# SEISMIC CHARACTERISTICS OF GROUND

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## PREFACE

Statistical studies on earthquake damage in Japan have revealed that the extent of the damage depends on the ground property. Every great earthquake in Japan has indicated that for wood frame houses the softer the site ground has been the greater is the degree of damage. Structures, other than those wood framed, exhibited different damage characteristics. For example, the damages caused by the Kanto earthquake of 1923 are cited. For brick buildings and warehouses, the relationship between the damage suffered and the ground properties is just opposite to that for wood-frame structures. For reinforced concrete buildings, the relationship between the damage suffered and the ground properties is not clear enough to draw definite conclusions. In this respect, the conclusions will vary, dependent upon the type and extent of damage studied.

It is reasoned that one of the most important factors in the development of earthquake resistant structural design is the determination of the seismic characteristics of ground. Accordingly, the study of the seismic characteristics of ground has been pursued by the writers with theoretical studies, observational studies and damage statistics.

In the theoretical studies, the main effort has been devoted to the propagation of elastic waves, and especially on the problem of multiple reflections in cases where the medium consists of either a single layer or plural layers. In the studies, comparative observations regarding various ground have been made. Comparisons have been made also between the observations made under the ground and those made on the ground surface. As an auxiliary study, micro-tremor measurements have been made on a large number of various kinds of ground.

## THEORETICAL STUDY OF SEISMIC WAVES

The Case of a Single Stratified Layer.

1. The case of an infinite train of harmonic plane waves. Here, we have tried to examine the simplest case in which distortional waves of a purely plane type are propagated vertically upwards in an elastic semi-infinite medium; are partially transmitted through the bottom boundary of the superficial visco-elastic layer; and are partially reflected at this bottom boundary as well as at the surface boundary of the same layer. Let the $x$-axis be drawn vertically upwards from the bottom boundary of the layer of thickness H, and let $u_1$, $\rho_1$, $\mu_1$ and $\mu'_1$; $u_2$, $\rho_2$, $\mu_2$, and $\mu'_2$ be the displacements, densities, elastic constants and coefficients of solid viscosity, respectively, of the subjacent medium and the stratum under consideration.

In the case of distortional waves, the equations of motion of the two media are expressed by equations 1 and 2.

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$$\rho_1 \frac{\partial^2 u_1}{\partial t^2} = \left(\mu_1 + \mu_1' \frac{\partial}{\partial t}\right) \frac{\partial^2 u_1}{\partial x^2} \qquad \text{....... (1)}$$

$$\rho_2 \frac{\partial^2 u_2}{\partial t^2} = \left(\mu_2 + \mu_2' \frac{\partial}{\partial t}\right) \frac{\partial^2 u_2}{\partial x^2} \qquad \text{....... (2)}$$

In the case of dilatational waves, it is necessary to replace $\mu_1$, $\mu_1'$, $\mu_2$, $\mu_2'$ by $\lambda_1 + 2\mu_1$, $\lambda_1' + 2\mu_1'$, $\lambda_2 + 2\mu_2$, $\lambda_2' + 2\mu_2'$ respectively.

If the incident waves in the subjacent medium are of the type given in equation 3,

$$u_0 = \alpha e^{i(pt - h_1 x)} \qquad \text{....... (3)}$$

the resulting displacement of the subjacent medium and the stratum are expressed by equations 4 and 5.

$$u_1 = u_0 + u_0' = \alpha e^{i(pt - h_1 x)} + A e^{i(pt + h_1 x)} \qquad \text{....... (4)}$$

$$u_2 = B e^{i(pt - h_2 x)} + C e^{i(pt + h_2 x)} \qquad \text{....... (5)}$$

where:

$$p = \frac{2\pi}{T} \qquad \text{....... (6)}$$

with, T = the period of the waves

and,

$$h_1^2 = \frac{\rho_1 p^2}{(\mu_1 + i\mu_1' p)} \qquad \text{....... (7)}$$

and,

$$h_2^2 = \frac{\rho_2 p^2}{(\mu_2 + i\mu_2' p)} \qquad \text{....... (8)}$$

and A, B, and C are the constants to be determined by the boundary conditions. The boundary conditions at the bottom boundary, $x = 0$, are given by equations 9 and 10.

$$u_1 = u_2 \qquad \text{....... (9)}$$

$$\left(\mu_1 + \mu_1' \frac{\partial}{\partial t}\right) \frac{\partial u_1}{\partial x} = \left(\mu_2 + \mu_2' \frac{\partial}{\partial t}\right) \frac{\partial u_2}{\partial x} \qquad \text{....... (10)}$$

At the free surface, $x = H$ , the boundary condition is given by equation 11.

