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ON THE DYNAMICAL PROCESS OF THE

PARKFIELD EARTHQUAKE OF

JUNE 28, 1966

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The seismic acceleration recorded at the Parkfield, Cholame No.2 sta-tion in California t the time of the Parkfield earthquake of June 28, 1966, is analysed to determine the focal parameters on the dynamical process of faulting.
A direct comparison of the calculated accelerations with the recorded
one yields focal parameter estimates of 0.5-0.7sec for the rise time of the source time function, 50-70cm for the average dislocation and 50cm/sec for the particle velocity of the fault motion. The effective stress is deter-mined from the particle velocity to be 25-50bars by the dynamic faulting models recently developed. The wave form of the calculated acceleration shows a good peak-to-peak correspondence with the recorded one, only when the source time function is assumed to be of a ramp type. This suggests that the ramp function is a good approximation for the source time function of this earthquake.
We obtain an amplitude of about 7cm for the perpendicular component
of the theoretical ground displacement if the values of 50-70cm for the average dislocation and of 0.5-0.7sec for the rise time as estimated above
are used. The value of 30cm for the amplitude of displacement, obtained
by previous investigators from numerical integration of the record acceler-
ation, seems to be too large. The integrated displacements may not be good approximations for the true ground displacements.

1. Introduction

The investigation fthe focal process from the data in the near-field has become more and more important because full data are required for a better understanding of the dynamic process of faulting, in view of the recent ad-vances in seismology.

MARUYAMA (1963) and HASKELL (1964, 1969) gave mathematical expres-sions of seismic waves due to a shear fault located in an infinite homogeneous medium. AKI (1968, 1972), KANAMORI (1971, 1972) and MIKUMO (1973) demonstrated the applicability ofthe theoretical seismograms calculated from

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formulae of Maruyama or Haskell in the focal-mechanism studies using the near-field data. These investigators discussed the focal parameters assuming that, doubling the displacements for an infinite medium, they obtain good approximations for the free surface displacements for a semi-infinite medium. However, the validity of this assumption of the doubling of the displacement
for the free surface effects was not evident.
KAWASAKI et al. (1972, 1973) applied the Cagniard method to the expres-sions given by SATO (1969), taking the free surface effects into account, and gave exact expressions of the seismic waves due to a double couple point source in a semi-infinite medium. They discussed the near-field characteristics of all phases in detail and pointed out some problems; for example, an SP wave refracted at the free surface has an unexpectedly large amplitude com-parable to that of the P wave and cannot be neglected when discussing the focal mechanism. KAWASAKI and SUZUKI (1974) synthesized the seismograms due to a moving shear fault model in the semi-infinite and infinite media and compared them with the actual records of the Sanriku earthquake of 1933. They estimated the rise time of the source time function to be 5sec or less, based on the fact that the SP phase can be discriminated as a later phase from the initial P motion for a rise time shorter than 5sec.
The Parkfield earthquake of June 28, 1966, has been studied by many investigators (AKI, 1968; CLOUD and PEREZ, 1967; EATON, 1967; EATON et al., 1970; FILSON and MCEVILLY, 1967; HOUSNER and TRIFUNAC, 1967; TSAI and AKI, 1969). However, it has been recognized that an analysis on the basis of a direct comparison between the theoretical nd recorded accelerations ivery difficult, although it is expected to yield some information on the dynamical process of faulting. The purposes of the present work are to calculate the ground displacements for the semi-infinite and the infinite media and to com-pare them with the numerical results obtained by AKI (1968, 1972), with particular attention to the free surface effects on the wave forms of the seis-mograms. Another purpose is to determine the focal parameters on the dynamical process of faulting, on the basis of direct comparison of the theo-retical accelerations with the recorded one. SATO (1973) derived mathematical expressions, in a form pertinent for numerical calculation, of the seismic waves due to a shear fault in a multi-layered medium by the Cagniard-de Hoop technique. However, since these expressions for the multi-layered medium require a large amount of numerical computation, we do not refer to them in the present study. We lack complete mathematical models and sufficient data to determine the effective stress precisely. We have used ap-proximate faulting models recently proposed by BRUNE (1970), KANAMORI (1972) and IDA and AKI (1972) in order to determine the order of magnitude of the effective stress which generated this earthquake.

