International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:12, No:1, 2018

Fragility Analysis of Weir Structure Subjected to Flooding Water Damage

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***Abstract*—**In this study, seepage analysis was performed by the level difference between upstream and downstream of weir structure for safety evaluation of weir structure against flooding. Monte Carlo Simulation method was employed by considering the probability distribution of the adjacent ground parameter, i.e., permeability coefficient of weir structure. Moreover, by using a commercially available finite element program (ABAQUS), modeling of the weir structure is carried out. Based on this model, the characteristic of water seepage during flooding was determined at each water level with consideration of the uncertainty of their corresponding permeability coefficient. Subsequently, fragility function could be constructed based on this response from numerical analysis; this fragility function results could be used to determine the weakness of weir structure subjected to flooding disaster. They can also be used as a reference data that can comprehensively predict the probability of failur,e and the degree of damage of a weir structure.

***Keywords*—**Weir structure, seepage, flood disaster fragility, probabilistic risk assessment, Monte-Carlo Simulation, permeability coefficient.

I. Introduction

RECENTLY, people are increasingly anxious about the global instability and large-scale natural disasters that occur frequently. As a result, the perception of safety is significantly growing. In this research, we focused on the safety evaluation of weir structure. Weir structure performs the role of electricity and water supply, as well as flood prevention against flooding disaster, as given in [1]. In case of weir structure, it can suffer from both natural disasters and human-induced disasters. Weir structure disaster has a major influence on water supply and electricity supply, and secondarily triggers inundation of the downstream area, and roads, public facilities, urban flooding, etc. It can cause great damage. This requires the focus on the examination and maintenance of the safety of the structure to prevent the occurrence of immense damage.

Fig. 1 shows the actual weir structure selected as the target structure in this study which is located in Daegu Metropolitan City. Based on the design plan and specifications, the commercially available finite element analysis program ABAQUS [2] was used to carried out the modeling and analysis. Moreover, the model was developed for each water level scenario and their corresponding permeability coefficient of the ground. Based on the results of structural analysis, we could determine the probability of failure which can incorporate with the lognormal cumulative distribution function to develop the fragility function of the weir structure. Fragility function can be used to construct damage prediction database and degree of damage which could aid in the preparation of future natural disasters.

Fig. 1 The focused weir structure

II. Basic Concept of Fragility Analysis

A fragility curve shows the probability of failure for the loading demand. When the loading demand exceeds a resistance capacity, the failure of the structure occurs. This failure criterion is the predefined limit state [3]. Because the fragility curve represents the probability that the weir structure exceeds any damage condition for a certain number of disasters, for example floods, thus the weir structure of several flooding disasters can be used as a very effective tool to evaluate fragility. Additionally, fragility function is a performance-based tool that links economic losses such as maintenance costs, maintenance periods and loss of human life with damage to structure systems and is essential for risk assessment and decision making. Subsequently, their application has become more and more necessary.

In order to create a fragility curve, several analytical methods and vulnerabilities functions were presented. In this research, fragility development used the Monte Carlo Simulation (MCS) technique to determine the probability of failure, then the maximum likelihood estimation (MLE) method was used to fit the probability of failure to the lognormal cumulative distribution function. The two parameters of lognormal cumulative distribution function were shown as the parameters of fragility function.

Fig. 2 shows the general concept of fragility analysis flowchart [4]. Fragility analysis and evaluation are also performed based on MCS. MCS generates random numbers loading demand and structure capacity correspond to the

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International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:12, No:1, 2018

probability distribution characteristics of random variables from the sample groups; and based on limit state condition, the estimation of failure probability was possible by repeating this process a sufficient number of times.

