17. *Relation between the Earthquake Damage of Non-wooden Buildings and the Nature of the Ground. II.*

By Kiyoshi KANAI and Shizuyo YOSHIZAWA,

Earthquake Research Institute.

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In the previous investigations,[1] it has been cleared up considerably that the softer the ground is, the less the damage done to ferro-concrete buildings and brick ones by earthquakes is. On the other hand, it has been shown that the first floor was the most severely destroyed on the firm ground, while on the soft ground the second as well as the third floors suffered most damage at the time of the great earthquake. The results obtained statistically were explained by the results of the theoretical studies based upon the idea that at the time of earthquake the vibration energy of buildings dissipates to the ground again as elastic waves starting from the foundation.

In the present paper the relations among the damage of buildings due to earthquakes and the ratio of the height of building (l) to the radius (ε') of the circle to which the sectional area of the building is transformed assumedly and the nature of the ground together with the relation between the damage ratio of every story of buildings and the nature of the ground are described based upon the same data as in the previous paper regarding the damage done to ferro-concrete buildings and brick ones in the former Tokyo city at the time of the Kwanto earthquake of 1923.

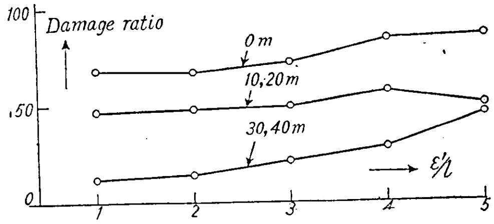

Fig. 1. The relation among the damage ratio, ground condition and ε'/l for the case of brick buildings in the former Tokyo city at the time of the Kwanto earthquake of 1923. $0_m \cdots 40_m$ represent the thickness of alluvium.

The results obtained are shown in Tables I-IV and plotted in Figs. 1-4. It is seen from Figs. 1 and 2 that the damage to buildings caused by earth-

1) K. KANAI, "Relation between the Earthquake Damage of Non-woodon Buildings and the Nature of the Ground", *Bull. Earthq. Res. Inst.*, **27** (1949), 97.

quake becomes greater as the ratio of ε'/l as to every condition of the ground increases. Figs. 3 and 4 show that the damage as regard each story of buildings decrease with the increase in the thickness of alluvium.

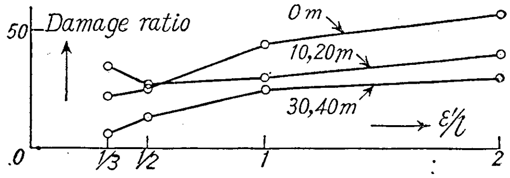

Fig. 2. The relation among the damage ratio, ground condition and ε'/l for the case of ferro-concrete buildings in the former Tokyo city at the time of the Kwanto earthquake of 1923. $0_m \cdots 40_m$ represent the thickness of alluvium.

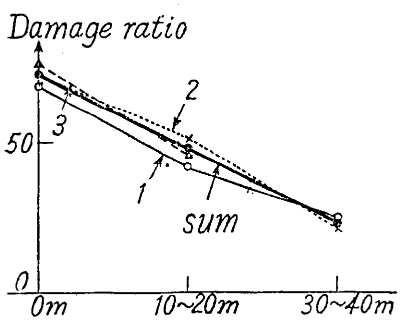

Fig. 3. The relation between the damage ratio and thickness of alluvium for the case of brick buildings in the former Tokyo city at the time of the Kwanto earthquake of 1923. 1, 2, 3 represent the number of stories.

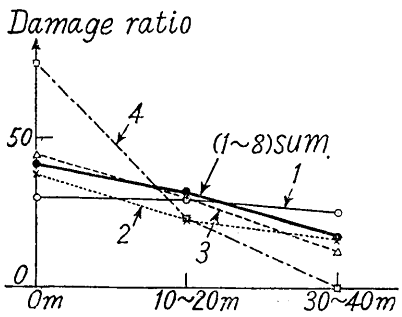

Fig. 4. The relation between the damage ratio and the thickness of alluvium for the case of ferro-concrete buildings in the former Tokyo city at the time of the Kwanto earthquake of 1923. 1, 2, ... represent the number of stories.

In order to explain this fact, we will touch the problem by mathematical calculations.

Table I. Brick buildings. Relation among damage ratio, ground condition and ε'/l.

