THE GROUND MOTION OF THE GREAT KWANTO EARTHQUAKE OF 1923

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Introduction

This paper is prepared under the same title of study which has been reported in the Proc. 4th Symposium on the Ground Vibration (of A.I.J.), Jan., 1976, for the purpose of introducing the further results obtained.

The scarcity of correct seismometric data for strong earthquake motions is keenly felt by the structural engineers. Owing to the lack of such necessary materials, some of the structural engineers have been obliged to use the strong-motion seismograms which were obtained in the United States of America, or to use the acceleration seismograms of the Japanese earthquakes by enlarging the values of acceleration, though the engineers were aware of unreasonableness of using such seismograms worked out artificially in the designs of buildings and other facilities. These earthquakes were not essentially strong enough to cause severe damage, and did not bear the character of the big earthquake.

In the aid of filling up the lack of scientific data for the strong earthquake motion, some research workers used the simulated earthquake motions and obtained fairly fruitful results¹⁾. Strictly speaking, however, it is questionable that these simulated motions fit the real ground motion of the earthquake which originates in a certain specified region, if we consider the fact that the ground motion pattern varies according to the place in which the earthquake occurs. After all, the strong-motion record actually obtained is the supreme for the engineering purpose.

In view of this point, the author took up the seismographical records of past major earthquakes some of which had not been shown to the public for a long time, and attempted to extract some valuable informations about the strong motions by reinvestigating the seismograms with the aid of electronic computer. It was our final aim to establish the ground motion patterns which are necessary in the field of engineering.

For these years, analyses of the ground motions have been done of the destructive and semi-destructive earthquakes which hit the Tokyo and Yokohama area during the past several decades. These earthquakes were observed at Hongo, Tokyo, by means of the displacement seismographs which were rather old-fashioned as compared with the modern ones.

In this paper are intended to introduce the method of wave-analysis and the characteristic ground motion of the great Kwantō earthquake of September 1, 1923.

1. The Ewing strong-motion seismograph

The great Kwantō earthquake of September 1, 1923 is so well-known that it requires no special mention. It brought us truly a major disaster of the first rank. In Tokyo and its environs, the motion of the ground was so large that all seismometric observations failed in obtaining the perfect record of this earthquake. There was, however, only one instrument which gave a record continued practically at least two minutes from the beginning, though interrupted several times shortly.

This instrument was invented by J.A. Ewing more than forty years prior to the 1923 earthquake, so it had been already out of date at the time of the earthquake, and not used in daily observations, but put on show as a teaching material. It was originally intended for use as a strong motion seismograph,

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and always lubricated and maintained in a good condition. For this reason it could record the big ground motion of the 1923 earthquake for a comparatively long time. The seismograph equipped with a continuously moving disk-recorder rotating at a comparatively high speed such as 3 degree of angle per second. The disk, however, was set in motion by the triggering device only when the earthquake began, and the pendulum had a period of 6 seconds (horizontal component), magnification=unity, and was not provided with dampers. Recently, this seismograph has been reproduced by us (Photo-1), for the purpose of checking its vibrational characteristics.

Figure 1 shows the conscientious hand-tracing of the record which was formerly carried out by N. Nasu. This time our analysis is mainly done for the S.W.-N.E. component motion which is separately shown in Fig. 2. In this figure, the parts denoted as A, D and F are the interrupted parts of the record as a consequence of the stylus having been swung off the recording disk by the big ground motions. On the other hand, parts B,C and E are at the turning points of the stylus on the recorded wave, so in these parts the traces are somewhat unclear because of skipping of the stylus, but they are treated similarly as the interrupted parts A,D and F, as will be mentioned later.

Photo 1 The Ewing-type of seismograph reproduced by us.

Fig. 1 The record of the great kanto earthquake of 1923.

(Hand-tracing was formerly carried out by N. Nasu.)

Fig. 2 The S.W.-N.E. component motion

2. Analysis of the ground motion

The actual ground motion may be generally obtained from the seismograms of the past earthquakes, according to the procedure as shown in Fig. 3. Here, each step of procedure is outlined by turns.

1) Digitization of seismogram

In the case of the disk-recorder, arc-shaped waves are recorded on the rotating disk by the stylus which rotates about its own axle correspondingly to the ground motion. So, this type of recorder is naturally inconvenient in the precise determination of period and amplitude of the ground motion, because the waves registered by this recorder are so complicated that they cannot be analysed, unless they are

reproduced in a rectilinear diagram.