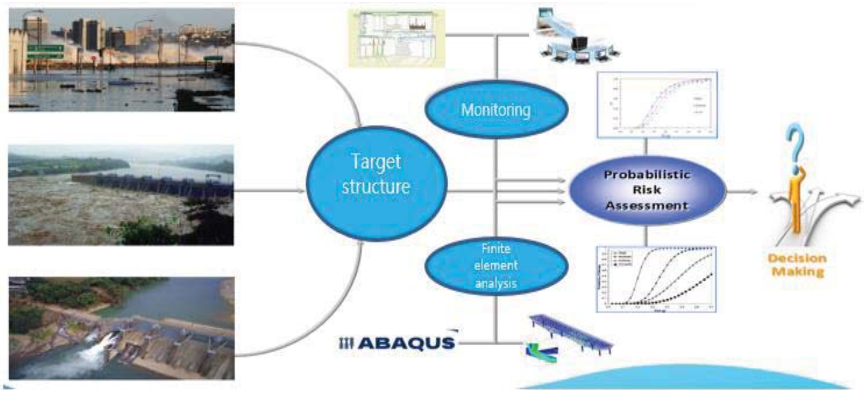

Fig. 2 Fragility analysis flow

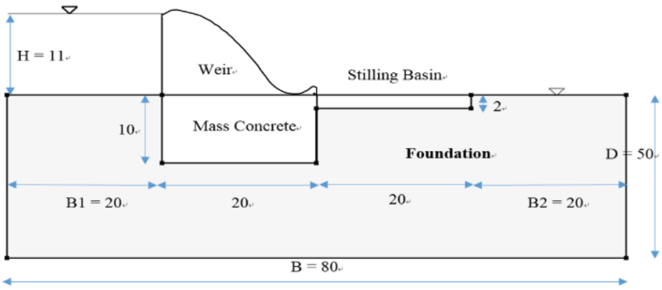

Fig. 3 Weir structure profile and dimensions

III. Weir Structure Modeling

In order to analyze structural weakness of weir, we first investigated the diagram of the structure, the material properties, and the physical properties of the adjacent ground. The diagram of the structure is shown in Fig. 3.

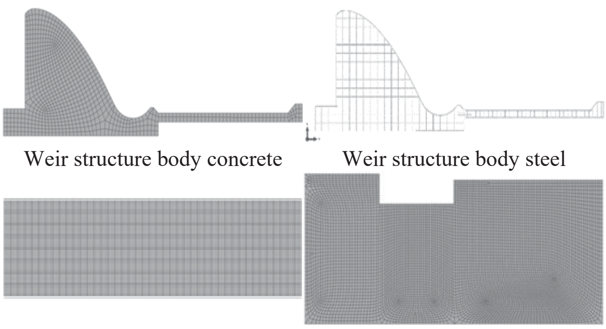

Fig. 4 Modeling of separated part of weir structure

Based on the specification and property of weir structure as shown in Fig. 3, the modeling of the weir was developed with the commercial finite element program ABAQUS. This finite element model was shown in separated part in Fig. 4 and with the fully contacted and integration in Fig. 5. Additionally, the material properties of weir structure component were based on the design guideline of concrete structure in Korea. The value in Table I was used in the finite element modeling of the weir structure in ABAQUS. Likewise, the ground material properties are the same as those of the actual weir structure. The value in Table II was applied using the general physical property values of the Daegu Metropolitan City ground in the Republic of Korea guideline.

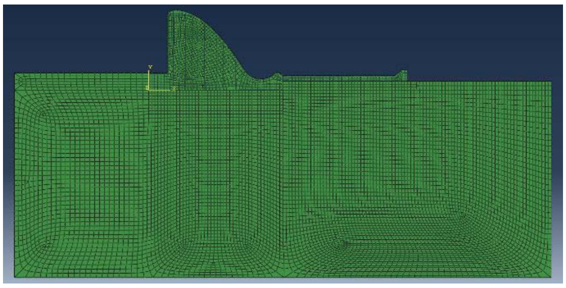

Fig. 5 Weir structure model

TABLE I
MATERIAL PROPERTIES OF WEIR STRUCTURE

Section	Compressive Strength (MPa)	Yield Strength (MPa)	Modulus of Elasticity (MPa)	Poisson's Ratio
Concrete	24	-	25,811	0.2
Steel	-	300	200,000	0.3
Mass concrete	18	-	25,181	0.2

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The load applied in the analysis of weir structure was shown in Table III and Fig. 6. Hydraulic forces and soil mechanic were applied based on the design situation.

