59. *Vibration Test of Actual Reinforced Concrete Building.*

By Kiyoshi KANAI and Teiji TANAKA,

Earthquake Research Institute.

(Read Feb. 18, 1947.—Received Sept. 20, 1951.)

1. Introduction.

Since the strength test of actual reinforced concrete building necessarily becomes large in scale, not so many buildings have been submitted to the test of this kind. The number of satisfactory seismic tests of applied to concrete buildings is still smaller. For in the test of strength against earthquake, the ordinary method of measuring the strength by applying to the building statical force does not satisfy the purpose fully, so a vibration test becomes necessary.

Generally in the vibration measurement of actual reinforced concrete buildings, the vibrations caused by the wind or small earthquake are observed and the natural period and oscillation type of the building are obtained. On rare occasions the free oscillation of building is measured by pulling the building and letting it go to get its natural period and damping coefficient.

However, it is quite difficult to learn the aseismatic property of building fully from such experiments only. This time, we applied for the first time the method, by which the vibration of wooden-house may be measured[1], to concrete buildings. The method is to apply forced vibration to the building.

The experiment showed that this method is considerably effective for the seismic test of reinforced concrete building, for we could get the exact value of the proper period and damping coefficient of the building as well as the quite approximate oscillation type and the data concerning the state of the base under the ground.

---

1) T. SAITA, "Study of Vibrations of Wooden House", (in Japanese), *Report Invest. Comm. Earthq.-proof Const. Japan Soc. Prom. Scien. Res.*, No. **1** (1937), 60, No. **2** (1942), 32.

K. KANAI, "Vibration Experiments with an Actual Wooden Building", (in Japanese), *Bull. Earthq. Res. Inst.*, **20** (1942), 538, **21** (1943), 206.

2. The building submitted to the experiment.

The building submitted to this experiment is four-storied reinforced concrete one, located at Kobiki-cho, Chuo-ku, Tokyo, and was once burnt during the late war. Figs. 1 and 2 show the photograph and plan view of the building respectively. As shown in this photograph and the plan view, the building, being small and simply constructed with a width of 4.4 m in beam direction and 11.6 m in girder direction, is suitable for analysing the experimental result.

Fig. 1.

Table I shows the floor height and the weight of each part of the building which is calculated from the plan.

In Table I the height of foundation was calculated inversely from the experimental result. The weight of the roof includes the parapet and the vertical members of the foundation, and the floor weight is a roughly estimated value.

From data obtained by boring the neighbouring ground we found that the building stands on ground having piled soil and reclaimed soil of 4 m thickness and diluvium of 14 m under them.

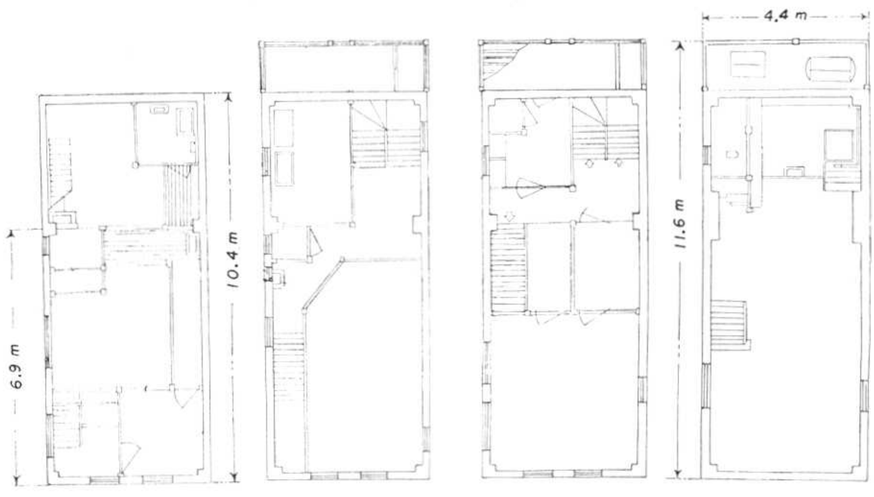

Fig. 2. The plan view of the building subjected to the experiment.

Table I.

