57. *Experimental Investigation of Lateral Earth Pressure during Earthquakes.*

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I. Introduction.

The previous experiment[1] with a shaking box, 1·33×1·33×2·74 m. in size and 8 tons in weight, proved that the max. lateral earth pressure against a wall during earthquakes may be calculated practically by applying common static earth pressure theories assuming g_e acts upon the back filling for this case instead of g for static case, both in its magnitude and direction. Here g_e represents the resulting acceleration of g, i.e. the acceleration of gravity, and the max. seismic acceleration.

But in the course of that experiment some unknown phenomenon were observed and they are traced here by more precise observations with a smaller swinging box, 0·40×0·43×1·10 m. in size and 560 kg. in weight, measuring the pressure against walls of 0·40×0·30 m. and several different sizes. The earth used was dry sand and the box was subjected to horizontal vibrations only.

II. Arrangements for Experiment.

Swinging Box. The box, filled with sand in the space 40×43×110 cm., is suspended from a rigid steel frame by 4 strips of steel and the frame is supported with 2 solid concrete piers (Fig. 1 and Pl. XCVII (1)). Thus it is given horizontal vibration parallel to the figure and the pressures against the walls are measured with piezo-electric pressure gauges. The frame of the box is made of steel angles and plates, the 2 longitudinal sides are of glass plates, so as the interior be observed from outside. Free test walls, made of boards, are set vertically on both ends of the box, the widths of which are 40 cm. at one end and 20 cm.

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1) *Proc. of the World Engineering Congress*, Tokyo, 1929, Paper No. 388; *Public Works*, Part 1.

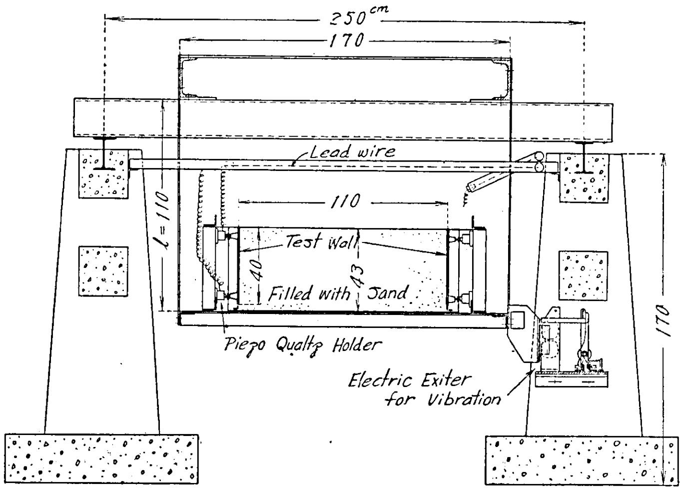

Fig. 1. Test box with the supports.

at the other. The period of vibration of the box is between 0·5∼2·0 sec. and is controlled with the steel strips changing the section between 3×3/16″ and 3 3/4×7/16″. The maximum horizontal acceleration of the horizontal vibration is about 3000 mm/sec/sec. or nearly 0·3 by the earthquake scale. Here the earthquake scale represents the ratio of the max. acceleration of vibration to the acceleration of gravity. The vibration most frequently adopted here is as follows; period $T=0{\cdot}88$ sec., max. amplitude 5·75 cm., the earthquake scale k_h being 0·3. The vibration for the box is given sometimes by hand and sometimes by electromagnetic action.

The weight of the box with sand is 560 kg.

Test Walls. The height of the walls are between 10 cm. and 40 cm. and Fig. 2 shows an example of the wall of which tests are made most frequently. According to the figure the wall is supported horizontally with A and B and vertically C and D. For the measurement of the deflection of the wall, strain dial gauges graduated 0·01 mm. are arranged at points 1∼9 and 10 in Fig. 2. (See also Pl. XCVII (2)). As it was necessary in the course of the experiment, to

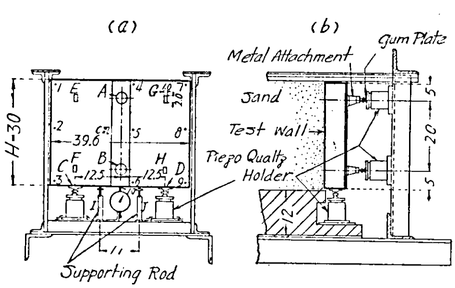

Fig. 2. Test wall installed for measurement.

support the wall besides the pressure gauges, 4 rods are arranged before the wall and 2 under it. The lengths of the rods are adjustable with the screws threaded on them. (Pl. XCVII (3)).

The experiments are made both with *solid* and *elastic* horizontal supports. Under the *solid supports* the metal attachments to the wall at A and B (Fig. 2) directly contact the steel piezo qualtz holders and under the *elastic supports* gum plates are inserted between the attachments and the holders so as the wall may yield against the holders during the vibration.

The reason why the wall was made of wood is that its section has relatively large moments of inertia as compared with its weight. The weight W of the wall was between 1·3～4·4 kg. varying with its thickness. The modulus of elasticity of the wood parallel to the grain is 90·3 t/cm². and crosswise 5·8 t/cm². and the wood of the wall was used grains horizontal. The effect on the horizontal pressure due to the mass of the wall during the vibration is $k_h W$, and the vibration of the earth pressure is determined by subtracting $k_h W$ from the horizontal pressure measured.

Pressure Gauges. The dynamometers with steel springs or oils are not appropriate for the measurement of the pressure which varies with small periods, and here the piezo-electric pressure gauges are adopted. The electric charges exhibited at the sides of the qualtz plates when subjected to pressures are measured by delicate string electrometers. The displacement of the string is magnified by the telescope and its image is taken in a photographic plate. Two electrometers are used and the pressures on the support A and B or C and D are measured simultaneously.

Effect of Side Walls. Various arrangements to eliminate the effect of the side walls were made by previous conductors of the tests on the lateral earth pressure, but as much as the authors are aware they seems not satisfactory. According to the tests made by G. H. Darwin[2] the effect of the side walls on the lateral pressure is rather small amounting only to 3%, and therefore no arrangement for that was made here. With the tests during the vibration, the pressure was much affected by other conditions described later and the effect of the side walls seems rather small as compared with that.

2) On the horizontal thrust of a mass of sand, *Min. of Proc. of the Inst. of C. E.*, **71** (1882-3), 350.

