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A CASE STUDY ON RECONSTRUCTION EFFECT FOR SMALL IRRIGATION TANK

*Alatannabuqi Zhang [1], Hideyoshi Shimizu [2] and Toshiharu Kojima[3]

[1]Graduate School of Engineering, Gifu University, Japan; [2]Emeritus Professor, Gifu University, Japan; [3]River Basin Research Center, Gifu University, Japan

*Corresponding Author, Received: 08 March 2019, Revised: 24 March 2019, Accepted: 21 April 2019

ABSTRACT: Irrigation tanks are indispensable water facilities for agriculture and flood control in Japan. However, most irrigation tanks in Japan have deteriorated and are suffering from damage such as water leaks and collapses due to heavy rain and earthquakes. Aging, a declining population, and current economic conditions are large hurdles for constructing new irrigation tanks. Therefore to prevent the occurrence of failures, the reconstruction of these deteriorated irrigation tanks is an urgent task. In this study, the reliability of the reconstruction work is analyzed by calculating the probability of failure caused by the infiltration of deteriorated Irrigation Tank H due to heavy rain. The probability of failure is calculated from the probable rainfall amount and the sliding failure. The annual probability of failure during heavy rain is obtained by considering both the safety factor which includes the variation in soil parameters and the probability of the occurrence of rainfall. Moreover, the benefit-cost ratio (B/C) is calculated to evaluate the reconstruction effect. As a result, B/C is found to exceed 1 when the social discount rates are 0~3% of half of the durable years of the irrigation tank. B/C is approximately 1 when the social discount rate is 4% of the durable years.

Keyword: Cohesion, Safety factor, Probability of failure, Reliability, Benefit-cost ratio, Seepage line

1. INTRODUCTION

Rice is the main staple in Japan, and stable water resources are indispensable for paddy fields. Water facilities, especially irrigation tanks, play a large part in agriculture. Irrigation tanks also delay flood peaks and protect inhabitants and field downstream. However, many irrigation tanks in Japan have deteriorated because most of them were constructed in the 19th century. Moreover, the frequency of heavy rain events has shown an increasing trend and the pattern of rainfall is changing due to climate change. Last but not least, rainwater cannot infiltrate grounds that are covered by concrete or asphalt. This causes an increasing inflow in irrigation tanks and raises the risk of failure. For the above key reasons, residents have recently suffered economic and mental damage from the collapse of irrigation tanks. Therefore, the maintenance of deteriorated irrigation tanks is a meaningful project for community stability.

The failure of many irrigation tanks has been triggered by rainfall [1, 2]. The cohesion and degree of saturation of the soil are significant factors in these slope failures. Hori [3] investigated the mechanism of the seepage failure induced by heavy rain through many case studies and experiments. It is shown that when the soil becomes saturated, the cohesion and angle of shear resistance show the minimum magnitude because of the zero matric suction [4]. Matsuo [5] stated that cohesion shows a decreasing trend with a rise in the degree of saturation. This means that slope stability is significantly related to the degree of saturation up to the level of rain infiltration.

The main objective of this study is to evaluate the effects of the reconstruction of irrigation tanks by analyzing the probability of failure and calculating the benefit-cost ratio.

2. STUDY AREA AND METHODOLOGY

2.1 Study Area

Irrigation Tank H is located in Gifu City, Gifu Prefecture, Japan; it was constructed in 1862 (Edo Period). The catchment and irrigation areas are 2.7 ha and 3.2 ha, respectively. The length of the tank is 43 m and the water storage capacity is 1300 m^3.

The dimensions of this tank are listed in Table 1.

Table 1 Dimensions of Irrigation Tank H before and after reconstruction

	Before reconstruction	After reconstruction
Height (m)	4.2	4.74
Type	Homogeneous	Inclined core
Freeboard (m)	1.2	1.6
Crest width (m)	2.2	3.0
Slope of upstream	1:2.0	1:1.8
Slope of downstream	1:1.7	1:1.8

The following damage or other problems, occurring before 2009, are the reasons for the reconstruction of Irrigation Tank H from 2009 ~ 2012.

1) Water management was difficult due to the deterioration of the water intake facility. Damage due to a water leak from the bottom drainpipe was discovered.
2) The basilar part of the spillway was partly broken and leaking water. Water was also leaking from the down tip of the bank (1.16 l/s per 100 m).
3) The slope of the embankment was not secured and the width of the crest was insufficient.

Thus, Irrigation Tank H was reconstructed from a homogeneous type to an inclined core type.

