An Experimental Study
Of Oscillating Earth Pressures Acting On A Quay Wall

By
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§ 1. Introduction

When a test quay wall of gravity type was shaken with artificial earthquakes which were caused by a huge vibration generator, the earth pressures at the back and bottom surfaces of the wall were observed by a number of specially developed pressure cells, and also the vibration of the wall by two vibration pick-ups of moving coil type. The general arrangement of the experimental equipments is shown in Fig. 1.

The results, as they are, are rather complicated; Then was tried the reduction of the records into two component parts, one is translational, the other rotational, which gives us, quantitatively, a fairly clear image of the behaviour and interaction of the wall and the mass of soil.

As the earthquake generator, having two axes of unbalanced masses, can give stationary and sinusoidal vibrations, so the pressure cells are not necessarily required to measure the pressure continuously. This is why the author used pressure cells of "Farnboro indicator" type with some modifications, which can measure oscillatory pressures as well as static ones, and are really reliable even for several years and more being layed underground.

Many illustrations with some notes in the following pages may suffice, the author hopes, to bring the readers good understanding of the subject. The arrangement of contents is shown below.

§ 2. Earthquake Generator and Model Quay Wall

Two unbalanced axes, arranged in a horizontal plane and parallel to each other, rotate in either the same or the opposite direction using a single coupling gear or two in series. The generated oscillations, therefore, are vertical and horizontal combined, or purely vertical respectively. Fig. 2, and 3 show the earthquake generator.

Ratings of the generator:
Unbalanced Moment (total values of two axes) 0 ~ 240 kgm (variable)
Number of revolution 3 ~ 6 r.p.s.
Vibrating Force (at 6 r.p.s.) 35 tons
Horizontal acceleration measured on the upper edge of the concrete bowl is about 300 gals at 6 cycles per second.

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The model quay wall and the backfill surcharge are shown in Fig. 4, 5, and 6.

§ 3. Measuring Instruments (I) Earth pressure cell

The prototype of pressure cells is the air-balanced on-off indicating system originated by Goldbeck. This has been modified into an oscillating pressure measuring apparatus by introducing the principle of Farnboro's high speed pressure indicator for internal combustion engines, because pressure variations to be measured are stationary-not transient, as stated in the introduction. A dummy weight is to be so added to the opposite end of the pressure disc of the cell as to balance its inertia force, which inherently and inconveniently influences the measurements when the cell is vibrating with the mass of soil.

The details of the cell and the explanation of the recording apparatus and their photos are shown in Fig. 7, 8, 9, 10, 11, and 12.

§ 4. Measuring Instruments (II) Vibration pick-up (Displacement, Velocity, Acceleration)

The set consists of moving coil type transducers, integrators and differentiators, and a dual beam cathode-ray oscilloscope. The oscillogram gives, at a time, any combination of two out of six wave-forms, i.e. displacements, velocities and accelerations of two transducers, by choosing positions of two selection switches.

In Fig. 13 and 14 are shown the schematic and block diagrams of the assembly of these vibration measuring elements. Some photos are also shown. (Fig. 15 and 16)

§ 5. Results

Some of the direct records of both earth pressures and motions of the quay wall are reproduced in Fig. 17, 18, and 19. In these figures, the position of P.M. (Phase Mark) indicates the instant when just maximum is the horizontal exciting force towards the model quay wall of the earthquake generator. We obtained a number of series of pressure records like Fig. 19, by changing the revolution of the earthquake generator. Those records, after every necessary correction was completed, and arranged with all their phase marks brought into the same position, are shown in Fig. 20, 21, 22, 23, 24, and 25. When we read out, from these records, only the maximum and minimum values of pressures of every cell ignoring their phases, and plot the values against their sand depths, we get Fig. 26 which is for Fig. 23, Data No. 4. Similar graphs for other series are omitted here.

The fundamental components of oscillations, both of earth pressures and wall displacements were calculated by a digital relay computer FACOM 128A, one cycle being divided into 12 divisions. The results are shown in Fig. 27, 28, 29, 30, 31, and 32. In Fig. 33, amplitudes of the fundamental components thus obtained are plotted, irrespective of their phases.

As the fundamental components are of course always quite predominant, we will discuss here-after only with them.

§ 6. Reduction of the fundamental oscillations into two components, translational and rotational around the centre of gravity of the wall

In the foregoing six plates (Fig. 27~32), all the fundamental components are given with utmost accuracy but no one can possibly tell what is happening. Now we will assume the fundamental components as resultants of two simpler components, and try to find these components with the assumption that one is translational and the other rotational. The way of reduction is best illustrated in Fig. 34.

1. Analytical reduction of displacement

Observed (fundamental oscillation) → (reduced to)	Components: Translational	Rotational around G
$A_1 \sin(\omega t-\lambda_1) =$	$a \sin(\omega t-\alpha)$	$-(z_1-z_0)\varphi \sin(\omega t-\beta)$
$A_2 \sin(\omega t-\lambda_2) =$	$a \sin(\omega t-\alpha)$	$-(z_2-z_0)\varphi \sin(\omega t-\beta)$

$A, \lambda, \omega, z,$ are all known
$a, \alpha, \varphi, \beta,$ are unknown

Solving these two equations with respect to $a, \alpha, \varphi, \beta$, and inserting the observed values $A_1, A_2, \lambda_1, \lambda_2$, we have:

Data No.	ω rad/sec.	mm degree mm second degree
1	26.1	$0.23 \sin(\omega t+55^\circ)-(z-z_0)\times 8.1'' \sin(\omega t+63^\circ)$
2	30.9	$0.29 \sin(\omega t-39)-(z-z_0)\times 19.0 \sin(\omega t-55)$
3	34.1	$0.23 \sin(\omega t-62)-(z-z_0)\times 13.3 \sin(\omega t-101)$
4	36.0	$0.16 \sin(\omega t-67)-(z-z_0)\times 5.7 \sin(\omega t-108)$
5	36.4	$0.16 \sin(\omega t-66)-(z-z_0)\times 8.4 \sin(\omega t-124)$
6	37.6	$0.19 \sin(\omega t-53)-(z-z_0)\times 5.0 \sin(\omega t-53)$

