English Translation of a Report by the Earthquake Prediction Research Group in Japan

PREDICTION OF EARTHQUAKES

Progress to Date and Plans for Further Development

JANUARY 1962

PREDICTION OF EARTHQUAKES

Progress to Date and Plans for Further Development

Compiled by

Chuji Tsuboi, University of Tokyo
Kiyoo Wadati, Japan Meteorological Agency
Takahiro Hagiwara, University of Tokyo

JANUARY 1962

Earthquake Prediction Research Group

Communication address :
Earthquake Research Institute, University of Tokyo,
Tokyo, Japan.

CONTENTS

A scene of Tokyo destroyed by the Great Kanto Earthquake, 1923.

All through her history, Japan has suffered frequent great earthquakes, and each of these have caused a large number of casualties and an enormous amount of damage. It is certain that earthquakes will occur in the future in a similar way as in the past and disasters as caused by them must be prevented as far as possible by ourselves. Prediction of earthquakes is an urgent necessity of the nation and is also the final aim of scientific endeavours in the field of seismology in this country. Seismological studies up to the present do suggest possibilities of realising this aim of earthquake prediction. In order to make such possibilities a practical reality, deep understanding and ample financial support by the government is indispensable, in addition to the constant and conscientious endeavours of all the researchers concerned.

INTRODUCTION

Prediction of earthquakes is one of the most important tasks of seismologists, in particular of Japanese seismologists. Studies of earthquakes are quite active in Japan, abundant sources of information being available. However, in spite of this, reliable prediction of earthquakes still belongs to the realm of fancy and not fact. Unless the following three elements, i. e. the time, place and magnitude, of any imminent earhquake are specified fairly accurately a prediction would not be of much value. Earthquake phenomena are fundamentally different from other natural phenomena that are continuous or reversible. Earthquakes are abrupt and sporadic in occurrence and this seems to be the fundamental difficulty in their prediction. Although the same word "prediction" or "forecasting" is used, the implication when it is applied to earthquakes is quite different from that when it is applied to a solar or lunar eclipse or the weather.

Earthquake research in Japan originated nearly 80 years ago, and has made steady progress ever since. The famous Imperial Earthquake Investigation Committee was established after the Nôbi Earthquake in 1891, and the Earthquake Research Institute of the University of Tokyo in 1923 after the Great Kanto Earthquake. Varied types of research, seismometric work and surveys are also being made by a number of universities, the Japan Meteorological Agency, the Geographical Survey Institute and so forth, and through the close cooperation of these institutions our knowledge of earthquakes is increasing rapidly.

During the past years of seismic study, problems directly related to earthquake prediction have been taken up from time to time. Today, an almost unanimous idea has come to prevail among Japanese seismologists and geophysicists as to "*what kinds of mearsurement should be done by what method.*" It is also a unanimous opinion that "*the measurements required would be necessarily of such a large scale that no single institution could adequately afford to operate and, moreover, a thorough consideration is needed regarding our existing scheme of seismic research* for the effective practice of such a nationwide project as required for earthquake prediction."

We, therefore, decided that we needed to make a systematic investigation on the kind and method of measurements for the purpose, and then to make some practicable recommendations and then initiate the first step towards their realization.

The present report is derived from studies and discussions of our Group comprising scores of those scientists who are particularly interested in the problem.

Although this is only a so-called blue print and outlines only briefly what should be done for the attainment of our purpose, it does represent an up-to-date summary of what we have discoverd concerning the problem of earthquake prediction.

§ 1. Crustal Deformations Revealed by Geodetic Measurements

1. Necessity for Expansion of Geodetic Services.

Geodetic surveys (triangulations, levelling, tidal observation etc) in Japan are now conducted by the Geographical Survey Institute of the Ministry of Construction. These surveys have been carried out continuously since as early as 1871 when the Land Survey Department, Imperial Japanese Army, was established. Until the end of the Pacific War, the surveys were the responsibility of this body. Whenever crustal deformations were suspected in relation to large earthquakes, a series of revision surveys were made in the area concerned. As a result of this, much information of importance has been obtained regarding both horizontal and vertical deformations associated with earthquakes. Later, revision surveys were made also in areas which suffered no major earthquakes. Subsequently it was found that *even at ordinary inactive times crustal deformations are proceeding slowly*. Such pieces of information have been analysed by geophysicists and the characteristic features of crustal deformations have gradually become elucidated. These researches have made a great contribution to geophysics.

However, when we wish to make a further clarification of the significance of crustal deformations, in particular their relationship with the occurrence of earthquakes, we face a great difficulty —the time interval between repeated surveys being too long; for instance, when we wish to ascertain the horizontal and vertical displacements of the earth's surface associated with an earthquake by comparing the old survey data with the new ones. If, in such a case, the old data were taken say 30～40 years ago, the apparent displacements cannot be free from a certain ambiguity, i. e. one can not say definitely whether the displacements were due to the earthquake or to some other cause during such a long period.

Moreover, with such long interval repetition surveys an approach of this kind is quite useless if one wants to detect crustal deformations possibly occurring immediately or shortly before a large earthquake. Unlike in other parts of the world where crustal deformations are so slow in rate that they can be followed in terms of centuries of time, in Japan they are comparatively so rapid that the allowable maximum time interval of revision surveys is 5～10 years. Levelling along the route connecting the datum bench mark in Kasumigaseki, Tokyo, and the Aburatsubo Tide Gauge Station (35.2°N, 139.6°E) has been repeated frequently (once in every two years in recent times), for the purpose of checking the datum. Every time this levelling was made, it was found that Miura Peninsula, on the extremity of which the Aburatsubo Station is situated, is undergoing remarkable tilting movement often in different directions. This phenomenon indicates that the time interval of revision surveys should be made as short as possible. For the purpose of obtaining information of the earth crust indispensable for earthquake prediction, *it is required that crustal deformations over the whole of Japan be traced continually through frequent repetition surveys over as large an area as possible.* In order to meet this demand, an enormous amount of work will be required. Taking into consideration the limited size of the budget and the numbers of personnel involved, we propose a project as follows.

