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Invited Paper

CONSIDERATIONS FOR LANDSLIDES IN NATURAL SLOPES TRIGGERED BY EARTHQUAKES

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1. INTRODUCTION

The hazards of landsliding caused by earthquakes have not oddly been an issue of considerable technical debate probably because many slides have taken place in remote mountain areas and consequent impact on human activities has not been very significant. However, the sprawl of urbanization and evolvement of highway networks in recent years have exposed various kinds of infrastructures to the potential hazards of landsliding during earthquakes. One of the recent events which have kindled a serious concern in Japan is the widespread occurrence of landslides and rock falls at the time of the 1978 Izu-Ohshima-Kinkai earthquake. Highways and railways running along hillsides and oversteepened slopes were crosscut at many places and traffic was completely paralized for a few months. Another round of catastrophic events was a huge scale landslide which took place at the time of the Nagano-seibu earthquake of 1984 in Japan. A vast amount of soils and rocks, as much as 35 millions m^3, was detached from the flank of the mountain and after bouncing off several times it plummeted down the gorge through a distance of about 12 km. In the course of a deluge of debris flow, there were a number of fatalities, loss of properties and devastation of forestry lands.

The features of the landslides in these two recent earthquakes are characterized by the fact that the slides took place on rather steep slopes near the shoulder of terrains of high relief, leaving the sliding planes exposed on the surface wherefrom recovery of undisturbed samples of soils could be made without difficulty. In many cases the soils involved are partially saturated silts of volcanic origin. There had been no trace of land movements prior to the earthquake, and therefore, the slides were those newly activated on fresh slip surface due mainly to inertia forces of the earthquakes. Evaluation of slope stability has been made using the strength parameters of soils obtained from the dynamic loading tests in which irregular time histories of shear stress were applied to undisturbed specimens of soils secured from sites of landsliding. The stress-strain curve and the definition of strength used in the stability analysis are illustrated in Fig. 1.

Another noteworthy type of landslides took place in central Italy at the time of the 1980 Irpinia earthquake. Following the earthquake, dozens of landslides took place over the gentle slopes in the hilly terrains east of Naples. The features of the landslides in this earthquake are charaterized by their

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occurrence on gentle slopes near the foot of the mountains, and as such the sliding debris remained around the place where it had existed before. This situations made it very difficult to execute on-the-spot recovery of undisturbed samples directly from the exposed slip plane. In many cases, the sliding surface was located in the deposit of variegated clay known as varicolored clay which lies below the ground water table. Therefore, the soil responsible for the slide was saturated. The landslides in this area were identified as revivals of old movements and therefore ancient landslides constituted the seats of new disturbances. In the light of such circumstances, it appears most appropriate to evaluate the degree of slope stability based on the strength parameters of soils obtained from the tests in which the stress history is reproduced in the laboratory sample as illustrated in Fig. 1.

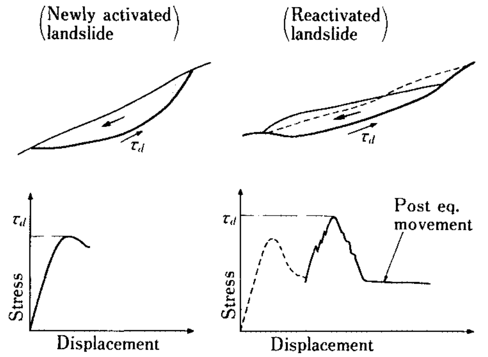

Fig. 1 Illustration for the definition of strength to be adopted for two kinds of landslides.

In view of the sharp contrast as mentioned above between the landslides in Japan and those in Itlay, it might be of interest to review the outcomes of the investigations conducted in each country and to seek for an integrated methodology for evaluating the degree of slope stability during earthquakes from a unified point of view. One of the purpose of this paper lies at this point. In the practical aspect, it will be useful to have a procedure preferably in a form of charts enabling hazards of earthquake-induced landsliding to be assessed on the basis of available information at hand. An attempt in this vein will also be made in the following pages of this paper based on case history evidences.

2. SIMPLE METHODS OF EVALUATING STABILITY OF SLOPES DURING EARTHQUAKES

One of the goals for making stability analyses would be to provide background for predicting stability or instability of given natural slopes during shaking of future earthquakes. In general, the problem will be posed in a form to ask under what intensity of shaking a given slope will initiate sliding. The intensity of shaking would be represented most conveniently by the magnitude of horizontal acceleration which the slope will undergo during an earthquake to come. It is most legitimate to assume that the stability of slopes during earthquakes is dependent on the degree of stability under the static conditions prior to the earthquake, which will be most logically expressed in terms of the static factor of safety. Therefore, the whole problem will be reduced to the determination of the threshold acceleration differentiating between occurrence and non-occurrence of landsliding as a function of the static factor of safety. The correlation between the static factor of safety and the acceleration required to cause landsliding may be established on the basis of detailed studies of many failure cases that have occurred during the past earthquakes. To this end, two procedures as follows are conceived to be applicable.

(1) When the strength parameters of key soil deposits associated with landsliding at a given site is known from some appropriate in-situ or laboratory tests for both static and dynamic loading conditions, the stability analyses can be made using the conventional formula to determine the static factor of safety. The stability analysis for the dynamic condition can also be made to determine the magnitude of horizontal acceleration required to induce sliding whereby the dynamic factor of safety must be equal to unity. Thus, for one site of landsliding thus analyzed, it becomes possible to obtain a pair of information, one on the static factor of safety and the other on the critical acceleration. If similar analysis is made for a number of cases of landslides, a number of such data pairs will be obtained. By plotting the critical accelerations thus obtained versus the static factor of safety and by drawing an average curve through the whole data points, the desired relationship will be obtained between the slide-inducing acceleration and the static factor of

safety. To implement this procedure, it is first necessary in each of failure cases to identify the position of a sliding surface. It is also necessary to be able to recover undisturbed samples from key soil deposits if the laboratory tests are to be run for determining the soil parameters. In case sliding masses have moved away downhill leaving intact sliding surface exposed, recovery of undisturbed samples can be executed without difficulty except for the case of materials such as gravelly or highly collapsible soils. If the sliding surface is entirely buried under the debris, it is difficult to recover high-quality undisturbed samples by means of the block sampling method.

(2) If the intensity of shaking during the earthquake is estimated in terms of the acceleration for a landslide site through the use of some empirical formulae or through some other means, and if the static factor of safety is calculated on the basis of soil parameters in static loading, it is possible to locate a point in the diagram where the estimated acceleration is plotted versus the static factor of safety. Provided similar pairs of data are collected for a number of cases of actual landslides, a cluster of data points can be obtained in the diagram in which these two pairs of data are plotted. By drawing a curve bounding all the data points with lowest accelerations, it will become possible to obtain the desired correlation between the slide-inducing acceleration and the static factor of safety. One of the advantages of using this procedure would be the fact that one needs not to know the strength parameters of soils under dynamic loading conditions which generally required high-quality undisturbed samples to be tested in the laboratory. However, the strength parameters in static loading conditions ought to be known by means of some tests. Rough estimate may be made for this purpose based on the field tests such as the standard penetration test or the cone penetration test.

