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Risk Evaluation Method for Road Slopes

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Roads support our daily life, and they play a crucial role in supporting the infrastructure for economic activities. However, the road disaster caused by slope failures, rock falls and so on has occurred frequently in Japan, because it is subjected to the severe natural conditions such as heavy rainfall, steep topography, brittle geology, etc. As the road disaster, not only the primary disaster (the road suffers damage directly) but also the secondary disaster (hindrance to the society and the economic activity by traffic stop) must be taken into account. In order to prevent or mitigate such road disasters caused by slope failures, it is important to determine the hazard level by quantitatively estimating the risk of slope failures and rock falls.

In this research, a risk evaluation method for slope failures and rock falls on road slope is proposed. The flow chart of this research is shown in Figure 1. The main features of this method can be summarized as follows:

1) Possible collapse mechanisms are divided into five different types: fall, roll, topple, glide, and slump. The conceptual figure of each collapse mechanism is shown in Figure 2.
2) The evaluation of collapse risk is undertaken by the mechanical model of slope failures and rock falls, with the uncertainty of the soil parameters as a primary cause.
3) The evaluation of road damage is performed by considering the effect of sliding blocks and rocks. Their probability of reaching the road is calculated.
4) By combining the above two evaluations, the risk level of road slope can be quantitatively obtained.

The results obtained by applying this method to an actual national road in Japan verify its usefulness as a quantitative risk evaluation method for the road slope.

Keywords: Road disaster, Risk evaluation method, Slope failure, Rock fall

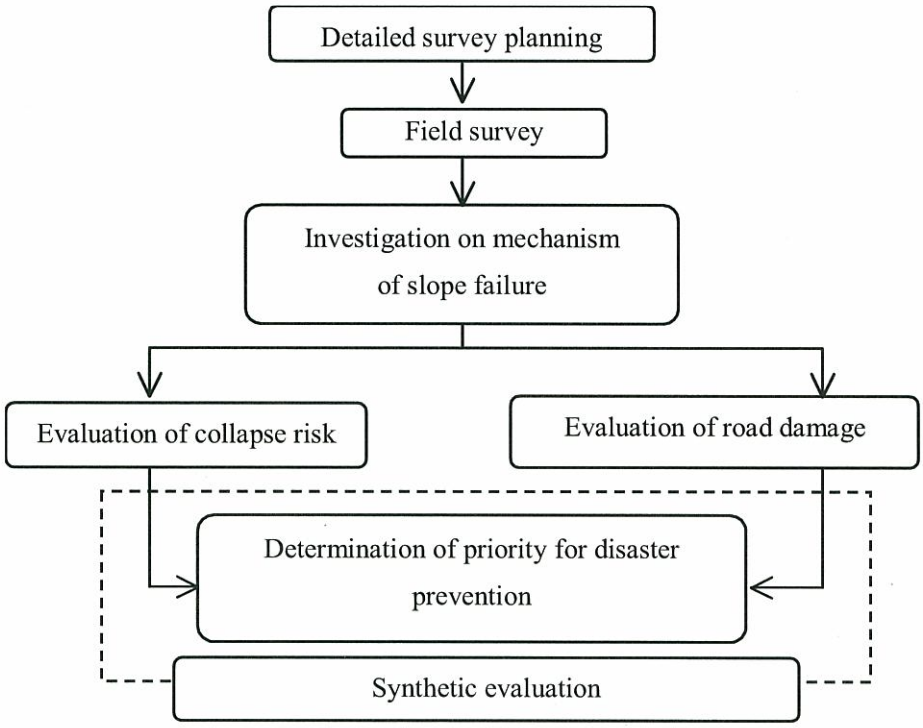


Figure 1. Flow chart of this research.

