Evaluation of expected damage costs for earth-fill breaches due to heavy rains by response surface method

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ABSTRACT

In this study, the damage costs due to dam breaches are estimated by the response surface method. The procedure for calculating the risks and the expected total cost at earth-fill sites, based on the estimated damage costs, is presented. The proposed approach is applied to actual earth-fill dam sites; and consequently, the possibility of its practical use is proved.

Keywords: earth-fill dam; reliability-based design; response surface method; damage cost; dam breach

1 INTRODUCTION

Floods due to dam breaches have the greatest influence on the infrastructures in the down-stream area, and estimating the costs of the damage to these structures is important for risk assessments. Nishimura et al. (2015a and 2015b) have tried to apply a reliability-based design for such dam breaches.

The existing methods for estimating damage costs require an exact flood simulation and usually is time consuming, because of complicated conditions. Thus, they are not efficient for application to practical problems. To overcome this dilemma, the authors propose a surrogate model called the response surface (RS) method (Yamada, 2014). The aim of this study is to validate the accuracy of the proposed RS for assessing the risk of dam breaches due to heavy rains.

The Monte Carlo method can be easily applied to RS with low computational and operation costs. The RS method, which estimates the damage costs in the downstream area submerged by floods, can be identified as a regression function of the volume of the reserved water, the average inclination of the flood runway, the density of the houses and the population inside the submerged area, and other factors. Then, the damage costs calculated by the RS method and the exact method, based on the flood simulation, are compared to verify the utility of RS. The expected total costs for the dam breaches and the dam improvements are also compared. Finally, the applicability of the RS method for prioritizing the improvement works, among the numerous deteriorated earth-fill dams, is considered through a case study.

2 QUASI-RAINFALL MODEL

In this research, rainfall events continuing for 72 hours are simulated based on the annual maximum rainfall intensities obtained from rainfall data records in Okayama City, Japan for a span of 45 years. A dam breach almost happens within 24 hours on an empirical basis. To cover all cases, the longer consecutive rainfalls of 72 hours are used. The cumulative distribution function F_k (x) of rainfall intensity x (mm/h), for k (=1~72) hours after the rain starts, is determined with the mean rank method (Iwai and Ishiguro 1970) as follows:

$$F_k\left(x\right)=m_k\left(x\right)/\left(N+1\right) \tag{1}$$

where $m_k(x)$ is the number of rainfall intensities after k hours that do not exceed x, and N denotes the number of years. Rainfall intensity x (mm/h) is then transformed into random variable y following the standard normal distribution as

$$y=\Phi^{-1}(F_k(x)) \tag{2}$$

where Φ is the standard normal distribution function. Correlation coefficients ρ_{ij} (i,j = 1, 2, …, 72) between probabilistic variable y, after i hours and j hours, can be estimated by the following equation:

$$\rho_{ij}=E\left[\frac{\left(y_i-m_i\right)\left(y_j-m_i\right)}{\sigma_i\sigma_j}\right] \tag{3}$$

in which m_i is mean and σ_i is standard deviation of y_i. Here, the set of correlation coefficients is viewed as a matrix, namely, $\mathbf{R}$ = [ρ_{ij}]. Since $\mathbf{R}$ is positive definite, lower triangular matrix $\mathbf{L}$, satisfied with $\mathbf{LL}^T = \mathbf{R}$, is obtained by the Cholesky decomposition. A normal random number vector, $\mathbf{Y}$ can be produced as follows:

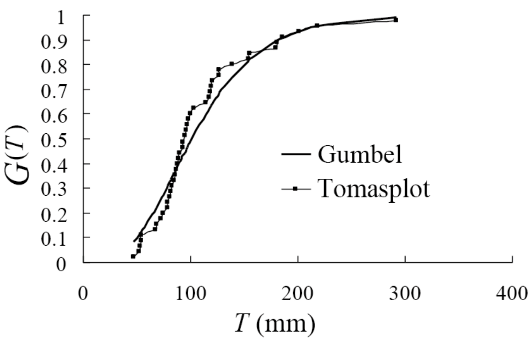

Fig. 1. Cumulative distributions of maximum annual continuous precipitation of 72 hours.