3. METHODS OF STABILITY ANALYSIS

The simplest and most convenient method for making slope stability analysis during earthquakes would be to use the formula,

$$F_d=\frac{\sum[W\tan\phi+C_D l\cos\alpha]/[\cos^2\alpha\,(1+\tan\alpha\tan\phi/F_d)]}{\sum\left[W\tan\alpha+\frac{a_{\max}}{g}W\right]} \quad\cdots\cdots\cdots (1)$$

where F_d is the factor of safety for dynamic loading, and W, l, and α denote, respectively, the weight, length and inclination of the sliding plane in each slice, as illustrated in Fig. 2. In this method, the effect of seismic loading is allowed for by a static force determined as the product of the maximum horizontal acceleration, $a_{\max}$, and the weight of the sliding mass. In Eq. (1), C_D denotes the cohesion of soil in dynamic loading and ϕ indicates the angle of internal friction. Previous studies by Ishihara et al. (1983) have indicated that the effects of dynamic loading on the strength parameters of soils are accounted for simply in terms of an increase in cohesion, while the angle of internal friction remains the same as in the case of static loading.

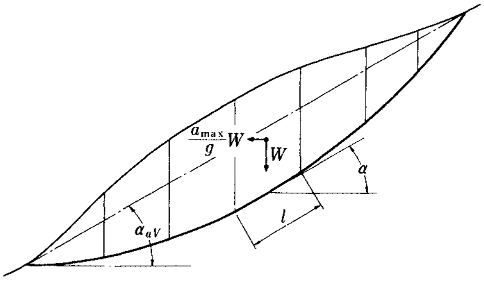

Fig. 2 Notations in the scheme of slope stability analysis.

The factor of safety in the static condition prior to the earthquake is thus calculated by

$$F_s=\frac{\sum[W\tan\phi+Cl\cos\alpha]/[\cos^2\alpha\,(1+\tan\alpha\tan\phi/F_s)]}{\sum W\tan\alpha} \quad\cdots\cdots\cdots (2)$$

where C is the cohesion in static loading conditions.

For the purpose of establishing a correlation between the static factor of safety and the failure-inducing horizontal acceleration on the basis of case studies, the magnitude of maximum horizontal acceleration,

$a_{\max}$, required to make the dynamic safety factor equal to unity is determined from Eq. (1). At the same time, the static factor of safety, F_s, is computed by the use of Eq. (2). A set of data thus obtained can be used to obtain the desired correlation.

In order to gain a more straightforward understanding for this relationship, let a simple case be considered in which the strength of soils is expressed only in terms of cohesion component. It is also assumed that the soils along the entire stretch of sliding surface are identical, giving the same cohesion value through all sliced elements in the computation of stability. Then, eliminating the term, $(l/\cos\alpha)$, between Eq. (1) and Eq. (2) with $F_d=1.0$, one obtains

$$\frac{a_{\max}}{g}=\left(\frac{C_D}{C}F_s-1\right)\frac{\sum W\tan\alpha}{\sum W}\cdots\cdots \tag{3}$$

At this stage, it may be convenient to introduce an average angle of slope, α_{av} which is defined as an inclination of a straight line connecting the top and toe of a curved sliding surface, as illustrated in Fig. 2. By introducing this average slope angle, Eq. (3) is simplified as

$$\frac{a_{\max}}{g}=\left(\frac{C_D}{C}F_s-1\right)\tan\alpha_{av}\cdots\cdots \tag{4}$$

Note that the same relation as above can be derived for the case of infinitely long slope with a constant angle. One of the important points implied by Eq. (4) is the fact that the magnitude of acceleration required to induce sliding in a slope becomes larger as the slope becomes steeper. Suppose there are two slopes with different angles of inclination but having an identical factor of safety under the static conditions, then, Eq. (4) implies that a greater acceleration is required for a steeper slope to induce landsliding than it is required for a more gentle slope.

4. CASE STUDIES OF SEISMICALLY INDUCED LANDSLIDES

(1) Izu-Ohshima earthquake of 1978, Japan

A destructive earthquake of magnitude 7.0 shook the south-eastern coast area of the Izu Peninsula on January 14, 1978. The locations of the epicenter and subsequent aftershocks are shown in Fig. 3. The damage due to this earthquake is characterized by a number of landslides which took place on the bluffs along the edge of mountains facing the east coast of the Izu Peninsula. The mountains are covered by a series of loam deposits from volcanic fallout and occasionally by residual soils resulting from weathering of volcanic rocks such as tuffs and andesites.

Among dozens of landslides, two sites were investigated in detail including soil sampling and testing in the laboratory. The first site investigated is located at Hokkawa as shown in Fig. 4, where a steep slope slid down thereby burying the highway and spreading debris over the beach downhill. Undisturbed

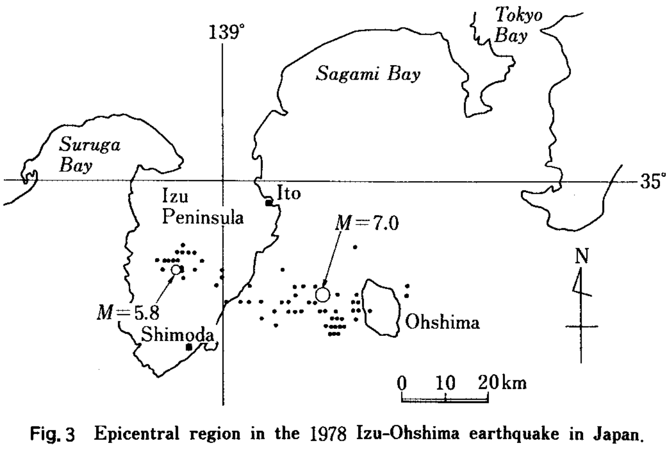

Fig. 3 Epicentral region in the 1978 Izu-Ohshima earthquake in Japan.

samples of highly weathered tuff identified to have triggered the slide were recovered in block from the exposed surface at the top of the slide area. The results of triaxial tests on partially saturated clayey silts (Ishihara, 1985) showed the strength parameters in terms of total stress, as indicated in **Table 1**. As a result of slope stability analyses using Eqs. (1) and (2) the horizontal acceleration needed to cause the sliding was computed as approximately 520 gal and the static factor of safety was calculated as 1.70, as listed in **Tables 1** and **2**.