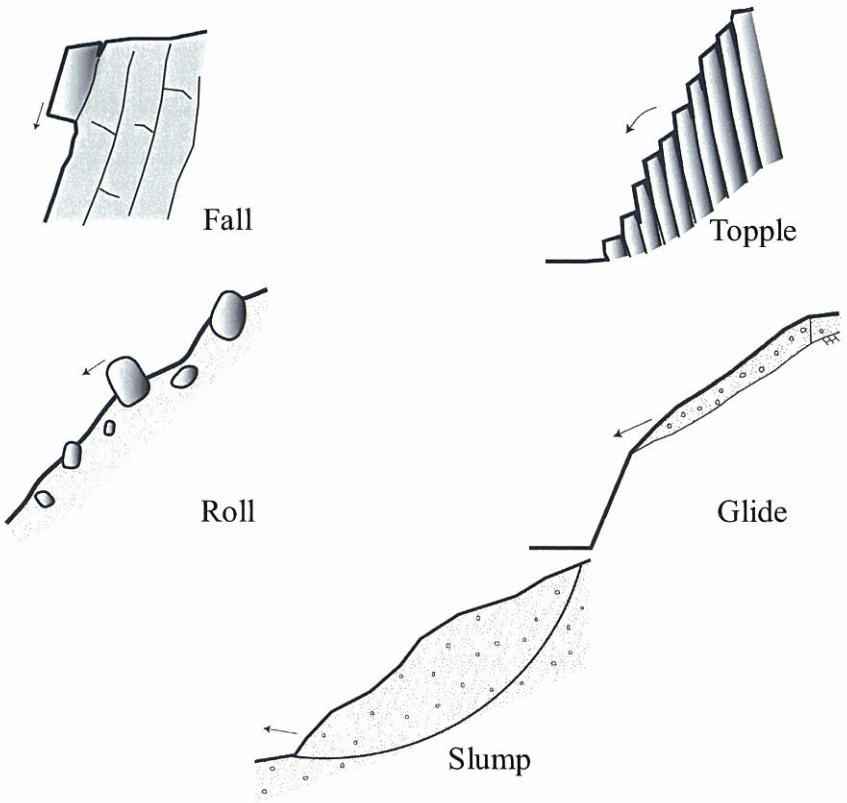


Figure 2. Five possible collapse mechanisms observed on existing slopes.

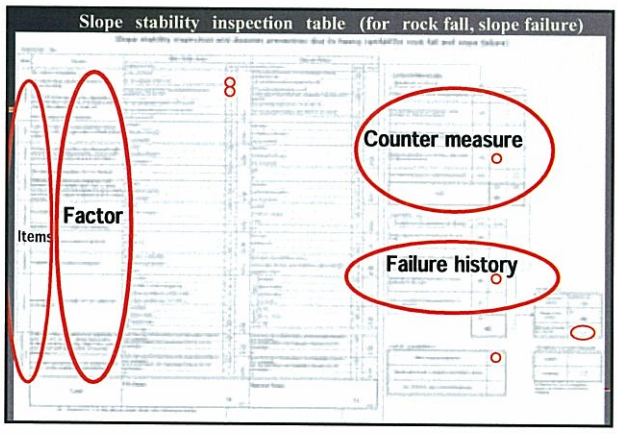
Risk Evaluation Method for Road Slopes

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Graduated student, Graduate School of Science and Technology, Kobe University
○ Tetsuo Watanabe

Introduction

Roads support the citizen life, and it is one of the important infrastructures for economic activity. However, the road disaster caused by slope failures, rock falls and so on has occurred frequently in Japan, because there is under the severe natural condition such as heavy rainfall, steep topography, brittle geology etc.

In order to prevent or mitigate such road disasters caused by slope failures and rock fall, it is important to determine the hazard level by quantitative estimation of the risk of them.



The problem of inspection for prevention of road disasters

①It is difficult to evaluate fittingly for each collapse mechanisms, because we use same slope stability inspection table throughout the country.

The problem of inspection for prevention of road disasters

②As road slope we should consider not only the primary disaster such as the road suffers damage directly but also secondary disaster such as hindrance to the society and the economic activity by traffic stop occurs. But the estimation is up to the judgment of the field engineer, and that estimation is qualitative things now.

The problem of inspection for prevention of road disasters

③There is no judgment standard of the priority for disaster prevention, when many risky slope exists there.

