LONG-PERIOD GROUND MOTION IN THE EPICENTRAL AREA OF MAJOR EARTHQUAKES*

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ABSTRACT


In view of the potential importance of long-period ground motion in the design of large structures, near-field ground displacement is computed by the elastic dislocation theory for several earthquake fault models. The validity of such computations is confirmed by comparing the computed seismogram with the observed long-period seismogram of the 1923 Kanto earthquake. The ground motions are computed for three hypothetical earthquakes, a hypothetical Kanto earthquake, Tokai earthquake and Nemuro–Oki earthquake. The location and the nature of the faulting of these earthquakes are predicted by plate tectonics and precise earthquake mechanism studies. Major conclusions are: Tokyo may suffer, in the hypothetical Kanto earthquake, ground motions about half as large as those experienced in the 1923 Kanto earthquake; Hamamatsu, a large city on the Tokai coast, may experience in the hypothetical Tokai earthquake ground motions which are as large as, or even larger than, those experienced in the epicentral area of the 1923 Kanto earthquake; the hypothetical Nemuro–Oki earthquake may cause ground motions as large as those experienced in the 1968 Tokachi–Oki earthquake on the coastal cities in Hokkaido.

INTRODUCTION

The most obvious effect of earthquakes on artificial structures in the epicentral area is exerted by the high-frequency \((f \gtrsim 1 \text{ Hz})\) ground shaking, which naturally has been one of the major subjects of study in engineering seismology. However, the recent increase of large constructions such as high-rise buildings, oil tanks, suspension bridges and reservoirs calls for a knowledge of longer-period ground motions. Owing to a lack of appropriate instrumentation, however, the nature of long-period ground motions caused by earthquakes is not known very well. The recent development of earthquake fault models as well as the concept of plate tectonics now enable one

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to predict, at least to the first approximation, where the faulting of a future major earthquake will take place and what the nature of the ground motion generated by such a faulting would be. Recent fault studies show that a relatively simple elastic dislocation model of faulting can explain the long-period (longer than several seconds) portion of observed seismograms very well. Thus it now seems worth-while to compute long-period ground motions on the basis of the dislocation model so that they can be examined from the point of view of engineering seismology to assess their usefulness in the design of various large constructions.

This paper represents a reconnaissance application of the foregoing idea to several sites in Japan which are candidate localities of future major earthquakes. The present calculations of course are not valid for short-period waves \( T \lesssim 1 \text{ sec} \) for which the simple dislocation model is obviously inadequate.

**KANTO EARTHQUAKE OF 1923**

This remarkable event \( (M \sim 8.2) \) devastated Tokyo, Yokohama, and their environs. More than 130,000 lives were lost. At the time of this earthquake, a low-magnification, long-period seismograph was operating at Hongo, Tokyo, and recorded the most important part of the ground motion (Fig.1). The E–W component is almost on scale indicating a maximum amplitude of about 10 cm. The N–S component recorded the ground motion during the first 15 sec, but thereafter was off scale. Imamura (1925) who experienced this earthquake in his laboratory of the Seismological Institute of Tokyo University made very careful descriptions of the ground motion: "...the ground motion which started more or less gradually became very strong 12 sec after the onset, and reached the maximum about 15 sec after the onset. During the following 5–10 sec, the ground motion was as strong as that at its maximum, but thereafter it became long-period although the amplitude became somewhat larger. This long-period motion lasted for several minutes..." The seismograms shown in Fig.1 together with Imamura's description give us some idea of the nature of the ground motion, but only at periods within the instrumental pass-band. The longer period motion, if any, must have escaped observation. In the following, we will compute the ground motion for various fault models, and will use these seismograms to examine whether the computed ground motions are consistent with the observation over the limited instrumental period range.

The fault model of the Kanto earthquake was discussed by Imamura and Kishinoue (1928). However, it was only recently that the fault parameters were determined quantitatively. Kanamori (1971a) examined the far-field body and surface waves recorded by classic instruments, and obtained the following fault model: dip direction: N20°E; dip angle: 34°; dimension: 130 × 70 km; right-lateral slip: 2 m; reverse dip-slip: 0.65 m. On the other hand Ando (1971) interpreted the geodetic data in terms of a static dislocation model, and obtained a fault model which is somewhat different from
Fig. 1. Seismograms of the 1923 Kanto earthquake recorded at Tokyo. The "N-S" component seismograph is oriented in N23°W–S23°E direction, and the "E-W" component in E23°N–W23°S direction. $V$ is the magnification and $T$ is the free period. Each component has an oil damper.