The second slide investigated is located at Nashimoto shown in **Fig. 4** where colluvial deposits on the mountain flank slid down (Ishihara, 1985). At this site, disturbed samples were obtained and the laboratory triaxial tests were conducted on samples of partially saturated silty sands compacted to densities nearly identical to the in-situ density. The strength parameters in terms of total stress established from the test results are indicated in **Table 1**. The result of stability analysis disclosed that the magnitude of horizontal acceleration required to bring the computed factor of safety to unity is on the order of 450 gal for the slide in this area. The factor of safety in the static condition prior to the earthquake was computed as 1.50 (**Table 1**).

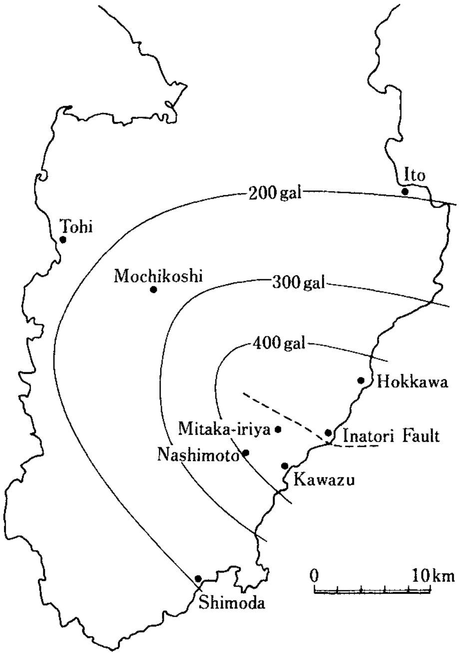

Fig. 4 Contour lines of equal maximum horizontal acceleration estimated from the analysis of overturned tombstones.

The intensity of ground shaking during this earthquake was estimated by the analysis of overturning of

Table 1 Key items of landslides caused by the two recent earthquakes in Japan.

Site of landslide	Earthquake	Distance from epicenter Δ (km)	Angle of internal friction ϕ^* (deg.)	Static cohesion C^* (kN/m^2)	Dynamic cohesion C_D^* (kN/m^2)	Static factor of safety F_s	Soil** type	References
Hokkawa	Izu-Ohshima (1978) $M=7.0$	18	35	120	205	1.70	Weathered tuff	Ishihara (1985)
Nashimoto		22	30	30	45	1.50	Weathered andesite	〃
Ontake headwall	Nagano-seibu (1984) $M=6.8$	10	23	150	230	1.53	Volcanic pumice	Ishihara et al. (1986)
Matsukoshi		1	15	20	60	1.48	Volcanic pumice	〃
			15	60	120			
Ontake highland No.1		3	14	20	40	1.53~1.60	Volcanic pumice	〃
Ontake highland No.2		3	14	20	40	1.78~1.83	Volcanic pumice	〃
Ontake highland No.3		3	10	20	50	1.60~1.62	Volcanic pumice	Ishihara et al. (1987)
Ontake highland No.4		3	14	15	45	2.10~2.12	Volcanic pumice	〃

* In terms of total stress

** All soils are partially saturated silty clay

Table 2 Estimated accelerations and computed accelerations required to cause landsliding in the two recent earthquakes in Japan.

Earthquake	Site of landslide	Average slope angle (deg.)	Depth of slide H (m)	Static factor of safety F_s	Computed acc.* required for F_d to become unity (gal)	Estimated** acceleration (gal)
Izu-Ohshima (1978)	Hokkawa	46	≑ 10	1.70	520	450~550
	Nashimoto	41	≑ 5	1.50	450	450~550
Nagano-seibu (1984)	Ontake headwall	30	≑100	1.53	270	300~360
	Matsukoshi	20	≑ 30	1.48	320	390~480
	Ontake highland 1	20	≑ 10	1.53~1.60	300~320	360~440
	Ontake highland 2	16	≑ 13	1.78~1.83	270~340	360~440
	Ontake highland 3	20	≑ 6	1.60~1.62	400	360~440
	Ontake highland 4	11	≑ 10	2.10~2.12	400	360~440

* Computed by Eq. (1)

** Estimated by the empirical formulae in Eq. (5)

tombstones in the cemetries in the affected area, as indicated in Fig. 4 in terms of the contour lines of equal horizontal acceleration. The approximate order of magnitude of the horizontal acceleration may also be inferred by the empirical formulae by Kawashima et al. (1984) as follows, which are applied to the firm, medium and soft ground, respectively.

$$\left.\begin{aligned} a_{\max} &= \frac{987.4\times10^{0.216M}}{(\Delta+30)^{1.218}} \\ a_{\max} &= \frac{232.5\times10^{0.313M}}{(\Delta+30)^{1.218}} \\ a_{\max} &= \frac{403.8\times10^{0.265M}}{(\Delta+30)^{1.218}} \end{aligned}\right\} \qquad (5)$$

where M indicates the magnitude of the earthquake and Δ is the distance in km between the epicenter and a site in question. The acceleration in the above formulae is calculated in terms of gal. The range of horizontal accelerations obtained by the above formulae is shown to coincide with that estimated by the analysis of tombstone overturning during the earthquake (Fig. 4). The approximate range of accelerations thus inferred for the above two cases of landslides is between 450 and 550 gal, as indicated in Table 2.

(2) Nagano-seibu earthquake of 1984, Japan

This earthquake took place on September 14, 1984 with its epicenter located at the southern foot of Mount Ontake about 100 km northeast of Nagoya, as indicated in Fig. 5. Its magnitude 6.8 in the Richter scale placed this event among the greatest to have occurred in this locality in historic time. The area of about 100 km^2 badly devastated is shown in Fig. 6. The damage by this earthquake is characterized by several medium to large scale landslides which took place on the southern flank of the Mount Ontake and surrounding piedmont apron areas.

By far the most spectacular event was a huge landslide triggered off near the mountain top, leading to a release of about 35 million m^3 of soils and rocks and consequent debris avalanche which travelled as far downstream as 12 km. As a result of extensive investigation, it was discovered that a pumice deposit of Pliocene age exists beneath the scoria and lava which are the products of a series of volcanic activities in

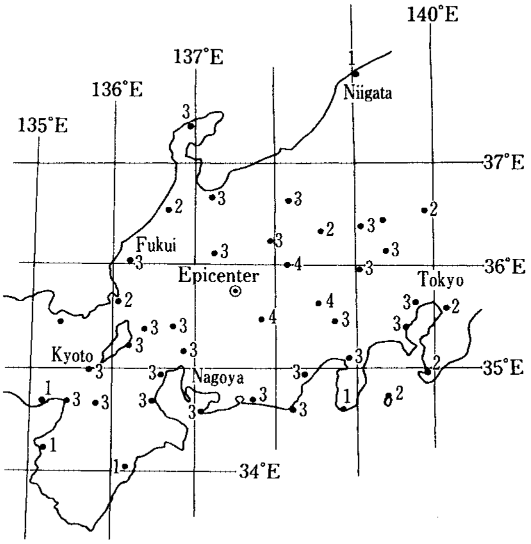

Fig. 5 Location of the epicenter of the 1984 Nagano-seibu earthquake in Japan.