$$\left(\mu_2 + \mu_2' \frac{\partial}{\partial t}\right) \frac{\partial u_2}{\partial x} = 0 \qquad \text{....... (11)}$$

Assuming, for the sake of simplicity, $\mu_1' \to 0$ , and $\mu_2' \ll 1$, and substituting equations 3 to 5 in equations 9 to 11, equation 12 is derived.

$$\frac{u_{2\,x=H}}{u_0} = \frac{2}{\sqrt{\Phi_1^2 + \Phi_2^2}} \qquad \text{.......} \ (12)$$

where:

$$\left.\begin{aligned}
\Phi_1 &= \cos P\, ch\, Q + \sqrt{\frac{\mu_2 \rho_2}{\mu_1 \rho_1}} (R \cos P\, sh\, Q - S \sin P\, ch\, Q), \\
\Phi_2 &= \sin P\, sh\, Q + \sqrt{\frac{\mu_2 \rho_2}{\mu_1 \rho_1}} (R \sin P\, ch\, Q + S \cos P\, sh\, Q), \\
\left.\begin{matrix} P \\ Q \end{matrix}\right\} &= pH\sqrt{\frac{\rho_2}{\mu_2}} \left\{ 1 + \left(\frac{\mu_2' p}{\mu_2}\right)^2 \right\}^{-\frac{1}{4}} \left\{\begin{matrix} \cos \\ \sin \end{matrix}\right. \left(\frac{1}{2} \tan^{-1} \frac{\mu_2' p}{\mu_2}\right), \\
\left.\begin{matrix} R \\ S \end{matrix}\right\} &= \left\{ 1 + \left(\frac{\mu_2' p}{\mu_2}\right)^2 \right\}^{-\frac{1}{4}} \left[ \frac{\mu_2' p}{\mu_2} \left\{\begin{matrix} \sin \\ \cos \end{matrix}\right. \left(\frac{1}{2} \tan^{-1} \frac{\mu_2' p}{\mu_2}\right) \right. \\
&\qquad \left. \left\{\begin{matrix} + \cos \\ - \sin \end{matrix}\right. \left(\frac{1}{2} \tan^{-1} \frac{\mu_2' p}{\mu_2}\right) \right]
\end{aligned}\right\} \qquad \text{.......} \ (13)$$

Using equations 12 and 13, some special cases are plotted in Fig. 1.

The diagrammatical features of the results of this theoretical investigation (1 and 2) closely resemble the features of the spectral diagrams of earthquake movements of the ground.

Systematic relationship of an earthquake at the free surface of a surface layer and those of bedrock are shown in Fig. 2. Shown is the relationship between the ratios of the synchronized amplitudes and the coefficient of solid viscosity, velocities and densities of surface layer and bedrock, and the thickness of the surface layer.

It is seen from Fig. 2 that the above mentioned amplitude is the greater as either the thickness of the surface layer increases or the softer becomes the ground. This graph will be of use in estimating the practical properties of ground, when the requisite constants are examined by means of geophysical prospecting.

2. The case of arbitrary plane elastic waves. Hereafter, it is assumed for simplicity that the surface layer as well as the subjacent medium are pure elastic bodies. In order to determine the nature of the free vibrations of the stratum, a generalization of the solution of equation 5 by means of Fourier's double integrals has been employed. If primary incident waves of the type given in equation 14

$$u_0 = F\left(\frac{v_1 t - x}{c}\right) \qquad \text{.......} \ (14)$$

are incident in the subjacent medium, the resulting free vibrations at the free surface of the weak surface layer are expressed by equation 15.

$$u_{2\,x=H} = 4\sum_{m=0}^{\infty} (-1)^m \frac{(1-\alpha)^m}{(1+\alpha)^{m+1}} F\left(\frac{\beta(v_2 t - \overline{2m+1}\,H)}{c}\right) \qquad \text{.......} \ (15)$$

where:

$$\alpha = \frac{V_2 \rho_2}{V_1 \rho_1} \qquad \text{....... (16)}$$

$$\beta = \frac{V_1}{V_2} \qquad \text{....... (17)}$$

and C = the length of the disturbed portion of the primary shock. Each term of the series gives every component of the succession of disturbances produced by multiple reflection in the stratified layer.

Whatever may be the type of the wave form of the initial disturbance, the decay factor of the vibrations is always the same. The ratio of the vibration amplitudes of successive similar phases is always constant and is expressed by equations 18 or 19.

$$\left(\frac{1-\alpha}{1+\alpha}\right)^2 \qquad \text{....... (18)}$$

$$\frac{1-\alpha}{1+\alpha} \qquad \text{....... (19)}$$

with the period being $\frac{4H}{V_2}$ or $\frac{2H}{V_2}$ according to whether $\alpha < 1$ or $\alpha > 1$, see (3 and 4).