2. Proposed Project.

(A) Nation-wide Repeated Surveying.

This survey is intended to clarify general features of crustal deformations in Japan. If this project gets under way, the state of strain accumulation in the crust will be ascertained over the whole Japanese area. *This work is of uppermost inportance as it will form the basis of the whole project "Earthquake Prediction".*

The work under this project consists basically of levelling and triangulation. Levelling requires tide measurements to maintain accuracy. For triangulation, astronomical survey and base-line measurement are necessary. An outline of the project is summarized in the following table.

Kind of work		Total work	Repetition interval
Levelling	1st order levelling	20,000 km	5 years
	Tide observation	27 stations	Continuous
Triangulation	1st order triangulation	330 stations	10 years
	Astronomical survey	330 stations	10 years
	Base-line measurement	40 sides	10 years

A new bench mark for levelling should be placed between every two existing marks. It is desirable that new bench marks be placed on fresh and solid rock masses.

(B) Repeated Survey in Limited Areas.

Detailed characteristics of crustal deformations associated with seismic activities can never be clearly determined as long as the time-interval between repeated surveys is protracted. Even in the project (A) above, the repetition interval is too long for the intended purpose. In order to learn in detail of relationships which might exist between earthquakes and crustal deformations, opportunities for coordinating earthquakes with surveys must be increased as much as possible: the repetition interval should be shortened and density of bench-marks increased even at the expense of precision to a certain degree. Taking this into account, it is proposed that the 2nd order levelling, 2nd and 3rd order triangulations and rhombus base-line measurements should be conducted more frequently in relatively limited areas.

Since the area concerned with an individual crustal deformation system may be fairly large, the 100 m base-line of the existing rhombus (situated in the ground of Tokyo Astronomical Observatory, Mitaka-city, Tokyo) is too short. Nowadays a 20 km length can be rapidly measured to a degree of precision 2×10^{-6}, with the aid of newly-developed geodimeters. It is desirable therefore to set up a large rhombus (side length 10 km～15 km) in required areas.

Through repetition of these surveys, the objectives of this project, i.e. the magnitude and distribution of crustal strains over the ground surface of the area will be determined in detail. The items in this project are summarized in the following table.

Kind of work	Amount of work	Repetition interval
2nd order levelling	2,000 km/year	1～2 years
2nd order triangulation	100 stations/year	〃
3rd order triangulation	600 stations/year	〃
Rhombus base-line measurement	12 sites/year	1 year

3. Expected Results.

There have been several examples, including the Ajigasawa Earthquake (40.8°N, 140.2°E) in 1793 and the Hamada Earthquake (34.9°N, 132.1°E) in 1872, where remarkable crustal deformations were observed by people several hours before the relative main shock.

Examples of cases where crustal deformations were detected by levelling prior to earthquakes are the Sekihara Earthquake (37.4°N, 138.8°E, M=5.7) of 1927, the Futatsui Earthquake (40.2°N, 140.2°E, M=5.7) of 1955, and the Nagaoka Earthquake (37.4°N, 138.8°E, M=5.0) of 1961. In all the cases, it happened that re-surveys of levelling routes passing the epicentral areas were made several months before the earthquakes. It is, however, too premature to generally conclude from the above evidence alone that there will always be some crustal deformation prior to an earthquake: above-mentioned being all relatively small destructive earthquakes with a very slight amount of crustal deformation.

A rhombus with 100 m base-lines is set up in the ground of the Tokyo Astronomical Observatory (Mitaka-city), the length measurement having been repeated from before the Great Kanto Earthquake. It was observed that a horizontal land deformation, though slight, started several years ahead of the earthquake and it intensified abruptly with the outbreak of the earthquake. The land deformation mentioned above may be regarded as a forerunner of the earthquake, but obviously one instance only is not sufficient to establish a general rule.

The idea that some crustal deformation may be detectable before a large earthquake is held by a number of scientists. But to support such a supposition we have only the above few examples. This project aims at founding a gateway to the prediction of earthquakes by obtaining detailed information on crustal deformation and its relationship with earthquake occurrence. Therefore, our effort will not be confined to the observation of deformations that will only occur immediately prior to earthquakes. Once this project gets under way, however, the crustal deformations as symptoms to earthquakes will be revealed, if they really exists at all, within a fairly short time. This period will become shorter with the establishment of more stations and shorter repetition intervals.

§ 2. Tide Gauge Stations for Detecting Crustal Deformations

1. Necessity for Establishment of New Tide Gauge Stations and Improvements of Existing Tide Gauge Stations.

If the sea level is invariable, upheaval and depression of the ground can thereby be easily discerned. In reality, however, the sea level variation is due not only to astronomical tides but also to a combined effect of weather, water temperature, ocean currents etc. so that it is required to neutralise these effects and to determine the mean sea level. Among the factors mentioned above, effects of astronomical tides can be eliminated fairly effectively by theoretical calculations. The effects of atmospheric pressure and the density of sea-water can also be got rid of, to some extent, by measuring atmospheric pressures and water temperatures in the neighbourhood of a tide gauge station. It is impossible, however, to eliminate completely part of the effects governed by the weather and the sea condition in distant areas, especially the effects of ocean currents. But, since weather and oceanic currents in distant areas would have almost the same effects on nearby tide gauge stations, we can anticipate that relative movements of the ground can be determined to the degree of precision required for our purpose, that is, if a sufficiently large number of tide gauge stations are established on the coasts of Japan and if the results of their observation are coordinated with one another. In other words, *by distributing tide gauge stations all along the Japanese coast at suitable distances, variations in crustal deformation in coastal areas can be continually observed.*

There have been several reports reguarding the occurrence of anomalous changes in the mean sea level preceding great earthquakes. For instance, the mean sea level at Aburatsubo in Miura Peninsula showed an anomalous descent from a time several years before the Great Kanto Earthquake. This is considered to be indicative of the fact that the southern end of the Miura Peninsula, which had been slowly sinking for many years, began to rise at that time. It is also reported that a statistical study on 98 earthquakes ($M>7$) occurring within the period 1900~1960 shows that there is, from several months before the occurrence of these earthquakes, a tendency for anomalous changes in the mean sea level at tide gauge stations situated in the area within 200–300 km from the epicentres. These reports, however, are based essentially upon the mean sea level at a particular station, and the elimination of the effects of weather and ocean currents are not guaranteed. Therefore, the reliability of these reports is not considered high enough for drawing any firm conclusion. Once such a nation-wide network of tide gauge stations is set as mentioned above, these problems will be automatically solved.