2. Analytical reduction of pressure

Observed (fundamental oscillation) → (reduced to)		Components: Translational	Rotational
$B_{13} \sin(\omega t-\mu_{13})$	=	$p \sin(\omega t-\tau)$	$+(z_{13}-z_0) q \sin(\omega t-\delta)$
$B_{14} \sin(\omega t-\mu_{14})$	=	$p \sin(\omega t-\tau)$	$+(z_{14}-z_0) q \sin(\omega t-\delta)$
$B_{15} \sin(\omega t-\mu_{15})$	=	$p \sin(\omega t-\tau)$	$+(z_{15}-z_0) q \sin(\omega t-\delta)$
$B_{16} \sin(\omega t-\mu_{16})$	=	$p \sin(\omega t-\tau)$	$+(z_{16}-z_0) q \sin(\omega t-\delta)$
$B_{17} \sin(\omega t-\mu_{17})$	=	$p \sin(\omega t-\tau)$	$+(z_{17}-z_0) q \sin(\omega t-\delta)$
$B_{18} \sin(\omega t-\mu_{18})$	=	$p \sin(\omega t-\tau)$	$+(z_{18}-z_0) q \sin(\omega t-\delta)$

$B, \mu, \omega, z,$ are all known
$p, \tau, q, \delta,$ are unknown

In order to determine the four unknowns by six equations, we calculated by the Method of Least Square and the Method of Successive Approximation with the aid of a digital relay computer FACOM 128A. We obtained:

Data No.	ω rad/sec.	gr/cm^2 degree	cm gr/cm^2/cm degree
1	26.1	$0.53 \sin(\omega t+111^\circ)$	$+ (Z-Z_0)\times 0.0302 \sin(\omega t+187^\circ)$
2	30.9	$11.9 \sin(\omega t+18)$	$+ (Z-Z_0)\times 0.157 \sin(\omega t+51)$
3	34.1	$20.8 \sin(\omega t+7)$	$+ (Z-Z_0)\times 0.295 \sin(\omega t+15)$
4	36.0	$26.6 \sin(\omega t-9)$	$+ (Z-Z_0)\times 0.327 \sin(\omega t-7)$
5	36.4	$24.4 \sin(\omega t-13)$	$+ (Z-Z_0)\times 0.323 \sin(\omega t-9)$
6	37.6	$31.3 \sin(\omega t-15)$	$+ (Z-Z_0)\times 0.375 \sin(\omega t-14)$

Thus we have become to know to the full extent the motions of the quay wall and the pressures on its vertical plane, and the next step to be taken is to show how they fulfil the theory of dynamics. That will be reported at the conference.

Acknowledgements

The author is much obliged to Dr. Masao Kondo, Professor of Gakushuin University, and Dr. Matsuhei Ichihara, chief of our group, for their incessant and valuable instructions.

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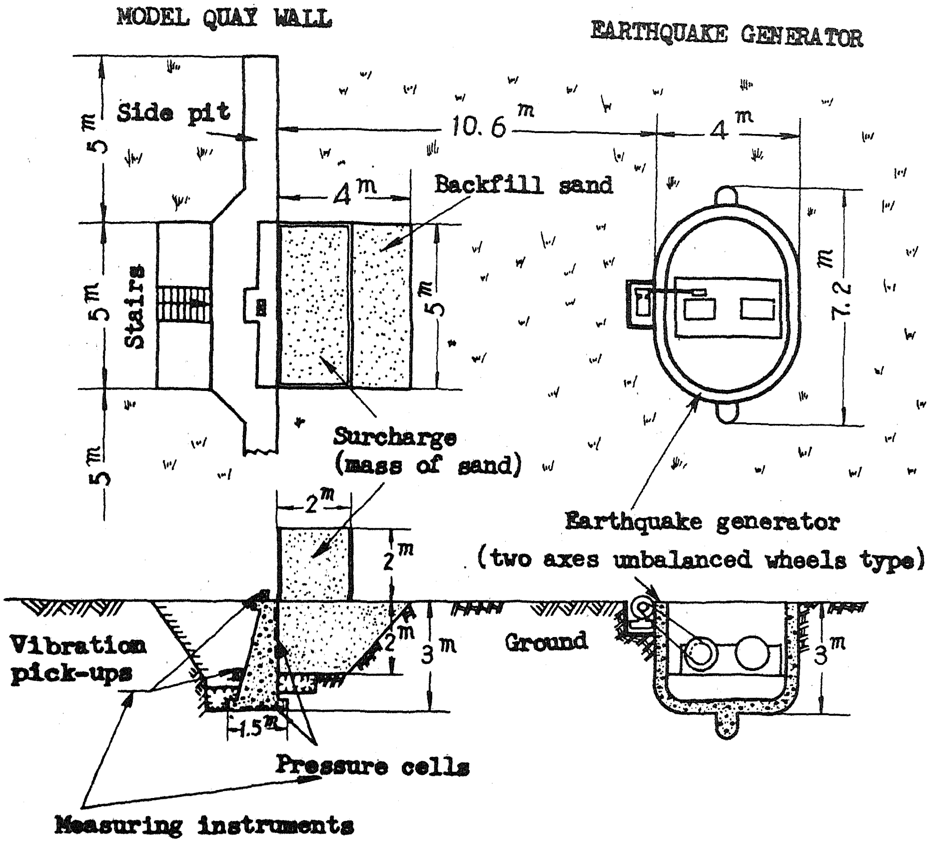


