ENGINEERING SEISMOLOGY

NOTES ON AMERICAN LECTURES

BY DR. KYOJI SUYEHIRO

LATE DIRECTOR, EARTHQUAKE RESEARCH INSTITUTE

IMPERIAL UNIVERSITY OF TOKYO

TOKYO, JAPAN

FOREWORD

In the fall of 1931 I had the pleasure of visiting the United States at the invitation of the American Society of Civil Engineers, for the purpose of lecturing on Engineering Seismology in some of the prominent American universities. At the kind suggestion of John R. Freeman, Hon. M. and Past-President of the Society, I have arranged my lecture notes in the present form for publication. As every reader is aware, the science of seismology—especially in its application—is far behind other sciences, and is still full of speculations and miscomprehensions. Although I have tried as far as possible to avoid these disputable questions, yet, owing to the great strides that will be made by seismology in the future, I shall not be surprised if much in this booklet will have to be altered and some of it scrapped altogether and rewritten. Indeed, for the well-being of the people of seismic countries, my fervent hope is that this will speedily come to pass.

I take this opportunity to express my sincere thanks to Mr. Freeman for his interest and zeal in the production of this little work and in my lecture tour, for without his efforts nothing could have been accomplished. My gratitude goes to George T. Seabury, the Secretary of the Society, and members of the Administrative Staff, and also to my colleagues and assistants in the Earthquake Research Institute, who have helped me in various ways.

KYOJI SUYEHIRO.

CONTENTS

INTRODUCTION

By John R. Freeman, Hon. M. and Past-President Am. Soc. C. E.

In the following pages the notes are presented from which Professor Kyoji Suyehiro, late Director of the Earthquake Research Institute of the Imperial University of Tokyo, Japan, delivered three lectures in November and December, 1931, at the University of California; Stanford University (California); California Institute of Technology; and Massachusetts Institute of Technology. The lectures were illustrated by lantern slides, most of which have been reproduced.

After graduating in Mechanical Engineering from the Imperial University of Tokyo, and, subsequently, taking special courses in its Physical and Engineering Laboratories pertaining to vibration research, Kyoji Suyehiro became a member of the Engineering Staff of the great ship-building works at Nagasaki. After a period of practical experience, he was called back to the University of Tokyo as Professor of Mechanical Engineering and, later, of Naval Architecture, meanwhile being called into consultation on many practical problems of ship building. His work was recognized to be of such excellence that, in course of time, he was given the degree of Doctor of Engineering.

By reason of his experience in Naval Architecture (which had required intimate study into the action of powerful waves and vibrations on the structure of ships and a familiarity with the means of resisting these stresses and strains by proper structural design, in which the steel framework was of great importance) Professor Suyehiro was particulary well fitted for the direction of researches into stresses caused in structures by earthquake waves, and for determining the requirements of designs for resisting them.

In organizing the work of the Earthquake Research Institute, he sought first to learn more of the character of the earthquake motion and of the forces which produced it. In other words, he sought a definite measure of the character and amplitude of earthquake motion and of its period of vibration. As a means of measuring this force he endeavored to determine its acceleration, which is the commonly adopted means of measuring a physical force. As he states in Lecture I, these measurements of earthquake motion and acceleration have not yet been satisfactorily accomplished; but, meanwhile, improved apparatus and new methods for measuring all effects that appear to have a bearing on the program are being worked out.

Immediately following an important earthquake, the disturbed district is visited by Professor Suyehiro's staff of about a half dozen specialists in various lines of research, who with most painstaking care collect all evidence which seems of importance for further study. In the intervals between such emergencies, these experts are kept busy in their respective fields of physical research, mathematical seismology, geology, and in the devising of new instruments and new means for accurately measuring earthquake motion,

force, and rapidity of vibration. The topographical engineers of the Government co-operate by running lines of precise levels in the district affected, for the purpose of discovering changes of level and earth tilt.

Obviously, in only three lectures of a little more than an hour each, Professor Suyehiro had time only to touch lightly on many of these interesting topics, and the following notes from which he spoke are more condensed than was his oral presentation. A brief synopsis precedes each lecture.

Professor Suyehiro's untimely death on April 9, 1932, creates a distinct loss to the Engineering Profession. His success in interpreting seismology in practical terms has made the entire world his debtor.

ENGINEERING SEISMOLOGY
NOTES ON AMERICAN LECTURES
By Dr. Kyoji Suyehiro [1]

LECTURE 1
HISTORY OF DEVELOPMENT OF SEISMOLOGY IN JAPAN

SYNOPSIS

Researches undertaken by the Earthquake Research Institute in connection with quakes that occurred in 1923 (the Kwanto), in 1927 (the Tango), and in 1930 (the Northern Idu), are discussed in this lecture. Studies of the Kwanto earthquake have led to the conclusion that, while the upheavals and depressions were, to some extent, the result of gradual changes, most of the changes occurred abruptly at the time of the earthquake. Much investigation is still necessary before scientists can predict earthquake shocks in such a way as to be useful to engineers.

Studies made after the Tango earthquake revealed that the crust of the earth consisted of a number of separate fault blocks. Post-seismic crustal movement was practically ended after four years of re-adjustment. Immediately after the earthquake, Ishimoto tiltgraphs were installed in two places near the epicentral region. A study of the records showed that the occurrence of most of the severe after-shocks were intimately correlated with the change of the direction of the ground tilt; but it has not yet been possible to say whether the tilting was due to meteorological causes or to subterranean changes.

During the Northern Idu earthquake, November 26, 1930, a fault, 30 km. long, appeared in a north-and-south direction through the middle of the Idu Peninsula. Displacements of 100 cm. were measured at the surface, and almost a year afterward daily displacements of 0.001 mm. were observed in the Tanna Railway Tunnel. Many attempts have been made to associate earthquakes with meteorological phenomena and crustal movements.

INTRODUCTION

It is a great honor to me to be invited to lecture at some of the famous universities in this country, and I am delighted to discharge my pleasant task and in that way express the good will of Japan to the United States through science.

First of all, I must emphasize the fact that I am neither a geophysicist nor a geologist (who are the ones best qualified to discuss problems concerning earthquakes), but a seismologist, interested in the study of the engineering phases of seismology.

The fundamental principles of seismology and general surveys of earthquake phenomena are given in Professor J. Milne's "Seismology," Professor R. A. Daly's "Our Mobile Earth," Professor B. Gutenberg's "Handbuch der Geophysik," and other textbooks. Therefore, I shall not enter into general questions, but shall confine my attention to those special problems which have an engineering interest, and which have not yet been discussed in any textbook. Moreover, in a short lecture such as this, it is not possible to describe this very complex subject in any great detail, so I am forced to refer only to some general features of phenomenon.

I wish to call your attention to the fact that my country, Japan, is generally believed to be one of the most seismic countries in the world. The late Professor J. Milne, a famous British seismologist, said in a joke that we have earthquakes for breakfast, dinner, supper, and earthquakes to sleep upon. Needless to say, this is merely a joke and is far from the truth. As a matter of fact, seismicity in my country is somewhat exaggerated, partly because after-shocks of the great 1923 earthquake are still occurring, and partly on account of the fact that whenever a severe earthquake occurs, it is known immediately throughout the world, because Japan is so densely populated that more or less damage is wrought by every severe earthquake, wherever it may take place.

You are in a quite different situation. For instance, you had a terrible earthquake in Northern Nevada in 1915, which left a remarkable fault having a displacement of about 20 ft., vertically, on the west side of the Sonoma Range, but so far as I am informed, only one ranch house close to the fault was seriously injured, and there was no damage to other structures because these were in general non-existent. In Japan we cannot dream of such a situation. I do not deny, however, that earthquakes are frequent in my country. Indeed, for that reason, we are doing our utmost to understand and conquer them; but I am sorry to say that our efforts thus far have not been fruitful.

The foundations of the present Japanese seismology were laid by a corps of American and English scientists who came to Japan about five decades ago. In 1880, these foreign scientists established the Seismological Society of Japan and studied seismological problems very eagerly. Among these men we may specially mention the names of J. Milne, C. G. Knott, J. A. Ewing, and T. C. Mendenhall. Professor Ewing succeeded in obtaining
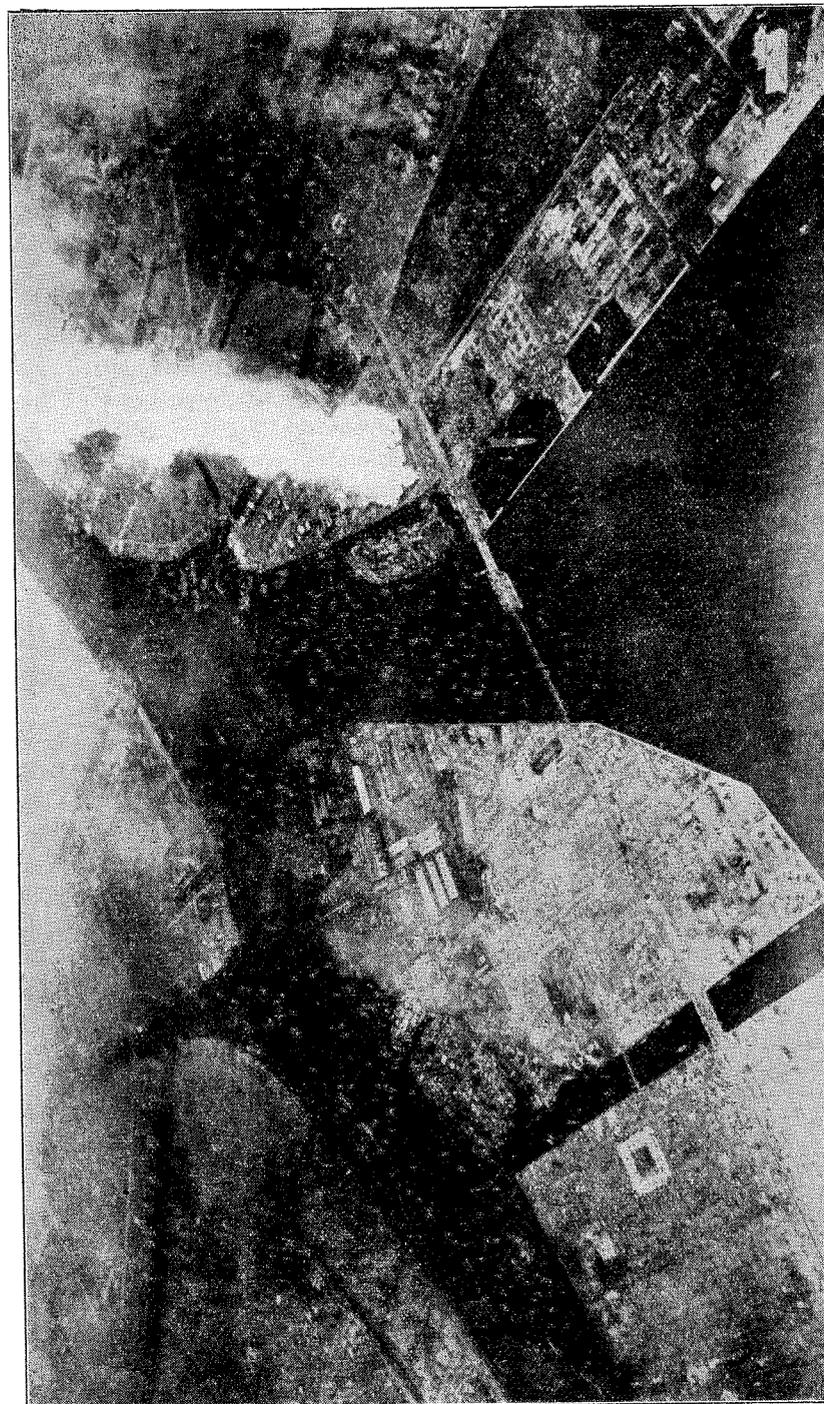
FIG. 1.—VIEW OF TOKYO, JAPAN, TAKEN SOON AFTER THE KWANTO EARTHQUAKE, SEPTEMBER 1, 1923.

the registration of horizontal components of earthquake motions by a newly invented horizontal pendulum. Professor Milne devoted himself with the utmost eagerness to the study of the nature of earthquakes, and fostered the development of this branch of science. We are very grateful for the work done by these eminent scientists.

When these men returned home, the work was taken up by the late Professor K. Sekiya and the late Professor F. Omori, most of their study being directed toward near-by earthquakes, which is characteristic of Japanese seismology.

The earthquake of October 28, 1891, in the Provinces of Mino and Owari, situated in the central part of the main island of Japan, was the first destructive earthquake to occur after we took up the Western science, and it caused the Japanese people to realize vividly the necessity of scientific studies.

The next year a Government institution, called the Earthquake Investigation Committee, was established for the study of both the scientific and engineering problems of earthquakes. Leading physicists, geologists, and engineers were appointed members and did splendid work, reports of which were published in the *Proceedings* of the Earthquake Investigation Committee.

Above all, the investigations of earthquake-resisting structures were most important. Buildings constructed to comply with the Committee's recommendations withstood the 1923 earthquake without damage.

After the 1891 earthquake, Japan enjoyed freedom from severe disturbances for more than thirty years, until, in 1923, the recent great earthquake took place. Forgetfulness is a trait of human nature. During the years that followed the earthquake of 1891, the members of this first scientific committee one by one returned to their customary vocations, leaving as the only continuous worker, Professor Omori, who, unfortunately, did not live to investigate the great earthquake of 1923.

A renewed interest in the study of earthquakes followed the great shock of 1923, and, in 1925, the Earthquake Research Institute was established at the Tokyo Imperial University, the active part of the work of the Earthquake Research Committee being transferred to this Institute.

Since its establishment, there have been two severe earthquakes, the Tango and the Idu. Our investigations of these two severe disturbances will be mentioned briefly with that of 1923. The great Kwanto earthquake, which took place on September 1, 1923, destroyed the greater part of the City of Tokyo as a direct result of fires that followed. The Tango earthquake occurred on March 7, 1927, in the central part of the main island of Japan, facing the Japan Sea. The Idu earthquake took place on November 26, 1930, and devastated the northern part of the Province of Idu, a peninsula projecting southward into the Pacific. The last two were quite local in character, but some of the damage was no less severe than in the Kwanto earthquake.
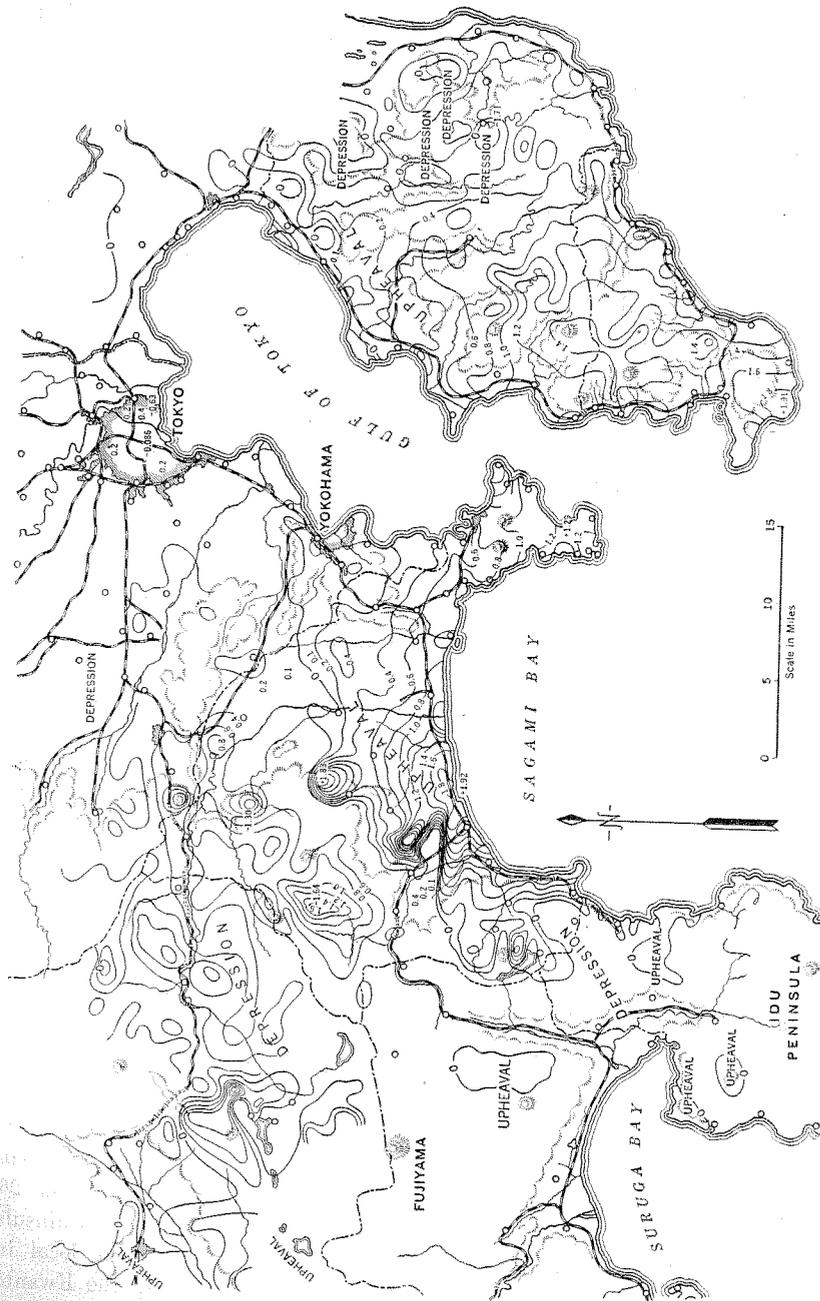
FIG. 2.—VERTICAL DISPLACEMENT OF THE GROUND IN THE AREA DISTURBED BY THE KWANTO EARTHQUAKE

(I) THE KWANTO EARTHQUAKE

This destructive earthquake is too well known to require any special mention, but I will just show by an airplane view taken soon afterward (Fig. 1) how the capital of Japan, although it was not situated in the zone of greatest shaking, was practically destroyed by the fires that followed. I will mention briefly some of the researches undertaken on this earthquake.

1.—Vertical Displacement of the Ground.—The result of precise levels taken by the Military Land Survey Department is shown in the map (Fig. 2). The work subsequent to the earthquake was done during the period between September, 1923, and March, 1927. The vertical displacement of the land was determined by comparing these results with data obtained from similar work done between 1888 and 1903.

The earth's crust forming the Japanese Islands, is remarkably unstable, even at ordinary times, so there is no doubt that the upheaval and depression that have been found, consist of both constant, gradual changes, and abrupt changes. Most of the changes occurred abruptly at the time of the earthquake, as has been clearly proved not only by the tide gauge record, or mareogram, taken at Yokosuka (Fig. 3), a port situated in the most violently shaken district, but also by newly raised beach lines in the devastated area.
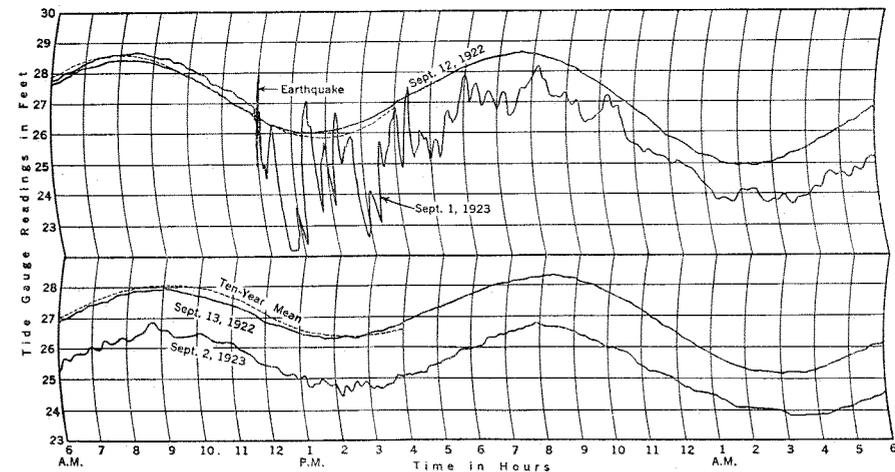
FIG. 3.—TIDE-GAUGE READINGS AT YOKOSUKA, SHOWING THAT CHANGES IN ELEVATIONS OCCUR ABRUPTLY.

Incidently, from a mareogram taken at Aburatubo, a village not far from Yokosuka, it was found that nearly a month previous to the earthquake the ground apparently began to upheave slowly relative to the sea level. Just before the occurrence of the earthquake, the total rise had amounted to about 2 cm. Some believed this uplift was the harbinger of the earthquake, and that means for predicting earthquakes might be obtained from such crust movements.

However, by a careful study of this phenomenon, Professor T. Terada, of our Institute, concludes that such an occurrence of pre-seismic upheaval relative to the sea level might have been due to meteorological causes. This would mean that the changes of the sea level were due to changes in barometric pressure. At the time, typhoon centers passed over the Pacific, one after another, south of the Japanese Islands. Taking this fact into consideration, Professor Terada showed that the earth's crust was not disturbed just before the earthquake. Thus, we might be hasty if we conclude that evidence of such a crustal movement can be depended upon to foretell an earthquake. There is still much to be investigated before we can hope to predict earthquake shocks. This question will be discussed later.

The second map (Fig. 4) shows the vertical displacements of benchmarks along the principal leveling traverses in the western half of the main island of Japan. Naturally, the land disturbance is most marked in the following three regions: The Kwanto District, the Tango Peninsula, and the Idu Peninsula, where great earthquakes have occurred recently. It will be seen, however, that there are a number of other places which are thus far intact, which have experienced decided crustal movements. We should watch closely the progress of these gradual changes.

Reverting to the subject of crust movements that followed the earthquake, analyses made in the Earthquake Research Institute, gave several interesting results. I will mention only one of these made by Mr. N. Miyabe. He analyzed the vertical land displacements by his original method, and made clear that the vertical movements of the Boso Peninsula were composed of block movements, the general features of which are shown in Fig. 5, indicating that the crust in this district probably was of mosaic construction.

His method is based on a simple trigonometrical relation,

$$\tan \phi = \tan \phi_m \cos (\theta - \theta_m) \dots\dots\dots\dots\dots\dots(1)$$

which holds when any number of points on one and the same block move *en masse*. In the equation, ϕ denotes the change in the slope of the line that connects a pair of points (or relative change in height divided by distance); θ denotes the azimuth of this connecting line as referred to a definite direction, while ϕ_m and θ_m, respectively, denote the direction and the magnitude of the change in slope of the block. Using Equation (1), Mr. Miyabe distinguished the different blocks by a graphical method.

He plotted the values of $\tan \phi$ of various points and their relations to θ, and segregated the groups of points that lie on one and the same block from the others, by judging whether or not they fell on a fairly well-defined sinusoidal curve.[2]

In order to determine how the crust movements progressed after the great convulsion, precise levels were repeatedly run along a line from Tokyo and Aburatubo, by the Military Land Survey Department, at the joint request of the Earthquake Advisory Committee and Professor A. Imamura.

[2] For details, refer to paper by N. Miyabe in *Bulletin*, Earthquake Research Inst., Tokyo Imperial Univ., Vol. 9, No. 3.
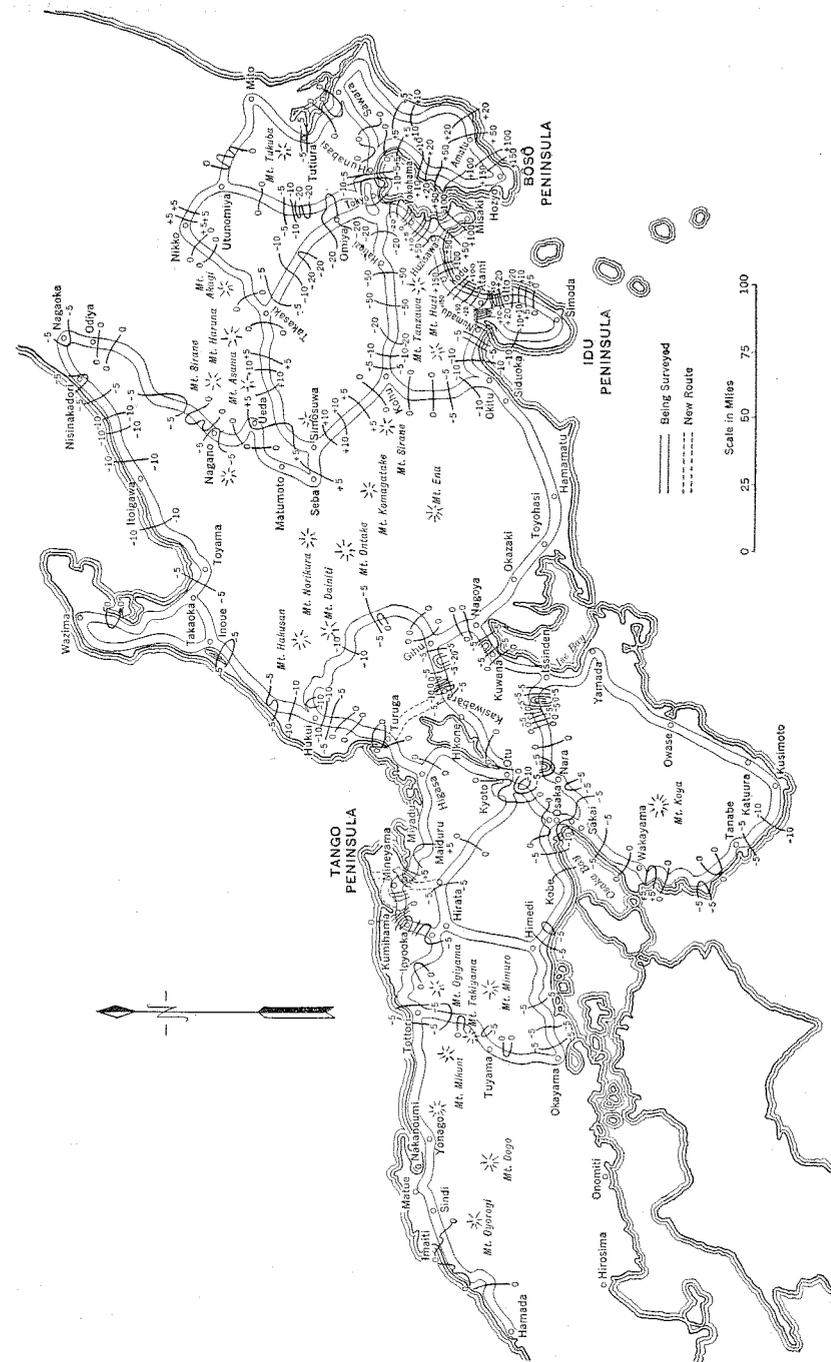
FIG. 4.—VERTICAL DISPLACEMENT OF BENCH-MARKS IN THE WESTERN HALF OF THE ISLAND OF HONSHU.

It was found that immediately after the earthquake the crust had moved in such a way as to resume its original level, but it was afterward subject to further uplift.[a]
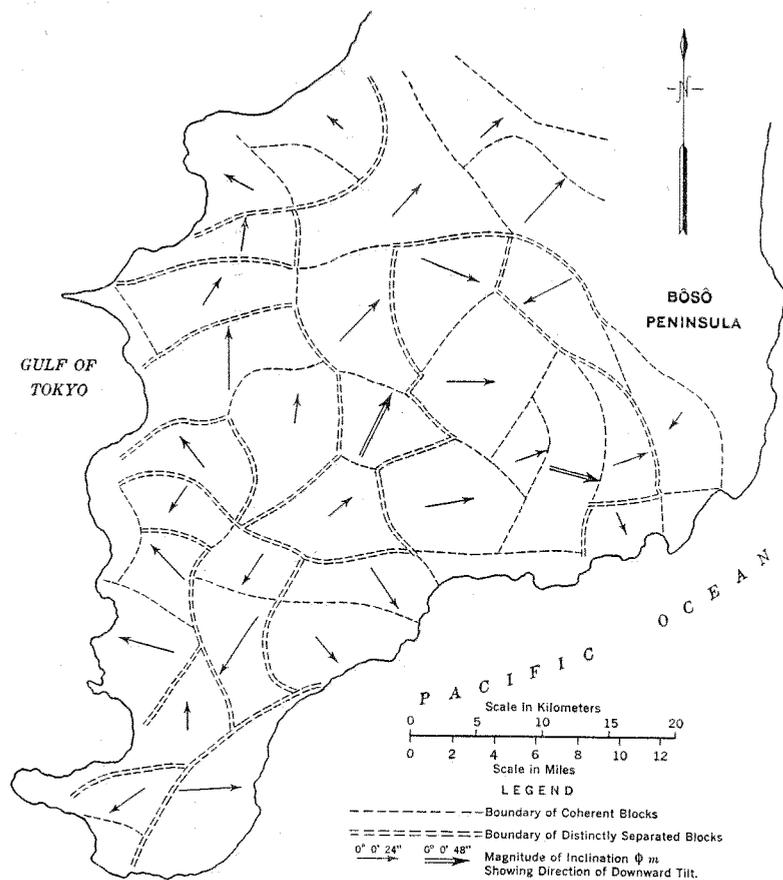
FIG. 5.—PLAN OF BOSO PENINSULA, SHOWING THE COMPOSITION OF THE TERRITORY INTO BLOCKS THAT TILT INDEPENDENTLY OF EACH OTHER.

An explanation of the geophysical causes that give rise to such phenomena is very important to the study of seismology, but as an engineer I hesitate to discuss such questions.

2.—Horizontal Displacement of the Ground.—The result of triangulations made by the Military Land Survey Department with reference to 778 secondary and tertiary triangulation points is shown in Fig. 6. The displacements of triangulation points are the differences in their positions as determined before and after the earthquake, the former having been determined during the period between 1890 and 1891 and the latter between 1924 and 1926. In drawing this map, it was assumed that the heavy boundary

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[a] See paper by A. Imamura, *Proceedings*, Imperial Academy, Vol. 6. (1930), No. 10.

lines connecting the principal primary points had not suffered any disturbance. This assumption was made for convenience in simplifying the work of revising the map, so that the displacements shown are to be understood as being only relative. Nevertheless, the map does not fail to impress one with the catastrophic nature of the earthquake.
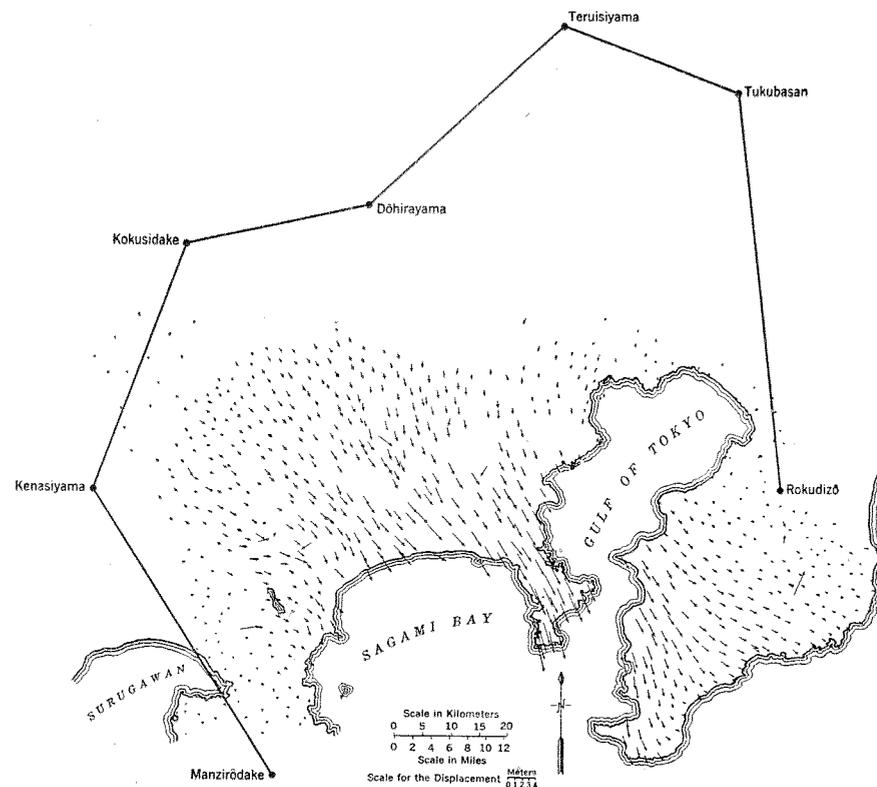
FIG. 6.—RESULT OF SURVEY TO DETERMINE HORIZONTAL DISPLACEMENTS.