In order to evaluate the risk of a road slope ・・・

○Evaluation of collapse risk

Reliable evaluation method in which the collapse mechanism was taken into consideration

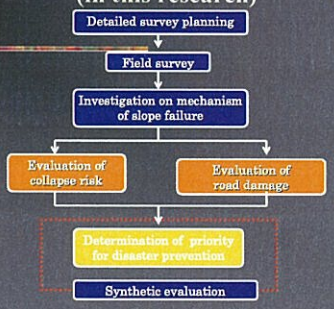
In order to evaluate the risk of a road slope ・・・

○Evaluation of road damage

Evaluation method of whether to affect a road, when collapse occurs



Risk evaluation method of the road slope (in this research)



Flow chart of this method

The main features of this method

① It is possible to evaluate fittingly for each collapse mechanisms.

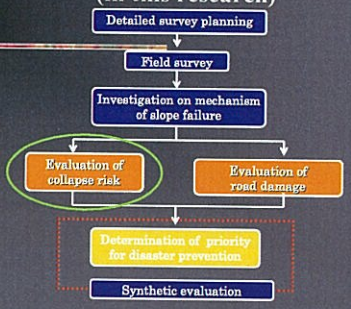
The main features of this method

②It is possible to evaluate road damage quantitatively.

The main features of this method

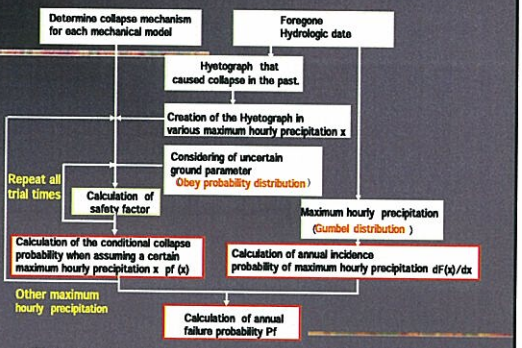
③ We can determine the priority for disaster prevention of the risky slope in consideration of the risk that occurs when slopes fail.

Risk evaluation method of the road slope (in this research)



Flow chart of this method

Evaluation method for collapse risk



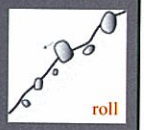
Flow chart of Evaluation method of collapse risk

Evaluation of collapse risk

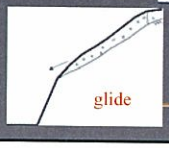
5 collapse mechanisms that appear the existing slope

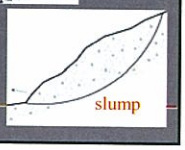
1） fall
2） roll
3） topple
4） glide
5） slump









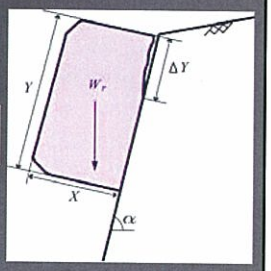


Analysis method of slope stability ～fall～

Analysis method of slope stability ～fall～

Overhang type

$$F = \frac{Q_{f1}}{P_{f1}} = \frac{W_r \cos\alpha \tan\phi + c(Y - \Delta Y)}{W_r \sin\alpha}$$

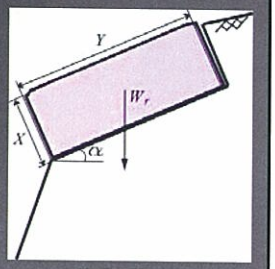


Overhang type

Analysis method of slope stability ～fall～

Fall off type

$$F = \frac{Q_{f2}}{P_{f2}} = \frac{W_r \cos\alpha \tan\phi + cY}{W_r \sin\alpha}$$



Fall off type

Analysis method of slope stability ～roll～

Analysis method of slope stability ～roll～

Rotation type

$$F = M_Q / M_P$$

$$M_p = M_A + M_{PU} + M_W$$

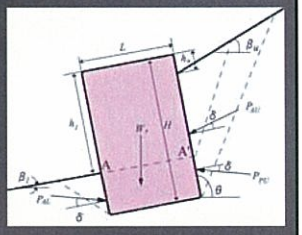
$$M_A = P_{AL}\cos\delta\cdot\{(H-h_l)+Z_c/2\}\cdot 2/3 + P_{AU}\cos\delta\cdot\{(h_l-h_u)-Z_c\}\cdot 1/3$$

$$Z_c = 2c/\gamma_t \tan(45+\phi/2)$$

$$M_{PU} = P_{PU}\sin\delta\cdot L$$

$$M_W = W_r\cdot\cos(180-\theta)\cdot(h_l - H/2)$$

$$M_Q = W_r\cdot\sin(180-\theta)\cdot L/2 + P_{PU}\cos\delta\cdot(h-h_l)\cdot 2/3 + P_{AU}\sin\delta\cdot L$$