From the theory of multiple reflection, equation 20 has been obtained expressing the relationship between the seismic vibrations of a ground with a weak surface layer $U_w(t)$ and the seismic vibrations due to the same earthquake in the ground without a surface layer, $U_S(t)$, (5).

$$\frac{\alpha+1}{2} U_w\left(t+\frac{H}{V_2}\right) - \frac{\alpha-1}{2} U_w\left(t-\frac{H}{V_2}\right) = U_S\left(t+\frac{H}{V_1}\right) \qquad \text{....... (20)}$$

With waves of a finite train of simple harmonic type which synchronize with the period $\frac{4H}{V_2}$, the ratio of the maximum amplitude at the free surface to the amplitude of the incident waves, $\frac{u_{2x=H}}{u_0}$, is given by equation 21.

$$\frac{u_{2x=H\,(max)}}{u_0} = \frac{2}{\alpha}\left\{1-\left(\frac{1-\alpha}{1+\alpha}\right)^{2n}\right\}, \qquad \left[n=\frac{1}{2}, 1, \cdots\right] \text{....... (21)}$$

Where $n$ represents the number of successive waves. The numerical examples are shown in Fig. 3. Fig. 3 shows that if waves (not less than 2) with periods nearly equal to the natural period of the surface layer appear in succession, the amplitude on the free surface may become approximately that in the case of perfect synchronization, as shown by equation 22.

$$\frac{u_{2x=H}}{u_0} = \frac{2\rho_1 V_1}{\rho_2 V_2} \qquad \text{....... (22)}$$

From equation 22 and Fig. 3, it is to be noted also that with a surface layer of soft substance, the amplitude on the free surface becomes very large with seismic waves that cause synchronization in the surface layer. However, even if the period of the incident waves closely approximate the natural period of the surface layer, the amplitude on the free surface will not become very large. This is so, regardless of the hardness of the surface layer, unless a sufficient number of incident waves appear in succession.

## THE CASE OF MULTIPLE STRATIFIED LAYERS

Since seismic wave forms are very complicated, unusual amplitudes of ground motion seldom occur when the vibrations are of such a short period that nodes may be produced in the surface layer (so-called higher harmonics). Graphical examination of the process of multiple reflection of seismic waves in the surface layer will confirm this fact. Accordingly, in analyzing earthquake motion in which there are more than two peaks of the spectral response of the amplitude, it is regarded as reasonable to consider that the surface layer consists of more than two layers.

The following studies have been made concerning the vibration of the ground from elastic waves propagated vertically from below to a surface layer consisting of several layers:

1. On the case where an infinite train of harmonic plane waves are transmitted to the surface layer which consists of two layers, taking the solid viscosity into consideration (6).

2. On the case where a finite train of harmonic plane waves is transmitted toward the surface layer consisting of two layers (7).

3. On the case where an infinite train of harmonic plane waves are transmitted toward the surface layer consisting of three layers (8).

In addition to the mathematical treatment of cases 1, 2 and 3 above, there has been:

4. A graphical study of the spectral response when an infinite train of harmonic plane waves are transmitted towards the surface layer consisting of multiple layers (9).

These studies, as itemized above, have revealed the following information, item by item:

1. The vibration amplitude on the free surface becomes the maximum when waves of such periods as result in nodes at the bottom layer boundary are transmitted. In the special case where nodes result both at the bottom layer boundary and the common boundary of the upper two layers, the maximum amplitude at the free surface becomes extremely large.

2. Since the wave reflections at the various boundaries interfere with one another, the spectral response of the amplitude of the surface layer is very irregular. Except in very unusual circumstances the maximum value of the peak is not as large as for the case of the single layer.

3. If about two only finite trains are transmitted successively and when the period of the incident waves is too large to result in a node in the surface layer, the maximum amplitude at the free surface will approximate in value that obtained in the case of an infinite train of waves.

4. If the period of waves is short enough to result in nodes in the

surface layer, the amplitude at the free surface will not approach an asymptotic value unless the wave trains occur successively in large number. Therefore, nodes will seldom exist at the same time near both the bottom and first boundaries, and as a result the amplitude seldom gets very large.

5. It is not always true that as the train of waves becomes longer, the amplitude becomes larger. There is a case where the amplitude on the surface becomes a maximum in the initial half wave. This is due to the interference of waves reflected from the various boundaries.

## OBSERVATIONAL STUDY OF EARTHQUAKE MOTIONS

1. Predominant Period of Ground. In Japan shortly after the invention of the seismograph towards the end of the 19th century, it was found from the displacement seismograph records that, in most cases, the waves of short period and small amplitude, so-called ripples, overlap those of long period and large amplitude. It became clear also that the characteristics of the ripples are peculiar to the respective grounds. It was then assumed that these ripples were waves generated near the surface of the earth.