III. Physical Properties of the Sand.

The sand was taken from the neighbouring river bed, washed thoroughly, removed large grains by the mesh having the clear distance of 0·5 mm., and finally was dried in an oven. A mechanical analysis is as follows,

Sieve number	20	30	40	50	80	100	200
Clear distances of the mesh (mm.)	0·85	0·50	0·36	0·29	0·17	0·14	0·074
Percentage passed	0·2	0·8	7·2	72·8	10·4	7·9	0·7

The mean diameter of the sand is 0·225 mm., the specific gravity 2·70, the unit weight between 1·25~1·48 kg/l., and the percentage of voids between 53·7~45·2%. The sand was filled into the test box by gravity from another box, the base of which was 1 m. above the top of the test box, through a hose 2·2 cm. diameter. Under the condition tested the unit weight was 1·29 kg/l. and the percentage of void 52·3%.

The result of the measurement of the internal co-efficient of friction of the sand was as follows:

$$p = 0{\cdot}56\, w + 0{\cdot}00159,$$

where p horizontal shear on the unit area in kg/cm². and w unit vertical pressure. Under the condition tested the angle of internal friction was $\varphi = 32°40'$. The co-efficient of friction of the sand against the wall was measured in the same way:

$$p = 0{\cdot}557\, w + 0{\cdot}00037,$$

$$\varphi_0 \fallingdotseq 30°.$$

Angle of natural slope was between 31°30′~34°30′, varying with the packing of the sand, and the condition under which the test was carried out was rather nearer to the former.

IV. Lateral Static Pressure against a Vertical Wall.

Several laboratory tests of the static pressure against a wall gave quite satisfactory results,[3] and at first it seemed not necessary to measure the *static* pressure. But in the course of our experiment, remarkable difference between the static pressures before and after the vibration was observed and it became necessary to measure them.

Method of measurement. The box is first made empty and the test wall is carefully set vertically on the supports C and D so as the face of the wall is perpendicular to the direction of vibration. The pieces

3) Among these we remenber with full respect the test made by Mr. J. Feld, *Proc. of Am. S. C. E*, (1923), 615-660.

of the attachments on the wall to transmit the horizontal pressure to the wall at A and B are so adjusted as they are just in contact with the piezo holders when the wall is vertical. (Fig. 2). Narrow strips of cloth are provided at the ends of the wall to prevent the escape of sand, and the box is filled in horizontal layers as described in the preceding article. The time necessary to finish the filling is about 5 minutes. Then the two electrometers are first connected to the piezo qualtz holders at C and D, and the two vertical supporting rods I and J (Fig. 2) are screwed off alternately, so as they are just in contact with the wall. Observing carefully the strings of the electrometers we can distinguish whether the rods touch the wall or not. Then the adjusting pieces against the holders are screwed in and the pressure against the wall is transmitted to the rods. Thus the pressure is observed by the minus readings of the electrometers. After the measurement of C and D the readings at A and B are taken simultaneously in the same way. The pressure measured immediately after the filling is called *the pressure before the vibration* and that after it *the pressure after the vibration*. The vibration was as follows:

Period $T=0{\cdot}88$ sec.; amplitude (half) $r=5{\cdot}75$ cm., this corresponds $k_h=0{\cdot}3$ by the earthquake scale (§ II); time of the vibration about 2 m.

Tests were made both with *solid* and *elastic* horizontal supports (§ II), the vertical supports at C and D being always *solid*. For elastic supports the diameter of the gum plates were always 20 mm. The walls used and the thicknesses of gum plates were as follows:

Test No.	Test wall		Thickness of the gum plates at the supports.	
	Dimension $b\times h\times d$ (cm.)	Weight (kg.)	A (mm.)	B (mm.)
No. 4	39·6×30×6	3·63	solid	solid
„ 20	„	„	4	0·8
„ 21	„	„	8	1·6
„ 34	„	„	16	3·2
„ 23	39·6×30×1·5	1·36	4	0·8
„ 24	„	„	8	1·6
„ 25	„	„	16	3·2

Lateral Static Pressure. From the readings at C and *D* the weight of the wall was excluded and togather with the readings at A and B the pressure was expressed by the co-efficients of earth pressure. The notations are

C_{oh}=co-efficient of the horizontal component; i.e., the sum of readings at A and B is divided by $\frac{1}{2}wH^2b$, where

w=unit weight of the sand 1·29 kg/l.

H=height of the wall; 30 cm.

b=width of the wall; 40 cm.

C_{ov}=co-efficient of the vertical component; i.e., the weight of the wall is subtracted from the sum of the readings at C and D and this is divided by $\frac{1}{2}wH^2b$.

C_o=co-efficient of the resultant.

$\tan\delta = C_{ov}/C_{oh}$

h_c=height of the point of application measured from the base of the wall.

$$M_{oh} = C_{oh} \times \frac{h_c}{H}$$

Pressures before the vibration measured are as follows:

Test No.	C_{oh}	h_c/H	M_{oh}	C_{ov}	C_o	C_{ov}/C_{oh}	δ
4	0 276	0·397	0·1095	0·142	0·310	0·514	27°10′
20	0·242	0·337	0·0816	0·145	0·282	0·601	31° 0′
21	0·254	0·337	0·0856	0·154	0·296	0·605	31°10′
34	0·246	0·377	0·0927	—	—	—	—
23	0·278	0·374	0·1040	0·127	0·305	0·455	34°30′
24	0·248	0·310	0·0770	0·146	0·289	0·590	30°30′
25	0·243	0·400	0·0971	0·149	0·285	0·613	31°30′
Mean	0·255	0·362	0·0925	0·144	0·295	0·563	29°20′

After the vibration these values are

Test No.	C_{oh}	h_c/H	M_{oh}	C_{ov}	C_o	C_{ov}/C_{oh}	δ
4	0·362	0·294	0·1064	0·128	0·382	0·354	19°30′
20	0·336	0·370	0·1240	0·132	0·361	0·394	21°30′
21	0·354	0·354	0·1252	0·124	0·374	0·350	19°15′
34	0·332	0·370	0·1242	0·149	0·368	0·445	24° 0′
23	0·334	0·370	0.1235	0·090	0·346	0·270	15°10′
24	0 334	0·357	0·1190	0·127	0·357	0 380	20°50′
25	0·382	0·410	0·1565	0·114	0·399	0·298	16°30′
Mean	0·348	0·361	0 1256	0·124	0·370	0·356	19°35′

The results extend pretty wide range and the values of the solid supports can not be distinguished from those of the elastic supports, yet there is remarkable difference between those before and after the vibration.

The ratios of the mean values of the two cases are:

	C_{oh}	C_{ov}	C_o	$\tan\delta$
Ratio = (After)/(Before)	1·36	0·86	1·25	0·63

The most remarkable difference is the increase of the horizontal component and the decrease of the angle δ. (Fig. 3).