2. Proposed Project.

It is proposed that use will be made of 92 tide gauge stations, which will be situated approximately every 100 km along the coast of our land. Sites for these stations should be chosen away from the mouth of rivers and on fresh rock. In order to obtain 92 necessary stations, 26 new stations must be established in addition to the 66 existing ones.

Among the existing stations, there are some which require improvement in the recording system and the installation of a water temperature recorder. The number of tide gauge station classified by their affiliation is as follows.

	Existing	New	Total
Japan Meteorological Agency	34	3	37
Geographical Survey Institute	9	18	27
Hydrographic Department	13	5	18
Others	10	0	10
Total	66	26	92

3. Standardization of Data Recording System and Modernization of Data Processing.

All the records from tide gauge stations should be collected monthly at a central bureau. In order to obtain the monthly mean sea level, the collected records will have to be quickly read and computations for eliminating effects of astronomical tides, atmospheric pressures and sea water temperatures made immediately. This process would necessitate a large amount of tedious work every month for many years. It would be required to standardize the reports from all the stations and to modernize the method of processing such data, for instance, automatic record reading and high speed computers should be fully utilized.

§ 3. Continuous Observation of Crustal Deformation

1. History and Necessity.

Geodetic methods, described in § 1, are useful in that they are able to detect deformations of the crust with certainty, but at the same time they are disadvantageous because they are essentially intermittent: in practice the time interval for repeat surveys cannot be rendered infinitesimal. In order to obtain continuous information on crustal deformation some kind of routine instrumental observation is necessary. For this purpose, ground tiltmeters and extensometers have been developed. Both the University of Tokyo and the University of Kyoto have experience of using these instruments over the last 20 years, during which time both methods and instruments have been continually improved.

There are two types of tiltmeters: the horizontal pendulum type and water-tube type. Horizontal pendulum type tiltmeters have advantages of being compact and highly sensitive, but they are not suitable for long term observation of slow secular variations because of the flow of the zero-line. Although requiring much space, water-tube type tiltmeters are indispensable for the measurement of secular variations. Consequently, it is considered appropriate to install both instruments, so that relatively rapid changes can be recorded by the horizontal pendulum type meter and slow ones by the water-tube type meter.

As for extensometers, two types of instruments have been developed: one using a suspended invar wire and the other a silica tube supported horizontally. In view of their higher reliability in recording secular variations, silica tube extensometers are more efficient.

Thus, it is desirable that a station designed for continuous recording of crustal deformation be equipped with horizontal pendulum type tiltmeters, water-tube type tiltmeters and silica-tube type extensometers. Among the existing 28 stations measuring crustal deformation throughout the country, only eight satisfy the above requirement.

In the present project, it is intended that information complementary to that obtained by geodetic measurement, which is essentially intermittent, will be gained from the continuous recording of tilt and strain at densely spaced stations. In other words, *geodetic measurements are for the detection of crustal deformation over a certain region, a fixed station revealing their time variation continuously at a point in the region.* In this case, also, more stations will afford more information. Considering the actual feasibilities, however, the following proposal is made.

2. Proposed Project.

(1) The distribution of stations should be made denser.

Each 100 km^2 should have a station, which produces a total of 70 stations in the whole country. In addition to this, in some areas even denser spacing, i.e. one station per 50 km^2, is planned. In fact a total of 30 such stations is planned. Therefore, altogether, 100 stations should be established.

(2) Simultaneous use of various instruments.

Information will be collected by every possible means at each station. This will be done by equipping each station with I) horizontal pendulum type tiltmeters (2 components), II) 25 m water-tube type tiltmeters (2 components), III) 25 m silica-tube type extensometers (3 components), IV) microbarometer V) precision thermometers (placed at 6 points both in the open air and underground), VI) rain gauge and VII) gravity variometer.

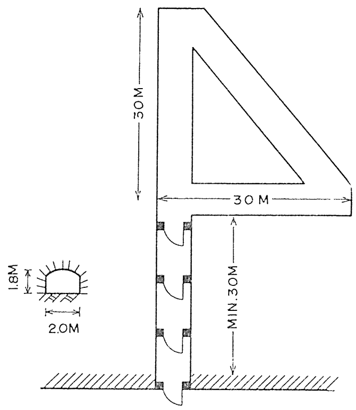
To prevent temperature disturbances in the underground gallery where the instruments are installed, the entry and exit of observers should be minimized, and all the recording should be either automatic (change of recording paper or films should be done once a week or less frequently), or remote controlled or remote reading. Precision levelling instruments, staffs, geodimeters and so forth will also be attached to each station.

(3) Repeated geodetic measurements near stations.

In the vicinity of each station, at least 40 levelling points (distance between two points will be 250 m) should be set up and precision levelling repeated at least once a year. This will provide a check on the results of tiltmeter observations. 15 km long base-lines should be taken from the station in at least three directions, and the variations of these base-line lengths measured from time to time by a geodimeter. This will serve as a check on the results of secular variation observation by extensometers. This work is treated in this report as an independent item from those items in § 1.

(4) Proposed structure of a station.

