THE INTERRELATION BETWEEN FREQUENCY CHARACTERISTICS OF GROUND AND EARTHQUAKE DAMAGE TO STRUCTURES

HIROSHI YAMAHARA*

INTRODUCTION

It goes without saying that the dynamic behavior of a building during earthquakes is much affected by the dynamic properties of ground on which the building is founded. In order to investigate the dynamic properties of ground, the observation of microtremors or earthquake ground motion is generally done.

Up to the present days, the main object of the observation of microtremors or earthquake ground motion is to detect the most predominant period within the original record, and the period is generally called the predominant period of ground.

A sort of resonance phenomenon between the predominant period of ground and the natural period of buildings has been thought to be one of the important elements which cause structural damage.

Four multistory buildings were reported to have collapsed during the Caracas earthquake of 1967. At that time, there were over 7,000 modern reinforced concrete buildings of more than four stories in the city, about 180 buildings (about 2.6 percent) of which were heavily damaged (M.A. Sozen et al., 1968). In the Tokachioki earthquake of 1968 in Japan, the percentage of heavily damaged buildings was also fairly small while the structural strength of the buildings was thought to be nearly the same.

There will be no problem if the damage can be explained from the reason that the natural period of the damaged buildings was close to the predominant period of the ground. But, as the results of our inquiry in Hachinohe (170 km from epicenter, Yoshimi and Akagi, 1968) soon after the Tokachioki earthquake, it cannot but be concluded that the damage could not be explained only from the resonance phenomenon between structure and ground.

The natural period of reinforced concrete buildings from three to eight stories in Japan generally have the range from 0.2 to 0.5 sec. On the other hand, the predominant period of ground also takes a value within the same range in many cases. Thus the probability of matching both periods is thought to be more frequent than one would expect. Nevertheless, the actual damage ratio is far smaller than expected.

Considering those facts, it seems that another important factor must be noticed. The

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factor is thought to be the degree of density of frequency component contained in the
original ground motion, and the factor will be called "frequency selectivity" in this paper.

Sometimes the peak of the predominant period is distinguishable very sharply in the
frequency spectrum of microtremors or earthquake motion (Fig. 1b), and some other
times such a peak is barely recognized in the spectrum (Fig. 1a). There should be sig-
nificant difference between them from the viewpoint of earthquake engineering even if
both may have the identical predominant period.

![Low Frequency Selectivity](image1) ![High Frequency Selectivity](image2)

**Fig. 1.**

Thus it becomes necessary to define a quantity that represents the sharpness of the
frequency component in the spectrum when the relation between the dynamic properties
of ground and the earthquake damage to structures is to be discussed.

As a result of our investigation on the Tokachioki earthquake, it was proved that
there was a close relation between the frequency selectivity and structural damage. A
greater part of the damaged structures were found to be built on the ground having
higher values of the frequency selectivity. Also found is the fact that the spectrum
characteristics of microtremors and various earthquakes do not resemble one another
when the ground has a low frequency selectivity, and the predominant peak does not
always show at the same period. However, if the frequency selectivity of ground is
comparatively high, the predominant peak of microtremors and that of earthquakes occur
at the same period with high probability.

In this paper, the earthquake damage to buildings in Tokachioki earthquake of 1968
are discussed on the basis of the frequency selectivity.

THE CORRELATION BETWEEN THE PREDOMINANT PERIODS OF
GROUND AND THE NATURAL PERIODS OF BUILDINGS

The periods of buildings and their surrounding ground obtained from microtremor
observations in Hachinohe and vicinities are shown in Table 1 and Fig. 4. The pre-
dominant periods of the ground took a value within the range from 0.21 to 0.47 sec. On
the other hand, the natural periods of the building were from 0.23 to 0.44 sec, in the
same range as the ground. From the figure in which the heavily damaged buildings are
shown in square symbols, it can not necessarily be concluded that the natural periods of
damaged buildings are close to the periods of the surrounding ground.
It must be borne in mind, however, that those are the results obtained from the observation of microtremors, the amplitude of which is less than several microns. It can not be considered that the dynamic properties of buildings and ground during microtremors may remain the same during strong motion earthquakes. The periods of the heavily damaged buildings were measured after they had been damaged, and were probably much longer than the periods before they were struck by the main shock. The response records of rigid buildings obtained from several aftershocks in Hachinohe proved that the period