3.—Disturbance in the Sea Bed.—The disturbance that occurred on the sea bottom of Sagami Bay was far more severe. Fig. 7 shows the differences in the depths between the soundings made by the Naval Hydrographic Department immediately after the earthquake, during the period between September, 1923, and February, 1924, compared with those made in 1912 and thereafter.

Since the apparent changes in depth amounted to as much as 200 m. in several places, one may well doubt the accuracy of the soundings. However, the soundings not only were made by highly trained men, but the results have been carefully checked by Professor Terada for the purpose of determining whether the reported changes were independent of the declivity of the slope of the sea bed or of the determined depths of the bed. He found that the results of the measurements were not unreliable. The fact that when

FIG. 7.—CHANGES IN DEPTH OF SAGAMI BAY AND VICINITY BETWEEN 1912 AND 1923 (IN METERS).

—on April 5, 1930,—a few points were sounded a second time, they gave practically the same readings, seems to prove further the reliability of the soundings. However, in view of the additional fact that in the seaquake of August 15, 1886, near Zante, Greece, a sudden increase of from 4 500 to 5 800 ft. in the depth of the sea bed was reported, one might be convinced that the sea bed behaves quite differently from dry land in an earthquake.

Although without any direct connection with the problem under consideration, it is worth mentioning that while taking soundings in the Pacific Ocean, south of Japan, the Naval Surveying Ship, the *Mansui*, found a deep yawning chasm along the dotted islands of Idu, having a depth far in excess of the well-known Tuscarora Deep.

4.—Changes in the Length of the Ground.—Crustal deformation was again well illustrated by the changes in the lengths of periodic base lines established on the grounds of the Astronomical Observatory of the Tokyo Imperial University at Mitaka, a village just outside of Tokyo. The results of measurements that have been made annually by the Geodetic Commission have been plotted and are shown in Fig. 8. The changes in the area of the

FIG. 8.—MEASUREMENTS OF BASE LINE ON THE GROUNDS OF THE ASTRONOMICAL OBSERVATORY OF TOKYO IMPERIAL UNIVERSITY, SHOWING CHANGES OF LENGTH.

geodetic rhombus computed from these data by Mr. C. Tsuboi are shown in Fig. 9. The fact that the peculiar compressional change of area which was going on just before the earthquake was succeeded by an enormous expansion just after the shock, deserves attention.

I may add that we are now preparing to provide for taking continuous observations of the changes in measured distances at one of our observation

stations. For this purpose, quartz tubes, 20 m. long, installed in covered trenches, will be used as standard scales of reference. It is expected that observations will begin some time during 1932.
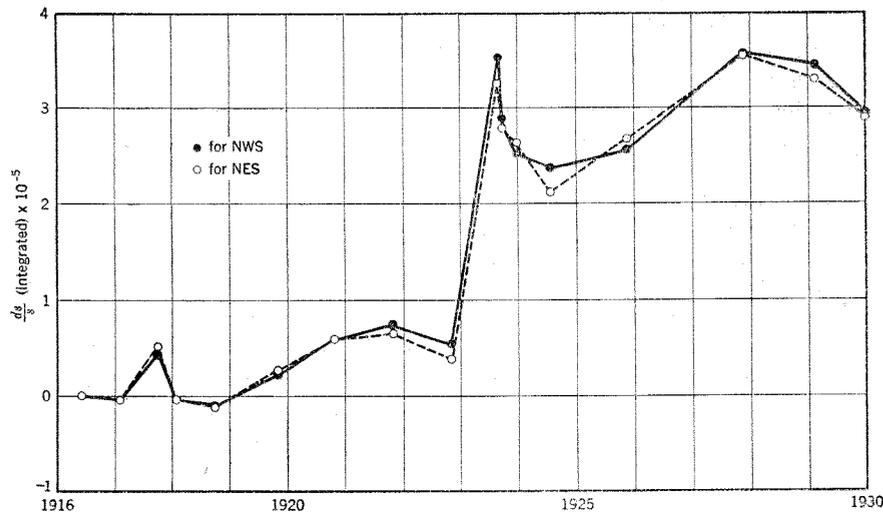
5.—Acceleration Due to Gravity.—There were various phenomena which attracted our attention, but were found to have no intimate relation to the earthquake. As an example, I will cite the change in the time rate of Riefler's standard clock installed in the Observatory. A decided change in the rate of the clock before and after the earthquake indicated that the earthquake had changed the value of the gravitational acceleration in this locality. To determine whether the change in the rate of the clock was in reality due to a change in the value of gravity, Mr. Tsuboi, of our Institute, made gravity measurements, in the spring of 1931, with the Nagaoka Tungsten Pendulum in Tokyo and at distant stations, well beyond possible range of earthquake effects. To our disappointment it was found that, at least within the order of 10 milligal[4] (0.01 cm. per sec.²), no change in the value of gravity at three places, as compared with pre-earthquake measurements, could be observed.

Such investigations should have been made immediately after the earthquake. I regret that on account of the limited funds available, we are continually missing good opportunities for studies of this nature. We are really disappointed that our contributions to the development of this branch of science are relatively incomplete although, whether fortunately or unfortunately, we have always been, and no doubt always will continue to be, well supplied with abundant material for investigation.

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[4] 1 milligal=1/1000 gal.=1/1000 of the centimeter-gramme-second unit of acceleration; 1 gal.=g/980=1/980 of the foot-pound-second unit of acceleration.

(II) THE TANGO EARTHQUAKE

After the Tango earthquake—in addition to the usual routine work, consisting of seismometric observations of after-shocks, geological and geographical surveys, soundings of sea beds, and engineering inspections, the following work was undertaken:

(1) Precise levels run over the disturbed area were repeated five times, the last series having been completed in the fall of 1930.
(2) Triangulation traverses in the same area were re-run three times.
(3) Immediately after the earthquake, Ishimoto tiltgraphs were installed in two places near the epicentral region, and tilting of the ground was observed continuously.

1.—Precise Leveling.—The routes of the survey are shown in Fig. 10, in which the approximate locations of the two principal fault lines, or rather the fault echelons, have been located. The five sets of profiles, showing the
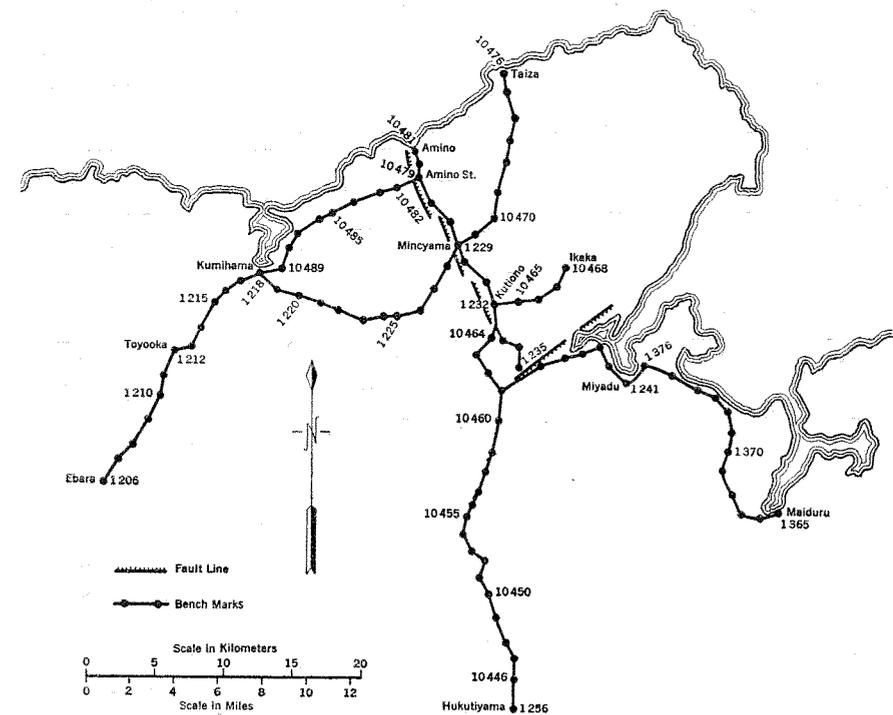

FIG. 10.—LEVELING TRAVERSES FOR USE IN OBSERVING EFFECTS OF THE TANGO EARTHQUAKE.

upheaval and the depression that occurred during the interval between successive surveys along one of the routes, are embodied in Fig 11. It is interesting to note that during the early stages of crustal re-adjustment, both sides of the fault lines moved independently toward each other, but later behaved as one block—especially the north and south lines—suggesting that the fault fissures were consolidating; and also that in the course of settling,

the disturbed areas moved upward at one time and downward at another, the movements gradually fading out.   Since in the profiles the curved routes are expanded into straight lines, it is somewhat difficult to visualize the real nature of the crustal movement.
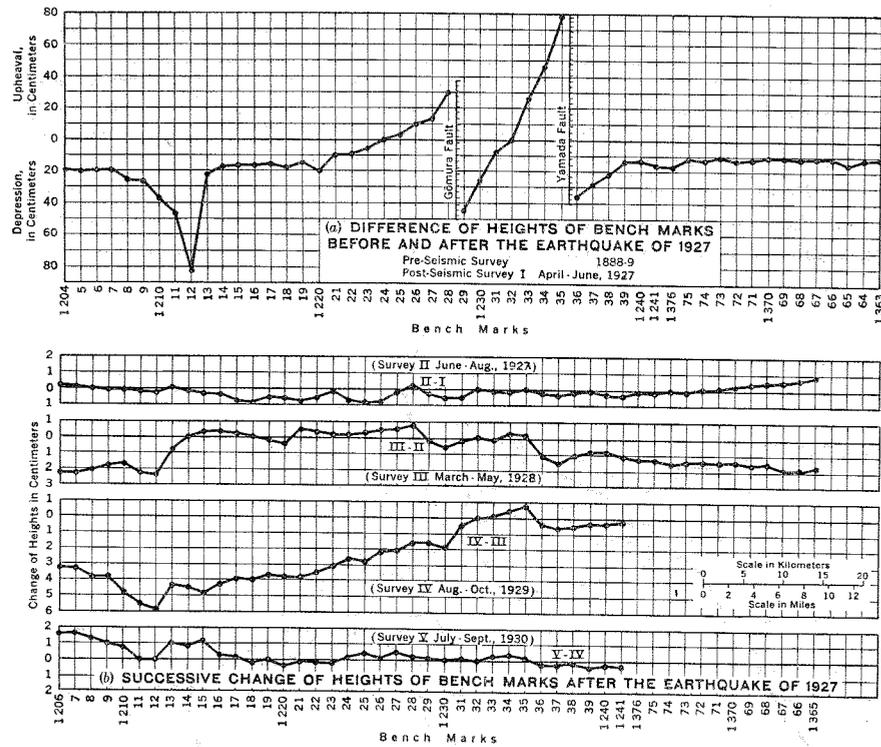

FIG. 11.—PROFILES SHOWING UPHEAVAL AND DEPRESSION THAT OCCURRED DURING EACH SURVEY ALONG ONE OF THE LINES SHOWN IN FIG. 10.

Mr. Tsuboi studied the nature of the movement by projecting on to vertical planes the vertical displacements along the curved routes, and found that, just as in the Kwanto earthquake, the crust is likely to consist of a number of separate blocks which move individually, independent of contiguous blocks.   Moreover, the last survey seems to indicate that the post-seismic crustal movement has at last practically come to rest after the continual re-adjustments that went on for four years.

2.—Triangulation.—After the earthquake, triangulation was also repeated three times, between May and June, between August and September, and between October and November, 1927.   The pre-seismic surveys were made between 1884 and 1889.   The displacements of principal triangulation points during each successive survey—taking the position of a point farther south of the affected area, as well as the direction of a line connecting this point to another distant point, as fixed—are shown in Fig. 12.

The diagram may be valuable for studying the nature of earthquakes. However, I refrain from discussing the subject, and will only say that several important investigations based upon these surveys have been made by members of our staff, such as that by Professor Terada on the distribution of the dilatation and the rotation of the ground over the disturbed area, the results of which have been published in the *Bulletins* of the Earthquake Research Institute of the Tokyo Imperial University.

3.—Tilting of the Ground.—The Ishimoto tiltgraphs were used for the first time after the Tango earthquake, to observe post-seismic crustal movements.   This instrument is essentially a horizontal pendulum with Zöllner's
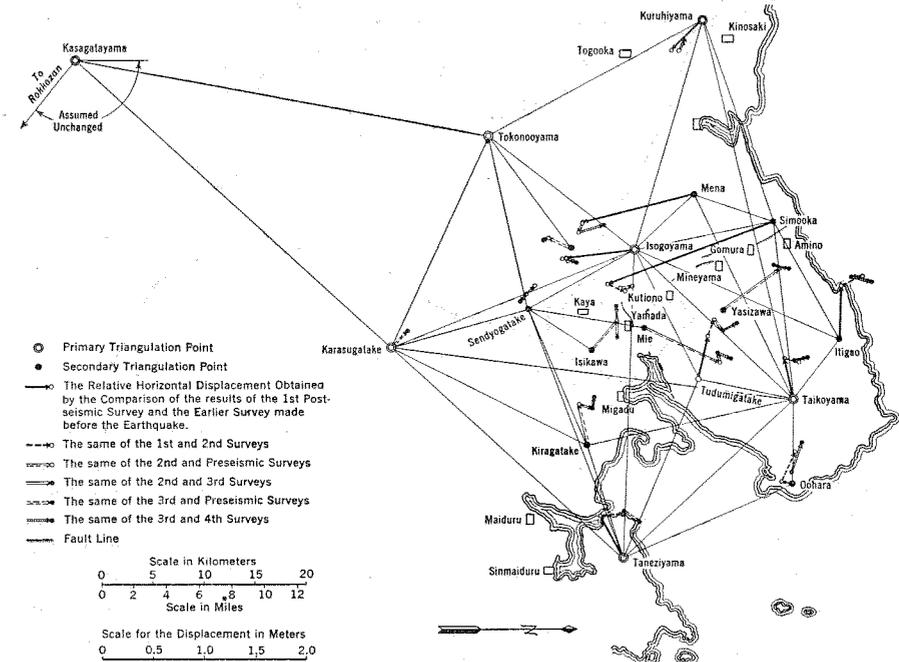

FIG. 12.—HORIZONTAL DISPLACEMENT OF TRIANGULATION POINTS OBSERVED AFTER THE EARTHQUAKE IN THE TANGO DISTRICTS, MARCH 7, 1927.

suspension and is made of fused silica throughout, in order to reduce to a minimum the effects of temperature variation.   It indicates ground tilts as small as $0°-0'-0.1''$.   The instruments were installed in two places in the disturbed region.   The important after-shocks seem to be closely related to the tilting of the ground.   This is shown in the vector diagram (Fig. 13) of the ground tilts, as recorded by the tiltgraph.   An Ishimoto tiltgraph is shown in Fig. 14.

It is seen that the occurrence of most of the strong after-shocks (marked by a ringed dot) was intimately correlated with the change of the direction of the ground tilt.   We are not sure, however, whether these tiltings were

due to meteorological causes or to subterranean changes. Whatever the
cause, we are not yet in a position to say that such tilting movements do
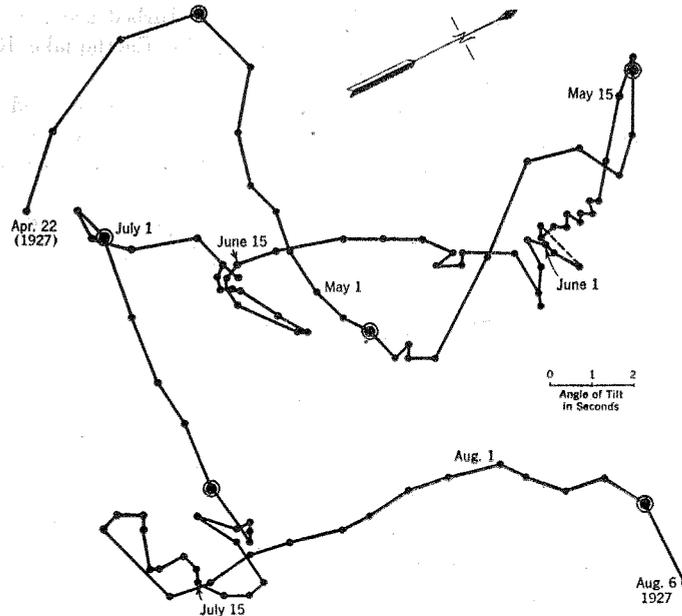unmistakably foretell an earthquake.

FIG. 13.—TYPICAL VECTOR DIAGRAM, SHOWING GROUND TILTS AS
RECORDED BY TILTGRAPH.

4.—Miscellaneous.—In addition to those mentioned, various other investigations were made, but it is beyond the scope of this lecture to describe all
of them in detail. As an example, however, I will mention a seismometric
triangulation that was made by Mr. S. Nasu, under the direction of Professor
Imamura. He determined the positions of hypocenters of after-shocks by
means of seismographs installed at four places around the epicentral region.
The distribution and position of the hypocenters thus found may prove to be
useful data for seismologists.

(III) THE NORTHERN IDU EARTHQUAKE

Since investigations of this destructive earthquake are still in progress
(September, 1931), the report will be somewhat incomplete.

1.—General Descriptions.—This earthquake, although very local in character, was destructive, causing a loss of 261 lives and the destruction of more
than 2 000 houses. According to Professor Imamura, the origin of this earthquake was in Longitude 139°.0 E. Latitude 35°.2 N. A great fault 30 km.
long appeared along a well-known tectonic line in a general north and south
direction, and running through the middle of the Idu Peninsula. The land
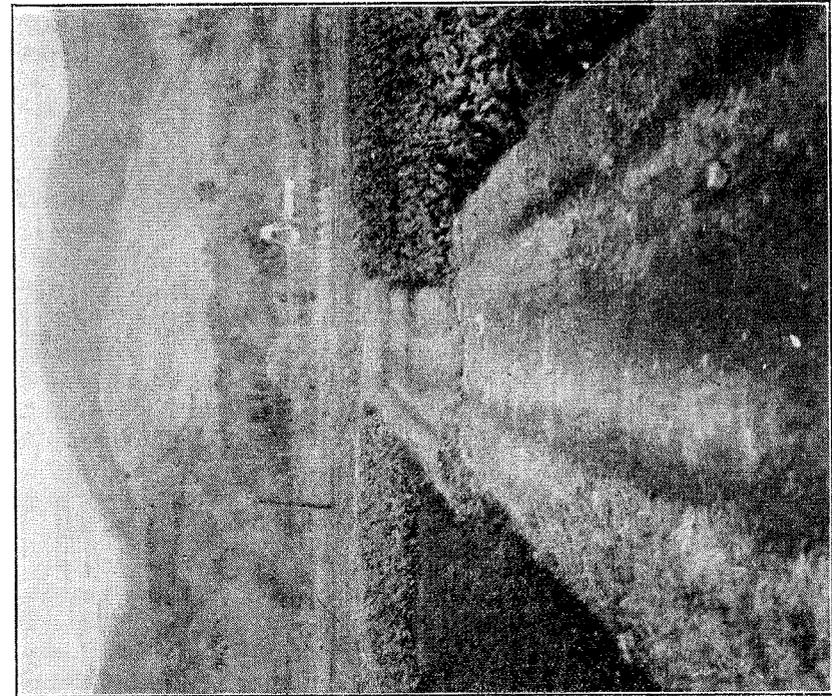east of the fault was displaced northward relative to that lying to the west

FIG. 15.—SEVERE EARTH DISPLACEMENT THAT OCCURRED IN MIDDLE OF
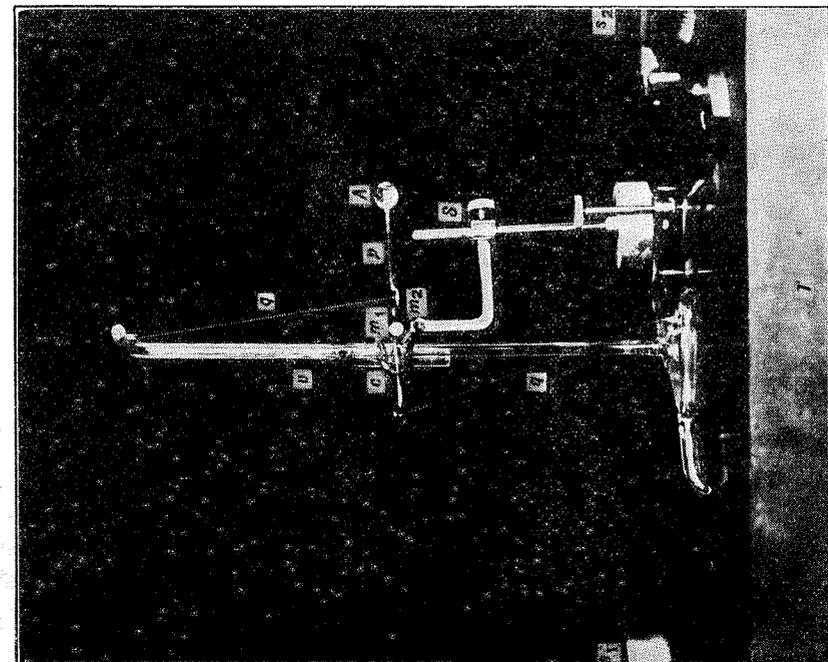THE IDU PENINSULA.

FIG. 14.—AN ISHIMOTO TILTGRAPH.

of it, the horizontal displacement being about 100 cm., as measured on the ground surface in the Tanna Basin, where the fault was well developed. (Fig. 15). This displacement phenomenon was especially interesting in that it was also observable inside the Tanna Railroad Tunnel, as will be described in detail later.

2.—Fore-Shocks and After-Shocks.—A remarkable feature of this earthquake was the great number of fore-shocks that began as early as November 7, preceding the main earthquake, and culminating in a shock on November 26, which attained destructive intensity. According to the Central Meteorological Observatory, 789 shocks were recorded at its observing station at Misima on the day previous to the occurrence of the main earthquake. A rapid succession of shocks, or earthquake "swarms," also began to occur on February 13, 1930, from the sea bed off Ito, a spa on the western coast of the Idu Peninsula, situated about 10 km. from the epicenter of this destructive earthquake. These earthquake "swarms" may also be regarded as fore-shocks. Perhaps they hold the record in frequency of occurrence, 3 715 shocks with motions exceeding 1 micron having occurred between February 14 and April 11.

The three-dimensional distribution of the hypocenters of the Ito earthquakes as determined by Mr. Nasu and others, with five seismographs installed at five places encircling the epicentral region, is shown in Fig. 16. It will be seen that the foci are clustered within a small, horn-shaped volume. Consequently, some are of the opinion that this seismic activity was due to the action of some dormant submarine volcano.[5]

3.—Ground Tilting Caused by Ito Earthquakes.—Ishimoto tiltgraphs were installed at two places (Ito and Kawana), near the epicentral region, in order to find the correlation, if any, between the titling motion of the ground and the earthquakes. Fig. 17 is a vector diagram showing the direction and magnitude of the ground tilts observed at Ito. The conspicuous shocks with their dates of occurrence are marked, the former with letters of the alphabet and the latter with numerals.

It will be seen that while one group of shocks was associated with a ground tilt toward the west, another group was associated with a tilt toward the south. During April, there was a period of quiet when tilting movements were hardly in evidence—possibly "marking time", thus appearing to confirm the seeming relationship of the crust tilts·to earthquakes. It should be noted, however, that although the earthquake of March 22 (marked *K* in the diagram), was very destructive, nothing like a warning of its coming was ever noticed.

Partly through unavoidable circumstances, and partly through lack of thought on my part, observations were discontinued in October. Unfortunately, the destructive earthquake of November 26 occurred before we had resumed observations as contemplated, thus causing us to miss excellent opportunities of observing crustal movements just before and after a destruc-

[5] "Recent Seismic Activities in the Idu Peninsula", by S. Nasu, F. Kishinouye, and T. Kodaira, *Bulletin*, Earthquake Research Inst., Vol. 9 (1931), No. 1.

tive earthquake, although, as we have subsequently learned, we could not have accomplished much because of the fact that the crustal movements connected with the main earthquake in this particular district were not at all conspicuous.
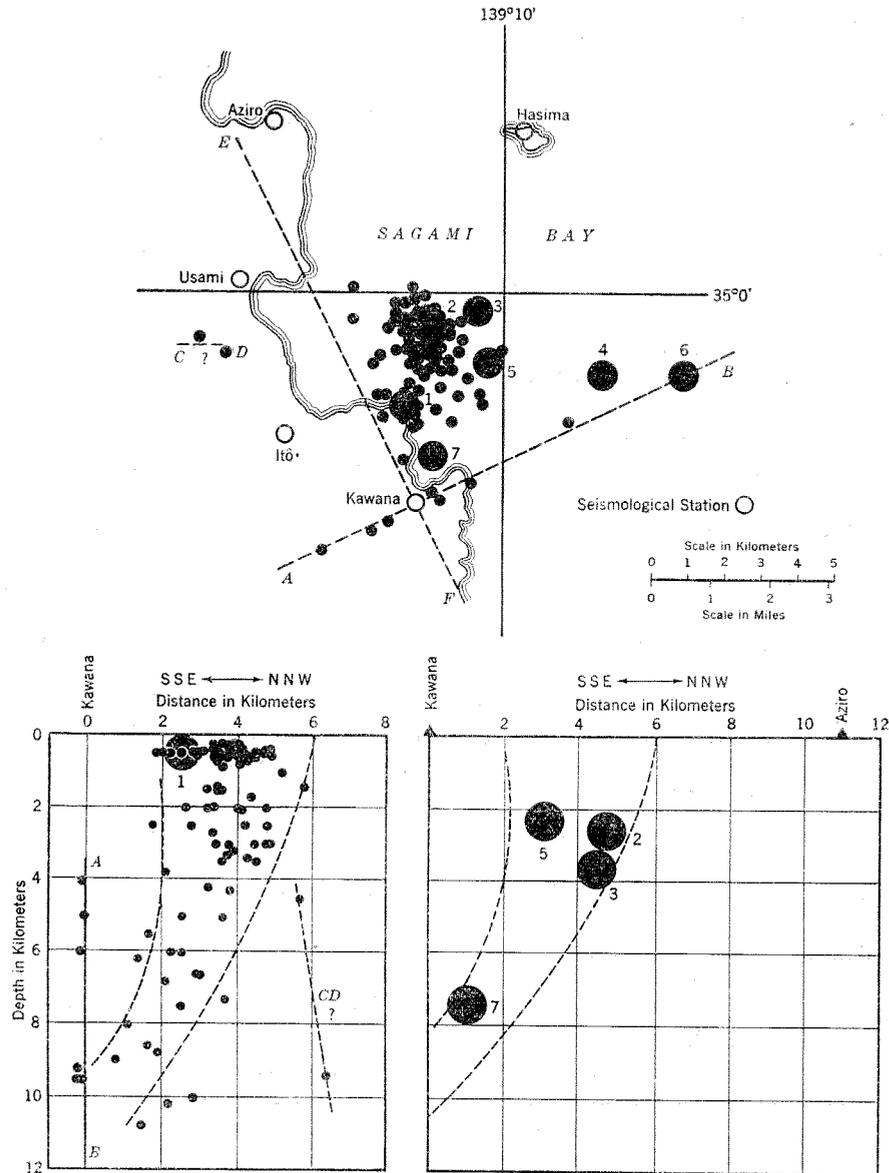

FIG. 16.—THREE-DIMENSIONAL DISTRIBUTION OF THE HYPOCENTERS OF THE ITO EARTHQUAKE.

4.—Precise Leveling and Triangulation.—On the other hand, we had seen the necessity of running a line of precise levels along a route passing close to the epicentral region of the Ito earthquakes, as shown in Fig. 18. The work was entrusted to the Military Land Survey Department and the survey was repeated along the same route, while the shocks were still going on.
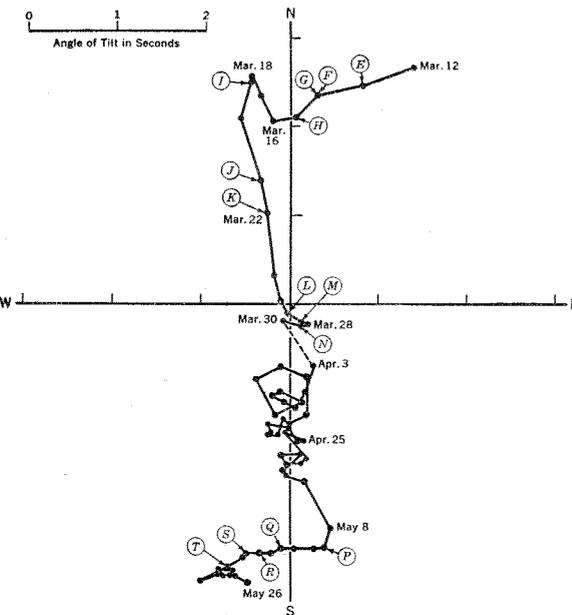

FIG. 17.—VECTOR DIAGRAM SHOWING THE DIRECTION AND MAGNITUDE OF GROUND TILT, OBSERVED AT ITO.

Thus—together with the surveys made by the Survey Department both before and after the Kwanto earthquake, and after the severe Idu earthquake on November 26—precise levels were repeated five times along this route. The vertical displacements observed after each survey as referred to previous findings are shown in Fig. 18.

The following points are worth noting:

(a) The destructive earthquake occurred while our second survey (marked II) was being carried out. Indeed, the survey between Bench-Marks Nos. 9 339-9 341, was made in one direction on November 25, the day previous to the occurrence of the earthquake, and in the opposite direction on the next day, just after the earthquake; no appreciable change, however, was observed.

(b) During the short interval of seven months between our first and second surveys, the coastal bench-marks facing the epicenter from which the seismic group originated upheaved enormously.

In addition to those just mentioned, the Land Survey Department, immediately after the destructive earthquake, ran precise levels around the Idu Peninsula, the northern route of which crosses a fault line. The vertical

displacements, referred to those of the previous survey, are shown in Fig. 19. Analyses and interpretations of these results were made by Mr. Tsuboi and other members of the Staff of the Institute, and were published in the *Bulletins*.