Rotation type

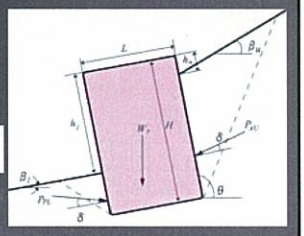
Analysis method of slope stability ～roll～

Sliding type

$$F = Q_r / P_r$$

$$P_r = W_r\cos(180-\theta)+P_{AU}\cos\delta$$

$$Q_r = \{W_r\sin(180-\theta)+P_{AU}\sin\delta - P_{PL}\sin\delta\}\cdot\tan\phi + P_{PL}\cos\delta + cL$$

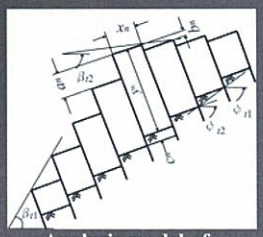


Sliding type

Analysis method of slope stability ～topple～

Analysis model of the limiting equilibrium that occurs on the step bed rock. (Hoek and Bray, 1979)

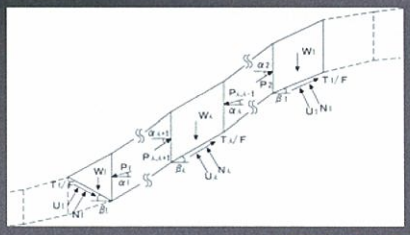
$$F = \frac{\tan\phi}{\tan\phi_L}$$



Analysis model of the limiting equilibrium

Analysis method of slope stability ～glide～

Multi Planar Sliding Surface *MPSS* method (Okimura, 1982)

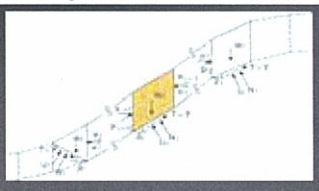


MPSS method

Balance of force on i block

$$P_{i-1,i}\cos\alpha_i - \frac{T_i}{F}\cos\beta_i + (U_i+N_i)\sin\beta_i - P_{i,i+1}\cos\alpha_{i+1} = 0$$

$$-P_{i-1,i}\sin\alpha_i - W_i + \frac{T_i}{F}\sin\beta_i + (U_i+N_i)\cos\beta_i + P_{i,i+1}\sin\alpha_{i+1} = 0$$

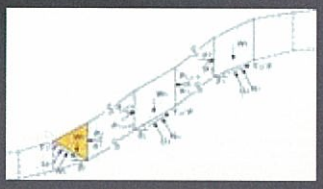


Balance of force on i block

Balance of force on last block

$$-W\ell - \frac{T\ell}{F}\sin\beta\ell - P\ell\sin\alpha\ell + (U\ell + N\ell)\cos\beta\ell = 0$$

$$\frac{T\ell}{F}\cos\beta\ell - P\ell\cos\alpha\ell + (U\ell + N\ell)\sin\beta\ell = 0$$

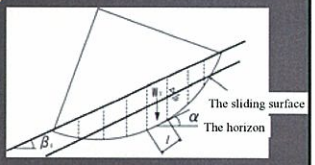


Balance of force on last block

Analysis method of slope stability ～slump～

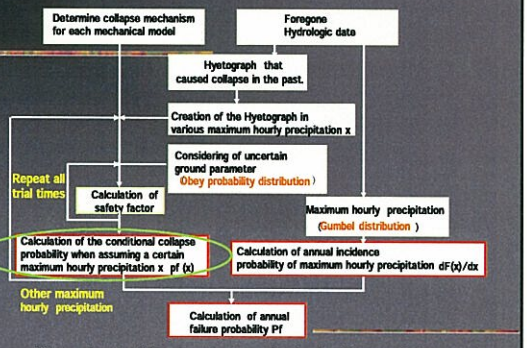
Fellenius solution

$$F_S = \frac{Q_S}{P_S} = \frac{\sum\left[c' \cdot l + (W \cdot \cos\alpha_S - u \cdot l) \cdot \tan\phi'\right]}{\sum W_S \cdot \sin\alpha_S}$$



Fellenius solution

Evaluation method for collapse risk



Flow chart of Evaluation method of collapse risk

Calculation of conditional failure probability when assuming a certain maximum hourly precipitation x pf (x)

Determination of basic hyetograph from foregone hydrologic date.

