Risk Analysis of Slope due to Rainfall

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1. INTRODUCTION

In Japan, many slope failures due to rainfall occur every year especially during the typhoon period. Therefore, risk analysis of slope due to rainfall should be taken into consideration in slope design. Some studies proposed the rainfall intensity that triggers slope failure based on the past records but it is not sufficient to make decision of the appropriate design or countermeasure. In this study, the methodology to evaluate risk of slope due to rainfall is presented.

2. FAILURE MACHNISM OF SLOPE DUE TO RAINFALL

There are a lot of factors related to slope failure during rainfall period. In this study, increase of pore pressure due to rainfall infiltration was considered as the important factor to slope failure (Yagi et al., 1983). The performance function of slope (shown in Fig. 1) can be expressed as follows:

$$Q=\left(1-\frac{\gamma_w H_w}{\gamma H}\right)\cdot\frac{\tan\phi_d}{\tan\beta}+\frac{c_d}{\gamma H}\cdot\frac{1}{\sin\beta\cos\beta}-1 \qquad (1)$$

where γ_w is unit weight of water (10 kN/m^3), γ is unit weight of soil (18 kN/m^3), ϕ_d is internal friction angle (40°), c_d is cohesion (10 kN/m^2), β is slope angle (35°), H is thickness of failure surface (1 m), and H_w is water height of groundwater above failure surface (Enoki, 1997).

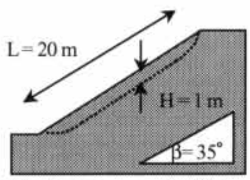

Fig. 1: Modeled slope and assumed failure surface

Tank Model

In order to relate the amount of rainfall to the increase of pore pressure, *tank model* was applied (Yoshikawa, 1976). The amount of runoff and infiltration of each tank can be expressed as follows:

$$q_{ij}=\alpha_{ij}\cdot\left(H_i-m_{ij}\right) \qquad (2)$$

$$p_i=\lambda_i\cdot H_i \qquad (3)$$

where q_{ij} is outflow from j^{th} outlet of i^{th} tank, α_{ij} is ratio of outflow, m_{ij} is height of j^{th} outlet of i^{th} tank, p_i is infiltration from i^{th} tank, λ_i is ratio of infiltration, and H_i is water height of i^{th} tank. The change of water height with time can be expressed as follows:

$$\frac{dH_i}{dt}=p_{i-1}-\left(\sum_j q_{ij}+p_i\right) \qquad (4)$$

The amount of rainfall can be considered as p_0 for the first tank. In this study, model of two tanks was considered sufficiently for analysis. Each parameter is shown in Fig. 2.

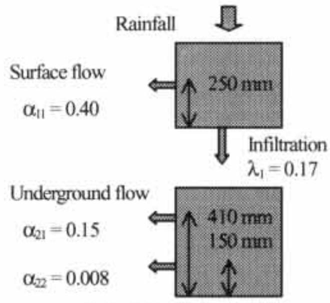

Fig. 2: Tank model

Modeling of Rainfall Distribution

Based on the rainfall data in Kyoto city during the year 1994 to 1998, the distribution of one-day rainfall used in tank model calculation is under these assumptions:

- the rainfall period in one day is continuously 12 hours.
- the amount of peak four hours rainfall is 60 % of the total.

Probability of failure

Firstly tank model is used to find out the water height after one-day rainfall. The water height due to each rainfall intensity is shown in Fig. 3.

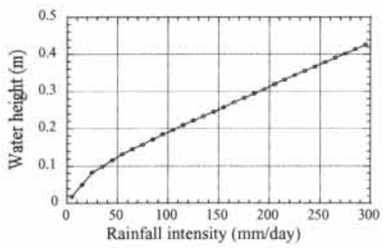

Fig. 3: The relationship between water height and rainfall intensity

To find out the probability of failure, First Order Second Moment method (FOSM) was applied. Internal friction angle (ϕ_d) and cohesion (c_d) were considered as uncorrelated variables, which can be modeled as the normal distribution. Coefficients of variance were assumed to be 0.10 and 0.07 for ϕ_d and c_d respectively. The probability of failure is shown in Fig. 4.

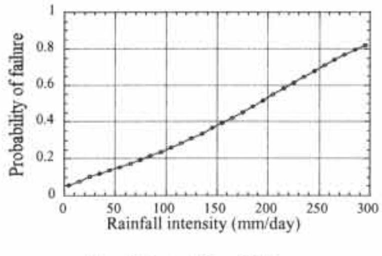

Fig. 4: Probability of failure

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3. EVALUATION OF RISK

In this study, risk (R) is defined as an expected loss, which is the product of the state probability and loss amount associated with the state.

$$R = P_i \times C_i \tag{5}$$

where P_i is occurrence probability of state i and C_i is loss amount associated with state i.