Fig. 1. General arrangement of the experimental equipments

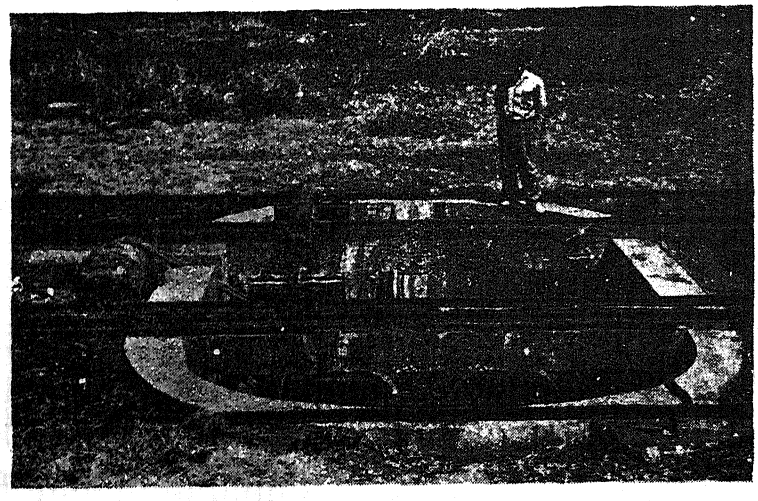


Fig. 2. General view of earthquake generator

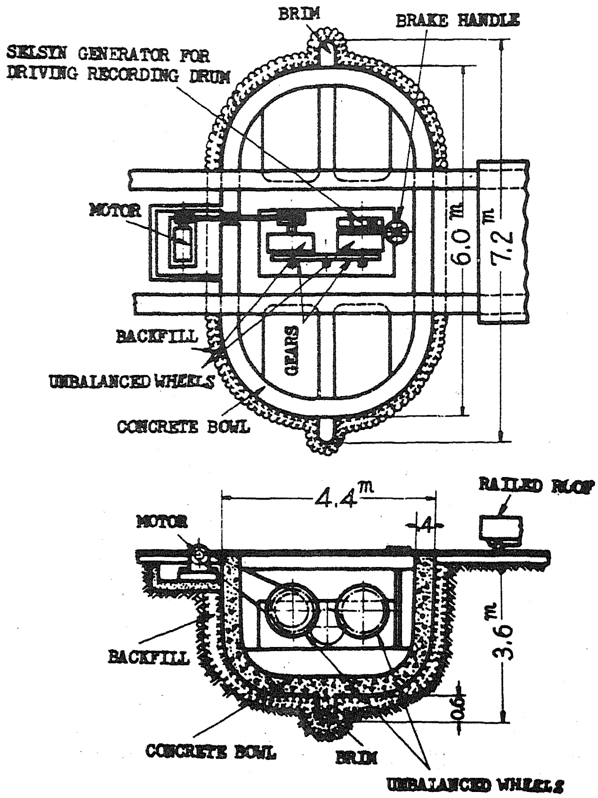


Fig. 3. Earthquake generator

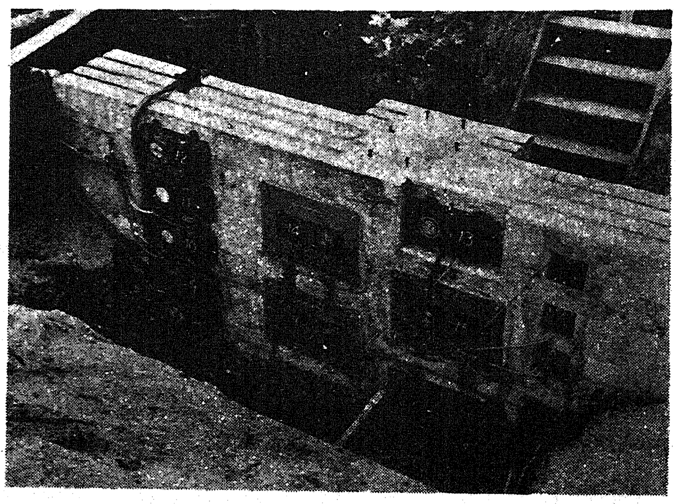


Fig. 4. Pressure cells are mounted on the vertical surface of the model quay wall, backfill materials being removed

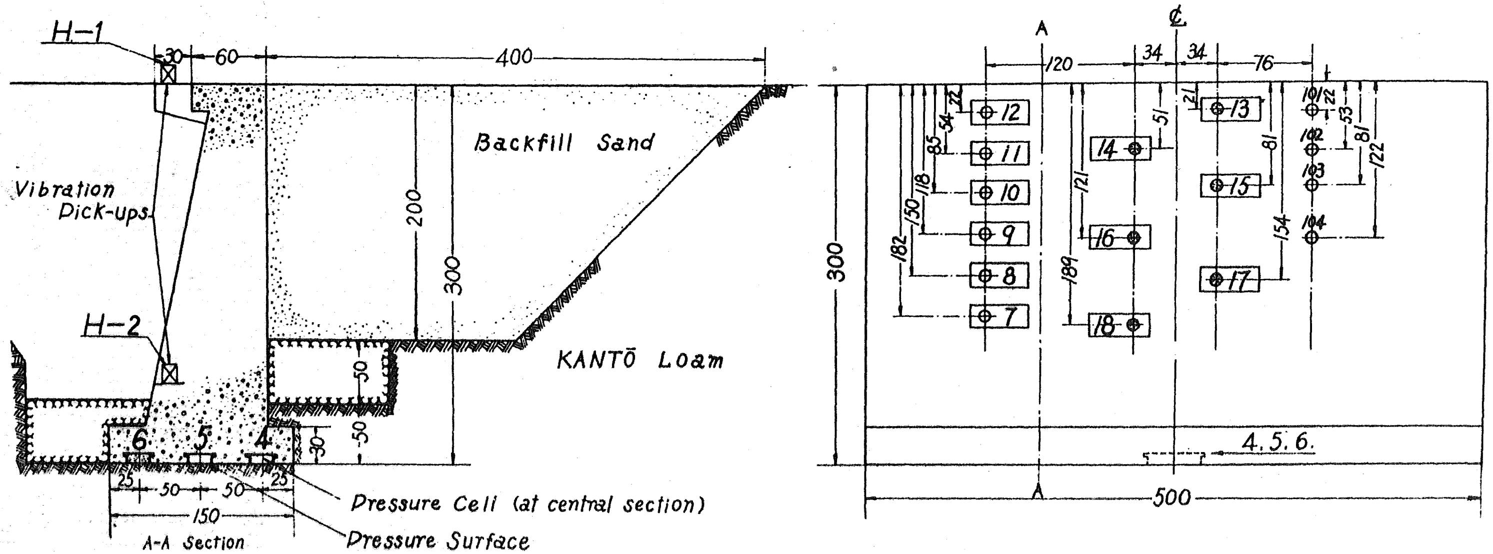
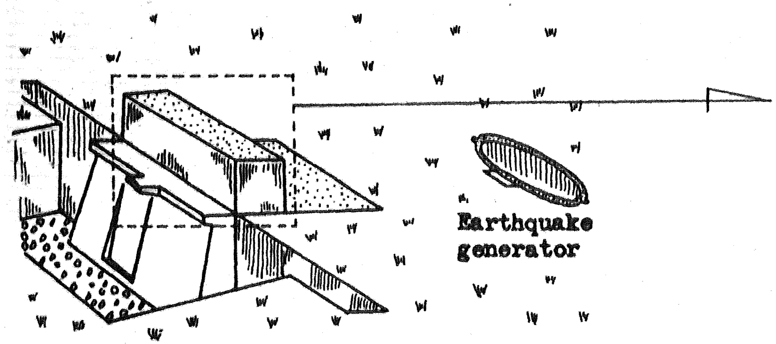


Fig. 5. Details of the model quay wall and the arrangement of pressure cells. The experimental data of cell No. 13～18 and 6 are shown in § 5, unit: cm