2.2 Methodology

This study is conducted by the following process:

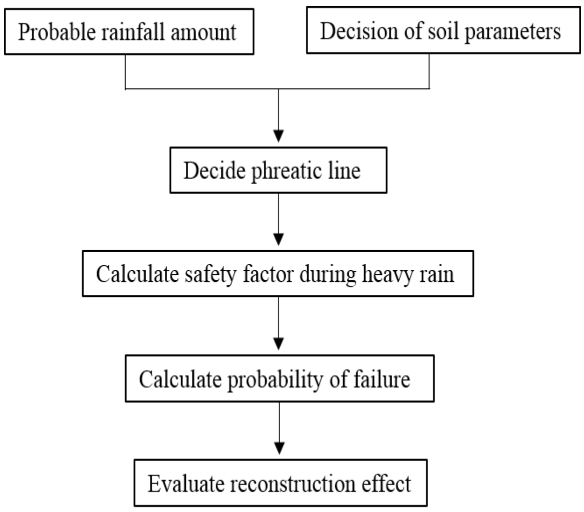


Fig. 1 Flow chart of the methodology

2.2.1 Calculation of probable rainfall amount and determination of soil parameters

The annual maximum rainfall, R (24 hours, 1 hour, and 10 minutes), of Gifu City, is estimated from the Gumbel distribution (Eq. 1) using rainfall precipitation data [6].

$$R = -a \ln[-\ln(1 - 1/T_R)] + b \quad (1)$$

where a and b are coefficients; T_R is the return period.

The 24-hour annual maximum rainfall data from 1969~2007 and the 1-hour and 10-minute maximum rainfall data from 1942~2007, respectively, are used (Fig.2).

Void ratio e and wet unit weight γ_t are obtained from the N-value and relative density D_r. Internal friction angle ϕ' (°) is estimated from the N-value and effective overburden pressure σ'_v(kN/m^2) using the following equation [7]:

$$\emptyset' = 25 + 3.15\sqrt{N/(\sigma'_v/98 + 0.7)} \quad (2)$$

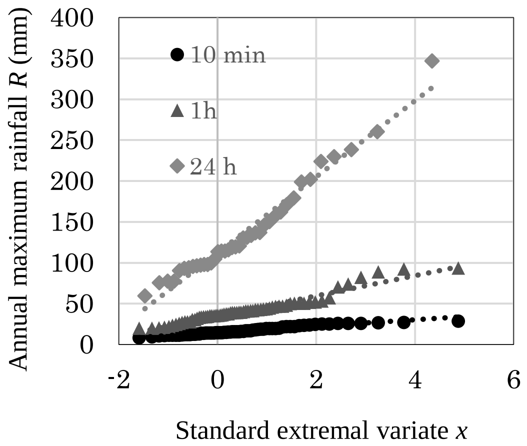


Fig. 2 Annual maximum rainfall of Gifu City

Degree of saturation S_r^*, when apparent cohesion c' becomes the maximum value c'_{max}, is calculated from Eq. (3) [5].

$$S_r^*(\%) = -100.0\, e + 128.8 \quad (3)$$

The relation between apparent cohesion c' and degree of saturation S_r is presented as Eq. (4) [5].

$$c'/c'_{max} = 1.0 - 0.018\,(S_r - S_r^*) \quad (4)$$

Apparent cohesion c' is in the range of 1 to 9.8 kN/m^2 according to Eq. (4) [5, 8]. The values for all the soil parameters are shown in Table 2.

Table 2 Soil parameters of Irrigation Tank H

	Value
N-value	3
Void ratio e	0.8
Wet unit weight γ_t (kN/m^3)	17.4
Saturated unit weight γ_{sat} (kN/m^3)	19.0
Submerged unit weight γ' (kN/m^3)	9.0
The initial degree of saturation S_{r0} (%)	60
Cohesion c' (kN/m^2)	1~9.8
Internal friction angle $\emptyset'$ (°)	30
The specific gravity of soil particles G_s	2.65

2.2.2 Determination of seepage line

In this study, only the sliding failure caused by the rain water infiltration is considered because the overflow did not occur by the previous calculation. Stone masonry was constructed just under the toe of the slope to protect the base failure. Thus, the probability of toe failure for the tank was analyzed.

Eq. (5) is used to calculate safety factor F_S in order to obtain the critical slide circle using the slice method.

$$F_S = \sum_{i=1}^{n}(W'_i cos\theta_i \cdot tan\emptyset' + c' \cdot l_i) / \sum_{i=1}^{n} W_i sin\,\theta_i$$
$$= (\beta c' + \gamma \tan \emptyset')/\alpha \quad (5)$$

where W (kN/m) is the wet weight of the soil, W' (kN/m) is the submerged weight of the soil, θ (°) is the slope inclination angle, l (m) is the length of the slip surface, $\alpha, \beta, and\ \gamma$ are constants.

