48. *The Result of Observation concerning the Waves caused in the Ground by Building Vibration.*

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1. Introduction.

It had been believed that the damping resistance of buildings implies the damping in the material used in structure, the air-resistance and the plasticity of the foundation. But recently we came to have the idea that the dissipation of vibrational energy in the form of seismic waves transmitted into the ground is also a contributory cause,[1] and the theoretical result obtained from this concept was found to agree very well with the various statistics concerning earthquake damage[2]. Naturally the relation of the building to the ground became an important factor in the aseismatic property of buildings.

The present paper treats the experiments conducted in order to ascertain the above-mentioned property. We observed the motion of the ground caused by the vibration of a full-size 3-storied building made for experiments and a small one-storied house of masonry of reinforced concrete blocks. They were located on the Loam Layer in the compound of Architectural Research Institute, Hyakunin-chō, Shinjuku-ku, Tokyo.

2. The case of small one-storied house.

Fig. 1 is the schematic view showing the buildings for vibration experiments and the observing points of the ground. The left part of the figure represents those in the case of the one-storied small house, while the right part those in the case of the full-size 3-storied building.

In the former case vibration was caused by the vertical-type vibrator consisting of 4 wheels set on 2 counter rotating shafts (unbalanced mass = 50 kg,

1) K. SEZAWA and K. KANAI, "Improved Theory of Energy Dissipation in Seismic Vibrations of a Structure", *Bull. Earthq. Res. Inst.*, **14** (1936), 164.

2) K. KANAI and S. YOSHIZAWA, "Relation between the Earthquake Damage of Non-wooden Buildings and the Nature of the Ground. II", *Bull. Earthq. Res. Inst.*, **29** (1951), 209.

eccentricity = 11 cm) which was installed on the roof floor. Table I indicates the constants of seismographs used in the vibration observation of the ground.

Table I. The constants of the seismographs.

	Number	Period (sec)	Geometr. Magnif.
Horizont.	2	3	14
	3	1	180
Vertical	1	0.09	4.5 gal./mm

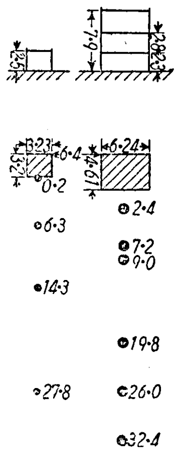

Fig. 1. Schematic view showing the buildings for vibration experiments and the observing points of the ground.

Observation was made on the points of 0.2, 6.3, 14.3 and 27.8 m off the side of the building.

The ground vibration was examined by observing three components. Neglecting the vertical component and horizontal one normal to the vibration direction of the building, as they are very small, we have treated in this paper the observed ground vibration concerning only the horizontal component in the direction of building vibration. The result of observation is shown Fig. 2.

The record of observation shows that the displacement at the ground close to the building is almost equal to the amplitude at the

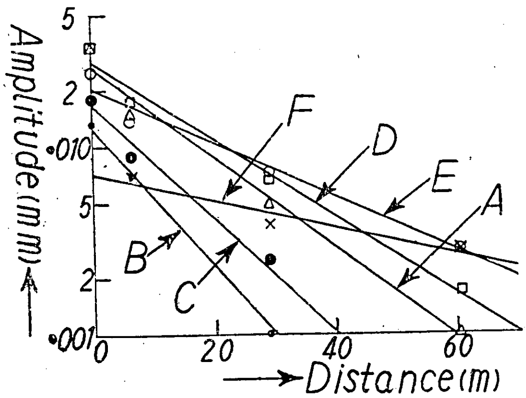

Fig. 2. Relation between the amplitude of ground oscillations and the distance from the building.

A; T=0.134 sec, k=0.055 m^{-1}, B; T=0.140, k=0.0090,
C; T=0.156, k=0.068, D; T=0.184, k=0.0433,
E; T=0.201, k=0.0341, F; T=0.260, k=0.0216.

building base, and the wave form is always sinusoidal even at the point nearest to the building.

In the vibration experiments we saw at the boundary of the ground and the building opening and shutting motion done or the ground crumble. This seemed to indicate the elastical discontinuity of building and ground, but as the result of observation we concluded that it is natural to think that these phenomena appear only on the surface and under the ground the building vibration propagates as elastic waves into the ground.

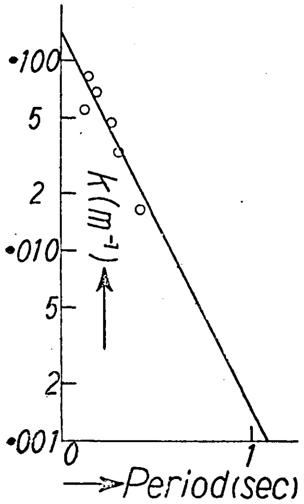

Fig. 3. Relation between the damping coefficient and the period of ground oscillations.