For the benefit of this reproduction work, a curve-reader is devised by us. This device is mainly consisted of a potentiometer and a digital resistance-meter as shown in Fig. 4. By the aid of this device, the deflections of the curve-reader's stylus which strokes the recorded waves conscientiously, are digitized at an interval of 1/50 second. The electric resistance of the potentiometer is strictly in a linear

Fig. 3 Procedure of the wave-analysis

1. Boom
2. Gear to magnify the rotation of boom by $\times 10$
3. Digital resistance-meter
4. Graduated circle for driving the disk
5. Worm-rear
6. Potentiometer
7. Handle

Fig. 4 Curve-reader for digitization of the disk-record

proportion to the amplitude of wave, and hence the electric resistance can be easily converted to the amplitude by referring to the result of calibration. In our case, the unit in digitization of wave amplitude is proved to be 0.16 mm. By the way, it should be added that, for a precise digitization work, a close attention is paid to the linearity which exists between the electric resistance and the amplitude of wave mentioned above.

2) Mending the interrupted parts of seismogram

In the disk-record of the 1923 earthquake, the interrupted parts of registration are seen at

Fig. 5 Procedure of mending the interrupted parts of the record

Fig. 6 Method of mending the interrupted parts

Fig. 7 Reproduced wave in a rectilinear diagram after mending the interrupted parts of the record

several places, as already mentioned. These parts must be mended reasonably to obtain a continuous trace. Usually, the mending is made separately for the shorter period waves and the longer period waves according to the procedures as shown diagrammatically in Fig. 5.

To mend the shorter period waves in the interrupted parts, we must take into consideration the changes of period and amplitude of the waves recorded before and behind the parts which should be mended. In this work, it is convenient to adopt the method of digital filtering, Fourier transform and inverse Fourier transform, etc. As for the longer period waves, a parabolic curve is interposed by using least-square, so as to fit the waves lying before and behind the mended part. These procedure are schematically illustrated in Fig. 6.

After such works were done, we could obtain the continuous trace for about two minutes as shown in Fig. 7. In this figure the parts denoted A, B, ..., F correspond to the mended parts.

3) Clearing-off undesirable effect of seismograph

In the recorded waves there may be latent the characteristics of the seismograph which registered these waves. The defects due to the non-existence of damper and the shortness of the proper period of seismograph are cleared off in order to obtain the actual ground motion.

4) Elimination of errors in reading

In order to determine the velocity and acceleration of the ground motion, we must differentiate the displacement record, once and twice with respect to time. In these differentiations the errors in reading misleads the results, and therefore a special attention was paid to the reading of waves. On the other hand, in the case of integration, proper correction should be made of the datum line of the accelerometer.

3. Ground motion of the great Kwanto earthquake of 1923

Through the course of our analyses which was started with reading of seismogram, we could make clear the acceleration, velocity and displacement patterns of this earthquake displayed for about two minutes (Fig. 8).

1) Consideration of the ground motion

As briefly mentioned before, the motion of this earthquake was enormously so large that, in Tokyo, the almost seismic observations which relied upon the sensitive instruments failed in getting the perfect record. But, there were some instruments which could register the ground motion, though for a short time, for example, the Imamura strong-motion seismograph. This instrument had been installed in the Seismological Institute of the University of Tokyo, and could continue the registration of the ground motion for a comparatively long time from the beginning of the earthquake. But, in this instrument, both the N.S.-and U.D.-component writing indices went out of the recording drum as soon as the principal motion of the earthquake set in, whereas the remaining E.W.-component writing index could continue to register for more 5 seconds. Since then, the pendulum repeated the collision with the stopper till the end of the registration, and consequently the true ground motion became unknown. The record of this component-motion (E.-W.), however, suggests us that the ground motion became gradually larger with time in the earlier stage of the principal portion, and the motions of large amplitudes continued for a fairly long time.