Triangulation surveys over twelve primary points and seventeen secondary points in the Idu Peninsula and environs were made in the summer of 1931, the results of which will soon be published in the *Bulletins* of the Institute.
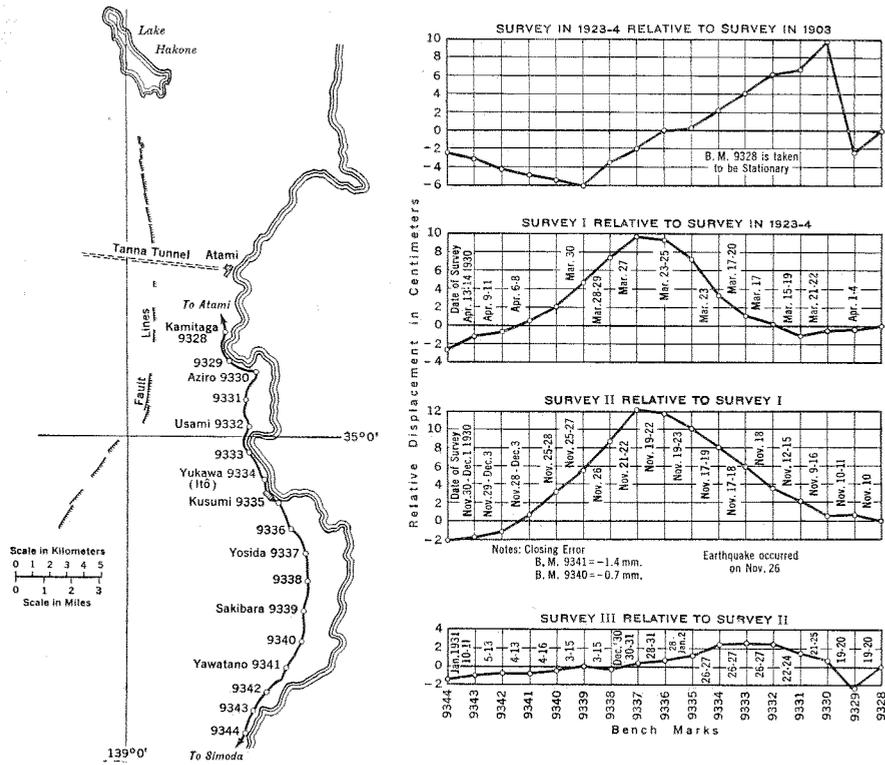

FIG. 18.—PRECISE LEVELS ALONG A ROUTE PASSING CLOSE TO THE EPICENTRAL REGION OF THE ITO EARTHQUAKE.

5.—The Tanna Tunnel.—In the location shown roughly in Fig. 18, a railroad tunnel having a total length of nearly 26 000 ft. is being bored in a general east and west direction. At the time of the earthquake, about 3 000 ft. remained unbored. (More detailed information is given in Fig. 20.) It will be seen that all fault planes are in a meridional direction, and that they crossed the tunnel perpendicularly. Of the four fault planes in the tunnel, the displacements of three were not serious, since they resulted in only slight cracks in the tunnel wall or small steps in the floor. One of them, which is probably a continuation of the main fault that appeared outside on the Tanna Basin, was very remarkable.

At the time of the earthquake, tunneling work from the west portal had proceeded to a point 11 920 ft. distant, where a muddy water-logged layer was encountered. It was along this muddy layer that the most remarkable dislocation occurred. At one end of the drain tunnels a sort of "slickenside"
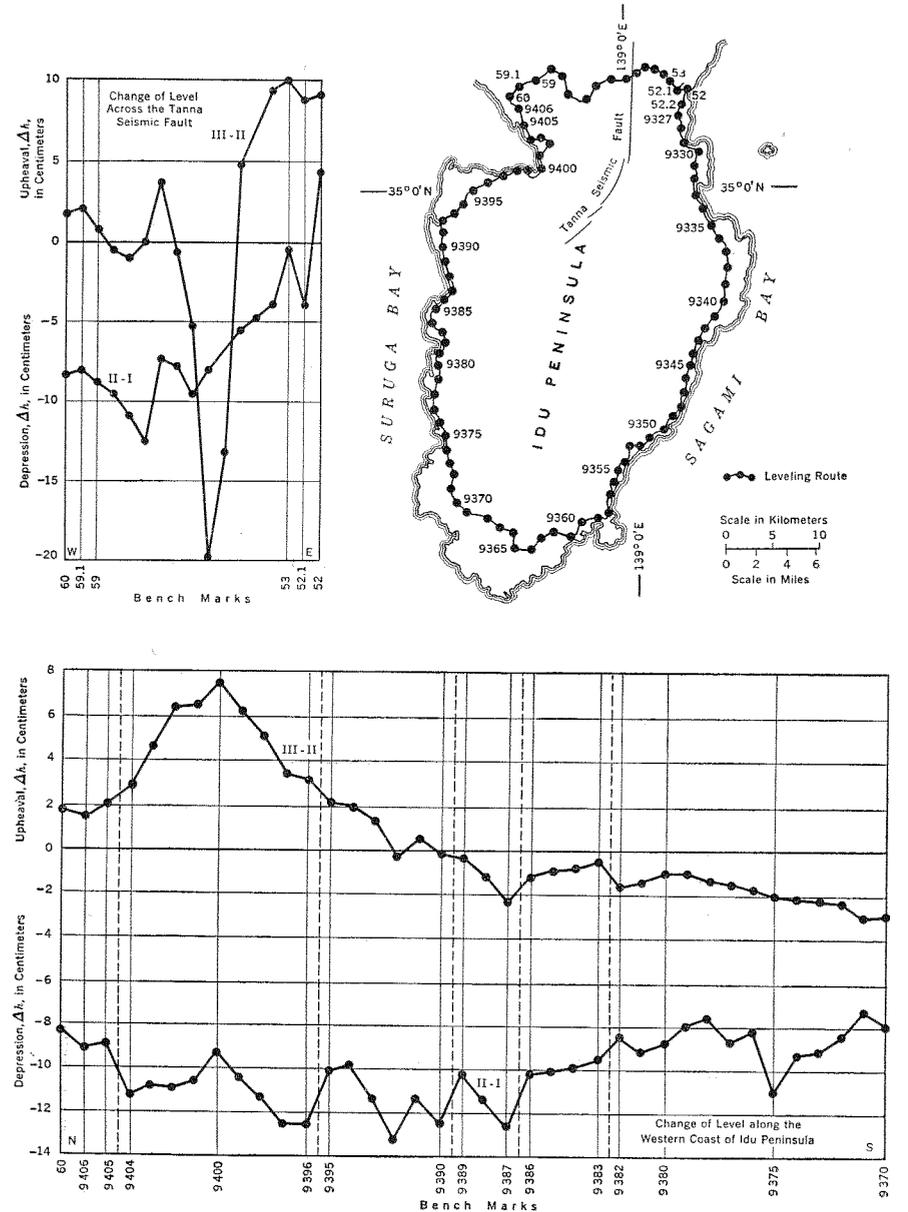
FIG. 19.—PROFILES AROUND THE IDU PENINSULA, TAKEN IMMEDIATELY AFTER THE IDU EARTHQUAKE.

FIG. 20.—EFFECT OF THE IDU EARTHQUAKE ON THE TANNA TUNNEL.

FIG. 22.—DIAL GAUGE FITTED TO STEEL RODS ON EACH END OF A FAULT PLANE IN THE TANNA TUNNEL.

FIG. 21.—FAULT PLANE THAT APPEARED IN ONE OF THE TANNA DRAINAGE TUNNELS AFTER THE IDU EARTHQUAKE.

or polished surface, due to dislocation at the fault plane, appeared, showing a relative horizontal displacement of nearly 8 ft. (See Fig. 21.) To measure the relative motion between the two sides of the fault plane, a stout steel rod was embedded in each side and the relative motion was measured by dial gauges fitted between the two rods. (See Fig. 22.) The observations that were begun on December 28, 1930, are still being continued (December, 1931). Although the observations were interrupted at the beginning (when our instrument was disturbed by the installation of another type of instrument by others), a general idea of the relative movement can be gained from Fig. 23. It is seen that in the earlier stage, the displacement had both northern and downward components, but the former component gradually decreased until now it can no longer be detected. The latter component also has diminished gradually, but at present (September, 1931), a displacement of 0.001 mm. per day is observable.

The deformation of the tunnel was surveyed twice by the engineers of the Railroad Department. The result, which is self-explanatory, is shown in Fig. 20. In addition to the aforementioned instruments, Ishimoto tilt-graphs have been installed in four places in the tunnel, for the purpose of measuring continuously the changes of level. The changes of level throughout its entire length were measured at intervals by Mr. R. Takahashi, of the Institute. As the changes of level have to be measured in seventy-two places, each 20 m. apart, the work is very laborious. It is accomplished by means of an apparatus designed by Mr. Takahashi himself, which essentially is a long flexible tube filled with water and fitted with micrometer screws at both ends, for measuring the heights of the free water surfaces. Thus far, this survey has been repeated five times, the results of which are shown in Fig. 24. It will be seen that the changes of level become smaller with time, thus showing the gradual settling of the disturbed crust of the earth.

6.—Underground Seismometry.—For seismometrical work, besides the seismographs that have been installed at several places in and around the disturbed area, two seismographs have been installed for the special purpose of comparing the seismic motions above ground and under ground. With this purpose in view, one instrument has been installed in the tunnel itself, about 500 ft. below the ground surface, and the other above ground on the Tanna Basin, in a position directly above the one in the tunnel. Observations with these instruments gave results very useful to geophysicists, but as they have an important bearing on engineering also, I shall refer to them in detail later.

(IV) Concluding Remarks

I have just given a general survey of geophysical research in connection with the investigations of the three destructive earthquakes, either already accomplished by us or taken up as subjects of intensive study. It has been necessary to confine the subject of this discussion to researches on destructive earthquakes. I have only been able to touch here and there upon even this limited subject. Those who are interested in a more detailed discussion should consult the original papers contained in the *Bulletins* of the Institute.
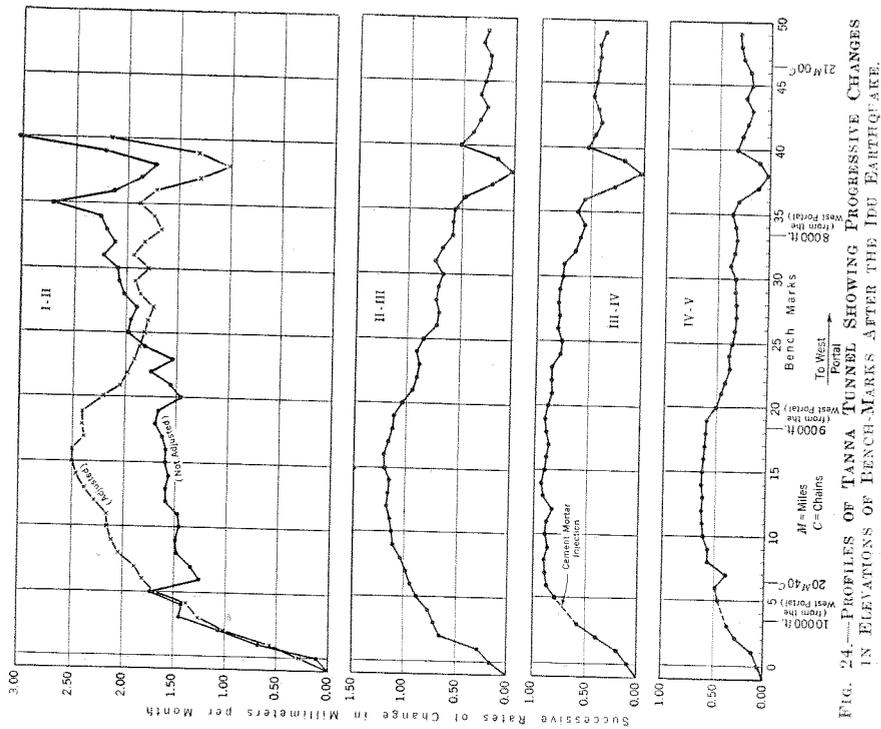
FIG. 24.—PROFILES OF TANNA TUNNEL SHOWING PROGRESSIVE CHANGES IN ELEVATIONS OF BENCH-MARKS AFTER THE IDU EARTHQUAKE.
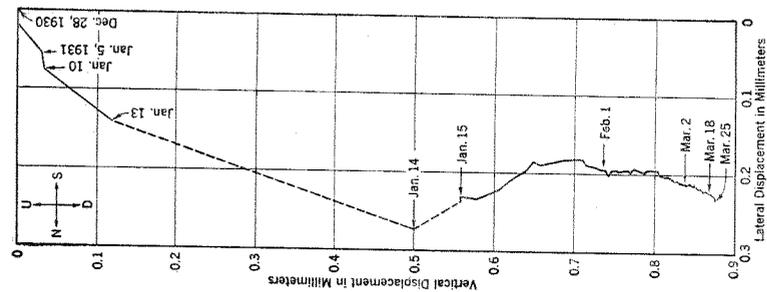

FIG. 23.—RELATIVE MOVEMENT OF STEEL RODS ON OPPOSITE SIDES OF FAULT PLANE IN TANNA TUNNEL.

I wish to take this opportunity to state that our activity is not limited to studies of destructive earthquakes, such as those I have mentioned. Since the establishment of the Institute in 1925, two destructive earthquakes have occurred. These have occupied so much of our attention that we have not had sufficient time to pursue the more fundamental researches. Nevertheless, in the meantime we have not neglected the other kinds of researches that have more direct bearing on urgent problems; nor have we neglected to make preparations for the study of fundamental problems. In addition to researches already mentioned in connection with the great earthquakes, such as seismometry, tilt-measuring, etc., the following work is now in progress, or is being planned for the immediate future:

(a) Construction of two underground chambers at depths of 30 and 60 ft., for the study of underground seismic motions.

(b) Construction of covered trenches in which to install 20-m. quartz scales, for continuous observations of length changes of the ground.

(c) Construction of a permanent seismological station inside the Tanna Tunnel.

(d) Continuous measurements of variations in the derivatives of gravity potential.

(e) Continuous measurements of the tilting of the ground by means of long water-tubes.

(f) Re-survey of heights of bench-marks on the leveling route over the middle part of the main island facing the Pacific.

(g) Occasional measurements of the altitudes of some mountains.

(h) Occasional precise levels of the City of Tokyo and its environs, and occasional measuring of the geodetic base line.

(i) Installation of accelerographs in various places to find the period of acceleration (not the period of motion), of earthquakes inherent to such localities.

(j) Concurrently with Project (i), observation of the inherent period by means of the seismic motion analyzer.

(k) Installation, in suitable localities, of perfect recorders for destructive earthquakes.

(l) Installation of strong earthquake recorders in certain suitable office buildings.

(m) Installation of strain-meters in certain buildings.

(n) Construction of a large shaking-table.

(o) Geological survey of Northern Idu.

(p) Mathematical investigations.

(q) Frequent soundings of Sagami Bay by Langevin's sounding machine. This plan has been proposed to a wealthy man interested in such research, but its realization is not certain.

Thus far, I have referred principally to the work done by our Institute; but that is not the only work done in Japan. The Central Meteorological Observatory and the Geophysical Institutes in the various universities have

accomplished many important investigations, although none of them is interested in the engineering side of seismology, which is the principal subject of this lecture.

For an excellent account of Japanese seismological research, past and present, I recommend the paper by Professor T. Terada, entitled "A Historical Sketch of the Development of Seismology in Japan," and published in "Scientific Japan," a pamphlet distributed to the members who attended the Third Pan-Pacific Congress, held in Tokyo in 1926. In this paper a concise digest is given of all seismological work accomplished in Japan from the time of its first inception until 1926. The work accomplished by our Institute is reported twice each year to Dr. V. Conrad, the Editor of *Gerlands Beiträge zur Geophysik,* and is published in that magazine.

Earthquake Prediction.—Earthquake prediction is naturally very keenly desired by every one living in a seismic country, and it has been the subject of speculation throughout all ages. Even in the present age of scientific development, a destructive earthquake has never been predicted. Instead, we are accustomed to hear after the shaking is over that such and such phenomena had taken place before the occurrence of the earthquake, and that if such phenomena had only been observed beforehand, the prediction might have been possible. It is a pity that in such a case we hear very little of the casual relation of the pre-seismic phenomena to the occurrence of the earthquake, and of whether the occurrence of the earthquake correlated with certainty or merely with some probability to the pre-earthquake phenomena, if correlation did really exist.

Even if earthquake prediction were possible, it must include a complete forecast of the time of occurrence, the place, and the intensity; none of these three items must be lacking. Suppose that a seismologist forecasts that an earthquake of unknown intensity—that is, whether it will overthrow buildings or whether it will be felt only by a tromometer—will take place in a certain locality at a certain time. The result will only be the causing of needless anxiety on the part of the public. In Tokyo, for instance, it is not uncommon to feel the ground shake once or twice in some weeks. For the inhabitants of such a district it is better that they have only incomplete forewarning, without any information as to probable intensity. A vague warning such as is sometimes given by careless seismologists, stating the locality and the probable intensity, but without giving any information as to the time of occurrence, is worse than useless for people living in a seismic country, even if it were a correct guess. In a sense, such a prediction is like stating that we are sure to die sooner or later.

Now let us consider briefly the prospects of earthquake prediction in the light of modern seismology.

(a) Meteorological Phenomena.—The occurrence of earthquakes, no doubt, has an intimate connection with meteorological phenomena, such as barometric pressure, its gradient, precipitation, tides, etc. In fact, their intimate correlation with earthquakes has been confirmed statistically by several investigators; but evidently meteorological phenomena merely act as a "trigger" for

starting the earthquake. An unloaded gun cannot be fired by pulling the trigger. Meteorological cause alone is unable to start an earthquake in an unstrained crust or by disturbing the equilibrium of quasi-solid magma. It is very probable that a minor cyclone which passed over the earthquake zone shortly before the occurrence had acted as the "trigger" that precipitated the destructive 1923 earthquake; but cyclones of equal or still greater intensity have passed over the same zone before, without starting an earthquake. Moreover, even if we admit that certain meteorological phenomena do unmistakably bring about an earthquake, the intensity of the induced earthquake may have no relation whatever to the meteorological phenomena. Thus, it seems that meteorological phenomena are not essential data for earthquake prediction.

(b) Crustal Movements.—In some quarters it is believed that an earthquake can be predicted from crustal movements, such as the tilting of the ground, the chronic rising or sinking of the land, the changes in the length of the land, and the like; but until we acquire more geophysical knowledge in these respects than we have at present, I cannot support such a view. It is an acknowledged fact that earthquakes are frequent where bradyseismical (slow or gradual) crustal movement is noticeable. We do not know, however, at what stage of a crustal movement of a certain type an earthquake starts in a certain district with a certain intensity at a certain time. Such a problem corresponds to that of the happening of a single one of a great number of events, the occurrence of which is governed by some statistical law yet to be found. To predict the occurence of such an event with certainty is almost hopeless.

According to our observations, the after-shocks of the destructive Tango earthquake and the Ito earthquake were closely correlated with the manner in which the ground tilted. The ground tilts were in turn correlated with the tides; but as already mentioned the manner of correlation is quite different in the two cases. In the case of the Tango earthquake, remarkable after-shocks occurred at the time the tilting of the ground temporarily ceased and began to change its direction (see Fig. 13), while in the case of the Ito earthquake, conspicuous shocks took place while the ground continued to tilt in a certain direction (see Fig. 17). The only condition that was common to both, was the absence of any signs foretelling the intensity of the earthquake that was to come.

Little information is available regarding the linear changes of geodetic base lines. Only one example has been shown (Figs. 8 and 9). If we accept the theory that the peculiar compressional motion observed just before the great earthquake is indicative of changes in the earth's crust that precede a violent convulsion, we should have expected another great earthquake in 1930; but, unfortunately, events have not proved it. Some one interpreted the available data to mean that that particular compressional strain was the harbinger of the Idu earthquake. Even so, the same peculiar compressional strains foretold on one occasion a tremendous earthquake affecting a vast area, and on the next occasion a destructive but local earthquake of different origin. Thus, so far as present knowledge goes, linear ground changes cannot serve as data for the complete prediction of an earthquake.

From the map showing the vertical displacement of the ground in Central Japan (Fig. 4), it will be seen that bradyseismical motion in Japan is very remarkable. If the elevations and depressions of the ground are unmistakable signs of the immediate occurrence of a destructive earthquake, then there is not a piece of land in Japan to-day that is not in imminent danger. Obviously, such is not the case.

In connection with this subject, it is necessary to make a brief mention of the upheaval of the Miura Peninsula, which is alleged to have taken place before the great 1923 earthquake. Common sense, derived from experience with the testing of materials, leads us as engineers to look for some sign preceding the crustal convulsion. It is a pity that we were not successful in obtaining a clue based upon something scientifically sound. As has already been mentioned, the apparent slow upheaval of the sea coast of Aburatubo preceding the great earthquake, as recorded by a mareograph installed there, was carefully analyzed by Professor Terada and Mr. Y. Yamaguchi, who found that the apparent upheaval was attributable to meteorological causes, rather than to any actual upheaval of the land.

It is true that an Omori tiltgraph in the Seismological Institute at the Tokyo Imperial University apparently indicated a gradual change of the inclination of the ground prior to the earthquake; but it must be remembered that the instrument, which is an ordinary long-period horizontal pendulum made of metal with a smoked drum recorder, was not suited for measuring a very small tilt. Moreover, the tilting of the ground where the University is situated is rather easily induced, either directly by precipitation, or indirectly by its cooling effect, and, unfortunately, on the very morning of the day of the great earthquake, the earthquake zone had received a shower followed by intense summer sunshine. The meteorological elements might have strongly influenced the tilting of the ground.

Professor Imamura has concluded, no doubt after taking into consideration the facts just mentioned, that an unusual pre-earthquake tilting actually did take place. Such a pre-earthquake tilting, granted that it did occur, cannot be taken as an indisputable warning of a destructive earthquake, because according to subsequent researches made by Mr. M. Ishimoto, of our Institute, and Mr. M. Tsuji, of the Astronomical Observatory, in which the more reliable Ishimoto tiltgraphs were used, tilts much larger than that claimed to have taken place just before the great earthquake were frequently registered in the Observatory grounds at ordinary times. Furthermore, on June 17, 1931, Tokyo was shaken by a fairly severe earthquake shock with its epicenter very near the Observatory grounds, and Mr. Tsuji found that no unusual tilting was observed either before or after this earthquake. Thus, tiltings of the ground, too, cannot be taken as indisputable signs of earthquakes.

I shall not discuss other phenomena, such as changes of ground-water level, changes in temperature of hot springs, changes in earth electric currents, disturbances of terrestrial magnetism, etc. There is no doubt that they are all in some way or other intimately related to earthquakes, but if they and other geophysical data, such as the form of the geoid and gravita-

tional acceleration, are properly examined, we should be able to throw considerable light on seismology, but it is a regrettable fact that, thus far, we have not been able to find a single indisputable sign by which we can foretell the coming of a destructive earthquake. Notwithstanding the meager appropriation of funds for research, we are doing our best to discover such a sign.

However, as to the possibility of complete prediction, foretelling not only the place, but also the time and the intensity of a destructive earthquake, I am rather pessimistic. While on this subject of earthquake prediction, I wish to acquaint you with what our most prominent geophysicist, Professor Terada, has said in his valuable essay entitled "Prediction of Natural Phenomena."

After mentioning the difference in the macroscopic and microscopic points of view, with special reference to the disposition of crystals in a labile supersaturated solution, he proceeds to the discussion of earthquake prediction. He states that, taking for granted that an earthquake is due to the failure of the elastic equilibrium of the earth's crust, under a certain definite law (actually not yet known), and that the measurement of the strain and other similar elements is possible in every detail, yet even in such a case accurate prediction of the time of occurrence will be impossible, because it resembles the starting of the crystallization of one particular crystal in a supersaturated solution, in that it is governed by some accidental microscopic condition. Needless to say, in this case the macroscopic condition that the solution is supersaturated indicates the possibility of the starting of crystallization as a whole. According to him, in the present state of our knowledge of seismic phenomena, we must rely upon the method of statistics, which ought to be elaborated before arriving at a definite conclusion.

I am of the same opinion as Professor Terada; but although we are unable to predict an earthquake in the strict sense, there seems to be little doubt that some day it will be possible for us to judge whether or not a district as a whole is in immediate danger, and thus to provide against a future destructive earthquake.

It is the duty of seismologists to hasten that day as much as possible. Until such a day comes, and even after it has come, security against earthquakes, in seismic countries, is entirely in the hands of the engineer. My anxiety, therefore, is not so much concerning the inability of seismologists to find Nature's unmistakable warnings of an impending destructive earthquake, as in the present indifference of the majority of architects and engineers to earthquake problems.

LECTURE II
ENGINEERING SEISMOLOGY

SYNOPSIS

Differences between basic data needed by the engineer and the geophysicist are outlined in this lecture. Ordinary types of seismographs are entirely unsuited for recording the motion of severe earthquakes directly on the site, because they must also be delicate enough to record far distant tremors. Requirements for the "strong-motion" seismograph and accelerograph that offer the best possibilities of supplying useful data to the engineer, are stated.

From observations and studies of the earthquake of 1923 in Tokyo, Dr. Suyehiro concludes that at present the best value to use as a guide to building construction is an acceleration of 0.15 g, although there was abundant evidence to show that still greater accelerations occurred in the epicentral region. Since, even in the most seismic country, however, any building is likely to be subjected to destructive earthquakes only once or twice in its lifetime, the element of economy enters the problem. Despite the fact that the 1923 earthquake was the most severe in the record of seismic history buildings designed on the basis of 0.1 g resisted damage quite well.

The lecture contains illustrative comparisons of simultaneous vibrographs recorded in building frames and in the adjacent ground. A seismic vibration analyzer that works on the principle of selective resonance as in Hartmann's reed frequency meter has been devised by Dr. Suyehiro. The records obtained by his instrument brings out the prevailing natural periods in any locality being studied.

In the design of buildings it is important to consider the relation between the natural period of the structure and that of the ground, the damping effect of the ground, and the mutual action between the ground and the foundation of a building. These problems are virtually impossible to compute mathematically, but one feasible solution seems to be experimentation with models, designed to satisfy the law of mechanical similitude. Experiments with models of wooden buildings are mentioned.

INTRODUCTION

Correct seismometric data are equally important for the geophysicist and for the structural engineer; but their needs are not the same. The former, particularly those in Europe, aim to observe the different phases and forms of earthquake waves with the view of locating the position of the origin of the earthquake, to find the velocity of propagation of the seismic waves, and to

study the nature of the different strata forming the earth's crust, etc. For the structural engineer in seismic countries, however, many of such data have little value, although they may interest him indirectly. The duration of preliminary tremors of an earthquake, for example, is of great interest to geophysicists; but structural engineers are generally indifferent to such things. The information urgently needed by the engineer is the intensity and the nature of the principal motions of destructive earthquakes.

The work of seismometric observation is usually in the hands of the geophysicist, who naturally uses seismographs suitable for his object of observation, namely, those instruments having high sensitivity and little stability. It is quite natural, therefore, that whenever a severe earthquake occurs, the recording styluses of all seismographs installed in the strongly shaken districts swing off their recording drums as soon as the principal motion of the earthquake begins, thus at best giving only the record of the preliminary tremor. Indeed, the fact that the recording stylus swings off the drum is generally taken to be evidence of a severe earthquake. Under these circumstances, we have not yet succeeded in obtaining a single complete and reliable diagram of a destructive earthquake, by a seismograph installed near its centrum, to say nothing, for the present, of accelerographs which are more important to engineers than seismographs.
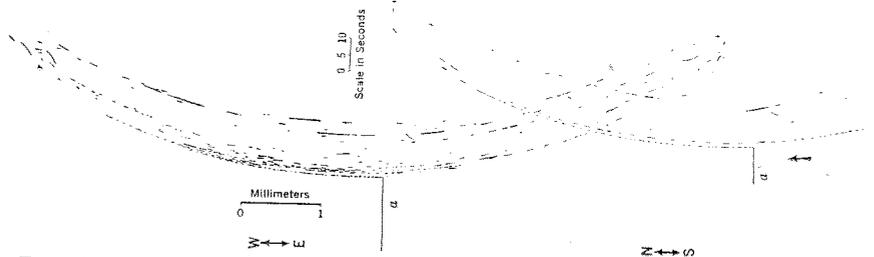

FIG. 25.—PARTIAL RECORD OF THE IDU EARTHQUAKE TAKEN IN THE EPICENTRAL REGION.

By "seismographs" I mean those instruments whose natural period is longer than the periods of any earthquake motions, and that are intended to record the earthquake motions themselves; and by "accelerographs" I mean those instruments whose natural period is shorter than the periods of any earthquake motions, and that are intended to record directly the accelerations due to such motions.

Accordingly, the intensities of acceleration claimed for past great earthquakes are merely guesses, having generally been estimated from the overturning or the displacement of tombstones, and other similar phenomena. Obviously, such methods are too crude, and sometimes even misleading for several reasons: First, the friction of solid bodies when subjected to a complicated vibration cannot be determined; and, second, as a rule, at the very beginning of a destructive earthquake of near-by and shallow origin, the motion starts suddenly. Fig. 25 is a partial record of the recent Idu earthquake to which I have already referred, taken in the epicentral region. Although the apparently abrupt motion at the moment of starting may be

due partly to the sudden release of the recording mechanism of the seismograph from the initial friction, or to the play in the mechanism, yet a more or less jerky start of the seismic motion is scarcely to be doubted.

The impulsive starting of a violent earthquake in the epicentral region was shown very clearly in the Tajima earthquake of 1925. On that occasion, in a village primary school in the epicentral district, copper coins saved by the children were kept in an empty tin can and covered with a lid. It was observed by the school-master that at the moment the earthquake began, the coins threw off the cover and jumped from the tin can, which was still standing. This phenomenon shows that at the beginning of the motion, the vertical acceleration was more than g, the acceleration due to gravity. As a matter of fact, however, the school building (a two-story wooden house), withstood the earthquake well, although it suffered more or less damage.

A motion of an impulsive nature, such as the blow of a hammer, can cause the shifting or the over-turning of small rigid objects, but evidently cannot cause damage to buildings having more or less flexibility. In some cases the intensity of a violent earthquake estimated in the manner referred to may be just such an initial acceleration, which, however, is not the information urgently needed by engineering seismologists.

Therefore, information regarding the intensity of an earthquake must be that obtained in a scientific manner from a reliable record given by a suitable instrument. Indeed, some records were obtained by seismographs in the 1923 Kwanto earthquake, of which I have already given a detailed description, and if those records are trustworthy, they would furnish valuable information, apart from the fundamental question regarding the value of seismograms, which will be considered later.

(I) STRONG-MOTION SEISMOGRAPHS

Before proceeding to the examination of these records, let us consider briefly the requirements necessary for a strong-motion seismograph, in order to see, on the one hand, if the instruments that registered the violent earthquake had been properly constructed, and, therefore, were serviceable; and, on the other hand, to see what the future design of this kind of instrument ought to be.

(1).—Type.—Let us first consider the type of the instruments. Among the horizontal seismographs, the horizontal pendulum type introduced by Professor Ewing is most widely used. Although for ordinary use the advantages of his principle in seismometry are scarcely to be doubted, it seems that for measuring an earthquake of unusual strength, there remains much to be desired.

Now let us inquire whether or not an instrument constructed under this principle is suitable for measuring a violent earthquake. As I have reported elsewhere[6], the horizontal pendulum ceases to be a faithful recorder if it is subjected to a strong acceleration in the horizontal direction perpendicular to the motion which the instrument is intended to record.

6 *Proceedings*, Imperial Academy, 3 (1927), No. 3; see, also, Gutenberg's Handbuch der Geophysik, Vol. IV, 2, p. 387.