$$\mathbf{Y} = \mathbf{Lz} \tag{4}$$

where **z** is a standard normal random number vector generated by the Box-Muller method (Rubinstein1980). Then, normal random number Y_k, (k=1,2,..., 72), which is a component of **Y** is transformed into random number X_k, which is a component of **X** and has the same distribution as the actual rainfall, using the following equation:

$$X_k = F_k^{-1}\left(Y_k\right) \tag{5}$$

If X_k, (k=1,2,..., 72) is used directly as the quasi-rainfall, the pattern causing overflows may be fixed, because the cases of heavy rains are very limited. To prevent this, a method is proposed whereby the rainfall intensity is decreased or increased, while keeping the shape of the hyetograph. The Gumbel distribution is assumed for the distribution of total rainfall T (mm/72hours) of the annual maximum 72-hour rainfalls, and $G(T)$ is determined as follows:

$$\sum_{i=1}^{72} x_i = T \tag{6}$$

$$G(T) = \exp\left(-e^{-s}\right), \quad s = a\left(T - T_0\right) \tag{7}$$

where x_i is the intensity of the annual maximum 72-hour rainfalls after i hours, and a and T_0 are the parameters employed to adjust the observed data to the theoretical distribution function (Iwai and Ishiguro 1970). Then, random variable T' is generated as the total rainfall from Gumbel distribution $G(T)$, as shown in Fig. 1.

Lastly, the adjusted rainfall intensity, X_k' (mm/h), is the random number of the intensity corresponding to the annual maximum 72-hour rainfalls after k hours and determined for each hour, as seen in the following equation:

$$X_k' = \left(T' \Big/ \sum_{i=1}^{72} X_i\right) X_k \tag{8}$$

3 EVALUATION METHOD FOR PROBABILITY OF OVERFLOW AND FLOOD SIMULATION

At first, the quantities of inflow, discharge, and storage are calculated. The inflow equation is defined as follows (JSIDRE 2002):

$$Q_{in} = f_p rA/3.6 \tag{9}$$

where Q_{in} = inflow to the reservoir (m^3/s), f_p is the peak runoff coefficient, r is the quasi-rainfall intensity (mm/h) generated in Chapter 2, and A is the area of the basin (km^2). Uniform random numbers are used for f_p in the range of 0.7 to 0.8 (JSIDRE 2002). The discharge equation for a rectangular weir, as used in this study, is

$$Q_{out} = CB_S h^{2/3} \tag{10}$$

where Q_{out} = discharge(m^3/s), C = discharge coefficient, B_s = width of spillway, and h = static or piezometric head on a weir referred to as the weir crest.

The probability of overflow is then defined by Equation (11) as the number of $Q_{out} < Q_{in}$ per iterations of the Monte Carlo simulation (Rubinstein1980).

$$P_{of} = \mathrm{Prob}\left[Q_{out} < Q_{in}\right] \tag{11}$$

As the basic governing equations, two-dimensional shallow water equations are employed. The equations are solved by the finite volume method (Toro 1999) (FVM), employing two-dimensional rectangular cells. The FVM is a numerical method based on an integral type of equation, with the HLL Rieman solver (Yoon and Kang 2004).

4 RESPONSE SURFACE METHOD

The response surface method, which is based on the experimental design concept (Yamada, 2014), can be expressed as a regression function, as seen in the following equation:

$$y_R = \boldsymbol{\beta}\mathbf{x}_R + \varepsilon_R \tag{12}$$

where y_R is the response surface, x_R is the factor variable vector, $\boldsymbol{\beta}$ is the regression coefficients vector, and ε_R is the error term. By substituting the matrix of several sampled values of $\mathbf{x}_R$, $\mathbf{X}_R$, and output vector $\mathbf{Y}_R$ into Equation (12), Equation (13) is obtained.

$$\mathbf{Y}_R = \mathbf{X}_R\boldsymbol{\beta} + \mathbf{E}_R \tag{13}$$

where $\mathbf{E}_R$ is the error term vector. By minimizing $\mathbf{E}_R^T\mathbf{E}_R$, the optimum regression coefficient vector, $\hat{\boldsymbol{\beta}}$, is determined as

$$\hat{\boldsymbol{\beta}} = \left(\mathbf{X}_R^T\mathbf{X}_R\right)^{-1}\mathbf{X}_R^T\mathbf{Y}_R \tag{14}$$

In this study, variable y_R represents the damage costs due to floods, and variable x_R represents the factors related to these damage costs, which are selected through a sensitivity analysis. Although the damage costs can be estimated precisely from the flood simulation described in Chapter 5, the procedure requires huge computing costs. Since efficient calculations are required for the risk evaluation at so many sites, the response surface method is introduced here as a more convenient approach. If precise flood simulations for sampled factors $\mathbf{X}_R$ are conducted, and corresponding damage costs $\mathbf{Y}_R$ are obtained, regression coefficient vector $\boldsymbol{\beta}$ is determined. Once

Table 1. Profiles of studied sites.