The late professor A.Imamura's experiences²⁾ are surely a precious material for the ground motion of the great Kwanto earthquake which we want to know. It will be noteworthy that we can find several

Fig. 8 Deduced ground motion of the great Kanto earthquake of 1923

points which are thought true in the Imamura's experiences, if we look at the acceleration pattern of this earthquake determined by us and will be shown later in Fig. 8(a). The points in which we can find a fairly agreement between the Imamura's experiences and the acceleration pattern lie in the following facts, that is, the gradual increase in intensity of the shock up to its maximum as can be seen in the earlier stage of the principal portion of the earthquake, the successive occurrence of severe aftershocks, the existence of large and slow undulations of the ground, and the times of occurrence of these facts on which Imamura counted mentally.

2) Types of ground motion

On looking at the earthquake catalogue, it will be seen that the earthquakes which ever brought about the seismic damage to Tokyo occurred in a certain number of limited regions, for examples, i) Sagami Bay and its coastal region, ii) Tokyo Bay, iii) Kinugawa Valley, iv) Off the coast of the Boso Peninsula, etc. Limiting the earthquakes only to those which were selected in our investigation, it is clear that the great Kanto earthquake of 1923 belongs to region i). According to Professor A. Imamura³⁾, this great earthquake is a multi-source earthquake, and consequently, the ground motion is complicated, but there can be seen a train of waves which have large amplitudes and long periods. The duration of these slow undulations is much longer than that in the case of other types of ground motion. In the great earthquake of 1923, it has been found by us that the largest amplitude exceeded 50 cm, and the longest period was 12 sec or more, as will be mentioned later.

3) The maximum ground motion

The reliable values of the maximum displacement and the maximum acceleration of the great Kanto earthquake have never been known until a recent year. According to the record obtained by means of the Omori seismograph (N.S.-component, natural period=40 sec, magnification=1.5), it is seen that the displacement of the ground had already a value of 17 cm in double amplitude, even at the time when the writing index went out of the recording drum soon after the principal motion began. This suggests that the range of displacement was fairly larger than that registered.

It is said generally that the ground motion had the maximum acceleration of 0.1 g at Hongo, Tokyo. This value was determined from the period of 1.35 sec and the amplitude of 4.45 cm of the wave which appeared in the initial part of the principal portion, by assuming the motion to be simple harmonic. But, it is hard to understand that the earthquake of such an acceleration could bring about a serious damage of the building which stood near the place where the observation was made. Concerning this

matter, the late professor K. Suyehiro gave a similar opinion in his writing⁴⁾.

According to the result of our analysis which was made of the S.W.-N.E. component motion, the maximum ground acceleration was 392 gals at 24 sec after the commencement of registration, and the maximum displacement was about 46 cm in its amplitude. By the way, it will be added that another component (S.E.-N.W.) had the maximum amplitude of 50 cm. Such large values of the acceleration may not be deniable, because there were abundant affirmative evidences, for example, the collapse of brick buildings existed near the Seismological Institute.

4) Orbital motion

The orbital motion of the ground which was drawn as an aid of investigating the characteristics of the large undulations displayed in a horizontal plane is shown in Fig. 9. This figure illustrates the resultant motions obtained by combining the two component horizontal motions from the commencement to the end of the seismograms. It must be added that the component motions cited here are those which were deduced after the correction was made for the displacements previously determined. This correction is necessary for the determination of the actual motion, when the pendulum of the seismograph is subjected to a large amplitude motion which acts in the horizontal direction perpendicular to the motion which the instrument is intended to record. A similar matter has been treated theoretically by K. Suyehiro and described in his writing previously mentioned.

Fig. 9 Orbital motion

Also in Fig.9, it can be seen that the main direction of the ground motion changes approximately from the N.-S. to the E.-W. with lapse of time, and the maximum motion appears about 75 sec after the beginning. The maximum ground displacement is worked out as 52 cm, and approximately toward the east.

5) Characteristic period of the ground motion

Next, the characteristic periods of this earthquake motion will be examined. Figure 10 shows the response spectrum curves which are constructed for the acceleration pattern of the motion as previously

Fig. 10 Response spectrum curves

shown in Fig. 8(a). From these spectrum curves we can determine the peak periods, or predominant periods, that is, the periods of 0.2 sec, 0.45 sec, 0.7 sec, 8~9 sec and 12~13 sec.