This is considered that during the vibration the sand settles down and some passive pressure occurs against the wall. The values of the active pressure calculated with the wedge theory for this case, $\varphi=32°40'$ $\varphi_0=\delta=30°$, are

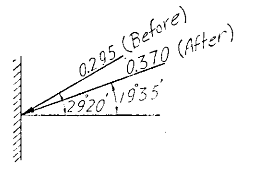

Fig. 3. Static pressures before and after the vibration.

$$C_{oh}=0{\cdot}234,\quad C_{ov}=0{\cdot}135,\quad C_o=0{\cdot}270,\quad \delta=30°,$$

these approximating the values before the vibration.

V. Variation of Lateral Pressure at the Beginning of Vibration.

After the test wall is set vertically, supported by A, B, C, and D, and filled with sand as described in § III, the box is given horizontal vibrations and records of the pressure variation are taken on the photographic plates. Two electrometers are used and the records at A and B or C and D are taken simultaneously.

As the pressure variation at the beginning differed much from that after several minutes vibration, the two cases are discussed separately, here the former and in the next paragraph the latter.

The pressure variation also differed with the condition of horizontal supports, i.e. between the solid and the elastic supports, they are also separately dealt with.

Elastic Horizontal Supports. With the elastic supports the thicknesses of the gum plates are so arranged as the wall may yield during the vibration around the back base line as shown in Fig. 4.

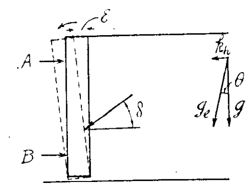

Fig. 4. Yielding of wall under elastic supports.

According to Fig. 5 which shows a typical record of the pressure at the beginning of the vibration, the mean value of the horizontal pressure increases gradually besides the periodical

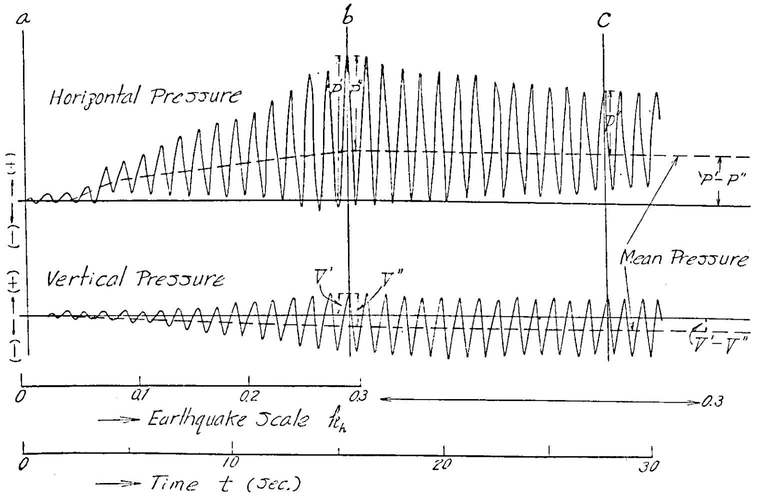

Fig. 5. Typical record of pressure at the beginning of vibration.

variation of the pressure as the amplitude of the vibration increases (between *a* and *b* of the figure). Where the amplitude reaches its max., at *b* in the figure, the increasing tendency of the mean pressure almost stops and when the amplitude of vibration is kept constant after that, the amplitude of the pressure variations tends to decrease (between *b* and *c*).

The mean value of the vertical pressure tends somewhat to decrease (between *a* and *b*) and when the max. amplitude of vibration is reached (at *b*) the decreasing tendency stops and after that the same pressure variation is repeated (after *b*).

The test was made under the following conditions:

Dimensions of the wall; $b=39\cdot6$ cm., $h=30$ cm., $d=1\cdot5$ cm.
Weight, 1·36 kg.
Thickness of the gum plate at $A=8$ mm., at $B=1\cdot6$ mm.
Period of vibration $T=0\cdot88$ sec.; max. amplitude (half) $r=5\cdot75$ cm., this corresponds $k_h=0\cdot3$.

For each test the following series of vibrations were given:

Series (1). The amplitude is made gradually large untill it becomes $k_h=0\cdot3$; this vibration is kept about 5 seconds and then gradually retarded and stopped.

Series (2). The same series of vibrations as (1) are repeated after the series (1).

Series (3). If necessary, the same vibrations again repeated after the series (2). Records of horizontal pressure of series (1) and (2) are shown in (4) and (5) of Plate XCVIII.

A result of the tests on the horizontal component of pressure is given in Fig. 6. For each series, the readings P' and P'' are taken at $k_h = 0{\cdot}1$, $0{\cdot}2$ and $0{\cdot}3$ and are denoted as $P_{(1)}'$, $P_{(1)}''$, $P_{(2)}''$, $P_{(3)}''$ and so on ; the number in the brackets represents that of the series. Here

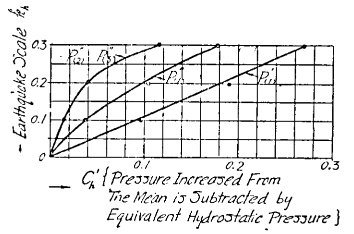

Fig. 6. Variation of horizontal pressure at the beginning of vibration under elastic supports.

P' = the increase of the instantaneous max. from the zero reading at the beginning of the vibration,

P'' = the increase of the instantaneous max. from the mean reading at that time, here the mean reading represents the reading which will be indicated when the vibration is stopped at that instant.

The readings of P' and P'' are remarkably different on series (1) but on (2) and (3) they differ but little and for these P'' only is taken. The effect of the wall to the horizontal pressure is $k_h W$, W being the weight of the wall, and this is subtracted from the readings and they are represented by the co-efficient of earth pressure C_h'.

The increase of the mean horizontal pressure during the vibration which is represented by $P_{(1)}' - P_{(1)}''$ in the figure is little influenced by the condition of supports and the mean values of 5 tests both of elastic and solid supports are

$k_h = 0{\cdot}1$	$0{\cdot}2$	$0{\cdot}3$
$C_h = 0{\cdot}038$	$0{\cdot}076$	$0{\cdot}106$

The difference of P'' at a and b (Fig. 5) is here represented (Fig. 6) by $P_{(1)}'' - P_{(2)}''$ or $P_{(1)}'' - P_{(3)}''$ and the max. values are

$k_h = 0{\cdot}1$	$0{\cdot}2$	$0{\cdot}3$
$C_h = 0{\cdot}04$	$0{\cdot}06$	$0{\cdot}08$

From the record of the vertical pressure the decrease of the mean vertical pressure is measured as

$k_h = 0{\cdot}1$	$0{\cdot}2$	$0{\cdot}3$
$C_v = 0{\cdot}007$	$0{\cdot}014$	$0{\cdot}020$

and as for the vertical components there is little difference between $P_{(1)}''$ and $P_{(2)}''$.