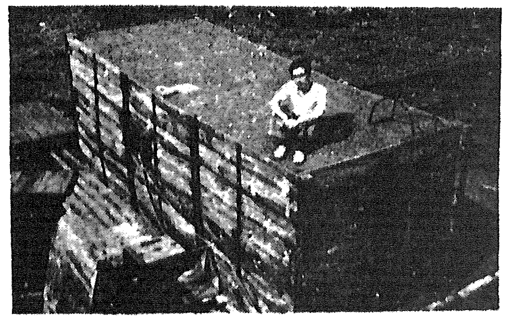


Fig. 6. Surcharge, mass of sand $5^m \times 2^m \times 2^m$ in a wooden frame

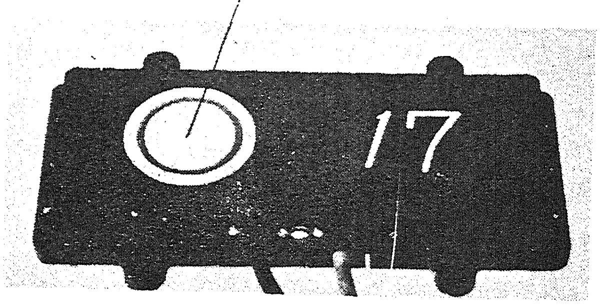


Fig. 7. Top view of pressure cell

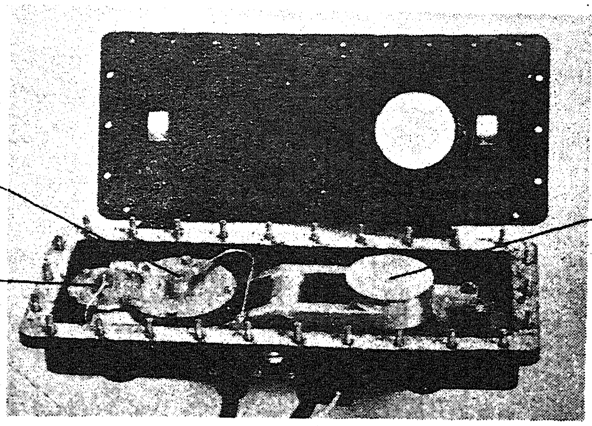


Fig. 8. Rear view of pressure cell, the cover removed

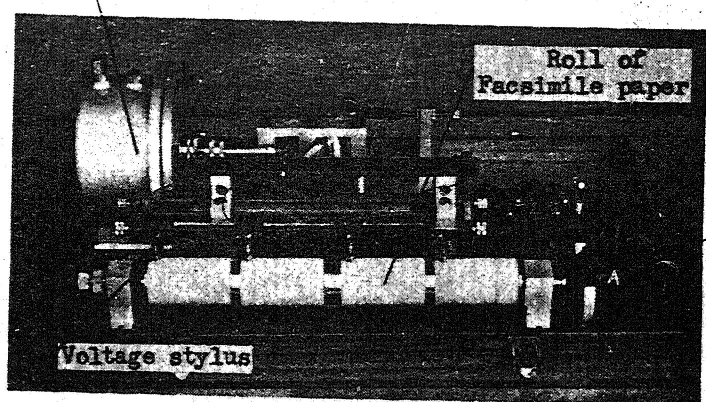


Fig. 9. Recorder

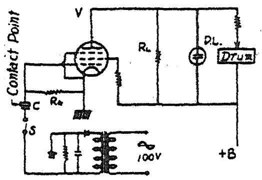


Fig. 10.
On-off indicating circuit

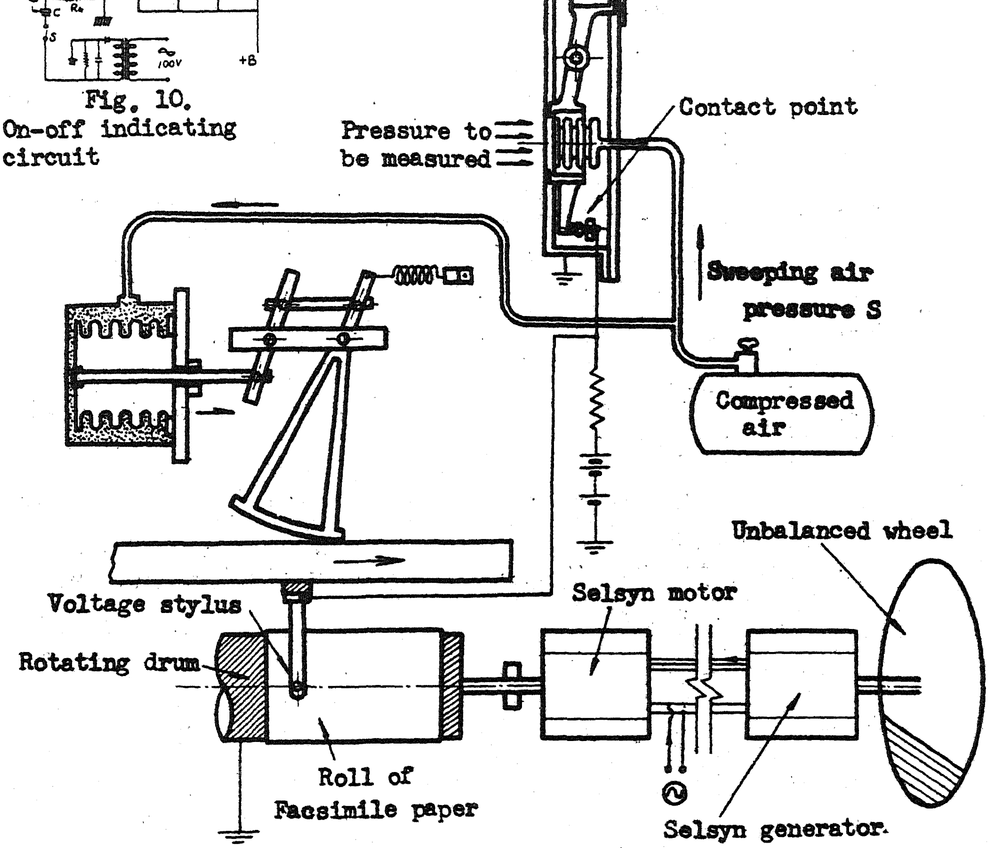


Fig. 11. Schematic diagram of oscillating earth pressure measuring instruments

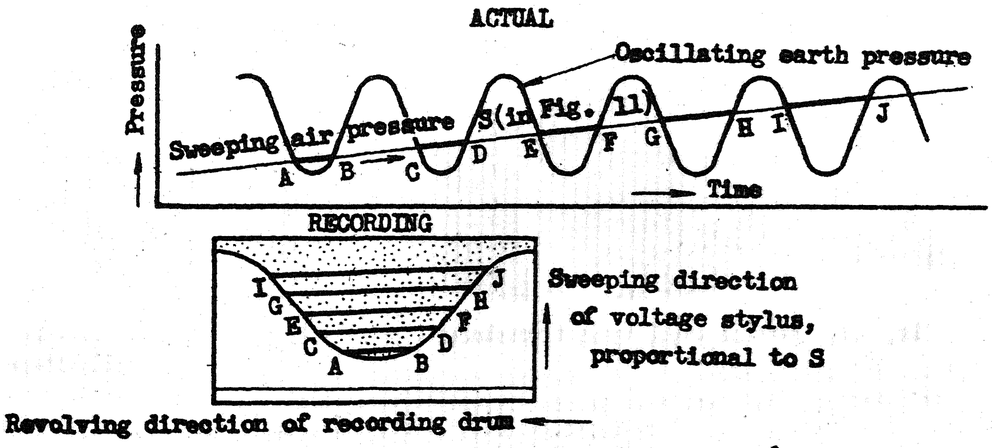


Fig. 12. The principle of making a record