In these periods, it may be considered that the three shorter periods correspond to the natural periods of the superficial soil layers lying at Hongo, where the observation was made. Consequently, they are always predominately seen in the spectrum curves which are constructed for the strong earthquake motion observed there, notwithstanding their types, whereas the values of the peak periods seem to vary in a range of period which is longer than 1 second, according to the type of earthquake motion. For example, the peak periods of 1.5 sec and 4 sec, which are common in the ground motion of the earthquakes specified as the Tokyo Bay type and the Kinugawa type, cannot be seen in the 1923 earthquake motion.

On the other hand, it may be considered that the longer two periods (of 8~9 sec and 12~13 sec) are liable to appear in the Sagami Bay type of earthquake motions. Indeed, either period appears remarkably in the motion of the Central Sagami earthquake of 1924, a severe aftershock of the great earthquake occurred in the year before. But, strictly speaking, the period in the range of 8~9 sec is much predominantly seen than another period in the case of this aftershock.

It has been known by some seismologists that the waves having longer periods are contained especially in the ground motions of the big earthquake which occurred in the distant regions, and the periods mentioned above have been picked up by the late professor F. Omori as one of the periods which are apt to be seen in the earthquake motion as cited above.

In the field of engineering, however, the existence of the waves having longer periods than several seconds and more has received no special attention generally until a recent year.

6) Effect of the large and slow ground motion on a low-frequency structure

Some new type of structures in recent years, such as a high-rise building, a long-span bridge and a large-sized oil tank, etc, have never experienced a big earthquake such as the great Kanto earthquake. So, it may be meaningful to examine how the large and slow motions, as has been found in the motion of the great Kanto earthquake, affect such a structure which has a long natural period and usually a small damping of vibration.

For trial, in order to estimate the effect of the motion, the dynamical behavior of the fluid in a container will be studied, taking up a large-sized cylindrical oil tank (80 m in diameter, 20 m in height and 100,000 kJ in content) which is commonly seen in the storing place of oil at present.

Let this tank be subjected to the ground of motion of the great Kanto earthquake, and we shall examine the sloshing motion of the oil contained in it. The ever-changing surface displacement of oil was calculated by using the Professor G.W. Housner's method⁵⁾, and the damping of oil was assumed to be 0.3% against the critical.

According to the result obtained, it will be of great interest that the gradual growth of the amplitude of sloshing motion is rather conspicuous in a later stage of the earthquake in which the maximum ground displacement is seen, than in the principal portion in which the acceleration of the ground motion is usually largest throughout the course of the earthquake motion. Finally, the maximum height of sloshing motion of about 2.6 m may be seen 2 minutes after the beginning of the earthquake. By the way, this value may correspond to 5 times as large as the amplitude of the maximum input motion.

As our study is made of the sloshing motion which lasted for about 2 minutes, the motions succeeded thereafter are unknown, but it is not hard to imagine that the motion would have grown more in amplitude having been excited repeatedly by severe shocks lasted for about 30 minutes, owing to the successive occurrence of the aftershocks.

A similar matter may be easily inferable as to the response of a high-rise building, if we consider the tendency that the height of the newly designed building increases gradually, correspondingly the natural period of vibration of the structure is increasing, and at present, the period of some high-rise building in Tokyo reaches 6 sec actually. Consequently, an attention should be paid to the large and slow ground motions as mentioned here.

4. Confirmation of the method of wave-analysis

To examine the result obtained by the method adopted in our investigation, the vibration test of the Ewing seismograph was carried out under a random vibration which was consisted of the waves of which periods lie in the same range as in the case of the great Kwantō earthquake. As diagrammatically shown in Fig. 11, the test was made for a comparison of the motion of the shaking table with that deduced from the Ewing disk-record.

Figure 12 shows an example of the results obtained by the test, in which we can see a good accordance between the two motions cited above.

Fig. 11 Schematic diagram of the vibration test

Fig. 12 Example of the results obtained by the vibration test

Thereafter, the earthquake observation has been continued by means of the disk-recording instrument for the purpose of checking the reliability existing in the record of the natural earthquake and that of the artificial vibration. For this purpose, two modern-type of seismographs were used in parallel. Fortunately, the disk-recording instrument could record the motion of the Off-Miyagi earthquake of June, 1978, of which record is shown in Fig. 13. In Fig. 14 are shown the velocity and displacement curves deduced from the disk-record as a comparison with the velocity and displacement curves deduced from the TUSS record.