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2. Fault Geometry

To construct a fault geometry for the Parkfield earthquake, we first
summarize the results of the source studies obtained by previous investigators.
BROWN and VEDDER (1967) inferred the fault length L to be 30-40km. EATON

(1967) estimated the rupture velocity υc to be 2.2km/sec. FILSON and MC-
EVILLY (1967) determined L=30km, υc=2.2km/sec from a spectral analysis
of Love wave. EATON et al. (1970) supposed the vertical extension of the
fault to be 10km, based on the aftershock distribution as shown in Fig. 1.
TSAI and AKI (1969) estimated the seismic moment to be 1.4×1025 dyne・cm
from the spectral analysis of long period surface waves. SCHOLZ et al. (1969)
inferred the dislocation distribution to be 30cm over the fault from 4km to
10km in depth from the geodetic and surface wave data.

Fig. 1. Aftershock distribution on the reference fault plane. (Reproduced from a
paper by EATON et al. (1970)).

Following the above-mentioned investigations, the focal parameters are assumed in the present study as follows:

δ=90°: dip angle (vertical fault),
λ=-180°: slip direction (right lateral),
υP=6.0km/sec: P wave velocity,
υS=3・5km/sec: S wave velocity,
vc=2.2km/sec: rupture velocity,

μ=2.0×lO11 dyne・cm: rigidity,
L=30km: fault 1ength,
W=10km: fault width.

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3. The Recorded Acceleration and the Integrated Displacement

At the time of the Parkfield earthquake, the perpendicular (to the fault)
component (S65°W) of the acceleration was recorded at Cholame No.2 sta-

tion at 80m from the fault, while an accelerograph of the parallel component

(S25°E) was unfortunately inoperative. The characteristic period of the
functioning accelerograph is 0.064 second, magnification 1.0 and damping

coefficient 0.57. Because the characteristic period of the accelerograph is

very short, the seismic motions recorded in the period range greater than

about 0.1 second are approximately proportional to the ground accelerations.
The full record is reproduced in the papers of CLOUD and PEREZ (1967) and

HOUSNER and TRIFUNAC (1967). The component dealt with in the following

is this perpendicular one except when otherwise specified.

HOUSNER and TRIFUNAC (1967) and AKI (1968, 1972) obtained the inte-

grated ground displacement from the recorded acceleration. The integrated

ground displacement had the duration of about 1.5sec and a maximum ampli-
tude of about 30cm as shown in Fig. 2. This is tentatively considered as
"the observed ground displacement" in the next section
, where a comparison
between the observed displacement and theoretical one is made.

AKI (1968, 1972), further, calculated the theoretical ground displace-ments by integration of the formulae given by MARUYAMA (1963). From comparison between "the observed" and the theoretical ground displacements,

Fig. 2. Acceleration of perpendicular component and its velocity and

displacement iegrated from the recorded acceleration. (Repro- d uced from a paper by AKI (1972)).

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he determined the average dislocation over a fault to be 60-90cm, the rise
time 0.4-0.9sec, and the stress drop 20-100bars and ησ 2bars, where η is
the efficiency of seismic radiation and σ is the average of initial stress σ0 and
final stress σ1 along the fault.

In this calculation, AKI (1968) used a fault segment as shown in Fig. 3.
The fault length and the fault width are taken to be 2km and 3km, respec-

Fig. 3. A fault segment used in the calculation of theo-
retical seismograms. Fault length is 2km; fault
width, 3km. Rupture is assumed to propagate uni-
laterally from the north to the south with a constant
velocity υc=2.2km/sec.

Fig. 4. The theoretical ground displacements and accelerations for the infinite mdium.

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tively. Evaluating the distance dependence of seismic spectra, he proved that the contribution from the other fault segments is small, and that the effects of the fault width on the seismic spectrum is negligible at this short distance. In Fig. 4, the theoretical ground displacement and acceleration of the perpendi-cular component for an infinite medium with a fault length of 4km are com-pared to those with a fault length of 2km. From this figure, we find that the contribution to the perpendicular component from the segments other than that of Fig. 3 may be small and may not alter the dislocation and rise time estimates in the following sections to a large extent.