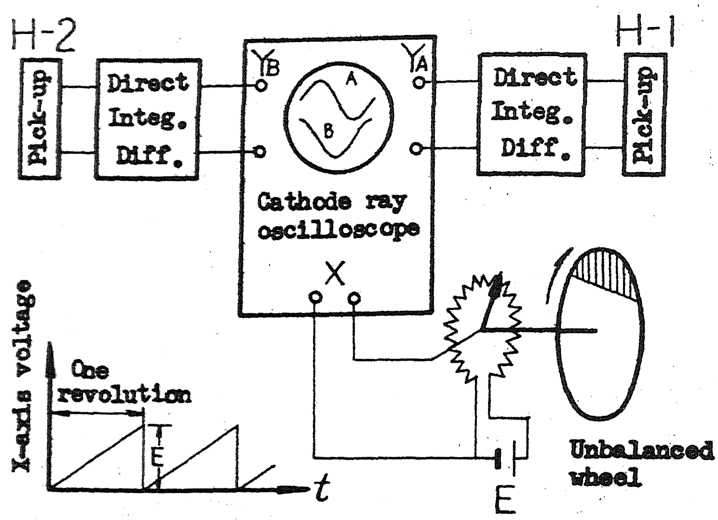


Fig. 13. Schematic diagram of vibration measuring instruments

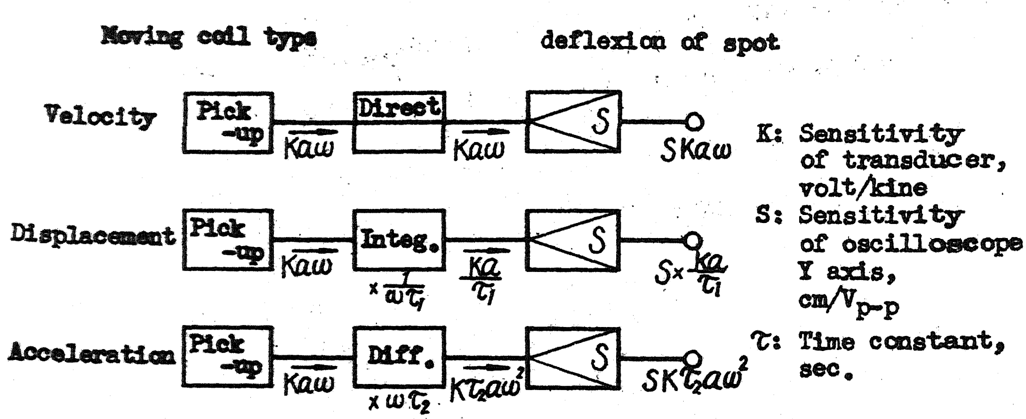


Fig. 14. Block diagram of vibration measurement

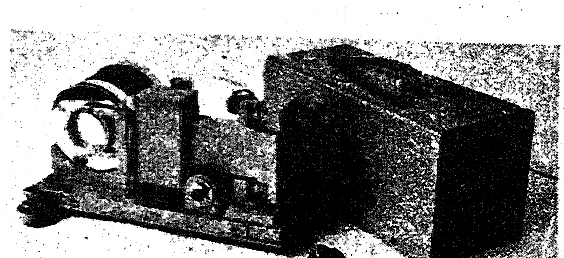


Fig. 15. Moving coil type transducer

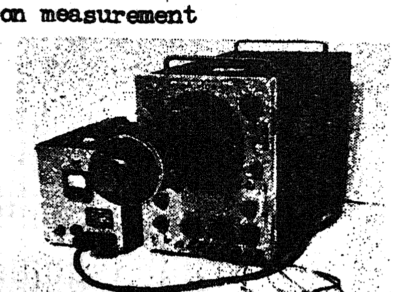
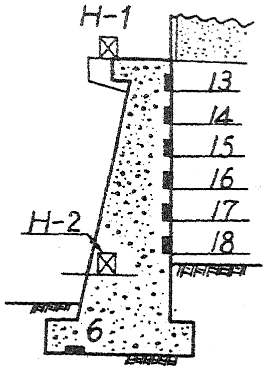


Fig. 16. Cathode-ray oscilloscope



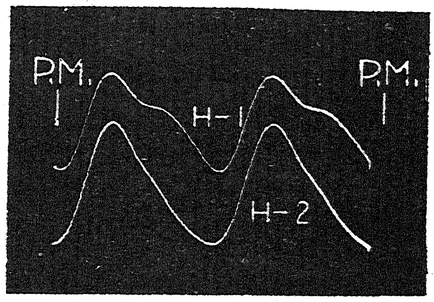


Fig. 17.
Oscillogram of displacements H-1, and H-2. Fig. 19 were taken at the same time

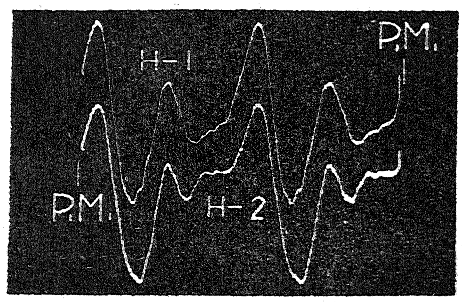


Fig. 18.
Oscillogram of accelerations H-1, and H-2. Fig. 19 were taken at the same time