Tiltmeters and extensometers should be installed in underground galleries. Up to the present, in many cases use has been made of old drifts of mines, old bomb-shelters, or discarded tunnels. In the present project it is very important that standardized horizontal galleries be newly made at desired localities. The plan of the galleries should be, if possible, as shown in the illustration. Under favourable conditions, the distance from the main entrance to the secondary entrance could be about 30 m, but sometimes considerably longer distance may be required. In addition to the galleries a recorder room (8 m^2) and a residence for observers will be required outside the gallery. For power supply, 100 volts, 5 kw is desirable.



(5) Regional Central Stations.

Regional Central Stations should be located at six places over the country. Well trained technicians who can supervise the work at stations in the district should be appointed. At these Central Stations, testing, calibration and standardization of new instruments should also be conducted.

(6) The Central Bureau

A Central Bureau which supervises the stations scattered over the country should be established. All the observational data should be collected and analysed thoroughly by this bureau. Based on the results of the analyses the bureau should take necessary measures to meet changing situations; for instance, shortening the repetition interval of geodetic measurements in a particular area. Here also, modernization in the method of data processing is desirable.

3. Anticipated Results.

Results of tilt and strain measurements so far obtained indicate that in several cases of earthquakes with M=6~7, anomalous tilting and strain in the area within 50 km from epicentres were noticeable from one to two months prior to main shocks. In some cases, rapid variation was noticed several days or several hours before a shock. However, more careful investigations will be required before concluding that such variations are really forerunners of earthquakes, since observation of this kind is apt to be affected by weather conditions such as barometric changes and rain-fall, and in the case of horizontal pendulum tiltmeters, the zero-line is never quite stable.

Continuous observation of crustal deformation as proposed here has *its main objective in obtaining information regarding the processes by which earthquakes occur, through a clarification of relationships existing between the process of strain accumulation in the crust and earthquake occurrences. This will be done by keeping track of crustal deformation from time to time. Of course continuous measurement should be made in conjunction with the geodetic measurements proposed in § 1. Thus our effort will not be confined only to securing direct forerunners of earthquakes.* Once this project gets underway, however, the station network will be able to definitely detect forerunners, or the relatively rapid changes in the tilt and strain of the ground immediately prior to earthquakes, if they exist at all.

In observing tilt and strain of ground, semi-diurnal changes corresponding to the elastic deformations of the crust caused by variations in the load of sea water due to the ocean tides are recorded. If the crustal characteristics of certain areas change, the response of the crust to the effect of ocean tides will also change. This leads to a supposition that detailed investigation of the changes of tilt and strain due to tidal loading will be a means of determining the physical state in the crust. There have been, in fact, several reports pointing out the changes with time of crustal response to tidal loading and their correlation with local seismicity. Although none of these reports is of sufficient reliability, such a phenomenon, if real at all, will bear some importance in earthquake prediction. This problem will also be solved automatically in the course of the investigation proposed here.

§ 4. Seismic Activity

1. The Magnitude of Earthquakes.

Before planning an investigation program on seismic activity for the purpose of earthquake prediction, it would be important to define the magnitude of earthquakes to be dealt with in the program. Here, the earthquakes are classified as follows according to their magnitude M.

Large earthquake	$M \geqq 7$
Moderate earthquake	$7 > M \geqq 5$
Small earthquake	$5 > M \geqq 3$
Micro-earthquake	$3 > M \geqq 1$
Ultra micro-earthquake	$1 > M$

The *large earthquakes* defined here are always destructive, except when the hypocentre is very deep. The *moderate earthquakes* are destructive when the hypocentre is shallow, but the afflicted area is comparatively small. Earthquakes smaller than the classified *small earthquakes* are not destructive.

Although earthquakes smaller than the classified small earthquakes are classified by their magnitude as described above, in actual practice the distinction can be drawn by the technique used in observing them. The magnifications, detectable ranges in epicentral distance, periods of recorded waves and the magnification of seismometers used for these earthquakes are roughly as follows.

Earthquake	Magnification	Detectable range	Period of waves
small earthquakes	<2,000	200 km	>1/10 sec
micro-earthquakes	$1\times10^4\sim2\times10^5$	60~80 km	1/20~1 sec
ultra micro-earthquakes	$10^6\sim10^8$	20~30 km	1/20~1/100 sec

2. Investigation of Seismicity Related to Large and Moderate Earthquakes.

It can be said that nearly all of the available bits of information concerning large and moderate earthquakes in the past have already been discovered. Collection of old documents relating to earthquakes which occurred in the entire historical age in Japan was one of the great accomplishments of the Imperial Earthquake Investigation Committee. This work has recently been extended and the results are published in "Nihon Jishin Shiryo (Japan Earthquake Records) (416-1867)." Its summary, i.e. the Large Earthquake Chronicle, is listed in "Rika Nenpyo (Science Chronicle)," in which all the destructive earthquakes in the past are classified by their estimated magnitude.

Data relative to large and moderate earthquakes after 1885 to the present time have appeared in the publications of the Japan Meteorological Agency (formerly Central Meterological Observatory), and the amount of information has increased year by year. The "Catalogue of Major Earthquakes Which Occurred In and Near Japan (1926-1956)" published recently by the Japan Meteorological Agency described the epicentre, depth and magnitude for those earthquakes larger than the classified moderate earthquakes. The "Jishin Geppo" (Seismological Bulletin of the Japan Meteorological Agency), which has been published since 1951, lists a detailed account of observational results on earthquakes larger than so colled "earthquakes of small felt area." Those observational results, of which publication will be continued as a routine work of the Japan Meteorological Agency, are indispensable to the study of seismicity related to large and moderate earthquakes. Thus, it may be stated that nearly all the necessary information is available to us as far as large and moderate earthquakes are concerned.