It has been proved that the result deduced from the disk-record agrees fairly with that obtained from the TUSS record, excepting a little difference existing in the short period waves, perhaps, owing to some difference in the condition of observation.

Conclusions

- 1) We could establish the ground motion of the past major earthquakes in Tokyo, including, espec-

Fig. 13 Disk-record of the off-Miyagi earthquake of June, 1978

Fig. 14 Comparison of the motion observed by means of the TUSS-type of seismograph with that deduced from the disk-record

ially, the great Kwantō earthquake of 1923. The ground motion of this great earthquake is surely indispensable, when we consider the problems pertaining to the anti-seismic design of structures, and mitigation and prevention of the seismic damage.

2) It will be important in the field of earthquake engineering to grasp various types of the characteristic motions, because the similar patterns of ground motion to those which have been clarified here might be expected naturally, in the future earthquake which originates in a certain definite region. It is known there are a certain number of types of ground motions of earthquakes originated in the Kwantō District. The great Kwantō earthquake of 1923 belongs to the Sagami Bay type.

3) Considering the big earthquake motions from the viewpoint of the effect exerted on the response of structures, it may be said that the Sagami Bay type of earthquake motion is clearly unfavorable to the structures of which natural period of vibration are long, because the ground motion contains many waves of large amplitudes and long periods and moreover, it lasts for a considerably long time. Here, the sloshing motion of the oil contained in a large-sized tank was examined as an example. Analogizing from the result, similar matter may be expected also in the case of a high-rise building or a long-span bridge.

4) It has been proved that the method adopted in our investigation did not lead us an unreasonable result, if we judge from the results obtained by the vibration test of the Ewing seismograph, which was reproduced by us for the purpose of checking its vibrational characteristics, and of the result of earthquake observation made by means of it.

5) By virtue of the recent electronic technics, it is possible to deduce much more informations about the earthquake motions from the seismograms which had been obtained by means of the strong-motion

seismographs in bygone days, prior to the invention of the accelerometers.

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References

- 1) Jennings, P.C., Housner, G.W. and Tsai, N.C., "Simulated Earthquake Motions", A report on research conducted under a grant from the National Science Foundation.
- 2) Reports of the Imperial Earthquake Investigation committee, Vol. 100, Part A.
- 3) Imamura, A., Theoretical and Applied Seismology.
- 4) Suyehiro, K., "Engineering Seismology, Note on American Lecture Proc. A.S.C.E., May 1932.
- 5) Housner, G.W., "Dynamic Pressures on Accelerated Fluid Containers", B.S.S.A. 47(1), 1953

1923 年 関 東 大 地 震 の 地 動

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ま え が き

わが国は地震国であるにも拘らず、烈強震の地動が完全に観測された例は少なく、とくに工学面で要求・利用される形でのデータは極めて少ない。従って、必要な場合には、例えば米国で得られた強震記録や、また場合によっては、わが国における微弱な地動の観測結果に補正を施して使用せざるを得なかった。このような烈強震動のデータの不足を補うため、各種の研究が行われ、それぞれかなりの成果を挙げている。しかしながら一方では、地震の発生する場所や、その規模によって異なる実際の地震動の性質に照らして、それらがどの程度フィットするのか、確認し難い面も残されているので、結局は実際の烈強度地動データの集積が最も必要であると思われる。

このような観点から、筆者は変位地震計によって東京・本郷で観測された過去の烈強度記象に着目し、これらを改めて解析することにより貴重な情報を引き出すべく努めてきた。

本論は、上記の記象から実際の地動を解析する方法と、この解析の結果得られた 1923 年関東大地震の地動を紹介し、地動の諸性状について若干の考察を行ったものである。

1. ユーイング円盤記録式強震計 (写真 1)

1923 年 9 月 1 日の関東大地震の地動はとくに大きかったため、東京およびその周辺におけるすべての地震計は地動の完全な記録を得ることに失敗した。しかしながら、これらの地震計の内ただ一台、本郷に設置されていたユーイング強度計のみが、もちろん完全ではなかったが、この大地震の地動を 2 分間にもわたって記録した (図 1)。この地震計は、地震計発明初期のものであり、大地震当時は正規の観測から除外され単に参考資料として設置されているに過ぎなかったが、元来、強震観測用に作られているため低倍率 (1 倍) で、また常に整備がなされていた。地震計の記録装置には直径約 60 cm の連続回転式円盤 (120 sec/rev) が用いられており、これはトリガ装置により駆動する。また水平振子の固有周期は 6 sec であり、ダンパは備えていない。