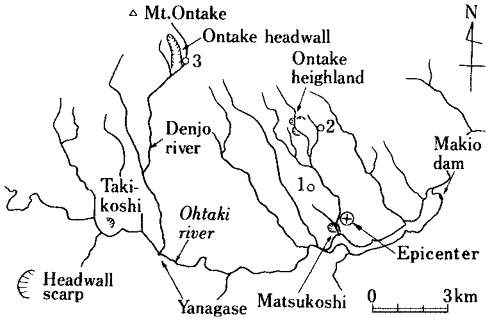

Fig. 6 Locations of major landlsides during the Nagano-seibu earthquake.

the subsequent Pleistocene era, and that this pumice, being highly porous and weak, had been responsible for triggering the slide. Following the earthquake, undisturbed samples of this pumice were secured and tested in the laboratory by means of the triaxial test device. The pumice was identified as partly saturated silts composed of highly porous halloysite, having a water content as high as 70 to 120 %. The results of static tests on this pumice showed an angle of internal friction of about 23° and a cohesion of $C=150$ kN/m^2 in terms of total stress. In the dynamic loading tests employing an irregular load time history, the cohesion was shown to increase about 1.5 times as much as that in the static loading, whereas the angle of internal friction was shown to remain approximately the same. Using these strength parameters for the soil and assuming the rocks on the sliding plane to have approprite strength parameters, the pseudo-static analyses of stability were made using Eqs. (1) and (2). The outcome of the stability analysis is presented in Table 2, where the horizontal acceleration on the order of 300 gal is shown to be strong enough to bring the safety factor to unity inducing the landslide over the slope of the mountain (Ishihara et al. 1986).

The next largest and certainly noteworthy landslide that took place during the 1984 Nagano-seibu earthquake is that at Matsukoshi located in close proximity to the epicenter as shown in Fig. 6. As a result of field investigation, it was found that some pumice deposits of Pliocene age exist on a small ancient valley which was later buried by a series of gravel-containing soil layers derived from volcanic activity. The deposit of halloysite containing pumice on the buried valley is nearly saturated and highly porous, and was identified to have triggered the slide during the earthquake. Undisturbed samples of this pumice were also recovered at two places from the exposed surface of the landslide area. The static triaxial tests on the sandy silt samples disclosed that the angle of internal friction in terms of total stress is equally 15° for both pumices from two nearby places, but the cohesion was 20 kN/m^2 for the upper portion near the bluff and 60 kN/m^2 for the downhill part of the slide area (Table 1). The results of irregular loading tests disclosed that the cohesion in dynamic loading is about twice as much as that in the static loading. Incorporating the strength parameters thus determined, the stability analyses were made for typical cross sections of the sliding surface at Matsukoshi. The results of the slope stability computation are demonstrated in Table 2. The horizontal acceleration necessary to make the dynamic factor of safety equal to unity is shown to be on the order of 320 gal (Ishihara et al. 1986).

The third area of landsliding investigated is located in the piedmont apron in the Ontake highland shown in Fig. 6. Four small-scale landslides took place in this area. The soil movement apparently developed along the sliding surface through pumice deposits located at shallow depths of 5 to 10 m. The pumice is of halloysite origin and partially saturated. One of the slide turned into debris flow and plummeted down the valley through a distance of about 1.0 km. Undisturbed samples were obtained from intact blocks perching over the sliding surface by carving them into small columns and encasing them into brass tubes. The results of the static loading tests disclosed that the angle of internal friction is 14° and the cohesion is 10 kN/m^2 in terms of total stress. The cohesion in dynamic loading was found to be twice as much as that in the static loading (Table 1). Using the strength parameters thus obtained, stability analyses were made for typical cross sections of the two slide areas. The analysis results revealed a horizontal acceleration of about 300 to 320 gal being great enough to trigger the slides at two locations with the dynamic factor of safety equal to unity, as shown in Table 2. Along with the dynamic stability analyses as mentioned above, the static factor of safety prior to the earthquake was also calculated for each of the sliding surfaces considered above using the cohesion values obtained from the static loading tests. The computed static factor of safety is also shown in Table 2.

(3) Irpinia earthquake of 1980, Italy

The south-central Italy was struck by a disastrous earthquake, on November 23, 1980, which affected the regions of Campania and Basilicate. The magnitude 6.5 earthquake, centered about 100 km east of Naples, caused severe damage to buildings and civil engineering installations in the towns near the epicentral area. The intensity of shaking is demonstratd in Fig. 7 in terms of MSK scale (Stratta et al. 1981). More detailed map in the epicentral area is shown in Fig. 8 in which the maximum horizontal accelerations monitored during the earthquake are also indicated. The maximum recorded acceleration was 340 gal at Sturno. One of the notable features of this earthquake was that the damage in the local provinces was more or less associated with numerous landslides which occurred over the wide areas in hilly countrysides. The reports on the effects of the Irpinia earthquake indicate that the area affected is located in the region of potential landslides and the movement of many slides was the reactivation of dormant landslides which had once slid in ancient times. It is also reported that many of the landslides did not run down immediately following the main shaking of the earthquake, but started to move slowly a few minutes to several hours after the shaking of the earthquake. The baserock and mountains in this area are composed of tectonically overthrusted and faulted units of dolomites and limestones of the Trias to Miocene era. The rock formations are overlaid by the deposits of variegated clay named varicolored clay, which is of marine origin. On top of this clay deposit, there exists a series of colluvium composed of chaotically positioned

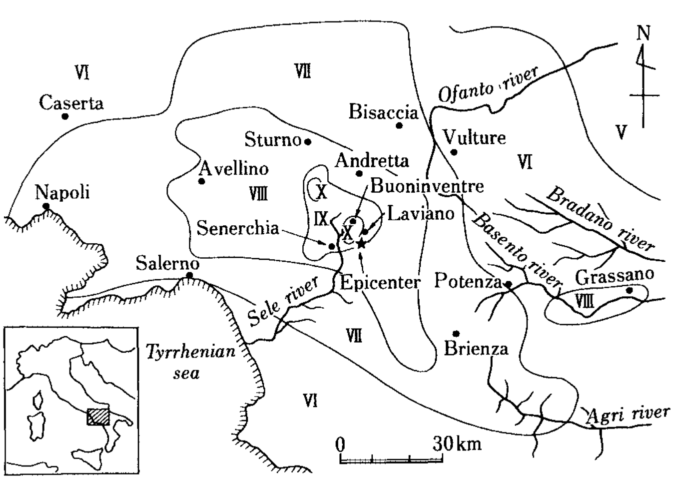

Fig. 7 Intensity distribution of the Irpinia earthquake, 1980.

sandy clays containing calcareous and marly pebbles of different size.