3. Investigation of Seismicity related to Small Earthquakes ($5>M\geqq3$).

A publication of the Japan Meteorological Agency "Jishin Geppo" (Seismological Bulletin of the Japan Meteorological Agency) gives detailed information on earthquakes larger than "earthquakes of small felt area." These-earthquakes on the whole are of magnitude greater than 5. In order to cover smaller earthquakes, the Japan Meteorological Agency now has a plan of doing the same for the earthquakes with $M>4$, instead of $M>5$. By re-reading the records of Wiechert Type seismographs at all the stations belonging to the Agency, past data will be obtained to some extent. At present, a modernization of seismometers projected by the Meteorological Agency is underway and high sensitivity electromagnetic seismometers are being installed at a number of branch stations over the country. When this is completed, our observational capacity on small earthquakes will be much improved. The present Earthquke Prediction Research Group strongly hopes that the Meteorological Agency will extend the modernization of seismometers and aim at recording all the $M \geqq 3$ earthquakes, so that as soon as possible *good observational data may be obtained for all the large, moderate and small earthquakes occurring in any part of the country. Such data will be an important element in the project "Earthquake Prediction".*

4. Seismicity of Micro-Earthquakes ($3>M\geqq 1$).

Observation of micro-earthquakes requires high magnification seismometers ($10^4 \sim 2\times 10^5$) which can be set only on exposed surface of solid rocks. At present, continuous observation of micro-earthquakes are carried out at Mt. Tsukuba (Earthquake Research Institute), Abuyama (University of Kyoto), Matsushiro (Japan Meteorological Agency) and so forth. These observations are mainly for research work. From the standpoint of earthquake prediction, it is required that *such an observation network be extended to cover the whole country and the rise and fall of micro-earthquake activity be ascertained in detail.*

Of course, in this case also a larger number of stations will give better results. Considering the feasibility of this project, we propose the following program.

System of network for micro-earthquake observation

a) Central Bureau

b) Branch Offices

20 Branch Offices should be distributed over the entire country. These should be located at places with good transportation facilities and, as a rule, no actual observation would be made there. Maintenance and supervision of stations of the district and data processing would be made by these Branch Offices.

c) First-Class Stations.

Under a Branch Office, three First-Class stations should be founded. At these stations, two kinds of high magnification electromagnetic seismometers should be installed (for instance, $T_p=1$ sec, $T_g=1$ sec and $T_p=1$ sec, $T_g=0.2$ sec). These stations would be expected to obtain complete records of waves not only to determine the epicentres but also to obtain information for estimating the magnitude (M), and the wave-generating mechanisms. Accordingly, in order to prevent going off scale of the records, either recordings with several different magnifications or some special device would be required.

d) Second-Class Stations.

Under a Branch Office, six Second-Class stations, where one component of high magnification electromagnetic seismometer would be installed, should be set up. Temporary moving stations of this class should be made for more accurate location of epicentres and observation of local seismic activity.

5. Seismicity of Ultra Micro-Earthquakes.

Observations of ultra micro-earthquakes would be made by ultra high-sensitive seismometers with electronic amplifiers. Sites for these instruments must be on hard rocks where ground noise is low, detecting transducers being placed in many cases in underground vaults and galleries. Since the number of observed earthquakes is large even in a short period of time, observation only for several hours per day will be necessary. Hours for observation would be selected by the manner of random sampling, but mostly from late hours at night when the noise level is low.

Advantages in the observation of ultra micro-earthquakes lie in the fact that the number of observed earthquakes is large so that the state of seismic activity can be assessed in a relativly short time However, the sites for setting up ultra high-sensitive seismometers are limited to exceptionally quiet places and observation times restricted to the night. For detection of ultra micro-earthquakes, a network consisting of more than three stations is required. The distance between two stations should not exceed 20～30 km because, as stated already, the range for detection is small. Hence, an enormous number, say some thousands, of stations would be required if the whole country were to be covered by such a network system. Considering these circumstances, we propose the following as the best possible program at the present stage: i. e. six special regions be selected and five fixed stations to be positioned in each region. Areas outside these regions would be investigated by moving stations. The details are as follows:-

(1) Base stations

One of the five fixed stations for the network would be a Base Station where necessary buildings, ancillary equipments including electric power supply, and seismometers (3 kinds of 3 component meters....1 set, one component meters.... 6 set) will be furnished. These seismometers will be positioned at four places (mutual distances being some several hundred meters).

(2) Further four stations

In addition to the Base Station, four other stations would be established, each of which would be equipped with necessary buildings, ancillary equipments and seismometers (2 kinds of 3 component instruments....one set, one component instruments....3 sets). The seismometers will be positioned at four places (mutual distances being several hundred meters).

(3) Car-borne moving stations

Each Base Station would have three observation cars. Each car would be equipped with seismometers (one set of two kinds of 3 component instruments). These seismometers would be set, on the field, at four places (mutual distances being some several hundred meters). Three cars would usually work together. In operation, these cars would be stationed in an area with 20~30 km diameter to form a temporary network.

Observation cars may utilize a magnetic recording system.

To administer the nation-wide network of stations, a Central Bureau would be required. Further study would be necessary before establishing the best methods for data processing.

6. Summary.

An observation program has been described above for earthquakes of different magnitudes. Here a summary of the program will be given.

For large ($M \geqq 7$) and moderate ($7 > M \geqq 5$) earthquakes, it appears that data has already been collected in the past, and for the future, accumulation of data will be conducted adequately by the Japan Meteorological Agency. No further program will, therefore, be required for large and moderate earthquakes.

For small earthquakes ($5 > M \geqq 3$), re-reading of past records and modernization of observatories, both being planned by the Japan Meteorological Agency, will supply adequate information. Hence, the present Group is not required to make any particular project for this purpose.

Observation of micro-earthquakes ($3 > M \geqq 1$) is contained in a special research project and is somewhat different from the routine seismometric work carried out by the Japan Meteorological Agency. The project currently proposed urges the new establishment of 180 continuous-recording stations. The scope of observation work, then, will no longer consist of ordinary pure research.

