The Seventh Asian-Pacific Symposium on Structural Reliability and Its Applications (APSSRA2020)
October 4–7 2020, Tokyo, Japan
T. Takada, I. Yoshida & T. Itoi (editors)

Risk Evaluation for Earth-fill Dams due to Heavy Rains
- Efficient Risk Evaluation by Response Surface Method -

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Abstract: Japan has many decrepit earth-fill dams that were constructed hundreds of years ago. As the breaches of earth-fill dams after heavy rains lead to downstream flooding and cause extensive damage to catchment areas, the implementation of countermeasures against the breaching of these decrepit dams is absolutely necessary. However, approximately 170,000 earth-fill dams exist in Japan, and it would be impossible to improve all the dams due to limited financial resources. In order to repair and reinforce earth-fill dams efficiently, it is necessary to establish criteria and to decide which dams should take precedence through risk evaluations based on the product of the damage costs and the probability of failure. This paper presents the estimation of the damage costs due to flooding after the breaches of 10 earth-fill dams in Hiroshima Prefecture. Although detailed analytical methods for estimating the damage costs have been established, they are complicated and require a great deal of time and effort. Therefore, simplified methods are needed for selecting the earth-fill dams that must be preferentially repaired and reinforced. The response surface method is applied to reduce the time and effort in estimating the damage costs. From the results, the practical application of a risk evaluation using the response surface method is verified in order to prioritize the order in which decrepit earth-fill dams are to be repaired and reinforced.

Keywords: Earth-fill dams, Risk evaluation, Response surface method.

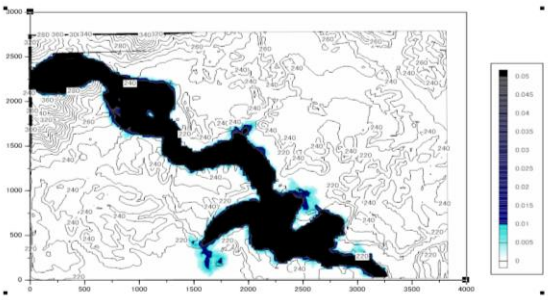
1. Introduction

In Japan, there are many decrepit earth-fill dams that were constructed hundreds of years ago. In addition, natural disasters, for instance, heavy rains, have been increasing recently because of climate change. When the breaches of earth-fill dams occur due to heavy rains, they frequently lead to downstream floods that have a great influence on the hydraulic structures for irrigation and drainage. Therefore, it is necessary to repair and reinforce decrepit earth-fill dams to prevent them from breaching. It would be impossible to improve all the hydraulic structures under limited financial resources, because approximately 170,000 earth-fill dams exist in Japan. In order to repair and reinforce the dams efficiently, it is desirable to establish criteria and to decide which dams take priority, based on flood damage, in terms of their repair and improvement.

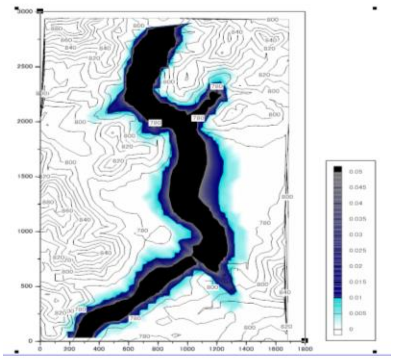
Although detailed analytical methods for estimating the damage costs have been proposed, they involve spending enormous amounts of time and effort. Therefore, simplified methods are necessary for prioritizing the

Table 1. Summary of earth-fill dam sites.