Solid Horizontal Supports. Tests were also made by the solid horizontal supports, the other conditions being exactly the same as the former case, and the results for the horizontal pressures are shown in Fig. 7.

As was already related the amount of increase of the mean horizontal pressure are aproximately the same as the former case, and the max. values of the differences between $P_{(1)}''$ and $P_{(2)}''$ in this case are as follows,

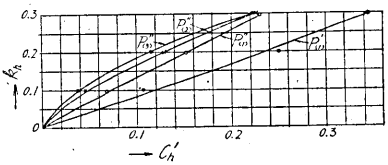

Fig. 7. Variation of horizontal pressure at the beginning of vibration under solid supports.

$k_h=0{\cdot}1$	$0{\cdot}2$	$0{\cdot}3$
$C_h=0{\cdot}035$	$0{\cdot}050$	$0{\cdot}020$

Effect of Tamping. The increase of the mean horizontal pressure at the beginning of vibration is considered to be due to the settling of the back filling, and this increase is expected to disappear when tamping of the back filling is made. Tests were made under the condition and a result is shown in Fig. 8.

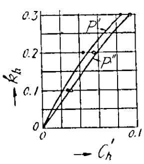

Fig. 8. Variation of horizontal pressure when tamping was made.

The tamping was made by falling an iron weight covering an area 10×10 cm. (weight 2·1 kg.) on the sand surface from the height of 10 cm. at every 2·5 cm. layer and one fall for every 10×10 cm. area of sand surface. According to the figure, the increasing tendency of the mean horizontal pressure disappears and the tamping seems very effective. But the absolute max. pressure against the wall is the sum of P' and the initial static pressure. This test shows that the sum of this case is larger than that when tamping was not made and from this point of view tamping seems not always effective. The most effective *ideal tamping* is that the back filling is tamped to that degree of packing that it is brought when the filling undergoes the earthquake assumed. For structures, even most careful tamping seems to be within this ideal state and it seems not necessary to guard against too much tamping.

VI. Variation of Lateral Pressure under Stable Condition.

After several minutes vibration, the mean pressure becomes constant and the same variation is repeated under the same amplitude of vibration. Under this condition, the relation of the deformation of the wall to the difference between the max. and the mean of the pressure was investigated. Dimensions of test walls are breadth $b=39{\cdot}6$ cm., heights $h=40$ cm., 30 cm. and 20 cm., thicknesses $t=6{\cdot}0$ cm., $3{\cdot}0$ cm. and $1{\cdot}5$ cm.

Solid Horizontal Supports. An example of the results of tests is shown in Fig. 9. Fig. 10 shows the relation of C_h' or M_h' to $\varepsilon_{max.}$ or $\varepsilon_{max.}/H$ for $k_h=0{\cdot}3$.

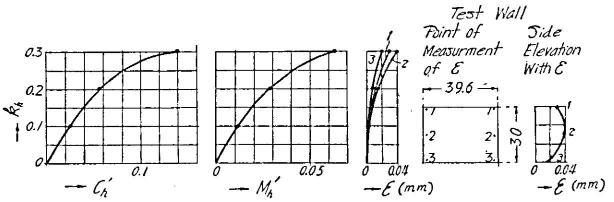

Fig. 9. An example of the results of tests under stable condition. (Solid supports; $b=39.6$, $h=30$, $t=1.5$ cm)

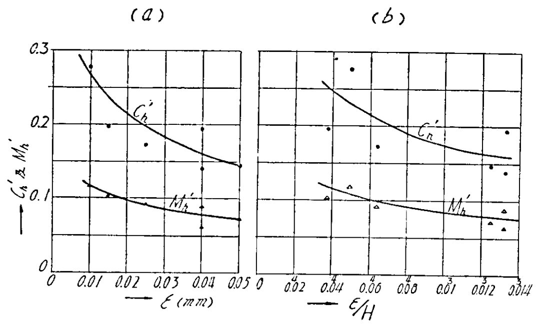

Fig. 10. Relation between ε and C_h' etc. under stable condition. (Solid supports; $k_h=0.3$)

The larger $\varepsilon_{max.}$ or $\varepsilon_{max.}/H$, the smaller C_h' or M_h' becomes. The means of all measured values are as follows,

k_h	C_h'	C_v'
0·1	0·034	0·012
0·2	0·093	0·023
0·3	0·195	0·037

The relations between these values and the static pressures are to be discussed in § VII.

Elastic Horizontal Supports. Tests were made under the arrangement that the wall may yield as shown in Fig. 4, and the readings were taken as shown in Fig. 11. The relations $\varepsilon_{max.}$ and $\varepsilon_{max.}/H$ to C_h' and M_h' for each tests corresponding $k_h=0{\cdot}3$ are plotted in Fig. 12. As a special case of this, the results of solid supports are also plotted in

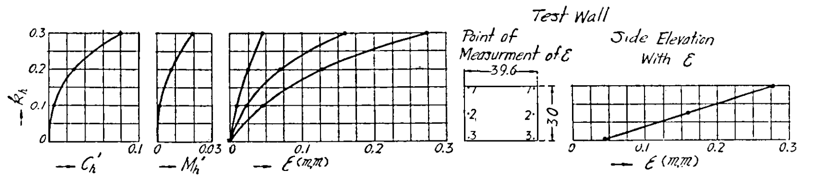

Fig. 11. An example of the results of tests under stable condition. (Elastic supports)