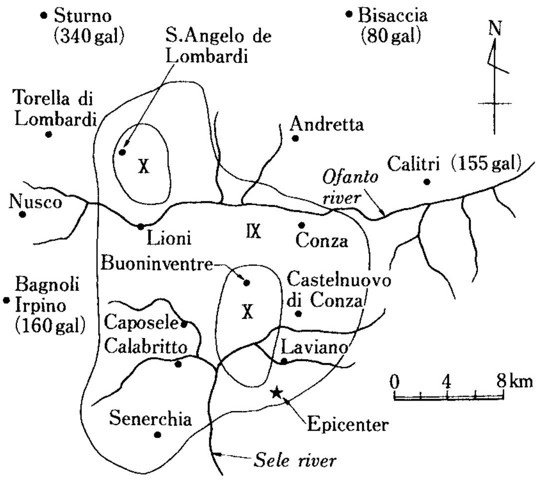

Fig. 8 Intensity distribution in the epicentral region, Irpinia earthquake, 1980.

As a result of extensive borings made in the landslide-affected area, it was discovered that the basal sliding surface runs mainly through the deposit of the variegated clay. This is a grey overconsolidated marly clay with prominent parallel flat laminae containing small-size calcareous pebbles. It is sometimes interbedded with calcareous marls, green clays and cemented fine-grained sandstones. According to the test results reported by Battista et al. (1986), the variegated clay at Calabritto has about 50 % clay, 30 % silt and 20 % fine sand content. The plasticity index of the varicolored clay ranges between 20 and 45 %. In most cases, major part of the sliding plane was found to be located at a depth of 40 to 50 m from the ground surface well below the elevation of the ground water table. Therefore, the varicolored clay associated with the landslide was fully saturated and most of the undisturbed samples recovered from bored holes were tested under drained conditions by means of the triaxial test apparatus. The results of the laboratory tests reported by some investigators are summarized in Table 3, where it may be seen that the angle of internal friction at peak and residual strength is, respectively, 20 to 30° and 9 to 13°. The cohesion corresponding to peak strength is between 20 and 50 kN/m^2 and the cohesion at residual strength is equal to zero except for one case. Most of the slides caused by the Irpinia earthquake are considered to have been the reactivation of quiescent landslides which had previously been triggered many years ago, and, therefore, the soils along the sliding plane is regarded as having undergone shear strains which are large enough to bring about a state in which the residual strength is mobilized under drained conditions. Therefore, all the investigators calculated the static factor of safety using the parameter, ϕ'_r and C'_r, at

Table 3 Key items of landslides caused by the 1980 Irpinia earthquake, Italy.

Site of landslide	Distance from epicenter Δ (km)	Estimated acc.* a_{max} (gal)	Angle of internal friction** (deg.)	Cohesion** (kN/m^2)	Static factor of safety F_s	Soil type	References
Buoninventre (Uphillslide)	8	250~300	$\phi'_r=10°$	$C'_r=0$	≑ 1.25	Vari-*** colored clay	Cotecchia et al. (1986)
Serra dell' Acquara (Senerchia)	10	240~280	$\phi'_r=9$ ~11.5°	$C_r=0$	≑ 1.23	〃	Cotecchia-Del Prete (1984)
Pergola (Senerchia)	10	240~280	〃	〃	≑ 1.40	〃	Cotecchia et al. (1986)
Grassano	80	70~80	$\phi'_r=13°$ $\phi'_r=22°$	$C'_r=0$ $C'=20$~50	≑ 1.18	〃	Cotecchia-Del Prete (1986)
Andretta	18	200~230	$\phi_r=13$~15° $\phi'=31°$	$C'_r=10$ $C'=40$~50	≑ 1.05	〃	D'Elia et al. (1985, 1986)

* Estimated by the empirical formulae in Eq. (5)

** ϕ', c' : Peak strength in terms of effective stress

ϕ'_r, C'_r : Residual strength in terms of effective stress

*** Saturated silty clay

residual strength on the basis of effective stress. The static factors of safety thus computed are quoted from the literatures and shown in Table 3. It may be seen that all of the landslides investigated had been narrowly on the verge of failure with a small margin in the factor of safety in the pre-earthquake condition.

In evaluating the static factor of safety as above, the strength of the varicolored clay along the slip plane was expressed in terms of the parameters ϕ'_r and C'_r, in effective stress. However, it would also be possible to express the residual strength along the slip plane alternatively in terms of an apparent cohesion, C, alone. Needless to say, the cohesion, C, is a function of an effetive confining stress which is determined from the depth of sliding plane in the field. If the stability analysis is made for the landslides listed in Table 3 using the undrained strength parameter, C, the same answer would be obtained for the computed factor of safety. Thus, it might as well be assumed that the same factor of safety as quoted in Table 3 could have been obtained in terms of total stress using an equivalent value of cohesion with $\phi=0$.

When the quiescent slopes underwent the ground shaking during the Irpinia earthquake, the soils in the slip plane must have been subjected to a series of shear stress under undrained conditions which changed rapidly. Effects of rapid and repetitive loading on the strength of cohesive soils have been investigated by Ishihara et al. (1983) and Ishihara (1985). The consequences of these studies revealed that the application of irregular loads such as those encountered in seismic shaking tends to increase the cohesion by a factor of 1.5 to 3.0 over the cohesion manifested in the static loading, whereas the angle of internal friction stays unchanged irrespective of whether the loading is static or dynamic. It is to be noted here that the above conclusion has been proved valid only when soils are sheared for the first time to the level of peak shear stress. In other words, this conclusion can be applied to the stability analysis of landslides which have been freshly triggered by an earthquake for the first time. However, the test results in support of the above point of view are also reported by Skempton (1985) and Lemos et al. (1985) for the soils having previously been sheared to a state where the residual strength is mobilized. Shown in Fig. 9 is one of the results of the ring shear tests on remolded clay from Kalabagh dam site (Skempton, 1985). The clay containing a clay fraction of 47 % has a plasticity index of $I_p=36$. A sample with a water content of 27 % subjected to a vertical stress of $\sigma'_v=205$ kN/m^2 was sheared slowly to produce a horizontal displacement of about 710 mm as indicated by point A in Fig. 9. Then, the shear stress was increased rapidly with a rate of 400 mm/min. The sample could sustain a shear stress ratio, τ/σ'_v, as much as 0.35 in the course of rapid application of shear stress (point B) as compared to the shear stress ratio of 0.156 which has previously been sustained during the slow application of shear stress. This implies that the sample exhibited 2.24 times greater stregth in the rapid loading than it did in the slow loading. Another sample with 40 % clay fraction tested at $\sigma'_v=400$ kN/m^2 showed an increase of 1.8 times the shear strength at residual state in show loading test. The results of similar ring torsion tests on the clay from Boniventre, Italy, are also reported by Lemos et al. (1986), who showed that the strength of this clay under fast dynamic loading condition is about 1.6 times the strength in the static slow loading. From the considerations as above, it may as well be mentioned that not only for previously unsheared clays but also for clays presheared to a residual state, the rapid application of loads such as seismically induced shear stress tends to increase the strength as compared to the case of slow application of shear stress. In the absence of any comprehensive test data on the varicolored clay, it may be difficult to accurately figure out how much gain in strength there will be for the clay undergoing irregular time histories of loads as induced by the ground shaking during earthquakes. Nonetheless, it is reasonable to assume that the strength of the varicolored clay in seismic loading conditions would probably be approximately 1.6 times greater than the strength in the static loading. On the basis of the reasonings as above, it will be also assumed that the cohesion of the varicolored clay in the dynamic loading is 1.6 times the cohesion in the static loading.