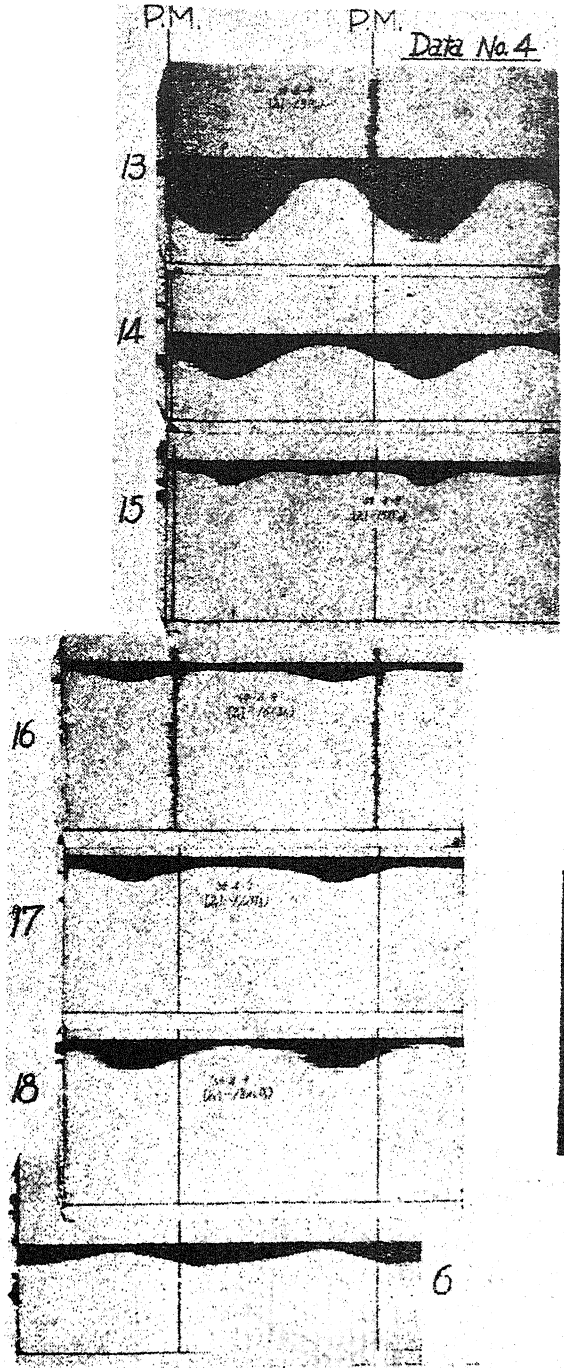


Fig. 19. Records of oscillating earth pressures, both unbalanced wheels of the generator running in the same direction at 5.7 r.p.s.. The backfill sand was filled and left intact for twenty months before this experiment

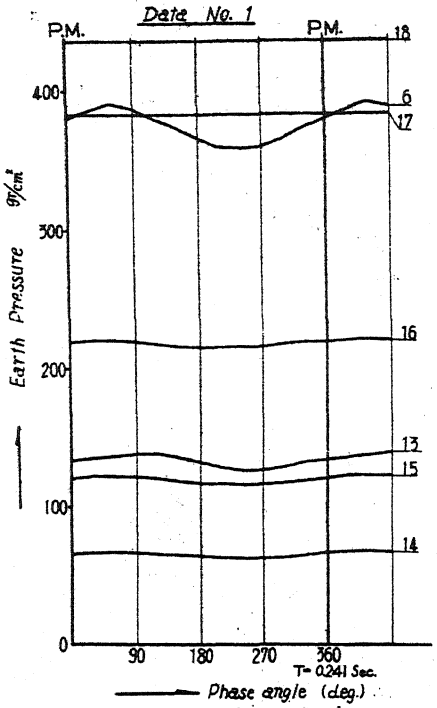


Fig. 20. ω = 26.1 rad/sec.

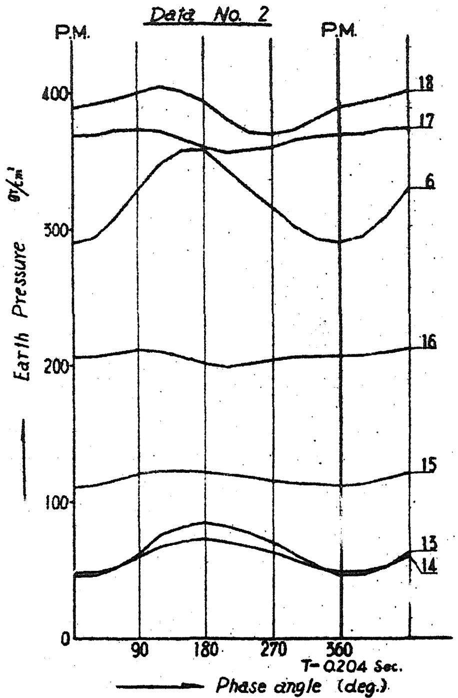


Fig. 21. ω = 30.9 rad/sec.

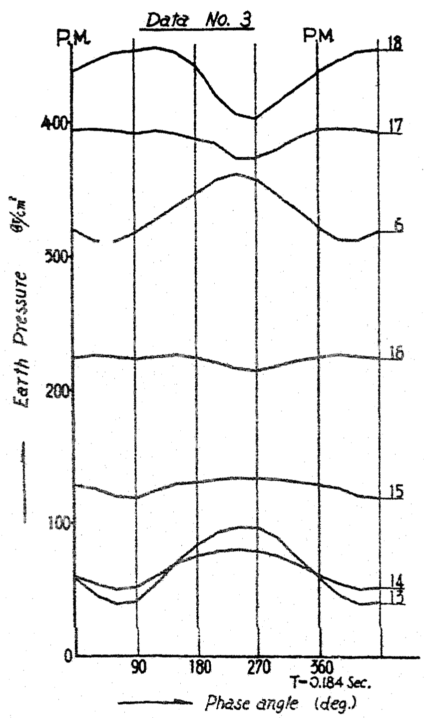


Fig. 22. ω = 34.1 rad/sec.

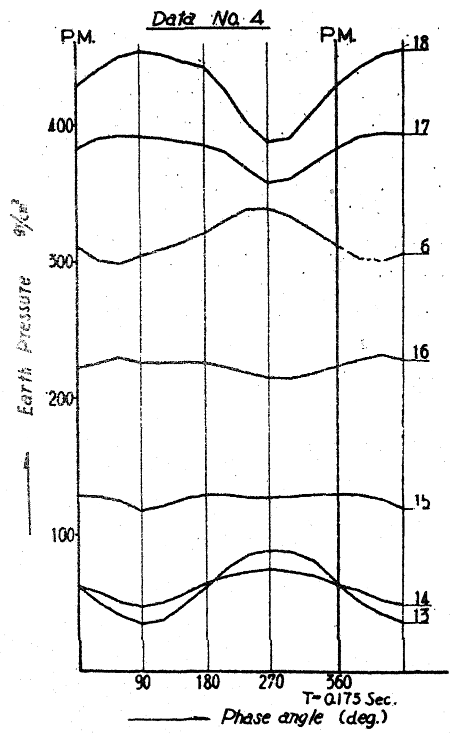


Fig. 23. ω = 36.0 rad/sec.