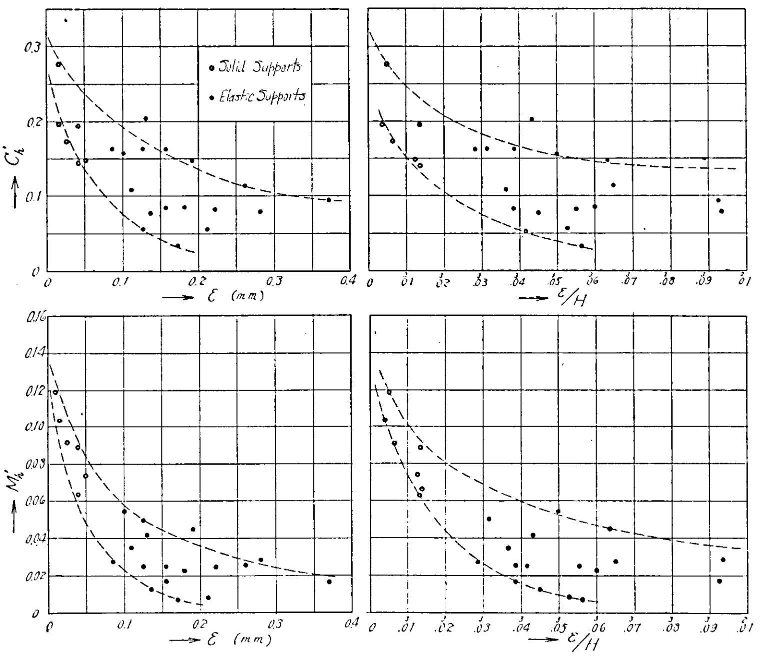

Fig. 12. Relation between ε and C_h' etc. under stable condition. (Solid and Elastic supports)

the same figure. According to the figure the results may be said to be involved between the two dotted curves which descend with the increase of $\varepsilon_{max.}$ or $\varepsilon_{max.}/H$. Discontinuity seems to exist near $\varepsilon = 0{\cdot}2$ mm. and this to be related with the size of the sand particles. With the amount of yielding less than the diameter of the particles the stability is retained without settling down of the particles but beyond that this is impossible. Dr. Terzaghi relates[4] concluding his experiment on static earth pressure that the min. co-efficient of earth pressure is obtained when $\varepsilon_{max.}/H = 0{\cdot}001$. This, however, seems not to be determined independently with the size

4) *Engineering*, May 30, 1930.

of the earth particles. With the sand used here, it is expected that the min. static pressure is exhibited when $\varepsilon_{max.}/H=0{\cdot}0006$ or thereabouts.

With the test of seismic earth pressure one point only for one k_h is obtainable and not the chain of the results as with static pressure.

The mean values of the 5 tests, in which both horizontal and vertical components were taken, are

k_h'	C_h'	C_v'
0·1	0·008	0·029
0·2	0·026	0·068
0·3	0·071	0·118

Pressure Distribution. With this test the wall was cut to parts of 10 cm. height and horizontal pressures against each horizontal strips were measured at the centre of each strips. Each strip of the wall was hanged from the frame by 2 fine steel wires and the horizontal pressure was transmitted to the piezo qualtz holder by the centre pin. The test was made under solid supports only and a result for $k_h=0{\cdot}3$ is as follows:

Height of strips (cm),	40∼30,	30∼20,	20∼10,	10∼0.	
Net horizontal earth pressure increased from the static pressure at $k_h=0{\cdot}3$; $T=0{\cdot}855$ sec; $r=5{\cdot}45$ cm. (kg).	2·42	2·62	2·02	1·82	$\sum=8{\cdot}88$

The deformation ε for the case is very small and for $k_h=0{\cdot}3$, $\varepsilon \fallingdotseq 0{\cdot}005$ mm. The height of the point of application of the pressure is $h_c=24{\cdot}9$ cm. or $h_c/H=0{\cdot}622$. Under elastic supports the point of application is quite different but we are sorry that the observation of this condition could not be carried out for the sake of the difficulty of arrangements. For the latter case it is calculated from the results of tests of the preceding article $h_c/H=1/3$ or less.

Special Horizontal Supports. Effect on the pressure due to small differences of displacements of the parts of the wall was observed. Pressures against the test walls of 10 cm. height of different depths were

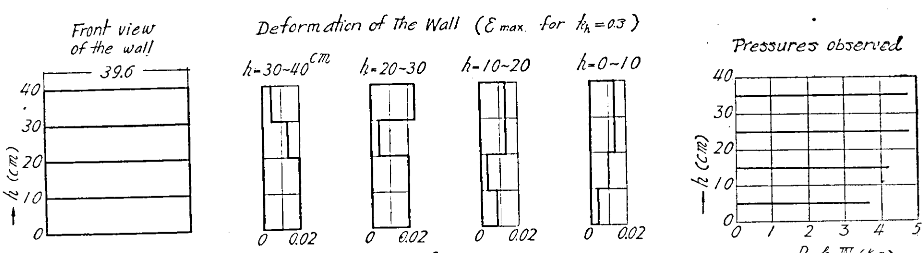

Fig. 13. Result of tests under partial yielding of the wall.

observed by allowing less displacement of the wall than the adjacent parts. Results of 4 tests are given in Fig. 13. For the part measured $\varepsilon \fallingdotseq 0{\cdot}005$ mm. where for the adjacent part $\varepsilon = 0{\cdot}01 \sim 0{\cdot}02$ mm. when $k_h = 0{\cdot}3$. Total sum of the pressures increased from the means for 4 different parts is 17·3kg. where the corresponding value of the preceding paragraph is 8·8 kg. This shows that the pressure is much influenced by the displacement of the adjacent walls and that the solid wall undergoes larger lateral pressure than the adjacent elastic walls.

Effect of Depth of Back Filling. To testify the effect of the depth d (Fig. 14a) of the back filling, the increase of the lateral pressure for $k_h = 0{\cdot}3$ was observed for

$d = 12,\ 20,\ 110$ cm. $\qquad H = 10,\ 20,\ 30,\ 40$ cm.

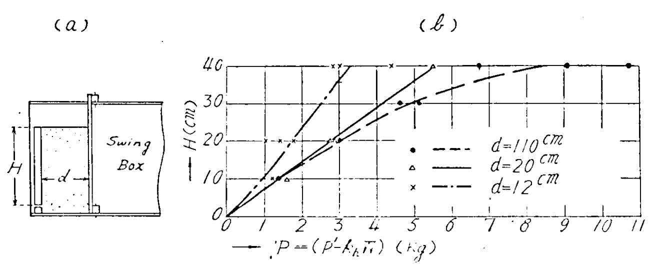

Fig. 14. Effect of d on the pressure.

and the results are given in Fig. 14b. For $H = 40$ cm. effect on P of 3 different values of d can be observed, for $H = 20$ cm. the difference between $d = 20$ and 12 cm. can be observed but that between $d = 110$ cm. and 20 cm. can not, and finally for $H = 10$ cm. effect of d can little be observed. The angle of rupture is calculated for this case $\varphi = 32°40'$, $\varphi_0 = 30°$, $\gamma = 37°$ or $\cot\gamma = 1{\cdot}33$ when $k_h = 0{\cdot}3$ and the result of tests coincides with the theoretical conclusion that the back filling outside the plane of rupture does not effect the lateral pressure. The pressure measured for different height of the wall is not proportional to the square of the height and this is considered due to the effect of the lateral displacement of the wall during the vibration.