<table>
<thead>
<tr>
<th>Building</th>
<th>Damage</th>
<th>Stories</th>
<th>Period of Bldg.</th>
<th>Period of Ground</th>
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<tr>
<td>Hachinohe Credit Depository</td>
<td>U</td>
<td>3-0</td>
<td>0.32, 0.24</td>
<td>---, ---</td>
</tr>
<tr>
<td>Tohoku Electric Power Co.</td>
<td>U</td>
<td>3-0</td>
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<td>0.35, 0.34</td>
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<td>U</td>
<td>5-1</td>
<td>0.31, 0.33</td>
<td>0.21, 0.28</td>
</tr>
<tr>
<td>Hachinohe Grand Hotel</td>
<td>U</td>
<td>5-1</td>
<td>0.29, 0.26</td>
<td>0.38, 0.36</td>
</tr>
<tr>
<td>Kosei H. S.</td>
<td>U</td>
<td>3-0</td>
<td>0.27, 0.30</td>
<td>0.21, 0.20</td>
</tr>
<tr>
<td>Seiwa Bank</td>
<td>U</td>
<td>3-0</td>
<td>0.35, 0.34</td>
<td>---, ---</td>
</tr>
<tr>
<td>Red Cross Hosp. of Hachinohe</td>
<td>U</td>
<td>6-1</td>
<td>0.23, 0.32</td>
<td>0.24, 0.21</td>
</tr>
<tr>
<td>Miman Department Store</td>
<td>U</td>
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<td>0.34, 0.35</td>
<td>---, ---</td>
</tr>
<tr>
<td>Marumitsu Department Store</td>
<td>U</td>
<td>6-1</td>
<td>0.36, 0.44</td>
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</tr>
<tr>
<td>Iwatoku Bldg.</td>
<td>U</td>
<td>4-0</td>
<td>0.36, 0.35</td>
<td>---, ---</td>
</tr>
<tr>
<td>Hachinohe Tech. H. S.</td>
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<td>3-0</td>
<td>0.39, 0.40</td>
<td>0.47, 0.47</td>
</tr>
<tr>
<td>Nejiro Primary School</td>
<td>U</td>
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<td>0.28, 0.32</td>
</tr>
<tr>
<td>Hachinohe Kita H. S.</td>
<td>U</td>
<td>3-0</td>
<td>0.34, 0.35</td>
<td>0.25, 0.23</td>
</tr>
<tr>
<td>Hachinohe Higashi H. S. (1)</td>
<td>H</td>
<td>3-0</td>
<td>0.30, 0.34</td>
<td>0.21, 0.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.33, 0.35</td>
<td>---, ---</td>
</tr>
<tr>
<td>Hachinohe Library</td>
<td>M</td>
<td>3-0</td>
<td>0.39, 0.40</td>
<td>---, ---</td>
</tr>
<tr>
<td>Hachinohe Tech. College (1)</td>
<td>H</td>
<td>1-0</td>
<td>0.41, 0.41</td>
<td>0.35, 0.27</td>
</tr>
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<td></td>
<td>(2)</td>
<td></td>
<td>0.26, 0.30</td>
<td>---, ---</td>
</tr>
<tr>
<td></td>
<td>(3)</td>
<td>3-0</td>
<td>0.28, 0.33</td>
<td>0.42, 0.42</td>
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<td></td>
<td>(4)</td>
<td>3-0</td>
<td>0.29, 0.31</td>
<td>---, ---</td>
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<td></td>
<td>(5)</td>
<td>3-0</td>
<td>0.24, 0.26</td>
<td>0.32, ---</td>
</tr>
<tr>
<td></td>
<td>(6)</td>
<td>3-0</td>
<td>0.30, 0.29</td>
<td>0.28, 0.27</td>
</tr>
<tr>
<td>Misawa Commercial H. S.</td>
<td>H</td>
<td>3-0</td>
<td>0.35, 0.40</td>
<td>0.28, 0.27</td>
</tr>
</tbody>
</table>

a $U$: practically undamaged, $M$: considerably damaged, $H$: heavily damaged.
b See Fig. 2 for points of measurements.
c Measured after the damaged building was demolished and removed.
d See Fig. 3 for points of measurements.
e $T$: transverse direction, $L$: longitudinal direction.
f Periods peculiar to ground could not be observed due to the interference of neighbouring building vibrations.
of the buildings was significantly prolonged by a growth of the amplitude even if the building had not be damaged. Such a tendency is caused mainly by the non-linearity of the stiffness of ground and is remarkable when the building is comparatively rigid. Although the period of buildings and that of the ground are close to each other in the observation of microtremors, the two periods may be reasonably separated each other.