		Site A	Site B	Site C
Outline of farm ponds	Number of dams	2	2	1
	Amount of effective reserved water ($1{,}000\ m^3$)	Upstream 216	Upstream 84	10
		Downstream 212	Downstream 96	
	Height of earth-fill (m)	Upstream 11.8	Upstream 9.0	6.7
		Downstream 11.6	Downstream 9.0	
	Longitudinal length of earth-fill (m)	Upstream 99	Upstream 129	56
		Downstream 111	Downstream 202	
	Beneficial area (ha)	Upstream 12	Upstream 12	5
		Downstream 12	Downstream 18	
Outline of downstream area	Population /km^2	915	946	368
	Houses /km^2	334	324	121
	Working persons /km^2	862	124	186
	Business facilities /km^2	42	25	24
	Area of farm (ha/km^2)	31.2	56.3	57.0
	Restoration cost of agricultural facilities (million JPY)	-	76	-
	Damage cost (1,000 JPY)	4,672,561	2,969,700	186,734

*Sites A and B have two sequential earth-fill dams of the upstream and downstream.

Table 2. Profiles of validation sites.

		Factor	Site D	Site E
Outline of farm ponds	Number of Ponds		1	1
	Amount of effective reserved water (1,000 m3)	a	105	200
	Height of earth-fill (m)		15.7	12.1
	Longitudinal length of earth-fill (m)		93.5	118
	Beneficial area (ha)		23	30
Downward area	Median inclination on main route of flood (%)	c	0.406	0.513
	Population /km^2		1,145	1,269
	Houses /km^2	e	407	454
	Working persons /km^2	f	528	235
	Business facilities /km^2		67	37
	Area of farm (ha/km^2)		27.2	39.3
	Median elevation of housing and business area in flood area	i	0.23	0.14
Damage cost (1,000 JPY)			3,279,482	3,314,806

coefficient β has been determined, the damage costs can be estimated by means of Equation (12).

5 CASE STUDY

5.1 Profile of studied site

Three earth-fill dam areas are selected for the studied area to determine the response surface. The profiles are presented in Table1. Site A is the maximum dam, while Site C is the minimum one. The damage costs can be estimated based on the results of the flood simulation and the costs for the loss of the facilities existing in the submerged area. The estimated damage costs are also presented in Table1.

5.2 Response surfaces of studied area

By means of the sensitivity analysis, the dominant factors affecting the damage costs are selected, namely, the factor variable vector can be determined. In this research, the following five factors are selected. Factor i is explained in Fig. 2.

a: Amount of effective reserved water ($1{,}000\ m^3$).

c: Median inclination on main route of flood (%).

e: Number of houses /km^2.

f: Number of working persons /km^2

i: Median elevation of housing and business area in flood area.

In order to determine the response surfaces, 21 sample cases are prepared by solving the flood simulation. The sample cases are created by assigning the variability to each factor based on the properties of Sites A, B, and C, hypothetically. Response surface RS, as the damage costs, C_{fRS}, is determined as

$$C_{fRS} = 15{,}880 \times a - 3.959 \times 10^8 \times c + 7{,}951 \times e + 1{,}492 \times f + 5.183 \times 10^6 \times i \quad (15)$$

A comparison of the calculated damage costs of 21 cases between exact method and the RS method is presented in Fig. 3. According to the figure, function C_{fRS} can approximate the 21 cases well, and the coefficient of the determination is $r^2 = 0.79$.

The RS is applied to other sites, namely, D and E, for validation. The profiles of the two sites are presented in Table 2, and the table includes the damage costs for Sites D and E calculated based on the exact flood simulation. Moreover, Fig. 3 includes the results for Sites D and E, and the damage costs of the two applied sites are predicted well by the RS.