VII. Summay of Tests.

Results of Tests. Results of tests described in § V and VI can be summarized as follows.

1. Mean horizontal pressure increases with the increase of the amplitude of vibration, and mean vertical pressure somewhat decreases.

2. The increase or decrease of the mean pressure during the vibration remains as it is after vibration.

3. Taking the vibration of a certain k_h, the difference between the instantaneous max. and the mean of the horizontal pressure at the beginning is larger than that after several minutes vibration; the difference of the vertical pressures remains always constant for the same k_h.

4. The difference between the mean and the instantaneous min. of the horizontal pressure is almost 75% of the difference between the max. and the mean (see Pl. XCVIII (6)), where for the vertical pressure the two differences are always the same. The instantaneous max. and min. together with the mean pressure, viz. the static pressure, are shown in Fig. 15; in which values under elastic supports (I), solid supports (II),

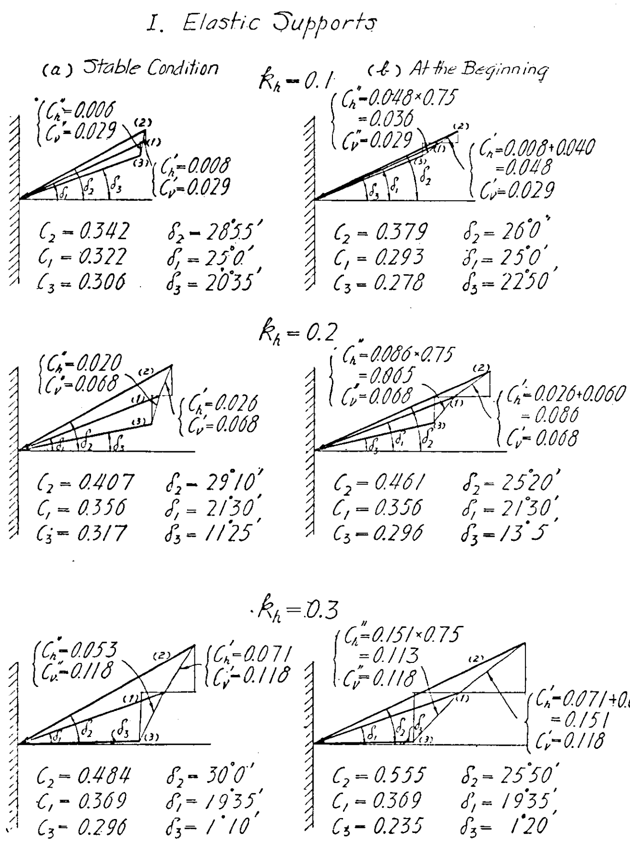

Fig. 15-I. Variation of earth pressure against a vertical wall during vibration.

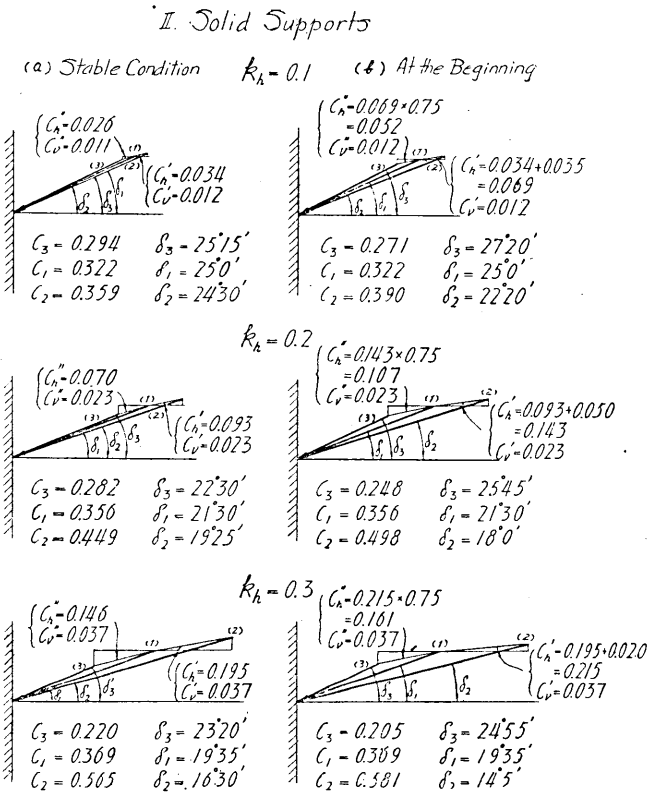

Fig. 15-II. Variation of earth pressure against a vertical wall during vibration.

and for each at the beginning (b), and after several minutes vibration (a) are given. These values are the means of several tests and not the exact values.

The pressure against the wall when the max. horizontal acceleration of vibration is directed towards the wall is shown as (2) in each figures and when directed against is (3) and the *mean pressure*, viz. the pressure which is expected when stopped at that instant, is shown as (1).

In general the structure is most dangerous under the condition (2) and for the design of earthquake-proof structures this state is considered.

Method of Calculation of Seismic Earth Pressure. A method of calculation for the design of the earthquake-proof structures was introduced by one of the authors[5] shortly after the Great Earthquake of

5) N. Mononobe, "On the Earth Pressure during Earthquake," *Journal of the Japanese Civil Engineering Society*, 10 (1924), No. 5, (in Japanese).

1923. He assumed that the resultant acceleration of earthquake and gravity acts for some time uppon the structure and the earth, and the stability is statically checked. For the calculation of the seismic earth pressure, the common wedge theory was applied taking the most dangerous direction of the resultant acceleration. Results of tests above mensioned are to be compared with the values of the calculation.

Comparison with the Results of Calculation. As was mentioned already the values shown in Fig. 15 are not exact ones, but for the present the max. of them, i.e. the values for (2) in Fig. 15, are compared with those of calculation.

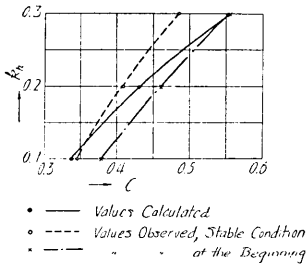

Fig. 16. Comparison of the values observed with calculated. (Elastic supports)

Under elastic supports the values of δ_1 are, according to Fig. 15-I, nearly equal to 30°—which is expected from the calculation—and therefore the little divergences of δ from 30° are neglected and the values C are compared in Fig. 16. At the beginning of vibration C is larger than the value due to calculation, especially when k_h is small, and after several minutes vibration C is smaller than that calculated, especially when k_h is large. The latter case also corresponds when *ideal tamping* is done and from this we can see the advantage of tamping. When the structure of gravity form or L shape is subjected to earthquake, the pressure against it is expected to have the tendency above mensioned rather than that next described.