It was found from the records of the acceleration seismograph that there is a period peculiar to each ground and that the frequency represents the predominant period (10). When the predominant period of the ground is approximate to the natural period of a site-situated building, a resonance phenomena is possible. It may be considered that earthquake damage to buildings has a close relationship to the predominant period of the site-situated ground.

From observations made in several locations in Yokohama, the relationship was studied of acceleration amplitude to frequency as well as the succession number of definite ground periods to the period of earthquake motion (11). The interval adopted, which is also used at present, consisted of the time interval between when the acceleration is half the maximum to when it becomes again half the maximum after reaching maximum. The results of the earthquake of Aug. 3, 1934 observed at Noge-Yama on diluvial loam having a thickness of 10 m are shown in Fig. 4. The following information resulted from this investigation: 1st, On firm ground, vibrations of large acceleration were found only within the narrow range of periods from 0.3 sec to 0.4 sec and; 2nd, On soft ground, large accelerations occurred over a wide range of periods from 0.2 sec to 1.5 sec.

Among the actions of earthquake motion against buildings, an important one is the frequency of the wave of a definite period following in succession. When the ground is firm, the waves of a definite period follow in succession only around that period when the acceleration reaches its maximum. On the contrary, on soft ground, the waves of a definite period follow in succession several times within a wide period range similar to both the distribution of acceleration to period and that of frequency to period.

2. Seismic Vibration of Soft Ground. In order to explore the seismic characteristics of ground, observations of earthquakes have been

made at the following three places in Tokyo: The Earthquake Research Institute and the Science Museum about 1 km east of the Institute, both of which have a surface layer of loam 10 m thick and diluvium 10 to 15 m thick; and the Shinobugaoka Primary School situated between these two places which has a surface layer of alluvium 10 m thick (12).

The results of analysis, using equation 20, of seismograms obtained at the Museum and the School and the seismogram are shown in Fig. 5. It will be seen in Fig. 5, although the seismograms differ entirely from each other, that the two curves after calculation are surprisingly similar in shape. This shows that the seismic waves which passed through the bed rock at the Museum and the School were of the same shape but at the School the vibrations on the surface were modified by multiple wave reflection in the weak surface layer.

3. Earthquake Observation Underground. A study has been made comparing underground earthquake motion with the earthquake motion at the surface at two locations which have different ground characteristics. Observations have been made at a depth of 300 m underground in the Hitachi Mine (paleozoic structure) in the Kanto District; on the ground surface of the same mine; and at the Hitachi First High School (alluvium) about 6 km southeast of the subject Mine (13).

From the seismograms of 14 earthquakes, ratios of amplitudes at the two surface locations to the amplitude underground were obtained. The relationship between these ratios and the period of earthquake motion at a depth of 300 m is represented in Fig. 6. The amplitude shown in Fig. 6 is the average of 1.5 waves in the vicinity of the maximum amplitude. The period shown in Fig. 6 is the average of the waves within a range limited to waves of a half amplitude of the maximum.

It is clear from Fig. 6, that the amplitude on the ground surface becomes a maximum when the period of earthquake motions at the 300 m depth coincides with that period corresponding to the peak of the frequency period distribution at the surface (the natural period of the ground). This study was concerned only with short period waves (about 0.1 to 0.3 sec) which were reflected from the surface back to the 300 m depth with a delay of more than one wave period. Consequently, it is concluded from the study that the amplitude and period of waves in the vicinity of the maximum amplitude, at a depth of 300 m, are influenced very little by waves reflected from the free surface. It may be stated that the relationship between the amplitude on the surface and the period of earthquake motions shown in Fig. 6 coincides very well with the results of mathematical study concerning the multiple reflection of seismic waves within a surface layer, which are shown in Fig. 1.

From Fig. 6, it can be noted that if the surface layer is of a soft substance, the amplitude at the surface becomes very large with seismic waves which induce synchronization in the surface layer. For just one wave succession, however, a difference in ground property will have but little influence upon the surface amplitude, even if the period of the incident waves may be approximate to the natural period of the surface layer. Good agreement between these observations and results of the mathematical studies, shown in Fig. 3, is indicated.

4. Comparative Observations of Earthquakes on Various Kinds of Ground. A considerable difference in dynamic characteristics has been noted for ground among the different kinds of ground observed in the case of earthquakes originating at short distances. In the case of earthquakes originating at some larger distances, no remarkable difference has been found.

