compressive stress due to impact force was calculated as 0.71 MPa. Considering the safety factor (2.0), we used 1.42 MPa as maximum compressive stress, and we compared this stress to time dependent strength model. However, we cannot estimate the effect of age degradation directly. Due to lack of data of aging effects on dynamic parameters of concrete, such as elastic modulus, we assumed that those parameters are constant during aging process. This means that maximum stress by impact force is constant during its life cycle. Thus, to consider the effect of aging of ECD, we need to compare maximum stress to compressive stress considering safety factor and strength reduction factor in structure design guideline.

Fig. 9 shows the results of comparison between compressive strength and stress regarding structure guideline. When we consider only debris flow impact force as force, modeled ECD in this study can bear impact force regardless aging deterioration. Thus, ECD constructed in the Hyungchong watershed is considered to be able to endure debris flow event without the loss of its function during its whole life. However, this result was obtained under the condition when debris flow impact force is only applied force. Especially, in upstream side of ECD, dead loads, such as water pressure and earth pressure due to sediment deposition, is continuously changed during its life cycle. Thus, in respect of managements, resistant capacity of ECD should be evaluated regarding not only age-dependent deterioration, but also continuous water and sediment change during life cycle of ECD.

3.4 Future works

In this study, we selected and simplified an ECD as object of analysis, and a simple model of concrete strength change over time was developed. Considering the strength reduction following to the aging process using our model, the response of ECD under debris flow disaster simulated using Kanako 2D was analyzed with Finite Element Method (FEM) conducted by COMSOL Multiphysics.

In terms of force applied in numerical analysis, both static and dynamic forces will be input. Although static pressure was already considered in design step of original dam, stability analysis at the time of design cannot ensure long-term stability regarding strength decrease on time. Thus, we will analyze the effect of static pressure under the condition that strength of dam degraded. Moreover, considering recently increased earthquake risk, seismic response of aged ECD will be also analyzed. Some researchers examined the effect of earthquake to structure using computer programs, such as SHAKE91 [*Tekie and Ellingwood*, 2003] or QUAKE/W [*Castro et al*., 1992].

4. SUMMARY

Aging is a natural phenomenon that leads to change in engineering strength with life cycle. This deterioration can reduce the resistance capacity of structure materials and give rise to serious problem of ECDs.

In this study, to examine aging degradation effects of concrete structures using finite element method, we targeted an ECD as the subject of study. Debris flow impact force was calculated and then input as dynamic load on modeled structure. Strength degradation over time was quantified according to previous study. As ongoing research, finite element analysis about the modeled ECD, which has decreased strength along time, will be conducted considering static load and dynamic load, such as debris flow impact force and seismic wave.

Engineering performance monitoring and structural maintenance (such as inspection and repair) are essential to reduce the risk of structural failure, and enhance structural functionality over operational period. This study provides with engineering techniques to assess the structural performance of landslide disaster mitigation/ prevention structures accurately.

4. SUMMARY

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REFERENCES

Armanini, A. (1997): On the dynamic impact of debris flows, Recent Developments on Debris Flows (eds A. Armanini and M. Michiue). Springer Berlin Heidelberg, pp. 208-226.

Burman, A., Maity, D., Sreedeep, S., and Gogoi, I. (2009): The behavior of aged concrete gravity dam under the effect of isotropic degradation caused by hygro-chemo-mechanical actions, Int. J. Eng. Stud., Vol. 2, pp. 105-122.

Castro, G., Seed, R. B., Keller, T. O., and Seed, H. B. (1992): Steady-state strength analysis of lower San Fernando Dam slide, Journal of Geotechnical Engineering, Vol. 118, No. 3, pp. 406-427.

Ellingwood, B., and Tekie, P. B. (2001): Fragility analysis of concrete gravity dams, Journal of infrastructure systems, Vol. 7, No. 2, pp. 41-48.

Gogoi, I., and Maity, D. (2007): Influence of sediment layers on dynamic behavior of aged concrete dams, Journal of engineering mechanics, Vol. 133, No. 4, pp. 400-413.

HüBl, J., and Holzinger, G. (2003): Development of design basis for crest open structures for debris flow management in torrents: miniaturized tests for the efficiency estimation of debris flow breakers. WLS Report, Vol. 50. (in German)

Hübl, J., Suda, J., Proske, D., Kaitna, R., and Scheidl, C. (2009): Debris flow impact estimation, The proceedings of the 11th International Symposium on Water Management and Hydraulic Engineering, pp. 137-148.