Seepage line y is calculated using Casagrande's method [9, 10], as shown in Eqs. (6) and (7).

$$y = \sqrt{{y_0}^2 + 2y_0 x} \quad (6)$$

$$y_0 = \sqrt{h^2 + d^2} - d \quad (7)$$

where (x, y) (m) is a value of the coordinates of the seepage line, h (m) is the depth of the stored water and d (m) is the horizontal length from the starting point of the basic parabola to the origin.

A schematic view of Irrigation Tank H before reconstruction is shown in Fig. 3.

The seepage line rises gradually with the infiltration of rainfall. It lowers the safety factor by reducing the cohesion and frictional resistance force.

In this paper, the degree of saturation S_r and seepage line y are obtained during each return period from the 24-hour annual maximum rainfall R (Fig. 2).

2.2.3 Water balance during heavy rain

The water balance of the embankment during rain can be described by Eqs. (8) and (9).

$$\text{(Amount of rainfall)} = \text{(Water increment of the embankment)} + \text{(Outflow } D\text{)} \quad (8)$$

$$D = k \cdot i_0 \cdot t_0 \cdot \Delta y/2 \quad (9)$$

where D (m^2) is the outflow, k (m/s) is the hydraulic conductivity, i_0 is the hydraulic gradient, t_0 (s) is the rainfall duration, and Δy (m) is the rising height of the leakage point at the downstream.

The embankment's water increment is obtained from the seepage line, so Δy is a function of rainfall.

Consequently, the safety factor during a heavy rain event is calculated based on the degree of saturation and the seepage line during each return period. Thus, the sliding safety factor F_S is calculated from Eq. (5).

2.2.4 Annual probability of failure

The probability of failure must be estimated to evaluate the reliability of an embankment. The annual probability of failure is an index for stochastically evaluating the safety of water facilities [11]. The annual probability of failure during heavy rain is obtained by considering the safety factor, the variation of soil parameters, and the probability of occurrence together. Safety factor F_S is a probability variable for considering the variability of the soil parameters. The probability of failure is P ($F_S \leq 1$) when the safety factor is smaller than 1. The conditional probability of failure with rainfall R is presented in Eqs. (10)-(13), assuming a normal distribution.

$$P(F|R) = P(F_S \leq 1)$$
$$= \int_{-\infty}^{1} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}((x-\overline{F_S})/\sigma)^2} dx$$
$$= \int_{-\infty}^{\frac{1-\overline{F_S}}{\sigma}} \frac{1}{\sqrt{2\pi}} e^{-\frac{t^2}{2}} dt$$
$$= \Phi(\frac{1-\overline{F_S}}{\sigma}) \quad (10)$$

$$\sigma = \sqrt{\beta^2 {\sigma_{c'}}^2 + \gamma^2 {\sigma_{tan\emptyset'}}^2}/\alpha \quad (11)$$

$$\sigma_{c'} = 0.4\overline{c'} \quad (12)$$

$$\sigma_{tan\emptyset'} = \sigma_{\emptyset'}/cos^2\overline{\emptyset}' = 0.1\overline{\emptyset}'/cos^2\overline{\emptyset}' \quad (13)$$

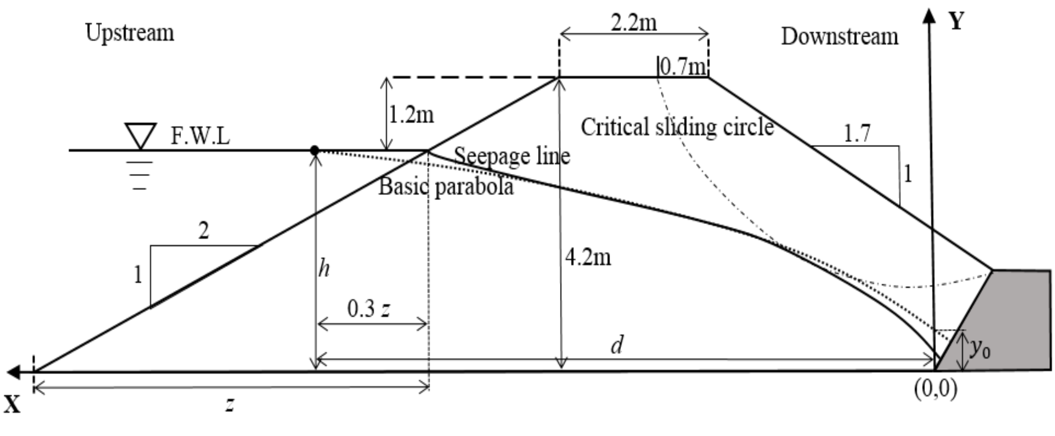


Fig. 3 Schematic view of Irrigation Tank H

where $\overline{F_s}$ is the central safety factor (Fig. 4), σ is the standard deviation, and Φ is the standard normal probability. The coefficients of variation of apparent cohesion c' and internal friction angle ϕ' are 0.4 and 0.1, respectively, according to past research [5].

