BACK-ANALYSES OF SEVERAL EARTHQUAKE-INDUCED SLOPE FAILURES ON THE IZU PENINSULA, JAPAN

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SUMMARY

The effect of vertical acceleration on slope stability is analysed and found to be insignificant in assessing the critical acceleration. A simple relationship between static factor of safety Fs and horizontal critical acceleration Kc is derived for an infinite slab- and a simplified slice model. The critical acceleration for a slope which slid in the 1978 Izu-Oshima earthquake and also during rainfalls prior to and after the earthquake is estimated. The weight increase of soil mass by sucking water may have caused instability. The speed of a sliding mass at another site is estimated by applying energy-conservation law.

INTRODUCTION

The importance of landslides among various types of earthquake hazard has been increasing in recent years(Ref.1). It was especially evident in those earthquakes in 1974 and 1978 on the Izu Peninsula, Japan, where more than 90 % of the deaths were brought about by landslides. It will be useful, therefore, to investigate the mechanisms and factors of those landslides for predicting them or for finding out necessary counter-measures at slopes which are not supposed stable enough. The present paper deals with back-analyses of failed slopes on the Izu Peninsula in the 1974 and 1978 events.

SEISMIC STABILITY ANALYSIS

The Effect of Vertical Acceleration

It is usual in most seismic-stability analyses of slopes to employ only a horizontal acceleration. The results thus obtained by ignoring a vertical acceleration may yield a too high factor of safety, since the stability becomes minimum when subjected to outward-above directing acceleration. In order to examine the inaccuracy through ignoring the horizontal component, we conducted a series of computations for cases subjected to vertical and horizontal accelerations at the same time.

Assuming a simple model as shown in Fig.1, the critical acceleration will be

$$Kc = \frac{cL/W+(1-U)\cos\theta\cdot\tan\phi - \sin\theta}{\cos(\theta+\alpha)+\sin(\theta+\alpha)\tan\phi} \qquad (1)$$

where c; cohesion, ϕ; angle of friction, U; pore-water pressure ratio, L; length of soil prism, and θ and α; angles shown in the figure.

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Since the numerator in (1) does not include the direction of applied acceleration α, the dependence of Kc on α is given only through its denominator. The reciprocal of the denominator versus $\theta+\alpha$ is illustrated in Fig. 2. Every curve has its minimum at a value of $\theta+\alpha$, implying that there is a most effective angle of application for causing sliding. The angle is equal to $\phi-\theta$. However, these minima are not very strong ones and 110 % of the minima are attained first at about $\phi-\theta\pm 25^\circ$, i.e. the widths of the minima should practically pretty wide. Since θ of natural slopes is supposed to be nearly equal to ϕ, Kc values computed on an assumption $\alpha=0^\circ\pm 25^\circ$ would not be too unreasonable. From this reasoning we will ignore the vertical acceleration or assume Kv=0 throughout the present study.

Factor of Safety Fs and Critical Acceleration Kc

Sarma(Ref.2) has proposed to use horizontal critical acceleration Kc for the purpose of evaluating a static factor of safety Fs based on an empirical relationship between Fs and Kc. By using this relationship we can calculate a factor of safety economically without iterating as usual to get Fs. It is a natural feeling that the smaller Fs is, the lower Kc will be, and vice versa. This relationship can be given also in a form of mathematical expression for simple cases. As an example, assuming a soil block of length L and weight W resting on a sliding surface of inclination θ as in Fig.3, the following two expressions can be derived.

$$Fs = \frac{(cL/W)+(1-U)\cos\theta\cdot\tan\phi}{\sin\theta} \tag{2}$$

$$Kc = \frac{(cL/W)+(1-U)\cos\theta\cdot\tan\phi - \sin\theta}{\cos\theta + \sin\theta\tan\phi} \tag{3}$$

By eliminating c from the both expressions, we get

$$Kc = \frac{\tan\phi}{1+\tan\theta\cdot\tan\phi}(Fs-1) \tag{4}$$

which is applicable only to the range for $c \geqslant 0$, i.e.

$$Fs \geqslant \frac{(1-U)\cos\theta\cdot\tan\phi}{\sin\theta}$$

or

$$Kc \geqslant \frac{(1-U)\cos\theta\cdot\tan\phi - \sin\theta}{\cos\theta + \sin\theta\cdot\tan\phi} \tag{5}$$

The expression (4) corresponds to a straight line in Fig.3, and from the figure we can see Kc=0 when Fs=1.0 and also Kc becomes higher as Fs increases. The gradient of the line is a function of only slope angle θ and angle of friction ϕ, and it becomes gentler as ϕ becomes greater. It is interesting that a relation similar to (4) between Fs and Kc holds not only for plane slides but also for simplified slice models, as far as we ignore internal forces exerted between slices, and that the relation has a form obtained just by replacing $\tan\theta$ in (4) by $\sum W_i\cdot\sin\theta/\sum W_i\cdot\cos\theta$. The suffices denote the slice numbers, W is weight and θ is slope angle.