Hungr, O., Morgan, G., and Kellerhals, R. (1984): Quantitative analysis of debris torrent hazards for design of remedial measures, Canadian Geotechnical Journal, Vol. 21, No. 4, pp. 663-677.

Jeong, S., Kim, Y., Lee, J. K., and Kim, J. (2015): The 27 July 2011 debris flows at Umyeonsan, Seoul, Korea, Landslides, Vol. 12, No. 4, pp. 799-813.

Koo, R., Kwan, J. S., Ng, C. W. W., Lam, C., Choi, C., Song, D., and Pun, W. (2017): Velocity attenuation of debris flows and a new momentum-based load model for rigid barriers, Landslides, Vol. 14, No. 2, pp. 617-629.

Kuhl, D., Bangert, F., and Meschke, G. (2004): Coupled chemo-mechanical deterioration of cementitious materials Part I: Modeling, International Journal of Solids and Structures, Vol. 41, No. 1, pp. 15-40.

Mori, Y., and Ellingwood, B. R. (1993): Reliability-based service-life assessment of aging concrete structures, Journal of Structural Engineering, Vol. 119m No. 5, pp. 1600-1621.

Nakatani, K., Wada, T., Satofuka, Y., and Mizuyama, T. (2008): Development of “Kanako 2D (Ver. 2.00),” a user-friendly one-and two-dimensional debris flow simulator equipped with a graphical user interface, International Journal of Erosion Control Engineering, Vol. 1, No. 2, pp. 62-72.

Proske, D., Suda, J., and Hübl, J. (2011): Debris flow impact estimation for breakers, Georisk, Vol. 5, No. 2, pp. 143-155.

Scheidl, C., Chiari, M., Kaitna, R., Mullegger, M., Krawtschuk, A., Zimmermann, T., and Proske, D. (2013): Analysing Debris-Flow Impact Models, Based on a Small Scale Modelling Approach, Surveys in Geophysics, Vol. 34, No. 1, pp. 121-140.

Shinozuka, M., Feng, M. Q., Lee, J., and Naganuma, T. (2000): Statistical analysis of fragility curves, Journal of engineering mechanics, Vol. 26, No. 12, pp. 1224-1231.

Song, B. (2013): Domestic current situation for Forest disaster prevention program, Geoenvironmental engineering, Vol. 14, No. 1, pp. 27-34.

Suda, J., Strauss, A., Rudolf-Miklau, F., and Hübl, J. (2009): Safety assessment of barrier structures, Structure and Infrastructure Engineering, Vol. 5, No. 4, pp. 311-324.

Tekie, P. B., and Ellingwood, B. R. (2003): Seismic fragility assessment of concrete gravity dams, Earthquake engineering and structural dynamics, Vol. 32, No. 14, pp. 2221-2240.

Koo, B. K., Oh, B. H., Kim, Y. E., Kim, T. B., and Han, S. H. (1994): Estimation of Compressive Strength for Existing Concrete Structures by Non-Destructive Tests, Magazine of the Korea Concrete Institute, Vol. 6, No. 6, pp. 159-172. (in Korean)

Kim, M.-h., Song, B.-C., Ko, J.-S., Jung, S.-C., Kwon, Y.-J., Kim, G.-Y., and Kang, S.-P. (2000): A Study on the Evaluation of Deterioration Degree for Reinforced Concrete Apartments in Korea, Journal of the architectural institute of Korea: Structure and construction, Vol. 16, No. 6, pp. 89-95. (in Korean)

Park, K.-H., Kim, M.-S., Joh, S.-H., Lee, C.-W., Youn, H.-j., and Kim, K.-h. (2013): Study on the Stability Evaluation of Concrete Erosion Control Dam by using Non-destructive Test for Compressive Strength, Journal of Korean Forest Society, Vol. 102, No. 1, pp. 90-96. (in Korean)

Song, J.-U., Park, H., and Kim, S.-K. (2010): A Study on the Physical Property and Damage Index of Decrepit Concrete Materials, Explosives and blasting, Vol. 28, No. 2, pp. 59-68. (in Korean)