4. Theoretieal Ground Displacements

When we calculate theoretical ground displacements, the fault segment
of the same dimension as Aki's in Fig. 3 (fault length=2.0km, the vertical extension of the fault=3.0km) is used for the purposes of direct comparison with Aki's results and for economy of computation time. A numerical com-putation for the semi-infinite medium requires atime as much as twenty or

Fig. 5. Ground displacements ofeach component for a semi-infinite medium (solid) as compared with those for an infinite medium (broken).

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more times as that for the infinite medium. In the following, we assume that the results obtained for the above small segment hold for the faulting process of the other segment of the fault. For the numerical integration along the fault, the area of the fault element is taken to be very small when the element

Fig. 6. The ground displacements for a semi-infinite medium
for various rise times.

Fig. 7. The ground displacements for an infinite medium for various rise times.

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is located close to the station, in order to secure convergence of the numerical integration.

In Fig. 5, theoretical ground displacements for the semi-infinite medium (solid curves) and those for the infinite medium (broken curves) are illustrated. For the displacements for the infinite medium, the amplitudes are doubled as a simple correction fthe free surface effects. Units of the amplitudes of the theoretical ground displacements and accelerations are D0 and D0/secsec2, rspec-tively, in this and the following figures. D0 is the average dislocation over the fault. The time increment in these seismograms is taken to be 0.1/6.0 (=0.0167)sec, small enough to be differentiable twice. As is seen in Fig. 5, the free surface ffects are small and the doubling of the displacements for the infinite medium is an excellent correction for the free surface effects in this case, such as the fault motion of the vertical strike-slip tye.
In Figs. 6 and 7 is illustrated howthe wave forms change, as rise time t0 varies. For example, when t0=0.5sec, the maximum amplitude and the pulse width of the perpendicular component of the displacement are about 0.12D0 and 0.5sec, while they are 0.06D0 and 1.0sec when t0=1.0sec. AKI (1972) obtained a maximum amplitude of (0.13-0.14)D0 when t0=0.4sec.
The ground displacement at this short distance may be approximately
contributed from the shallower segment of the fault. Consequently, the esti-
mated value of the dislocation from the above data probably indicates the
maximum dislocation, Dmax, at the uppermost segment of the faulting area.
A comparison of the calculated displacements with the "observed one" yields
estimates of 0.5-1.0sec for the rise time t0 and 250-500cm for the maximum
dislocation Dmax. From this, we obtain the average dislocation D0 over the
fault to be 200-400cm through the relation D0=(π/4)Dmax of KNOPOFF (1958).
However, this value disagrees considerably much with the estimate of D0=
15cm or 30cm derived from the surface wave data (TSAI and AKI, 1969) and
geodetic data (SCHOLZ et al., 1969).

5. Theoretical Accelerations of the Ground Motion

The theoretical accelerations are found by numerical differentiations of
the ground displacements and are compared with the main part of the record-
ed acceleration shown in Fig. 8. In the following sections, a dot・over a
letter denotes differentiation with respect to time. Only the theoretical accel-
erations for the semi-infinite medium are used unless specified for the infinite
medium.

The removable strip method (LANCZOS, 1956) is used to compute the second derivatives. The derivative at any time is found by the analytical differentiation of the parabolic curve determined by the least squares method

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Fig. 8. Main part of the recorded acceleration.

from the 5-points. We repeat this again to obtain the second derivatives, i.e., accelerations.

Namely,

(1)

Theoretical accelerations are exhibited in Fig. 9 for various rise times from 0.5sec to 0.7sec. From the figure, a significant peak-to-peak correspondence of the theoretical accelerations with the recorded one (Fig. 8) is found, while wave forms do not show a good resemblance. The above correspondence yields an estimate of 0.5-0.7sec for the rise time. Since the maximum ampli-tude of the recorded acceleration is about 500gal, we obtain Dmax=65cm for

Fig. 9. Theoretical accelerations for the rise times 0.5, 0.6 and 0.7sec.

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t0=0.5sec and Dmax=90cm for t0=0.7sec. This yields an estimate of the average dislocation D0=50-70cm. The particle velocity of the fault motion D0/2t0 is evaluated to be 50cm/sec for the respective rise time estimates. If a source time function of the ramp type is assumed, the maximum amplitude of the theoretical acceleration is approximately proportional to D0/t0, as is seen in Fig. 9. Hence, when discussing the seismic acceleration near a fault, the rise time, which is strongly connected with the dynamical process of faulting, is very significant.