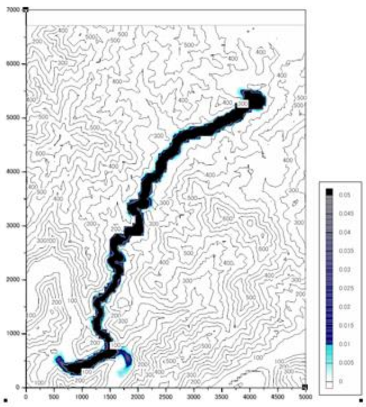
Dam site	Height (m)	Total volume of water (m^3)	Catchment area (km^2)	Spillway capacity (m^3/s)	Land use of catchment area	Observatory
A	10.0	66,210	0.32	1.96	Urban district	Kure
B	9.0	155,400	0.2	2.85	Urban district	Kure
C	26.0	255,000	2.5	25.4	Forest	Shiwa
D	5.5	21,600	0.72	Unknown	Forest	Yawata
E	9.3	49,600	0.193	3.04	Forest	Tsushimi
F	6.3	13,700	0.709	0.23	Forest	Miiri
G	4.7	1,019	0.23	11.3	Forest	Hiroshima
H	9.1	6,040	0.54	11.45	Forest	Hiroshima
I	9.9	27,868	0.03	23.27	Golf course	Shiwa
J	6.5	3,100	0.01	3	Urban district	Kure



(a) Dam *C*



(b) Dam *D*



(c) Dam *E*

Figure 1. Maximum flood depth (m).

earth-fill dams that must be repaired and reinforced. In order to reduce the total processing time and effort in estimating the damage costs, a simplified estimation method for damage costs due to flooding after the breaches of earth-fill dams is proposed using the response surface method. The purpose of this paper is to calculate the failure risks of earth-fill dams using a detailed analysis and the response surface method, and to evaluate the accuracy of this method.

2. Selection of 10 Earth-fill Dams

Hiroshima Prefecture is located in the Chugoku Region of Japan along the Seto Inland Sea; it has approximately 20,000 earth-fill dams. The heavy rain event of July 2018 caused serious damage to several of the dams in this prefecture. The 10 earth-fill dams listed in Table 1, with different sizes and catchment areas, are adopted as the target dams in this study.

3. Calculation of Failure Risks

A risk is defined as the product of damage costs and failure probability (Nishimura 2017, 2020). To calculate the damage costs, this paper combines information from the results of a flood analysis and land-use data. The probability of failure due to flooding is caused by slip failure and/or overflow. This chapter describes the calculation of failure risks.

3.1 Flood analysis

Various hydrological factors, which are computed by the flood analysis, affect the magnitude of flood damage. The flood analysis is carried out here by means of the shallow water equation, and the governing equations are denoted in the following forms (Toro 1999; Yoon and Kang 2004; Nishimura 2005):

$$\frac{\partial \mathbf{U}}{\partial t}+\frac{\partial \mathbf{F}}{\partial t}+\frac{\partial \mathbf{G}}{\partial t}=\mathbf{S} \tag{1}$$

$$\mathbf{U}=\begin{Bmatrix} h \\ uh \\ vh \end{Bmatrix} \tag{2}$$

$$\mathbf{F}=\begin{Bmatrix} uh \\ u^2h+gh^2/2 \\ uvh \end{Bmatrix} \tag{3}$$

$$\mathbf{G}=\begin{Bmatrix} uh \\ uvh \\ v^2h+gh^2/2 \end{Bmatrix} \tag{4}$$

$$\mathbf{S}=\begin{Bmatrix} 0 \\ ghS_{ox} \\ ghS_{oy} \end{Bmatrix}+\begin{Bmatrix} 0 \\ -ghS_{fx} \\ -ghS_{fy} \end{Bmatrix} \tag{5}$$