Fig. 2. Measured Points for Hachinohe Higashi High School

Fig. 3. Measured Points for Hachinohe Technical College

Fig. 4. Correlation between the Periods of Building and Ground
so as to evade the resonance owing to the change of building's period.

Judging from the above-mentioned results, it is unreasonable to explain the earthquake damage only from the relationship between the periods of buildings and ground.

THE FREQUENCY ANALYSIS OF GROUND MOTION AND THE DEFINITION OF FREQUENCY SELECTIVITY

Such methods as period-frequency spectrum, response spectrum and Fourier or power spectrum are generally used to express the frequency spectrum of microtremors or earthquake motion. For the purpose of investigating the relationship between ground conditions and ground motion, it is necessary to make clear the average power of an original motion and the degrees of each frequency component included in that power. The expression of power spectrum will be most useful for that purpose.

The autocorrelation function $R(\tau)$ are given as the following formula for random ground motion $f(t)$:

$$ R(\tau) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{T/2} f(t) f(t + \tau) dt $$

R(\tau) and the power spectrum $P(\omega)$ are expressed as two-sided Fourier transforms as follows:

$$ P(\omega) = \frac{2}{\pi} \int_0^\infty R(\tau) \cos \omega \tau d\tau $$

$$ R(\tau) = \int_0^\infty P(\omega) \cos \omega \tau d\omega $$

$R(0)$ is nothing but the average power of the original motion, and is expressed from Eq. (3) as

$$ R(0) = \int_0^\infty P(\omega) d\omega $$

If the power spectrum is calculated by normalizing $R(\tau)$ by $R(0)$ as follows

$$ \frac{P(\omega)}{R(0)} = \frac{2}{\pi} \int_0^\infty \frac{R(\tau)}{R(0)} \cos \omega \tau d\tau $$

the equation of the spectrum of $P(\omega)/R(0)$ becomes

$$ \int_0^\infty \frac{P(\omega)}{R(0)} d\omega = 1 $$

If a frequency spectrum is expressed as mentioned above, $R(0)$ means the average power of the original ground motion, and $[P(\omega)/P(0)]d\omega$ corresponds to the degrees to which the component of frequency $\omega$ contributes to that power. The frequency selectivity which has been discussed in relation to Fig. 1 may be defined by the peak density of the frequency component.

The problem is how to quantitatively define the frequency selectivity. If the dynamic mechanism yielding peaks in the spectrum of ground motion can be made clear, the
definition will easily be done. However, actual ground is too complex to be represented by a certain mathematical model.

Nowadays, the spectrum density of earthquake on a base layer is often thought to be constant, and the spectrum characteristics may be mainly introduced within the surface layer. The spectrum of microtremors is also considered to represent the characteristic of a surface layer. Assuming that a surface layer may be replaced by the multi-reflection system shown in Fig. 5(a), the frequency selectivity can be defined from the vibration impedance ratio \( \alpha(= \rho_1 V_1 / \rho_2 V_2) \). When a spectrum has a typical single peak, a surface layer could be replaced by a system of single degree of freedom shown in Fig. 5(b). In this case, the frequency selectivity can be expressed by the damping coefficient of the system. However, the composition of actual ground is so complicated that it cannot be properly represented by an idealized mathematical model. Therefore, it will be better to be objectively defined from the shape of peaks in a spectrum without taking mathematical model into account.

As the maximum value at a peak is more important than the relative shape of the peak for earthquake engineering purposes, it will be proper to define the maximum value of \( P(\omega)/R(0) \) as frequency selectivity. It may be readily understood that the frequency selectivity thus obtained means the degree to which the most predominant frequency component is contained in the average power of an original ground motion. The numerical values of the frequency selectivity used in this paper are based on the above definition.

![Multi-reflection System](a) ![Lumped Mass System](b)

**Fig. 5.**

THE RELATION BETWEEN THE FREQUENCY SELECTIVITY OF GROUND AND EARTHQUAKE DAMAGE TO BUILDINGS

At the beginning of our investigation on the Tokachioki earthquake, it was supposed that there might be a sort of resonance phenomenon between heavily damaged buildings and their surrounding ground. On the basis of the investigation in Hachinohe and vicinities, however, it was concluded that the cause of damage could not be explained only from the resonance phenomenon.

