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Risk Evaluation for Earth-Fill Dams by Response Surface Method

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Abstract: There are about 1.6 million earth-fill dams in Japan, which 70% of them were built before the year of 1850. The government has designated disaster prevention priority earth-fill dams and taking measures, but it is impossible to repair all of them. We propose a method to prioritize repairs based on risk to effectively prevent levee damage due to heavy rain. In this study, 31 earth-fill dams in Okayama and Hiroshima in Japan are selected as research subjects. First, we propose a method to easily calculate the potential damage costs caused by flooding in the downstream area due to the breach from the surrounding land use situation. Second, flood analysis that using the finite volume method is used to calculate the cost of submergence damage in the downstream area of the earth-fill dam. Since this work requires a large amount of calculation cost, to simplify this calculation, the response surface method is taken into consideration. The optimum response surface is determined by comparing the damage cost by the response surface method and the detailed method with flood analysis for the earth-fill dams in the studied area. In order to calculate the risk, it is necessary to determine the probability of the overflow on the levees due to heavy rain. The breach is assumed to occur when the inflow to the reservoir due to heavy rainfall exceeds the outflow capacity of the spillway. Finally, the risk by the breach of levees is calculated from the probability of the breach and the estimated damage cost. The accuracy of the response surface method is evaluated by comparing the risk ranking that means the priority of the repair by the detailed and the response surface methods. In conclusion, it has been clarified the proposed response surface can evaluate appropriate risk ranking.

Keyword: earth-fill dams; response surface method; risk evaluation; levee breach

1 Introduction

The breaching of the earth-fill dams due to natural disasters are frequently reported in recent years. After the disaster in July 2018, conducting an emergency inspection (Ministry of Agriculture, Forestry and Fisheries, 2019), the Act on the Management and Conservation of Earth-fill dams was enacted. It is necessary to reselect the ponds

Table 1. 10 examples of 31 sites.

Dam	Flooding ability (m^3/s)	Basin area A (km^2)	Water storage (km^3)
O-A	2.121	0.634	39,000
O-B	0.735	0.268	11,000
O-C	1.724	0.192	57,000
O-D	2.298	0.534	29,400
O-E	2.025	0.321	17,000
H-A	2.62	0.24	10,300
H-B	0.35	0.11	12,000
H-C	0.23	0.709	13,700
H-D	3.04	0.193	49,600
H-E	1.96	0.32	66,210

O-: Okayama, H-: Hiroshima

for disaster prevention, and evaluate their failure risk. In this study, the probability of the levee breach due to the overflow is calculated using detailed analysis and response surface method for the selected 31 sites that shown in

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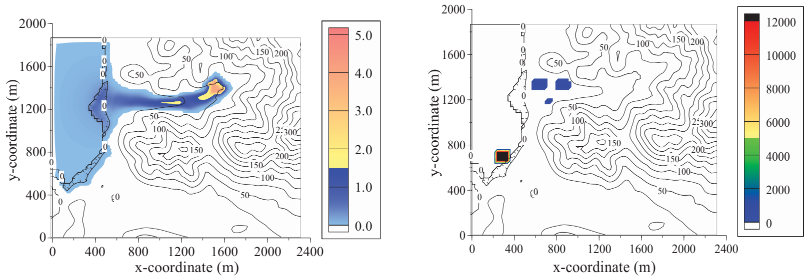
Table 1, and finally evaluated the risk of the overflow failure.

2 Flood analysis

Detail analysis and the response surface methods are used to determine the cost of damage. By plotting the maximum inundation depth according to the coordinates, it is possible to reproduce the inundation of the reservoir water in the downstream area of the earth-fill dams selected as the target site.

In flood analysis, the two-dimensional shallow water equation is used as the basic equation, and the analysis is used by the finite volume method from approximate Riemann solution method. (Nishimura, 2021)

Figure 1 shows the maximum inundation depth obtained from the flood simulation at a representative site.



(a) Submergence depth (m) (b) Damage cost (1,000JPY)

Figure 1. Result of flood simulation

3 Land use and asset data

In land use, in order to easily calculate the damage cost of the earth-fill dams, a method was proposed according to the national regulations (Ministry of Agriculture, Forestry and Fisheries Rural Development Bureau Development Department, 2015) by the asset data.

The damage is divided into direct damage and indirect damage. Direct damage includes assets such as residential damage, office building damage, crops damage. Indirect damage is loss of business suspension, first-aid measures costs at home, and first-aid measures costs at business establishments. The example of land use is shown as Figure 2.

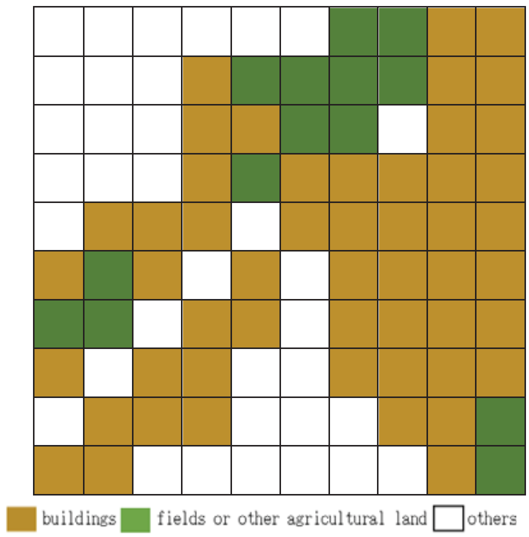


Figure 2. The example of land use

4 Detail approach and response surface methods

In the detail approach, the damage cost according to the land use and asset data is calculated by the inundation analysis mesh in units of 25m. The damage cost is divided into the industrial sector and the agricultural sector in general, the total of two sectors is the cost of damage.