By applying this type of relation to artificial slopes we can estimate their critical accelerations easily, since most artificial slopes in Japan are designed to have a factor of safety around 1.2 to 1.3. An example of Kc thus estimated is given in Fig.4, where Fs is assumed as 1.3. It is evident that Kc varies relatively widely, even for an equal value of Fs, depending on the combination of c and ϕ. This is caused by an assumption that the resistance due to c is not influenced by earthquake acceleration while that due to ϕ is affected by it through change of normal stress on the sliding plane. For this reason, even for an equal Fs, a slope which stability depends strongly on cohesion is not much affected by earthquake, while that depending much on friction is strongly affected by earthquake. The tendency is consistent with a gentler slope for a larger ϕ in Fig.3. From the foregoing discussion it is clear that not only a value of static factor of safety but also the composition of its resistance is important in evaluating a seismic stability of a slope.

Effects of Rainfall and Those of Shaking

It is clear from experience that a factor of safety of a slope becomes lower when subjected to rainfalls. Besides, a factor of safety will become drastically low if pore-water pressure builds up. However, there may be such slopes which fail without development of pore-water pressure but just due to increase of weight through sucking rain water. We applied this postulate to cut slopes at Nashimoto which failed in the Izu-Oshima earthquake of Jan. 14, 1978 and also during rainfalls prior to(Oct. 1976; 95 mm) and after(Mar. 1978; 55 mm) the earthquake. These slopes should have been at such a marginal stability as to fail by the rainfalls cited above and by the earthquake of January 14, 1978 with a maximum acceleration of 0.4g.

The rocks of the site consist mainly of Pleistocene to Holocene volcanic products and their debris underlain by Tertiary volcanic breccia or tuffaceous breccia. The build-up of pore-water pressure was not probable, since the rocks at the site were extremely permeable.

We computed critical accelerations of the slopes on an assumption for possible material properties; γ=1.0-1.7x10^3 kg/m^3 (ρ=1.0-1.7), c=0-50 KPa (=1/98 kgf/cm^2), and ϕ=10°-46°. Among the assumed values we supposed ρ under dry conditions as 1.0 to 1.3 and that under wet conditions as 1.7. Since these slopes failed in the earthquake as strong as 0.4g and also by rainfalls referred to in the above, Kc should be less than 0.4 when ρ=1.0-1.3, and Kc should be zero when ρ=1.7, as far as we do not assume a build-up of pore-water pressure. Probable combinations of c and ϕ are given in Fig.5.

From intersections of curves for different densities in Fig.5, i.e. if we assume the increase of density due to rainfalls from 1.0 to 1.7, we have as probable strength parameters

c=29 KPa and ϕ=20° for west slope

and c=31 KPa and ϕ=10° for east slope.

The curves for dry density of 1.3 and those for wet density of 1.7 have no intersection and any combination of c and ϕ cannot satisfy the failures due to earthquake and rainfall when we do not assume the increase of pore-water pressure. If we assume the increase of the pressure, every combination below a curve for Kc=0.4(dry state) would be satisfactory, because the effect of ϕ in those cases can be as low as zero depending on the values of pore-water pressure. The allowable regions are shown as shaded areas. However, the pressure build-up is not probable as described above, and the estimated values for c and ϕ are consistent with those estimated by Iwasaki et al.(Ref.3) who gave ρ=1.7 t/m^3, c=3 t/m^2(30 KPa) and ϕ=30° and reported that no ground water was observed near the sliding surface.

ESTIMATION OF SPEED OF SLIDING

Some of the slides triggered by earthquake are rapid and attain long distances causing catastrophic damage. A couple of slides which occurred at Mitaka-Iriya area in the Izu-Oshima earthquake in 1978 are such examples and one of which buried four houses killing seven people including farmers having been working in the field. Even one dog could not get rid of the slide evidencing a very high speed of the slide. Okusa et al.(Ref. 4) estimated the maximum speed as high as 15 m/sec.

