Mechanism of Earthquake Damage to Embankments and Slopes

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The study is intended to clarify the mechanism of the earthquake damage to soil constructions as railroad embankments or cuttings. Some examples of the damage in past destructive earthquakes in Japan are presented to give a general concept on the phenomena and possible mechanisms of the damage are studied under the seismic intensities deduced from various descriptions on the earthquakes in literature.

Mechanisms including 1) sliding of a mass, 2) collapse of an embankment, 3) failure of a slope of cohesive or of non-cohesive materials, 4) fissures on an embankment, 5) settlement of an embankment and 6) phenomena related to liquefaction of soil as flow or subsidence of an embankment are studied by referring to examples of actual damage. Sliding of a mass can most appropriately be explained by the block sliding theory by Newmark. The collapse of an embankment may also be explained by the theory with a little modification in the assumption for mechanical properties of soils. The mechanism of failure of a slope of cohesive material is essentially the same as that of 1) or 2); that of a slope of cohesionless material is different and is correlated with the acceleration of the ground motion. The fissures on an embankment can be divided into three groups which are connected with either sliding or displacement of a part adjacent to the slope of the embankment or with a local subsidence of the embankment. The settlement of embankments occurs in regions of earthquake intensity of VII to VIII in M.M. scale. In case of liquefaction of soils, flow of materials of an embankment as a liquid or subsidence due to decrease in volume of an embankment or an underlying layer may occur.

One of the most important factors which may influence the damage is the inequilibrium of the forces due to gravity and the resistance to failure which decreases noticeably with increasing inclination of the slope of embankment or cutting. A large initial static factor of safety, accordingly, leads to a high stability of a soil construction during earthquake. The change in mechanical properties of soils during vibration or failure is another important factor for the damage and it should be taken into consideration to understand the damage. As an extreme case for the change in mechanical properties of soils, the liquefaction of sand in the Niigata earthquake is pointed out. The change in properties seems to occur more or less in every case during vibration or failure of embankments. The number of effective pulses for damage during an earthquake is also important in estimating the extent of the damage. The number is estimated in the paper as 7 to 40 or more through considerations on the mechanisms of damage or records of destructive earthquakes. Intensities of the ground motion in the past destructive earthquakes are tabulated and compared with the maximum expected value in California after Newmark.

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by Yoshimasa Kobayashi(i)

Synopsis

The paper deals with possible mechanisms of earthquake damage to embankments and slopes due to past destructive earthquakes in Japan. A formula on sliding of a mass during an earthquake by Newmark seems to be applicable with a little modification to many examples of the damage. Factors which may influence the stability of embankments or slopes during an earthquake are investigated and a classification for the damage is proposed corresponding to the assumed mechanisms.

I. Introduction

Damage to embankments and slopes is often very remarkable in destructive earthquakes and is sometimes the main cause of interruption of rail- or road-traffics. The Tokachi-oki earthquake on May 16, 1968 is an example of such earthquakes which brought much damage to embankments and slopes, when the Tohoku main line of Japanese National Railways (J.N.R.)connecting Honshu with Hokkaido was stopped for a period as long as eleven days. The repair work, moreover, was slowed down considerably because of damage to embankments and slopes along the transportation roads.

The sort of earthquake damage has been remarkable enough to attract the attention of investigators. Ambraseys introduced many examples of effect of earthquakes on earthdams(1) and Duke presented a summary on earthquake damage to foundations and earth structures including embankments and slopes(2). There are many other theoretical and experimental studies concerning the problem. Newmark gave an inclusive lecture on the earthquake damage to dams and embankments, in which he elaborated mainly block or wedge sliding theory and compared the results of numerical analyses with the results of a model test by Davis et al. successfully.(3)

The phenomena of the damage to embankments and slopes are manifold and the range of applicability of the existing theories is not clear and the earthquake resistant designings and the reliable measures have not yet been established. Under these circumstances the author considers it appropriate to study examples of the damage in past destructive earthquakes further and to examine the applicability of the existing theories to actual damage and, when necessary, to improve them or to present a new hypothesis.

In this paper some examples of the damage to embankments and slopes, mainly of J.N.R., are presented to give a general concept on the phenomena and the mechanisms of the damage are studied under the seismic intensities deduced from literature on the earthquakes.

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II. Some Examples of Earthquake Damage to Embankments and Slopes

1. Damage in the Tottori earthquake(Sept. 1, 1943, M=7.3)(4)

Failure of a slope of a weathered material. The surface layer of a slope inclined about 40 degrees 5 km north-east of Tottori failed and debris buried the railroad 4 m deep over 10 m(Fig. 1). The size of the debris ranged 10 to 20 cm. The slope was composed of fairly weathered andesite with remarkable development of columnar joints.