今回、地動の解析に用いたのは、主に水平動 SW-NE

成分記象 (図 2) であって、図中、A, B, ..., F と記した部分は、過大な地動により振子の描針が円盤外に脱出した部分および、描針の跳躍等による記録の不明瞭な部分である。これらの部分はともに記象欠如部分として、その補修を行わなくてはならない。

2. 地動の解析

この円盤記象から実際の地動を算定するには、次の手順に従う。

1) 記象の数値化 円盤記象の数値化には専用に考察した読取り装置 (図 4) が使用された。この装置は、主としてポテンショメータ、デジタル抵抗計および微分的に円盤記象を回転させる装置より構成されており、地震計振子の腕と等長の腕の先端に取付けられた針の先で記録波形を逐次追跡することにより、波形は直交座標系データに変換される。数値化の際の読取り間隔は 1/50 秒とし、振巾の読取り最小単位は 0.16 mm である。

2) 記象欠如部の補修 記象欠如部の補修は、波形を長周期成分波 (周期 2 sec 以上の大波) と短周期成分波 (周期 2 sec 以下の小波) とに分離し、それぞれに対し別個に行った。すなわち、大波に対しては放物線による補修を施し、小波に対しては欠如部直前および直後部分の、小波の周期と振巾の特性に基づいて、欠如部の小波を推定し、最後に両方の波を加え合せる方法を用いた (図 6)。

3) 地震計の振子特性の補正 地震記象の中には、これを記録した振子の特性が潜在している。特性の補正は、振子固有周期の長さおよびダンピングの不適当な値により生じる波形の歪を除去して行われる。ここでは、振子の運動方程式を用いて、記録波形から逆に地動を求める方法をとっている。

4) 記象読取り誤差の除去および零基線の補正 記象読取り時に誤差の混入は避けられない。また記象を読取り装置にセットする時のわずかなズレ等は、後の結果に大きく影響する。そこで、この解析では、上記の原因による雑音の周期と振巾範囲の検討結果に基づいて、周期 0.2 sec 以下および 15 sec 以上の波動をすべて除去した。

3. 1923 年関東大地震の地動

円盤記象の読取りに始まる以上の手続きを経て、関東大地震の地動の推移状態を約 2 分間にもわたって明らか

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にすることができた (図 8)。

1) 地動に関する考察 前述の如く、この地震の東京における地動は過大であったため、高感度の地震計によってなされていた当時の観測は、完全な記録を得ることには失敗したが、これらの地震計によって得られた記録から多くの情報を汲みとることができる。例えば今村式強度計の東西動記象は、主要動に入ってから地動が時間とともに増大し、さらに大振巾の地動が長時間継続したことを示している。このような地動の時間的推移状況をよく物語っているのが故今村博士の体験談である。これより推定される地動を図 8(a) に示した加速度地動と照合すると、両者は次の点でかなりよく一致していると思われる。すなわち、主要動の初期においてみられるように、地動の強さが最大に達するまでの間の状況、引続いて起こる余震、大きな振巾をもつ長周期波動の存在等であり、さらにこれらの現象の発生時刻が、今村博士が暗算で数えた時刻とかなりよく一致している。

2) 地動の型式 理科年表によれば、東京に被害をもたらす地震は限られた地域で起っている。すなわち、i) 相模湾およびその付近、ii) 東京湾、iii) 茨城県南西部、iv) 房総半島沖などであり、これらの地域で起こる地震はそれぞれ固有の地動型式を呈している。関東大地震は震原 i) に起ったことは明らかである。今村博士によれば、この地震は多元地震であり、従って地動は複雑で、大きな振巾と長い周期をもつ波動が顕著であるとしている。この大波の周期は、他の型式の地震動に含まれる波動のそれよりも長い。