We take up this slide and try to analyse the movement of the soil mass. In order to simplify the problem, we assume that a finite-length of soil layer slid down on a surface of a form of y=f(x) without detaching the surface and without changing the thickness and the length along the sliding surface during the course of sliding. Then, it follows from the energy-conservation law

$$P_o = (1/2)MV_x^2+F_x+P_x = F_f+P_f \qquad (6)$$

where P; potential energy, F; energy consumed during sliding at the bottom of the sliding mass, M; mass, V; velocity, and suffices o, x and f denote beginning, intermediate and final stages, respectively. P and F are calculated by the next relations:

$$P(x) = \gamma\int_s^{s+l} h(s)\cdot y\ ds = \gamma\int_{x_1}^{x_2} h(x)\cdot y\cdot\sqrt{1+y'^2}\,dx \qquad (7)$$

and

$$F(x) = f\int_0^s ds\int_s^{s+l}\gamma h\cdot\cos\theta\cdot ds = f\int_0^x\int_{x_1}^{x_2}\gamma h(x)/\cos\theta\cdot dx^2 \qquad (8)$$

where s; distance measured along the sliding surface, y'; dy/dx, h; thickness of soil layer, γ; density, l; length, f; coefficient of friction, and $\theta=\theta(x)$; slope angle at distance x.

Prior to estimating the speed of sliding, we will examine if the critical stability is exceeded. We assume an infinitely long slope and strength parameters c=1.65 t/m^2 and ϕ=22° as well as ρ=1.3 to 1.4 for surface soil and ρ=1.5 for scoria(Ref.4). The inclination is assumed as 32° and 25°. Under the conditions the factor of safety when subjected to horizontal acceleration Kc(g) is given in Fig.6. The values of critical accelerations are 0.36, 0.27, and 0.24 for cases 1, 2, and 3, respectively, and it is possible that the slope slid by shaking as strong as 0.4g estimated at the site.

The speed of soil mass at every moment can be computed by step by step procedure by applying (6), (7), and (8), and the results are given in Fig.7. From the stopping distance in the figure, ϕ=15° would appear a probable value, which would give the maximum speed of only 8 m/sec. It is re ported that the soil mass climbed up the opposite bank up to a middle height and was reflected back to the position as it is. If we consider this situation, a lower ϕ value may be more probable, and Vmax 14 m/sec is also possible to which $\phi=11°$ corresponds. It is, however, impossible to determine which ϕ should be the best estimate, but it is at least probable that ϕ value during sliding must have been appreciably lower than that during static stability. A certain mechanism for reducing ϕ during sliding is necessary as Okusa et al.(Ref.4) suggested, who seeked the cause in a higher factor of sensitivity of soils ranging from 4.5 to 5.0.

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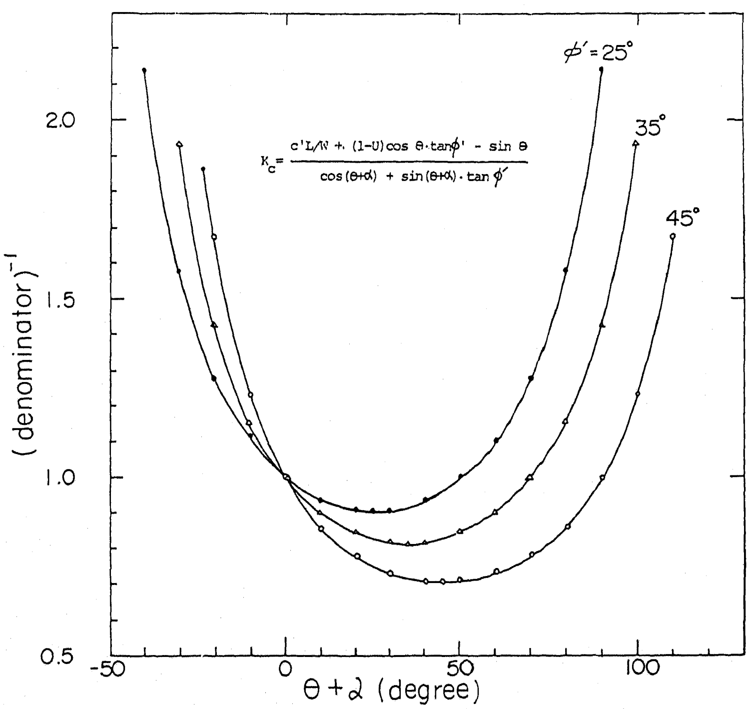


Fig.2 Effect of acting angle of earthquake force α from horizontal on stability of sliding block.