As an example, the results of comparative observations on two sites in Yokohama and two sites in Tokyo, will be given. These observations were made by seismographs with a period of 5.0 sec and a magnification of 47.5. In Yokohama one location was at the Meteorological Observatory situated on a tertiary hill covered with a layer of diluvial loam about 20 m thick, and the other location was at the Kyoshin Middle School which lies on an alluvial layer about 20 m in total thickness. In Tokyo one location was at Azumacho which lies on an alluvial layer 22 m thick, and the other location was at the Earthquake Research Institute where there is a surface layer of loam 10 m thick and diluvium 10 to 15 m thick underlain by tertiary layers.

Seismograms taken at the Yokohama sites were analyzed by a response analyzer (14) which yields a velocity spectrum out of a displacement seismogram. Ratios of the spectral intensities at the two Yokohama stations for the same earthquakes are shown in Fig. 7. The predominating periods at the Observatory and the School are 0.4 and 0.9 sec, respectively. The ratio curves indicate common features for all earthquakes; having minimum values at about 0.3 sec (predominant period at Observatory) and maximum values at about 0.9 (predominant period at School).

In the case of the Tokyo sites, photographically enlarged seismograms were read off to obtain 2A (from crest to trough) and $T/2$ (from trough to crest). From the A and T values obtained, $v = 2\pi A/T$ and $\alpha = 4\pi^2 A/T^2$ values were calculated for velocity and acceleration, respectively. The predominating periods at Azumacho and the Institute are 0.77 and 0.32 sec, respectively. The results tell us that the acceleration ratio for Azumacho to the Institute is 0.6 at a period of 0.32 sec, while the ratio becomes larger than 1.5 for a period over 0.5 sec. This same feature has been observed with regard to velocity and displacement values for earthquake motion recordings (15).

The studies show that each observation station has a characteristic spectral function and this coincides with the conclusions of the mathematical studies.

5. Measurements of Micro-Tremors. The ground is always vibrating with minute amplitudes of the micron order and periods up to 2 sec. Such vibrations are called micro-tremors. The writers have carried out systematic measurements of micro-tremors on a large number of various kinds of ground (16). From these investigations, it is known that the frequency distribution of periods of micro-tremors show definite shapes for particular districts. The shape coincides with that of earthquake motion and has a close relationship with the subsoil structure of the district. Generally speaking, on hard grounds a sharp peak appears at periods from 0.1 to 0.2 sec, while on firm diluvial ground the peak appears at periods from 0.2 to 0.4 sec. On soft alluvial ground the curve is irregular in

shape and a number of peaks appear in the period range from 0.3 to 0.6 sec. On especially thick layers of soft ground, the curve is flat for a period ranging from 0.2 to over 1.0 sec.

The properties of ground as inferred from micro-tremor characteristics are utilized in the determination of the foundation coefficients relating to earthquake resistant structural design.

6. Empirical Formula for Spectral Response of Ground. From the results of the mathematical and the observational studies on ground vibration, Fig. 8 has been obtained and represents the seismic characteristics of various types of ground. Fig. 8 represents the basis of an empirical formula, equation 23 (strictly speaking, the stratum alone cannot be regarded as a conservative system, but the vibrations in that stratum should be considered as taking place in a dissipative system),

$$D = \frac{T}{\sqrt{\left\{1-\left(\frac{T}{T_0}\right)^2\right\}^2 + \left\{\frac{0.1}{\sqrt{T_0}}\frac{T}{T_0}\right\}^2}} \times const. \qquad \ldots\ldots\ (23)$$

where $T_0$ and $T$ are the predominate periods of ground and incident waves, respectively.

By use of the results of the mathematical study, a plausible geophysical explanation of the seismic characteristics of ground as represented in Fig. 8 and by equation 23 may be possible, as follows:

1. In regards to the seismic waves around the earthquake origin, equipartition of energy is recognized.

2. The shorter the wave period, the greater is the influence of energy attenuation. This is dependent upon the viscosity of the medium.

3. From statements 1 and 2, concerning the seismic waves arrival at the bottom boundary of the surface layer, and excepting extremely short period waves, it is considered that the value of the amplitude is proportional to the value of the period.

4. Peaks will appear in the spectral response observed in the ground surface due to multiple reflection of incident waves in the surface layer.

5. In equation 23, ground vibration is replaced by pendulum vibration and the constants have the values obtained by consideration of the geophysical interpretations mentioned above. Namely, an assumption is made of a forced vibration of pendulum with displacement which increases proportional to period. Also, the value of $h = 0.05/\sqrt{T_0}$ is adopted for the damping of the pendulum; which value is obtained by taking into consideration the dissipation of wave energy to the subjacent medium, the attenuation due to the viscosity of the materials of the layer, as well as by reference to Fig. 2.

6. Extremely thick and soft ground is considered to consist of plural layers. Adding this influence of plural layers to the results obtained numerically by use of equation 23, the major curves of Fig. 8 were obtained.