TABLE II
GROUND PROPERTIES SUPPORTING THE WEIR STRUCTURE

Section	Unit Weight (kN/m^3)	Adhesiveness (kPa)	Internal Friction Angle (°)	Modulus of Elasticity (MPa)	Poisson's Ratio
Ground	21	30	30	200	0.33

TABLE III
LOAD TYPE APPLIED IN WEIR STRUCTURE

Load Type	Formula	Value Applied in ABAQUS		
		Low water level (N/mm^2)	Normal water level (N/mm^2)	Flood water level (N/mm^2)
Self - weight	ABAQUS automatic calculation	-9800 mm/s^2		
Hydrostatic pressure	$P_w = \gamma_w \times H^2 \times \frac{1}{2}$	0.1740	0.1911	0.2418
Hydrodynamic pressure	Westergaard hydrodynamic: $P_d = \frac{7}{8} \times K_h \times \gamma_w \times \sqrt{(H \times h)}$	0.01656	0.01859	0.02587
Uplift pressure	$U = \gamma_w \times C \times A \times [H^2 + \frac{1}{2}(H_1 - H_2) \times \tau]$	0.1776	0.1950	0.2645
Earth pressure	$H_s = Height\ from\ surface\ to\ base \times Underwater\ unit\ weight \times Earth\ pressure\ coefficient$	0.05		
		0.043		
		0.0098		

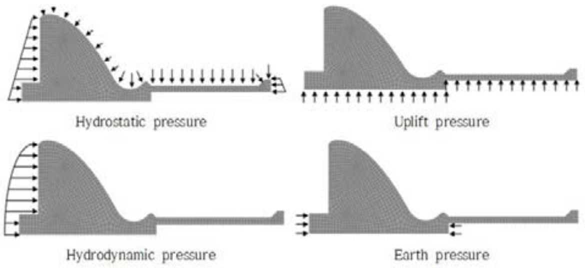


Fig. 6 Load applied to weir structure

The adjacent ground variables, permeability coefficients, with uncertainties discussed in this research were analyzed by various probability distribution models based on MCS. Fig. 7 and Table IV show three cases of permeability coefficient used in this study. CASE 1 is the actual value for ground properties in Daegu Metropolitan City. In CASE 2 and CASE 3, the artificial permeability coefficient probability density function was generated based on the probability density function of the actual ground property in CASE 1. Consequently, to determine the probability of failure of weir structure, we apply the three cases of permeability coefficient to each water level and compare their probability of failure.

IV. WEIR STRUCTURE FRAGILITY ANALYSIS

The collapse mechanism of the foundation of the weir structure occurs due to penetration phenomena through the foundation from the upstream to the downstream of the weir structure [5]. At this time, the penetration phenomenon can occur due to difference in water level between upper and lower stream due to flooding disaster.

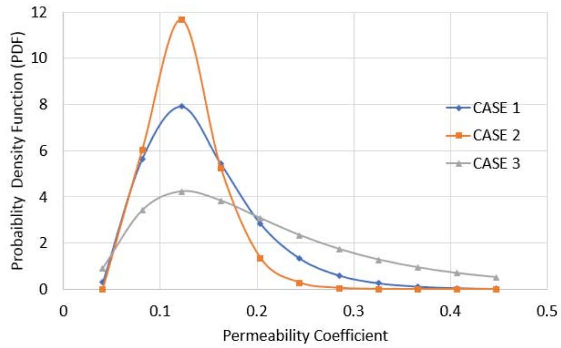


Fig. 7 Permeability coefficients log normal distribution

TABLE IV
PERMEABILITY COEFFICIENTS LOGNORMAL PROBABILITY DISTRIBUTION FUNCTION

Division	CASE 1	CASE 2	CASE 3
Permeability coefficients	0.134	0.1225	0.1827
M_u (Natural log)	-2.009	-2.1	-1.7
σ	0.402	0.280	0.630