The assumption to evaluate the risk in this study is summarized as follows:

1) The slope investigated here is closed to Meishin highway and the rainfall intensity to stop highway service (r_0) is taken into consideration for preventing damage of highway user.
2) Four types of losses are taken into account: restoration cost (C_1), commercial loss due to service interruption (C_2), loss due to detour (C_3), and damages to highway users (C_4).
3) Volume of collapsed debris amounts to 360 m^3 and restoration cost is estimated to be 5.68 million yen with 5 days to complete. Commercial loss due to service interruption and loss due to detour are evaluated as 21.27 and 27.01 million yen per day respectively. Damages to highway users are evaluated as 95.49 million yen if slope failure occurs during service.

Risk was evaluated after r_0 was set up, by dividing into two cases: risk caused by rainfall less than r_0 [$R_-(r_0)$] and risk caused by rainfall more than r_0 [$R_+(r_0)$]. The concept to evaluate risk can be expressed in equation (6), (7), and (8).

$$R(r_0) = R_-(r_0) + R_+(r_0) \tag{6}$$

$$R_-(r_0) = \int_0^{r_0} p_f(r)\cdot\left(C_1 + C_{2(5days)} + C_{3(5days)} + C_4\right)\cdot n(r)dr \tag{7}$$

$$R_+(r_0) = \int_{r_0}^{\infty}\Big[p_f(r)\cdot\left(C_1 + C_{2(5days)} + C_{3(5days)}\right) + \left(1 - p_f(r)\right)\cdot\left(C_{2(1day)} + C_{3(1day)}\right)\Big]\cdot n(r)dr \tag{8}$$

where n(r) is occurrence of rainfall of intensity r.

The occurrence of each rainfall, based on the rainfall data in Kyoto city during the year 1994 to 1998, is summarized in Fig. 5.

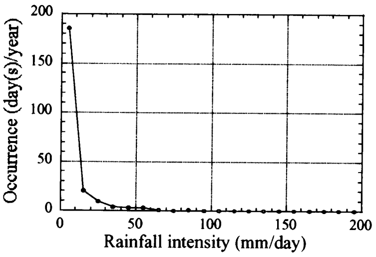

Fig. 5: Occurrence of each rainfall

4. RESULT AND CONSIDERATION

Fig. 6 shows the relationship between risk and rainfall intensity to stop highway service (r_0). Risk becomes the minimum value when r_0 is 120-140 mm/day. Therefore, based on the concept of risk minimization, the optimum solution considering risk due to rainfall is to set up rainfall intensity to stop highway service at 120-140 mm/day.

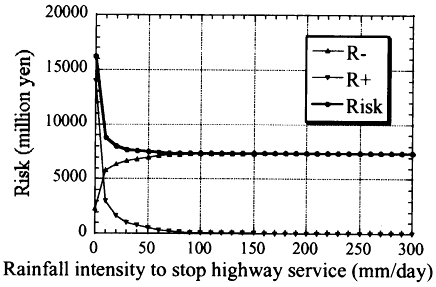

Fig. 6: Risk due to rainfall

However, according to the rainfall data of Kyoto city, the occurrence of more than 100 mm/day rainfalls is extremely low and the maximum rainfall intensity is only about 180 mm/day. Therefore, there is no significant change of risk value for more than 100 mm/day rainfalls and risk value becomes constant after 180 mm/day rainfall. In order to cope with this problem, modeling the occurrence of rainfall as a function of rainfall intensity was taken into consideration. In this study, an exponential function was used. Based on the least square method, occurrence function of rainfall can be expressed as follows:

$$y = 47.054 \cdot e^{-0.046822\cdot(x+5)} \tag{9}$$

where x is rainfall intensity (mm/day).

The relationship between risk and rainfall intensity to stop highway service using occurrence function in equation (9) is shown in Fig. 7. The optimum solution is to set up rainfall intensity to stop highway service at 130 mm/day.

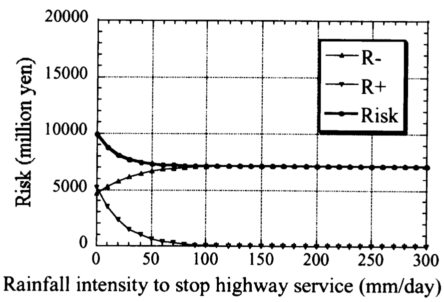

Fig. 7: Risk due to rainfall using occurrence function

5. CONCLUSIONS

This study presents the methodology to evaluate risk of slope due to rainfall. The slope closed to highway was analyzed and the optimum solution can be obtained by the concept of risk minimization.

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