Collapse of a high embankment. A part of a railroad embankment of 15 m high, crossing a paddy field 15 km north-east of Tottori, collapsed over 150 m and settled 7 m at the maximum. The embankment had dammed up water of the paddy field and the lower part of the embankment is considered to have been saturated, since the material of the embankment is said to have been a fine marine sand. The substratum at the site is supposed to be inclined from the surrounding topography.

2. Damage in the Nankaido-oki earthquake(Dec. 21, 1946, M=8.1)(5)

Sliding of an embankment. A railroad embankment 30 km **south-east** of Tanabe slided on a 30 degrees inclined substratum about 1.5 m below and as the result the level of the railroad was lowered about 0.8 m(Fig.2). There was a retaining wall at the end of the slope and the end could not slide and the lower part of the slope bulged.

Settlement of an embankment. During the earthquake a railroad embankment, 6 m high with berms on both sides, situated 2 km west of Tanabe, settled about 0.5 m. The deformation of the embankment and the berms, however, was not remarkable. It is said that the site used to be a marsh and the settlement of the embankment and the upheaval of the ground on both sides of the embankment occurred immeadiately after the main embankment was constructed, and further that the movement could be stopped for the first time after the berms had been placed as the counter-weight against the sliding.

3. Damage in the Fukui earthquake(Jun. 28, 1948, M=7.2)(6)

Collapse of an embankment(Hosorogi embankment). A railroad embankment 8 m high, 20 km north of Fukui, collapsed and settled about 4 m over 400 m(Fig.3). Several longitudinal fissures were observed on the top of the embankment and the base widened to about twice of the original dimension. The surface of the slope was preserved relatively undamaged. The upheaval of the ground on both sides was not remarkable. The embankment was founded on a deep soft alluvium layer composed of silty clay.

Fissures on a low embankment. A railroad embankment 2 m high was damaged, 15 km north of Fukui, at the center of the Fukui plain. (Fig.4) Several longitudinal fissures were observed near the shoulder of the embankment and also on the slopes.

Opening and closing of fissures on the ground.(7) Opening and closing of fissures on the ground surface is reported in the central part of the Fukui plain with victims crushed to death in the fissures.

4. Landslide in the Imaichi earthquake(Dec. 26, 1949, M=6.5)(8)

During the earthquake a large scale landslide occurred in Imaichi. The area of the sliding block amounted to 3.4 km^2 and the thickness 6 to 7 m. The block slided about 6 to 7 cm downhill on a sliding surface 6 to 7 m deep. The surface was inclined 1 degree in the mean and lubricated with white clay whose mechanical properties are shown in Table 1.

5. Damage in the Niigata earthquake(Jun. 16, 1964, M=7.5)(9)

Flow of the material of an embankment due to liquefaction. A railroad embankment, 7 m high at Dedo-Nishime, 100 km north-east of the origin, collapsed and the fill material flowed to a side of the embankment about 115 m. According to the story by a farmer who observed the collapse, the material broke the surface of the slope and flowed fast on the surface of the paddy field. The material settled 1.0 to 1.5 m deep at 50 m and 0.3 to 0.5 m deep at 90 m from the railroad, respectively. The surface of the paddy field was not damaged and rice-plants were kept standing through the deposited material. The site is a valley with a width of 100 m and the embankment was founded on a 10 m deep weak deposited layer consisted of peat, clay and sand(Fig.5). The material of the embankment was a sand having an effective size of 0.15 to 0.22 mm and a uniformity coefficient of 2.0 to 2.3(Fig.6).

Subsidence of embankments due to liquefaction of soil. Many railroad embankments near Niigata, especially on the Echigo line, subsided into the liquefied ground. The upheaval of the ground surface on both sides of the embankments was, in general, not remarkable and the spouting of the liquefied sand was observed in the vicinity of the subsidence.

6. Damage in the Tokachi-oki earthquake 1968(May 16, 1968, M=7.8)(10)

Failure of the slope of an embankment. Two failures occurred in an embankment 10 m high at Kogawara station, 6 km north-west of Misawa, leaving typical three dimensional scars. The rail-track was suspended over the slid distances and the sliding blocks were displaced downwards preserving the original continuity. There is a marsh-like pond on the side of the sliding and the ground is supposed to be soft and the lower part of the embankment to be nearly saturated.

Great fissures on an embankment. On a newly constructed 3 to 4 m high embankment near Ottomo, 16 km north-west of Misawa, numerous great fissures occurred. The slope of the embankment slided on both sides, and great vertical fissures 0.3 to 1.5 m wide and 2 to 3 m deep occurred generally in parallel to the axis of the embankment. The soil of the embankment was well-compacted sand. The ground is, however, soft and spouting of mud at the end of the slope was observed in several places.