# EARTHQUAKE EFFECTS ON SOILS AND FOUNDATIONS

## STATISTICAL STUDY ON EARTHQUAKE DAMAGE

1. The Case of Wood Framed Houses. Recently, in Japan, in order to attempt clarification of the question why the degree of earthquake damage varied with the ground conditions, many investigations have been conducted (17 and 18). These investigations have considered damages from many standpoints.

Observations of after-shocks on various types of ground have been made to determine the relationships of the period, amplitude and movement of earthquake motion to the geologic properties of the ground. It has been found that the thicker the alluvium, the larger are the period, amplitude and total movement of ground vibration caused by after-shocks.

The relationships between the damage degree to wooden houses in Tokyo caused by the Kanto earthquake of 1923 and the thickness of the alluvial layer upon which the houses were built is shown in Figs. 9 (19).

The statistical studies show that where the alluvial layer has large thickness and the predominant period is large, the degree of earthquake damage becomes large.

2. The Case of Brick and Masonry Buildings. Generally speaking brick and masonry buildings suffered severe damage in past large earthquakes where the ground is firm (20 to 24). The relationship between the degree of damage to brick buildings in Tokyo caused by the Kanto earthquake of 1923 and the thickness of the alluvial layer is shown in Fig. 10. In this figure, it will be noted that the less thick the alluvial layer, the greater is the degree of earthquake damage, not considering the number of stories in the buildings. Earthquake damage to brick buildings, therefore, shows the opposite damage degree tendency to that suffered by wood framed buildings.

3. The Case of Reinforced Concrete Buildings. As the numbers of this type of a structure in areas suffering earthquake damage to buildings are few compared to the number of wood framed buildings, the observations were based necessarily on a smaller scale. Accordingly, many aspects of damage to this type of a structure still require study of the statistical damage degree.

Fig. 11 shows the relationship between the damage degree to reinforced concrete buildings in Tokyo suffered in the Kanto earthquake of 1923 to the thickness of the alluvial layer on which the buildings were sited. These figures show that, generally, the harder the ground, the more severe the overall damage degree seems to become. These facts seem to have little relationship to the number of stories to a building. On the basis of damage to main structural members in certain sections of the building, many investigators find contradictions to this general statement. Evidence is not sufficient to draw any definite conclusions for this type of building between building damage and the properties of the ground. That is to say, the conclusion will vary dependent upon what type and what extent of damage was the object of statistical study (25).

Using data from the Kanto earthquake of 1923, the relationship between the properties of the ground and the story in the building most severely damage was examined. The results show that on firm ground the first story was damaged most severely. On soft ground, the first floor was damaged most severely when the total number of stories was small; and the second and third stories were damaged most severely when the total number of stories was large. This fact can be explained by the results of theoretical studies based upon the assumption that at the time of an earthquake the vibration energy of building dissipates to the ground again as elastic waves, which start from the foundation (26).

Using the same data, the relationship between the ratio of the sectional area of the building to the height of the building and the degree of earthquake damage has been examined. The results show that the earthquake damage to buildings became greater with an decreasing ratio of sectional area to height and this result existed for all ground conditions. The results coincide also with the theoretical results mentioned above.

There are many elements involved in the relationship between damage degree to buildings and the properties of the site ground but, at least, the following statements can be made: Japanese wood-framed houses and other buildings do not always show equal damage tendencies relative to ground properties. In short, and generally speaking, the results of this study tell us that the softer the ground, the larger is the earthquake damage degree to buildings of large natural period and; to the contrary, the firmer the ground, the larger is the damage degree to buildings of short natural period.

## CONCLUSION

From mathematical and observational study of earthquake motion, such seismic characteristics of ground were obtained that enabled explanations of damage caused by large past earthquakes. Such explanations are summarized:

1. Seismic characteristics vary with the properties of ground.

2. The ground with a surface layer has spectral response of the resonance curve type. The period, of which the frequency is predominant, coincides with the period, of which the amplitude is predominant. Consequently, when the proper period of a building is approximate to that of the ground on which the building is sited, an earthquake may exert force adversely on the building.

3. When the number of surface layers are in excess of one layer , the so-called resonance phenomena, in which frequency as well as amplitude are particularly predominant, occurs very seldom. However, as such ground generally consists of thick and soft layers, the earthquake motion may have a comparatively large amplitude over a wide period range. Consequently, buildings which stand on such ground are at a disadvantage in an earthquake, regardless of their proper period.

