Dynamics of dip-slip fault rupture

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Abstract. This contribution summarizes our recent findings related to the dynamics of shallow dip-slip earthquakes, especially that of the asymmetric seismic motion in hanging walls and footwalls. First, by means of experimental dynamic photoelasticity and numerical finite difference simulations, dynamic rupture of a relatively large fault plane near a free surface is studied. It is found, for instance, that upon surfacing of the primary upward fault rupture, Rayleigh surface waves traveling outwards to the far-field and Rayleigh-type interface waves moving downwards back to the source can be induced. For an inclined fault plane, these Rayleigh and interface waves can interact with each other in the hanging wall to produce a “corner” shear wave with concentrated energy and thus the asymmetric seismic motion. Then, instead of considering only one single large-scale fault plane, more geometrically complex dip-slip faults that consist of damage zones with sets of smaller-scale parallel cracks are examined. The photoelastic study shows that depending on the dip angle, the rupture behavior may differ considerably. For a larger dip angle, secondary and further downward ruptures can be initiated, arrested and resume dynamic movement even without additional external load, seemingly due to the dynamic waves caused by the primary upward rupture.

1. Introduction
In our contribution to ARMS10 in 2018 [1], through dynamic investigations into some instances of enigmatic earthquake-related structural failures, possible crucial mechanical roles of higher-frequency seismic waves over 1 Hz have been pointed out. Here, based on our earlier discussion at ARMS8 [2], another enigma in earthquake dynamics, namely, the asymmetric seismic motion near a rupturing shallow dip-slip fault plane, is treated. Generally, the ground motion experienced on the hanging wall is much stronger than that on the footwall, but the mechanics behind this asymmetry has not been fully clarified yet. In addition to the 1976 Friuli, Italy, earthquake [3] that caused an “unexpected” structural failure pattern in the epicentral region [1], examples of asymmetry include the 1971 San Fernando and the 1994 Northridge earthquakes in California, the United States [4] and more recently, the 2008 Iwate-Miyagi Inland [5] and the 2014 Nagano-ken Hokubu (Kamishiyo Fault), Japan, earthquakes.

In the Nagano case with the moment magnitude $M_w$ 6.3, the main seismic rupture started at a shallow depth of 5 km, and the hanging wall on the east side of the fault plane shifted upwards with regard to the footwall on the west side. The dip angle of the fault plane is estimated to be in a higher range (40-70 degrees), and the seismic inversion of the main shock together with the aftershock foci distribution indicates that the ruptured fault plane is almost vertical near the hypocenter of the main shock. If the dip-slip fault plane is nearly vertical, then, the seismic motion in the hanging wall and in the footwall should be roughly of the identical level. The seismological recordings of the National
Research Institute for Earth Science and Disaster Prevention KiK-net, however, show that the peak ground acceleration, PGA, on the hanging wall at the Shinshuushin station with the epicentral distance of 19 km is 185.8 gal (1.858 m/s²) whereas PGA on the footwall at the Ohmachi-C station with the approximately same epicentral distance of 20 km is 74.4 gal (0.744 m/s²). Although the station on the footwall is located closer to the surface trace of the fault system, the ground acceleration recorded on the hanging wall is about 2.5 times as large as that on the footwall [6].

In this contribution to ARMS11, some findings associated with the dynamics behind the asymmetric seismic motion, obtained by dynamic photoelastic experiments and finite difference simulations in the two-dimensional framework, are briefly mentioned. Firstly, through the study for dynamic rupture of a relatively large, vertical or inclined fault plane near a horizontal free surface, it is shown that Rayleigh-type waves induced upon surging of the primary upward fault rupture play a decisive role in the generation of the asymmetric motion. Secondly, ruptures of more geometrically complicated dip-slip faults with damage zones represented by sets of relatively smaller-scale parallel cracks are considered under the condition of quasi-static horizontal external tension. It is indicated that the rupture development depends strongly on the dip angle, but in general, after upward extension of the primary rupture, the secondary rupture can be initiated on the horizontal free surface of the hanging wall at a remote distance from the primary one, and the secondary and further ruptures can propagate downwards into depth, even without the action of additional external loading.