Pure research procedure is even more vital for the observation of ultra micro-earthquakes ($1 > M$). Under the present proposal, networks for ultra micro-earthquakes would be set up in six regions and other areas would be investigated by car-borne seismometric stations.

7. Expected Results.

It is a well known fact that destructive earthquakes tend to recur in the same area. In this regard, "Nihon Jishin Shiryo" (Japan Earthquake Chronicle), a complete collection of old data on earthquakes made throughout the historical age, plays an important role in estimating the possibilities of future destructive earthquakes in different areas.

Since it is expected that the state of activity of smaller earthquakes is closely connected with the occurrence of larger ones, accumulation of data on small earthquakes by instrumental observation will be of great significance in earthquake prediction. In fact, there have been several reports of frequent small earthquakes just prior to a large one. At the same time, in a majority of cases, large earthquakes have occurred without any such forerunners. Behaviour of micro- and ultra micro-earthquakes before large earthquakes are of great interest to seismologists but their observation started only recently. *If, by the practice of the present proposal, enough data is accumulated and any regularity between the* *state of activity of very small earthquakes and the occurrence of large earthquakes is found, it will serve directly for earthquake prediction.* However, our interest in small earthquakes is not confined to their behaviour as possible forerunners of great earthquakes. Our proposal intends to make a thorough investigation of activities and mechanisms of earthquakes of a variety of magnitude, and to steadily approach a successful prediction of earthquakes by combining seismic data with geodetic data and that from the continuous observation of crustal deformations described earlier.

§ 5. Determination of Seismic Wave Velocity by Means of Explosion Seismology

1. Necessary Requirements.

There have been a few reports of changes in seismic wave velocity before a large earthquake. These changes indicate that the elastic properties of the crust of the area concerned might have undergone some modification. But all the reports so far presented were based on the observation of natural earthquakes, and, therefore, precision of observation was not high enough to ensure a good degree of reliability. Because of the possible importance of this phenomenon, investigation of wave velocity by explosion seismology (that can attain much higher precision) is required. The changes, if they exist at all, are presumed to be of such small magnitude as to be detectable only by highly sensitive apparatus.

2. Program.

Explosion of charges of one to two tons capacity would be made at night time, and observations made at quiet stations in a 250～300 km range. At least six sites for explosion would be necessary to cover the whole country and the number of observation stations for a shot 20. The stations would not have to be fixed in position, and observation cars would be used. In the initial stage, the time interval of consecutive explosions at each shot point would be one month.

Regarding the stations, those for large, moderate and small earthquakes defined in § 4 would not be adequate, but most stations for micro-earthquakes and all the stations for ultra micro-earthquakes would be useful for the present purpose.

Seismometers for the purpose would be the same kind as used for the observation of ultra micro-earthquakes. Hence, the programs in this section may partly overlap the programs for ultra micro-earthquake observation of § 4. Some useful adjustments would, therefore, be possible between the two projects. Each shot point would be equipped with boring machines, shooting boxes and other items necessary for explosions.

§ 6. Active Faults

1. Necessity of Investigation.

It is a well known fact that in many cases faults accompany destructive earthquakes. Now, although it is obviously very important for earthquake prediction to know the history of seismic activity over a long period of time, no records of individual earthquakes themselves are available for prehistoric times. Therefore, we believe that investigation on the distribution and characteristics of faults which have been active in recent geologic ages (referred to as "active faults" in the following) is one of the first items that would be taken up in a project of earthquake prediction. This investigation, moreover, would certainly offer important information when it was necessary to choose the most suitable areas for detailed observations of crustal deformation for earthquake prediction.

2. Clue to the Investigation.

In Japan, more than ten earthquake faults are known to have been formed during the last century. However, there are usually a number of other geological faults in the identical area as the above-mentioned earthquake faults. Of these two kinds of faults, some are similar to each other and some are not and although it is generally considered that there must be some relationship between the two kinds of faults, nothing definite is known at present. For instance, it is not always possible to point out which of the numerous geological faults are similar to the earthquake faults. If it could be done, we could estimate the activity of past earthquake faults.

For example, the earthquake fault formed in case of the Nôbi Earthquake in 1891 at Neodani, Fukui Prefecture, runs northwest-southeast with the western side displaced southward. Now, if one studies the geological faults in this vicinity it will be found that there are certain similarities between the earthquake fault and the geological faults which run in a northwest-southeast direction. Such similarities seem to suggest that the investigation on the distribution of active faults will be useful for earthquake prediction and for the fundamental research of earthquakes.

3. Program of Investigation.

Eight out of ten earthquake faults, formed in the last century, are located in the area 133.5°E～139.5°E and 34.5°N～36.5°N. Properties of rocks of the fault plane would be examined closely for all the major geological faults in the above area. The results of the study would be compared with the results of similar investigations on earthquake faults. Then, it would be possible to ascertain which geological faults are related to earthquake faults of the past.

In the second stage, geomorphological study would be made at places where such faults cut through coastal or fluvial plains. This study would give approximate ages of the activity of faults.

In addition to active faults, nation-wide and quantitative surveys of distributions of active folding, basin forming movement and other Quaternary crustal movements would be important for assessing crustal movements at the present time. Historic and archaeological studies on topographic changes are also recommended.

§ 7. Geomagnetism and Earth Currents

1. History of the Research.

There have been a number of studies on the changes in geomagnetism and earth currents as forerunners of earthquakes. When we make a proposal for the project "Earthquake Prediction", it is important to examine thoroughly past works and to make a sound judgement as to along which line of the studies we should make further investigation. A summary of past studies is as follows.

(1) Local changes in the earth magnetic field.

Local changes in the geomagentic field before and after an earthquake have been studied by making dip surveys in the epicentral areas of a number of large earthquakes. As for the cause of such changes, some scientists point to the subterranean temperature change which would result in changes of magnetism of crustal rocks. But, the precise consideration of observations renders the more fundamental problem still a matter of controversy. In other words, it is still open to question whether or not the alleged geomagnetic variations were really associated with the earthquakes. This problem should be re-examined by means of the newly developed nuclear precesion magnetometers. These magnetometers make the truly absolute measurement of geomagnetism very easy.