During the flood the penetration phenomenon becomes more severe as the water depth increases at the upstream part of the weir structure. These penetration phenomena induce corrosion and migration of the soil particles inside the foundation layer. This resulted in the destruction of the soil in the ground. Since gradual corrosion leads to the loosening of the underwater soil particles at the time of penetration, the foundation destruction of the downstream of the weir structure is imminent. When this process is deepened, ground sinking continues up to the upstream part of the target structure throughout the foundation [6]. Permeation occurs along a series of lines, and penetration of 2D steady state as homogeneous and anisotropic soil can be represented by the Laplacian equation as:

$$K_x \frac{d^2\Phi}{dx^2} + K_y \frac{d^2T}{dy^2} = 0 \quad (1)$$

where, K_x and K_y are permeability coefficients in the X- and Y-axis directions, respectively, and Φ is pressure head. The performance failure function can be expressed as in (2). Also, the probability of failure can be expressed as in (3):

$$Z_r = i_{cr} - i_{ex} \quad (2)$$

$$P_f(failure) = P(Z_r < 0) \quad (3)$$

Using the commercially available finite element program ABAQUS, the determination of water seepage due to the increase of water level was shown in Fig. 8. The contours in Fig. 8 show the increment of water level from 1 m to 11 m. As shown in the figure, the direction of penetration and magnitude of force could be seen in the model of the ground section. This contour showed the water penetration from upstream to downstream through the lower ground of weir structure due to the difference in water depth between the two regions.