Kanamori's (1971a). In particular, the slip determined by the geodetic data is about 7 m which is three times as large as the one determined by the seismic data. It is considered that the geodetic slip represents the seismic slip plus a gradual slip which presumably followed, or preceded, the earthquake (Kanamori, 1971a; Ando, 1971). Since we will be primarily concerned with the seismic displacement, we will adopt, in the following, the fault parameters determined by the seismic data.

In computing the near-field displacement we employed the De Hoop-Haskell method (De Hoop, 1958; Haskell, 1969). Specifically we numerically double-integrated the expressions (3.1)–(4.3) in Haskell (1969) over a fault plane placed in an infinite homogeneous medium. In carrying out this integration, we need to know, in addition to the fault geometry and the dis-
location, the rise time of the slip dislocation. For the Kanto earthquake, the fault geometry and the dislocation are known but the rise time is not determined. In the present computations, a rise time of 5 sec is taken on the following grounds. In the simplest dynamic fault model, the particle velocity of the fault dislocation, \( \dot{D} \), is proportional to the effective stress \( \sigma_{\text{eff}} \) acting on the fault plane (Brune, 1970). For the Tottori earthquake of 1943, \( \dot{D} \) is estimated as 83 cm/sec and a value of 30–100 bar is obtained for \( \sigma_{\text{eff}} \). This stress turned out to be about the same as the stress drop, \( \Delta \sigma \), which is estimated to be 83 bar (Kanamori, 1972b). For the Kanto earthquake, only the stress drop is known, but we may assume that the effective stress is about the same as the stress drop. The stress drop for the Kanto earthquake is determined as 18 bar with uncertainty of factor 2 (Kanamori, 1971a). Thus \( \sigma_{\text{eff}} \) may be estimated to be about 40 bar at the largest which is about half the effective stress for the Tottori earthquake. It follows that the particle velocity of the slip dislocation for the Kanto earthquake is about half the particle velocity for the Tottori earthquake, i.e., a value of 40 cm/sec may be adequate for the maximum particle velocity for the Kanto earthquake. Since the dislocation is about 2 m, the above estimate leads to a value of 5 sec for an appropriate rise time.

With these parameters, the ground displacements at Tokyo are computed for a fault geometry shown in Fig.2. The free-surface effect is accounted for by doubling the amplitude computed for an infinite homogeneous medium.

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**Fig.2.** Fault planes of the 1923 Kanto earthquake and a hypothetical earthquake. The inset shows the aftershock areas of the 1923 Kanto earthquake and the 1953 Boso-Oki earthquake. The epicenters of the 1703 Kanto earthquake and the 1909 event are also shown.
Fig. 3. Synthetic seismograms at Tokyo computed for a fault model of the 1923 Kanto earthquake. S is the fault area, $\bar{D}_s$ is the right-lateral slip, $\bar{D}_d$ is the reverse dip-slip, $\tau$ is the rise time and $v$ is the rupture velocity. The instrument constants used for the computation are: magnification = 2.0; free period = 10.0 sec; damping ratio = 3.0. The short-period ripples are due to the errors in the numerical integration.