The probability of failure is then calculated with the probable rainfall using $\overline{F_s}$, α, β, γ, and σ.

The annual probability of failure P_F is calculated with Eq. (14).

$$P_F = \int_0^{\infty} P(F|R) f(R) dR \tag{14}$$

where P_F is the annual probability of failure and $f(R)$ is the probability density function (PDF) of the annual maximum 24-hour rainfall (Fig. 5).

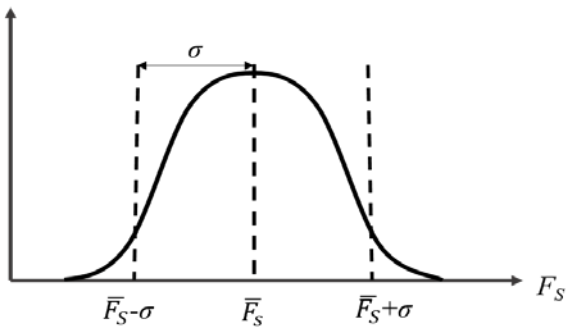


Fig. 4 Distribution of safety factor

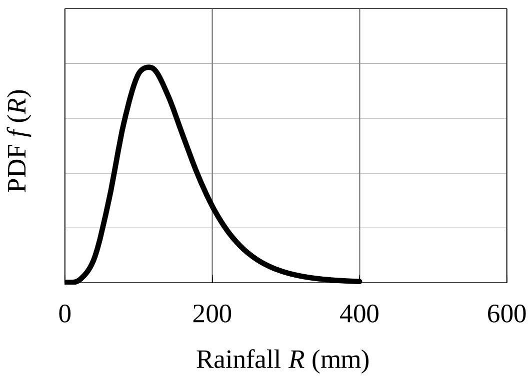


Fig. 5 PDF of annual maximum 24-hour rainfall

2.2.5 Benefit-cost analysis

The benefit-cost analysis is a significant decision-making method for large-scale public works. The benefit-cost ratio (B/C) is an essential index of whether a project is advisable or not. Even if the benefit can be evaluated from public works, it is necessary to discount the future benefit to the current value.

Generally, a social discount rate of 4% is used in Japan now [11-13] in the case of evaluating public works projects. In this study, the total benefit is the difference between the failure loss before and after reconstruction. The total benefit is evaluated just from the loss caused by sliding failure with heavy rain. In this study, the total cost is the difference between the reconstruction cost and the remnant value of Irrigation Tank H. Reconstruction projects are determined to be effective when the total benefit is more than the total cost.

$$\frac{B}{C} = \frac{\text{Expected loss before construction } E(B_t)}{\text{Reconstruction cost } C_I - \text{remnant value } C_R} \tag{15}$$

$$E(B_t) = \sum_{k=1}^{t} P_F C_F / (1+j)^k \tag{16}$$

where C_I is the current value of reconstruction cost C_0, C_R is the current value of the facility and land cost, C_F is the failure cost after k years, j (%) is the social discount rate and t (year) is the durable years.

Table 3 shows failure cost C_F and reconstruction cost C_0 at Irrigation Tank H. In this study, the annual changes in the benefit-cost ratios are calculated with social discount rates of 0~4%.

Table 3 Failure and reconstruction cost of Irrigation Tank H

Failure cost C_F		114,488	
Reconstruction cost C_0	Facility	57,535	72,000
	Land	1,940	
	Other	12,525	

(Unit: thousand-yen)