Ground conditions	Damage ratio (%)				
	$\varepsilon'/l=1$	2	3	4	5
Thickness of alluvium, 30∼40 meter	12	14	21	28	45
Thickness of alluvium, 10∼20 meter	47	48	49	57	50
Diluvium or tertialy	68	67	72	84	86

Table II. Ferro-concrete buildings. Relation among damage ratio, ground condition and ε'/l.

Ground conditions	Damage ratio (%)			
	$\varepsilon'l=1/3$	1/2	1	2
Thickness of alluvium, 30∼40 meter	6	13	25	30
Thickness of alluvium, 10∼20 meter	35	27	30	40
Diluvium or tertiary	22	25	44	57

Table III. Brick buildings. Relation between damage ratio as to every stories and ground condition.

Ground conditions	Damage ratio (%)			
	1 storey	2 stories	3 stories	total
Thickness of alluvium, 30∼40 meter	25	21	—	23
Thickness of alluvium, 10∼20 meter	42	51	46	48
Diluvium or tertiary	69	73	76	73

Table IV. Ferro-concrete buildings. Relation between damage ratio as to every stories and ground condition.

Ground conditions	Damage ratio (%)				
	1 storey	2 stories	3 ,,	4 ,,	(1∼8) total
Thickness of alluvium, 30∼40 meter	25	16	12	0	17
Thickness of alluvium, 10∼20 meter	29	22	30	23	32
Diluvium or tertiary	30	38	44	75	41

As was shown in the previous paper,[2] the motion of a tall building with rigid floors subjected to horizontal oscillation of the ground is analogous to the case of shearing vibrations of a simple structure, so we shall deal with the vibration problem of a tall structure with rigid floors subjected to incident transverse waves, under the dissipation of vibrational energy in the form of elastic waves transmitted into the ground.

Let the incident transverse waves with their displacements orientated vertically be

$$u_0 = \cos(pt + kx) \quad \text{.}\,\text{.}\,\text{.}\,\text{.}\,\text{.}\,\text{.}\,\text{.}\,\text{.}\,\text{.}\,\text{.}\,\text{.}\,\text{.}\,\text{.}\,\text{.}\,\text{.}\,\text{.}\,\text{.}\,\text{.}\,\text{.}\,\text{.} (1)$$

2) K. SEZAWA and K. KANAI, "Some New Problems of Free Vibrations of Structure", *Bull. Earthq. Res. Inst.*, **12** (1934), 819.

The final solutions of the stress in a structure are expressed by[3)]

$$S = 4\pi\,\varepsilon^2 G k' \sqrt{\frac{\Gamma_1^2+\Gamma_2^2}{P^2+Q^2}}\,\sin k'(x+l)\cos\left(pt+\tan^{-1}\frac{\Gamma_2}{\Gamma_1}-\tan^{-1}\frac{Q}{P}\right), \quad (2)$$

where

$$\left.\begin{aligned}
P &= 2\Gamma_1 \cos k'l + \frac{3G\varepsilon}{\mu l}\Lambda_1 k'l \sin k'l,\\
Q &= 2\Gamma_2 \cos k'l + \frac{3G\varepsilon}{\mu l}\Lambda_2 k'l \sin k'l,\\
\Gamma_1 &= 3\left(\frac{\lambda}{\mu}+2\right)+\nu(k'l)^2\left(\frac{\lambda}{\mu}-3\sqrt{\frac{\lambda}{\mu}+2}\right),\\
\Gamma_2 &= \sqrt{\nu}\,(k'l)\left\{3\left(\frac{\lambda}{\mu}+2+\sqrt{\frac{\lambda}{\mu}+2}\right)+\nu(k'l)^2\left(\sqrt{\frac{\lambda}{\mu}+2}-2\right)\right\},\\
\Lambda_1 &= \left(\frac{2\lambda}{\mu}+5\right)-\nu(k'l)^2,\\
\Lambda_2 &= \sqrt{\nu}\,(k'l)\left(2\sqrt{\frac{\lambda}{\mu}+2}+1\right),\\
\nu &= \frac{\rho G\varepsilon^2}{\rho'\mu l^2}, \quad k'^2 = \frac{\rho'^2 p^2}{G},
\end{aligned}\right\} \quad \dots\dots (3)$$

in which ρ, λ, μ; ρ' $(=m/al_1)$, $G(=12.4\,Ej^2/l_1^2)$ are the density and the elastic constants of the earth, and the effective density and the effective rigidity of the structure, where E, j, l_1, l, a and ε are Young's modulus, radius of gyration of section, length of the column between two adjacent floors, height of the structure, sectional area of the column and radius of the column respectively.