Collapse of an embankment with subsidence in the central part.
An embankment 3 to 4 m high at Kawadai on the Ohata line, on the marshland in the Shimokita peninsula, collapsed and subsided all over 600 m except three culverts for irrigation and rail-track was suspended like a suspension bridge in the vicinity of the culverts. The subsidence amounted to 1.5 to 3.5 m and the width of the embankment was widened nearly twice to the original dimension. It is noted in the subsidence that the central part of the embankment subsided most and the amount of subsidence decreases stepwise at fissures toward the side of the embankment(Fig.7). The spouting of mud was observed in places at the end of the slope.

III. Mechanism of the Damage

1. Sliding of a mass

Newmark developed the block sliding theory in the lecture on the earthquake damage to dams and embankments in which he considered sliding of a mass on a sliding plane with resistance against sliding or "resisting acceleration" N (3). Although N may change as a function of displacement or reversal of displacement, the analysis becomes particularly simple when the resistance is essencially "rigid plastic"; corresponding to no displacement until the yield point is reached, after which the displacement may have any value. Under the condition the maximum displacement of a sliding mass relative to the ground is

$$u_m = \frac{V^2}{2Ng} \left(1 - \frac{N}{A} \right)$$

where u_m, N, V and A are the maximum displacement of the mass, the resisting acceleration against sliding, the maximum velocity and the maximum acceleration of the ground motion, respectively. In case of sliding of a mass, as shown in Fig.8, the yield point is reached when

$$A = \frac{cS/W + \cos\theta \tan\phi - \sin\theta}{\sin(\delta + \theta)\tan\phi + \cos(\delta + \theta)} g$$

where A, δ, θ, W, S, c, ϕ and g are the acceleration, the inclination of the acceleration, the angle of the slope, the weight of the mass, the bottom area of the mass, the cohesion of soil, the angle of internal friction of soil and the acceleration of gravity, respectively.

The sliding of an embankment in Nankaido may be considered to be a sliding of a mass. Assuming $\delta = 0$ i.e. only horizontal acceleration, $c = 0.1$ kg/ cm^2 and $\phi = 40^\circ$, one obtains A = 0.15 to 0.20 g in the case of Nankaido as the condition for the acceleration from the relation above. The condition is considered to have actually been satisfied from the report by the Research Committee of J.N.R. on data of overturning of gravestones in Tanabe city(5). Assuming further T = 0.5 sec., the common value in the mountaineous district, one obtains the estimated maximum velocity of the ground motion V = 12.5 cm/sec. for the case A = 0.15 g. Substituting the values in the formula by Newmark, one obtains $N = (\cos\theta \tan\phi - \sin\theta) g = 0.1 g$ and $u_m = 0.2$ m. The total amount of sliding of 1.5 m had, therefore, occurred in 7 to 8 steps and the number is comparable with the number of the predominant pulses at observatories of Japan Meteorological Agency(J.M.A.) surrounding the site(11).

An extraordinary strong acceleration with a relatively short period is reported for the ground motion in the Imaichi earthquake; 3.7 cm, 60 cm/sec. and 90 cm/sec.^{2}. The duration of the predominant motion was about 10 seconds or the number of predominant pulses about 25(8,12,13,14). The number of pulses is the sum of that of the two earthquakes with nearly equal intensity which occurred 8:18' and 8:26' on the same day. Assuming the landslide occurred during the predominant ground motion, one obtains the displacement of the slid block per step as $u_m = 6/25 = 0.24$ cm. Substituting the value of u_m in the formula by Newmark, one obtains the resisting acceleration $N = 0.84$ g. Equating the value with the resistance which would be caused by cohesion and friction, one obtains the relation;

$$cS + Mg \cos\theta \tan\phi - Mg \sin\theta = M\ 0.84\ g$$

From the relation and the unconfined compressive strength, 0.5 kg/cm^2 after Okamoto and Kubo(8), one obtains $c = 0.14$ kg/cm^2 and $\phi = 36°$ (Cf.Fig.9). Although the value for c seems too low and that for ϕ too high as compared with usually believed values for clays, c will not be unusual as compared with values obtained in large scale in situ rock tests and the higher value for ϕ is also plausible if one considers the scale of the sliding surface of undulated structure.

2. Collapse of an embankment

The collapses of the embankments in Fukui, Tottori and on Ohata line are the typical examples of earthquake damage to embankments. As a first approximation the mechanism of the collapse may be assumed to be similar to that of sliding of a mass.