3) 最大地動 従来、関東大地震の地動の最大動に関し、信頼できる値が知られていない。強震に際し最も信頼し得る記録を与えるとされている大森式地動計は、主要動の最初で描針がドラム外に脱出してしまったが、この時全振巾はすでに 17 cm であった。つまり、最大変位はこれよりかなり大きかったことは明らかである。一方、最大加速度は、本郷で 0.1 g とされていた。しかしながら、この程度の加速度があのような震害をもたらすとは考え難い。SW-NE 成分の結果では、最大変位が 46 cm であり、最大加速度は 392 gal である。このような値は、種々の観点からして充分推定し得る。

4) 地動の軌跡 この地震動の始動部分から現われている大波の性質を調べるため、一方法として水平面内軌跡を描いてみた (図 9)。ユーイングの水平振子等この種の振子は、とくに変位が大ききとき、振子の運動方向に直交する方向の地動によって、その応答に影響を受けることが知られている。図 9 は、その影響を補正し、周期 5 sec 以下の波動を濾波した結果を示している。この図によれば、地動の主方向は N-S から E-W へと時間とともに変化しており、最大変位は始動より約 75 秒後に現われ、その値は東に約 52 cm である。

5) 地動の周期特性 図 10 に示した地動の応答スペクトルよりピーク周期を読みとると、0.2 sec, 0.45 sec, 0.7 sec, 8~9 sec および 12~13 sec である。これらの周期のうち、短周期の 3 個は観測場所の極表層地盤の固有周期と考えられ、前述の地動の型式に関係なく、本郷で観測される強度地動の中に常に認められる。他の長周期 (8~9 sec および 12~13 sec) は震原 i) の地動型式の地動に現われ易いと考えられる。事実これらは、関東大地震の大きな余震の一つである 1924 年の相模中部地震の地動中にも見られ、故大森博士も、大規模な遠地地震に際して現われやすい周期としてとりあげている。ところが工学分野では、このようなやゝ長周期地動に対し、一般に最近まで特別な関心が払われていなかった。

6) 大波の長周期構造物に及ぼす影響 近年の超高層ビルや大型油槽等、いわゆる長大構造物は関東大地震の如き大地震を経験していない。そこで、関東大地震に認められる大波がこれらの構造物に及ぼす影響を調べておくことは意味あることと思われる。ここでは大型石油タンク (容量 10 万 kl) 内の油のスロッシングを例にとって上記影響を調べてみた。その結果によると、油の揺動は、強い加速度の主要動部分で大きくなるのではなく、地動の継続とともに増大し、初動より 1 分程度経過後より著しく増大する傾向を示している。この解析で用いた入力地動の継続時間は 2 分間に限られているが、実際の地震は更に長時間継続したことは明らかであり、とくに相次ぐ余震により、タンクは大きな加速度と、油の揺動による大きな力を同時に受けることになると考えられる。関東大地震の地動のこのような性質を考えれば、同様な傾向が、近年ますます高層化の情勢にある超高層ビル等の応答に関しても容易に推測される。従って、このような地動に対しては、充分な注意が必要であると思われる。

7) 地動解析方法の確認 地動の解析結果を検討するため、復元したユーイングの地震計に対し、関東大地震の地動と同様の周期成分をもつランダム波を用いた振動実験を行った。その結果は図 12 に示すように、地震計への入力と円盤記象より求めたそれとはよく一致する。また同地震計によって観測された 1978 年 6 月の宮城県沖地震の解析結果は、短周期波動にみられる若干の相違を除いて、これと併行して行っている TUSSE 型地震計による観測結果とよく一致することが確認された (図 14)。

結 論

1) 1923 年の関東大地震をはじめ、東京における過去の主要な地震の地動を明らかにできた。とくに上記大地震の地動は、構造物の耐震や震害の低減・防止を考えるうえで重要である。

2) かつて東京を襲った、それぞれの型式を異にする強震は、将来、再来することが予想される。したがって、これら地震の地動の性質を把握しておくことが必要である。

3) 構造物に及ぼす応答効果という観点から地震動を見ると、とくに構造物の周期が長い場合、相模湾型の地震動が明らかに不利であると考えられる。それは地動が大振巾の長周期波動を含んでおり、更に地動の継続時間

が長いためである。石油タンクのスロッシングの例からしても、同様な傾向が超高層ビル等の応答についても推測される。

4) 復元したユーイング地震計に対して行った振動実験結果ならびに同地震計による自然地震の観測結果から判断すると、ここで行った解析方法は適当であると考え