Let the free oscillation of a Ewing horizontal pendulum (Fig. 26) be given by,

$$I \frac{d^2\theta}{dt^2} + M g \phi l \theta = 0$$

in which,

$I =$ mass moment of inertia of bob weight (including accessories) about the pivoting axis, AC;

$M =$ mass of bob weight;

$l =$ distance of center of mass from pivoting axis;

$\phi =$ inclination of pivoting axis to the vertical; and

$\theta =$ angle of oscillation of the central plane, CD, about the position of equilibrium, CE.
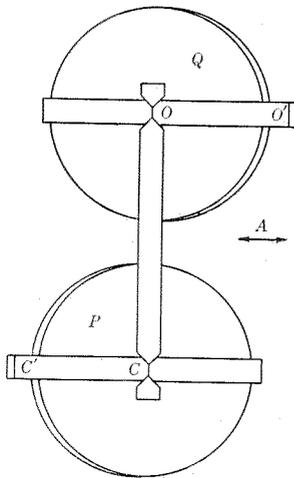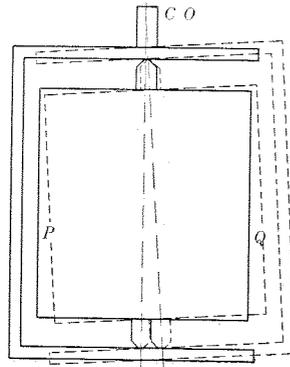
When the instrument is subjected to a harmonic oscillation (of maximum acceleration, α, and of circular frequency, p) in the longitudinal direction (H), horizontally, as stated, it can be shown that the motion of the pendulum is given by the equation,

$$\frac{d^2\theta}{d\tau^2} + \left\{ p_0 + p_1 \left(l^{2i\tau} + e^{-2i\tau} \right) \right\} \theta = 0 \dots\dots\dots\dots(2)$$

in which,

$$\tau = \frac{p}{2} t; \ p_0 = \frac{\dfrac{M g \phi l}{I}}{\left(\dfrac{p}{2}\right)^2}; \ p_1 = \frac{1}{2} \frac{\dfrac{M \alpha l}{I}}{\left(\dfrac{p}{2}\right)^2}; \ \text{and} \ i = \sqrt{-1}.$$

Equation (2) is a particular form of Hill's equation, named after G. W. Hill, an eminent American astronomer. As the equation is very important to astronomy, thorough investigations have been made of it, and it has been described in several textbooks dealing with advanced differential equations; therefore, it is not necessary to recapitulate them herein. It may be mentioned, however, that a deduction from the differential Equation (2) shows that when the longitudinal acceleration, α, is large, the horizontal pendulum loses its stability, this effect being especially conspicuous when the frequency of the longitudinal motion is one-half the natural frequency of the instrument. A record under such circumstances is obviously untrustworthy.

This behavior of the Ewing horizontal pendulum need not be specially considered in the case of an ordinary seismograph for measuring distant earthquakes, but in constructing a strong-motion seismograph it is very important.

To eliminate this undesirable feature of the Ewing horizontal pendulum, the simplest way is to make its natural period of oscillation large, retaining its stability to a reasonable extent. The only way to attain these two counteracting requirements simultaneously in a simple manner is evidently to make the size of the instrument sufficiently large. Another less simple but practicable method which I propose is to arrange a pair of Ewing horizontal pendulums of the same construction side by side, in opposite directions and parallel to each other, the bracket frames holding the bobs being united by a coupler link over the axis holding the weights (Fig. 27). When such an arrangement is subjected to an accelerating motion in the longitudinal direction, obviously, the instability, if any, of one of the pendulums is compensated by the increased stability of the other, and the instrument is thereby prevented from making an undesirable motion.

(2).—*The Length of the Boom.*—For ordinary seismographs, the length of the arm is immaterial; but for a strong-motion seismograph this matter must not be overlooked. It will be seen that when a seismograph with a short arm is subjected to a vibration having a large amplitude, its behavior can no longer be inferred from the theory of forced harmonic motion, as it then belongs in the category of forced pseudo-harmonic motion. No mathematics are needed to see that, if the amplitude of an earthquake is comparable to the length of the arm, the insensibility of the bob to the external motion can scarcely be expected.
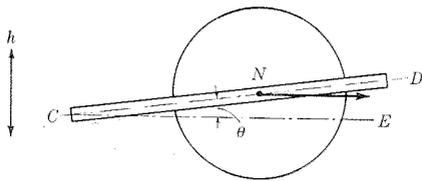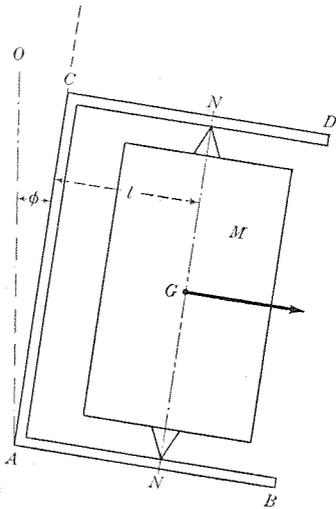
FIG. 26.—DIAGRAMMATIC SKETCH OF EWING'S HORIZONTAL PENDULUM.

FIG. 27.—PROPOSED ARRANGEMENT OF TWIN EWING PENDULUMS.

For this reason, the arm must be sufficiently long; but it must be borne in mind that the longer the arm the more sensitive is the instrument to the tilting of the ground, so that too much length is not desirable; 1 m., or so, seems to be the proper length.

Besides these fundamental requirements, there are several minor but no less important points advisable in the construction of a strong-motion seismograph, as follows:

(1) The instrument should be capable of recording a maximum amplitude of vibration of ground equal at least to 30 cm.

(2) Every part of the apparatus should have ample strength and stiffness.

(3) The record of motion should not be multiplied, but on the contrary it should be reduced, say, to one-half.

(4) The bob should be sufficiently heavy, so as to prevent it from being dragged by the friction of the recording point and other parts.

(5) The natural period of the pendulum should be sufficiently long; but if it is obtained only by greatly lessened stability, the period to a certain extent, should be sacrificed to stability.

(6) The construction of the axis of suspension should receive careful attention so that the connection does not give way under a strong impulse. The use of ball-bearings immersed in lubricating oil is advisable.

(7) The recording drum should have an ample margin of length at both ends, so as to insure a perfect recording of an earthquake, even when it occurs at the beginning or at the end of a record.

(8) A delicate damper often becomes a cause of trouble.

(9) The use of clock-work for driving the recording drum is not advisable, but if its use is unavoidable (for instance, for seismographs to be used in country districts), the speed governing the rotation should be regulated by an eddy current brake, or by a suitable governor, but not by an air-brake.

(10) To obtain a diagram with open time scale (as distinguished from condensed scale), the circumferential velocity of the recording drum should be as high as possible (say, at least 12 cm. per min.). For this purpose alone, the use of an electric motor having a uniform rotation for driving the drum is highly recommended. Needless to say, in this case the electric current should not be taken from the municipal supply.

(11) The trigger arrangement for starting the recording drum is not convenient for estimating the period of motion, owing to the accelerating speed of the drum at the beginning. If it is used, the recording stylus or the beam of light (but not the drum), should be controlled by the trigger. I had two bitter experiences with the trigger arrangement. On a certain midnight, a slight fore-shock preceding the main disturbance started the recording arrangement (described in Lecture III) before it could record the main shock. On another midnight, a distant earthquake caused the same premature starting, so that no record was taken of the main disturbance.

(12) The time should be marked independently of recording points. Simultaneous use of the recording point as a time marker is objectionable.

(13) The bed-plate of the instrument should be strongly attached to the ground by studs or by other means.

(14) The instruments should be well protected from injury by falling débris.

In the foregoing I have merely enumerated precautions and suggestions so far as my knowledge permits, from past experience. I am, therefore, afraid that other equally important matters have not been mentioned.

(II) Intensity of the Destructive 1923 Earthquake

Having described the necessary requirements for a strong-motion seismograph, let us now revert to the question of the intensity of the 1923 earthquake.

True, some records of this earthquake have been taken, as previously mentioned, but none of them was successful, being either incomplete or unreliable. Moreover, it is regrettable that at that time we had neither the seismographs satisfying the necessary conditions just enumerated, nor any accelerographs. For the purpose of reference, however, I will show some diagrams obtained by seismographs. One of them (Fig. 28) gave a comparatively continuous record, but was nevertheless imperfect.

The record in question was obtained by a seismograph, the particulars of which are, as follows:

Type	Ewing's horizontal pendulum.
Length of arm.............	20 cm.
Weight of bob..............	2.1 kg.
Natural period of pendulum..	10 sec.
Drum	Driven by clockwork controlled by an escapement.
Damper	Vane immersed in oil bath.
Pointer magnification	Two times.
Peripheral speed of recording drum	4 cm. per min.

From what I have said before, it is seen that in many respects this instrument was not suitable for registering a violent earthquake, especially one like that of 1923, in which the main motions had enormous amplitudes and long periods.

However, Professor Imamura, after a careful examination of this record, concluded that at the beginning of the principal motions (marked fg in Fig. 28), the full amplitude was about 9 cm. and the period about 1.3 sec., for which the computed acceleration proves to be about one-tenth of the acceleration due to gravity. It is a pity, however, that not only did the point of the stylus for the north-and-south (NS) component run off after a few oscillations of the principal motion, but the record of the other component shows that the motion of the earthquake exceeded the maximum limit of amplitude allowed for recording. No doubt the record is very valuable, yet it failed to give us information urgently needed by engineers, aside from the more basic question of the seismograph records themselves.

However, as the preliminary portion was perfectly recorded, this record is invaluable to geophysicists. Indeed, it was by means of this record that

within half an hour of the occurrence of the great earthquake, Professor Imamura located its origin with confidence and explained the nature of the earthquake to the general public.
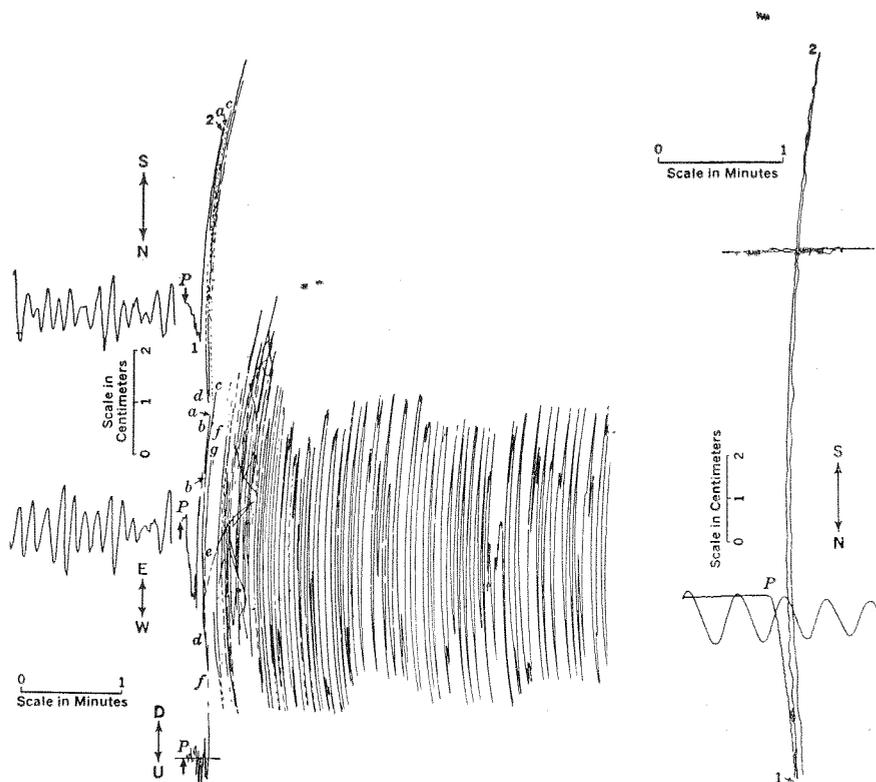

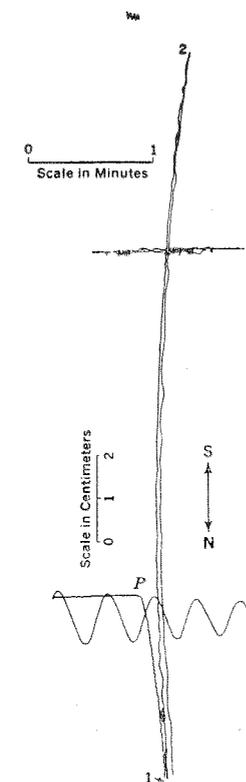FIG. 28.—SEISMOGRAPHIC RECORD OF THE 1923 EARTH-QUAKE BY MEANS OF A EWING HORIZONTAL PENDULUM

FIG. 29.— SEISMOGRAPHIC RECORD OF 1923 EARTH-QUAKE BY MEANS OF OLD-FASHIONED OMORI HORIZONTAL PENDULUM (T_o = 40 sec.; V_o = 1½).

Now let us examine another record given by a seismograph that was more suitable for registering a violent earthquake. (See Fig 29.)

The instrument had the following characteristics and constants:

Type	Omori's horizontal pendulum.
Length of boom	1 m.
Weight of bob	15 kg.
Natural period of pendulum	40 sec.
Drum	Driven by clockwork controlled by an air-brake.
Damper	None.
Magnification	1.5 times.
Peripheral speed of drum	4 cm. per min.

It will be seen that this instrument was more suited to registering a violent shock than the one previously described. In fact, successful recordings of several other severe earthquakes in the past proved its competency; but, unfortunately, the pointer went off the drum at the beginning of the principal motion. It is, however, worth special mention that, according to the record, even at the first motion of the earthquake, the amplitude of one component of the motion was about 17 cm. (the possible tilting of the ground might have affected the record to a certain extent. However, as the period of the instrument was very long, the effect due to the tilting on the record, of comparatively quick earth vibrations, was probably not conspicuous). The accelera-
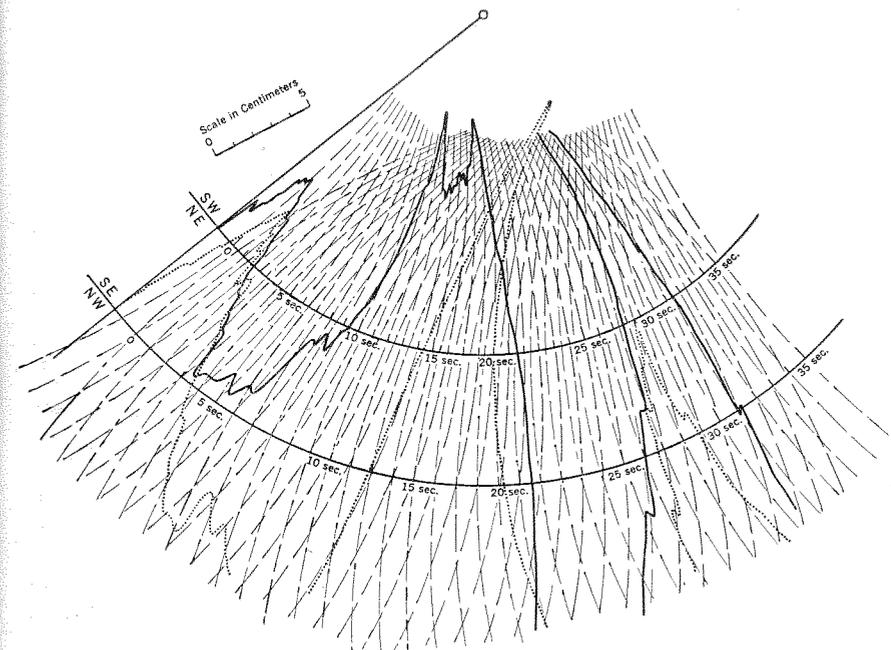

FIG. 30.—SEISMOGRAPHIC RECORD OF THE 1923 EARTHQUAKE BY MEANS OF AN OLD-FASHIONED EWING SEISMOGRAPH.

tion of this motion as calculated was not large, being only about 15 gal. (15 cm. per sec.²) or so, estimating the period at 4.9 sec. and assuming that the motion was simple harmonic. (This assumption is open to question, although it is generally accepted.) The successive waves, if my memory serves right, had probably still larger amplitudes. At first thought one might question the likelihood of such a large motion occurring; but another record (Fig. 30) obtained with an old-fashioned and less reliable Ewing seismograph with a disk recorder, practically confirmed the large amplitude. Moreover, the fact that the full amplitude (as registered in Tokyo) of the Idu earthquake of 1930 was 15 cm., strengthens the conclusion that the occurrence of such a large amplitude as that mentioned is not impossible.

With regard to the record given by the Ewing seismograph, it was practically continuous from beginning to end, except that at intervals the pointers went off the recording disk and thus interrupted the record. Although the instrument was originally intended for use as a strong-motion seismograph, it had several drawbacks. The most serious was that, notwithstanding the defective mechanism for driving the recording disk, it was not provided with a time marker. Moreover, the natural periods of the pendulums were comparatively short, being only about 7 sec. Therefore, the acceleration computed from it is not trustworthy. Disregarding these defects, however, by roughly calculating in the usual way, by means of the amplitude and the period of the main motion, and by assuming that the motion was simple harmonic, we find that the resultant acceleration of the motion marked, A, on the record is roughly 120 gal., or 0.12 g.

However, as will be discussed later, the maximum acceleration of the earthquake motion and the period that gives this maximum acceleration do not, as a rule—especially in a severe earthquake—arise from the main motion. Instead of that, they arise from secondary motions that are superimposed on it, or from that part of the cycle of the main motion which is actually not harmonic. To measure exactly such an acceleration and its period from an ordinary seismogram is difficult, if not impossible. This fact in itself is enough to convince us of the necessity of using properly designed accelerographs in engineering seismometry; needless to say, improper accelerographs are nearly as valueless as ordinary seismographs. As this is one of the most important of our problems, I will deal with it fully later. For this reason, and also because the instrument was defective, the calculated intensity cannot be accepted as a datum needed for the design of structures.

Now let us see what our past experience has to say in the matter. The most important experience in the past is the semi-destructive Tokyo earthquake on June 20, 1894. The record of this earthquake was taken perfectly at Hongo, situated on the higher section of Tokyo, and its principal motions were very simple in their nature.[7] The late Professor Omori calculated from the record that the maximum acceleration up town was nearly 0.05 g. He also estimated that in the lower town, which lies on low alluvial ground, the maximum acceleration was about 0.1 g. This latter value was perhaps less correct than the former, because it was deduced merely from the over-turning of columns and tombstones.

As will be seen later, however, it has been observed that, in general, the intensity of earthquakes down town is 1.5 to 2.0 times that of those up town. This fact does not seem to disprove Professor Omori's estimation. Now, the damage to buildings caused by the great 1923 earthquake up town was somewhat more severe than that caused down town by the semi-destructive 1894 earthquake. From this fact, too, it can be inferred that the maximum acceleration of the great earthquake up town was of the order of about 0.15 g. Moreover, according to my experience at Hongo, at the moment of greatest severity of the shock, I felt the intensity to be nearly the same as what one

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[7] See Milne's "Seismology," p. 138.

feels in a motor car driven at moderate speed on a poorly paved road, or as that in a street car, the average acceleration of which, according to the measurement with an accelerograph by Professor Ishimoto and Mr. Nasu, is between 0.15 g. and 0.20 g.

Thus, unfortunately, no recording apparatus gave a reliable record of the great earthquake of 1923, so that the correct value of its maximum acceleration is unknown; but it seems that the estimated value gives an idea of the order of magnitude, and we cannot but adopt it, namely, 0.15 g, or a little larger, as a datum for guiding earthquake-resisting structural design, keeping the fact in mind at the same time that the part of Tokyo in which the earthquake motion was observed was not the most affected. There is abundant evidence to show that the motion had a still greater acceleration in the epicentral region.

What is more regrettable is the fact that absolutely no information as to the intensity of the great earthquake was obtained for the down-town district where comparatively high modern masonry buildings were standing. Every effort was made, however, by Mr. Nasu of our Institute (then assistant to Professor Imamura), to compare the intensities of one and the same earthquake in the up-town (mostly diluvial) and in the down-town (mostly alluvial) districts of Tokyo by measuring simultaneously the after-shocks of the great earthquake at various points in the capital. The observations revealed the fact that neither the periods nor the amplitudes in these two different districts had any definite ratio, but, generally speaking, the computed accelerations were approximately 50 to 100% stronger in the down-town than in the up-town districts.[8] The late Professor Omori's observations on the semi-destructive Tokyo earthquakes of December 8, 1921, and January 14, 1923, showed similar results, the observed data being as in Table 1.

TABLE 1.—OBSERVATIONS BY F. OMORI ON THE SEMI-DESTRUCTIVE TOKYO EARTHQUAKES OF DECEMBER 8, 1921, AND JANUARY 14, 1923

Name of place	EAST AND WEST COMPONENT				NORTH AND SOUTH COMPONENT			
	Double amplitude, in centimeters	Period, in seconds	Accelerations, in centimeters per second ^{2}	Ratio of acceleration	Double amplitude, in centimeters	Period, in seconds	Accelerations, in centimeters per second ^{2}	Ratio of acceleration
EARTHQUAKE OF DECEMBER 8, 1921								
Hongo (up town)	5.0	3.6	8	1	3.0	1.7	20	1
Hitotsubashi (down town)	6.6	3.2	13	1.6	3.5	1.6	27	1.4
EARTHQUAKE OF JANUARY 14, 1923								
Hongo	1.3	1.4	13	1	1.4	1.3	16	1
Hitotsubashi	1.8	1.3	21	1.6	1.4	0.9	34	2.4

With regard to these data, it must be said that, for reasons which will be given later, the intensity of acceleration computed from a seismogram is rarely correct, so that the ratios of the intensities of acceleration just men-

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[8] Rept., Imperial Earthquake Investigation Committee, No. 100A, 1925.

tioned should be understood as being merely qualitative. According to Professor Ishimoto's most recent investigation of this problem with accelerographs, the ratio of the intensity of acceleration on low ground to that on high ground seems to depend upon the nature of the earthquake; for instance, in earthquakes of slow motion the ratio varies between 1.5 and 3, while in those of quick motion the ratio is unity or slightly larger. Thus, it can be accepted as established that the intensity of ordinary earthquakes is larger down town than up town, but I cannot supply the correct ratio of the intensities in the case of the great 1923 earthquake. The ratio might not have been very different from that in ordinary earthquakes.

The distribution of collapsed wooden houses in the great earthquake showed that the ratio of its intensities in these two sections of the city also followed the same rule. The intensity was far greater in the low ground than in the up-town districts, which are situated on diluvial ground.

Thus, there is every reason to believe that the acceleration of the great earthquake on the low alluvial ground of Tokyo reached the enormous intensity of, say 0.2 g, or more (taking a conservative value, say, 1.5, as the ratio of intensities just stated). Therefore, remembering that the capital is situated some distance from the epicentral region, it will not be improper to assume that the acceleration in the worst locality along the coast of Sagami Bay, which is believed to be the central area of the earthquake, was more than 0.3 g.

(III) Seismic Factor and the Lack of Seismic Data

To build a structure to withstand such a large acceleration as 0.3 g, or greater, and to provide it with a sufficient margin of strength, is evidently a matter of the utmost difficulty, if it is possible at all. As a matter of fact, however, a building even in the most seismic country is likely to be subjected to destructive earthquakes only once, or at the most twice, in its life time. Therefore, too ample strength means only extravagance. Thus, remembering that Tokyo was not the worst locality, it seems to me that a building properly designed to provide against a horizontal acceleration of, say, 0.15 of the gravitational acceleration, with a reasonable factor of safety, would safely withstand destructive earthquakes of the intensity of that of 1923, which is one of the most severe in the record of seismic history. Indeed, our own building code provides for a horizontal acceleration of 0.1 g, but some engineers are not satisfied with this seismic factor and voluntarily increase it.

However, owing to lack of reliable information on the intensity of destructive earthquakes, I cannot make positive statements. Until we are informed of the intensity and the period of destructive earthquakes that have been measured in a scientific manner, we can design an earthquake-resisting building only under assumptions based on such rather unsound premises.

As a practical problem, however, the actual fact that buildings designed on the 0.1 g basis (or thereabouts), resisted this earthquake fairly well is a datum more valuable than any other argument. In an engineering design there is nothing more important than practical data. In naval architecture we design a sea-going ship under the assumption that the maximum bending

moment to which it will be subjected is when it rides on a "standard wave" (a trochoidal wave having the length equal to the ship's length and the height one-twentieth of the length) without knowing much about the actual seas which it will possibly encounter. Long experience justifies such an assumption, provided we judge the "working stress" properly.

If such a practical method of designing a ship is successful, why can we not follow the same procedure in the design of earthquake-proof structures? Needless to say, the number of data are incomparably abundant in naval architecture. It is very likely that even at this moment ships in some part of the ocean are struggling with a heavy gale and their strengths are being tested.

Happily for human beings and unfortunately for seismologists, earthquakes do not occur as often as the launching of ships, and, therefore, our data are very scant. The most modern buildings, built of reinforced concrete or of steel framing, have so far been "tried at the bar" of the most severe earthquake only twice in the history of seismology—once in San Francisco, Calif., and once in Tokyo; but most unfortunately for the science, in both cases nothing more than flimsy evidences of the intensity of the earthquake have been left to us. Therefore, we cannot but avail ourselves of practical data obtained in these two earthquakes.

In any case, more information is urgently needed. Engineering seismologists must prepare suitable strong-motion seismometers and accelerographs, and after distributing them in the seismic regions, await with patience the useful data that must come in the future. If, however, circumstances do not permit the installation of both these instruments at the same place, then the latter should be preferred to the former. Moreover, these instruments should be placed on the ground where important buildings are standing, and not on specially selected firm ground, as is generally done.

In Japan, since the occurrence of the 1923 earthquake, the need of severe earthquake recorders has keenly been felt in seismological circles. At present, not only our Institute, but also some of the principal observatories are provided with seismographs intended to record severe earthquakes; but it is to be regretted that none of the instruments is equipped in all respects for the purpose intended. For instance, in the recent Idu earthquake, a strong-motion seismograph that was installed in the epicentral region failed for the reason that not only was the magnification excessive (two times), but also because the maximum amplitude allowed for was too limited.

This failure for the second time, stimulated us to take up the matter more seriously, and Dr. T. Okada, the Director of the Central Meteorological Observatory, intends to distribute more perfect strong-motion seismographs among his principal observing stations. As for me, our Institute is manufacturing not only strong-motion seismographs, but also accelerographs, to meet the necessary requirements just enumerated. In the present state of the development of seismology, we cannot yet foretell where the next great earthquake will occur, so we are unable to select the proper localities for their installation. If, however, a great earthquake were to occur in a district where such seismographs and accelerographs are installed, I expect with confidence that we shall not repeat the failure.

(IV) Accelerographs

Thus far I have dealt principally with the seismic motion recorder; but, as I have remarked, according to our experience, an accelerograph for recording directly the acceleration of an earthquake is more important for us; because seismic waves, especially those of an earthquake of near-by origin, are far from being of the simple harmonic type, so that the acceleration computed

by the ordinary formula, namely, amplitude $\times \left(\dfrac{2\,\pi}{\text{period}}\right)^2$, has little physical

meaning, and, moreover, in some cases, the form of the wave is so choppy that even the determination of the amplitudes and the periods themselves is impossible. It is also to be remembered that the maximum acceleration is frequently given by the secondary motions, with comparatively small amplitude but short period, which are apt to be masked by the main motion. The necessity of an accelerograph in such a case cannot be too strongly emphasized.

As the principle of the accelerograph is described in some of the modern textbooks on seismology, it is not necessary to give a description here; but it may not be without interest to you to see some results of the comparison of the intensity of the maximum acceleration of earthquakes given directly by an accelerograph with that computed from seismograph records (see Table 2).

TABLE 2.—Comparison of Intensities of Maximum Acceleration by Seismograph and Accelerograph

Tokyo earthquake	Maximum Motions Given by Seismographs				Record of an Accelerograph	
	Full amplitude, in centimeters	Period, in seconds	Computed acceleration, in gal.	Speed of drum	Full amplitude, in centimeters	Acceleration, in gal.
August 20, 1930......	0.042 (4S–5N)	0.30	9.2	Slow	4.14	5.6
The same earthquake.	0.064 (4S–5N)	0.46	5.9	Rapid	....	....

The accelerograph used is that designed by Professor Ishimoto, one of our colleagues, particulars of which are as follows:

Type .... Inverted pendulum, and optical recording.
Weight of bob.............. 3.2 kg.
Natural period of oscillation without damping .... 0.08 sec.
Attenuation value $\left(\dfrac{K}{2}\right)$ of the damped oscillation .... Nearly 30.
Optical magnification of motion of center of bob....... 1 700 times.

One centimeter of the amplitude of record corresponds to 2.7 cm. per sec.² This instrument has subsequently been remodeled to be used for engineering researches. For that purpose the magnification was reduced for recording mechanically, and the natural period of oscillation of the bob was increased properly, the particulars being as follows:

Natural period of oscillation without damping .... 0.15 sec.
Damping .... Nearly critical.
Indication constant .... 1 cm. = roughly, 10 cm. per sec².

An instrument for recording severe earthquakes is now under construction, in which the indication constant is 1 cm. = 50 cm. per sec².

For the purpose of reference, the records of the earthquake mentioned in Table 2, taken with the Ishimoto optical accelerograph, an ordinary seismograph, and a seismograph of the same type but with a rapidly revolving
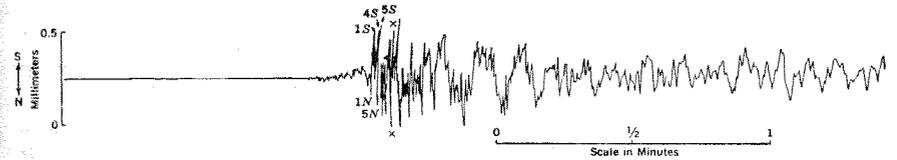

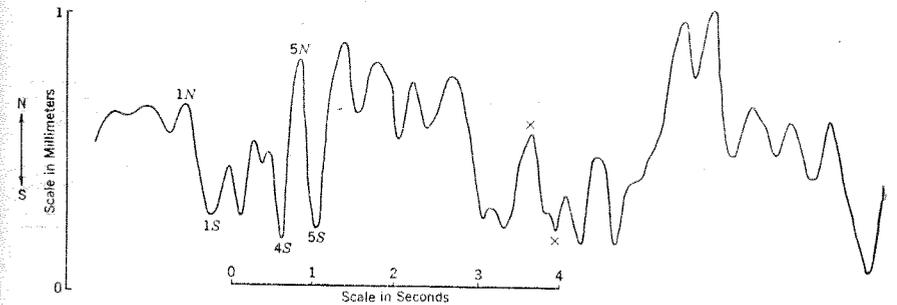Fig. 31.—Curve Recorded by an Ordinary Seismograph

Fig. 32.—Curve Recorded by an Ordinary Seismograph with a Rapidly Revolving Recording Drum
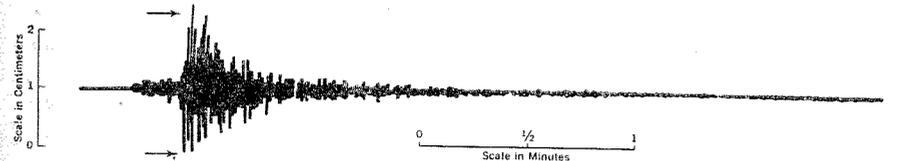

Fig. 33.—Curve Recorded by an Ishimoto Optical Accelerograph

recording drum, are shown in Figs. 31, 32, and 33. The computed values of acceleration in Table 2 are those of the motion marked 4S–5N in Figs. 31 and 32. It is seen that the value computed from the diagram with the condensed time scale (the upper row) is quite erroneous, while that obtained from the one with open time scale (the middle row) is less so. This fact also shows that a quick-running recording drum in a seismograph is desirable, if it is to be used for obtaining engineering data.