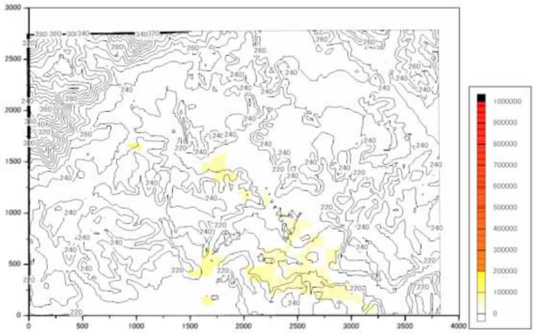
where t is time, u and v are the flow velocities in the x and y directions, respectively, h is the inundated water depth, and g is the gravitational acceleration. S_{ox}, S_{oy}, S_{fx}, and S_{fy} are expressed as follows:

$$S_{ox}=-\frac{\partial z_b}{\partial x} \tag{6}$$

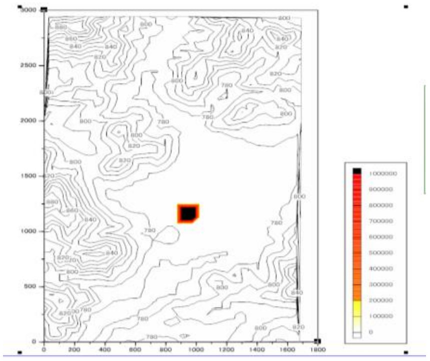
$$S_{oy}=\frac{\partial z_b}{\partial y} \tag{7}$$

$$S_{fx}=\frac{n^2u\sqrt{u^2+v^2}}{h^{4/3}} \tag{8}$$

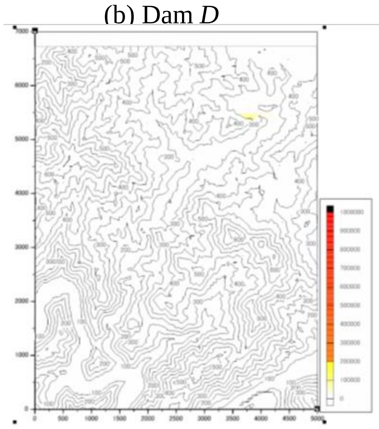
$$S_{fy}=\frac{n^2v\sqrt{u^2+v^2}}{h^{4/3}} \tag{9}$$



(a) Dam *C*

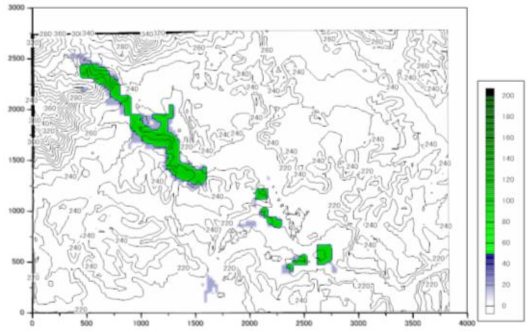


(b) Dam *D*

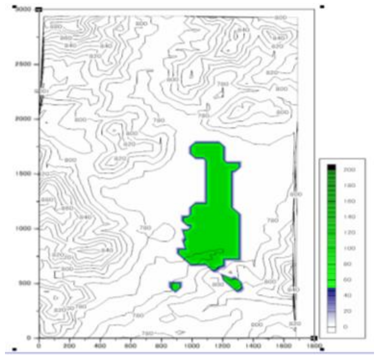


(c) Dam *E*

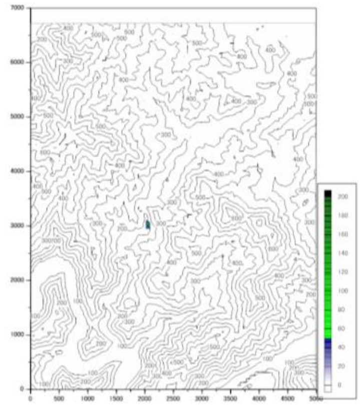
Figure 2. Distribution of damage costs of industry (1,000 JPY/m^2).



(a) Dam *C*



(b) Dam *D*



(c) Dam *E*

Figure 3. Distribution of damage costs of agriculture (1,000 JPY/m^2).

where z_b is the ground elevation and n is the Manning roughness coefficient. The equations are solved by the finite volume method with the HLL-Riemann solver for indicating the flood areas of the dams and the distribution of the maximum inundation depth of each cell. The mesh sizes are set at 25 m and 50 m, based on GIS information, and the minimum depth of 0.01 m and the Manning roughness coefficient of 0.035 s/m$^{1/3}$ are employed. Example distributions of the maximum inundation depth around dams *C*, *D*, and *E* are exhibited in Figures 1(a), (b), and (c), respectively.