For solid supports the observed values of δ are quite different and therefore the two components are shown separately in Fig. 17. In this

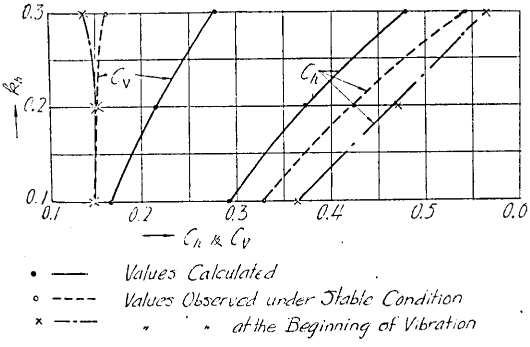

Fig. 17. Comparison of the values observed with calculated. (Solid supports)

case, contrary to the former case δ_2 is smaller than δ_3. This seems due to the different kind of deformation of the wall. Under the elastic supports the wall yields as shown in Fig. 18 (a) when subjected to the acceleration g_e—this causing max. δ—but under solid supports the wall yields as shown in Fig. 18 (b). According to Fig. 17 the horizontal components observed are larger than calculated. In general the amount of ε/H of the structure is expected to be larger than that of the test under solid supports, but if such amount of ε/H should occur in a solid structure, the pressure against it is expected to be larger than that calculated.

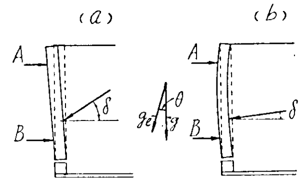

Fig. 18. Yielding of the wall under elastic supports (a) and solid supports (b).

VIII. Conclusions.

The pressure against a wall during vibration is influenced by many conditions such as,

1. The amount and manner of yielding of the wall,
2. Condition of the packing of the back filling,
3. Time of vibration and so on,

and, as a matter of course, the exact values of the pressure including these conditions can not be expressed in a simple formula. But concerning the max. pressure, results of tests deviate but little from the values calculated, except some special cases, and the authors would conclude that the values of the calculation may be taken as approximating the max. pressure against the wall during the vibration, so long as the exact values of the effects of the conditions are not determined by further experiments.

The conclusions drawn from the experiments are

1. Under the vibration of a certain k_h, structures are subjected to max. seismic lateral pressure at the beginning of the vibration. (§ V).

2. The lateral static pressure after vibration is larger than that before vibration and this is considered to be due to the passive pressure caused by *settling* of the filling. (§ IV and V)

3. For smaller k_h, the effect of the settling is large and for which the max. lateral pressure larger than calculated is measured. (§ VII)

4. Carefull tamping has the advantage to reduce the max. pressure at the beginning of vibration. (§ V).

5. The max. pressure against the structure, for which ideal tamping

of the back filling is carried out, is somewhat smaller than that calculated. (§ VII).

6. The max. pressure during the vibration is much effected by the deformation of the wall and solid walls undergo larger seismic earth pressure than elastic walls. (§ VI).

7. The earth outside the plane of rupture calculated does not effect the max. seismic pressure. (§ VI).

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57. 地震時土壓の實驗的研究

地震研究所 物部長穗
松尾春雄

地震時土砂が構造物壁面に及ぼす壓力變化の狀態を明かならしむる爲、振動函(寸法、內法 40×43×110 cm.)に乾燥せる砂を滿し之に水平振動を與へ、振動の方向に直角に支へたる垂直壁に作用する壓力の變化をピエゾ電氣壓力計にて記錄し、その時間的變化を研究した。試驗の結果を綜合すれば次の如くである。

1. 擁壁が地震を受くる場合、之に働く土壓力は最大震度に達したる初期に於て最大である。

2. 振動後に於ける靜止土壓力は、振動中の土砂の沈定の爲、振動前の靜止土壓力より大なる値を示す。

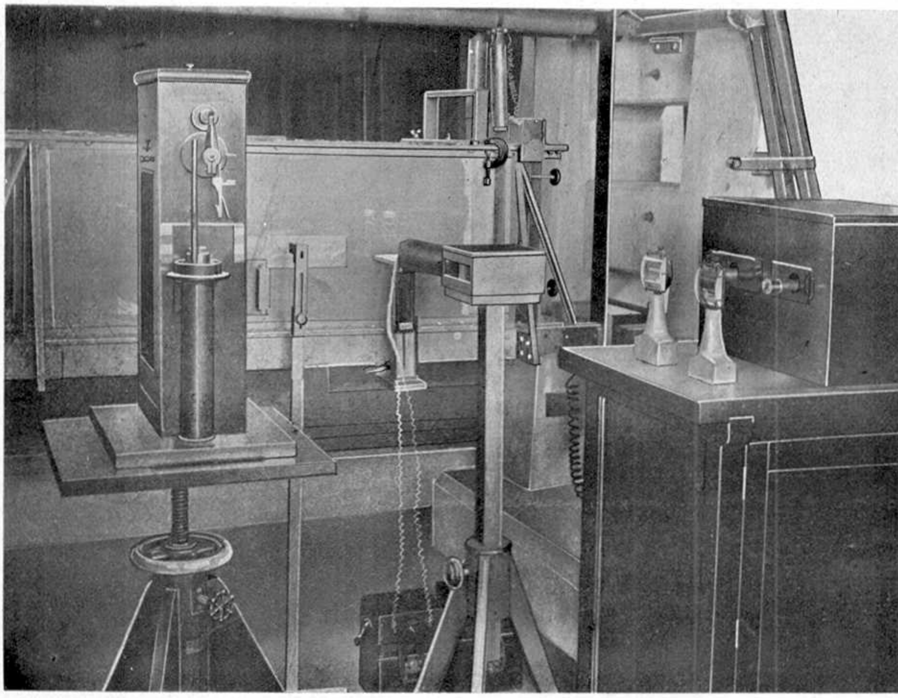
3. 土砂沈定の影響は震度が小なる時比較的大にして、振動中の最大壓力の測定値は、震度が小なる場合には計算値より一般に大である。