Creation of the Hyetograph to enter as external force in various maximum hourly precipitation

Calculation of safety factor in consideration of uncertain ground parameter by using Monte Carlo simulation.

Calculation of conditional failure probability when assuming a certain maximum hourly precipitation x pf (x)

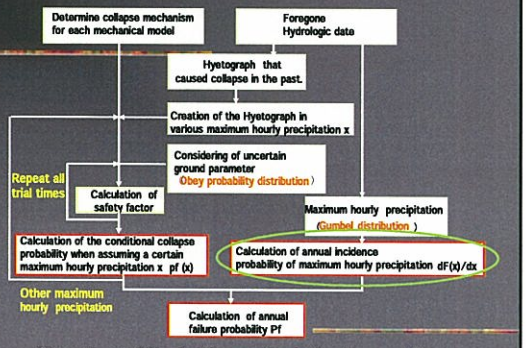
Calculation of pf(x)

$$pf(x) = t / T$$

t : times that safety factor is under 1.0

T : all trail times

Evaluation method for collapse risk



Flow chart of Evaluation method of collapse risk

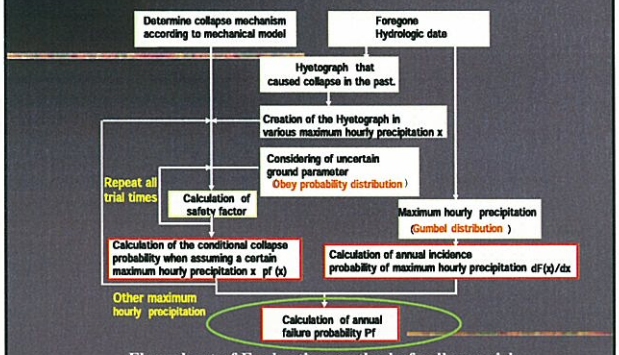
Calculation of annual incidence probability of maximum hourly precipitation dF(x)/dx

Determination of the probability distribution of maximum hourly precipitation .

Generally Gumbel distribution is adjust for the probability distribution of maximum hourly precipitation .

Calculation of d F(x)/dx by using probability distribution function that is got from Gumbel distribution.

Evaluation method for collapse risk



Flow chart of Evaluation method of collapse risk

Calculation of failure probability Pf

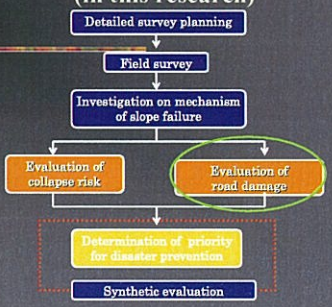
We calculate annual failure probability Pf in consideration of incidence probability of rainfall by using the following equation.

$$P_f = \int_0^{\infty} p_f(x) \cdot \frac{dp(x)}{dx} \cdot dx$$

p(x) :conditional failure probability when assuming a certain maximum hourly precipitation x pf (x)

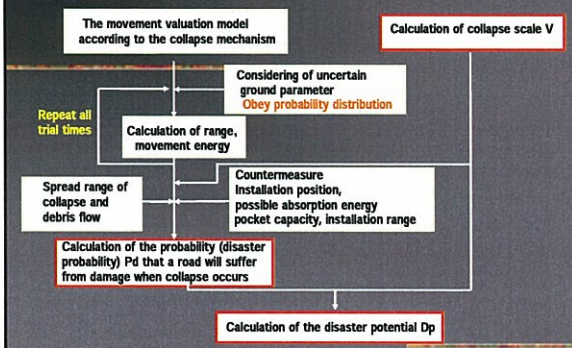
dF(x)/dx : annual incidence probability of maximum time rainfall