6. Check of the Method of the Numerical Differentiation

We check the error attributed to the numerical differentiation as shown
in Fig. 10. The respective curves are the accelerations found by the follow-ing methods:

the removable strip method as described by the formula (1)

(2)

(3)

(4)

The formula (2) is the primitive method and causes much short-period
noise. Formula (3) is the analytical second derivative of the parabolic curve
determined by the least squares method from 5-points. Formula (4) is the
Fourier transformation method. As is seen in Fig. 10, it is concluded that
the numerical differentiation does not cause such substantial disturbance to
the wave forms as to alter the estimate of 0.5-0.7sec for the rise time, while
the values of the maximum amplitudes may contain error within a factor of 2.
A variation of the wave form of the theoretical acceleration for various
rupture models is examined in Fig. 11. The graph (A) is the same as shown
in Fig. 9 for t0=0.5sec. The graph (B) is the acceleration for a fault model,
in which the rupture velocity has a downward component of υc=3km/sec.
The graphs of (C) and (D) are those for fault models, in which the top of the
fault is located at 50m and 100m in depth, respectively. From the graphs
of (C) and (D), it is found that the deeper the top of the fault is located, the
smaller the maximum amplitude of the acceleration. Therefore, a fault model
which has no dislocation distribution on a shallow portion of the fault as

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Fig. 10. Theoretical ccelerations found by various methods of the nu-
merical differentiation. Rise time is 0.5sec.

Fig. 11. Theoretical accelerations for various fault models.

presented by SCHOLZ et al. (1969) will never explain the large amplitude of the recorded acceleration.
From the above comparisons and considerations, we can conclude that the error caused by the numerical differentiation and the faulting models Can be neglected, except for the error of the maximum amplitude within a factor of 2.

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7. Source Time Function

In Section 4, it is pointed out that, in the near-source region, the rise time plays a great role in seismic waves. This fact suggests a possibility of finding the type of the source time function, due to the comparison of the synthetic acceleration with the recorded one.
We denote the free surface displacement and acceleration by u(t) and u(t), when the source time function is of a ramp type with a rise time t0. Then u(t) and u(t) are expressed by u0(t) and u0(t), functions not subject to the rise

time, through the following relation:

(5)

Displacement u(t) and acceleration u(t) for an arbitrary source time function D(t) are given by the following Duhamel (convolution) integral,

(6)

Illustrations (E) and (F) in Fig. 12 (in these figures, the rise time is fixed
at 0.5sec) show the accelerations for source time functions which rise sud-denly at the start and arrive at the final dislocation value smoothly as desig-nated at the right-hand side of the figure. (G) and (H) are those for the source time functions, the First derivatives of which are continuous. The wave forms presented in Fig. 12 have fewer peaks and do not give a satisfactory peak-to-peak correspondence with the main part of the recorded acceleration of Fig.
8. This fact indicates that the source time functions considered here are not proper for this earthquake, suggesting that the simple ramp function is a good approximation for the source time function of this earthquake. The theo-retical ground displacements for the cases of (A), (B), (G) and (F) are illus-trated in Fig. 13.

8. Effective Stress and Stress Drop

Recently, several investigators (BRUNE (1970) and others) developed mathematical models of crack, in order to estimate the effective stress which generates an earthquake. However, the source time function of their models are not of a ramp type and are inconsistent with the result obtained in the previous section. Moreover, OHNAKA (1973) pointed out, on the basis of the

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Fig. 12. Theoretical accelerations for various types of source time function. Source
time functions and their second derivatives are given at the right-hand side of
this figure.

results of laboratory experiments, that mathematical modelings of the crack
without consideration of the effect of friction on the rupturing process are invalid. Therefore, although we calculate the value of the effective stress
based on their models in this section, it is only a tentative value at this stage.

BRUNE (1970), taking deceleration by the effects of the edge of the dislo-
cation surface into account, gave a simple relation between D(t) and σe (ef-
fective stress) in the case of instantaneous crack with finite length 2a,

(7)

Averaging D(t) over a time a/υs, we have

(8)

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Fig. 13. Theoretical ground displacements for the cases of (A), (B), (G),and (F) in Figs. 10 and 11.