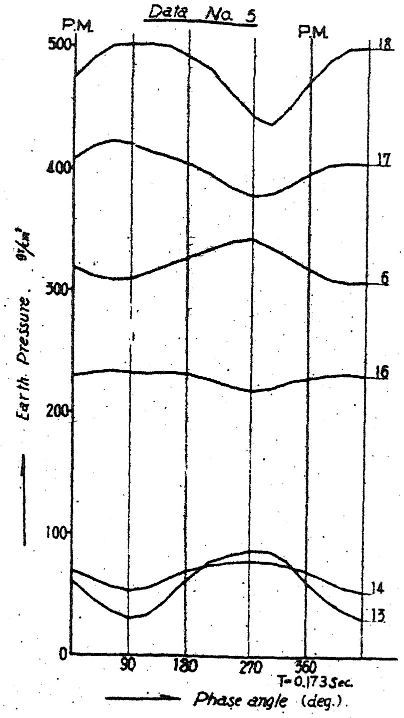


Fig. 24. ω = 36.4 rad/sec.

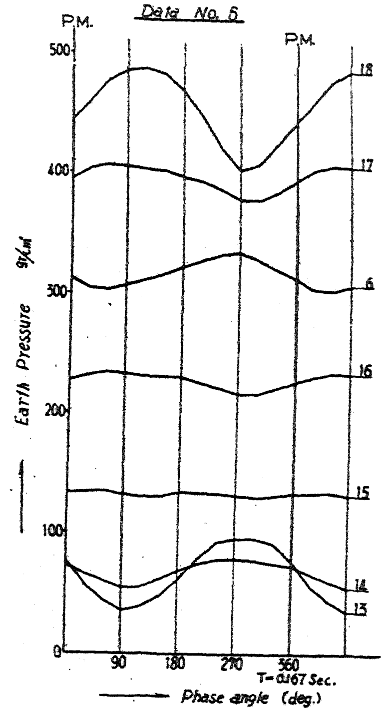


Fig. 25. ω = 37.6 rad/sec.

Fig. 20 ~ 25. Earth pressures during oscillation

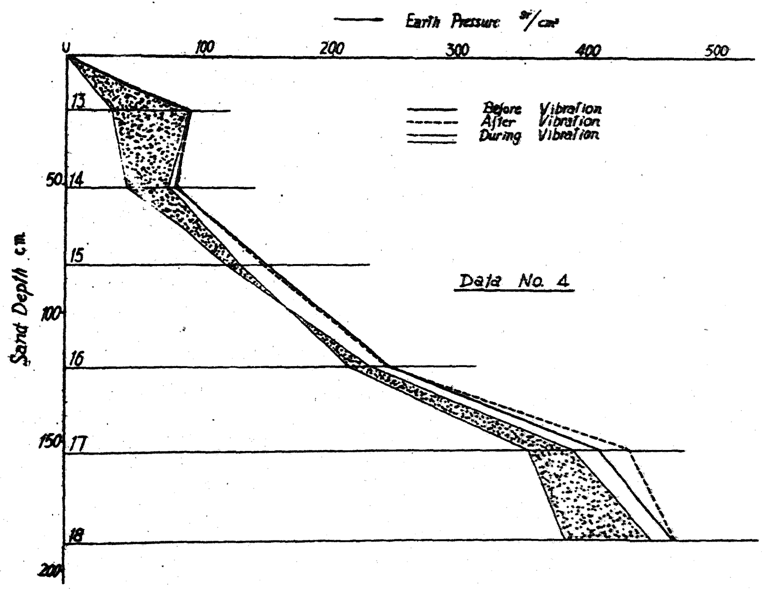


Fig. 26. Vertical distribution of max. and min. earth pressures during oscillation, phase angles being ignored, with the static pressures before and after the vibration

Fig. 27 ~ 32. Fundamental oscillations of pressures and displacements, calculated by Harmonic Analyses