Table 2. Detail approach of 10 examples.

Dam	Industry (1000JPY)	Agriculture (1000JPY)	Detail approach (1000JPY)
O-A	23,351.26	12,295.16	35,646.41
O-B	534,485.4	4,708.3	539,193.8
O-C	2.249,471	20,477.85	2,269,949
O-D	277,068	2,682	279,750.2
O-E	6,568,840	11,525.75	6,580,366
H-A	4,680,750	727	4,681,478
H-B	5,965,054	5,884	5,970,939
H-C	168,148	922	169,070
H-D	214,581	11,930	226,511
H-E	5,566,045	9,796	5,575,842

O-: Okayama, H-: Hiroshima

Table 2 shows that the results of calculating the damage cost by detail approach for the 10 examples of 31 earth-fill dams in this study.

Four factors obtained from sensitivity analysis *a*, *c*, *e* and *f* affecting the damage cost are selected, and the response surface to present the damage cost is created from the variables requested by the regression methods. From the 31 cases of the evaluated damage costs, the response surface methods is created as the Equation (1).

The cost of damage=

$$\begin{cases} -1.04 \times 10^6 ln a - 5.02 \times 10^7 ln c + 5.64 \times 10^6 ln a \cdot ln c + 1.67 \times 10^3 e + 1.07 \times 10^4 f & (a \leq 11000) \\ -7.30 \times 10^4 \, ln\, a - 2.33 \times 10^7 \, ln\, c + 2.01 \times 10^6 \, ln\, a \cdot ln\, c - 6.29 \times 10^2 e + 4.29 \times 10^3 f & (a > 11000) \end{cases} \quad (1)$$

a : effective water storage (km^3)
c : median gradient of the main inundation channel (%)
e : average density of the number of households in the inundation area (households /km^2)
f : average density of employees in the flooded area (person/km^2)

Since a regression equation with a high coefficient of determination (R^2=90.0%) is obtained, this equation is used as the response surface methods to calculate the cost of damage.

5 Risk assessment

As for the probability of breach breakage, the breach was assumed to be an overflow. In this study, Gumbel distribution is used to predict the probability hourly rainfall for each probability year, and the peak flood flow was obtained from the probability hourly rainfall.

The following formula (2), (3) is used to calculate the peak flood discharge

$$Q_p = \frac{r_e \times A}{3.6} \quad (2)$$

$$r_e = f_p \cdot r \quad (3)$$

Q_p: peak flood flow rate (m^3 / s), A: catchment area (km^2), r_e: average effective intensity within the flood arrival time (mm / hr), r: maximum rainfall intensity (mm / hr), f_p: peak outflow coefficient.

It is assumed that the design flood discharge capacity of the reservoir is given by Q_d (m^3 / s) and the overflow levee probability P_f is given by the following equation.

P_f=Prob[Q_d<Q_p] (4)

The calculated levee risk and ranking of 31 earth-fill dams in detailed approach and the response surface methods are shown in the Figs.3 and 4. According to the Figure, the risk of Okayama seems to be lower, but the risk ranking is scattered over a wide range. It is show that the appropriate risk is evaluated by the response surface methods.

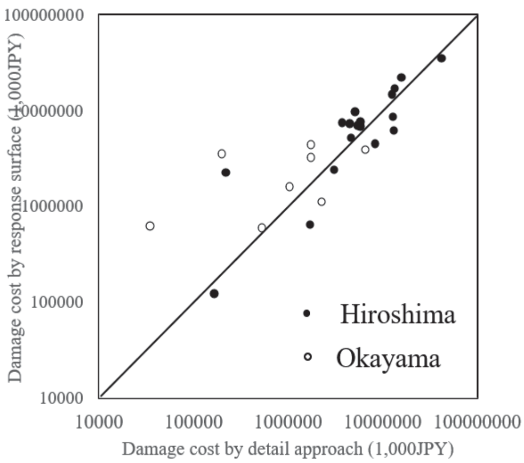


Figure 3. Comparison of risk by two methods.

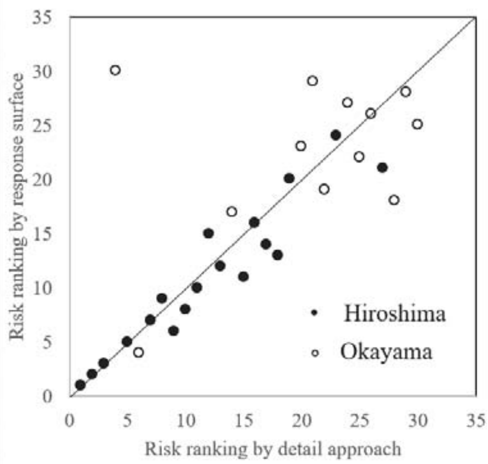


Figure 4. Risk ranking by two methods

6 Conclusion

(1) In this study, the damage costs of 31 earth-fill dams are estimated using detailed approach and response surface methods. The detail approach is composed of the flood analysis and the land use and asset data, while the response surface methods is based on the regression equation of the influential parameters *a, c, e*, and *f*.

(2) According to the comparison of the risk and the ranking of the risk by detail approach and response surface methods, two methods could present similar order of the risk, and the response surface method is clarified to be possibly applied to determine the priority of the renovation works of the earth-fill dams.

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