Risk evaluation method of the road slope (in this research)



Flow chart of this method

Evaluation method for road damage



Flow chart of Evaluation method of road damage

Evaluation method of road damage

Fall, roll ,topple ・・・ Rock fall simulation

Glide, slump ・・・ Collapse and debris-flow model

Rock fall simulation using Monte Carlo algorithm (Ushiro, 1998)

「~~linear motion~~ (sliding) 」

「 linear motion (rolling) 」

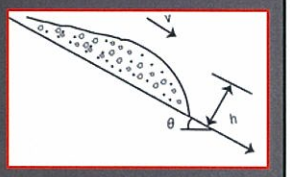


Definition of Falling-rock movement

Collapse and debris-flow model (Ashida · Egashira, 1984)

$$v'\frac{dv'}{dx'} = -av'^2 + b$$

$$v' = v(gh)^{-1/2},\ x' = x/h$$



Collapse and debris-flow model

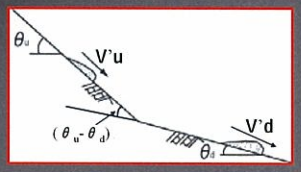
v : moving speed, x : moved distance
g : the gravitational acceleration
h : thickness of debris-flow
a: flow resistance , b:clone resistance

Collapse and debris-flow model (Ashida · Egashira etc, 1984)

$$v' = \left\{ v_0'^2 e^{-2ax'} + \frac{b}{a}\left(1 - e^{-2ax'}\right) \right\}^{1/2}$$

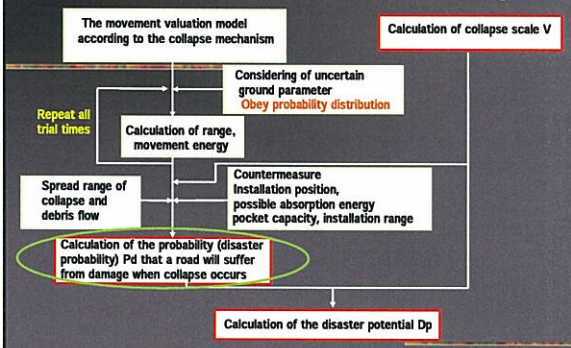
v_0' is non-dimensional moving speed when x'=0

$$v_d' = v_u' \cos(\theta_u - \theta_d)$$



The definition of the speed in concave slope

Evaluation method of road damage



Flow chart of Evaluation of road damage

Calculation of disaster probability Pd

Pd is the probability that a road is damaged when a collapse occurs.

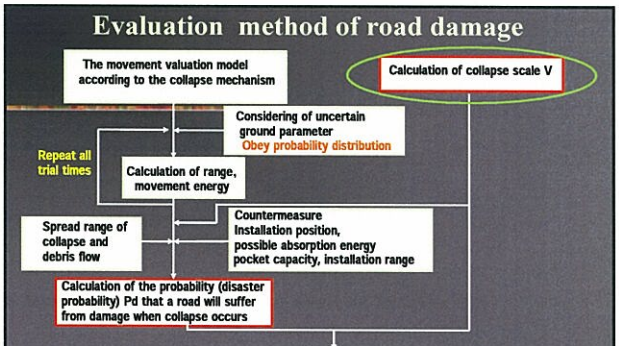
Calculation of range and moving energy in consideration of uncertain ground parameter by using Monte Carlo simulation.

$$Pd = t / T$$

t : times that collapse soil and rock fall reach a road and their energy is over the countermeasure's possible absorption energy

T : all trail times

Evaluation method of road damage

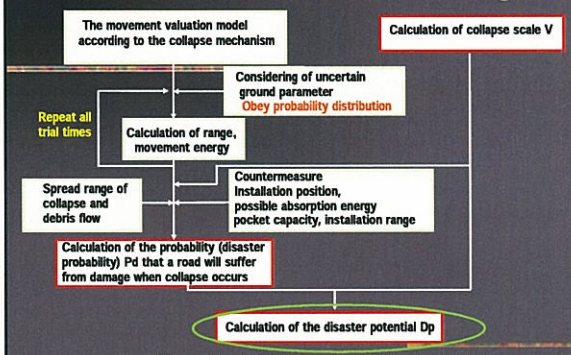


Flow chart of Evaluation of road damage

Calculation of collapse scale V

The losses are considered that is up to collapse scales(amount of collapse soil, scale of rock fall), so losses that is occurred by slope failures regard as collapse scale V.