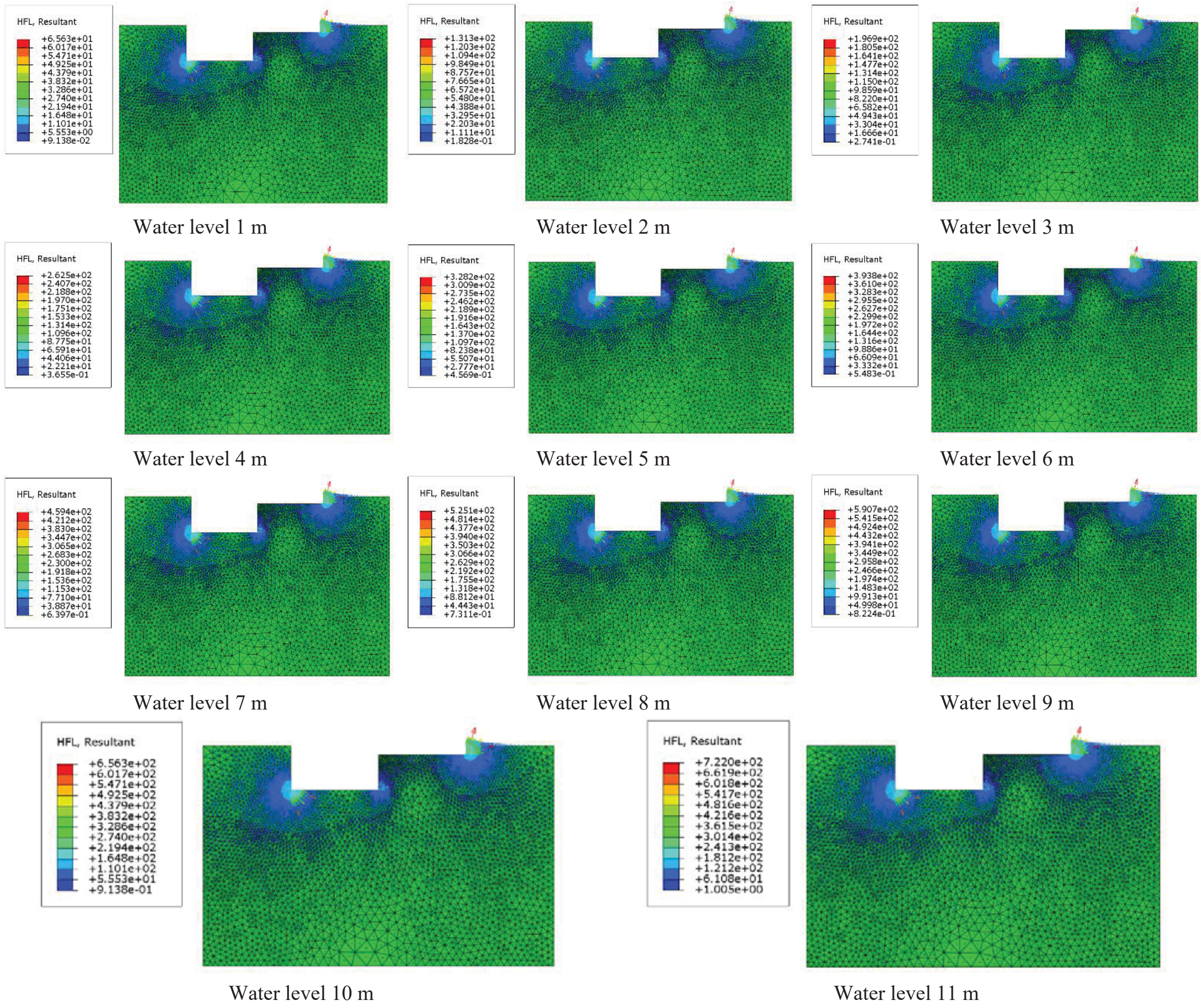
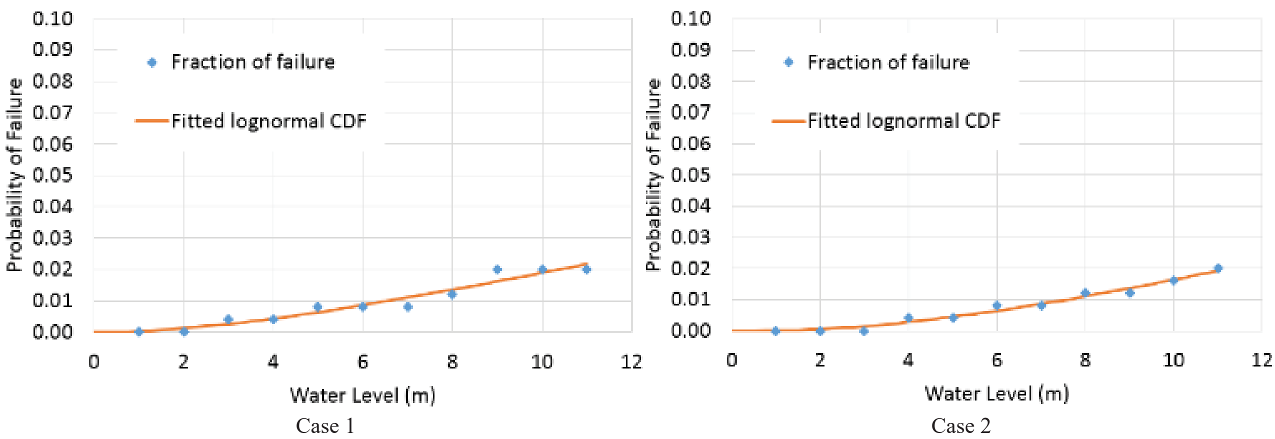
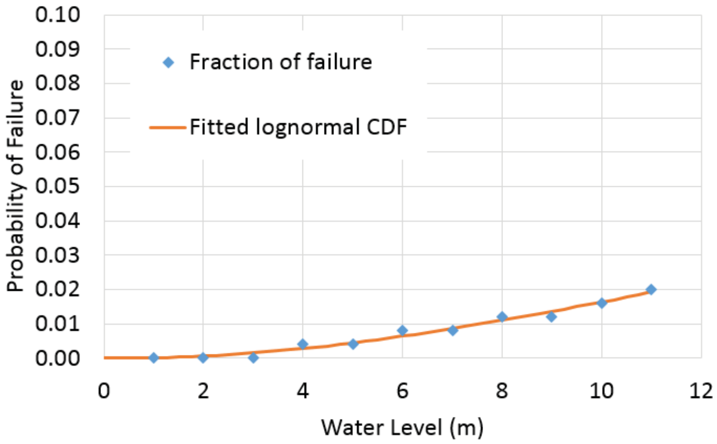