5.3 Evaluation of risk and expected total cost

The risk is evaluated from the probability of overflow and damage costs. The following equation is proposed for the risk at the two states, namely, the original and the improved earth-fills.

$$C_T = C_0 + C_f \times E[n] \quad (16)$$

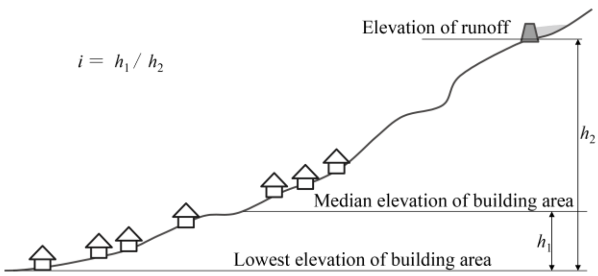

Fig. 2. Description of factor i.

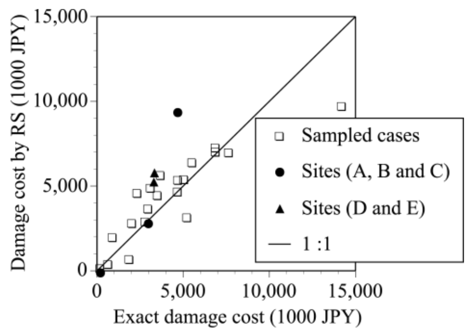

Fig. 3. Comparison of exact and RS approaches.

Table 3. Results of reliability analysis.

	Sites	A	B	C	D	E
Probability of overflow	Original (Priority)	0.02262 (1)	0.00516 (5)	0.00895 (3)	0.02239 (2)	0.00664 (4)
	Improved	0	0	0	0	0
Improvement cost (1000JPY)	C_B	387,009	469,940	55,287	129,003	285,650
Exact approach	Damage cost (1,000 JPY)	4,672,561	2,969,700	186,734	3,279,482	3,314,806
	Expected total cost (1000,JPY) C_A	3,184,135	676,856	67,609	2,222,453	939,106
	Effect of improvement work A-B (Priority)	2,797,126 (1)	206,916 (4)	12,322 (5)	2,093,450 (2)	653,456 (3)
Response surface method	Damage cost (1,000JPY)	7,997,972	3,094,007	199,743	4,343,181	4,632,453
	Expected total cost (1,000 JPY) C_A	5,450,249	705,188	72,319	2,943,305	1,312,404
	Effect of improvement work C_A-C_B (Priority)	5,063,240 (1)	235,248 (4)	17,032 (5)	2,814,302 (2)	1,026,754 (3)

$$E[n] = \begin{cases} \sum_{k=1}^{t_l} \left[P_O (1-P_O)^{k-1} \{1+(t_l-k)P_I\} \right] & \text{(Original)} \\ t_l \cdot P_I & \text{(Improved)} \end{cases} \qquad (17)$$

in which C_T is the expected total cost, n is the frequency of overflows within a lifetime span of t_l (years), P_O and P_I are the probabilities of overflow a year corresponding to the original and the improved states of the embankment, respectively, C_0 is the cost of the improvements, and C_f is the damage cost due to flooding. P_O and P_I coincide with the P_{of} derived from Equation (11), corresponding to the two states. The improved state means that the function of the spillways of the dams has been reinforced and that the surfaces of the earth-fills have been compacted with additional materials. In this study, the case of t_l =50 years is considered.

The results for the five sites are presented in Table 3. The response surface is revised incorporating the results of the Sites D and E as the next equation.

$$C_f = 13,275 \times a - 2.913 \times 10^6 \times c + 5,278 \times e + 1,325 \times f + 5.582 \times 10^6 \times i \qquad (18)$$

The effect of the improvement work can be evaluated by the difference between the expected total costs of the original and the improved earth-fills, C_A-C_B. The order of the effects. C_A-C_B corresponds to the priority of the planning of the improvement works. In the table, the exact method and the RS method are compared. Although there is a relatively large gap for the absolute values of the expected total costs between the two approaches, the predicted priorities are the same.

6 CONCLUSIONS

(1) An evaluation method for the damage costs of earth-fill dams due to heavy rains has been proposed based on the response surface (RS) method.

(2) The RS of the damage costs has been determined based on the properties of three studied sites, and the method has been validated by applying it to two other sites. Consequently, the determined RS method has been presented as being applicable to other sites.

(3) The risks and the expected total costs of the original and the improved states of five earth-fill dam sites have been given. The priorities of the improvement works among the five sites are found to be the same for the exact and the RS approaches. Thus, the applicability of the proposed approach for practical use has been proved.

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