Thus, introducing the value of $C_D/C=1.6$ into Eq. (4), it becomes possible to approximately assess the magnitude of the maximum horizontal acceleration, $a_{\max}$, required to trigger the landsliding, if the average angle of a given slope, α_{av}, is known together with the static factor of safety, F_s. It is to be

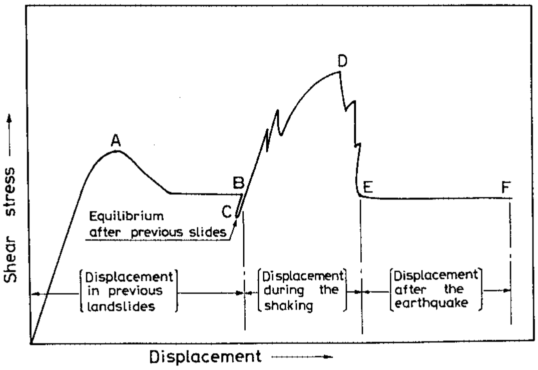

Fig. 9 Stress-deformation relation during unloading and reloading processes with with different speed of deformation.

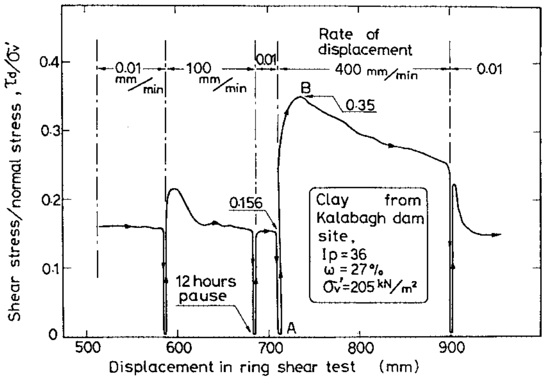

Fig. 10 Schematic illustration of displacements developing at different stages.

remembered that the application of Eq. (4) is approximate in the sense that the strength of soils is assumed identical through the entire stretch of sliding surface. The magnitude of the critical horizontal acceleration thus computed for each of the landslides investigated is presented in Table 4. Also indicated in Table 4 is the approximate range of horizontal acceleration estimated by the empirical formulae in Eq. (5). It can be seen that the magnitude of acceleration estimated by the empirical formulae is larger than that required to cause landsliding except for the case of the landslidee in Grassano.

With the background information as above, the occurrence of the landslides in the Irpinia region during the 1980 earthquake may be visualized as follows. Prior to the 1980 event, the varicolored clay in the sliding plane must have suffered a large displacement due to landslides in the historic time. Thus, in terms of the stress-displacement relation, shown in Fig. 10, the peak stress had been passed over and the clay had been brought to a residual state, thereby establishing a narrowly balanced state of equilibrium with a small margin of factor of safety (point C). The value of safety factor at this stage was probably less than 1.25 in most cases as indicated by the case studies presented in Table 4. During the Irpinia earthquake of 1980, the shear stress much greater than the residual strength must have been applied to the clay in the slip zone, but because of the rapid nature of load application, the clay was able to sustain a greater shear stress than

Table 4 Estimated accelerations and computed accelerations required to cause landsliding in the Irpinia Earthquake in Italy.

Earthquake	Site of landslide	Average slope angle (deg.)	Depth of slide H (m)	Static factor of safety F_s	Computed acc.* required for F_d to become unity (gal)	Estimated** acceleration (gal)
Irpinia (1980)	Buoninventre (Uphill slide)	12	40	≑1.25	210	250~300
	Serra dell' Acquare (Senerchia)	8	40	≑1.23	135	210~250
	Pergola (Senerchia)	8	60	≑1.40	170	210~250
	Grassano	10	40	≑1.18	155	70~ 80
	Andretta	8	50	≑1.05	95	200~230

* Computed by Eq. (4) with $C_D/C = 1.6$

** Estimated by the empirical formulae in Eq. (5)

that at the residual state as indicated by point D in Fig. 10. According to the reports of the Irpinia earthquake, the main shaking of the ground lasted for about 10 to 20 seconds. Therefore, it appears that the duration of shaking was so short as to produce a significant amount of displacement at the instant of the earthquake shaking. In fact, as mentioned before, evidences of the landslides visible on the ground surface immediately after the earthquake were reportedly minor distorsions such as fissures and differential settlements, and it was not until some hours or days later that the appreciable amount of displacement was seen developing in many places of landslides in the Irpinia region. Then, it may be speculated that, following the cessation of the seismic shaking, the clay in the slip zone was brought back to a residual state on the verge of failure, and owing probably to unfavorable changes in the ground water conditions, the clay became unable to sustain the existing shear stress due to gravity and complete failure took place. The small amount of displacement probably on the order of several tens of centimeter occurring in the slip zone at the time of the earthquake is schematically indicated by C to E in Fig. 10, and much larger displacement on the order of several meters occurring after the earthquake is represented by E to F.

5. CONSIDERATIONS AND DISCUSSIONS

The landslides in the Irpinia region in Italy have several characteristic features which are in sharp contrast with those of the landslides having taken place in Japan in the recent earthquakes. First, most of the landslides in Japan took place on steep slopes near the top of hills or mountains and as such the slides are identified as having been those developing on freshly formed planes without any trace of previous slips. Therefore, the use of the results of dynamic triaxial tests on undisturbed samples is warranted for evaluating the degree of stability. This situation is illustrated in Fig. 11. In contrast to this, the landslides in Italy took place on gentle slopes, with known movements in the past, which are located near the foot of hills or mountains where the ground water is generally high. Therefore, the landslides did take place in the clay deposit which is known to have developed slippage before. The degree of stability for such slides needs to be evaluated, therefore, on the basis of the results of laboratory tests in which the stress history as above is reproduced correctly. The loading scheme to be executed on representative samples in the laboratory tests is illustrated in Fig. 11, where the sample is sheared largely until it reaches a residual state, whereupon dynamic loads are applied to determine the strength parameters. At present, available data on this type of tests are scarce and much more study is yet to be done in this derection.