Fig. 8 Contour results of seepage analysis





Case 3

Fig. 9 Fragility curves for each case of permeability coefficient

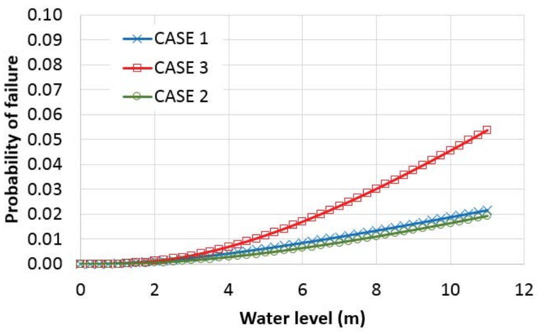


Fig. 10 Comparison of fragilities for all cases of permeability coefficient

Based on the seepage vulnerability analysis result of the weir structure for several flooding disasters, the failure probability corresponding to each water level of 1 m to 11 m was calculated and the fragility curve was developed. The fragility curves for each case were shown in Fig. 9; furthermore, for comparative analysis of all cases, the curves were plotted together as shown in Fig. 10. The overall fragility did not show a significant difference. The probability of failure in the case of applying probability distribution model of the permeability coefficient in CASE 2 has the lowest failure rate. However, when the probability distribution model of the permeability coefficient in CASE 3 was applied, the failure rate shown the highest value among all three cases.

TABLE V
FRAGILITY CURVE RESULT DATA

	μ	σ
CASE 1	5.749	1.659
CASE 2	5.399	1.450
CASE 3	4.310	1.188

Fragility parameters for the curves in Fig. 10 were shown in Table V. As can be seen, the parameters for CASE 1 and CASE 2 had similar value; however, for CASE 3, it has a smaller value which indicated a higher probability of failure. Therefore, the failure of weir foundation due to seepage is more likely for higher permeability coefficient.

V. CONCLUSIONS

In this research, we conducted a seepage fragility analysis of the weir structure subjected to flood disaster. Since the ground shows the difference in characteristics remarkably for each position, we investigated this randomness. Accordingly, adjacent ground variables, i.e. permeability coefficients, were analyzed and applied with three appropriate probability distribution models by considering their uncertainty. Moreover, the study was carried out for the three cases of the probability distribution of the permeability coefficient at the water level of 1 m to 11 m and the results were analyzed. Additionally, maximum principal stress and minimum principal stress of concrete and reinforcing bars of the weir structure were all calculated within the limit state range. As a result, the input values used in this study did not cause destruction exceeding the limit state of concrete for a weir structure corresponding to the water level.

The failure of weir structure adjacent ground could occur, based on the results of seepage analysis. The failure occurs for both the lower and upper limit of the water depth difference. However, the probability of occurrence is extremely low even in the case of the highest water depth difference. Therefore, the susceptibility of the weir structure to the influence of permeability coefficient was small for this case of study. But, the results showed that the probability of weir structure foundation failure increases proportionally with the permeability coefficient.

ACKNOWLEDGMENT

This research was supported by a Grant (17SCIP-B065985-05) from Smart Civil Infrastructure Research Program funded by Ministry of Land, Infrastructure and Transport (MOLIT) of Korea government and Korea Agency for Infrastructure Technology Advancement (KAIA).

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