IDA and AKI (1972), considering the conditions that the dislocation dis-tribution over the fault is uniform except near the edges and that excessive stress concentration near the edges disappears, gave the following relation,

(9)

KANAMORI (1972), studying the deceleration effects of the stopping of the propagating front on the basis of the results of HANSON and SANFORD (1970) and Hamano (personal communication), derived the following relation,

(10)

Taking the values, μ=2×1011 dyne・cm-2, υs=3.5km/sec, υc=2.2km/sec,
D0/(2×t0)=50cm/sec, we have 45bars,25bars and 40bars from Eqs. (8),

(9), and (10), respectively. This leads to the possible range of the effective
stress,

σe=25-50bars. (11)

From a relation M0(1.4×1025 dyne・cm)=μD0LW(L=30km), we get W=
3.5-5km. From the formula (12) given in the paper of KNOPOFF (1958),

(12)

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we get
Δσ=25-50bars, (13)
for the estimate of the stress drop. If we fix W=10km following EATON et al. (1970), we get
Δσ=12.5-17.5bars. (14)

For the possible range of the stress drop, we get

Δ σ=10-50bars, (15)
taking uncertainty of the used value of the parameters into account.

9. Concluding Remarks

9-1. The focal parameters determined in the present work are listed in Table 1. However, the values connected with the dislocation estimate may contain an error within a factor of 2.

Table 1. Source parameters obtained in this study.

The average dislocation D0=50-70cm seems to be contradictory to the surface fracture of 5-10cm reported by BROWN and VEDDER (1967). It should be considered to be due to the soft, thin sediment layer, overlying the base-ment rock, as AKI (1968) pointed out. The fact that the large recorded ac-celeration is inexplicable without the large dislocation distribution (Dmax= 60-90cm) at the shallow segment on the fault is rather important.
9-2. The ramp function may be a good approximation for the source
time function.

9-3. Parallel (to the fault plane) and vertical components of the theo-retical acceleration computed by the focal parameters obtained in this study are presented in Fig. 14. The vertical component does not show a significant resemblance to the recorded one (see HOUSNER and TRIFUNAC, 1967). Since the amplitude of the acceleration of the vertical component is small and comparable with the short-period noise, the main feature of the acceleration controlled directly by the faulting may be hidden in the short-period noise.

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Fig. 14. Theoretical ccelerations of parallel and vertical com-ponents calculated bythe source parameters determined by this tudy. As D0/t0 is estimated to be 50cm/sec, the calcu-lated amplitudes of the acceleration of these components take the same values irrespective of the rise time estimate.

9-4. We obtain a maximum amplitude of about 7cm and a pulse width
of 0.5-1.0sec for the perpendicular component of the ground displacement if we use the values of the source parameters as listed in Table 1. The value of about 7cm remarkably disagrees with the estimated value of about 30cm of the integrated ground displacement obtained by HOUSNER and TRIFUNAC (1967) and AKI (1968). If we estimate the average dislocation D0 for this earthquake by this value of about 30cm, we obtain D0=250-500cm as dis-cussed in Section 4. Therefore, the estimated value of about 30cm seems to be too large for the perpendicular component of the ground displacement due to this earthquake.

Since the relative magnification of the operated accelerograph at the period 1-2sec is 0.004-0.001, the information included in this period range is presumed to be decreased too greatly. Therefore, it is suspected that the short period noise and a constant base line error might be magnified in the numerical integration fthe recorded acceleration with respect to time be-yond expectation. From these reasons, the integrated ground displacements in this case may not be good approximations for the true ground displace-ments.

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9-5. The theoretical maximum acceleration umax and the effective stress
σe are approximately proportional to D0/t0, if a source time function of a ramp type is assumed:

(16)

Therefore, asource study on the dynamical process in the near-source region is very important from the viewpoint of earthquake engineering.
9-6. The demerit of the direct comparison of the accelerations is that the error caused by the numerical differentiation of the theoretical ground displacements may be large and that the wave forms are easily disturbed by the minor process of rupturing. However, as indicated in the present work, for the acceleration recorded at the Cholame No.2 station, the above demerit can be eliminated and more extensive information on the dynamical process of faulting can be obtained by direct comparison, though it may include some uncertainty in the dislocation estimate.

9-7. All of the results in this study are derived under the assumption that the seismic waves for the semi-infinite mdium are good approximations for those in the multilayered medium partially including trans-sonic rupture

propagation. In order to analyse the record more exactly, further progress in the investigation fseismic waves in the multilayered medium as SATO'S (1973) is needed.

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