It was noticed that the oscillograph records of microtremors tended to be comparatively simple and regular in heavily damaged areas. When the records were expressed in the form of a power spectrum, there appeared a remarkably predominant peak, which corresponded to a high frequency selectivity according to the definition presented in the
preceding chapter.

Many school buildings were included in the category of totally damaged buildings, and that was one of the characteristics of the Tokachioki earthquake. There occurred such strange results among school building that some were heavily damaged while others were left without a slightest crack although the structural strength of the buildings was thought to be nearly identical.

The most heavily damaged school buildings we investigated are Hachinohe Technical College, Hachinohe Higashi High School, and Misawa Commercial High School, and their spectra obtained from the microtremors of their surrounding ground are shown in Fig. 6.

![Microtremor Spectra of Ground Adjacent to Heavily Damaged School Buildings](image)

On the other hand, the spectra of ground at Nejirou Primary School, Hachinohe Kita High School, Kosei High School and Hachinohe Technical High School which were practically undamaged are shown in Fig. 7.

Comparing Fig. 6 and Fig. 7, it is found that the heavily damaged buildings were founded on the ground having higher frequency selectivity, whereas the undamaged buildings except one case out of four stood on the ground of lower frequency selectivity.

Fig. 8 shows the spectra on the ground of Hachinohe Library and Hachinohe Tower which were heavily damaged, and also indicates the characteristic of higher frequency selectivity.

It cannot be stated, however, that all of the buildings founded on the ground having high frequency selectivity were damaged by the earthquake. The Hachinohe Office of Tohoku Electric Power Co. as well as Japan Red Cross Hospital in Hachinohe were founded
Fig. 7. Microtremor Spectra of Ground Adjacent to Undamaged School Buildings

Fig. 8. Microtremor Spectra of Ground Adjacent to Heavily Damaged Buildings in Hachinohe

Fig. 9. Microtremor Spectra of Ground Adjacent to Undamaged Buildings in Hachinohe
on the ground with high frequency selectivity as shown in Fig. 9, but they received no damage. The reason why they were not damaged may be related to the structural characteristics of the buildings, i.e., the former is a structure having high rigidity as indicated by the natural period of the building, and the latter has one basement surrounded by dry area.

It may be concluded from the above discussion that there seems to be a significant relationship between the frequency selectivity of ground and the earthquake damage to buildings.

SIMILARITY IN THE SPECTRUM CHARACTERISTICS OF MICROTREMORS AND EARTHQUAKE MOTION

After the main shock of the Tokachioki earthquake, a number of aftershocks were observed at several locations. Three kinds of ground motions, i.e., main shock, after-
shocks and microtremors were successfully recorded at the port of Hachinohe where a strong motion accelerometer (SMAC-B2 type) was installed, as shown in Fig. 10. It can readily be seen in the figure that there is hardly any similarity among these spectrum characteristics. These data may seem to lead to a conclusion, contrary to an established theory, that there are no common predominant peaks among these ground motions.

However, an opposite tendency could be observed on the ground of Hachinohe Technical College as shown in Fig. 11, where the predominant peaks occurred at nearly identical period of about 0.4 sec. There were, in fact, a few cases in which the spectra had no peak at that period. The reason will be discussed in the next chapter. At any rate, it may be concluded for the ground of Hachinohe Technical College that the predominant peak of not only microtremors but also earthquake motion was likely to occur at nearly identical period. Moreover, the frequency selectivity in those spectra obtained at the college is found to be very high in comparison with those obtained at the Port of Hachinohe.

![Fig. 11. Power Spectra of Microtremors and Aftershocks on the Ground at Hachinohe Technical College](image)

Therefore, it may be concluded that the ground having a high frequency selectivity is highly probable to have a fixed predominant period for both microtremors and earthquake ground motions. On the other hand, for the ground with a low frequency selectivity, the probability of having a predominant peak at a fixed period is fairly low, and there is poor correlation between the period of microtremors and that of earthquakes.