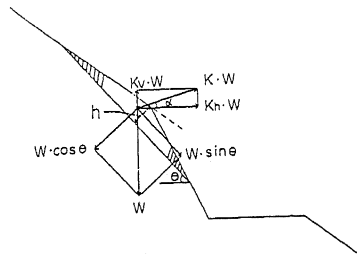
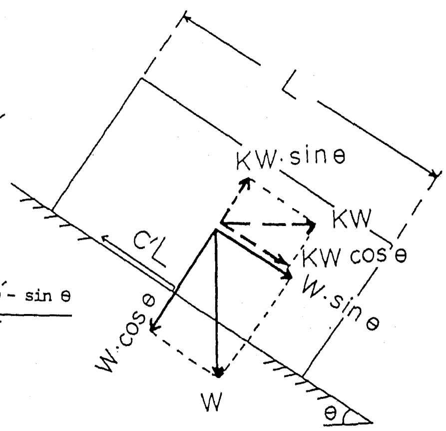


Fig.1 Force equilibrium for a sliding block under the action of earthquake force.

$$F_s = \frac{c'L/W + (1-U)\cos\theta\cdot\tan\phi'}{\sin\theta}$$

$$K_c = \frac{c'L/W + (1-U)\cos\theta\cdot\tan\phi' - \sin\theta}{\cos\theta + \sin\theta\cdot\tan\phi'}$$



$$K_c = \frac{\tan\theta}{1 + \tan\theta\cdot\tan\phi'}(F_s - 1)$$

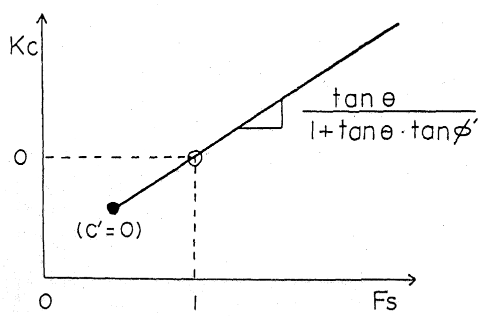


Fig.3 Factor of safety Fs and critical acceleration factor Kc for a sliding block.

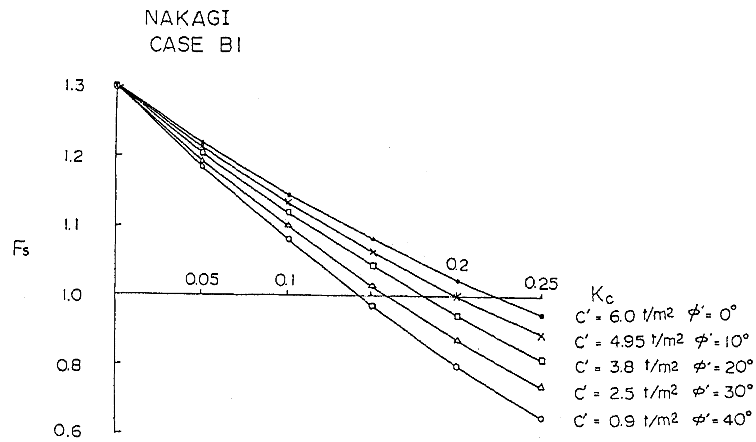


Fig.4 Critical acceleration factor Kc for slopes of Fs=1.3. It depends on the values of c and ϕ.