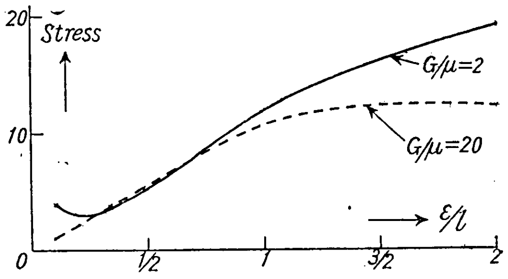

Fig. 5. The results of mathematical calculations of the relation between stress and ratio of ε/l.

3) K. SEZAWA and K. KANAI, "Improved Theory of Energy Dissipation in Seismic Vibrations of a Structure", *Bull. Earthq. Res. Inst.*, **14** (1936), 168.

Using equation (2) we calculated the stress and the height where the stress reaches a maximum in column at resonance condition under the conditions $\rho = \rho'$, $\lambda = \mu$. The results are plotted in Figs. 5, 6 and 7.

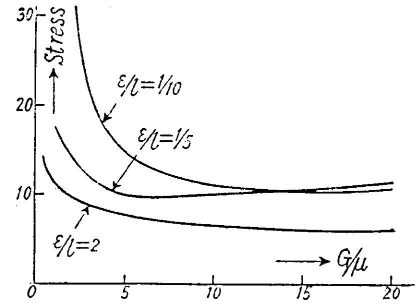

Fig. 6. The results of mathematical calculations of the relation between stress and ratio of G/μ.

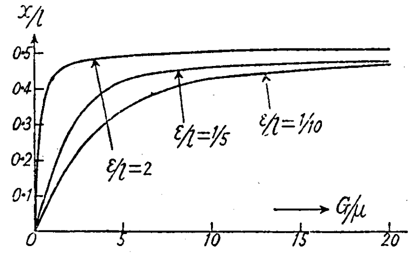

Fig. 7. The results of mathematical calculations of the relation between height where stress take maximum and ratio of G/μ.

Comparing the curves in Fig. 2 obtained statistically and the curves in Fig. 5 calculated mathematically, it will be seen that, the relation between the earthquake damage to buildings, on the ground where the thickness of alluvium are 0 meter and 10~20 meter and the ratio ε'/l fairly resembles the relation between the stress in columns under the two conditions, say $G/\mu=2,20$, and the ratio of ε'/l. And the features of the relation between the damage ratio as well as the places where the buildings suffered most by earthquake and the ground condition, as plotted in Figs. 3, 4 and shown in Table I, II, III, of the previous paper[4] are explained somewhat quantitatively by the results of mathematical calculations plotted in Figs. 6, 7.

The results above-mentioned tell us again that the results of theoretical studies, based upon the idea that at the time of earthquake the vibration energy of buildings dissipates to the ground again as the elastic waves which start from the foundation, are applicable to the earthquake-proof problem of structure.

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4) *loc. cit.*, 1).

17. 非木造建物の震害と地盤の性質との關係　第2報

地震研究所　金井　清
　　　　　吉澤靜代

關東地震の舊東京市における鐵筋コンクリート造建物及び煉瓦造建物の震害と地盤の性質との關係を，前回と同じ資料を使つて別の方面からしらべてみた。

即ち，建坪を圓に假定したときの半經 ε' と建物の高さ l との比 (ε'/l) と被害率の關係は第1, 2圖になる。第2圖は建物の振動勢力の地下逸散の問題の數値計算の結果の第5圖と模樣が非常によく似ている。次に，層數別の建物の被害率と地盤との關係は第3, 4圖になり，前記の數値計算の結果の第6圖と性質が等しいことがわかる。建物における應力が最大になるところの高さと地盤との關係は數理的には第7圖になり，實際の震害狀態を說明するに足りそうである。要するに，地震の際に建物の振動勢力が地中に逸散するために生ずる建物の振動減衰性は建物の耐震性に非常に大きな影響があることが相當具体的にわかつた譯である。