As mentioned in the foregoing section, the final goal of the studies on landslides would be to establish methodologies for evaluating the degree of stability or instability of a given slope subjected to a certain magnitude of ground shaking during earthquakes in future. One of the methods to achieve this would be to provide charts in which the intensity of shaking required to cause landsliding can be made known from the static factor of safety indicative of the degree of stability of slopes in the ordinary condition prior to the advent of earthquakes. Such charts for practical purposes can be established by plotting the horizontal maximum acceleration required to cause landsliding versus the static factor of safety, on the basis of case studies of actual failures which have occurred during past earthquakes. To make up this kind of charts, all the available data shown in Tables 2 and 4 are plotted in the diagrams in Fig. 12. It has been shown in Eq. (4) that the magnitude of acceleration required to cause landsliding tends to increase as slopes

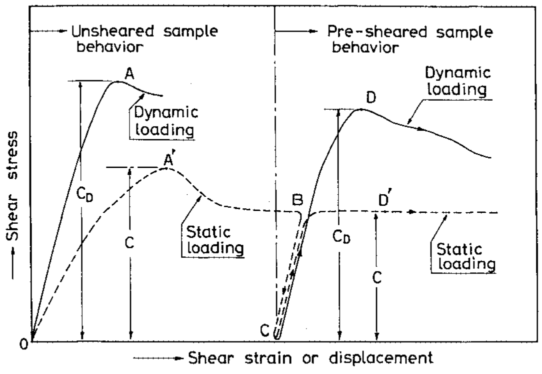

Fig. 11 Schematic illustration of stress-strain behaviors for unsheared and pre-sheared samples under static and dynamic loadings.

become steeper. In view of this, the data in Tables 2 and 4 are divided into three groups each having different angle of slopes. Fig. 12(a) shows the plot of data pertaining to the landslides on the steepest slopes with an angle of inclination between 40 and 50°. A similar plot is shown in Fig. 12(b) for the case of landslides on slopes having an intermediate angle of inclination between 20 and 40°. It is to be noted that all the data plotted in these figures are those from the landslides in Japan which occurred on the steep slopes near the shoulder of hills or mountains. As indicated in Table 4, all the landslides during the Irpinia earthquake took place on gentle slopes with an angle of inclination on the order of 10°. These data are all plotted in Fig. 12(c), together with one case of landslide in Japan. In each of the three diagrams shown in Fig. 12, a straight line is drawn through entire data points, which appears to indicate approximately the correlation between the slide-inducing acceleration and the static factor of safety.

One of the important points which should not be overlooked in establishing the curves shown in Fig. 12 is the fact that the acceleration plotted in the ordinate has been obtained through the use of Eq. (4) which is basically an equation of force equilibrium. Although it is a kind of universal equation, there still remains a ripple of doubt as to whether or not it could truly be the case that the increasing steepness of slopes requires an increasing acceleration to trigger the slide. The best way to confirm the validity of this concept would be to see if the accelerations at landslide sites estimated from other independent means show a tendency to increase with increasing steepness of the slope involved in the landslides. To explore this

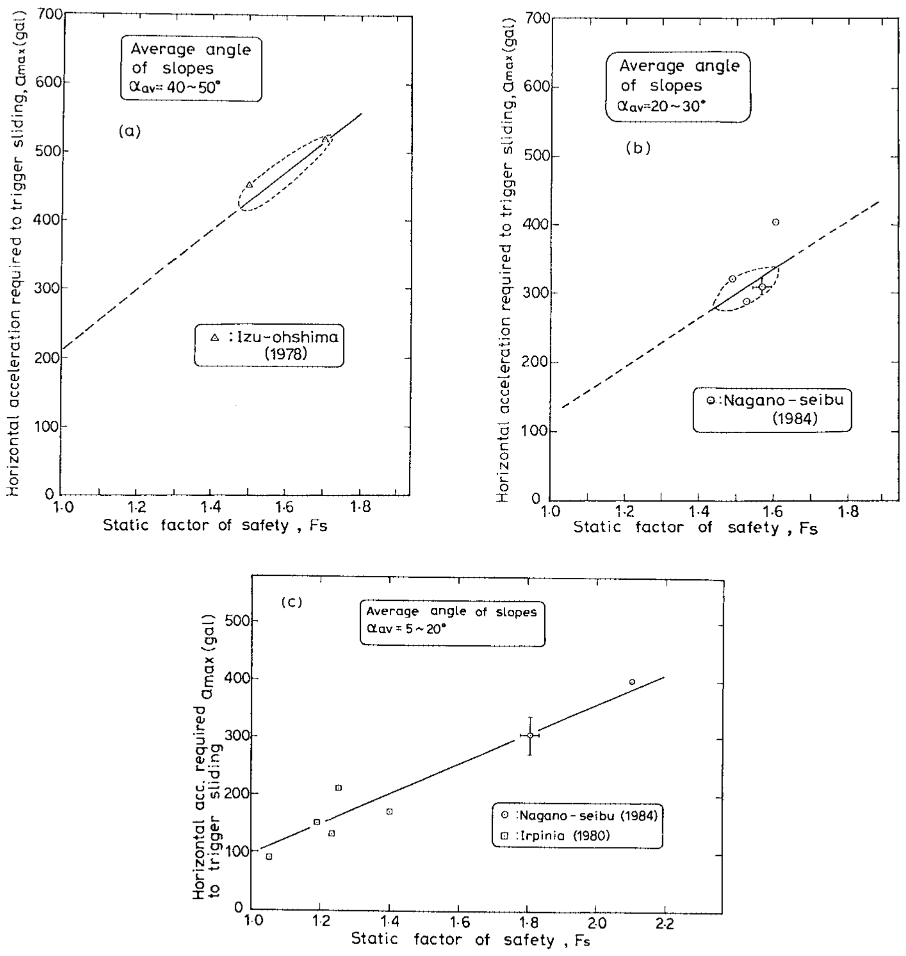

Fig. 12 Relation between the slide-inducing acceleration and static factor of safety.

aspect, the range of accelerations in Tables 2 and 4 estimated from the empirical formulae of Eq. (5) or from the analysis of overturning of tombstones is plotted versus the static factor of safety in Fig. 13 for each of the three groups of the landslides having different angles of slopes. In each of the diagrams in Fig. 13, a straight line quoted from the corresponding diagrams in Fig. 12 is drawn superimposed. It may be seen in Fig. 13 that the straight lines transferred from the diagrams in Fig. 12 lie approximately along the lower limits of the accelerations estimated by the empirical formuale. Once a landslide has taken place, the acceleration actually encountered at this site must have been equal to or greater than the critical acceleration required to induce the landslide. Therefore, the lower limit of the accelerations estimated by other means should coincide with the slide-inducing accelerations obtained through the use of Eq. (4). This reasoning appears to be valid from the comparison of the two sets of independent data arrangements presented in Figs. 12 and 13. Returning to the issue of effects of slope angle, one may see in Fig. 13 that the lower limits of accelerations estimated from the empirical formulae for each site show a tendency to increase as the angle of slope involved in the landslides increases. This fact appears to provide convincing evidence in support of Eq. (4) indicating that, under an identical static factor of safety, the steeper a slope the greater the magnitude of acceleration required to trigger the landslide during an earthquake.