Evaluation method of road damage



Flow chart of Evaluation of road damage

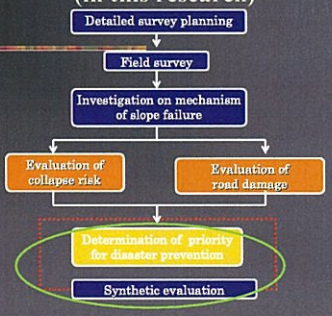
Calculation of the disaster potential Dp

$$D_p = P_d \cdot V$$

Pd :disaster probability

V :collapse scale

Risk evaluation method of the road slope (in this research)



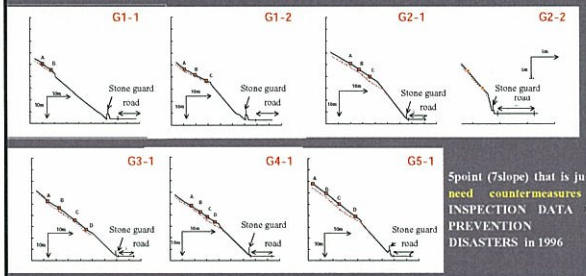
Flow chart of this method

Determine the priority for disaster prevention

Synthetic evaluation is calculated by the risk that product failure probability Pf and the disaster potential Dp

$$R = P_f \times D_p$$

Case study (glide)

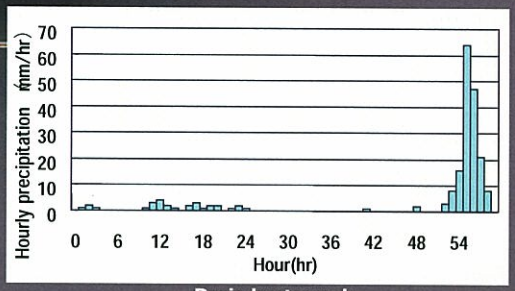


5point (7slope) that is judged need countermeasures by INSPECTION DATA FOR PREVENTION OF DISASTERS in 1996

penetration test position

Surface of bedrock

Evaluation of collapse risk



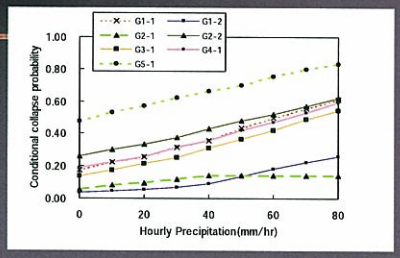
Basic hyetograph
(Maximum hourly precipitation 64mm/hr,
Continuous Precipitation 199mm)

Evaluation of collapse risk

Parameter for calculation

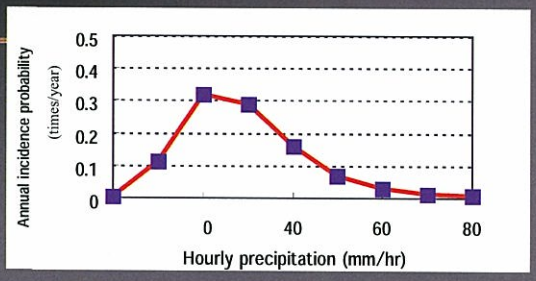
parameter	average	standard deviation	PDF
c' (kN/m²)	3.92	1.56	Normal distribution
φ' (°)	30	6	
γ sat (kN/m³)	1.8	—	
γ t (kN/m³)	1.6	—	
k (m/hr)	0.2	—	
λ	0.35	—	