Even with such a seismograph, however, we cannot realize our object in some cases. In the foregoing I have selected, as an illustration, the record of an earthquake in which seismic waves were composed of comparatively regular trains of nearly harmonic motions, and, therefore, the ordinary method of computing the acceleration could be applied without much error. It will be remembered that even in such an exceptionally favorable case, an ordinary close diagram (with a recording speed of, say, less than 6 cm. per sec.) is apt to lead to a false estimate. As another example, I will show, side by side, a seismogram of an earthquake and its accelerogram taken by Ishimoto's mechanical accelerograph (Fig. 34). This earthquake showed the characteristics so commonly observed in that the principal motions had large amplitudes, but comparatively long period, and, on which motions, secondary motions were superposed. It is evident that an accurate estimation of acceleration as well as the "period of accelerations" (the time interval between two
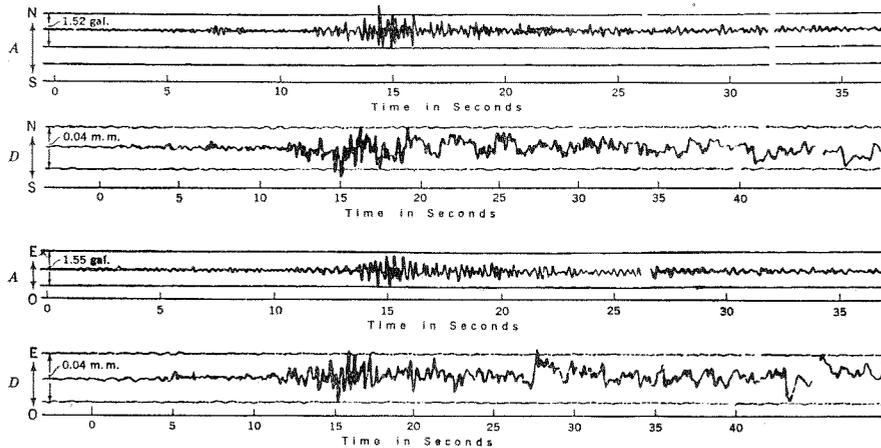

FIG. 34.—COMPARISON OF A SEISMOGRAM AND ITS ACCELEROGRAM TAKEN WITH ISHIMOTO'S MECHANICAL ACCELEROGRAPH.

successive maxima of acceleration) is almost impossible. Thus, a seismograph is practically useless for the determination of these two important items urgently needed by the engineer, whereas they are available with an accelerograph.

Although it is only a short time ago that these accelerographs were installed in our Institute—as after-shocks of the great 1923 earthquake have frequently taken place of late in the marginal region of the disturbed area— we have succeeded in obtaining valuable information on two quite severe earthquakes from them. One was the severe earthquake of June 17, 1931, whose epicenter was about 40 km. north of Tokyo. Its acceleration diagram recorded by an Ishimoto mechanical accelerograph is reproduced in Fig. 35. A record taken by a seismograph which is equipped with an automatic starter and which gives an open diagram, is also shown in Fig. 35. It will be seen that the sharp motion that was the cause of the maximum acceleration was not the conspicuous principal motion of the earthquake, such as b c d e, but

most probably the secondary motion, such as a b, or that part of the principal motion, such as b c, on which a secondary motion was most likely superimposed. Nevertheless, the intensity and the period of acceleration are very difficult to estimate, even from such an open diagram as shown in Fig. 35. Still more difficult will be the estimate from an ordinary condensed seismogram. Indeed, an experienced seismologist estimated from a record obtained by a seismograph for the use of geophysicists, that the maximum acceleration
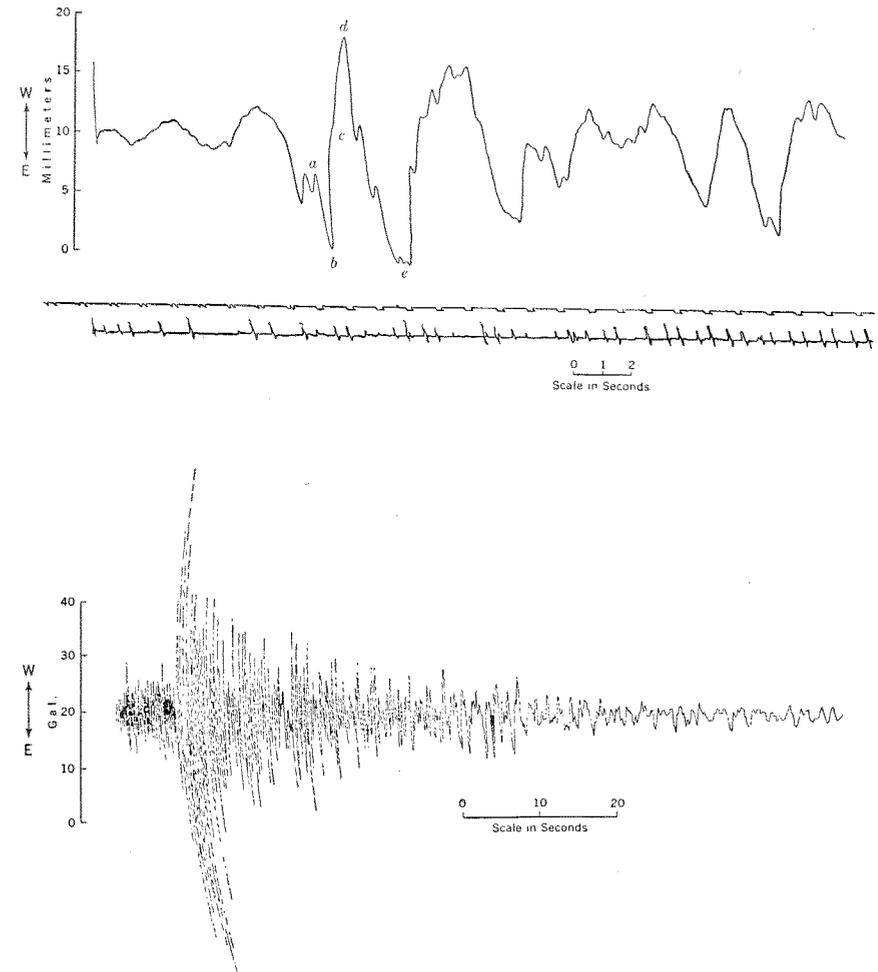

FIG. 35.—ACCELERATION DIAGRAM OF AN EARTHQUAKE ON JUNE 17, 1931.

of that earthquake was 25 gal. and its period, 2.1 sec. As a matter of fact, however, the maximum acceleration of its north and south component of motion was about 43 gal., and its period, 0.4 sec., as recorded by the accelerograph, which had been carefully calibrated both statically and dynamically.

Another earthquake whose accelerogram was successfully taken in our Institute was that which occurred on September 21, 1931, in the Mt. Chichibu region in Northern Musashi, about 60 km. northwest of Tokyo. This earthquake was semi-destructive, and in the alluvial district caused the loss of 16 lives and the collapse of 76 houses, although in a district much nearer the epicentral region, where the ground is of hard paleozoic formation, no casualties were reported. This earthquake shook Tokyo quite severely, although, except for a few cases of cracks in the pavement in the low ground, no serious damage occurred.
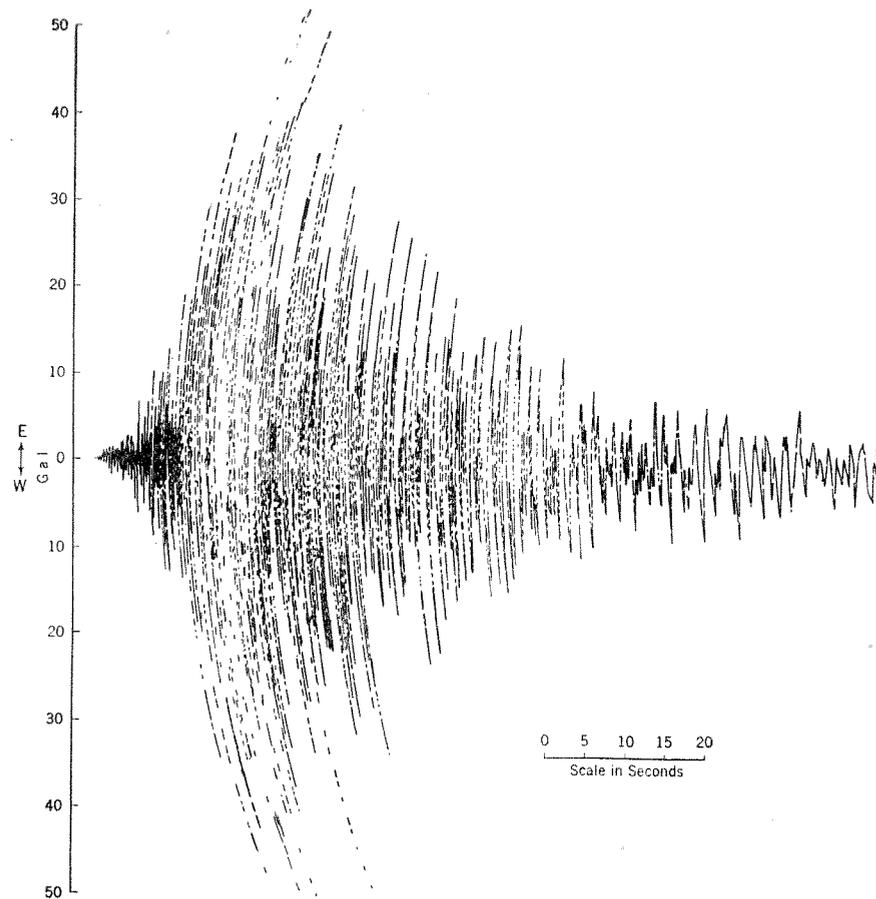

Fig. 36.—Accelerogram of Semi-Destructive Earthquake, September 21, 1931, in Mt. Chichibu Region in Northern Musashi About 60 Km. Northwest of Tokyo.

The accelerogram of this earthquake is reproduced in Fig. 36, to compare with the seismogram (Fig. 37) taken with an Omori strong-motion recorder. It should be stated that this earthquake occurred on a warm day, with the result that the oil damping of the accelerograph was somewhat insufficient, although not to the extent of rendering the record untrustworthy. It will be seen that the east and west component of acceleration is about 70 gal.

and its period about 0.4 sec. The seismogram, however, gives no useful information except that the ground moved about 3.5 cm. in the principal motion. It is interesting that no casualty occurred in Tokyo notwithstanding the fact that the acceleration attained was so intense that the east-west component was 70 gal. and the other component (the accelerogram of the north-south component is not shown) was 60 gal.
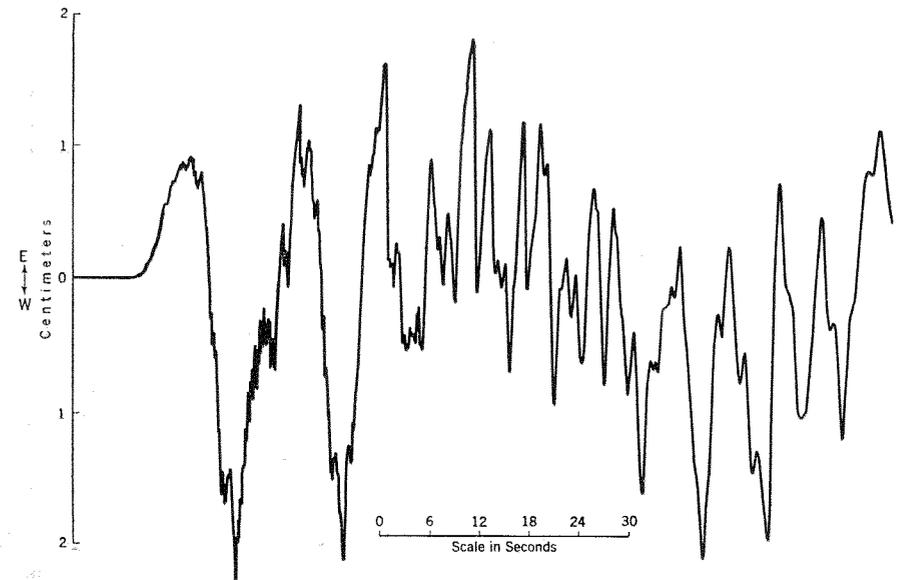

Fig. 37.—Seismogram of Earthquake of September 21, 1931, Taken with an Omori Strong-Motion Recorder.

Although, as the recording drum of the accelerograph was driven slowly, the relative phase of the acceleration components could not be detected, so that the intensity of the maximum resultant acceleration is unknown, yet there is no doubt that the intensity of acceleration was between 70 and 92 ($= \sqrt{70^2 + 60^2}$) gal. Nevertheless, this intensity corresponds to strength, IX, of Cancani's seismic scale. Therefore, if the seismologists were right, the earthquake should have caused a catastrophe, but actually it was not so. This fact is worth the special attention of engineering seismologists.

Also, my view that the acceleration of the great 1923 earthquake in up-town Tokyo was more than, say, 0.15 g, as against the general belief that it was 0.1 g, seems to be supported by the observations of this earthquake. Although at the time of this earthquake there was installed in the low grounds a similar accelerograph, it is unfortunate that a record from it could not be obtained on account of the break-down of the recording points by the shock, suggesting the important fact that the intensity was greater down town than up town.

It is to be remarked that not only the three earthquakes whose records are reproduced in Figs. 34, 35, and 36, but all acceleration records so far

taken showed a similar result to the effect that the period of acceleration is not the same as the period of motion, as apparently indicated in a seismogram. This is only natural in view of what has just been mentioned regarding the main and secondary motions of an earthquake. In specifying the intensity of an earthquake, the amplitude and the period of the most conspicuous motion are generally given; but, as a rule, such a motion does not cause the maximum acceleration, and it seldom appears in an accelerogram as a predominant component of acceleration.

Moreover, according to our experience on Tokyo's high ground (Hongo, where our Institute is situated), it is likely that in all earthquakes the period of acceleration of the principal motion was confined within a very limited range of, say, from 0.3 to 0.4 sec., irrespective of the fact that the period of the main waves of the principal motion varied widely. This is clearly seen from Figs. 34, 35, and 36. With respect to this important fact, it is worthy of note that Hongo is habitually subjected to micro-tremors at ordinary times, and during earthquakes to habitual motions with a period 0.3 sec., or so, and it is this period that prominently appears in the accelerations. Therefore, although I cannot say positively, the motions of an earthquake that cause the predominant accelerations seem to be due to the habitual motions inherent in the district.

To test whether the same rule holds in other districts, an Ishimoto accelerograph has lately been installed at Marunouchi, the business center of Tokyo, situated on low ground, where I have already studied the behavior of the motions of the ground both at ordinary times and in earthquakes. As we have not yet obtained a sufficient number of accelerograms in this district, it is too early for me to deduce any positive conclusions from them; but it is almost certain that nothing will develop to contradict the results obtained from investigations on high ground. It is very important to note that on low ground, the period of acceleration of an earthquake of intensity, say, "moderate" and higher, is not uncommonly close to 0.7 sec., while in small earthquakes belonging to the "feeble" class, the period of acceleration is generally 0.2 or 0.4 sec., according to their sharpness. These three different periods correspond closely to the periods of the habitual motion of the ground.

Thus, so far as our latest experience goes, we must radically modify our views on earthquake motions. The amplitude and the period of the main principal motions taken from a seismogram have generally not much significance for the engineer. The requisite data for him are the acceleration and its period as recorded directly by an accelerograph suitable for engineering use.

Here I say emphatically "an accelerograph suitable for engineering use," because our object is achieved only by accelerographs having suitable characteristics. As the acceleration given by harmonic motions is inversely proportional to the square of their periods, it may happen, particularly in the case of earthquakes of near-by and shallow origin, that motions having very short periods (say, less than 0.1 sec.) give the maximum acceleration of an earthquake.

Now, the elementary principle of forced harmonic vibrations tells us that an accelerograph having a damping of, say, 0.7 times the critical value, gives practically correct indication, if the period of excitation almost exceeds two times the undamped natural period of the instrument, and also that it gives reduced indication for quicker motions, the general feature being as shown in Fig. 38. Therefore, if an accelerograph having a very short natural period, such as that sometimes used for geophysical study, is employed, then the record obtained may be only a train of extremely sharp waves, making the detection of more important components practically impossible.
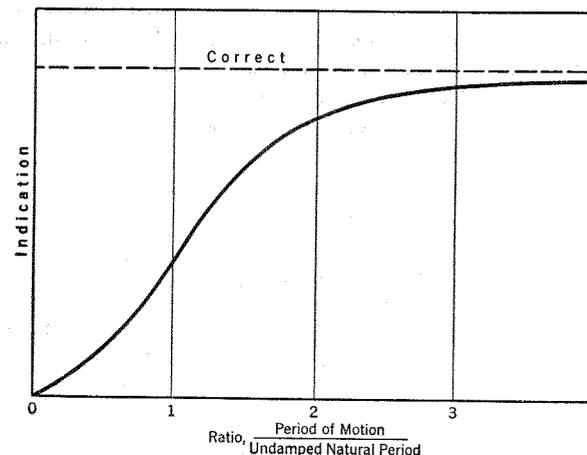

Fig. 38.—Relation Between Ratio of Period of Motion to Natural Period of an Accelerograph, and the Indication of the Instrument.

Motions having extremely short periods are not of interest to structural engineers, while motions having somewhat longer periods, say, more than 0.3 sec., or so, are of importance. Therefore, for engineering purposes, accelerographs having a suitable period, say, 0.15 sec., or so, must be used; if not, the record of motions in which we are interested will be masked by less important rapid ones, and the record will be nearly as bad as the condensed record of a seismograph, in which, on the contrary, important waves are masked by slow main motions.

Now, reverting to the question under consideration, although the general question of this habitual motion is still *sub judice,* yet the fact that the period of acceleration of earthquakes on Tokyo high ground is generally between 0.3 and 0.4 sec. is very serious to us, because masonry buildings on the high ground are generally of three or four stories in height, and, as will be shown later, their natural periods of vibration are generally of the same order of magnitude as that of the earthquakes. It is also disconcerting to us that in Tokyo the low ground, where comparatively tall buildings (although low for this country) having eight stories or more are standing,

often has an acceleration period of about 0.7 sec., so that the free vibration of such buildings, if not made especially strong, is nearly co-periodic with this period of acceleration of the ground.

I am not well informed as to the nature of earthquake motions in the United States. Presumably, it may not be very different from that in Japan. If so, sky-scrapers that have generally a long natural period of more than 2 sec. seem to be very favorable in this connection. I cannot see the reason why they are sometimes made intentionally more flexible, irrespective of the fact that they are intrinsically flexible.

Nevertheless, I wish to impress on you the fact that the use of the accelerograph is urgent for obtaining the engineering data of an earthquake; for our object it far surpasses the seismograph in importance. I am sure that by pursuing the study of engineering seismology by means of the accelerograph we may make discoveries that will cause us to modify some of our accepted ideas. To give an example, offhand, of an erroneous idea, I take Cancani's well-known seismic scales which give the seismic accelerations and their corresponding damage to buildings. The faith of some seismologists in this scale of intensity is so great that they ridiculously make distorted computations of acceleration in order to make it correspond to the scale. The intensities of acceleration given in the middle part of the scale were probably computed from the principal motion recorded in a seismogram, and are, therefore, greatly under-estimated. The scale must be revised. With regard to the problem under consideration, I highly appreciate Professor Ishimoto's work in constructing a simple accelerograph, and in giving us useful information on engineering seismology.

The Wood and Anderson torsion-seismograph invented in the United States seems to be one of the best instruments for use as an accelerograph, and I highly recommend the distribution of the instrument in every seismic district for installation, both directly on the ground and in the principal buildings.

(V) The Period of the "Natural" Ground Motion

It is hardly necessary to say that the period of an earthquake motion, or in a stricter sense, the period of accelerations, plays an important rôle in the destructive effect of an earthquake on buildings and other structures. It is important, therefore, to investigate this period of habitual motion peculiar to the ground, if such motion does really exist, at ordinary times and during earthquakes. At first thought, it seems rather odd to speak of a period of the ground when the ground has practically unlimited extension both laterally and downward; but when we remember that the ground of a district like Tokyo, which is of sedimentary formation, is made up of several strata, it is not difficult to understand the existence of a period of motion peculiar to the district. In a mathematical paper entitled "Possibility of Free Oscillation of the Surface Layer Excited by Seismic Waves,"[9] Professor K. Sezawa, of our Institute, showed the possibility of motions having a natural period proper to the surface layer of a stratified crust, and also that the period

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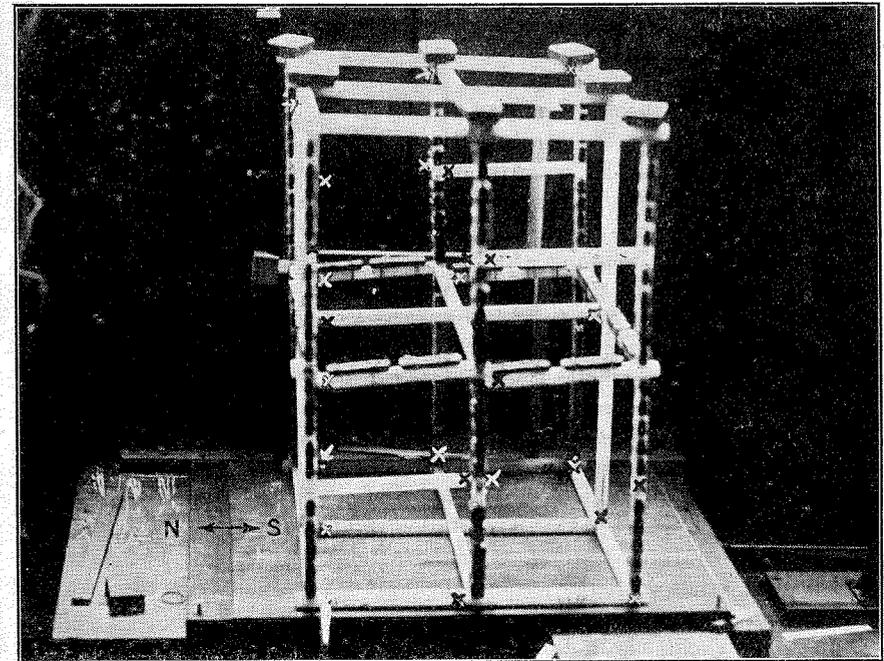[9] *Bulletin*, Earthquake Research Inst., Vol. 8 (1931), 1.

FIG. 39.—MECHANICAL MODEL OF A WOODEN FRAME BUILDING (x INDICATES POINT OF BREAKDOWN).
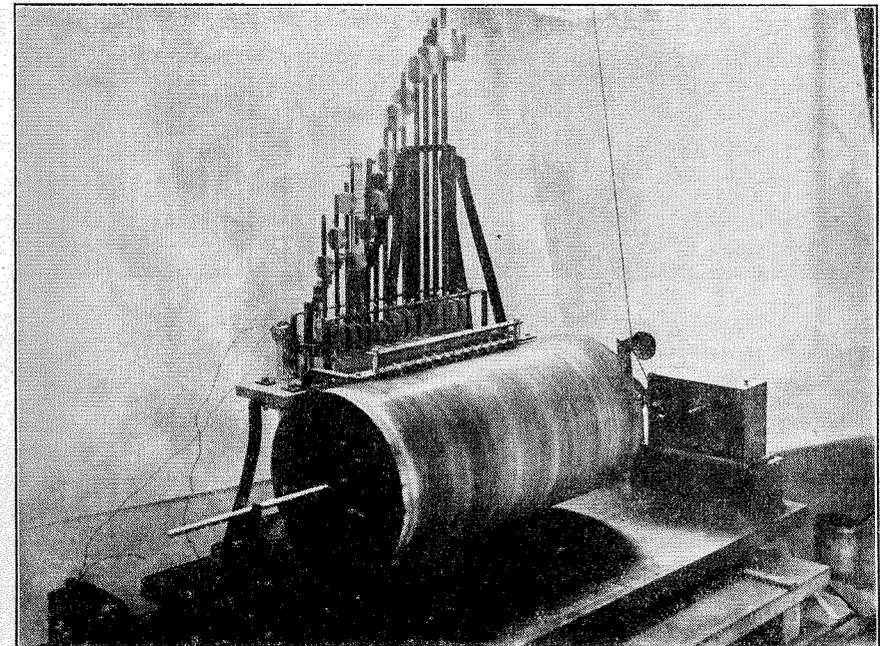

FIG. 40.—A SEISMIC VIBRATION ANALYZER DEVISED BY DR. SUYEHIRO.

depends on the nature of the crust forming the strata as well as on the thickness of the surface layer. Not only has the mathematical solution proved the possibility, but observations have actually shown the existence of these habitual ground motions. (Fig. 39 is a mechanical model of a wooden frame building, discussed later.)

For detecting the prevalent period, if any, of earthquakes in a particular locality, I have used a seismic vibration analyzer, devised by myself.[10] This instrument works on the principle of selective resonance as in Hartmann's well-known reed frequency-meter. As shown in Fig. 40, the analyzer consists of a number of compound pendulums having different natural periods, the shortest period being 0.2 sec. and the longest 1.8 sec., and they are arranged side by side in a row along the side of a recording drum. Each pendulum is provided with a separate water damper to wipe out the free oscillation, and each damper is so adjusted as to make the magnification of the amplitude of the resonance vibration of each stylus practically equal. The instrument shown in Fig. 40, although very clumsy in appearance, works satisfactorily. The making of a new one of smaller size and more finished appearance is now under contemplation.

A typical record with this instrument obtained at Hongo is shown in Fig. 41. In this diagram the numerals at the top show the natural periods of the pendulums. The record clearly shows that only motion having a period of 0.3 sec. persisted, and that this motion was likely to be of the harmonic type. The other motions gave merely inconspicuous and irregular, jagged undulations. This feature is characteristic of all earthquakes in Hongo, irrespective of their intensity and the distance from the origin.
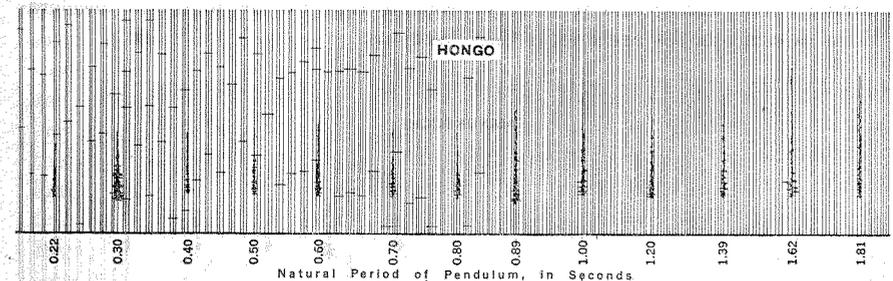
FIG. 41.—TYPICAL RECORD OBTAINED BY SUYEHIRO VIBRATION ANALYZER AT HONGO, ON HIGH GROUND OF TOKYO.

It can be inferred, therefore, that this district has a natural period of motion of about 0.3 sec. When Professor Ishimoto and I were measuring the vibration of low monolithic buildings with a mercury tube microvibrograph designed by us, we took records at the same time of micro-tremors of the ground on which the buildings stood. In one of them a record of the micro-tremor of the northern part of Hongo was obtained. By analyzing those parts of the record that were undisturbed by passing traffic, I obtained curves

[10] For details, see, "A Seismic Vibration Analyser and the Records Obtained Therewith," *Bulletin*, Earthquake Research Inst., Vol. 1 (1926).

showing the frequency of occurrence of motions having different periods, one of which is shown in Fig. 42. The diagram shows that the motion having a period of 0.3 sec. has the maximum frequency of occurrence. A similar observation was made later by Professor Ishimoto and Professor Takahashi with an Ishimoto microvibrograph on the grounds of our Institute, which is

FIG. 42.—DISTRIBUTIONS OF VARIOUS PERIODS OF TREMORS ($F =$ FREQUENCY OF OCCURRENCE; $P =$ PERIOD; AND $S =$ STANDARD PERIOD OF 0.3 SEC.).
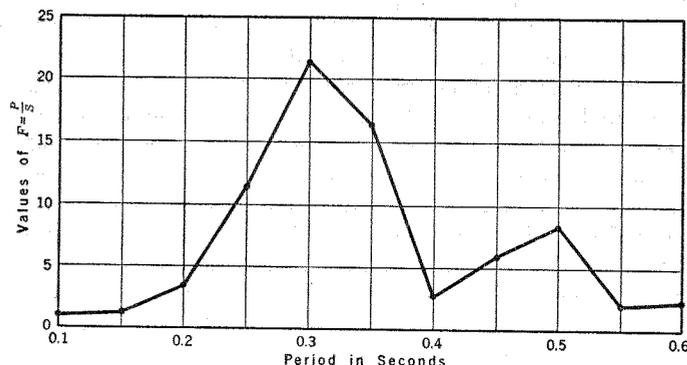
situated 2 km. south of the place mentioned, when exactly the same behavior of the ground was observed.

Thus, it will be seen that Hongo, on the high ground of Tokyo, has a habitual motion with a period of about 0.3 sec., both at ordinary times and during earthquakes; and it is very probable that the predominant accelerations in earthquakes are due to these motions.
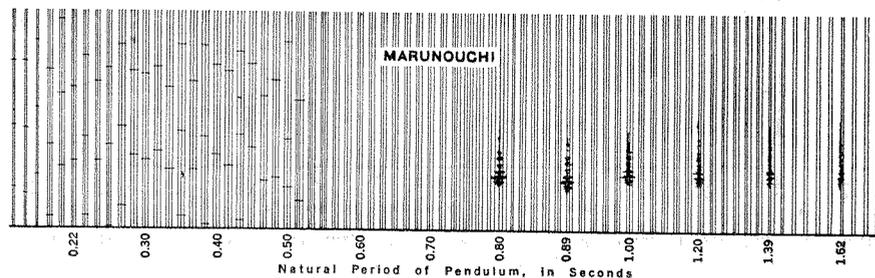

FIG. 43.—TYPICAL VIBRATION ANALYZER RECORD TAKEN AT MARUNOUCHI IN THE LOW PART OF TOKYO.

I have carried out similar observations at Marunouchi, on the low ground of Tokyo. There, matters are not so simple as at Hongo. The seismic vibration analyzer indicates that the prevailing periods in earthquakes are generally from 0.7 to 0.9 sec. (in the record shown in Fig. 43, 0.8 sec. predominates). This accords well with the fact that the period of acceleration of moderate earthquakes in that district is sometimes about 0.7 sec., or more; but as shown in Fig. 44 (which is a reproduction of a record of the micro-

tremor taken with an Ishimoto microvibrograph by Professor Takahashi, Mr. K. Sato, and myself), the prevailing period of the micro-tremor in that district is from 0.4 to 0.45 sec., being nearly one-half the prevailing period in an earthquake. With these are mixed some motions having smaller amplitudes, and periods varying from 0.2 to 0.3 sec. Remembering that the period of acceleration of feeble earthquakes in Tokyo low ground is sometimes 0.2 to 0.4 sec., it can be inferred that, according to circumstances, the secondary and tertiary free motions of this district are excited by minor but sharp earthquakes.