The maximum intensity of the ground motion in the central part of the Fukui plain, i.e. at the site of the Hosorogi embankment, is estimated to have been D = 25 to 30 cm, V = 100 cm/sec., A = 450 cm/sec.^{2} and T = 1 to 2 sec.after Suzuki(6)(ii) and Kawasumi(7). The number of the predominant pulses is estimated 15 to 40 from the report by J.M.A.(11). The horizontal displacement of the end of the slope due to the earthquake was measured by the Research Committee of J.N.R. as tabulated in Table 2 a (6). If the amount of the displacement of the end of the slope is assumed to have occurred in 15 to 40 steps, the corresponding displacement per step must have been 0.2 to 1.0 m as shown in Table 2 b. The resisting acceleration after Newmark corresponding to the displacement per step above is obtained as 0.045 to0.16 g as shown in Table 2 c. From the results the collapse of the Hosorogi embankment would be realizable if N is not greater than 0.16 g under the condition cited above concerning the ground motion. It is, however, difficult to imagine that the intensities of all 15 to 40 effective pulses reached the maximum estimated above; thus it would be more natural to consider that the above estimated value of N was that for the initial stage of sliding and after the initiation of the sliding the mass of soil could slide 0.2 to 1.0 m by a weaker pulse than the maximum because

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(ii) Suzuki observed marks of collision of a bell on beams of a bell-house in two temples near Fukui and analysed the transient vibration of the bell to estimate the intensity of the ground motion.

of decrease in shearing strength along the sliding surface.

The cause of the decrease in shearing strength along a sliding surface may be spontaneous liquefaction of soil or effect of remoulding of a sensitive clay and likes. The material of the embankment in Tottori is said to have been a fine marine sand(4) and liquefaction seems to be possible. In case of the Hosorogi embankment in Fukui the embankment was founded on a very soft alluvium and the lower part of the embankment composed of silty material is supposed to have been saturated(Fig.6). In case of the collapse in Kawadai on the Ohata line at least a partly liquefaction of material is supposed to have occurred in the lower part of the embankment or the underlying layer of the embankment. The shape of the collapse and the spouting of mud at the end of the slope support the above assumption(Fig.6).

3. Failure of a slope

The failure of a slope is divided into either that of cohesive or non-cohesive materials. The mechanism of failure of a slope of a cohesive material does not differ essentially from that of sliding of a mass or of collapse of an embankment and will not be dealt with in this section. The examples of the type of the damage are the two failures of the embankment at Kogawara station in the Tokachi-oki earthquake.

The failure of a slope of cohesionless material such as debris or weathered material is of a different mechanism from these described above. The failure seems to occur at a stroke when a limit of acceleration is exceeded. The limit for a slope of inclination θ composed of a cohesionless material with internal friction ϕ is

$$A \geqq \tan(\phi - \theta)\, g$$

In case of the failure of the slope in the Tottori earthquake, the inclination θ was 40°; thus if $\phi = 45^\circ$, then $A \geqq 0.1$ g, and if $\phi = 55^\circ$, then $A \geqq 0.25$ g. Actually the acceleration at the site is estimated to have been between the above two values because the site is 5 km more distant from the origin of the earthquake than Tottori city, where the acceleration of 0.3 to 0.4 g is reported(4, 15, 16, 17). There is a more refined criterion for failure of a slope of cohesionless soils by Seed and Goodman taking an actually existing small cohesion into consideration(18) and it is naturally preferable to apply the refined criterion in case the constants are more reliable.

4. Fissures on an embankment

A type of damage which frequently occurs is the fissures on an embankment. The phenomenon is accompanied in most cases by either the subsidence of a part of an embankment or sliding or displacement of a part adjacent to the slope of an embankment. The vertical fissures run mostly in parallel to the axis of the embankment except the cases where the local subsidence occurred. The fissures are observed only where there are free slopes of vertical sections in the vicinity implying an effect of free surface and the mechanism of the fissures seems to be different as that of the opening and closing of fissures on a plain ground surface. Mononobe gave as the criterion for the fissures at the shoulder of an embankment the following relation(19);

$$Px \geqq Q + \tau x + cH$$

where Px, Q, τx and cH are the horizontal seismic force, the resisting earth-pressure acting on AO-plane, the bottom friction and the cohesion acting on BC-plane in Fig.10, respectively. The relation corresponds to the outward displacement or inclination of the part adjacent to the slope of the embankment. The relation should more appropriately be modified in case of "fissures", because the passive pressure Q cannot be taken into consideration in case of only "fissures". Ignoring Q and replacing the bottom resistance with $cH + \tan\phi \int \rho gx \, dx$, one obtains as the criterion for fissures at the shoulder of an embankment with the slope of inclination 45°

$$A = \frac{2}{H^2} \left(2\ cH + \tan\phi \int \rho g \frac{H^2}{2} \right)$$

In case of the fissures in the Fukui earthquake, where $\rho = 2\ g/cm^3$, $\phi = 27°$, H = 2 m are assumed, one obtains as the criterion for the fissures

$$A = (c \times 10^{-2} + \tan\phi) g = \tan\phi\ g = 0.5\ g$$

The great fissures in Ottomo in the Tokachi-oki earthquake can also be dealt with in a similar manner.