3.2 Land Use and Asset Data

The classification data on land use and the asset data around the earth-fill dam sites are collected via the Internet. In order to simplify the evaluation of the failure risk, only free data are acquired from an online database. Regarding the classification data on land use, such as forests, building sites, and roads, the 100-m mesh data on land use can be obtained from the website of the National Land Information Division of National Spatial Planning and Regional Policy Bureau in the Ministry of Land, Infrastructure, Transport and Tourism.

The asset data are obtained from e-Stat which is a portal site for Japanese Government Statistics. The asset data are the number of offices, employees, and households in 500-m mesh, the number of offices and employees classified by industry in each area, the number of households for each style of building, the total

Table 2. Daily precipitation.

Observatory	Probability distribution curve	Daily precipitation (mm/day)				
		10 years	50 years	100 years	200 years	400 years
Kure	SqrtEt	154	216	245	276	308
Shiwa	SqrtEt	161	229	260	291	325
Yawata	SqrtEt	223	320	366	414	465
Tsushimi	Gumbel	170	229	254	278	303
Miiri	Gumbel	173	227	250	273	296
Hiroshima	SqrtEt	158	219	248	278	310

Table 3. Failure probability.

Dam	Slip failure	Overflow
A	1/400	1/10
B	1/400	1/50
C	1/400	1/10
D	1/400	1/10
E	1/400	1/50
F	1/400	1/10
G	1/400	1/400
H	1/400	1/400
I	1/50	1/400
J	1/400	1/400

floor area, crop acreage, and annual yield in the local area.

Data on the relationship between the flood depth and the damage percentage, and the appraised value of the assets are taken from the flood control and economic research manual (The Ministry of Land, Infrastructure and Transport 2005) to calculate the damage costs. The flood area and land-use data are placed in layers; the approximate damage costs of each mesh are estimated from the maximum flood depth, classification data on land use, and asset data. Example distributions of the damage costs around dams *C*, *D*, and *E* are simply displayed in (a), (b), and (c), respectively, of Figures 2 and 3.

3.3 Calculation of Failure Risks

The risk is equal to the product of the failure probability of earth-fill dams due to heavy rains and the damage costs due to flooding after breaches (Nishimura, et al. 2020). Failure due to flooding is caused by slip failure and/or overflow, and the probability of failure stems from the probabilistic hyetograph based on the past rainfall data obtained at the point closest to a Japan Meteorological Agency (JMA) observatory. The rainfall time series for the heaviest rainfall in the past was adopted as the base waveform, and a hyetograph was prepared for each return period. Table 2 summarizes the maximum value of the daily probabilistic precipitation at each rainfall observatory corresponding to return periods of 10, 50, 100, 200, and 400 years. The cumulative probability distribution curves in the second column of the table fit well for the observations, and SqrtEt stands for the square root index-type maximum distribution.

The failure probability of overflow is calculated when flood inflow Q_{in} in Eq. (10) is larger than the discharge capacity of the spillway, Q_s, in Eq. (11) based on the return period at the dam site.

$$Q_{in} = \frac{1}{3.6} \cdot r_e \cdot A \tag{10}$$

$$r_e = f_p r \tag{11}$$

$$Q_s = C_d \cdot B_e \cdot h_s^{3/2} \tag{12}$$

where r_e is the mean effective strength within the flood concentration time (mm/hr), A is the catchment area (km^2), f_p is the peak runoff coefficient, r is the maximum rainfall intensity (mm/hr), C_d is the discharge coefficient, B_e is the width of the spillway (m), and h_S is the static or piezometric head on a weir referred to as the weir crest (m). The probability of slip failure is calculated by the modified Fellenius method, based on the return period. A safety factor of less than 1 represents likely failure. The modified Fellenius method in conjunction with an unsaturated seepage flow analysis is carried out with the change in the subsurface water level.