This procedure is not completely rigorous but the results of Kawasaki et al. (1972) show that it is a reasonably good method to account for the free-surface effect. In order to compare the calculated displacements with the observed seismograms (Fig.1), synthetic seismograms are calculated for the computed ground displacement. Fig.3 shows the computed synthetic seismograms. Since the observation point, Tokyo, is very close to the fault plane, the mode of the rupture, namely where and how the rupture starts and grows on the fault plane, greatly affects the very beginning of the seismogram. The synthetic seismograms shown in Fig.3 are computed for a rupture starting at a point marked by a cross in Fig.2 and growing bilaterally. The rupture is assumed instantaneous widthwise. For this mode of rupturing, a reasonably good agreement is obtained between the synthetic and the observed seismograms. However, in view of the assumption of the instantaneous rupture in the width direction, the good agreement obtained for the
initial part of the seismogram may be to some extent fortuitous. On the other hand, the amplitude of the major motion, about 10 cm for the E—W component and about 20 cm for the N—S component, of the synthetic seismograms depends little upon the details of the rupturing process. The approximate equality of the amplitude of the major motion between the synthetic and the observed seismograms strongly favors the present fault model, in particular, the amount of dislocation, 2 m. The long-lasting reverberations found on the observed seismograms are evidently a result of the multiple reflection and refraction in the crust and the alluvium, and cannot be explained by the present simple dislocation model. The above comparison also supports the previously suggested idea that about 2/3 of the geodetic slip must have taken place aseismically. Fig. 4 shows the calculated ground displacement at Tokyo. It is to be noted that a displacement as large as 70 cm takes place within a period of 10—20 sec (N—S component). This result provides a fundamental nature of the long-period ground motion which may be experienced in the epicentral area of major earthquakes, although the actual ground motion would be somewhat more complex because of the layerings and heterogeneity in the crust and the sediment.

The same fault model is used to calculate the ground motion at Hatano where the damage caused by the ground shaking was very severe. Fig. 5 shows the result. The nature of the ground displacement is very similar to that at Tokyo but with an amplitude about twice as large.

![Graph](image)

Fig. 4. Computed ground displacement at Tokyo for a fault model of the 1923 Kanto earthquake.
Fig. 5. Computed ground displacement at Hatano for a fault model of the 1923 Kanto earthquake.

TOKACHI–OKI EARTHQUAKE OF 1968

This is the largest event ($M \sim 8.0$) that occurred in Japan during the last quarter of a century. Although the epicenter is located about 200 km off the coast, considerable damage was caused by the ground shakings at several localities on land. Notably, several modern reinforced concrete buildings were severely damaged in cities like Hakodate and Hachinohe which are about 200 km away from the epicenter (see Fig.6). Since most of these reinforced concrete buildings were designed to withstand accelerations larger than those believed to prevail at such distances, the extent of damage renewed seismologists' interest in the nature of ground motion caused by such large earthquakes (Kobayashi and Osawa, 1971; Ogura, 1971). Nagamune (1971) suggests, on the basis of a later phase, that the center of the major energy release is located about 100 km towards the coast from the epicenter. Further, the fault plane of this earthquake determined by the far-field data and the aftershock area extends towards the land as shown by
Fig. 6. Fault plane of the 1968 Tokachi-Oki earthquake.
Fig. 7. Computed ground displacement at Hakodate for a fault model of the 1968
Tokachi-Oki earthquake.

Fig. 6. These results together render the extent of the severe damage less surprising. It is instructive, in any case, to examine what kind of ground displacement can result from the fault model determined by the far-field data. Fig. 7 shows the ground displacement at Hakodate calculated by the same method as that employed in the previous section. The fault parameters are taken from Kanamori (1971b) as: dip direction: S66°W; dip angle: 20°; dimension: 150 × 100 km; left-lateral slip: 3.2 m; reverse dip-slip: 2.5 m. The rise time of 8 sec is assumed with much the same consideration as that made for the Kanto earthquake. The rupture is assumed to have started at the southeastern end of the fault and propagated unilaterally with a velocity of 3 km/sec. The amplitude of the ground displacement is about 2/3 of that at Tokyo for the Kanto earthquake. The motion is gradual, and lasts for more than a minute. Thus it is to be remarked that, for large earthquakes of this kind, a large long-period ground motion can still prevail even at epicentral distances as large as 200 km.

HYPOTHETICAL EARTHQUAKES

The long-period ground motion is most efficiently excited by earthquakes having a large fault plane. In the Japanese region, such large earthquakes are most likely to occur along the Pacific coast of the Japanese Islands. In the framework of plate tectonics, most of these earthquakes represent a slip at the boundary between the continental and the oceanic lithospheres. If a certain portion of the boundary slips once, then that part is unlikely to slip again within a short period of time (100 years or so depending upon the
region). On the contrary, a portion of the boundary which has experienced no major earthquake for a considerably long period of time is a candidate locality for a major earthquake in the near future. This idea has been applied to predict the location of future major earthquakes by many people, among others, Fedotov (1965), Mogi (1968), Kelleher (1970; 1972), and Sykes (1971), although plate tectonics is not necessarily a common basis to these works. This idea of course is applicable only to the plate boundaries where the mode of the plate interaction is simple and well defined. In the vicinity of Japan, at least three localities may be considered in this regard: the regions off the Boso peninsula, off Nemuro and off the Tokai coast (see Fig.2, 10, and 12). The ground displacements for hypothetical earthquakes in these localities are computed in the following.