Evaluation of collapse risk



Conditional collapse probability on each Maximum hourly precipitation

Evaluation of collapse risk



Annual incidence probability of Maximum hourly precipitation

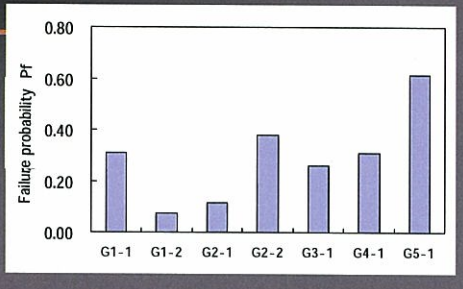
Evaluation of collapse risk

Example of failure probability Pf (G5-1)

Max hourly precipitation (mm)	0	10	20	30	40	50	60	70	80
Annual incidence probability f(x)	0.476	0.531	0.572	0.621	0.662	0.699	0.752	0.797	0.833
Conditional collapse probability dP(x)/dx	0.004	0.112	0.318	0.290	0.158	0.070	0.029	0.011	0.007
Failure probability Pf	0.614								

$$P_f = \int_0^{\infty} p_f(x) \cdot \frac{dp(x)}{dx} \cdot dx$$

Evaluation of collapse risk



Calculation results of each slope's P f

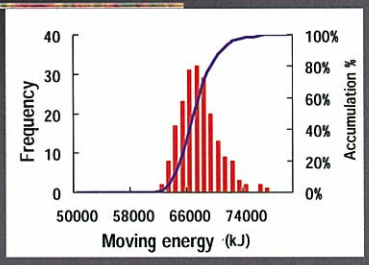
Evaluation of road damage

Parameter for calculation

Parameter	Average	Standard deviation	PDF
ρ (kg/m^3)	1000	—	
σ (kg/m^3)	2650	—	
ϕ (°)	30	—	
d(m)	0.03	—	
cd	0.5	0.1	Normal distribution
ke	0.85	—	

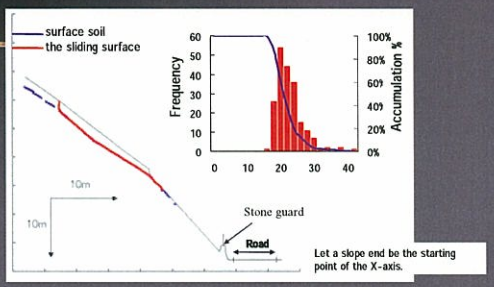
Evaluation of road damage

possible absorption energy of countermeasure 90kJ



Example of movement energy (G5-1)

Evaluation of road damage



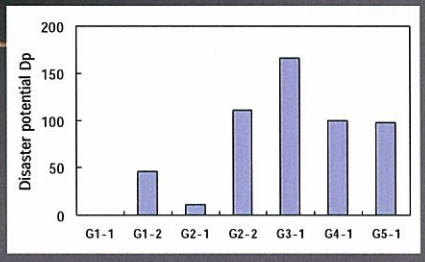
Example of collapse and debris flow range (G5-1)

Evaluation of road damage

Calculation results of each slope

Slope No.	G1-1	G1-2	G2-1	G2-2	G3-1	G4-1	G5-1
Damage probability Pd	0.00	1.00	1.00	1.00	1.00	1.00	1.00
Collapse scale V(m^3)	25.67	46.27	10.82	110.9	166.5	99.09	97.34
Disaster potential Dp (m^3)	0.00	46.27	10.82	110.9	166.5	99.09	97.34

Evaluation of road damage



Calculation results of each slope's Dp

Synthetic evaluation

Calculation results of risk and priority for disaster prevention

Items \ Slope No.	G1-1	G1-2	G2-1	G2-2	G3-1	G4-1	G5-1	
								High ↓
Failure probability P_f	0.311	0.076	0.114	0.378	0.258	0.309	0.614	
Disaster potential D_p (m^3)	0.00	46.27	10.82	110.93	166.50	99.09	97.34	Risk
Risk R (m^3)	0.00	3.52	1.23	41.93	42.96	30.62	59.77	
Priority for disaster prevention	7	5	6	3	2	4	1	↓ Low

Conclusion

In this study we propose the Risk Evaluation Method for Road Slopes for the area in which granite are distributed along national highways

In case there are slopes that have road as physical object of maintenance like road slope, it is effective to evaluate the collapse risk and the risk of the road disaster quantitatively, and to consider the risk for Synthetic evaluation.

We can determine the priority for disaster prevention by using the results.

Thank you!