From Fig. 2 it is found that the relation of the amplitude at observing point (a) to the distance between the building and observing point (x) can be expressed as follows:

$$a \propto e^{-kx} \quad \text{............(1)}$$

where k denotes the damping coefficient concerning the distance of which the value is a constant at each vibration period. Fig. 3 represents the relation between the damping coefficent (k) and the period (T) of ground oscillations. Then we have

$$k \propto T^{-2}. \quad \text{..........(2)}$$

From equation (1) and (2), we get

$$a = Ae^{-\frac{kx}{T^2}}. \quad \text{........................(3)}$$

Equation (3) shows that the property of the vibration in the ground in this case corresponds to that of the plane waves propagating in elastic body of solid viscosity. Namely the propagation of visco-elastic wave is denoted by[3]

$$a = Ae^{ip\left(t-\frac{x}{v}\right)-\frac{\xi}{2\rho}\frac{p^2}{v^3}x} \quad \text{..................(4)}$$

where $p=2\pi/T$, T=period, ξ=damping coefficient, ρ=density and v=velocity. Calculated from the result of the experiment, ξ becomes 7.6×10^5 C.G.S. Comparing it with other experimental values[4] we obtain Table II, which shows

3) K. SEZAWA, "On the Decay of Waves in Visco-Elastic Solid Bodies", *Bull. Earthq. Res. Inst.*, **3** (1927), 43.

4) T. SUZUKI, *Zisin*, **16** (1944), 170, (in Japanese).

Table II.

Ground	v (m/sec)	$\xi/2\rho$ (C.G.S.)	$\xi/2\rho v^3$ (C.G.S.)	Operator
Sandstone	3,300	1.8×10^9	5×10^{-3}	Suzuki
Tuff-shale	2,000	1.4×10^9	18 〃	〃
Loam	700	1.2×10^8	35 〃	〃
	80	1.9×10^5	37 〃	authors

that the difference due to the physical property of ground becomes small if we take $\xi/2\rho v^3$ into consideration.

3. The case of the full-size 3-storied building.

In this case vibration was forced by a horizontal-type vibrator with one wheel (unbalanced mass=130 kg, eccentricity=100 cm) set on the roof floor. The constants of seismographs used in observation of ground vibration, the observing points and the direction of measurement are shown in Table III.

Table III. Constants of the seismographs, the observing points and the direction of measurement.

No. of exper.	Seismographs									
	No. 1		No. 2		No. 3		No. 4		No. 5	
	Period=1.0 sec						4.0 sec			
	Geometr. Magnif.=210						10			
	dist. (m)	direct.	dist. (m)	direct.	dist. (m)	direct.	dist. (m)	direct.	dist. (m)	direct.
I	—	—	0	EW	—	—	2.4	NS	2.4	EW
II	0	EW	2.4	EW	2.4	NS	—	—	—	—
III	—	—	2.4	EW	—	—	2.4	NS	0	NS
IV	7.2	EW	2.4	EW	7.2	NS	—	—	—	—
V	9.0	EW	19.8	EW	9.0	NS	—	—	—	—
VI	26.0	EW	19.8	EW	23.0	NS	—	—	—	—
VII	—	—	32.4	EW	46.5	NS	—	—	—	—

The observed records of ground oscillations are shown in Fig. 4.

The maximum acceleration at the roof floor of the building in NS direction

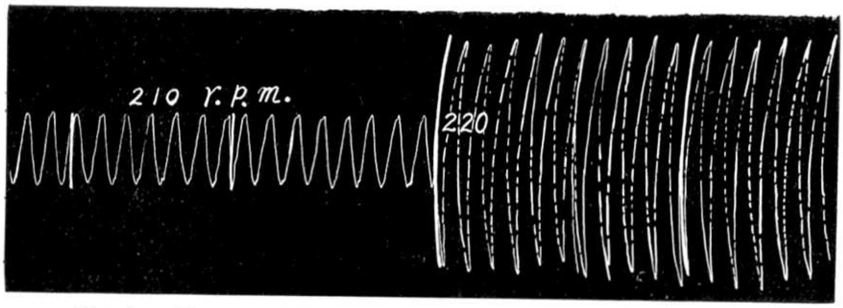

Fig. 4a. The record (Original) of transversal waves. Distance from the building; 9.0 m, Magnif. of seismograph; 210, No. of exper.; V.