The opening and closing of fissures during an earthquake without any free slope or vertical section in their vicinity seems more difficult to occur and the criterion for the phenomenon can be deduced in a different way. The phenomenon occurred in the Fukui plain, where the intensity of the ground motion is estimated as D = 25 to 30 cm, V = 100 cm/sec., A = 450 cm/sec.^{2} and T = 1 to 2 sec.. When a plane wave is propagating horizontally, the particle displacement of the ground is

$$D = D_0 \exp \left\{ 2\pi n \ (t - x/C) \right\}$$

Accordingly the absolute value of the strain in the ground is estimated as

$$|\varepsilon| = |\partial D / \partial x| = |V|/C$$

where V and C are particle velocity and velocity of wave propagation, respectively. Assuming V = 100 cm/sec. and C = 100 to 500 m/sec., one has the critical strain 2 to 10 x 10^{-3}. The value is supported by another consideration. If the soil is assumed to have been elastic until the failure, the stress of 2 to 10 kg/cm^2 is expected corresponding to the strain of order of 10^{-3}. The stress is plausible as the strength of soils near the ground surface.

The fissures on an embankment might, therefore, be attributed to large strain of soil of an embankment due to either subsidence or sliding or displacement of parts of the embankment and probably of a different mechanism from that of fissures on the plain ground due to large wave motion.

5. Settlement of an embankment

Settlement of an embankment is one of the most common types of damage to embankments due to earthquakes and the settlement occurs in regions where the intensity of an earthquake exceeds the value "higher IV" to V in J.M.A. scale or VII to VIII in M.M. scale. The phenomenon can naturally take place in a region of even lower intensity when soil conditions are especially unfavourable.

The settlement of the embankment in the Nankaido-oki earthquake amounted to 0.5 m. If one assumes the height of the settled layer to have been 6 m which equals the height of the embankment, the corresponding ratio of deformation is 8.3 %. The maximum acceleration at the site was estimated as 0.15 to 0.20 g, or 15 to 20 % of the gravity, and predominant pulses repeated around 10 times as described before.

According to the experimental study by Seed on soil strength under simulated earthquake loading conditions(20), the deformation induced in a soil sample depends on the initial factor of safety, the simulated earthquake stress and the number of application of stresses.
In case of the settlement of the Nankaido embankment the initial static factor of safety might be assumed 1.1 from the fact that the subsidence after the construction could just be stopped by placing a pair of berms. According to the data by Seed the deformation amounts to 6 % in case of the initial factor of safety of 1.1 and of 30 pulses of the intensity of 20 % of sustained stress. The agreement of resulting deformation with the estimated one is fairly well in view of the uncertainty of assumptions made in the above estimation.

6. Phenomena related to liquefaction of soil

The liquefaction of soil plays sometimes an important role in damage to embankments. The most remarkable examples occurred in the Niigata earthquake. The material changes into a fluid state as in the case of the flow of fill material of the Dedo-Nishime embankment, during the Niigata earthquake and it decreases in volume to change into a more compact state discharging the interstitial water as in the case of the subsidence of embankments on the Echigo line, also during the Niigata earthquake.

Tsuchida made a qualitative study on liquefaction of a sandy soil and found that the sand-water system turns into a liquid of the density equal to that of the saturated sand under the perfect liquefied state and it returns to a more dense state as the initial after discharge of the interstitial water(21). The flow of the material at the Dedo-Nishime embankment and the decrease in volume of the embankments on the Echigo line correspond to the mechanisms described above. There is another fact to be noted concerning the liquefaction of soil which was pointed out by Tanimoto(22) and Kokota and Morioka(23). They found experimentally that the recovery from the liquefied state takes comparatively long and the term is of order of some ten minutes or hours.

The fact that the deformation of constructions due to a large aftershock in the Tokachi-oki earthquake 1968 was, in some cases, larger than that due to the main shock preceding the aftershock cited above about ten hours might be attributed to the reason.

IV. Conclusion

The frequent types of the damage to embankments and slopes are presented in the paper and the mechanisms of the damage are studied with the aid of some existing theories concerning the problem.

The damage to embankments is classified into 1) sliding of the embankment on an inclined substratum, 2)a collapse of an embankment with decrease in strength during vibration or failure, 3) three dimensional slope- or base-failure of parts of an embankment, 4) vertical fissures mostly parallel to the axis of an embankment, 5) settlement of an embankment and 6) phenomena as flows or subsidences due to liquefaction of soil.

The damage to slopes is classified into 1) failure of a cohesionless material as debris or weathered material and 2) sliding of a mass of soil or rock including the large scale landslide.

One of the most important factors which may influence the damage is the inequilibrium of the forces due to gravity. The static inequilibrium caused by gravity has an effect to decrease the resisting acceleration after Newmark and results in an increase of displacement of a sliding block by an equal pulse. In case of a sliding block on an inclined plane

$$N = W \cos\theta \tan\phi - W \sin\theta$$

where N, W, θ and ϕ denote the resisting acceleration, the weight of the mass, the inclination of the slope and the angle of friction, respectively. The value of N decreases with θ as shown in Fig.11. In the sense above a larger initial static factor of safety of an embankment or a slope leads to a higher stability of them also during an earthquake.