3. RESULTS

3.1 Critical Sliding Circle and Seepage Line

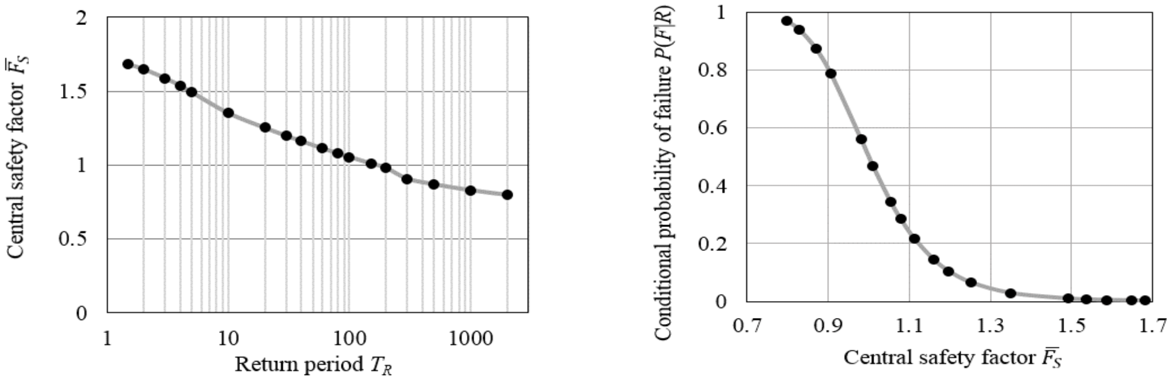
The critical slide circle with the smallest safety factor passes 0.7 m from the top of the downstream (Fig. 3). y_0 is 0.455 m from Eqs. (6) and (7).

3.2 Safety Factor and Probability of Failure

Fig. 6 (a) shows the transition of the central safety factor in the case of varying the return period of heavy rainfall. Fig. 6 (b) also shows the conditional probability of failure at different central safety factor.

This indicates that the central safety factor becomes less than 1 with a return period of over 150 years. Irrigation Tank H is not safe when heavy rainfall with a return period of over 150 years occurs. However, if Irrigation Tank H is reconstructed, it will involve quite a high cost. Therefore, the probability of failure was calculated with the probable rainfall to judge whether or not the reconstruction project would be worthwhile.

As a result of calculating the annual probability of failure, necessary for the benefit-cost analysis, P_F is 0.023 and the return period is 43 years (Table 4).



(a) (b)

Fig. 6 (a) Central safety factor vs. return period and (b) Conditional probability of failure vs. safety factor

Table 4 Annual probability of failure

Annual probability of failure P_F	The return period of failure T_F (year)
0.023	43

3.3 Benefit-Cost Analysis

Fig. 7 shows the value of *B/C* within the durable years of the irrigation tank. In this figure, it is seen that *B*/*C* exceeds 1 when the social discount rates are 0~3% for half of the durable years. However, *B*/*C* is approximately 1 near the point of 80 durable years when the social discount rate is 4%. This is because the benefit was evaluated only from the sliding failure by infiltration. Other benefits, like the effects of preventing flooding and seepage failure, were not considered. It is obvious that the rise in *B*/*C* becomes smaller with the increase in the social discount rate along with the durable years. The proper social discount rate is a fatal point for benefit-cost analysis.

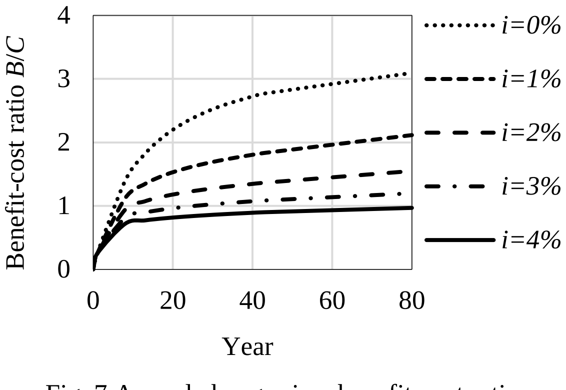


Fig. 7 Annual changes in a benefit-cost ratio

In this study, the social discount rate of 4% is used. The benefit continues for decades after construction. Consequently, the benefit evaluation is largely influenced by little changes in the social discount rate [4]. Moreover, the effects of insurance should also be taken into account, *i. e.*, the effects of the renewal of intake works.

4. CONCLUSIONS

The sliding failure was analyzed for the purpose of quantitatively evaluating the reliability of the embankment of Irrigation Tank H during heavy rain. The annual probability of failure is 0.023. This means that the probability of failure is very small. However, it is the result obtained when only considering the sliding failure against the infiltration. The seepage failure should be analyzed too.

Some soil parameters used in this study were estimated from the *N*-value. The results of the analysis were largely influenced by the value of cohesion and then the safety factor of the embankment. For an exact reliability evaluation, it is important to obtain data with accurate soil parameters by conducting laboratory tests.

The benefit has been evaluated by just using the reduced damage amount during heavy rain. For comprehensively evaluating the benefits that can be expected from reconstruction, a future task will be to consider the accompanying effects from the renewal of the water intake facility and the improvement brought about by the earthquake-proof construction.

5. ACKNOWLEDGMENTS

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