Number of stories			Base	1	2	3	4	Roof
Height of column (m)			2.0	3.7	3.2	3.1	3.2	—
Weight (ton)	Floor+Beam	Dead load	—	16.8	16.8	16.8	16.8	11.0
		Live load	—	14.4	14.4	14.4	14.4	12.8
		Total	—	31	31	31	31	24
	Column+Wall+Staircase		66	76	71	66	64	—

3. Method of experiment.

As for the experiment, the vibration was caused on the building by a vibrator installed on the roof floor, driven by an electric motor and producing centrifugal force, and amplitudes of vibration corresponding to various r.p.m. were measured by two kinds of portable seismograph. One of them is of inverted pendulum type with air-damper, smoked paper for recording, period of 6 sec and magnification of 20. Another has an oscillograph for recording equipped with induction type transducer, of which the magnification is about 200 at critical damping.

Vibrational force was given to beam direction and girder direction individually, and vibrational displacement of each floor was observed by carrying the transducer to every floor. The observed displacement was compared with the one measured by seismograph installed on the floor of forth story.

4. Results of Observation.

The vibrational force produced by the vibrator is represented by $F=M(4\pi^2/T^2)r(\sin\theta/\theta)$, where $M=5.5$ kg, $r=20$ cm, $\theta=44°$. Therefore, the observed values represent the amplitudes corresponding to the applied force which changes according to frequency. This makes theoretical consideration rather complicated. So the values are converted into the amplitudes supposing that the constant force acts regardless of frequency. Next, as the transducer is of the induction type which records the values proportional to velocity, the values were also converted into vibrational displacement. Making these two conversions we made clear the relations of amplitude and frequency concerning every floor of the building, which are shown by mark ● in Figs. 3∼7. The

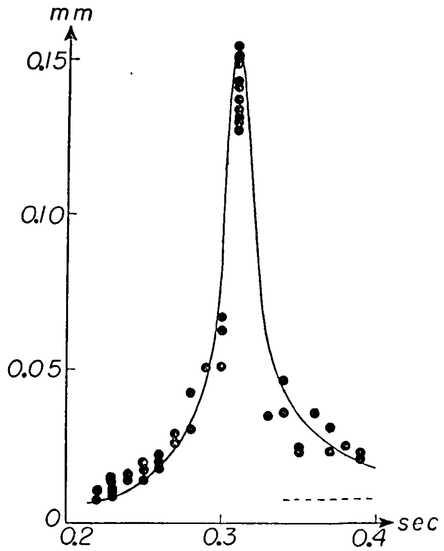

Fig. 3. Relation of amplitude at roof floor and vibration period. Mark ●; experimental result, curved line; theoretical result.

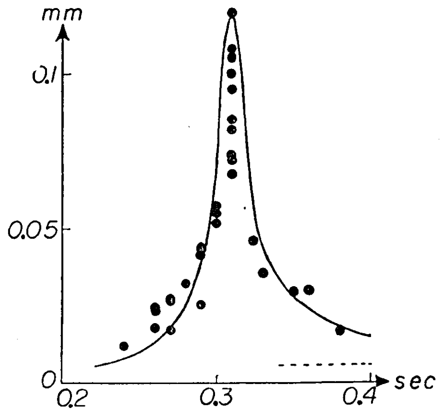

Fig. 4. Relation of amplitude at third floor and vibration period. Mark ●; experimental result, curved line; theoretical result.

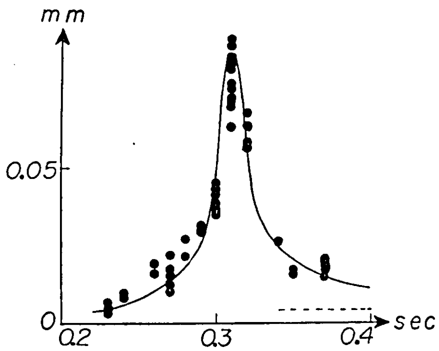

Fig. 5. Relation of amplitude at second floor and vibration period. Mark ●; experimental result, curved line; theoretical result.

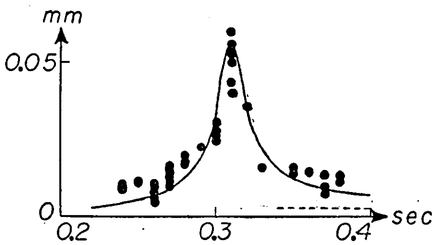

Fig. 6. Relation of amplitude at first floor and vibration period. Mark ●; experimental result, curved line; theoretical result.