Another important factor in the damage is the change in mechanical properties of soil during vibration or failure. The liquefaction of sand in the Niigata earthquake is the extreme case of change in mechanical properties of soil. The change in properties seems to occur more or less in every case during vibration or failure as described in the section for collapse of an embankment. A failure can take place without any strong vibration only if the condition for the failure is prepared by preceding vibration or other causes. The damage due to the Tokachi-oki earthquake 1968 is supposed to have become severe because of rainfalls and saturation of soils with water as the result, preceding the earthquake (Fig.12). The theory by Newmark on sliding of a mass will become applicable in more cases if the change in mechanical properties of soil is taken into consideration properly.

In many cases of damage to embankments and slopes the effective number of pulses is an important factor to determine the extent of the damage.

Newmark analysed the sliding of a mass on a high speed digital computer for four normalized accelerograms and obtained the result that the effective number of pulses is around A/N in case of $A/N \leq 0.5$ and less than 6 in case of $A/N > 0.5$ (3). The result is shown in Fig.13. The number is at the most 10 to 20 for a fairly strong earthquake and a rather weak structure of N = 0.05 g. He states, however, that for earthquakes lasting longer the number of effective pulses would be greater. Muramatsu studied the records of the past destructive earthquakes in Japan and estimated the effective number to be 2 to 10 probably for Japanese wooden houses(24). Seed and Clough referred to the number of repeated pulses 30 in consideration on the difference between the strengths of soils in a transient loading and during vibration(25). In this paper the author studied the mechanisms of the damage to embankments and slopes and estimated the number of effective pulses as 7 to 8 in case of the sliding of an embankment in the Nankaido-oki earthquake, 15 to 40 in case of the collapse of the Hosorogi embankment in the Fukui earthquake and 25 in case of the landslide in the Imaichi earthquake. In the last case the number is the sum of the two earthquakes on the same day. The duration of the strong ground motion in the Niigata earthquake and the Tokachi-oki earthquake 1968 are estimated 2.5 and 3 minutes, respectively.

The ground motion in the epicentral or destroyed regions is in most cases unknown, since the amplitude of the ground motion is, in general, too large for usual seismographs. The Niigata earthquake is one of the few destructive earthquakes in Japan of which some seismograms are available. A tripartite logarithmic plot of the ground motion of the Niigata earthquake based on Strong Motion Accelerograms is shown in Fig.14. In this paper the intensities of the Tottori, Nankaido-oki, Fukui, Imaichi and Tokachi-oki earthquakes are estimated from various phenomena during the earthquakes as tabulated in Table 3. It should be noted that the values concerning the intensity correspond to the maxima and the number of the predominant pulses is that of pulses comparatively intense as the maxima. As a comparison the expected value in California by Newmark is shown in the same table(3). From the table it is recognized that in spite of the great difference in displacements and accelerations the velocities of the ground motion in these destructive earthquakes are comparable, suggesting that the velocity is most closely related with failures of soil constructions due to earthquakes.

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Table 1. Mechanical Properties of Clays on the Sliding Surface in Imaichi

Spec.Gravi. Soil Grain gr./cm^3	Apparent Spec.Grav. gr./cm^3	Water Content %	Dry Density gr./cm^3	Void Ratio	Deg. of Saturat. %	Unconfined Strength kg/cm^2	Modulus of Elasticity kg/cm^2
2.62	1.31–1.35	127–136	0.57–0.60	3.51–3.60	94–99	0.33–0.54	4.5–13.6

Table 2 a. Displacement of the Slope of the Hosorogi Embankment

Section	Left	Right
1	11.6 m	1.6 m
2	6.8	7.2
3	16.0	6.8
4	12.8	8.0
5	12.8	5.6
6	8.4	9.6
Max.	16.0	9.6
Mean	12.3	7.4

Table 2 b. Displacement per Step Corresponding to the Number of Effective Pulses

Number of Vibration	u_m	Left	Right
15	Max.	1.07 m	0.64 m
	Mean	0.82	0.49
40	Max.	0.40	0.24
	Mean	0.31	0.19

Table 2 c. Resistance Corresponding to the Displacement per Step

u_m	N
0.2 m	0.16 g
0.4	0.091
0.6	0.070
0.8	0.055
1.0	0.045

Table 3. Intensity of Ground Motion in Destructive Earthquakes

Earthquake	Locality	Acceleration in cm/sec.^{2}	Velocity in cm/sec.	Displacement in cm	Period in sec.	Number of Predominant Pulses or Duration
Tottori	Tottori	400	100	25	1.5	
Nankaido	Tanabe	150	12.5	0.9	0.5	7 to 8
Fukui	Fukui	450	100	20	1.2	15 to 40
Imaichi	Imaichi	950	60	4.0	0.4	25
Niigata	Niigata	150	100	60	4.0	2.5 minutes
		200	50	15	1.2	
Tokachioki	Shimokita peninsula	400	60–100	10–20	1.0–2.5	3 minutes
California	Californ.	320	36	30		(after Newmark)