# EARTHQUAKE EFFECTS ON SOILS AND FOUNDATIONS

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NOMENCLATURE

| | | | Unit |
|---|---|---|---|
| $u\,(U)$ | = | Displacement | cm |
| $\lambda, \mu$ | = | Lame's elastic constants | dyne/cm$^2$ |
| $\rho$ | = | Density | g/cm$^3$ |
| $\lambda', \mu', \xi$ | = | Coefficient of solid viscosity | sec.dyne/cm$^2$ |
| $V$ | = | Transmission velocity | cm/sec$^2$ |
| $p$ | = | Frequency of waves | 1/sec |
| $T$ | = | Period of waves, $T = \frac{2\pi}{p}$ | sec |
| $H$ | = | Thickness of surface layer | cm |
| $i$ | = | Imaginary | none |
| $x$ | = | Coordinate | cm |
| $t$ | = | Time | sec |

$$h = \sqrt{\frac{\rho p^2}{\mu + i\mu' p}}, \quad \alpha = \frac{V_2 \rho_2}{V_1 \rho_1}, \quad \beta = \frac{V_1}{V_2}.$$

Suffix 1 and 2 represent the subjacent medium and the surface layer, respectively.

## FIGURE CAPTIONS

Fig. 1 The spectral response of the ground. $\mu_2' = 10^6$, $\mu_1 = 6\times 10^8$, $\mu_2 = 1.5\times 10^8$, $\rho_1 = \rho_2 = 1.5$ c. G. S. Ordinate and abscissa represent $u_{2\,x=H}/u_0$ and period, respectively.

Fig. 2 Relationship between the amplitude, impedance ratio of two media, coefficients of viscosity and thickness of surface layer. Ordinate and abscissa represent $u_{2\,x=H}/2u_0$ and $\pi\xi_2/2\rho_2 v_2 H$, respectively.

Fig. 3 Relationship between the maximum amplitude on the free surface and the number of successive waves.

Fig. 4 Relationship between number in succession, frequency and acceleration to period at Nogeyama in Yokohama.

Fig. 5 Seismograms obtained on the two different properties of ground and the calculated results.

Fig. 6 Relationship between the amplitude ratio on the free surface to a depth of 300 m and the period at a depth of 300 m.

Fig. 7 Ratios of the spectral intensity on the two different kinds of ground in Yokohama.

Fig. 8 Empirical graphs of the spectral response of various types of ground.

Fig. 9 Relationship between the damage degree to wooden houses and the thickness of alluvium in Tokyo at the time of Kanto earthquake of 1923.

Fig. 10 Relationship between the damage degrees and thickness of alluvium in the case of brick buildings in Tokyo in the Kanto Earthquake. 1, 2, and 3 represent the numbers of stories.

Fig. 11 Relationship between the damage degree and thickness of alluvium in the case of reinforced concrete buildings in Tokyo in the Kanto Earthquake. 1, 2 ... 8 represent the number of stories.