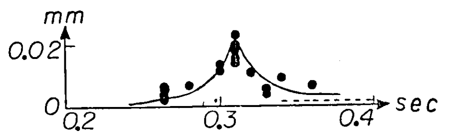

Fig. 7. Relation of amplitude at ground floor and vibration period. Mark ●; experimental result, curved line; theoretical result.

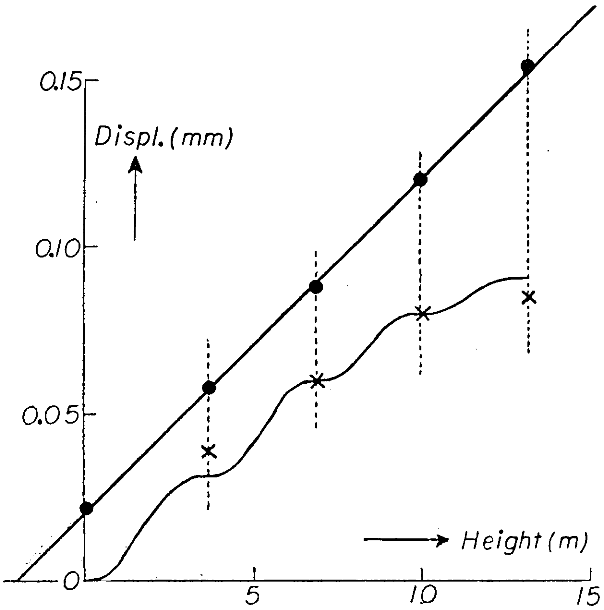

Fig. 8. Distribution of resonance amplitude of each floor. Mark ● ; beam direction, × ; girder direction. Two lines represent the theoretical results of rocking vibration and bending vibration respectively.

constant force applied here is $F=5\times 10^7$ dyne which means actual force in case of $T=0.31$ sec.

The maximum amplitudes (resonance amplitudes) of each floor in both the beam and girder direction are represented respectively by ● and × in Fig. 8. At the present it is difficult to speed up the rotation of vibrator over 300 r. p. m. For this reason, the relation between frequency and amplitude in the girder direction, where the resonance frequency is very high, cannot be made so clear as in the beam direction.

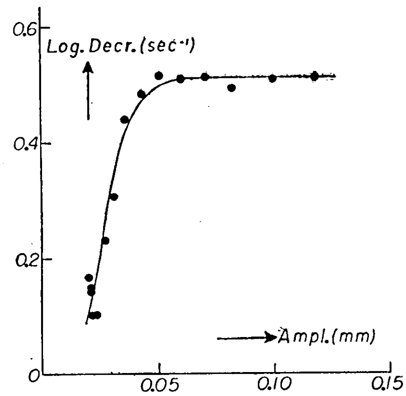

Fig. 9. Relation of damping coefficient and vibration amplitude of the beam direction.

Producing free oscillation, we got damping coefficient as shown in Fig. 9.

5. Theoretical consideration.

In considering the vibration in the girder direction, we found that the whole building may be fairly considered as a rigid body making a rocking oscillation around the axis which lies about 2 m under the ground. This is shown in Fig. 8. Now let us go a step further with theoretical consideration, assuming this building to make a complete rocking oscillation.

Constants concerning the building are represented as follows: mass moment of inertia of building $= I$, damping coefficient $= \varepsilon$, pressure corresponding to unit depression of ground $= p_0$, geometrical moment of inertia of base $= i$, weight of whole building $= W$, height of the center of gravity from base surface $= h$, gravity acceleration $= g$, vibrational force $= f$, height of the point where force acts from the base $= H$.
Then the equation of rocking oscillation is

$$I\ddot{\theta} + 2\varepsilon\dot{\theta} + (p_0 i - Wh)g\theta = fH. \qquad (1)$$

if we represent the vibrational force $f = F\sin pt$ and write $\varepsilon/I = \lambda$, $(p_0 i - Wh)g/I = n^2$, θ becomes

$$\theta = \frac{FH}{I}\frac{\sin(pt-\delta)}{\sqrt{(n^2-p^2)^2+4\lambda^2p^2}} \qquad \left[\delta = \tan^{-1}\left(\frac{2\lambda p}{n^2-p^2}\right)\right] \qquad (2)$$