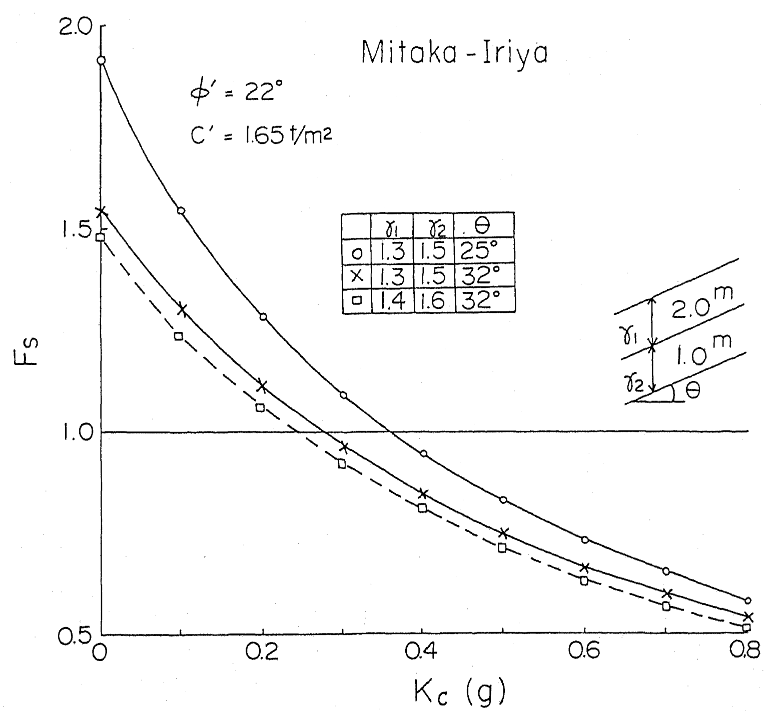


Fig.6 Critical acceleration factor Kc for the slope at Mitaka-Iriya.

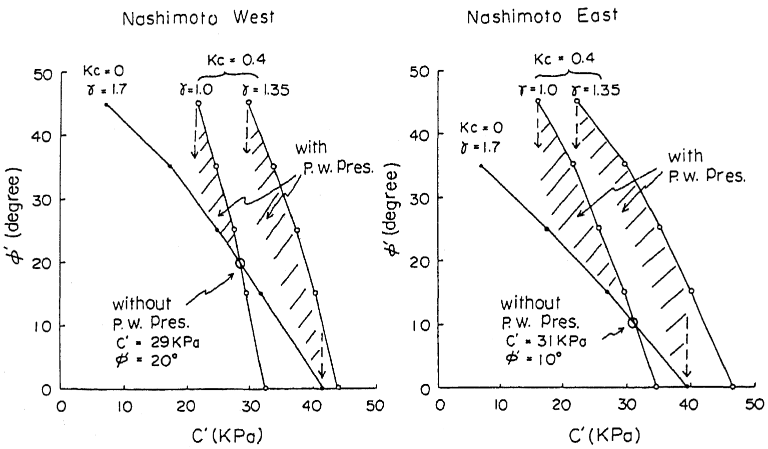


Fig.5 The estimated c and o for the slope at Nashimoto which slid by Kc≤0.4 in dry state and by Kc=0 in saturated state.

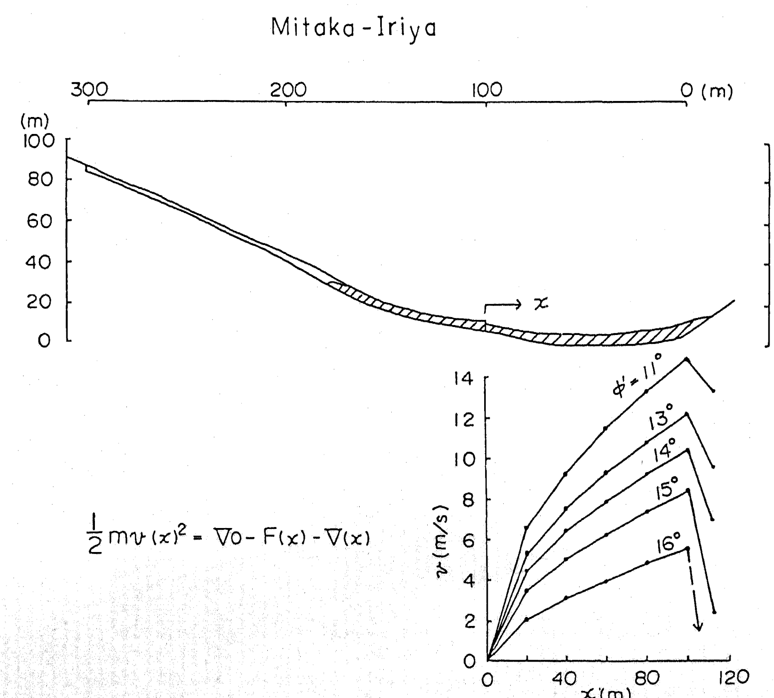


Fig.7 Estimated sliding speed for the slope at Mitaka-Iriya.