**Hypothetical Kanto earthquake**

The Kanto earthquake of 1923 is considered to represent a slip on a fault along the Sagami trough. Because it is only about 50 years since it occurred, it is very unlikely, if not totally impossible, that the same fault plane rebounds again to cause the next major event in near future. The repeat time of major earthquakes in this region is somewhat uncertain, but it is probably longer than 200 years. In fact, historical records show only two events, one in 818, and the other in 1703, comparable to the 1923 event (e.g., Imamura, 1937). These records are of course subject to large uncertainty, but it seems irrefutable that the occurrence of major earthquakes in this region is less frequent and less regular than in the Tokaido and the Nankaido regions where major earthquakes occurred very regularly with an average repeat time of about 120 years. This difference probably reflects the difference in the mode of the plate interaction between these two regions. Earthquake mechanism studies suggest that the Tokaido and the Nankaido regions are characterized by a low-angle underthrusting, while in the region along the Sagami trough the relative motion between the oceanic and the continental plates is primarily right-lateral.

In considering the hypothetical earthquake in this region, the 1703 event has a crucial importance. Imamura suggests (see Imamura, 1937) that this event is very similar to the 1923 event in many respects but several lines of evidence suggest that the 1703 event is significantly larger than the 1923 event. Recent re-examination of the old macro-seismic data suggests (Hagiwara, 1972) that, on land, in the Miura and the Boso peninsula areas, the seismic intensity distribution of the 1703 event is very similar to that of the 1923 event. However, along the southeastern coast of the Boso peninsula, the land upheaval associated with the 1703 event is significantly larger than that associated with the 1923 event. Further, the tsunami generated by the 1703 event was much larger and more extensive than that by the 1923 event. Thus there is a possibility that the faulting of the 1703 event involves not only the fault plane of the 1923 event but also an area extending south-east along the Sagami trough towards the Pacific Ocean (see Fig.2). This area
constitutes a gap between the 1923 event and the 1953 Boso—Oki earthquake \((M \approx 8.3)\). In this case, the 1923 event represents a slip over a part of the fault plane of the 1703 event, and the remaining part may be considered as a candidate slip plane for the next earthquake.

There is, however, another complication. Japan Meteorological Agency (J.M.A.) located an event of \(M = 7.7\) off the eastern coast of the Boso peninsula in 1909 (see Fig.2). If the magnitude and the location of this event are correct, this event may represent a slip on the eastern half of the fault plane of the 1703 event. In this case, the possibility that Tokyo will experience a major earthquake of this type in near future becomes less likely. Unfortunately, however, the 1909 event is not documented very well; the location and the magnitude are very uncertain. In fact, Gutenberg and Richter (1954) locate this event about 400 km south of the J.M.A. epicenter at a depth of 80 km; in this case, this event has nothing to do with the slip along the Sagami trough.

Fig. 8. Computed ground displacement at Tokyo for a fault model of the hypothetical Kanto earthquake. Solid wave is computed for a rise time of 5 sec, and dotted curve for 1 sec.

Fig. 9. Computed ground displacement at Kamogawa for a fault model of the hypothetical Kanto earthquake.
Under these circumstances, the possibility of the occurrence of a major event in this region is somewhat uncertain. Nevertheless, in view of its potentially large effect, it seems worthwhile to compute the ground displacement for a hypothetical earthquake located on the eastern half of the fault plane of the 1703 event. For the computation, the fault size, the dip angle, the dip direction, the rise time, and the rupture velocity are assumed to be the same as those of the 1923 event. A right-lateral dislocation of 2 m is assumed, and the rupture starts at the southeastern end and propagates unilaterally.