If x denotes displacement and L the height from the base surface, $x = \theta l$ and the absolute value of equation (2) becomes

$$|x| = \frac{FHT^2L}{4\pi^2 I}\frac{1}{\sqrt{\left\{\left(\frac{T}{T_0}\right)^2-1\right\}^2+\frac{\lambda^2T^2}{\pi^2}}} \qquad (3)$$

In this equation, T_0 means the natural period of the building, and T the period of oscillation force. As F, H, l, I, T_0 and λ are known, we get the resonance curve from equation (3). I is calculated from Table I, namely, $I = 3.8\times10^{14}$ grcm^2, $F = 5\times10^7$ dyne, $H = 1520$ cm, T and λ are found to be $T_0 = 0.31$ sec, and $\lambda = 0.5$ sec^{-1} according to the experiment.

Putting these value in equation (3), the resonance curve of every floor is got, which is shown in Fig. 3∼7. Every curve agrees well with the values of which show the experimental results.

The period of rocking oscillation T_0 is

$$T_0=2\pi\sqrt{\frac{I}{(p_0 i-Wh)g}}\,, \qquad \ldots\ldots\ldots\ldots\ldots\ldots(4)$$

and p_0 results in from equation (4)

$$p_0=\frac{I}{ig}\left(\frac{2\pi}{T_0}\right)^2+\frac{Wh}{i}. \qquad \ldots\ldots\ldots\ldots\ldots\ldots(5)$$

Now let us assume that the side of the buried part (l) of the building and the half of the base surface act as resisting surface. t and b represent the width in the beam direction and in the girder direction of the building respectively. Then the geometrical moment of inertia i becomes

$$i=\frac{bt^3}{24}+\frac{bt^3}{8}\left\{\frac{\sin\varphi}{2\cos^2\varphi}+\frac{1}{4}\log\left(\frac{1+\sin\varphi}{1-\sin\varphi}\right)\right\} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(6)$$

where

$$\varphi=\tan^{-1}\left(\frac{l}{t/2}\right). \qquad \ldots\ldots\ldots\ldots\ldots\ldots(7)$$

The first and the second term on the right side of equations (6) denote the geometrical moment of inertia at the base surface and the side surface respectively. Putting $b=1040$, $t=440$, $l=200$ into equations (6) and (7), we have

$$i=16.4\times10^9\,\mathrm{cm}^4. \qquad \ldots\ldots\ldots\ldots\ldots\ldots(8)$$

Next, we put this value of i and the values calculated from Table I, that is, $I=3.8\times10^{14}$ grcm^2, $W=4.9\times10^8$ gr and $h=750$ cm, and $T_0=0.31$ sec which was obtained from experiment, into equation (5). Then p_0, the pressure corresponding to unit depression of ground is

$$p_0=9.5\times10^3\,\mathrm{gr/cm}^3. \qquad \ldots\ldots\ldots\ldots\ldots\ldots(5')$$

This value is almost equal to p_0 of Loam layer, $4.8\times10^3\sim9.6\times10^3$ gr/cm^3.[2)]

From these two examinations into the values of resonance curve and the pressure corresponding to the unit depression of ground, the vibration in the beam direction in this experiment was found to be an almost perfect rocking oscillation.

The experiment concerning the oscillation in the girder direction has not produced satisfactory results due to imperfection in the instal-

2) K. SUYEHIRO, "The Vibration of Structures and a Method of Measuring It", *Journ. Archit. Inst. Japan,* **40** (1926), 531, (in Japanese), *Tech. Papers A. Inokuty* (1928), *Memor. Lect.*, 138,

lation of the vibrator, but we shall at present make a brief examination taking into consideration the amplitude only.

Assuming that the columns are clamped completely to the base and the beam, that the masses of vertical members are concentrated at each floor and that the columns of each story have equal stiffness, height and concentrated mass, we made the calculation regarding the four storied building. Then the displacement distribution becomes as is shown by the lower curve in Fig. 8 which fairly coincides with the experimental results denoted by $\times$ marks.