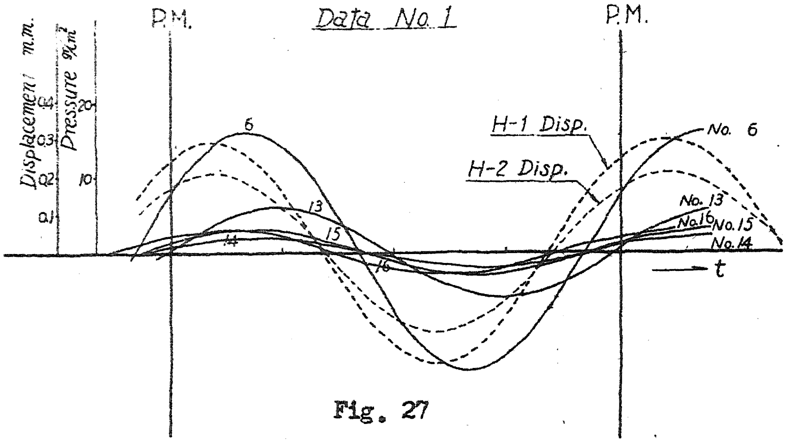


Fig. 27

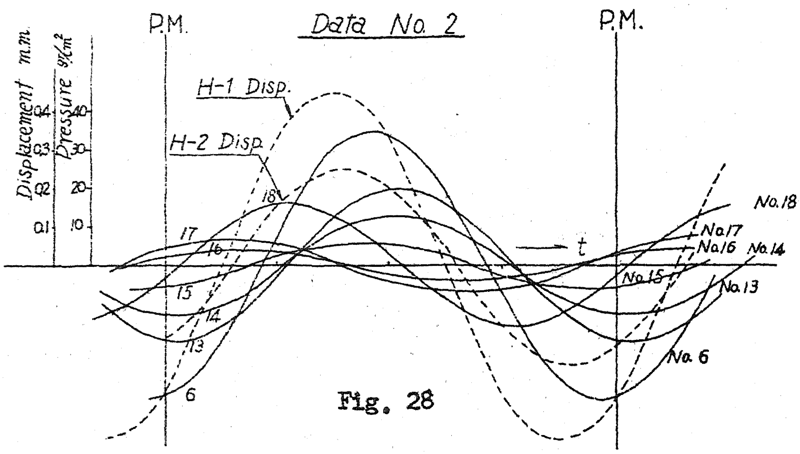


Fig. 28

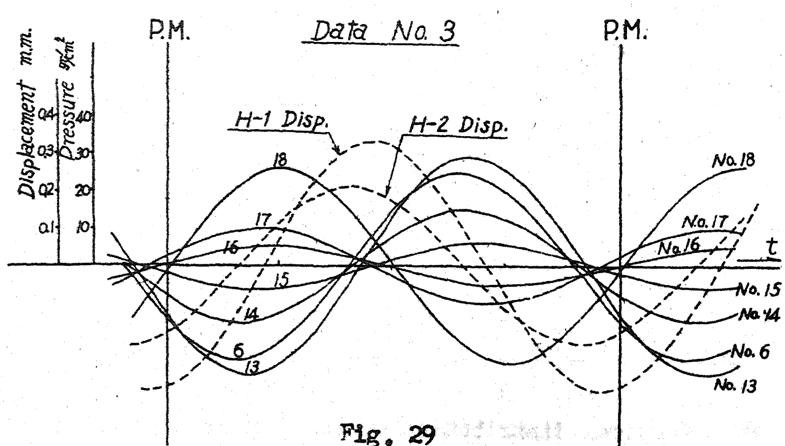


Fig. 29

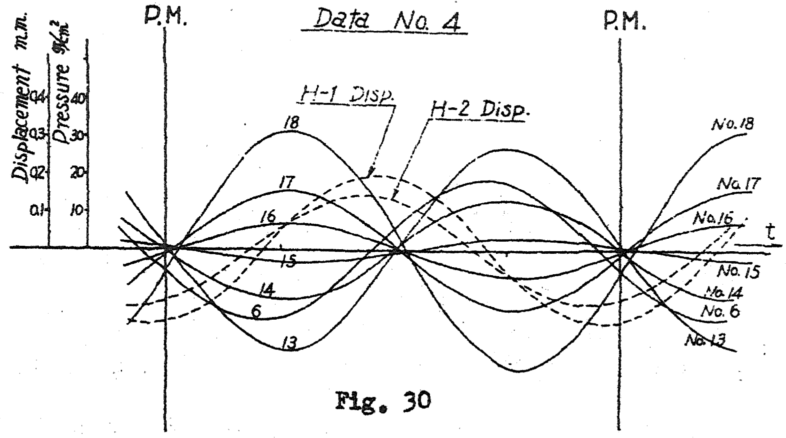


Fig. 30

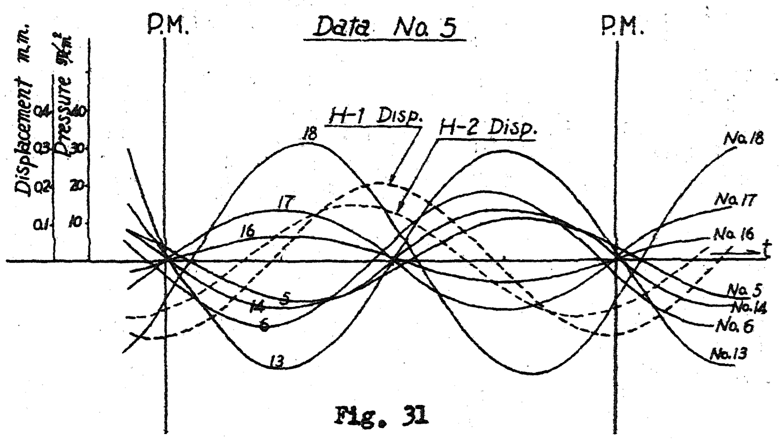


Fig. 31

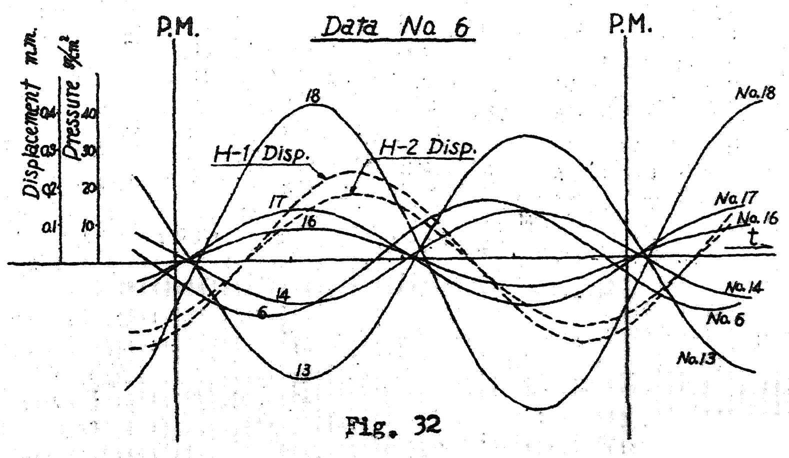


Fig. 32

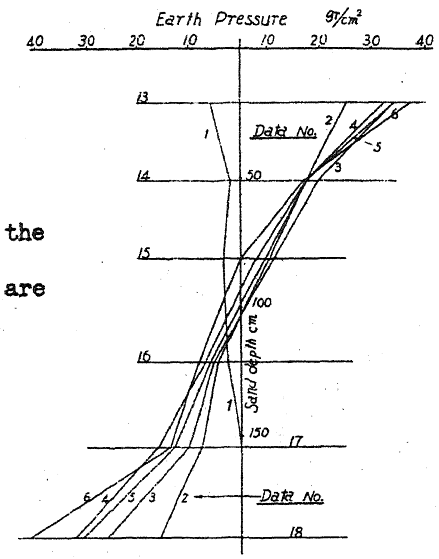


Fig. 33.
Vertical distributions of the amplitudes of fundamental oscillation, their phases are ignored.

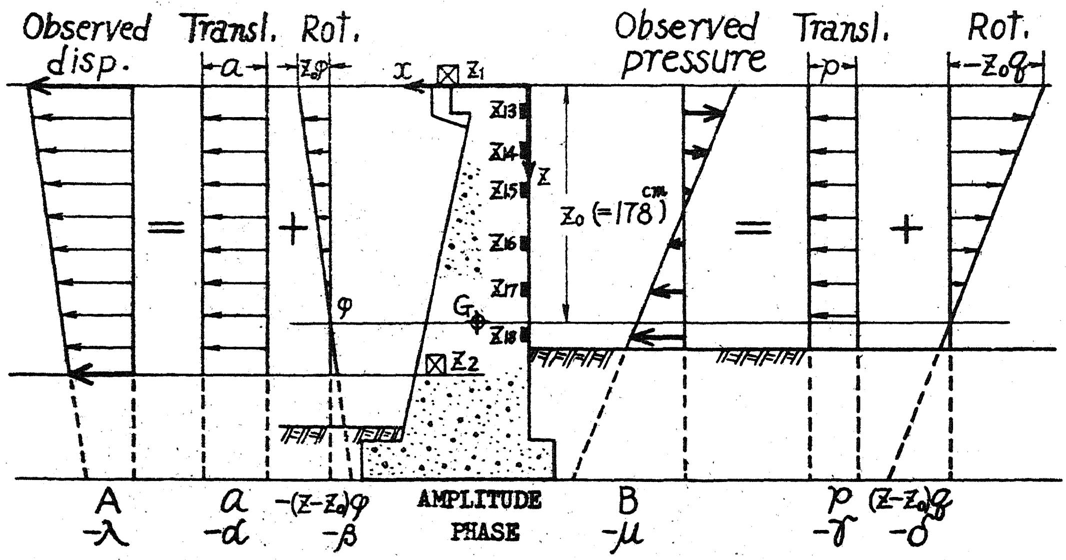


Fig. 34. Schematic view of reduction