Thus, this district is remarkable in that there exist secondary and tertiary motions, having natural frequencies of twice and three times the motion that appears to be the fundamental one. Such behavior of the ground is not conceivable from the mathematical solution for an elastic ground, just cited,
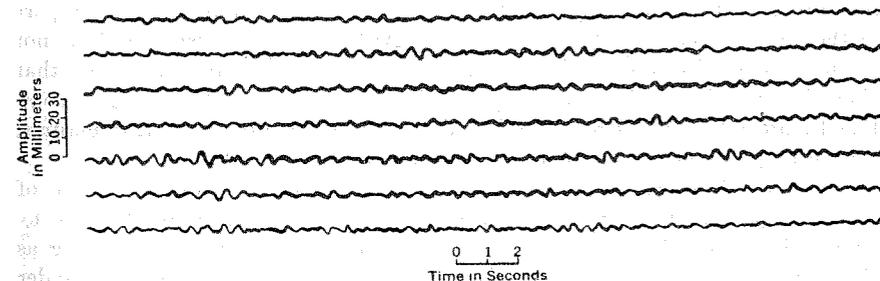
FIG. 44.—RECORD OF MICRO-TREMOR TAKEN IN THE LOW PART OF TOKYO WITH AN ISHIMOTO MICROVIBROGRAPH.

as given by Professor Sezawa. As the district was once marshy, and as the earth is oozy even now, it is not unreasonable to consider the ground as having the character of a semi-fluid. If so, a district in Tokyo the surface and subsurface stratifications of which are very irregular, may have a multiple periodicity in harmonic order just like water in a tank. In my estimation, the fundamental motion has a period of about 0.8 sec., but the period is too long to be excited by traffic and other minor disturbances, and it is only in the case of earth movements having a period approaching 0.8 sec. that the fundamental motions come out clearly. However, I shall not go further into this question, but shall leave it to competent investigators.

The only thing that I wish to emphasize is that every locality has its own "natural" motion during an earthquake, and we must pay careful attention to it.

(VI) STRAIN MEASUREMENT OF BUILDINGS IN EARTHQUAKES

With regard to the strength calculation of buildings and other structures in an earthquake, I had better say nothing; because this country is the birthplace of most of the methods of calculation, such as the "slope-deflection method" by Professor W. M. Wilson, the "portal method," etc. If I do so, I shall just be "carrying coals to Newcastle" as they say in England; but whatever elaborate method of calculation we may use, it is a matter of

utmost difficulty to calculate the accurate stress and strain induced in a member of a complicated statically indeterminate structure under a given seismic force, especially when such a structure is fitted with diagonal bracings, partition walls, and the like. Besides, as an actual problem, we have to consider other important items, such as the relation between the natural period of the structure and the period of acceleration, the damping against vibrations, mutual action between the foundation of the structure and the ground bed, etc., some of which will be taken up as subjects of Lecture III. If we take all these matters into consideration, the strength calculation is virtually impossible.

One feasible step in this direction is to make experiments with models satisfying the law of mechanical similitude. I am now making experiments for simple wooden frame structures with a mechanical model made of a mixture of paraffin and other materials (see Fig. 39). A preliminary report of these experiments has been published.[11] Although the experiments have not yet been concluded, there being still much to be developed, it seems to me that there is great hope of success. However, with regard to structures of combined materials, such as reinforced concrete and steel-framed brick structures, I have no prospect of success from experiments with models.

Another thing feasible in a seismic country is to set up a number of strain recorders in standard buildings, and to make observations side by side with an accelerograph. If such observations are made, then as long as the observed strain is within the limit of elasticity, the induced stress under a known acceleration can be estimated. Fortunately, in any district, the period of acceleration is practically fixed. Therefore, we can estimate under what earthquake intensity the construction members exceed the elastic limit (for steel structures), or crack (for masonry structures), although for obvious reasons we cannot estimate the break-down of steel structures; for this, calculations are equally impossible.

I regret, however, that having been kept very busy of late on account of the occurrence of severe earthquakes one after another, as was mentioned in Lecture I, I could not fully extend my researches to this problem. At present, I have only one strain-recorder fitted to a low wooden building; the data for such a building are evidently of no use to you; but I am now ready to extend the strain measurements to high buildings, and hope that at no distant date I shall be able to supply useful data covering such buildings.

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[11] *Proceedings*, Imperial Academy, Vol. 6 (1930), No. 7.

LECTURE III
VIBRATIONS OF BUILDINGS IN AN EARTHQUAKE

SYNOPSIS

The behavior of vibrating buildings and the mutual action between their foundations and the adjacent ground, are the subjects of Lecture III. Dr. Suyehiro gives the results of actual observations on buildings of different types of construction and emphasizes the features of certain buildings that explain why they withstood the great 1923 earthquake. He also points out why certain buildings failed.

A rigid building was found to move in the same manner as the adjacent ground and was insensible to the ground vibrations of very short periods of the order of 0.1 sec. In the less rigid buildings the motion is complicated by secondary vibrations, and such buildings have less damaging effect. Consequently, their own free vibration predominated during earthquakes with irregular motions.

Wood frame buildings—carefully constructed—and steel frame structures with masonry walls were found to have high earthquake-resisting qualities. The cushioning action of the ground may serve more or less to relieve the destructive action of a strong earthquake in the case of masonry buildings in which the weight is relatively great. In Tokyo, buildings with monolithic, flat-slab foundations and without piles, but located on soft, compacted soil, withstood shocks better than buildings with individual pile footings. Studies of underground earthquake motions led to the opinion that the idea of extending the footings of a tall building, with a long natural period of vibration, deep into the ground is not so advantageous as is believed by some engineers. For low buildings with a short natural period, on the other hand, the advantages of deep footings are unquestioned.

INTRODUCTION

The structural members of a building in a seismic country must have sufficient strength to withstand not only the static vertical forces due to dead and live loads, but also the horizontal dynamic forces due to earthquake motion. In most seismic countries, therefore, the seismic force to be considered in the strength calculation is stipulated in the building code. For instance, in Japan, it is required that the horizontal seismic acceleration must be taken as at least one-tenth of the acceleration due to gravity. The horizontal force due to this acceleration is included in the strength calculation as if it were a sort of wind pressure, but with the slight difference that in this case the horizontal force is proportional to the weight of the structural

members and acts on every part of the building. Thus, it would seem that determination of the scantlings of the structural members of an earthquake-resisting building is achieved in a simple manner.

On reflection, however, we find that the problem is not so simple as it appears at first sight. First, the prescribed intensity of the maximum seismic acceleration which forms the basis of the strength calculation is nothing but an arbitrarily assumed quantity. This seismic intensity was not fixed either by past experience or because of possible occurrence in the future. Perhaps it is because one-tenth is a convenient number, seeing that the sizes of members calculated from it generally turn out to be moderate. There is no sound scientific basis for adopting this seismic factor, except that as mentioned in Lecture II, it is known in a hazy way that, at the beginning of the principal motion of the 1923 Kwanto earthquake, an acceleration of this order is likely to have taken place in the higher ground of Tokyo; but there are reasons to believe that the actual intensity was somewhat greater. Until we succeed in determining the real intensity of a destructive earthquake in a scientific manner, we are not in the position to say positively whether or not this seismic factor is the proper one to use, except from a practical point of view. Thus, the most urgent necessity is to be prepared for measuring the intensity when the next severe earthquake comes.

No less important is the study of the vibration of buildings in an earthquake, whether severe or otherwise. Here, the behavior of the vibrating buildings and the mutual action between the foundation of the building and the ground are the items to be investigated. Evidently, these two questions are intimately correlated and need to be considered together.

(I) FREE VIBRATION PERIODS, THE EFFECT OF THE 1923 EARTHQUAKE, AND OTHER OBSERVED DATA CONCERNING THE BEHAVIOR OF BUILDINGS

For the problems now under consideration, it is necessary, first, to know the period of the free vibration of actual buildings, because their vibration (free or forced), in an earthquake largely depends on the ratio of the natural period of the buildings to that of the imposed vibration, and also upon the damping of the vibration, which is closely related to the natural period.

In Japan, buildings taller than 100 shaku (1 shaku = 0.994 ft.), irrespective of type of construction, are prohibited. Consequently, our data may possibly give little information useful to American engineers, whose principal interest is to build sky-scrapers; yet it may not be out of place to present some of these data, as my discussion refers to them from time to time.

In order to give an idea of the effect of the 1923 earthquake on the buildings listed in Table 3, I will show photographs of some of them taken after the earthquake, and will make a brief explanation of them. Fig. 45 shows one of the burned districts in Tokyo. In the center stands the Ryounkaku Tower (No. 15, Table 3) ruined by the earthquake. It will be noted that, except for a brick building on the right, no houses are to be seen in the background, showing how the fires that followed the earthquake converted this quarter of the city into a barren field. In contrast, Fig. 46 shows the

TABLE 3.—USEFUL INFORMATION CONCERNING SOME IMPORTANT BUILDINGS IN JAPAN

No.	Name of building	Construction	Size — Height above street level, in feet	Size — Floor area, in square feet	Stories	Ground	Condition	When measured	Periods, in seconds — Longitudinal	Periods, in seconds — Transverse	Observer	Type of instrument	Remarks
							STEEL FRAME BUILDINGS						
1 (a)	Marunouchi Building	Office building.	109	67 600	Nine and cellar	Alluvial	Nearly completed.	Before the semi-destructive earthquake of April 26, 1922.	0.94	0.89	Omori	Seismograph	
1 (b)		Brick and hollow-tile					Slightly damaged.	Just after this earthquake.	1.01	1.09	Omori	Seismograph	Suffered moderate damage by the great earthquake
1 (c)		Curtain wall.					Repaired and strengthened.	When repairs nearly completed.	0.51	0.67	Omori	Seismograph	
1 (d)		Separate foundation.					Moderately damaged; skeleton intact.	Just after the 1923 earthquake.	0.71		Horikoshi	Seismograph	
1 (e)		Reinforced concrete wall.					Thoroughly repaired and additionally strengthened.	When the second repairs completed.	1.18 0.48 0.25	1.11 0.50 0.23	Saita	Seismograph	
2 (a)	Tokyo Kaikan	Restaurant: Brick curtain wall. Separate foundation.	86	18 200	Five and cellar	Alluvial	Nearly completed.	Before the great earthquake.	0.72	0.54	Omori	Seismograph	Severely damaged
2 (b)							Severely damaged.	Just after the great earthquake.	1.30	1.20	Horikoshi	Seismograph	
3 (a)	Yuen Building	Office building: Brick and hollow-tile curtain wall. Separate foundation.	100	43 400	Seven and cellar	Alluvial	Completed.	Before great earthquake.	0.69	0.77	Omori	Seismograph	Fairly serious damage
3 (b)							Severely damaged.	After great earthquake. During repairs.	0.90	0.80	Saita	Seismograph	
4 (a)	Yurakukan Building	Office building: Brick and hollow-tile curtain wall. Separate foundation.	100	22 600	Seven and cellar	Alluvial	Completed.	Before the great earthquake.		0.61	Omori	Seismograph	Moderate damage
4 (b)							Moderately damaged.	Just after great earthquake.	0.80	0.80	Taniguchi	Seismograph	
4 (c)		Partly reinforced concrete wall.					Additionally strengthened.	Repairs completed.	0.55	0.45	Taniguchi	Seismograph	

TABLE 3.—(Continued)

STEEL FRAME BUILDINGS (Continued)

No.	Name of building	Construction	Size: Height above street level, in feet	Size: Floor area, in square feet	Size: Stories	Ground	Condition	When measured	Periods, in seconds: Longitudinal	Periods, in seconds: Transverse	Observer	Type of instrument	Remarks
5	Kaijo Building	Office building: Brick and reinforced concrete curtain wall. Foundation connected.	87.5	26 500	Seven	Alluvial	Long completed.	Before the great earthquake.	.....	0.45	Omori	Seismograph	Slight damage
6	Kogyo Bank Building	Office building: Brick and reinforced concrete curtain wall. Foundation connected.	98.5	23 500	Seven and cellar	Alluvial	Long completed.	Before the great earthquake.	0.61	0.65	Omori	Seismograph	Very slight damage
7	Ginza Building	Department store. Reinforced concrete wall.	100	22 000	Eight	Alluvial	....	After completion (After the great earthquake)	0.70	0.70	Saita	Seismograph	Half finished. No damage.
8	Marunouchi Hotel	Reinforced concrete wall.	100	6 580	Nine	Alluvial	....	After completion (After the great earthquake)	0.60	0.50	Saita	Seismograph	Half finished. No damage.
9	Earthquake Research Institute	Reinforced concrete wall.	31	5 170	Two and two cellars	Diluvial	....	After completion.	0.30 (not elastic vibrations)	0.30	Ishimoto	Micro-vibrograph	Built after the great earthquake

REINFORCED CONCRETE BUILDINGS

No.	Name of building	Construction	Size: Height above street level, in feet	Size: Floor area, in square feet	Size: Stories	Ground	Condition	When measured	Periods, in seconds: Longitudinal	Periods, in seconds: Transverse	Observer	Type of instrument	Remarks
10	Naigai Building	Office building: Reinforced concrete frame with brick filler wall. Separate foundation	100	21 950	Seven	Alluvial	Nearly completed	Before the great earthquake.	0.65	0.65	Nagata	Seismograph	Collapsed
11	Nippon Bank Annex	Office building: Reinforced concrete frame with brick filler wall	100	11 300	Seven	Alluvial	Long completed	Before the great earthquake.	0.43	0.43	Nagata	Seismograph	Moderate damage
12	Tokyo Nichinichi Shinbun Sha	Newspaper office: Reinforced concrete frame and wall	80	2 860 / 2 860 / 5 190	Two / Four / Five	Alluvial	Long completed	Before the great earthquake.	0.52	0.52	Nagata	Seismograph	Slight damage
13	Old Aeronautical Laboratory	Reinforced concrete frame and wall	36	7 500	Two	Reclaimed	Long completed	After the great earthquake.	Transversal Fundamental 0.50	Fundamental, 0.30; Secondary, 0.10	Ishimoto and Suyehiro	Micro-vibrograph	No damage

TABLE 3.—(Continued)

REINFORCED CONCRETE BUILDINGS (Continued)

No.	Name of building	Construction	Size: Height above street level, in feet	Size: Floor area, in square feet	Size: Stories	Ground	Condition	When measured	Periods, in seconds: Longitudinal	Periods, in seconds: Transverse	Observer	Type of instrument	Remarks
14	Mitsubishi Laboratory	Reinforced concrete frame and wall	33	7 500	Two and cellar	Diluvial	Long completed	After the great earthquake.	0.35	Transversal Fundamental, 0.35; Secondary, 0.15	Ishimoto and Suyehiro	Micro-vibrograph	No damage

BRICK BUILDINGS

No.	Name of building	Construction	Size: Height above street level, in feet	Size: Floor area, in square feet	Size: Stories	Ground	Condition	When measured	Periods, in seconds: Longitudinal	Periods, in seconds: Transverse	Observer	Type of instrument	Remarks
15	Ryounkaku Tower	Observation tower, octagonal section. Small wooden two-storied superstructure on top	130 (main structure)	40 (in external diameter)	1.0 (main structure)	Alluvial	Long completed	August 5, 1919	1.08		Omori	Seismograph	Collapsed
16	Natural History Museum, Tokyo University	Wooden floor; high gables	37	4 700	Two	Diluvial	Long completed	1902	0.33	.....	Omori	Seismograph	Severe damage

WOODEN BUILDINGS

No.	Name of building	Construction	Size: Height above street level, in feet	Size: Floor area, in square feet	Size: Stories	Ground	Condition	When measured	Periods, in seconds: Longitudinal	Periods, in seconds: Transverse	Observer	Type of instrument	Remarks
17	Asakusa Pagoda, Tokyo	Temple tower; four strong columns on each side	81.7	16 (basement story) / 10 (fifth story)	Five	Alluvial	Built in 1692	1919	1.35		Omori	Seismograph	Absolutely intact in all earthquakes
18	Japanese hotel in Idu	Japanese style: frames are strongly connected	40	4 450	Three	Diluvial	Nearly completed	After the 1930 Idu earthquake.	0.7	0.07	Saita	Seismograph	Intact in the Idu earthquake
19	Japanese dwelling house in Idu	Ordinary Japanese style	18	930	Two	Alluvial	Long completed	Before the 1930 Idu earthquake.	0.48	0.52	Suyehiro	Seismograph	Intact in the Idu earthquake
20	Naval Architectural Laboratory Annex	Western style	15.5	4 440	One	Diluvial	Long completed	1930	0.3	0.5	Suyehiro	Vibration analyzer	Intact in the great 1923 earthquake

Marunouchi Quarter, the most unharmed part of the city. It is the business center of Tokyo. Except for the unsightly appearance of the Naigai Building (No. 10, Table 3), no one would suppose, without careful examination, that these views were taken just after the great earthquake and the fires that laid waste the greater part of the city. This remarkable contrast is the natural consequence of the fact that in the former district most of the houses were of fragile wooden or brick construction having little resistance against earthquake and fire, while in the latter district, buildings with a few exceptions (such as the Naigai Building), were built substantially, being owned by the Mitsubishi Company which has the reputation for being one of our soundest business concerns, and which constructs its buildings with strength and with the utmost care.

It is remarkable that, except for the single case of the Marunouchi Building, which was built by a foreign contractor with slight experience in destructive earthquakes, all buildings owned by the Mitsubishi Company were perfectly intact. This building (No. 1, Table 3) is shown in Figs. 46 and 47. About 80% of the brick buildings either collapsed or suffered damage in the great earthquake. One of these was the office of the Yeiseikai (the Hygienic Society). This house was built in the German fashion, with thin walls, and had not been provided with sufficient margin of strength against earthquakes.

It is interesting to quote a passage regarding the old Engineering Building of the Tokyo Imperial University, from Milne's "Seismology." He says:

"Certain roofs which are of considerable span in the old Engineering School, Tokyo, were built so that they rested freely upon the supporting walls, and were not carried with them in horizontal displacements. Although during the last thirty years they have experienced many severe shakings, hitherto they have remained uninjured."

Although the merit of such construction is open to question, there is no doubt that some attention was given to the possible seismic effect on the building. Nothwithstanding this fact, the building suffered severe damage as shown in the photograph.

Amidst the failure of the majority of brick buildings, none of those owned by the Mitsubishi Company (Dr. T. Sone, Chief Architect)—one of which is seen in the foreground of Fig. 46—suffered even a single crack, and they stand as monuments of good work. The reason for this is that not only was the construction excellent, but the workmanship was also excellent; the bricks were reinforced by horizontal iron bonding and vertical rods embedded in the joints. The fact that whenever the outdoor temperature fell below a certain point, the brick-laying was stopped, is sufficient to show with what care the construction was executed.

The Yusen Building (No. 3, Table 3) is seen on the left side in the background of Fig. 46, and is shown in Fig. 48. This building was constructed of steel frames with curtain-walls of hollow tiles one and one-half bricks thick, covered with ornamental terra cotta facing. It suffered moderate damage, such as cracks in the external and partition walls, although the steel framing was unharmed. Yurakukan (No. 4, Table 3), Marunouchi
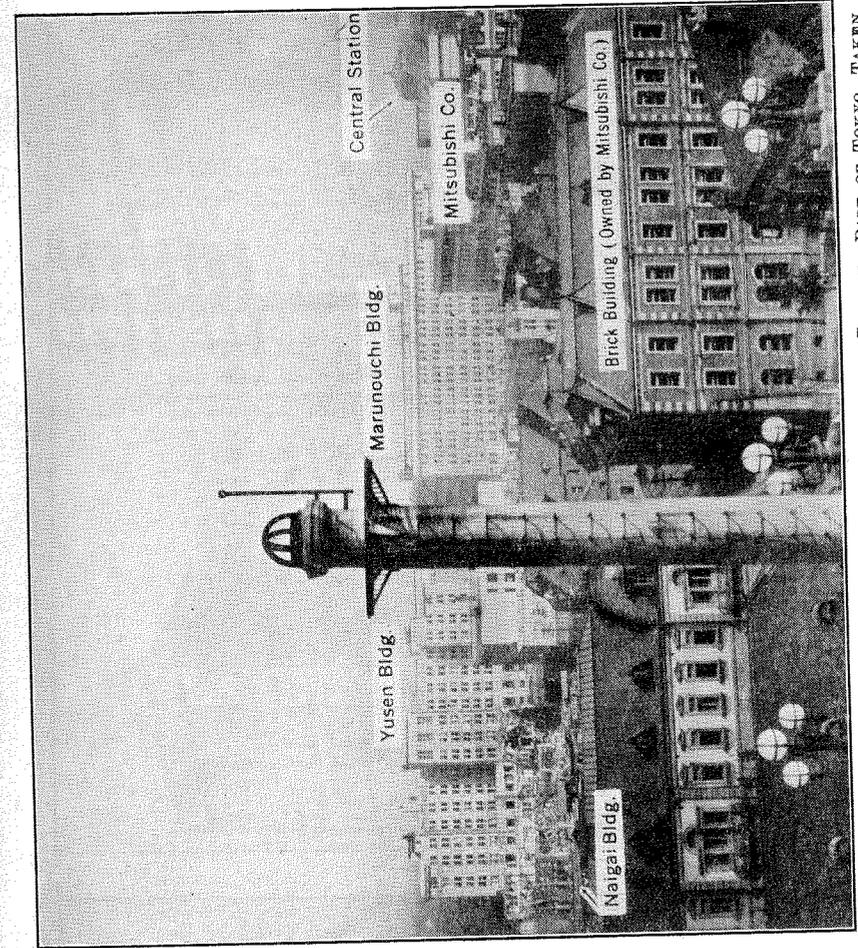
FIG. 46.—BUILDINGS IN MARUNOUCHI QUARTER, THE LEAST DAMAGED PART OF TOKYO, TAKEN AFTER 1923 EARTHQUAKE.
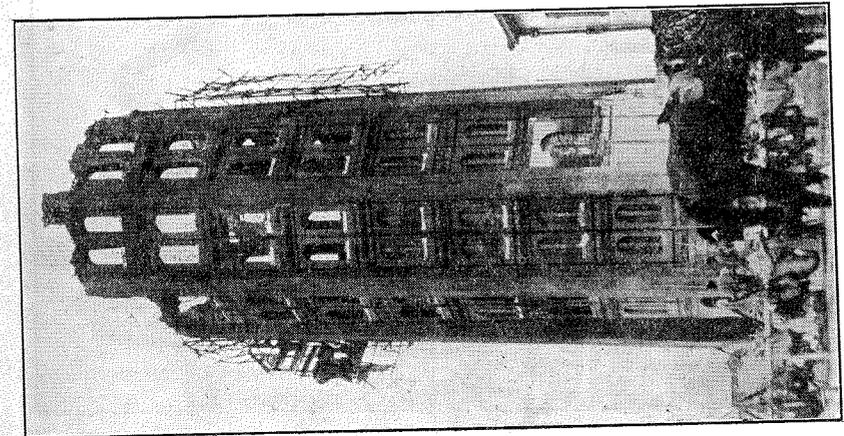

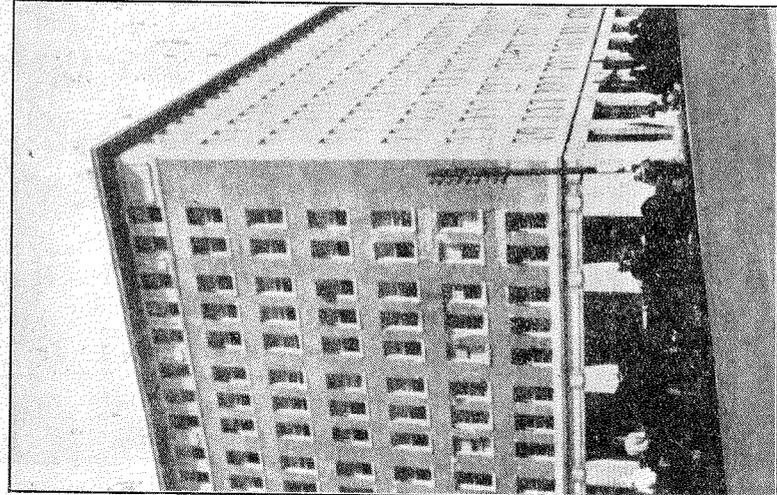FIG. 45.—RYOUNHAKA TOWER RUINED IN 1923 EARTHQUAKE
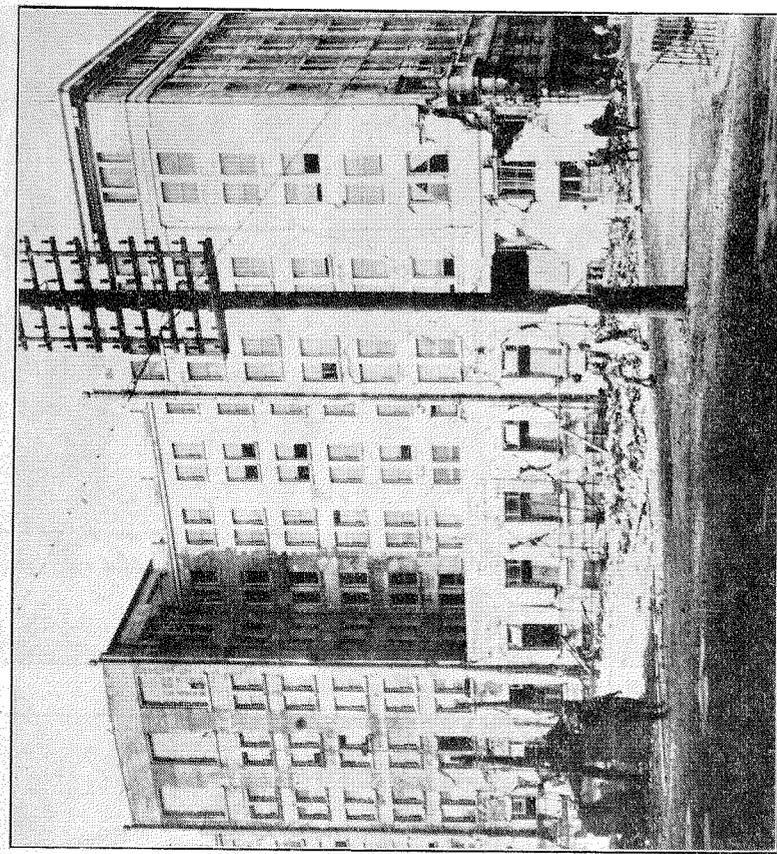
FIG. 48.—THE YUSEN BUILDING AFTER THE EARTHQUAKE OF 1923.

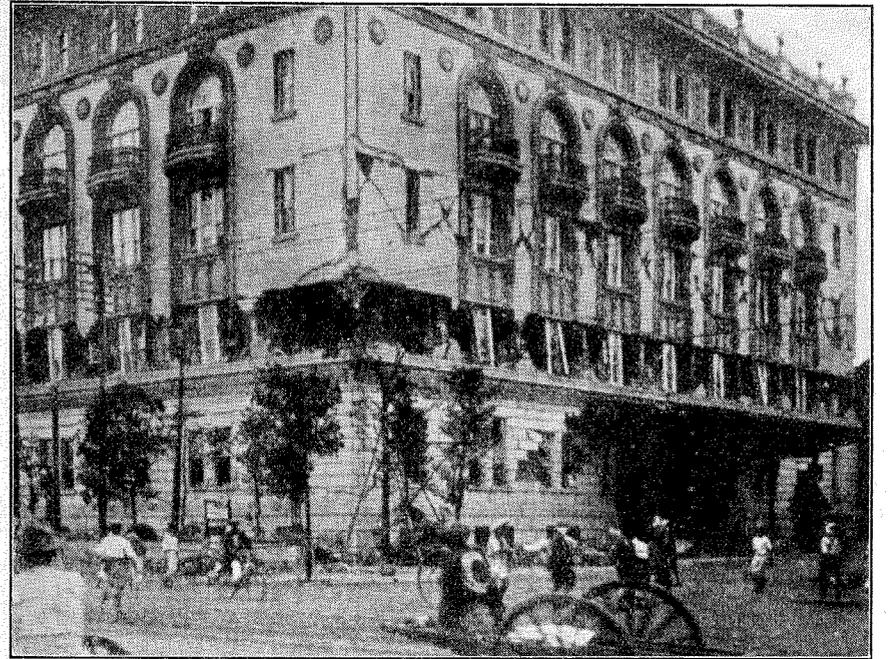FIG. 47.—MARUNOUCHI BUILDING AFTER 1923 EARTHQUAKE.