If it is taken into consideration that the floor height of the first story is larger and the mass of roof floor smaller than those of the other stories, the result concerning the first floor have a tendency to be more and the result concerning the roof floor to be less. Therefore the results almost coincide with bending oscillation form of concentrated mass under clamped condition.

Thus, from the result of theoretical analysis of the vibration in both the beam and the girder directions, we found that if the effective resistance in the contact surface of building and ground is small as in case of the beam direction, it produces rocking oscillation, and if the effective resistance is as large as in the case of the girder direction, it is near to a bending oscillation with fixed base.

The condition to overturn a rigid structure with basement by vibration is complicated. For the simplest case, we take the worst condition for a building, that is the state of resonance, to seek the condition under which the vertical line through the centre of gravity of the building comes off the base surface.

If a represents the horizontal acceleration of earthquake, θ becomes

$$\theta = \tan^{-1}\frac{t}{H} = \frac{ahT_0M}{4\pi I\lambda} \qquad \text{(9)}$$

and putting the constants of building and measured value into this equation, we have

$$a = 5.9\times 10^3\ \text{cm/sec}^2 . \qquad \text{(10)}$$

Namely, even in the case of resonance condition where the basement is of no use in preventing the building from overturning, an acceleration more than ten times larger than that of actual great earthquake is neccessary for the overturning of this building. Therefore, we can induce from the experiments that there is no possibility of an earthquake large enough to overturn this building.

5. Conclusion.

From the experiments above stated, it was made clear that rigid structures on soft ground is very capable of rocking oscillation. As the damping at basement in case of rocking oscillation is larger than damping due to solid viscosity etc., in case of elastic oscillation, if there is even a little rocking property in vibration, it is proof of so much aseismaticity of the building.

Considering the character of oscillation induced from these experiments as well as the improvement of the tendency that the vibration energy of building dissipates to the ground again transforming itself into the elastic waves as the rigidity of the building becomes larger in comparison with that of the ground, we find that the softer the ground on which rigid structure stands is, the less serious its damage by earthquake is. This coincides with the data obtained from the exploration of damaged districts.[3]

However, there are pretty many cases of earthquake damage due to inequal sinking of building base on soft ground, against which caution must be taken in designing and executing.

In conclusion, the writers wish to express their hearty thanks to Mr. M. Tachikawa and Prof. H. Tsuya for the greatest help to this experiment and they are also indebted to Messrs. T. Suzuki and S. Kaneko for their kind assistance throughout the progress of this experiment.

---

3) K. KANAI, "Relation between the Earthquake Damage of Non-wooden Buildings and the Nature of the Ground", *Bull. Earthq. Res. Inst.*, **27** (1949), 97, **29** (1951), 209.

59. 實在鐵筋コンクリート建物の振動實驗結果

地震研究所 { 金井 清
田中貞二

建物の耐震性を調べる方法として，近年，遠心力を利用する起振機が盛に使われ，起振機の改良や測定方法の研究が次々に行われてきた。

本報告の實驗は，起振機を使つて，實在の鐵筋コンクリート建物の振動實驗を行つた，おそらく最初のものであるから，今日からみると，いろいろ不備なところが，めだつようである。

實驗建物は，東京都中央區木挽町にある 4.4×11.6 m の 4 階建の燒ビルで，構造が簡單なので，實驗結果を數理的に吟味するのに適している。

實驗結果から，軟弱地盤上の剛構造物は地震のときに動搖振動をする可能性が多いことが，一層明かになつた。この性質は，地震のときに建物の振動勢力が逸散波として地中に再び出てゆく性質とあいまつて，構造物の振動減衰性を增すことに役にたつ。從つて，構造物は軟弱地盤上の方が耐震的に有利なことになり，關東地震のときの非木造建物の震災調査の結果と合うことになる。

たゞし，軟弱地盤上では，地震中に，基礎の不同沈下をおこす可能性が相當にあり，そのため思はぬ災害を受けた實例も少くない。この點は設計ならびに施工上で十分に注意を要するところであろう。なお，土の單位壓下に要する壓力として，9.5×10^3 gr/cm²/cm という値が得られたが，この値は，かつて，末廣博士が推定した値に一致する。