Fig. 8 shows the computed ground displacement at Tokyo. It is to be noted that, despite the fairly large distance from the fault plane, the amplitude of the ground displacement can be as much as 70% of that of the 1923 event (see Fig. 4). The ground displacement at Kamogawa, a city on the eastern coast of the Boso peninsula (see Fig. 2) is also computed and is shown in Fig. 9. The amplitude is as large as that at Tokyo for the 1923 event. Thus should the hypothetical earthquake occur, Tokyo and the Boso peninsula area are likely to experience a long-period ground displacement as large as that caused by the Kanto earthquake of 1923.

Tokai earthquake

In the Tokaido and the Nankaido regions, great earthquakes have occurred very regularly with a repeat time of about 120 years. At the western end of the Tokaido region, a major earthquake occurred in 1854 (Fig. 10). No major earthquake has occurred ever since in the same epicentral area. Recent investigation by Hagiwara (1970) confirmed that the epicentral area of the 1854 event occupies a large area off the Tokai coast. That this area may be a site of a future major earthquake has been occasionally remarked by several people; e.g., Mogi (1970) made such inference on the basis of the secular horizontal movement of the crust.

In this region, the following hypothetical earthquake is considered. The fault plane of this hypothetical earthquake is located off the Tokai coast as shown in Fig. 10. The strike of the fault is taken more or less parallel to the local strike of the Nankai trough. The fault is assumed to share the same properties as the 1946 Nankaido and the 1944 Tonankai earthquakes (Kamamori, 1972a). The fault parameters assumed are: dip direction: N27° W; dip angle: 10°; fault dimension: 120 × 80 km; rise time: 5 sec; dislocation: 3.5 m. Since the slip direction of the 1944 Tonankai and the 1946 Nankaido earthquakes is oblique to the dip direction of the hypothetical Tokai earthquake, the total dislocation of 3.5 m is partitioned into 2.1 m of strike-slip (right-lateral) and 2.1 m of dip-slip (reverse) components. The rupture is assumed to start at the southwestern end and propagate unilaterally with a velocity of 3 km/sec. The ground displacement is computed at Hamamatsu, one of the largest cities along the Tokai coast (see Fig. 10), and is shown in Fig. 11. Because the fault plane is very close to the coast, the amplitude is very large. If compared with the 1923 Kanto earthquake, the amplitude at Hamamatsu is larger than that at Tokyo for the Kanto earthquake, and is
Fig. 10. Assumed fault plane of the hypothetical Tokai earthquake, and the aftershock areas of the 1944 Tonankai and the 1946 Nankaido earthquakes.

Fig. 11. Computed ground displacement at Hamamatsu for a fault model of the hypothetical Tokai earthquake.

comparable to that at Hatano. In any case, the hypothetical Tokai earthquake, should it occur, may cause a very large amplitude ground displacement along the Tokai coast.

*Nemuro—Oki earthquake*

The region between the 1952 Tokachi—Oki earthquake and the 1969 Kurile Islands earthquake constitutes a typical "seismic gap" (see Fig. 12). From the size of this gap Utsu (1972) suggests a possibility of an occurrence of a major earthquake of $M \sim 8$ in this gap. Utsu predicted the distribution of seismic intensity that may result from this hypothetical earthquake. Shimazaki (1972) discussed the crustal deformation on the coast of Nemuro in terms of a pre-seismic crustal deformation caused by the underthrusting oceanic plate. Precise determinations of earthquake mechanism of several major earthquakes in the neighboring regions (Kanamori, 1970; Abe, 1973a) consistently suggest that the oceanic plate in this region is, as a whole, underthrusting beneath the Kurile Islands, and Hokkaido with a relatively low dip angle, about 20°. The dislocation associated with these major earthquakes is relatively constant ranging from 3 to 4 m.

Because the last major event that occurred within this "seismic gap" is in 1894, it now seems worthwhile to consider a hypothetical earthquake in this gap. For this earthquake, it is reasonable to assume fault parameters similar
Fig. 12. Assumed fault plane of the hypothetical Nemuro–Oki earthquake and the aftershock areas of the 1968 Tokachi–Oki, 1952 Tokachi–Oki, 1969 Kurile Islands, 1958 Kurile Islands, and 1963 Kurile Islands earthquakes.