FIG. 49.—VIEW SHOWING DAMAGE TO THE TOKYO KAIKAN

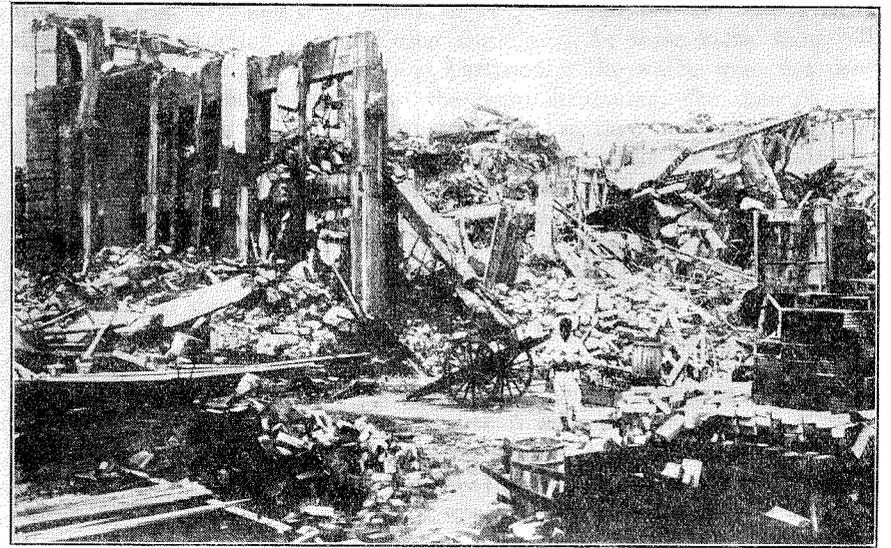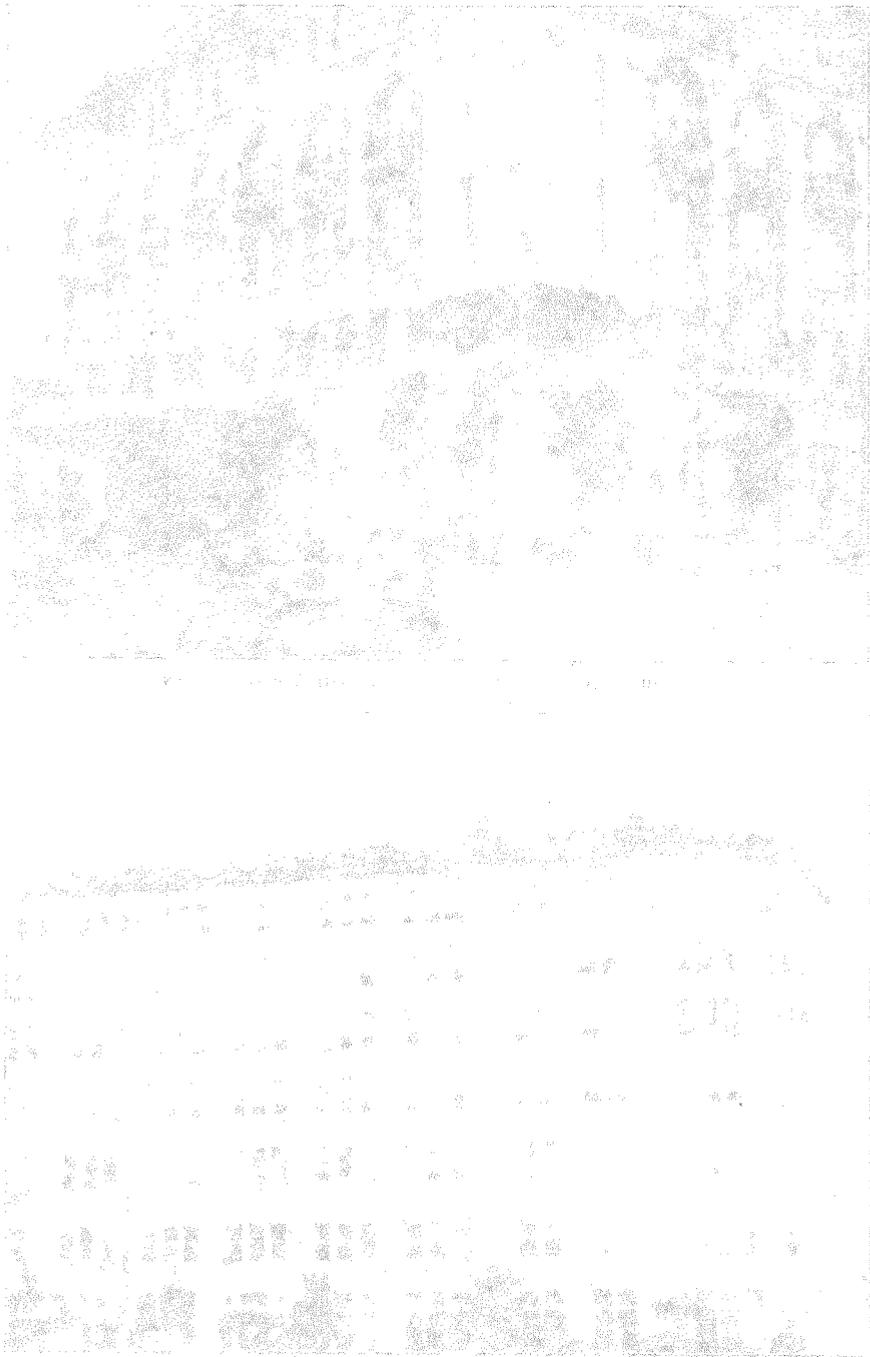FIG. 50.—VIEW OF THE KAIJO BUILDING.
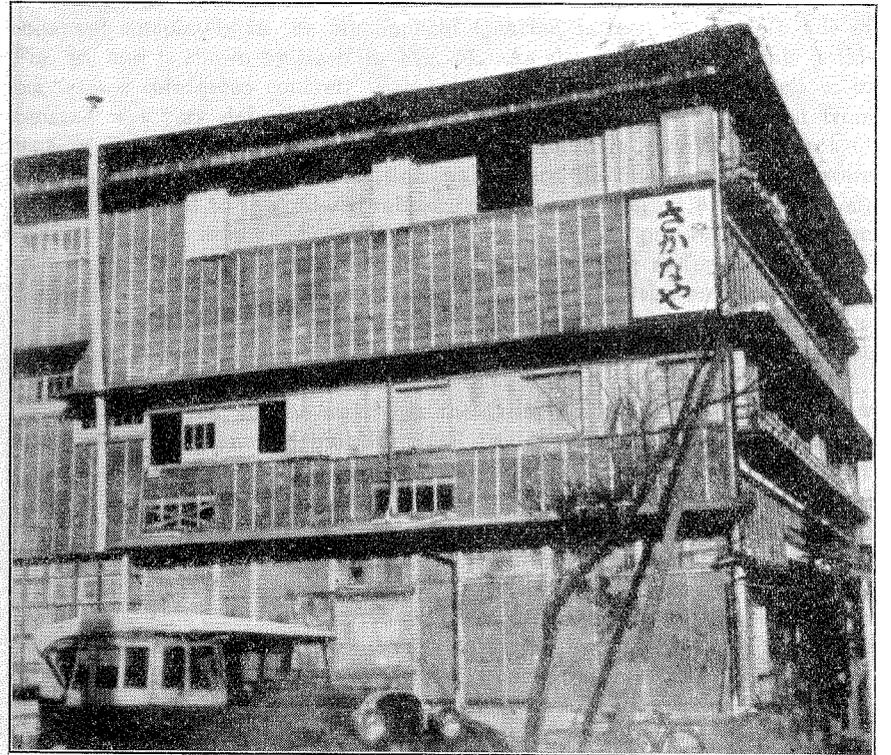
FIG. 51.—RUINS OF THE NAIGAI BUILDING

FIG. 52.—VIEW OF WOODEN THREE-STORY BUILDING OF JAPANESE ARCHITECTURE THAT WITHSTOOD THE IDU EARTHQUAKE.

Building (Fig. 47), and Tokyo Kaikan (Fig. 49 and No. 2, Table 3), are similar in construction to the Yusen Building. As these views show, all suffered damage in the external and partition walls, which were not constructed to contribute strength to the main structures; the damage was comparatively slight in the first two buildings, so that the tenants did not have to vacate them during the subsequent repairs; while the damage in the last-named building was serious, the second-story walls being shattered and the columns badly bent. Among these three buildings, the last two had comparatively light framing, but the Marunouchi Building had been additionally strengthened before the great earthquake and had a narrow escape from suffering heavy damage.

Other steel-frame buildings, such as the Kaijo Building (Fig. 50 and No. 5, Table 3), and the Kogyo Bank Building (No. 6, Table 3), were more substantially constructed than those just mentioned. The column footings were well connected with each other, and their walls were constructed of reinforced concrete and bricks, in such a way as to act as more than mere curtain-walls. Naturally, they withstood the earthquake splendidly. The Marunouchi Hotel (No. 8, Table 3), was of steel-framed construction with reinforced concrete, and was subjected to the great earthquake while it was being built. It suffered no damage.

The Naigai Building (No. 10, Table 3) which was the only building that collapsed completely in the Marunouchi Quarter, is seen on the left side of Fig. 46, and is shown by itself in Fig. 51. As shown in Table 3, this building was of reinforced concrete with brick filler walls. The construction, in general, was very defective, the structural design being boldly copied from that in vogue in an aseismic country. The footings were independent of each other; no substantial partition walls were provided; the beams were loosely connected to the pillars; reinforcement bars were not properly joined; and the stirrups were deficient in number. In short, no precaution was taken to provide against a severe earthquake. The building suffered the fate it deserved. It is worthy of notice that the collapse of the building did not occur with the first shock of the earthquake, but nearly 10 sec. after the principal motion had begun. The destruction was probably caused either by the cumulative effect of the vibration or by the gradual development of cracks.

I must tell you, by the way, that the failure of this building and a few other reinforced concrete buildings (all badly constructed) are exceptional cases (in the city, only 7 cases of total failure out of 593 buildings were reported). Therefore, it is a hasty conclusion to judge from these exceptional cases that the reinforced concrete building has little resistance against a severe earthquake. On the contrary, the result of tests with this severe earthquake was fairly good; nearly 78% of this class of buildings in the city, and 75% of the same class in the environs, were perfectly intact in the earthquake. Except those already mentioned, most of the buildings seen in Fig. 46 are of reinforced concrete, and nearly all of them were uninjured.

A wooden building, (No. 18, Table 3) is shown in Figs. 52 and 53. It is a three-story hotel built in the Japanese style. As will be seen from the photograph, it stood unharmed in the general wreckage in the Idu earthquake. This

building not only had strong pillars, extending its entire height, but in the joints of all structural members iron strips and bolts were freely used, mortise, tenon, and joints being avoided as far as practicable. It seems that regardless of the building material, those buildings that are constructed honestly and with good sense can withstand severe earthquakes.

Thus far, I have stated roughly the effects of the great earthquake on some of the buildings listed in Table 3. More complete descriptions of the damages suffered by various kinds of buildings would no doubt be found instructive. However, I must leave such descriptions to the various reports on the 1923 earthquake, which were abundantly published in my country, and among which the Reports of the Imperial Earthquake Investigation Committee, No. 100, C and D, and Reports on the 1923 Earthquake Damages, published by the Civil Engineering Society, Japan, are most commendable. Although these reports are in Japanese, a large part of the volumes consists of photographs and drawings, which are, in effect, an international language, so that there should not be much difficulty in studying them.

((II) Vibration of a Rigid Building in an Earthquake

We shall now proceed to investigate the problem under consideration. To study, in the first place, to what extent the motion of a rigid building follows that of the ground, and, at the same time, to study the nature of its vibration in an earthquake, I have measured the vibration of our Institute building in an earthquake. (See Fig. 54). It is a steel-framed, reinforced concrete structure and is extra strong (weight 53 lb. of steel framing and bars per square foot of floor area). The nature of the vibration of this building in ordinary times was exhaustively investigated[12] by one of my colleagues, Professor Ishimoto. Fig. 55 shows, side by side, the vibrations of the basement floor and the neighboring ground as recorded simultaneously by Ishimoto's microvibrographs with a high magnification (about 3 000 times). It will be seen that the building moved persistently to and fro with a period of about 0.3 sec. Simultaneous observations of the motion in different parts of the building showed that the oscillation was not an elastic one, but very probably the motion of a rigid body on the ground-bed.

For comparing the vibration of the building with that of the neighboring ground in an earthquake, two horizontal pendulum seismographs of the same construction were used. One of them was set on the floor of a penthouse on the flat roof, and the other on the ground beneath a temporary shelter close to the building. The special feature of these instruments is that the record is taken with an open time scale. In earlier observations, the recording drums, which were driven by clockwork, had a peripheral speed of about 6 cm. per min., but it was soon found that, with such a condensed time scale, the motions could not be studied in detail. For this reason, the clockwork was replaced by an electric motor which ran continuously at such a rate as to make the time scale about 10 mm. per sec., in order to make such quick vibrations as 0.1 sec. clearly observable.

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[12] *Bulletin,* Earthquake Research Inst., Vol. 7 (1929), No.1.

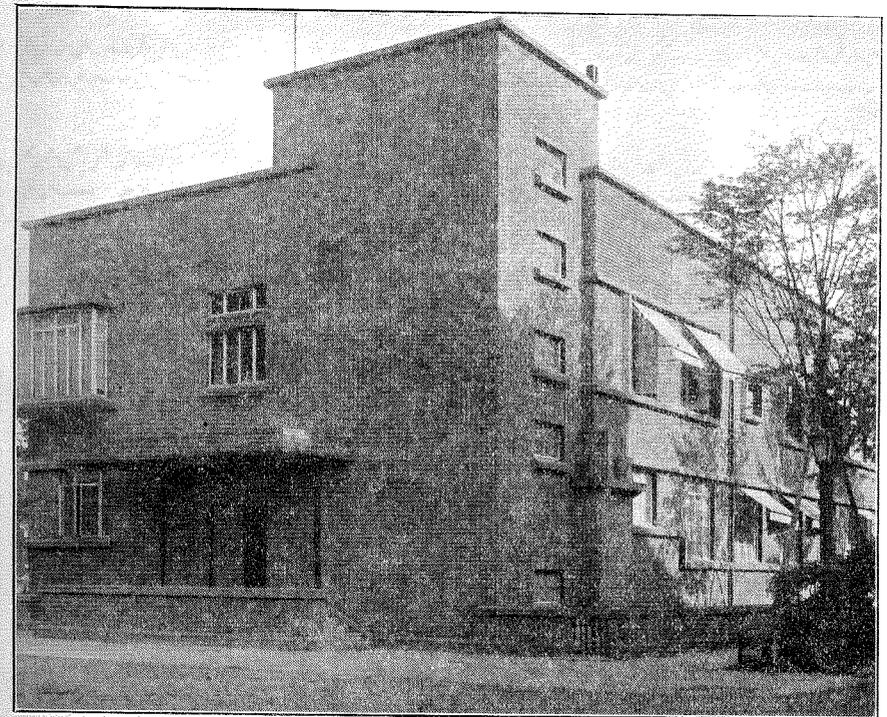FIG. 53.—View of Destruction in a Village in the Province of Idu.

FIG. 54.—Earthquake Research Institute, Tokyo Imperial University.

Needless to say, an equally open diagram can be obtained by using a rapidly running drum driven by clockwork, the motion of which is started by a trigger arrangement; but, in that case, there will be difficulty in maintaining the same speed for the drums of the two instruments, a condition desirable for comparing the motions.

To simplify the mechanism, the recording drums were rotated in a fixed position without displacement in the direction of the axis. Therefore, it became necessary to keep the recording points clear of the smoked surface of the drum at ordinary times, lest it be marked for no purpose by a group of straight lines. To this end, an electric trigger was used to hold or release the recording pen according to necessity.
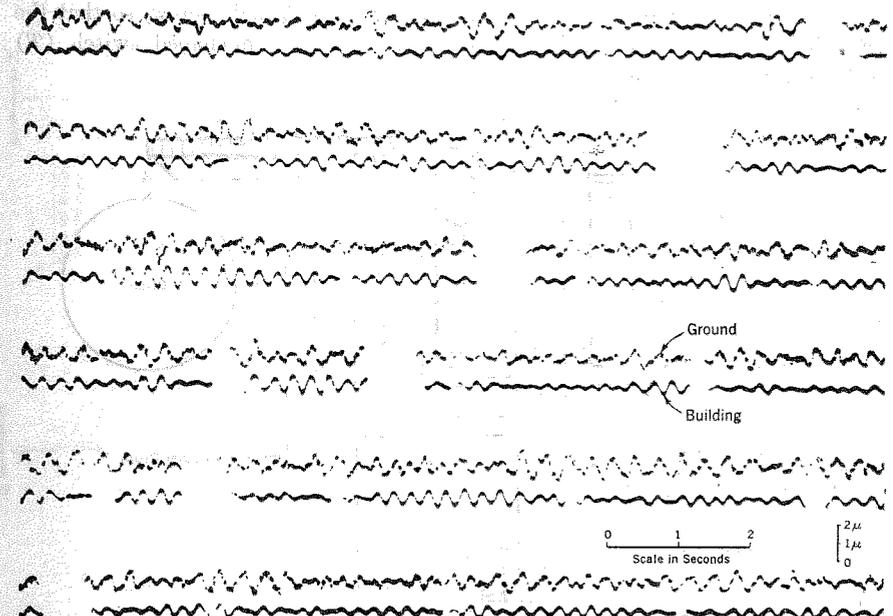

FIG. 55.—MICROTREMOR CURVE OF EARTHQUAKE RESEARCH INSTITUTE (A STEEL-FRAME, REINFORCED CONCRETE BUILDING) COMPARED WITH THAT OF THE ADJACENT GROUND.

As shown in Fig. 56, an electric current is ordinarily passed to the coil of a broad electric magnet (N) over the recording point (A) through a pendulum (P) and a catch-lever (C), under which another electric magnet (M) is located. Through the last-named electro-magnet (M) no current is passed at ordinary times, but when an earthquake occurs and sets in motion the trigger pendulum (B), then its point comes into contact with the mercury in an annular cup (Q), and an electric circuit is closed to excite the electro-magnet (M) and detach the catch (C). Thus, the electric current to the electro-magnet (N) is cut off to make the recording point fall on the surface of the drum, when it begins to record the earthquake motion. The recording point, however, must not be left in contact with the drum for an unduly long time, because then the useful portion of the record

is impaired by a series of unnecessary lines in the trail of the earthquake and after it is over. Obviously, an engineer does not need the whole of a seismic record. He only wants the most destructive part of it; the trail and the preliminary tremors are not very important.

For this reason, an arrangement is made to pull the recording point back again after a reasonable time (say, about 3 min.). For this purpose, a clockwork (U) is started by releasing another catch (D) by means of a magnetic relay (R), the electro-magnet of which works in parallel with that of (M) used for releasing the catch (C). Thus, as soon as the pendulum (P) is released, the clockwork is started and begins to revolve a spur wheel (S), which, in turn, drives another wheel (W). On the shaft of the wheel (W) is cut a helical groove, which is engaged to a fixed female screw, so that the wheel, while revolving, moves axially and closes a cam-shaped switch (T) after a predetermined time.
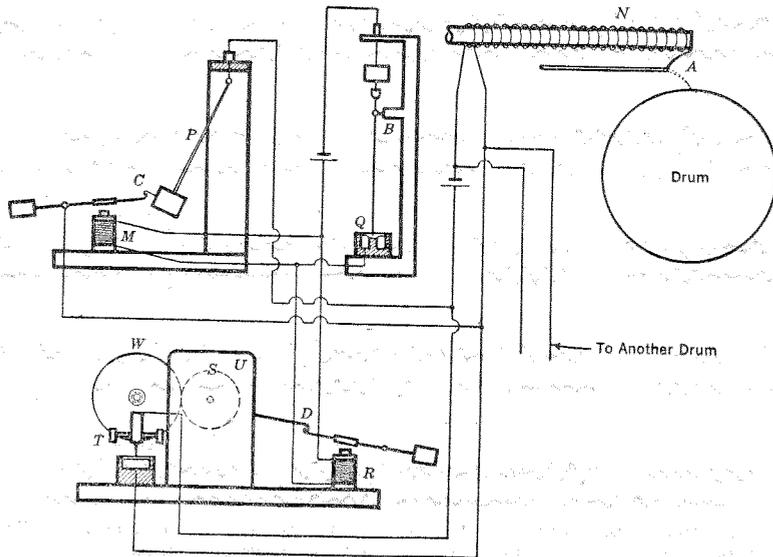

FIG. 56.—TRIGGER ARRANGEMENT FOR A HORIZONTAL PENDULUM SEISMOGRAPH.

In this manner, the electric circuit to the electro-magnet (N) over the recording point is again closed, and the latter leaves the surface of the smoked drum. In this way, the desired portion of an earthquake record is taken with an open time scale. The arrangement (Fig. 56) can be greatly simplified in an instrument that is to be newly made; but as I had to use an old Milne starter, the arrangement became very complicated.

Thus far, only one set of earthquake records have been taken, and that with partial success. This is shown in Fig. 57. Now, comparing the record of the motion on top of the building with that of the neighboring ground, two important facts are revealed: First, that so far as the general motion in

a moderate earthquake is concerned, a strongly constructed building like our Institute building, moves in just the same way as the surrounding ground; and, second, that the building is insensible to those vibrations of the ground having very short periods of, say, about 0.1 sec.

From these facts, it can be inferred that the dynamic stress induced in a strongly constructed rigid building by an earthquake is likely to be equal to the static stress which would be induced, had the building been subjected to
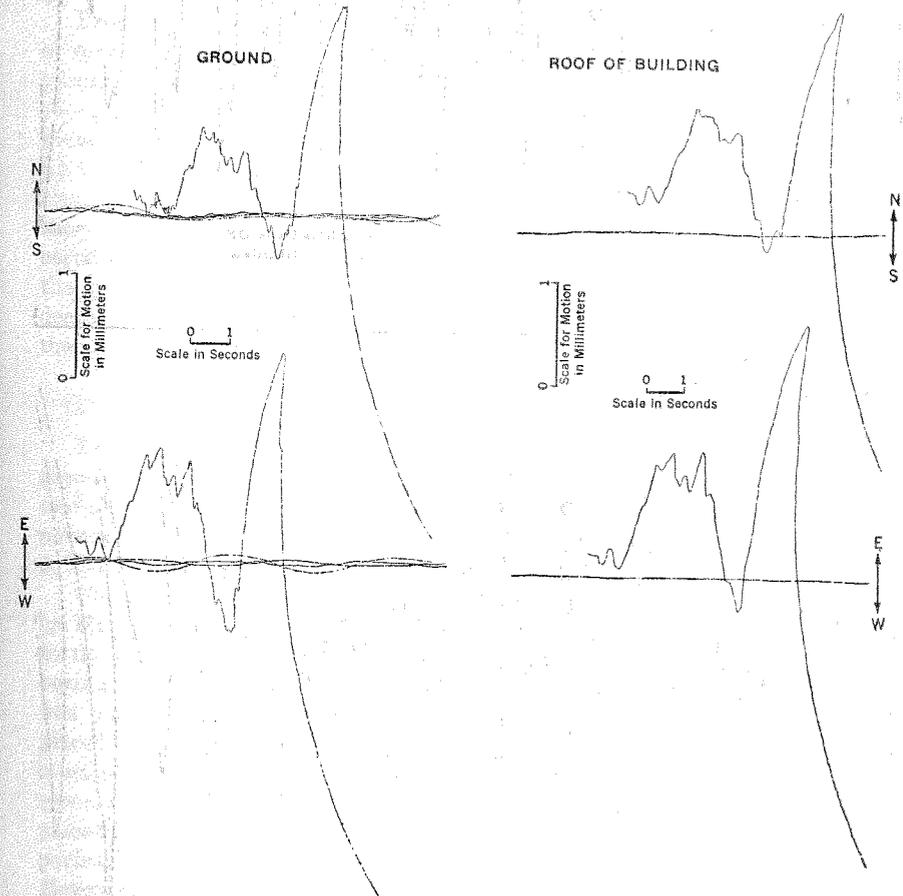

FIG. 57.—RECORDS OF AN EARTHQUAKE TAKEN NOVEMBER 26, 1930, ON THE ROOF OF THE INSTITUTE BUILDING, COMPARED WITH THOSE OF THE ADJACENT GROUND.

the static load of the intensity given by the mass of the building multiplied by the horizontal acceleration of the seismic vibration; and, also, that the component of seismic vibrations having a very short period, say, less than 0.1 sec., is not of much consequence for the building under consideration, although as stated in Lecture II, there is the possibility in some cases that such a quick vibration may cause a fairly intense acceleration.

W ↑ ↓ E

Scale in Millimeters: 4 3 2 1 0

**FOUNDATION OF
DIET BUILDING**

0   0.5   1

Scale in Minutes

W ↑ ↓ E

NEIGHBORING GROUND

0   0.5   1

Scale in Minutes

FIG. 58.—VIBRATIONS IN AN EARTHQUAKE IN THE DIET BUILDING FOUNDATION,
COMPARED WITH THE ADJACENT GROUND DURING CONSTRUCTION.

(III) MOTION OF THE BUILDING FOUNDATION

The last-mentioned fact would seem to be self-evident, since the natural period of oscillation of the building itself is greater than 0.1 sec.; but it is not the only evidence. According to observations made by Professor Imamura on the vibration of the Diet Building during construction, some very rapid ripples, having a period of about 0.1 sec., disappeared in the motion of the foundation, although the foundation moved about as much as the neighboring ground. One of the records is shown in Fig. 58.

Professor Ishimoto's investigation of the velocity of ripples on the ground is very useful in this connection. According to him, on the surface of the ground where our Institute building stands, the P-wave has a velocity of above 120 m. per sec. and the S-wave about 65 m. per sec. Therefore, very probably, the wave length of ripples having a period of 0.1 sec. is between 6.5 to 12.0 m.; hence, they are less than the linear dimensions of the building. Consequently, a building on soft ground is not sensible to those quick and short ripples. It may also be mentioned that this fact may be attributed to a certain extent to another behavior of the vibration of soft ground, in which the amplitude of the component of a seismic vibration of very short period decreases quickly with depth. Therefore, foundations at some depth below the surface will be less affected by the rapid components of seismic vibrations.

(IV) VIBRATION OF A BUILDING OF MEDIUM RIGIDITY IN AN EARTHQUAKE

The foregoing discussion refers to a very rigid building. Now I shall proceed to the discussion of a building belonging in the same class, but of moderate rigidity, and then to a weaker (non-rigid) structure. The Maru-nouchi Building which was strengthened after it was built (No. 1 (c), Table 3, and Fig. 47), may be taken as an example of medium rigidity.

The records of the vibration of this building in an earthquake were taken by Mr. T. Saita of our Institute. In this case, since the building is situated in the business center of Tokyo, no vacant space was available in the neighboring ground to install a seismograph. For this reason, one seismograph was placed on the floor of the basement, while an identical instrument was placed on the eighth floor. A set of records of an earthquake taken simultaneously at these two places are shown in Fig. 59. As the time scale of these records is not open (being nearly 60 mm. per min. for the seismograph placed high, and 65 mm. per min. for that placed in the cellar), detailed comparison of the motion, as in the previous case, is impossible with these records. Moreover, the usual period of main earthquake motions in this district is 0.7 sec., or more, and waves having shorter periods are superposed merely as secondary motions.

Since the period of exciting motion is thus generally greater than the natural period of the building, and since also the motion of the ground was recorded in the basement floor, instead of on the ground itself, the former of which would have more or less filtered or distorted the earthquake motion, comparison of these simultaneous records may be less instructive than the one previously mentioned. It is worth mentioning, however, that the general
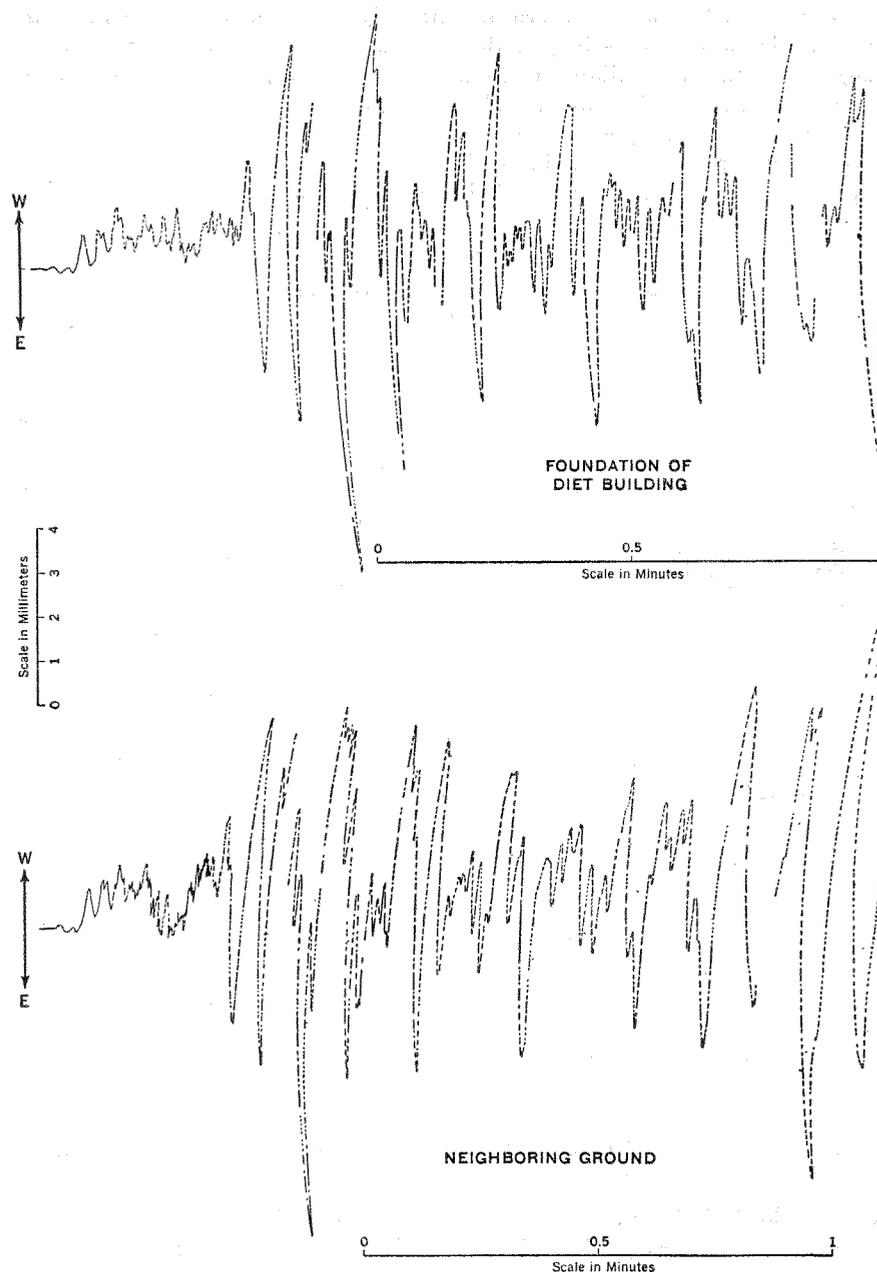
motion at the top of the building is nearly the same as that in the basement, as regards its period, phase, and form, but the amplitudes are greater at the top by about 20 to 70%, depending on the nature of the motion; and on this general motion of the top of the building secondary motions having a period of about 0.5 sec., are superimposed, here and there. These secondary motions are likely to be the free vibrations of the building.
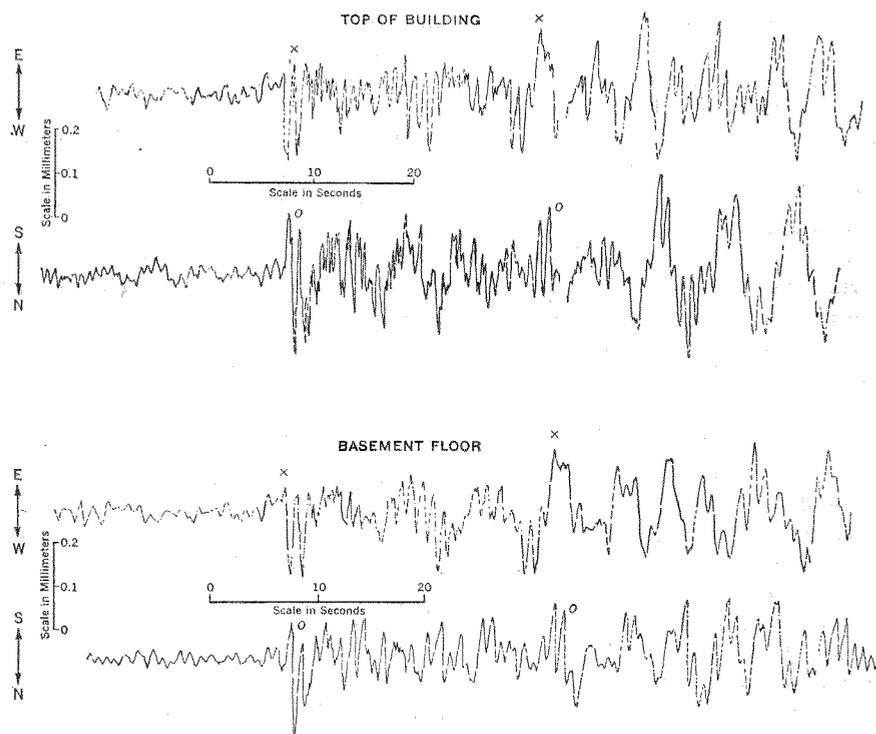

FIG. 59.—VIBRATIONS OF AN EARTHQUAKE MEASURED ON THE EIGHTH FLOOR OF THE MARU-NOUCHI BUILDING COMPARED WITH THOSE IN THE FLOOR OF THE BASEMENT.

(V) VIBRATION OF WEAK (NON-RIGID) BUILDING IN AN EARTHQUAKE

We will next take up the behavior of the Yurakukan Building (No. 4, Table 3), in an earthquake. This building is similar in construction to the Marunouchi Building. Like that building, it suffered moderate damage in the great 1923 earthquake, but has since been thoroughly repaired and strengthened, so that at present its strength has quite come up to the standard. This is seen from the fact that the period of free vibration is now 0.5 sec. as against 0.81 sec. just after the great earthquake, and its vibration in an earthquake now is similar to that of the Marunouchi Building; but at the time the earthquake record was taken by Professor T. Taniguchi, of the Tokyo Engineering University (shown in Fig. 60), the

damage had not yet been repaired, so that the building was classed as weak. As was done in the previous case, one seismograph was installed on the basement floor and the other on the topmost floor.