(2) Rapid changes in geomagnetic and earth currents.

Among the researches on the relation between earth currents and earthquakes, the following is based on the fact that such earth currents are controlled by subterranean structures which are at a shallower depth than those affecting changes in geomagnetic field. Even along the same direction, the earth potential per unit length differs for different spans of elecrodes. From a perusal of records of the difference in the local potential it has been frequently found that some large earthquakes bear a certain correlation with a special kind of change in the earth current. Although sufficient examination has not been made to rule out the possibility that this kind of earth current variation may be due to some other causes, this phenomenon seems to well deserve further investigation.

It has been reported, on the other hand, that a particular type of geomagnetic variation (with period shorter than 1 sec) is recorded before an earthquake by the Takagi-type astatic magnetometer. It is also a debatable matter whether such variations are really connected with earthquakes. Further investigation on this problem is now being planned and will be put into effect by the Japan Meteorological Agency.

(3) Variation of subterranean electrical conductivity.

From a comparison of records of geomagnetic and earth current variations, subterranean electrical conductivity can be estimated under certain assumptions. Experiments are now being made to extend this and to detect a correlation between the time variation in the electrical conductivity and earthquakes. It is doubtful, considering the inaccuracy of measurements at present, if such an approach is rewarding. At the same time, however, it has been reported that the specific electrical resistance of the ground changes remarkably due to the extension-contraction of the ground by tidal loading. This kind of measurement should be further made because of its possible significance in earthquake prediction.

2. Research Project for the Future.

The items mentioned above should be re-examined and those which seem promising pursued from the standpoint of earthquake prediction. As for the adopted item or items, full use of modern methods and equipments, completion of the observation network, and automation of analysis should be applied. Several items should be carried out at the same place and at the same time. Simultaneous practice of other kinds of observation, such as seismic or geodetic measurements at the same place would also be desirable.

This work would have a very strong nature which is characteristic of pure research, as it is still in a stage where possible new methods are being sought. It is planned, therefore, that some special areas should be selected and an observation network be set in them.

(I) The areas for the network would be selected from existing data such as the results of magnetic survey of the whole country.

(II) Stations: several fixed stations would be set up and continuous observation of the geomagnetic field and earth currents would be made.

(III) Repeated measurement of the geomagnetic field by the Geographical Survey Institute would be conducted every ten years for the 1st order points, and every five years for the 2nd order points. Under the present project, repeated measurement would have to be made more frequently in the areas concerned. In doing so, regular measurements at the 1st and 2nd order points of the Geographical Survey Institute would be ultilized as much as possible.

3. Results Expected.

In spite of many investigations and reports, the relationship between the geomagnetism and the earth current with earthquakes has produced no conclusion up to the present time, because of the poor reliability of measurements and insufficient statistical examination. *If the present project is put into practice, these problems will be solved in a relatively short time.*

It will be expected to be difficult, from the beginning, to separate out those parts of geomagnetic and earth current variation associated with earthquakes from those which are not, since such variations are caused also by a great number of other phenomena. In spite of such essential difficulties, many scientists have long tried to predict earthquakes from measurements of the geomagnetic field and earth currents. The reason for this may be as follows.

All the measurements and observations concerned with earthquake prediction, such as those of crustal deformation and seismic activity, require large-scale operations. The measurement of the geomagnetism and earth currents, on the other hand, is far simpler in practice and can be done with much less cost and personnel. Such simplicity of operation is advantageous and it seems to be this ease of handling which has made people interested in the study of the geomagnetism and earth currents for earthquake prediction. Inasmuch it is attractive to many people, it is also very important to clarify ambiguous points that feature in the results so far presented. Doing so will expedite the progress of the projects for earthquake prediction from other aspects. Many researchers have come to realize that effective prediction of earthquakes will never be attained so far as such simple operations and the efforts of individual persons only are relied upon, and this accounts for the reason why the present Group responsible for the project "Earthquake Prediction" has decided to start working on a larger scale.

§ 8. Organizations for Promoting "Earthquake Prediction" Project

The aim of the present Group has been to draw up a blue print of the Project "Earthquake Prediction" which is in fact outlined in the preceding seven chapters. For the actual implementation of this program, a number of organizations and institutions would have to participate. Basing the program on the present blue print, individual institutions would have to make more concrete plans regarding the personnel and budget required. In this Chapter, considerations will be made as to which institutions are thought suitable to undertake which specific items and in what ways, in view of the present state of various geophysical institutions in this country.

Firstly, all of *the investigations by geodetic methods* can be considered as extensions of the geodetic services now carried out by the Geographic Survey Institute. Although the proposals in §1 were made from the standpoint of earthquake prediction, they will well meet national demands for the maintenance of high precision land survey and for the preservation of the land. In view of this, the Geographical Survey Institute is considered to be the most suitable organization for carrying out the geodetic measurements.

At present, *tide-gauge stations* are operated by the Japan Meteorological Agency, Geographical Survey Institute, Hydrographic Department and other institutions for their own purposes. Consequently, in the present program, expansion and improvement of tide-gauge stations would be conducted by each of these institutions. However, for data processing, a Centre would need to be set up in an appropriate organization and modern methods for quick analysis fully employed.

For the *continuous observation of crustal deformation*, in accordance with the present proposal, 100 stations would need to be set up in the whole country. Incidentally, there are only eight existing stations which satisfy the specifications required in the present program. These stations belong to the Earthquake Research Institute, University of Tokyo, and the Disaster Prevention Research Institute, University of Kyoto. Maintenance of 100 stations would involve an enormous amount of work quite beyond the capacity of a conventional resarch project because such work would require every aspect of routine service observations. But still the actual operation for such observations would require too much research to be handled entirely by the governmental agencies. Thus the following two necessities emerge.