The remarkably predominant peak in the spectrum is probably brought about by the
Fig. 12. The Soil Profile at the Port of Hachinohe
surface layer of the ground. If there is no such a layer capable of selecting and amplifying a specific frequency component, the earthquake wave will pass through the surface layer without changing its frequency characteristics and will show a spectrum having a low frequency selectivity which is the characteristic of input wave motion itself.

If the surface stratum can be properly represented by a theoretical model, and if the

<table>
<thead>
<tr>
<th>Elevation (m)</th>
<th>Depth (m)</th>
<th>Thickness of Layers (m)</th>
<th>Soil Symbol</th>
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</tr>
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<tr>
<td>0.00</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.20</td>
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<td>8.70</td>
<td>6.50</td>
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<tr>
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<td>3.80</td>
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<td>gravel</td>
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<tr>
<td>16.10</td>
<td>3.60</td>
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<td>25.10</td>
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<td></td>
<td>gravel</td>
</tr>
<tr>
<td>30.00</td>
<td></td>
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Fig. 13. The Soil Profile at Hachinohe Technical College
earthquake waves are treated as vertically traveling plane waves, the mechanism can be numerically explained from the multi-reflection theory presented by Sezawa (1929) and Kanai (1957, 1962). But, as will be mentioned in the next chapter, there often occur phenomena that cannot be explained from the theory, probably because the actual ground is too complex to be replaced by a simple idealized model, and the mechanism of wave transmission within the surface layer cannot simply be treated as plane waves.

For reference, soil profiles at the Port of Hachinohe and Hachinohe Technical College are shown in Figs. 12 and 13 respectively.

GROUND MOTIONS AND THEIR SPECTRUM CHARACTERISTICS

Supposing that the earthquake wave-motion having an uniform spectrum density (white noise) is transmitted to a surface layer and follows multi-reflections of plane wave within the surface layer, several contradictions are found in interpretation of observed results. For instance, for the case of the Port of Hachinohe as shown in Fig. 10, it can not but be concluded that the earthquake wave-motion itself has a typical characteristic of spectrum before transmitted to a surface layer, even if there is no surface layer producing a specific predominant peak. Furthermore, even at Hachinohe Technical College, earthquakes having no predominant peak at specific period were observed once in five or six. A typical example is shown in Fig. 14.

![Diagram](image)

Fig. 14. Power Spectra of Aftershock on the Ground in Hachinohe Technical College in Which Typical Peaks can not be Found Near 0.4 sec

Although the complexity of natural soils and of the wave transmission make it difficult to obtain analytical solutions to earthquake ground motion problems, we can assume that a surface layer has the characteristics of a sort of frequency filter and a power amplifier. Those characteristics can be grasped for a given ground by the observation of microtremors or earthquakes (Fig. 15).

The spectrum characteristics at ground surface when white noise comes into the surface layer may be considered to show the characteristics of a filter, the surface-to-base ratio of the average power being the amplification ratio. Supposing the spectrum of earthquake waves at base layer as $G(\omega)$, and the spectrum characteristics of surface layer as $S(\omega)$, the average power of ground motion at a surface $R(0)$ is expressed as follows:

$$R(0) = \int_{0}^{\infty} G(\omega)S(\omega)d\omega$$  \hspace{1cm} (7)
and its power spectrum becomes

\[ P(\omega) = G(\omega)S(\omega) \]  \hspace{1cm} (8)

The function \( P(\omega) \) can be readily calculated by multiplying spectrum density of two spectrum functions \( G(\omega) \) and \( S(\omega) \).

Fig. 16 shows schematically the spectra at surface when two kinds of earthquakes having the peak and no peak at the period \( T_n \) come into the surface layer having a sharp predominant peak at the period \( T_n \). It can be seen in the figure that not only the frequency selectivity but also average power itself is increased when earthquake waves having a peak at the period of surface layer are transmitted through a layer having high frequency selectivity.
The above phenomenon is also illustrated by the actual data shown in Figs. 17 and 18 which were observed in Hachinohe. Fig. 17 shows the spectrum of one of the after-shocks which was observed where the SMAC-type accelerometer was located at the Port of Hachinohe. This spectrum shows the characteristics of earthquake waves reaching the Hachinohe district prior to entering the surface layer. This spectrum indicates a very sharp predominant peak at a period near 0.4 sec which coincides with the period of the ground of Hachinohe Technical College. This earthquake was simultaneously observed on the ground of the college, and its spectrum is shown in Fig. 18.