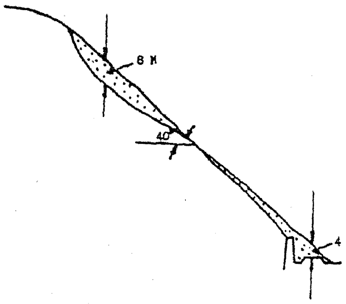

FIG.1 FAILURE OF A SLOPE OF WEATHERED MATERIAL IN THE TOTTORI EARTHQUAKE

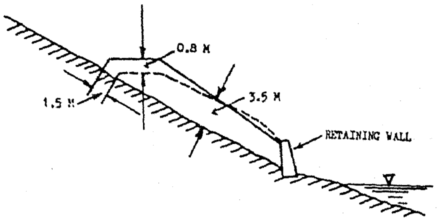

FIG.2 SLIDING OF AN EMBANKMENT IN THE NANKAIDOOKI EARTHQUAKE

FIG.4 FISSURES ON A LOW EMBANKMENT IN THE FUKUI EARTHQUAKE

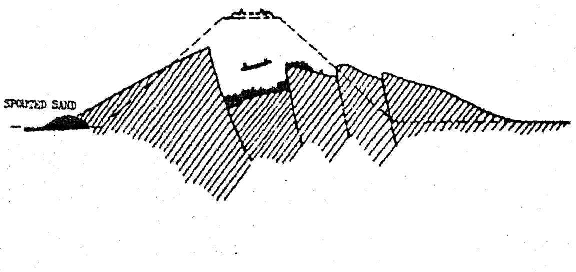

FIG.7 COLLAPSE OF AN EMBANKMENT WITH SUBSIDENCE IN THE CENTRAL PART

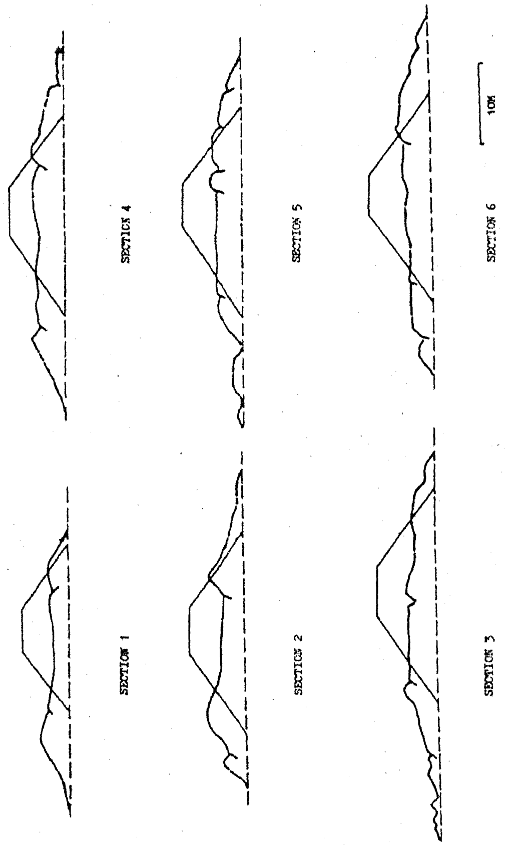

FIG.3 COLLAPSE OF THE HOSOROGI EMBANKMENT IN THE FUKUI EARTHQUAKE

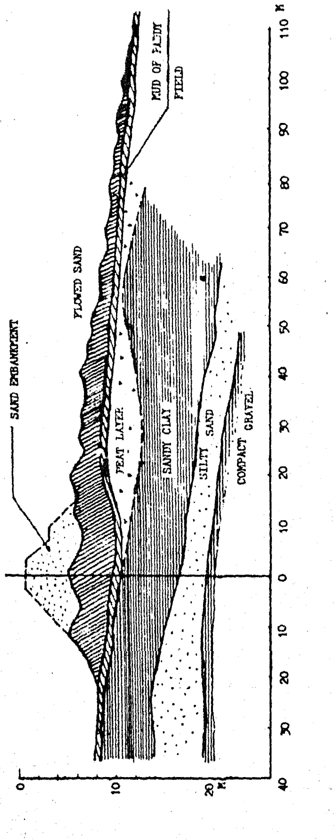

FIG.5 FLOW OF THE FILL MATERIAL OF AN EMBANKMENT DUE TO LIQUEFACTION IN THE NIIGATA EARTHQUAKE

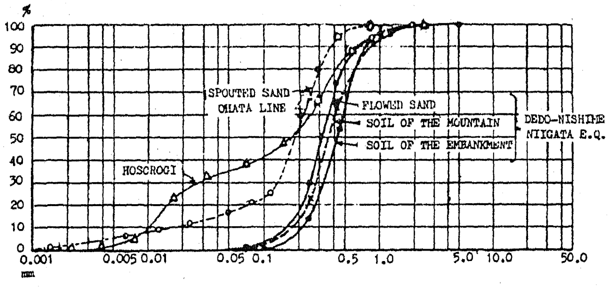