Three straight-line relationships established in Figs. 12 or 13 are brought together in Fig. 14 for comparison sake. The curves in Fig. 14 might be used for practical purposes for assessing an approximate

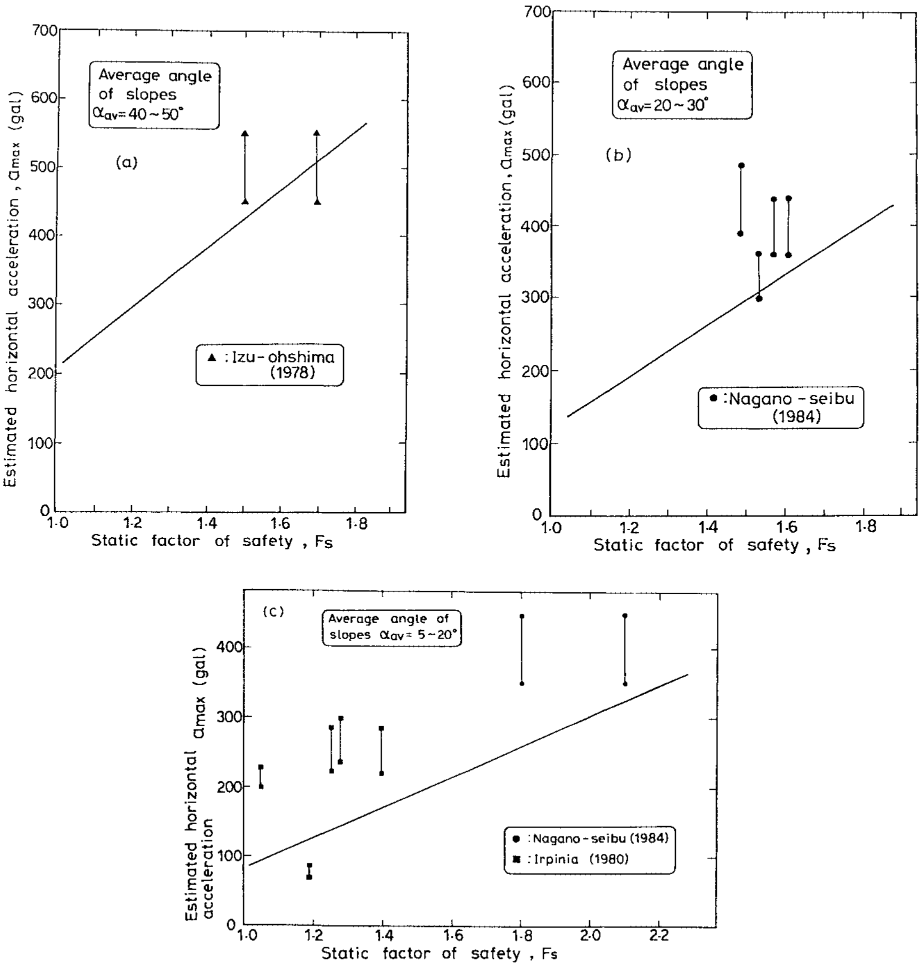

Fig. 13 Estimated horizontal acceleration plotted versus the static factor of safety.

magnitude of acceleration necessary to cause landsliding at given sites under consideration.

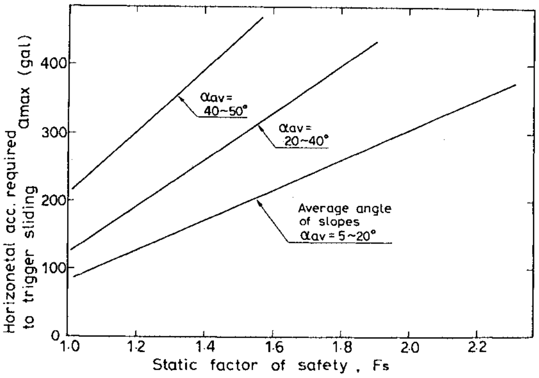

Fig. 14 Summary of the relations between the slide-inducing acceleration and static factor of safety.

6. CONCLUSIONS

A brief review is made of the reported investigations on the landslides which occurred in Japan and in Italy during recent earthquakes. The landslides in Japan at the time of the Izu-Ohshima earthquake of 1978 and at the time of the Nagano-seibu earthquake were shown to be characterized by their occurrence on steep slopes near the shoulder of terrains of high relief. The slides were shown to have taken place on freshly formed slip plane without any trace of previous movement. To obtain strength parameters for key soils responsible for the slide, undisturbed samples were tested in the laboratory under irregular loading conditions simulating the stress changes during earthquakes. The results of such tests were used to evaluate the degree of stability in terms of the horizontal acceleration required to trigger the slide. The critical acceleration thus determined was correlated with the static factor of safety prior to the quake in the form of charts that may be used for practical purposes.

On the other hand, the landslides in Italy during the Irpinia earthquake were shown to be characterized by their occurrence on gentle slopes near the foot of the mountains. The slides were shown to have taken place along the sheets of ancient landslides and as such they were a reactivation of dormant landslides. Reflecting such a stress history, it was suggested that the test in the laboratory be conducted first by applying shear stress over the peak strength to reach a residual state and then by again applying irregular time histories to reproduce a failure state corresoponding to in-situ conditions. Although such a test has not been carried out, the strength of the clay under approximately the same conditions was estimated from the results of dynamic tests conducted by Skempton (1985) and Lemos et al. (1985). The results of stability evaluation are expressed in the form of charts in the same fashion as for the case of the landslides in Japan.

It is shown that the magnitude of horizontal acceleration required to induce landsliding on slopes with identical static factor of safety tends to increase, as the slopes become steeper. In other words, provided two slopes with different angles exist with the same factor of safety in the static condition before the earthquake, the slope with the gentle angle tends to fail under the shaking with smaller acceleration than does the steeper slope.

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