(1) Drastic Expansion of University Research Institutions.

There would be much objection, from the coventional standpoint, against the proposal that university research institutions should undertake such a large-scale operation as normal routine services. But in recent years, accompanying the expansive progress of science, the scale of research work is becoming progressively large. Geophysical researches, in particular, have required observations on a very large scale and the cooperation of a number of scientists. It may be a good idea to modify conventional procedures and to venture on a policy of university institutions also undertaking such tasks.

(2) To Entrust Institutions Attached to Governmental Agencies with Such Task.

An alternative to (1) would be to set up a subsidiary research institution attached to a relative governmental agency, such as the Geographical Survey Institute, and have such research institutions conduct work according to the demands of their research program.

As for *the investigation of seismic activity*, large, moderate and small earthquakes, as defined in § 4, are either already planned or in the process of being handled adequately by the Japan Meteorological Agency. So these three kinds of earthquakes need no special attention here. The immediate problem would be to assign suitable organization(s) to take care of micro- and ultra micro-earthquakes. Observation of these extremely small earthquakes as planned here would be, just as that in the case of crustal deformation, a large-scale project. Therefore, the following possibilities may exist.

(1) The Japan Meteorological Agency could set up a department for research observation. But, observation of micro- and ultra micro-earthquakes requires special places to install highly sensitive seismometers, and consequently, only a few existing stations of the Japan Meteorological Agency could be utilised for this purpose. There is, thus, no reason why the Japan Meteorological Agency would be suitably adoptable to this task.

(2) For precisely the same reason as in that of observation of crustal deformation, university institutions would need be drastically strengthened, so that observation of micro- and ultra micro-earthquakes for the whole country could be carried out by them.

(3) A new department for research observation would be set up in the Geographical Survey Institute. If observation is handled by this institute in close coordination with the observations of crustal deformation, the nature of the work would become quite different from conventional seismic observations carried out by the Japan Meteorological Agency, No serious overlapping would, then, occur between the above two activities.

Determination of seismic wave velocity by means of explosion seismology would not be on such a large-scale as observations of crustal deformation and earthquakes. But, nevertheless, it would be non-academic and too large an enterprise for a purely conventional university research project.

Since the actual operations involved have a great similarity with those required for observation of micro- and ultra micro-earthquakes, it may be a good idea to organize a moving party in a project of micro-earthquake observation and utilize this party for explosion seismological purposes.

The amount of work for the *investigation of active faults* planned here would remain for some years within the capacity of individual experts at universities, so that no special consideration need be given here.

Lastly, *investigation of geomagnetism and earth currents* features somewhat different from those of crustal deformation and seismic activity. That is, in the former, our knowledge is still so poor that suitable and significant kinds of observation should be determined as soon as posible, and then extended over the whole country. For this purpose, it is now planned that proper areas should be selected and a certain number of stations equipped with many kinds of instruments established there: in practice, therefore, it would be sufficient for the Kakioka Magnetic Observatory of the Japan Meteorological Agency, the Kanozan Geodetic Observatory of the Geographical Survey Institute, and the Shimosato Observatory of the Hydrographic Department to perform the major part of the work and the universities to cooperate with them.

In this chapter, a proposal on the organization for the advancement of the project "Earthquake Prediction" was made taking only the existing facilities into consideration. But, in view of the frequent sufferings by Japan from many kinds of natural disasters, it is beginning to become vital that a large organization, that may be called the "Ministry of Territorial Welfare", be established, so that coordinated measures can be taken against such disasters. If such a governmental organization is established in the future, most of the work under the present proposal could be handled by it most effectively.

§ 9. Anticipated Results

In this Chapter, the expected outcome of the present proposal will be synthesised; Anticipated results from individual items have been mentioned in respective Chapters. Here, mention should be made of questions which will surely be raised in the mind of the reader, namely, the problem of the expected length of time necessary for attaining effective earthquake predictions provided that the present proposal is put into practice.

It is proposed, with regard to *investigations by geodetic methods*, that the time interval for nation-wide rapeated surveys be five years for levelling and ten years for triangulation. Hence, it would be some ten years or so before the program really got under way. For certain special areas, a considerable amount of information should be obtained within five years. But when we realise that during the initial years of the project much work in instrumentation and education of personnel will be demanded, five years should reasonably be allocated for the preparatory stage.

Tide-gauge stations would be completed in two years, but data covering several years would be necessary to be really useful.

Continuous observation of crustal deformation: Six base stations would be established under a three-year project, and personnel trained in these stations. Then, such trained personnel would construct the proposed 100 stations under an eight-year scheme. If things work out as planned, completion of stations would be accomplished in eleven years.

Observation of micro-earthquakes: Twenty branch stations and their subsidiary stations would be established under a ten-year project.

Observation of ultra micro-earthquakes: A small network of stations in six special areas would be carried out under a six-year project.

Determination of seismic wave velocity by means of explosion seismology: Regular operation would be continued with explosions at six places under a six-year project.

Investigation of active faults would be completed in two years.

Investigation of geomagnetism and earth currents: Several fixed stations in special areas would be completed in three years.

Provided that the project is promoted as planned above, an amount of useful information would be obtained in five years and after ten years the amount of data should be fairly adequate for earthquake prediction.

In other words, it will take at least ten years before the survey and observation under the present proposal really get under way. After that, the stage for processing data would start. At present, statistics show that earthquakes with magnitude $M>6$ occur about five times every year in and near Japan. Among these, one is usually destructive. If we aim at predicting earthquakes with magnitude $M>6$, *it seems highly probable that we would be able to find some significant correlation between earthquake occurrence and observed phenomena merely by accumulating data for several years.*

Now, when will earthquake prediction become possible and an efficient forewarning service be available? This question cannot be answered now. But if we start the project presented here we should be able to answer the question with sufficient certainty within ten years.

Remark: Publication of this report was sponsored by the Research Fund for Sciences of the Ministry of Education.