Table 3 shows the failure probability calculated by the inverse of the return period. For some locations, the uncertainty in the return periods is very large. If the return period exceeds 400 years, it is set at 400 years. The table implies that overflow is more dominant than slip failure as a factor in the damage of earth-fill dams.

4. Response Surface Method

4.1 Outline

The response surface method is included in the experimental design (Yamada 2005). The methodology produces regression equations, called the response surface, that quantitatively express the relationships between responses (output) and factors (input) by a regression

Table 4. Results of risk evaluation and comparison of detailed analysis and response surface.

Dam site	Detailed analysis		Response surface	
	Failure risk (Millions of JPY)	Ranking	Failure risk (Millions of JPY)	Ranking
A	1,167	**2**	2,446	**2**
B	373	**3**	1,097	**3**
C	1,850	**1**	7,265	**1**
D	348	4	203	5
E	0.2	9	44	8
F	34	7	-2,225	9
G	23	8	254	4
H	136	5	181	6
J	57	6	116	7

analysis. The basic function is the following equation:

$$y_R = \beta x_R + \varepsilon_R \tag{13}$$

where y_R is the function that represents the response surface, β is the regression coefficient vector, x_R indicates the variable vector that represents the dominant factor, ε_R is the error term, and y_R represents the damage costs due to flooding. Regarding x_R, a sensitivity analysis for the screening experiment is applied to narrow down the sensitive and dominant factors from all the factors. Although damage costs can be accurately calculated by a flood analysis and a land-use evaluation, such detailed analyses cannot be applied to so many earth-fill dam sites because of the huge calculation costs. It is suggested that the response surface method would be useful for simplifying risk evaluations.

4.2 How to Find Response Surface

The following five parameters are adopted as the dominant factors for determining the response surface:

a) Effective volume of water
b) Median of inclination of main flood watercourse
c) Number of households per available 1-km^2 area
d) Number of employees per available 1-km^2 area
e) Ratio of median of altitude of flooded buildings' to altitude of source

Among the 10 earth-fill dam sites, the damage cost of Dam *I* cannot be accurately calculated, because the catchment area is used for a golf course. Thus, the other nine sites are targeted for the risk evaluation. Furthermore, in order to improve the accuracy of the response surface, 18 analysis patterns are added by dispersing the parameters of each earth-fill dam site. Finally, response surface C_f (JPY) is determined by analyzing 27 cases.

5. Results

The following equation, that represents response surface C_f, was found:

$$C_f = 326 \times a + 3.947 \times 10^6 \times b + 26{,}788 \times c - 24{,}881 \times d - 4.153 \times 10^7 \times e \tag{14}$$

where *a*, *b*, *c*, *d*, and *e* are the dominant factors, as previously mentioned. Table 4 shows a comparison of the detailed analysis and the response surface for the failure risks and their rankings for each earth-fill dam site. The bold numbers represent the higher-ranking failure risks. As for the failure risks, there were differences between the detailed analysis and the response surface. On the other hand, the higher-ranking risks of the detailed analysis were consistent with those of the response surface.

6. Conclusions

In this paper, an evaluation of the failure risks for 10 earth-fill dam sites due to heavy rains was conducted. In order to simplify the evaluation, the response surface method was adopted. As a result, there were differences in the failure risks between the detailed analysis and the response surface, although the tendency of their rankings was similar.

The response surface should be applied to many of the earth-fill dam sites that exist nationwide because it will enable a drastic reduction in calculation costs. The practical application of risk evaluations using the response surface is recommended in order to prioritize the order in which decrepit earth-fill dams are to be repaired and reinforced.

Acknowledgments

This work was supported by Grant-in-Aid for Scientific Research (A) Grant Number 16H02577 (Representative: Shin-ichi Nishimura) from the Japan Society for the Promotion of Science (JSPS) KAKENHI.

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