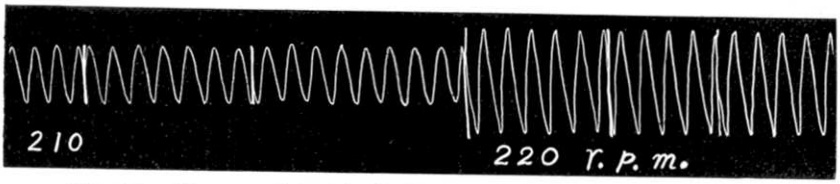

Fig. 4b. The record (Original) of longitudinal waves. Distance from the building; 19.8 m, Magnif. of seismograph; 210, No. of exper.; V.

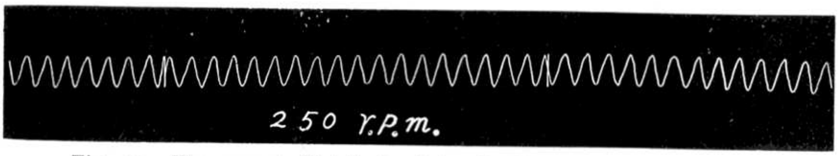

Fig. 4c. The record (Original) of longitudinal waves. Distance from the building; 32.4 m, Magnif. of seismograph; 210, No. of exper.; VII.

is about 600 gal and in EW direction 400 gal[5]. The record of the waves in the travelling direction (EW direction) and normal direction (NS-direction) shows sinusoidal form even in a point considerably near the building. The waves of travelling and normal direction come to have the properties of longitudinal and transversal waves respectively according to the phase relation. Thus we found that the vibration of the base of the building which was vibrated by the horizontal-type vibrator is transmitted into the ground in the form of longitudinal and transversal waves.

The relation between the amplitude at the observing point (a) and the distance from the observing point to the building (x) is denoted in Table IV and Figs. 5, 6. These figures show that there exists the relation approximate to

5) *Report of the Committee for Seismic Tests of Structures*, **1** (1948–1950), 104, (in Japanese).

Table IV. The values of amplitudes of dissipated waves in mm unit.

Direct.	Period (sec)	Distance (m) 0	2.4	7.2	9.0	19.8	26.0	32.4	46.5
NS (Trans. Waves)	0.35	.086	—	.024	.0205	—	.0048	—	—
	0.40	.082	.053 } .051 }	.013	.014	—	.0029	—	.0009
	0.45	.076	.044 } .042 }	.0093	.0105	—	.0024	—	.0007
EW (Longi. Waves)	0.35	.160	.044	.026	.022	.0125	.0093	.0083	—
	0.40	.116	.020	.0094	.0087	.0048	.0040	.0037	—
	0.45	.081	.014	.0074	.0058	.0034	.0026	.0024	—

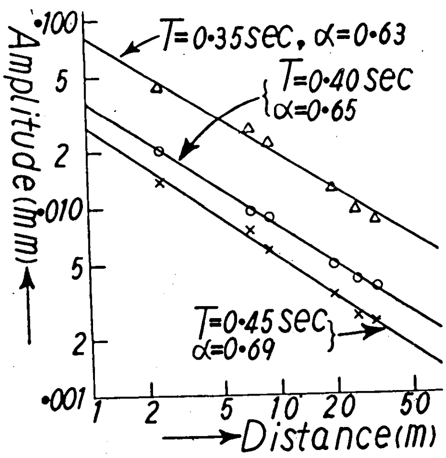

Fig. 5. Relation between the amplitude of longitudinal waves and the distance from the building.

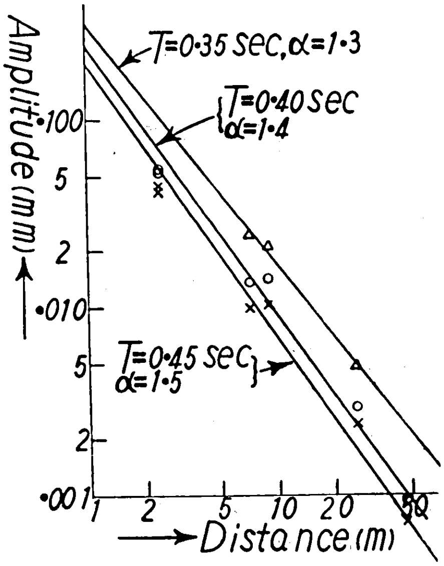

Fig. 6. Relation between the amplitude of transversal waves and the distance from the building.

$$a \propto x^{-\alpha} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (5)$$

α in equation (5) is a constant, and each figure in the diagram represents α concerning correspondent curve. When the waves propagate in two dimensions, $\alpha=0.5$, and in three dimensions, α will be 1. According to the value of α shown here, it can be seen that the damping of waves of large amplitude in travelling and normal directions tends to be a little larger than the damping of vibration amplitude concerning the distance when the wave propagates in two and three dimensions.