Fig. 13. Computed ground displacement at Kushiro for a fault model of the hypothetical Nemuro–Oki earthquake.

to those of the neighboring major earthquakes. Fig. 13 shows the computed ground displacement at Kushiro (see Fig. 12) resulting from this hypothetical Nemuro–Oki earthquake whose fault plane is located between the aftershock areas of the 1952 and the 1969 events (see Fig. 12). The assumed fault parameters are: dip direction: N50°W; dip angle: 20°; fault dimension: 150 × 100 km; dislocation: 3 m (reverse dip-slip); rise time: 5 sec. The rupture starts at the northeastern end and propagates unilaterally with a speed of 3 km/sec. The nature of the computed ground motion is very similar to that at Hakodate computed for the 1968 Tokachi–Oki earthquake (Fig. 7); the motion is very gradual lasting for about a minute.

DISCUSSIONS AND CONCLUSIONS

The present computations provide an assessment of long-period ground motion caused by major earthquakes. The computed ground motion is shown to be consistent with the observed long-period seismograms at relatively short distances. One example is given here for the 1923 Kanto earthquake. Other examples are the 1966 Parkfield earthquake (Aki, 1968), the 1933 Sanriku earthquake (Kanamori, 1971c), the 1943 Tottori earthquake (Kanamori, 1972b), the 1948 Fukui earthquake (Kanamori, 1973a), the 1971 San Fernando earthquake (Mikumo, 1973; Trifunac, 1974) and several other moderate-size Japanese earthquakes (Kanamori, 1973b; Abe, 1973b).

The actual ground motion may become more complex because the fundamental wave form can be considerably modified by the soft alluvial layers and the lateral heterogeneity of the structure. For extremely large earthquakes, aftershocks or secondary faultings immediately after the main fault-
ing may contribute significantly to the complexity. One such example is found on the E–W component seismogram of the 1923 Kanto earthquake (Fig.1). An aftershock is recorded about 3 min after the onset. It is very probable that aftershocks of this kind contribute to the complexity in the earlier part of the seismogram as well.

In the preceding calculations a rise time of 5–8 sec was adopted. This value which was estimated from the effective stress is admittedly the most uncertain of all the fault parameters. Since the shorter the rise time, the larger the effect of ground motions on buildings would be, it is instructive for engineering purposes to compute a ground displacement for a shorter rise-time and to compare it with the one calculated above. Such comparison is made for the ground displacement at Tokyo for the hypothetical Kanto earthquake. The dotted curve in Fig.8 shows the displacement computed for a rise time of 1 sec. Although the overall wave form does not change very much, the motion becomes more jerky as expected.

The high-frequency spectrum of the ground motion cannot be treated by the present dislocation model. Such high-frequency waves are probably excited by the irregular interactions between the opposing sides of the fault plane during the slippage, and by the irregularities in the stress condition at the growing fault edge. It is not possible at present to include these irregular conditions in the dislocation model. One possible way of treating these high-frequency waves is to treat them as a random process and to relate the bulk fault parameters such as the dislocation and the dislocation velocity to the average property of such random process. In such a model, the duration of the long-period ground motion calculated here primarily governs the duration of the short-period ground shaking. More detailed analysis along this line will be made in a separate paper.

The effect on the actual structures of the fundamental long-period ground motions calculated for the hypothetical earthquakes must await future investigations. At present, some empirical relations based on the past experience may be useful. That is, for the 1923 Kanto earthquake and the 1968 Tokachi–Oki earthquake, both the damage on various structures and the computed ground motions are known. The empirical relation between the kind of the damage and the nature of the ground motion for these earthquakes may be used as a reference in considering the nature of the damage which may be caused by the ground motions resulting from the hypothetical earthquakes. It is suggested that Tokyo may suffer ground motions about half as large as those experienced in the 1923 Kanto earthquake. Hamamatsu may experience, in the hypothetical Tokai earthquake, ground motions as large as, or even larger than, those experienced in the epicentral area of the 1923 Kanto earthquake. The hypothetical Nemuro–Oki earthquake may cause ground motions in Kushiro which are as large as those experienced in Hakodate in the 1968 Tokachi–Oki earthquake.

The present method may be applied to other regions where the location and the mode of faulting of future earthquakes can be predicted in the framework of plate tectonics.
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