![Fig. 17. The Power Spectrum of an Aftershock Observed at SMAC Situation in Which a Predominant Peak Reveals at the Period Near 0.4 sec](image)

![Fig. 18. The Power Spectrum of the Earthquake Simultaneously Observed at the Ground in Hachinohe Technical College](image)

Just as expected, a very sharp predominant peak appeared in the spectrum of Fig. 18, and the frequency selectivity amounted to over 0.20 in spite of the average value at the ground being from 0.10 to 0.15. Because the earthquake waves of the main shock contained a predominant peak at the period near 0.4 sec, the ground surface at the Hachinohe Technical College was likely to severely vibrate in nearly sinusoidal form.

An attempt will be made subsequently to answer the question why the buildings founded on a soil layer having high frequency selectivity are disadvantageous during earthquakes. In the first place, the average power, or amplitude itself, grows in proportion to an increase in frequency selectivity of the ground. Such a tendency is especially remarkable when the periods of earthquake waves and surface layer approach each other.

Secondly, a greater part of the ground motion is occupied by a specific frequency component, when a ground motion has a high frequency selectivity. Thus the form of vibration is very close to sinusoidal motion.
When the earthquake response of a building is considered as shown in Fig. 19, the maximum acceleration ratio between ground motion and building \( (S_d) \) is generally calculated to be from 3 to 4 at most for various earthquakes assuming a damping coefficient of 0.05. But the ratio \( S_d \) amounts to 10 when the ground motion is perfectly sinusoidal and the damping coefficient is 0.05.

Consequently, a ground motion having high frequency selectivity is disadvantageous to the earthquake response of buildings, even if the accelerations of the ground motion are in the same level with other ground motions having lower frequency selectivity.

Fig. 19. Difference between the Response for Sinusoidal Ground Motion and Ordinary Earthquake

SUMMARY AND CONCLUSIONS

A sort of resonance phenomenon between the natural period of a building and the predominant period of the ground has been believed to be one of the important causes of structural damage during earthquakes. With the object of ascertaining if there might be this phenomenon concerning the damaged buildings during the Tokachioki earthquake of 1968, Japan, many observations on the periods of buildings and ground were carried out by means of microtremors for not only heavily damaged buildings but also for undamaged buildings. As a result of these investigations, it could not be necessarily concluded that the periods of buildings and ground are closely related to the earthquake damage to buildings.

A much more important factor which is one of the dynamic characteristics of ground was found from the spectrum analysis of the observed data. The factor is the density of the most predominant frequency component included in ground motions and is called
frequency selectivity in this paper. The frequency selectivity was proved to have a very close relation to the earthquake damage to buildings. Such results will be considered to be commonly applied to any ground and earthquakes.

If the frequency selectivity of ground is very high, the ground motion is not only unusually amplified but also changed to sinusoidal form during earthquakes. Moreover, such a tendency is promoted if frequency component close to the period of ground is predominant in the original earthquake waves.

It was found that amplitude and frequency characteristics at several locations were far different with one another where an earthquake was simultaneously recorded, even the distance among them were as close as several kilometers at most. Such a fact may be attributed to the difference in the amplitude and frequency characteristics of surface layer, and can be proved on the basis of amplification and spectrum characteristics of surface layer. Especially, if earthquake waves having a remarkably predominant period come into a surface layer having a high frequency selectivity and if the periods of the waves and the soil approach each other, the ground surface motion is not only remarkably amplified but also transformed to a sinusoidal form. Thus the building is subjected to large earthquake force even if there is no resonance phenomenon between the periods of buildings and ground. Those explanations can be reasonably applied to the earthquake damage during the Tokachioki earthquake of 1968.

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NOTATION

\( f(t) \): Time-dependent function of ground motion
\( G(\omega) \): Power spectrum function of base motion
\( h \): Damping coefficient of structure
\( P(\omega) \): Power spectrum function on ground surface
\( R(\tau) \): Autocorrelation function
\( S(\omega) \): Power spectrum function of surface layers
\( T \): Overall duration of earthquake
\( T_s \): Fundamental period of building or soil ground
\( t \): Time variable
\( V \): Propagation velocity of shear wave
\( \ddot{z} \): Input acceleration
\( \alpha \): Vibration impedance defined by \( \rho_1 V_1 / \rho_2 V_2 \)
\( \rho \): Mass density of soil
\( \tau \): Time variable
\( \omega \): Circular frequency
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