Then, assuming the damping of vibration concerning distance to be

$$a \propto x^{-\alpha} \cdot e^{-kx} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

and k to be the value obtained in the previous chapter, we can replace Fig. 5 and 6 by Fig. 7 and 8. Fig. 7 and 8 indicate that the longitudinal and transversal waves propagate in the form of

$$a \propto \frac{e^{-kx}}{\sqrt{x}}, \quad a \propto \frac{e^{-kx}}{x}. \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

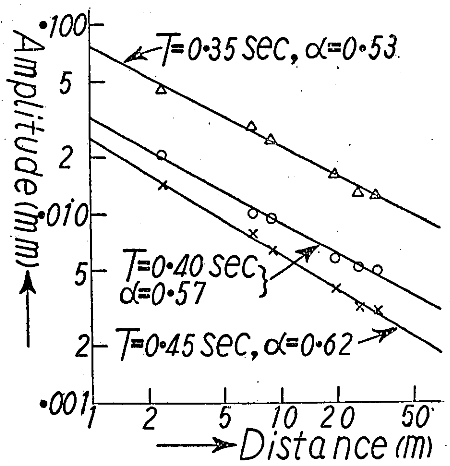

Fig. 7. Relation between the amplitude of longitudinal waves excluding the influence of solid viscosity of ground and the distance from the building.

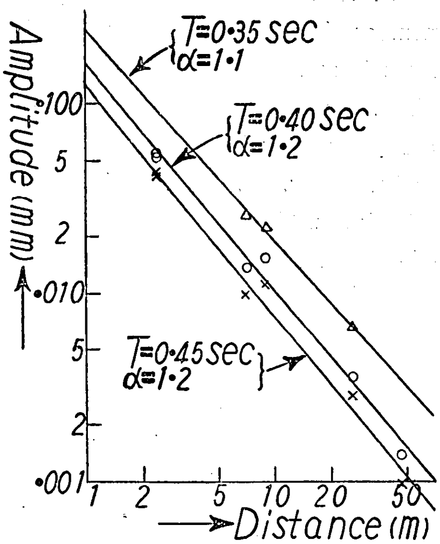

Fig. 8. Relation between the amplitude of transversal waves excluding the influence of solid viscosity of ground and the distance from the building.

4. Conclusion.

The result of the observation stated in previous chapters made us understand that the displacement at the building base is transmitted into the ground in the form of seismic waves. Since this property is considered to determine the damping resistance of building, it becomes very important to take into consideration the relation between the construction of building and the ground property, in order to design aseismatic buildings economically and rationally.

As to the damping resistance of dissipated waves concerning distance, there are two kinds of property. When the direction of forced vibration is single, the damping has a property of plane waves in longitudinal waves: when the direction is rotated, it has the property of longitudinal waves transmitted in two dimensions and transversal ones transmitted in three dimensions. In each case there is the damping due to solid viscosity of which the value is $\xi/2\rho v^3 \fallingdotseq 3.7\times10^{-7}$ C.G.S., where ξ=viscosity coefficient, ρ=density, and v=velocity. It was found that even when the physical property of ground differs somewhat the value will always assume the same order if the form $\xi/\rho v^3$ is used.

In conclusion it must be added that the above is a research work as a member of the Committee for Seismic Tests of Structures, undertaken under the grant from the Scientific Research Expenditure of Department of Education to whom the authors wish to express their gratitude. The authors also wish to express their hearty thanks to Mr. K. Nakagawa of the Architectual Research Institute, Mr. M. Suzuki of the Faculty of Engineering of Tokyo University and Messrs. T. Tanaka, T. Suzuki, Miss S. Yoshizawa of our Institute, who has aided the authors in carrying out the investigations successfully.

48.　建物振動に伴う土地の震動の測定結果

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起振機使用の建物の振動に伴う，土地の震動を測定した結果，建物の基礎のところの振動變位は，そのまま土地に彈性波として傳播して行くことが明かになつた。この性質は，建物の振動減衰性を支配するものと考えられるから，耐震建築を經濟的でしかも合理的に行うには，建物の構造と地盤の性質との關係を考慮に入れることが極めて大切なことになる。

なお，建物からの逸散波の距離についての減衰性は起振方向が1方向の場合には縱波の平面波の性質を示し，起振方向を回轉させた場合には2次元的に傳播する縱波と3次元的に傳播する横波の性質を示す2種類がある。いづれの場合にも土地の固體粘性による減衰の性質があらわれ，その値は ξ を粘性係數，ρ を密度，v を速度とすると，$\xi/2\rho v^3 \fallingdotseq 3.7\times10^{-7}$ C.G.S. となる。縱波，横波のいづれについても，$\xi/\rho v^3$ の形にすると，大體同じ値となり，土地の物理的性質が少しぐらいかわつても $\xi/\rho v^3$ の形にすると大體同じぐらいの數になることもわかつた。