FIG.6 GRAIN SIZE CURVE OF SOIL OF DAMAGED EMBANKMENTS

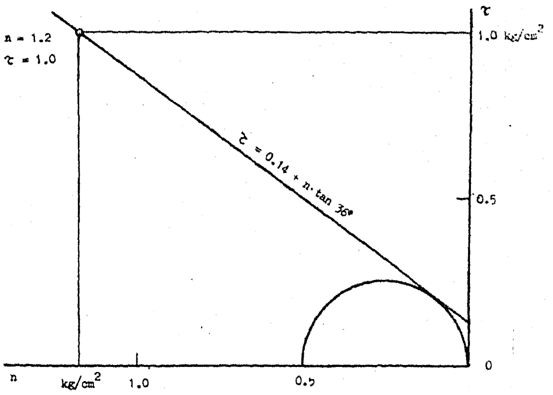

FIG.9 MOHR'S CIRCLE FOR THE LANDSLIDE IN THE IMAICHI EARTHQUAKE

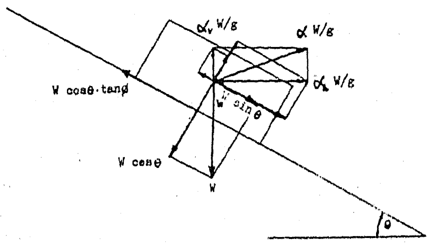

FIG.8 SLIDING OF A MASS

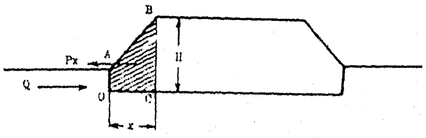

FIG.10 VERTICAL FISSURES ON A LOW EMBANKMENT

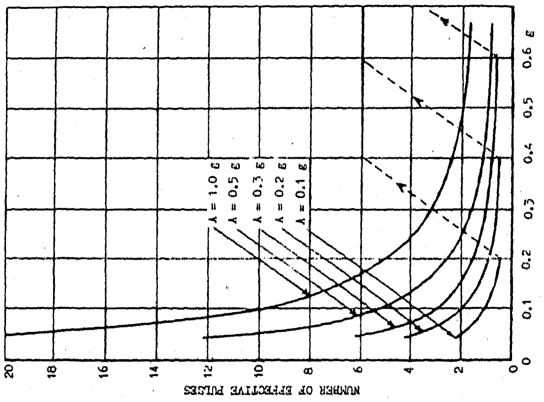

FIG.13 NUMBER OF EFFECTIVE PULSES AFTER NEWMARK

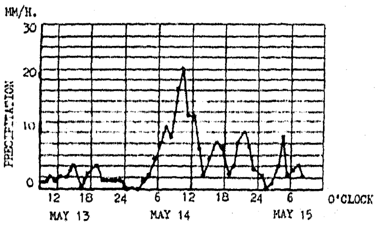

FIG.12 RAINFALLS PRECEDING THE TOKACHIOKI EARTHQUAKE 1968

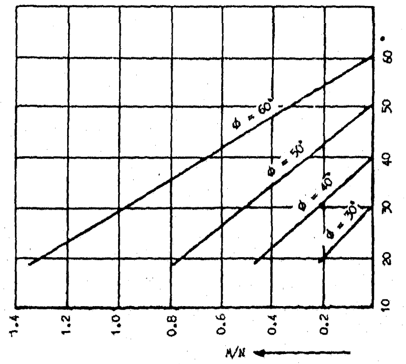

FIG.11 SLOPE ANGLE AND RESISTANCE AGAINST SLIDING

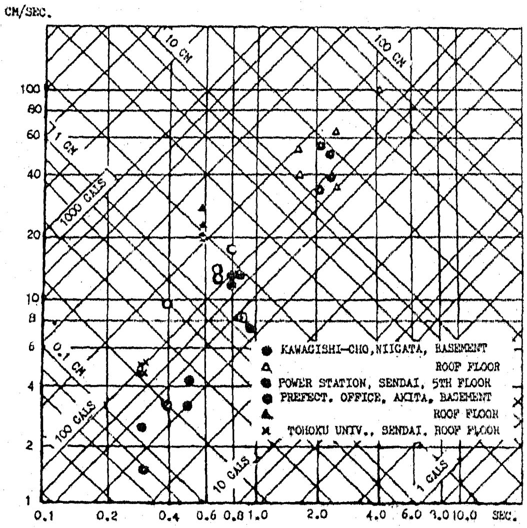

FIG.14 TRIPARTITE LOGARITHMIC EXPRESSION OF GROUND MOTION IN THE NIIGATA EARTHQUAKE