4. 裏込土砂の搗き固めを十分にする事は、振動初期の增加壓力を小にする效果がある。

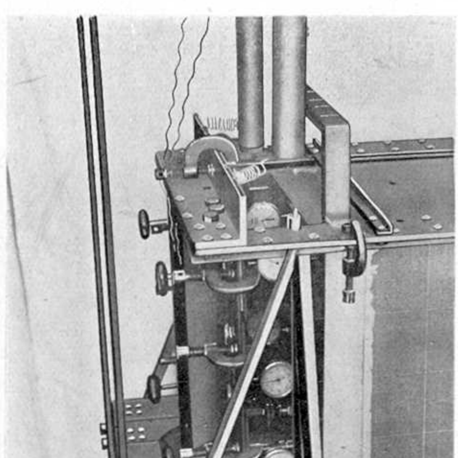
5. 「理想的の搗き固め」をなした場合に限り、地震時壓力は計算値より小である。

6. 振動中の最大土壓は壁の歪と大なる關係を有し、殆ど變形なき剛性壁には特に大なる地震時土壓が働く。

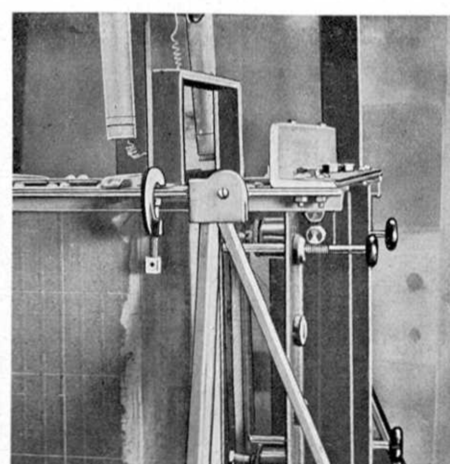
7. 計算せる地震時崩壞面より外方にある土砂は、最大土壓には影響を及ぼさない。



(1) Test box and measuring apparatus.



(2) Measuring apparatus of the deflection of the wall.



(3) Auxiliary supporting rods of the wall.

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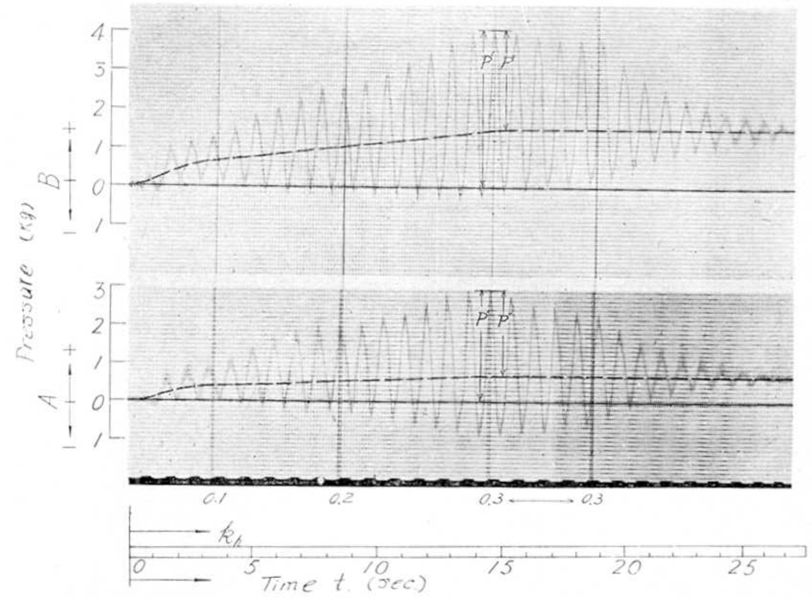
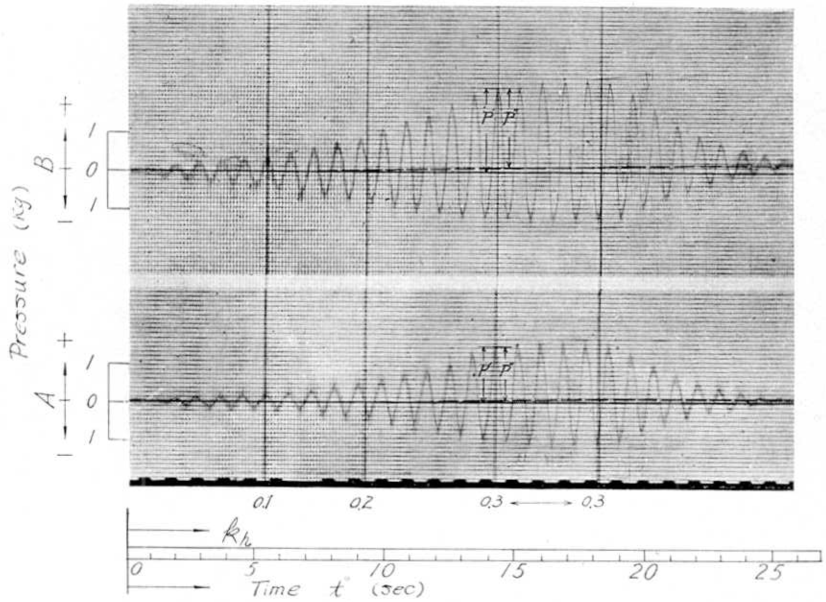
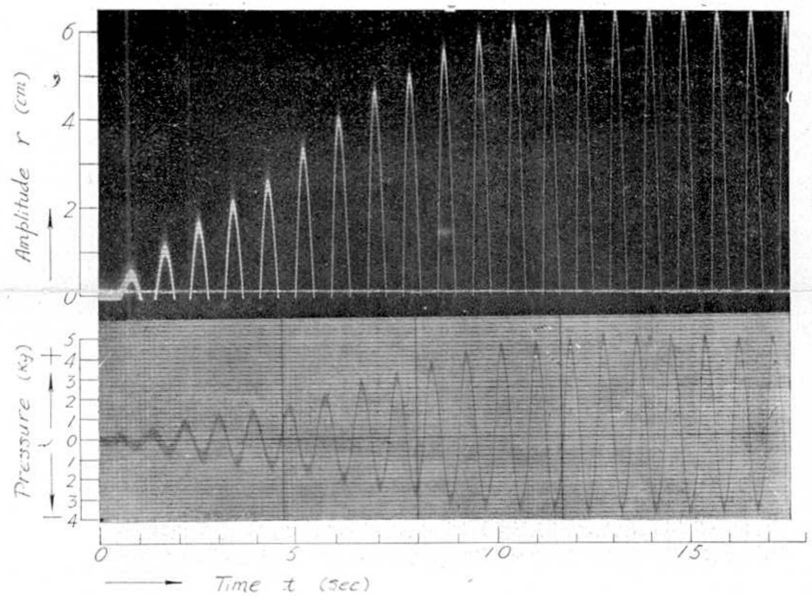


(4) Record of horizontal pressure at the beginning of vibration, Series (1)



(5) Record of horizontal pressure at the beginning of vibration, Series (2).



(6) Record of the vibration of the box and the horizontal pressure variation.

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