As will be seen from Fig. 60, the nature of the vibration of this building in an earthquake is quite different from that for a rigid building and a building of medium rigidity. The motion of the basement floor which might not have been very different from that of the neighboring ground, was, as usual, very irregular, consisting of vibrations having periods varying from 0.7 sec. to 1.1 sec. On the other hand, the top of the building moved principally with a definite period of 1.0 sec., the amplitude of the maximum motion at the top being from two to three times that of the basement floor.
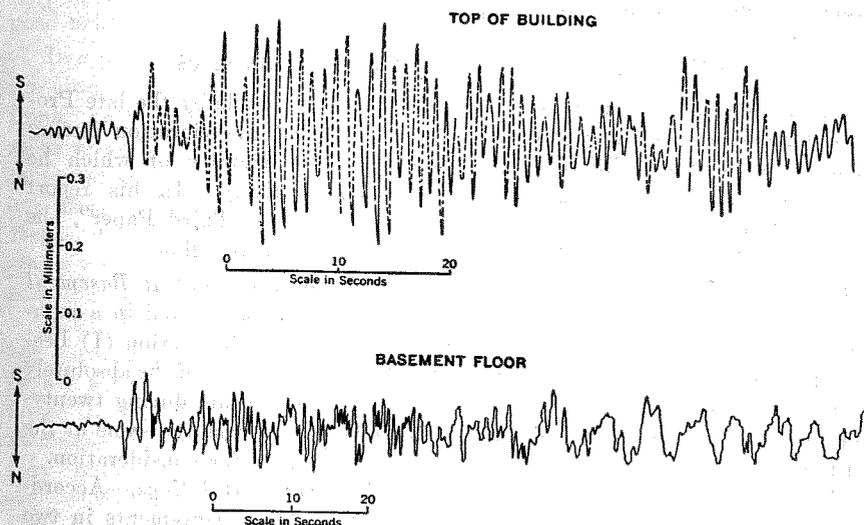

FIG. 60.—VIBRATIONS OF AN EARTHQUAKE MEASURED AT TOP FLOOR OF THE YURAKUKAN BUILDING COMPARED WITH THOSE IN THE FLOOR OF THE BASEMENT.

It will thus be seen that, so far as rigid buildings are concerned, a building not provided with ample rigidity has less damping against vibrations, and, consequently, its own free vibration predominates under the action of earthquakes having irregular motions. The motion in this case is very analogous to the oscillation of a ship on a turbulent sea.

To recapitulate, in an earthquake a rigid building moves nearly the same as the surrounding ground; a non-rigid building moves with its own period; and the motion of a building of medium rigidity is intermediate between these two.

By the way, I wish to say a few words about scientific researches on the behavior of structures in an earthquake. Generally, such researches—whether they are mathematical or experimental—are made under the assumption that earthquake motions are a continuation of one and the same simple harmonic motions. This is far from the truth. Still worse is the method in which only the established, forced vibration of structures is considered, little

attention being given to the free vibration and to the nature of damping against vibration. As every one knows, pure, forced vibrations are established only under the excitation of pure, harmonic motions and after a sufficient time —depending upon the resistance against vibrations—from the starting of the motion.

Such an argument as the foregoing will be unnecessary in view of what I have just mentioned of the actual behavior of structures in earthquakes. Also, it is a well-known fact among Japanese engineers that the fate of structures in a destructive earthquake is decided in the first 30 sec. of the principal motions, which is just contrary to the saying that the issue of a battle is decided in the last 5 min. These facts may be worth the attention of investigators of engineering seismology.

(VI) OMORI'S INVESTIGATIONS OF BRICK BUILDINGS

I wish, here, to refer to a very useful investigation made by the late Professor Omori on a similar problem. He investigated the vibration during earthquakes, of three different brick buildings, the rigidity of which he judged to be ample, medium, and deficient, respectively. In his report entitled "Earthquake Measurement in a Brick Building; Third Paper",[13] he summed up the result of his investigations substantially as follows.

Comparison of Earthquake Movements at Third Story and at Basement of Old Mitsubishi Bank Building.—This building was constructed in a manner similar to those Mitsubishi brick buildings mentioned in Section (I) Lecture III. Professor Omori observed the double amplitude ($2a$) of the absolutely greatest vibration and the average period in each seismogram during twenty-nine earthquakes. He found that the earthquake motion was the same at the third story and at the basement of the brick building under consideration.

Comparison with Earthquake Measurements in Other Buildings.—According to Professor Omori, the results of the earthquake measurements in two other brick buildings were as follows:

(a) External Wall of Upper West Corridor of Engineering College, Tokyo Imperial University.—In the case of minor earthquakes, which consisted of vibrations of comparatively long period, that is, more than 0.5 sec., the motion was practically equal in the upper story and on the ground surface. On the other hand, in earthquakes which consisted of short-period vibrations, the motion at the top of the wall was greater than that of the ground surface in the average ratio of 2 to 1. As the period of vibration was the same for the two places of observation (this building and the Seismological Institute), it seemed to Professor Omori that in shocks of violent nature the wall, on which the roof rested, behaved like an inverted pendulum, its motion synchronizing with the earthquake motion.

(b) The Eastern End Wall of Natural History Museum of Tokyo Imperial University.—This is a two-story brick building situated not far from the College of Engineering. The total height of the wall is 53 ft., and the seismograph was attached to this wall at a height of 31 ft. from the ground.

[13] *Publications*, Earthquake Investigation Comm., No. 20, p. 73.

The wall, which was evidently weak, was shaken considerably by earthquakes, the duration and amplitude of motion being nearly three times those at the ground surface. In this case, the period of vibration of the wall was practically constant (according to Professor Omori), the mean value being 0.33 sec. This was taken to show that in an earthquake the wall acted as an elastic spring and vibrated with its own period, whatever the period and amplitude of the ground motion might be.

Commenting upon these examples, Professor Omori stated that they show, "* * * that the movements of brick buildings produced by earthquakes differ very much, according to the quality of the structures. In fact, the Natural History Museum, the Engineering College, and the Mitsubishi Bank may be taken as exemplifying respectively a very bad, an ordinary, and a good brick building, regarded from the seismological point of view."

In a poorly constructed building (according to Professor Omori), the walls are always shaken several times more severely at the top than at the foundations. An "ordinary" building in this category is one whose walls are shaken more severely than the foundation only in earthquakes of violent nature, or those consisting of vibrations of short period; and, finally, a "good" building is one whose walls have the same motion as the ground in all the earthquakes. Hence, a brick building such as the Mitsubishi Bank, which is shaken as a single unit by earthquakes, is to be regarded as having a great advantage in resisting earthquake shocks.

It will be very interesting to see just how the destructive 1923 earthquake has borne out Professor Omori's views. His conclusions were, indeed, confirmed with remarkable exactness, although, unfortunately, he did not live to see it. The Mitsubishi Bank Building (the "good" building according to Professor Omori), was perfectly intact; the Engineering College (the "ordinary" building), suffered more or less damage to gables, towers, coping stones, etc.; while the Natural History Museum (the "bad" building), suffered the most severe damage, although its walls remained standing. These may be valuable facts in the investigation of the earthquake-resisting quality of masonry buildings.

(VII) DAMPING AGAINST THE VIBRATION AND THE NATURAL PERIOD OF BEAMS

Theoretically speaking, the fact that one building is more effectively damped against vibrations than other buildings belonging to the same class and similarly built means nothing more than that its natural period is shorter than that of other buildings, because, as I have shown elsewhere[14], the "decay" of the free vibration of a beam is given by,

$$e^{-0.5kt} = e^{-b} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots (3)$$

in which, $b = \dfrac{0.5\,\xi}{E}\left(\dfrac{2\pi}{T}\right)^2$, and ξ is the coefficient of normal viscosity of

[14] *Bulletin*, Earthquake Research Inst., Vol. VI, p. 63.

the material composing the beam (in actual structures, the dissipation of vibrational energy due to other causes, such, for instance, as the dissipation through the foundation, etc., is to be included in this); E, the Young's modulus; T, the undamped natural period of the vibration of the beam; and e, the base of the Naperian logarithm. Evidently, the value of $\dfrac{\xi}{E}$ will be equal for similar buildings of the same material on the same ground, so that the "decay" constant, $\dfrac{k}{2}$, is inversely proportional to the square of the natural period of vibration.

Indeed, such a correlation between the damping and the natural period is seen in the studies of seismic vibrations of the steel-framed concrete buildings just described. Our Institute building, the most rigid of the three just mentioned, has the most effective damping, while its natural period is probably the shortest (the elastic vibration is not measurable). The Marunouchi Building, of medium rigidity, has a fairly large damping with intermediate natural period (0.5 sec.). Lastly, the Yurakukan Building, which was weak (non-rigid) at the time of observation, has the least damping and the longest period (0.8 sec.). As for brick buildings, Professor Omori has not given their natural periods, but very probably a relation similar to that just mentioned must have held among them.

(VIII) Strength of Buildings and Their Natural Periods

Now, the natural period of the transverse vibration of a beam is inversely proportional to the square foot of I, the geometrical moment of inertia of the section about its neutral axis, while both the induced stress in the bar and the deflection of the bar are inversely proportional to I. Therefore, it may be expected that, with similar buildings belonging to the same class, the shorter the natural period the stronger (more rigid) the building will be, apart from the question of resonance.

It may interest you to know how actual experience has shown that the natural period of a building decreases by increasing its rigidity. I will take the Marunouchi Building as an example. As will be seen from Table 3, and as already mentioned, this building had suffered damage from two earthquakes, and each time it was additionally strengthened the consequence being that the natural period became shorter with each repair. Originally, this building was constructed of comparatively light steel framing with curtain-walls of hollow tile, one and one-half bricks thick; the columns were covered with hollow tile and the partition walls were of hollow tile or metal lath, while the floors were of reinforced concrete without strong connections to the pillars. Thus, the steel frames were the only substantial members contributing to the rigidity of the building.

By the semi-destructive earthquake that occurred on April 26, 1922, one year before the great earthquake, the building suffered moderate damage, consisting of cracks and fissures in the curtain-wall and partition walls in the

second and third stories. The building was additionally strengthened as follows: (a) Most of the inside and outside pillars were strengthened by covering them with reinforced concrete and also by installing large knee-braces of the same material; (b) the principal partition walls were reconstructed of reinforced concrete; and (c) the diagonals and bracings were newly fitted between pillars on 172 panels, including the bearing partition walls.

By such additional strengthening, the original period of 0.9 sec. had been reduced to 0.7 sec. Then the great earthquake took place, resulting in similar damage as before. This second time the repairs were made more thoroughly, the principal work being as follows: (d) The old curtain-wall was entirely replaced by a reinforced concrete bearing wall; (e) the pillars were again additionally strengthened; and (f) 414 new reinforced concrete partition walls were added (some of them covering old bracings).

According to the estimate of the architect in charge, these alterations added about 20% to the weight of the building.[15] By this second strengthening the natural period was decreased to 0.5 sec. This actual example shows how the strength, or rigidity, of a building is intimately related to its natural period of vibration.

Thus, it will be seen that, in buildings similarly constructed and of nearly the same size, those having a shorter natural period have greater rigidity and more damping against vibration than those having a longer natural period. In other words, the former have more resistance against earthquake forces than the latter, provided the natural period of the building does not synchronize with that of the earthquake.

This view seems fully justified in the light of the 1923 great earthquake. It will be seen from Table 3, that Buildings No. 2(a) (Tokyo Kaikan), No. 3(a) (Yusen Building), No. 1(c) (Marunouchi Building), No. 6 (Kogyo Bank Building), and No. 5 (Kaijo Building), which are arranged in descending order of their natural periods, are nearly in descending order as to extent of damage suffered from the great earthquake.

(IX) Behavior of Buildings Constructed of Flexible Materials

One must not extend this inference too far for buildings constructed of flexible materials. Wooden-frame buildings constructed with reasonable care, and steel-frame structures without masonry walls are evidently highly resistant to earthquakes, the principal reason being that the ratio of the strength of these materials to their density is higher, and their ultimate elongation is greater than brick and concrete. Wooden buildings and bare steel structures, however, generally move with vibrations of their own period in an earthquake, just like weak masonry buildings.

For an explanation of this fact, let us again refer to Equation (3), and see how the "decay" constants differ with the various building materials. For this purpose, I have deduced the values of $\dfrac{\xi}{E}$ from various vibration

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[15] For details, see report by Mr. T. Saita in *Journal,* Inst., Japanese Archts., Vol. 41, No. 498.

Mr. F. Kishinoue, and Fig. 62 shows the same for a wooden building at Ito. This wooden building survived two destructive earthquakes. It will be seen that although both these buildings are strongly resistant to earthquakes, they vibrate remarkably during an earthquake with their own period. Therefore, with these types of buildings, the fact that they vibrate with their own period in an earthquake is no evidence of weakness.
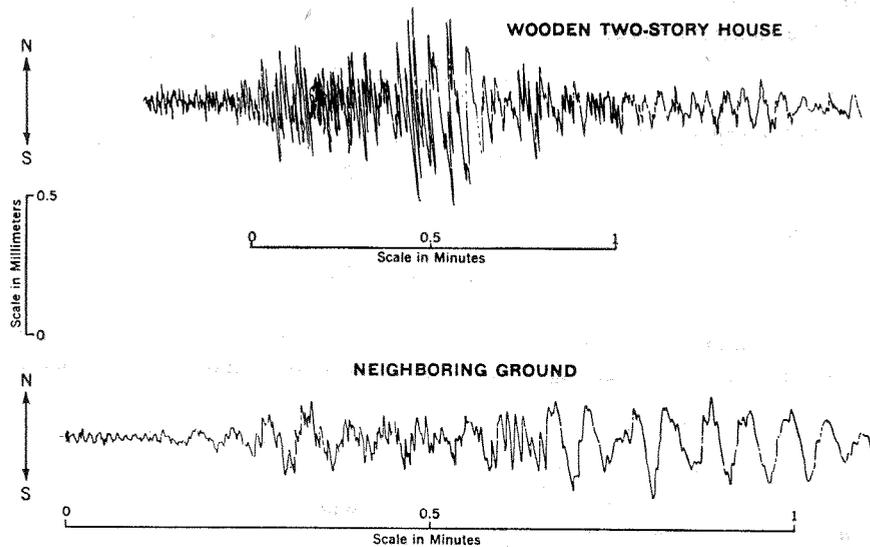

FIG. 62.—VIBRATIONS OF A WOODEN BUILDING AT ITO DURING AN EARTHQUAKE AND A SEISMOGRAPH OF THE ADJACENT GROUND.

(X) PERIOD OF FREE VIBRATION DEPENDING UPON AMPLITUDE

We will now consider briefly the relation of the period of vibration of a building to its amplitude, because it has an important bearing on the behavior of buildings in an earthquake. First, it must be understood that the free vibrations of these buildings, whether of steel or wood, do not differ in an earthquake from that in ordinary times, being always 0.75 sec. for the Diet Building and about 0.5 sec. for the above-mentioned wooden house (Fig. 62). Thus, in these light structures, the vibration seems to be principally of a purely elastic nature. As for masonry buildings, the free vibrational period of the Yurakukan Building in an earthquake is 1.0 sec., while at ordinary times it is 0.8 sec. The same thing was also noticed by the late Professor Omori for the Nippon Bank Annex (No. 17, Table 3), namely, that in an earthquake the period of free vibration was somewhat lengthened, although not to such an extent as in the Yurakukan Building, the observed periods being 0.50 longitudinally and 0.46 transversely in an earthquake, as against 0.48 sec. and 0.43 sec., respectively, in ordinary times. I also observed it when measuring the microtremors of low reinforced concrete buildings in

ordinary times, namely, that the period of the microtremors depends more or less upon the amplitude of the tremor, being longer for larger amplitudes. This was reported in a paper to the Third Pan-Pacific Science Congress, 1926. This fact is also observable with our Institute Building (Fig. 55).

(XI) YIELDING OF GROUND

Such a pseudo-harmonic nature of the vibration of masonry buildings may be attributed partly to imperfect elasticity of the material composing the buildings; but for small vibrations this effect is evidently too slight to be taken into consideration. Very probably its primary cause is the yielding of the ground-bed due to oscillation of the foundation of the masonry building, the weight of which is heavier than those built of wood or of bare steel framing.

As was described in my paper mentioned previously, the micro-vibrating motion of low monolithic buildings at ordinary times may be attributed to yielding of the ground-bed or of the rammed stone that lies beneath the footing of the foundation. It may be due partly to this yielding that, as previously mentioned, very rapid components of seismic waves cannot set a building into co-periodic vibrations.

It has also been observed that with a tall and narrow building, the earthquake motion recorded on the basement floor was intermingled with free vibrations of the building in a manner similar to those observed on high floors of weak but broad buildings. This shows that, like a rod, the foundation of a tall building is not "fixed", but more or less "free." Without the yielding of the ground such a motion is obviously impossible.

Such cushioning action of the ground at the time of an earthquake may serve more or less to relieve the destructive action of a strong earthquake in the case of masonry buildings. As has been mentioned, the 1923 Kwanto earthquake was more severe down town on the low oozy alluvial ground than on the high diluvial compact ground up town, so that the number of wooden houses overthrown down town was far greater than up town; but statistics of damage suffered by rigid masonry buildings for the two districts showed contrary results, as indicated in Table 4.

TABLE 4.—PERCENTAGE RATIOS OF DAMAGED BUILDINGS TO THEIR TOTAL NUMBER

	Wooden buildings *	Brick buildings †
High ground	3.7%	87.7%
Low ground	17.0%	81.4%

* From a report of Mr. G. Kitazawa, of the Metropolitan Police Board.
† From a report of Mr. K. Sato, of the Metropolitan Police Board.

As a matter of fact, those rigidly constructed buildings stood the earthquake comparatively better down town than up town. A similar condition was pointed out by the late Professor Milne in his book, "Seismology" (page 146), where he states that "Mallet, after his survey of the district devastated

by the Neapolitan earthquake in 1857, states that more places were destroyed upon the rock than upon loose clay or other materials," although Mallet attributed it to the fact that "there were more places situated upon the rock and hills than upon the alluvium and the plains." I cannot, of course, say whether or not, Mallet's explanation points to the real condition of things, but can merely remark that the phenomenon was quite the same as that which happened in Tokyo.

Besides these, the damage to buildings by the Northern Musashi earthquake which was mentioned in Section (IV), Lecture II, is of considerable importance in connection with the present question. As stated, this earthquake originated beneath a compact paleozoic region and then spread out to the alluvial plain of a large river. As may easily be imagined, the damage suffered by ordinary wooden houses was worse in the alluvial district than on the high paleozoic ground. On the other hand, rigid buildings like "dozos" (Japanese fireproof warehouses which are constructed of closely-spaced strong wooden pillars covered outside with thick plaster walls, and which stand on strong foundations), had their walls cracked to a greater extent on paleozoic than on alluvial ground.
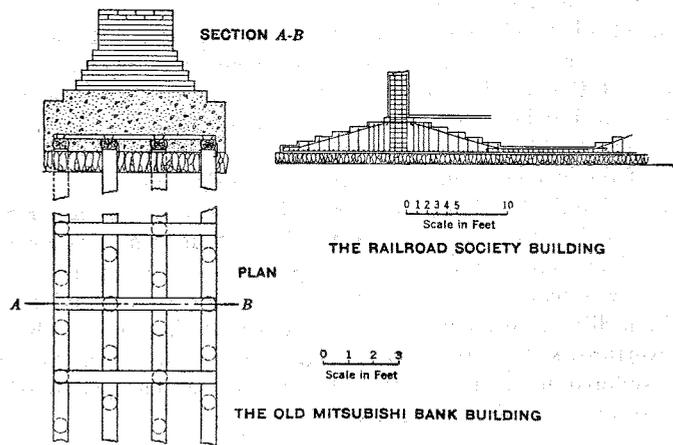

FIG. 63.—FLOATING FOUNDATION OF RAILROAD SOCIETY BUILDING.

Now, there is no doubt that the intensity of the 1923 earthquake was stronger down town where rigid buildings were less damaged. In my opinion, such an apparently paradoxical phenomenon was due to a certain extent, if not entirely, to the behavior of soft ground in an earthquake. A marshy alluvial ground could not exert more force on a building than the comparatively cohesive diluvial ground. There is, besides, the fact that the energy of elastic vibrations dissipates more quickly in the loosely fixed condition of a foundation on soft ground. It would more than counterbalance the stronger seismic motion down town. As a matter of fact, those buildings on soft ground with foundations consisting of one slab on rammed ground without any pilings (see Fig. 63) stood the shock far better than those having comparatively

strong individual footings resting upon deep pilings. It is also frequently observed after a severe earthquake that the soft ground surrounding a rigid building is permanently raised by the action of the earthquake, eloquent testimony to the fact that the foundation of the building did not move exactly as did the surrounding ground. These facts seem to support my views as to the behavior of soft ground in an earthquake. It may be worth the attention of architects and engineers.

(XII) THE MOST DESTRUCTIVE PART OF EARTHQUAKE MOTION

I should like to add a little more about the vibration of comparatively tall buildings at the time of the 1923 earthquake. As has been already mentioned, we have no data as to the motion of the earthquake in down-town Tokyo. In the circumstances, there is still more obscurity regarding the motion of the buildings in that district during that great earthquake; but the observation made by Professor T. Naito, of Waseda University, and by Mr. Y. Nagata, as Architect to the Metropolitan Police Board, on the number of broken electric pendant globes (all nearly 2 ft. 0 in. in length) in some of the office buildings, is very useful in that it indicates the mode of vibration of these buildings on that occasion.

According to their examinations, immediately after the earthquake, the percentage of broken electric light globes suspended beneath each floor was as shown in Table 5.

TABLE 5.—PERCENTAGE OF BROKEN ELECTRIC LIGHT GLOBES OBSERVED AFTER THE 1923 EARTHQUAKE

Item No. corresponding to Table 3	Name of building	NUMBER OF FLOOR FROM WHICH GLOBES WERE SUSPENDED								Remarks
		Second	Third	Fourth	Fifth	Sixth	Seventh	Eighth	Ninth	
1 (c)...........	Marunouchi Building......	..	94	99	99	100	99	98	99	† Ground floor
3 (a)...........	Yusen Building...........	4	82	85	85	85	85	64	..	* Is numbered
4 (a)...........	Yurakukan Building.......	16	43	55	56	63	64	30	..	* First
6...............	Kogyo Bank Building......	27	44	23	44	50	58	44	..	*
....	Kogyo Club Building......	..	33	23	14	9	..	..	..	†

* T. Naito, Rept., Imperial Earthquake Investigating Comm., Vol. 100, c 1.
† Y. Nagata, Rept., Imperial Earthquake Investigating Comm., Vol. 100, c 2.

It will be seen that in all buildings other than the Marunouchi Building, the breakage in lamp globes was less on the highest and lowest floors than on the intermediate floors, suggesting that the middle parts of these buildings vibrated more than any other part. As to the Marunouchi Building, I cannot see why it behaved differently; perhaps the reason is that it moved so violently that even ahose globes in favorable positions were shaken so severely as to strike the ceilings.

Moreover, in all tall buildings that suffered more or less damage—for example, the Marunouchi Building (Fig. 47), the Yurakukan Building, the Yusen Building (Fig. 48), the Kaijo Building (Fig. 50), the Tokyo Kaikan (Fig. 49), etc., the damage that manifested itself as fissures and cracks

in walls, developed in the second and third stories. Thus, the damage resembled that usually suffered by chimneys, in which, on account of their having a natural period longer than that of the most destructive part of a violent earthquake, the damage occurs, as a rule, not at the base, but at some point above it.

These two facts seem to indicate that the earthquake motions which had the most detrimental effect on tall buildings were those components having periods shorter than the natural period of the building. This seems to endorse the view mentioned in Section (IV), Lecture II, that the predominant acceleration of an earthquake is generally due to secondary motions. It will be seen that such secondary waves manifest themselves here and there on the record which I have previously shown (Fig. 30), although, owing to the instrument being defective, the motion is not recorded as it really occurred.

(XIII) Underground Earthquake Motion

Lastly, a few words concerning the seismic motion underground may not be out of place, because it has an important bearing on the motion of a deeply seated foundation. Some seismologists and engineers seem to believe
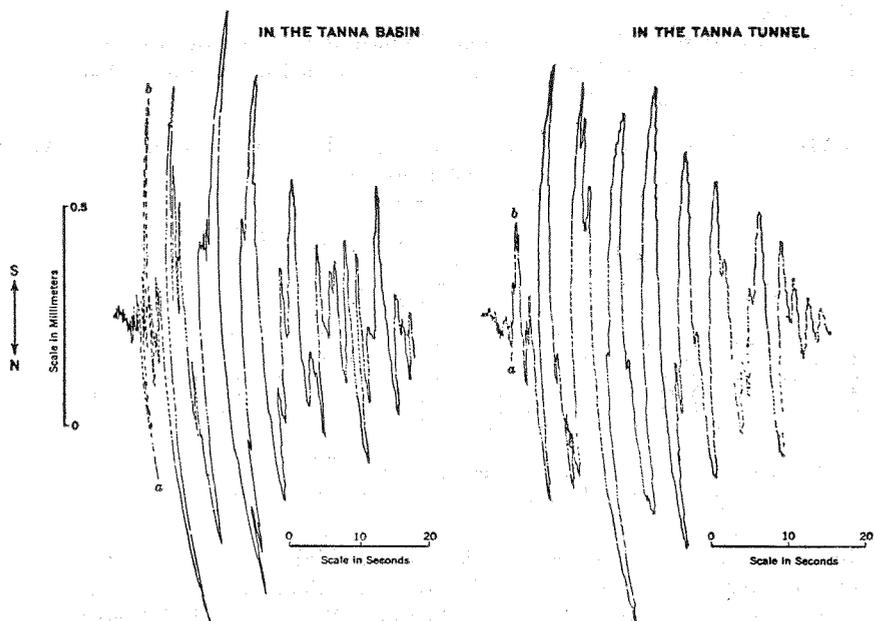
Fig. 64.—Simultaneous Observations in the Tanna Tunnel and in the Tanna Basin Directly Overhead.

profoundly in a decrease in earthquake intensity underground. The idea has perhaps originated from the result of a series of observations that were carried out by Professor Milne.[16]

[16] "A Seismic Survey Made in Tokyo," *Transactions,* Seismological Soc. of Japan, Vol. 10 (1887).

As mentioned in his paper, Professor Milne compared the seismic motion experienced at the bottom of a pit 10 ft. in depth with that experienced immediately above it, and found that the amplitude and the period of motion in the pit to those on the surface was as 1 to 3.4 and 1 to 0.65, respectively, thus making the ratio of maximum acceleration at these two places, 1 to 8.1; but it seems to me that there was something wrong in his observation. In our University there is an independent underground room for seismometric purposes, of nearly the same depth. Comparison of records taken on the floor of the underground room, with those on the surface, never showed such an enormous difference of motion as that observed by Professor Milne, although
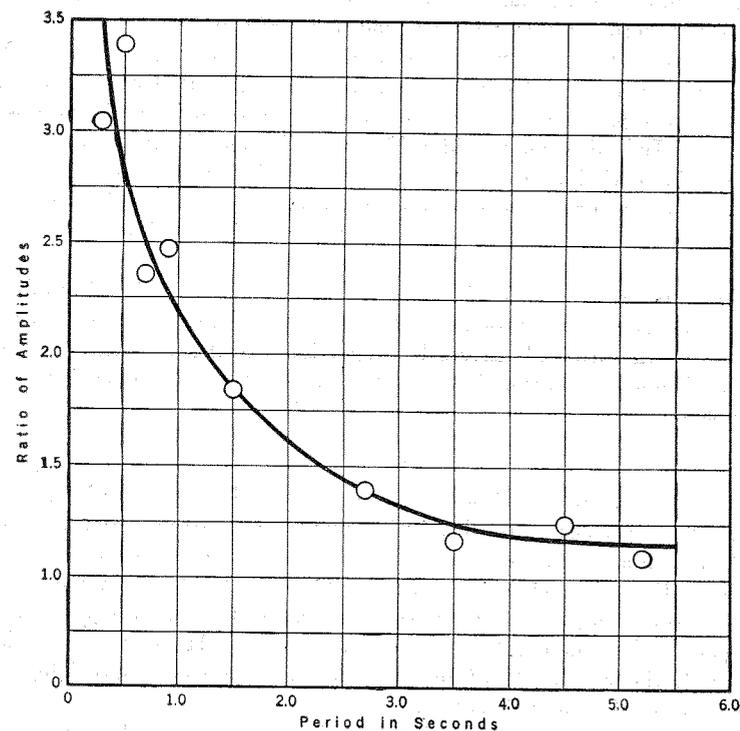
Fig. 65.—Relation Between Periods of Motion and Ratios of Underground and Surface Amplitudes.

a slight difference was observable. As can easily be imagined, this effect is only noticeable in vibrations having very short periods. For example, in vibrations having a period of about 0.2 sec., the amplitudes of motion in the underground room and on the ground surface vary nearly as 1 to 1.5. In vibrations having a period of about 0.4 sec., the ratio is 1 to 1.3, and so on. For vibrations having a moderate or long period (say, more than 0.8 sec.), no difference within the accuracy of ordinary seismographs is observable. At all events, the difference in periods mentioned by Professor Milne could never be observed. Generally, it is possible to identify each wave.

With regard to this matter, an important seismometric observation which we have been carrying out continuously since the occurrence of the Idā earthquake may be suggestive. As I have already mentioned, just after the occurrence of that earthquake, we installed two seismographs at Tanna, a village in the epicentral region; one on the surface of the Tanna Basin and the other inside the tunnel (Fig. 20), in a position 524 ft. perpendicularly below the former. Its purpose is to compare the earthquake motion underground with that on the ground surface, taking advantage of the probable occurrence of after-shocks. The seismographs in use are of the same construction and made of stainless steel, in order to withstand the corrosive effects in a damp place like a tunnel or a mine-pit. We have succeeded in taking a number of simultaneous records, one of which is shown in Fig. 64.

It will be seen that although some of the motions on the ground surface with very short periods did not appear underground, or that only a very few of them did; comparatively noticeable ones were present at both the observing stations. Indeed, even the identification of each of the waves was not impossible, the period and the phase of each being the same. Mr. Nasu examined all the records, and determined the ratio of the amplitudes on the surface and underground. Fig. 65 shows this ratio in relation to the period of motion.

It will be interesting to notice that if, instead of the ratio of amplitude, we take its logarithm and draw a similar diagram, we find that the logarithm of the ratio of amplitudes is inversely proportional to the periods, or, in other words, the following relation between the amplitude and the period of the motion holds:

$$a = a_0 e^{-\frac{K}{T}}$$

in which a and a_0 are amplitudes underground and on the surface, respectively; T is the period; e, the base of Naperian logarithms; and K, a constant. Although as yet we have no information on the relation of the ratio of amplitudes with depth, yet mathematical analysis of Rayleigh's wave and the form of the function just obtained seem to suggest that the assumption that K is proportional to the depth is not too extravagant. If so, at a small depth underground, the amplitude of motion does not decrease appreciably, provided the motion is not very active.

For very active motions at a short depth underground, this observation does not furnish us with useful data. As mentioned before, more or less decrease in amplitudes is certain in this case. Thus, in general, the decrease of amplitude underground is not so marked as stated in some textbooks. It appears, therefore, that the idea of constructing the footing of the foundation of a tall building, that has a long natural period, deeply underground for the purpose of reducing earthquake action is not as advantageous as believed by some engineers, although its advantages to a certain degree are unquestioned for a low building with a short natural period.