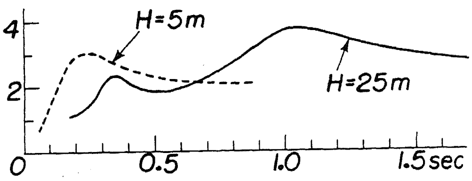



FIG. 1

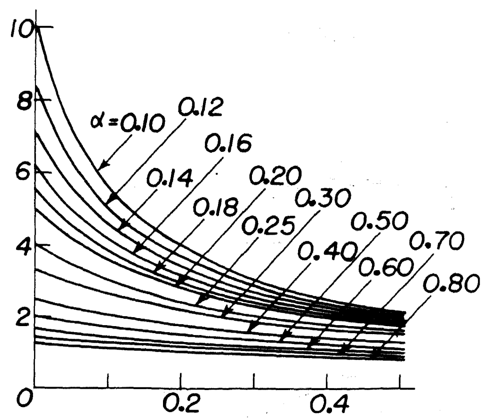



FIG. 2

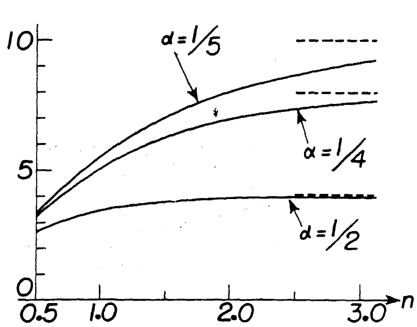



FIG. 3

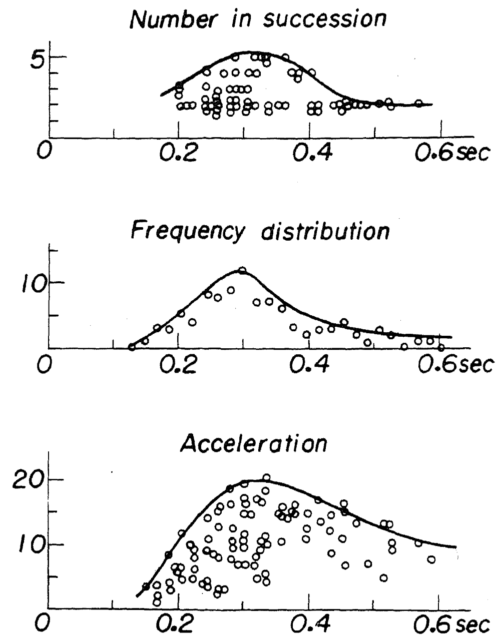



FIG. 4

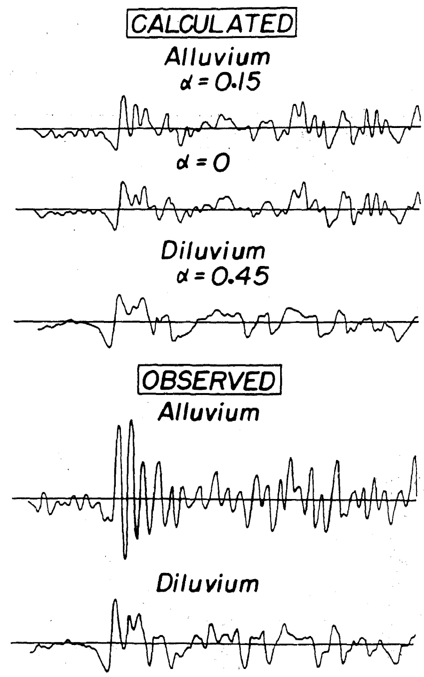
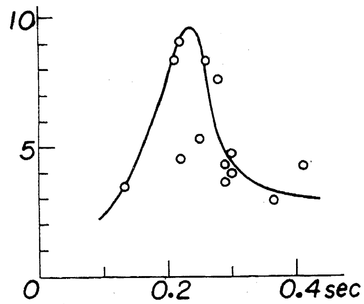



FIG. 5



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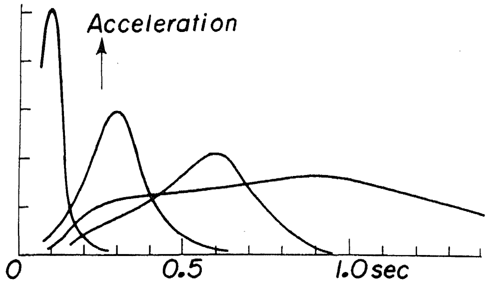

FIG. 8a

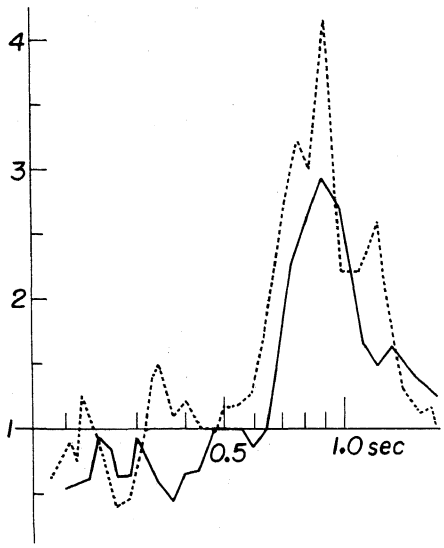

FIG. 7

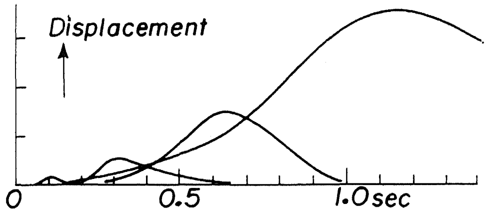

FIG. 8b

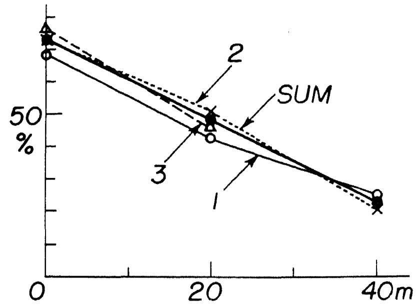

FIG. 10

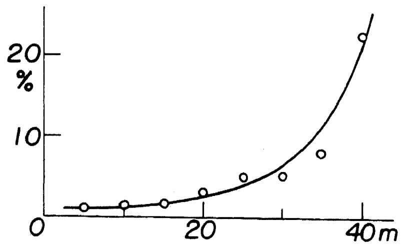

FIG. 9

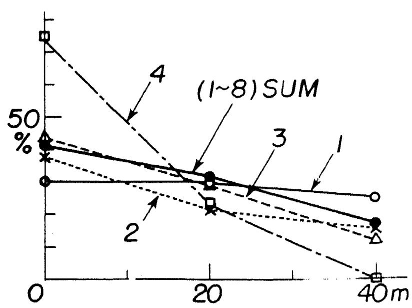

FIG. 11