2. Large-scale dip-slip fault planes at shallow depths

2.1. Corner waves induced by geometrical asymmetry

In order to observe the dynamic dip-slip fault rupture at a laboratory scale and investigate possible mechanisms to generate the asymmetric seismic motion, a series of dynamic photoelastic rupture experiments are conducted using monolithic, transparent, birefringent and linear elastic polycarbonate plates (thickness 10 mm). In each plate that is mechanically fixed at both ends, a pre-cut but welded interface modeling a geological fault plane dipping either 90 (figure 1(a)) or 45 (figure 2(a)) degrees is prepared. The material properties of the polycarbonate plate, mass density 1,200 kg/m³, shear modulus 786 MPa and Poisson’s ratio 0.38, give the longitudinal (P), shear (S) and Rayleigh surface (R) wave speeds roughly as \( V_p \approx 1,840 \text{ m/s} \), \( V_S \approx 810 \text{ m/s} \) and \( V_R \approx 760 \text{ m/s} \). Dynamic rupture is initiated by a spherical projectile (diameter 6 mm, mass 0.2 grams) that is launched by a gun and impinging at an average speed of 83 m/s upon the bottom of the single, relatively large-scale fault plane. Time-dependent development of ruptures and waves is observed at a frame rate of 75,000 fps (frames per second) with a high-speed camera (384 × 224 pixels for this frame rate), Photon FASTCAM SA5.

Figures 1(b)-(d) and 2(b)-(d) are experimentally obtained snapshots showing the dynamic wave fields associated with dip-slip faulting near a free surface. The isochromatic fringe patterns or contours of the dynamic maximum in-plane shear stress in the figures indicate that the rupture tip propagation speed \( V_r \approx 1,600 \text{ m/s} \) (figure 1) or 1,400 m/s (figure 2), is at a “supershear” (transonic) level, i.e. it is larger than the S wave speed \( V_S \) but smaller than the P wave speed \( V_P \) (\( V_R < V_S < V < V_P \)). Here, the upward rupture front waves developing near the moving tip of the fault rupture run also at a supershear speed and they form Mach cones, sometimes called “shock waves” or Mach waves (figures 1(b) and 2(b) at relative time 0 µs). Then, strong Rayleigh-type interface (I) waves, totally separated from the rupture front Mach waves, propagate also upwards along the ruptured fault plane (figures 1(c) at time 80.00 µs and 2(c) at 93.33 µs), and at a later stage, four Rayleigh-type waves may be generated (clearly visible in figures 1(d) at 160.00 µs). Two of them move as outward R waves into the opposite directions along the top horizontal free surface to the far-field, and the other two downward I waves travel back into depth along the ruptured fault plane. For the geometrically symmetric vertical fault plane, the dynamic wave pattern is always symmetric (figure 1(d)). For the asymmetrically inclined fault plane, the dynamic stresses induced in the hanging wall and in the footwall may be completely different (figure 2(d) at 226.67 µs). The interaction of the outward R wave with the downward I wave gives a specific “corner” (C) shear wave only in the hanging wall. The C
Figure 1. (a) Dimensions of a specimen having a single, vertical dip-slip fault plane [unit: mm]. (b)-(d) Experimentally taken photographs of the dynamic isochromatic fringe patterns that are generated by supershear (transonic) rupture of the fault plane (modified after [6]).

Figure 2. (a)-(d) Same as figure 1, but for a specimen with an inclined fault plane [unit: mm]. (e) Numerically generated asymmetric distribution of velocity vectors associated with the subsonic rupture of an inclined fault plane. Calculations are performed without loss of generality by assuming the normalized $V_P$ being 1 and Poisson’s ratio 0.25 as well as by setting $201 \times 201$ orthogonal grid points with uniform grid spacing $\Delta x = 0.05$ and time step equal to $\Delta x/(2V_P)$. The energy absorbing boundary conditions prevail on the outer boundaries except for the top horizontal free surface (modified after [6]).
wave, carrying intense kinetic energy, induces strong seismic motion in the hanging wall. On the contrary, the mechanical interaction of the outward R wave with the oppositely moving I wave in the footwall is very small so that the dynamic disturbance becomes weak in the footwall. Figures 1 and 2 unambiguously show the presence of the C and downward I waves and the symmetric and asymmetric dynamic wave fields induced by dip-slip fault ruptures.

The presence of the C wave can be confirmed also numerically by finite difference simulations with the second order spatiotemporal accuracy. For example, figure 2(c) illustrates the numerically estimated particle movement related to the subsonic fault rupture (more exactly, sub-Rayleigh rupture, i.e. \( V = 0.4 \, V_P \approx 0.69 \, V_S \) and \( V < V_R < V_S < V_P \)) in a homogeneous, isotropic and linear elastic material. The dynamic rupture is initiated at depth 2 and reaches the free surface. Here at normalized time 5.1 after rupture initiation, in the footwall, the well-known classical particle movement of elastic waves is recognized: P wave with motion parallel to the propagation direction, S wave with shear movement perpendicular to the direction of propagation and R wave with retrograde particle motion on the horizontal free surface. In the hanging wall, the particle movement is much more complicated and non-classical. Inside the C wave, large shearing movement can be clearly identified, and the associated radical change of the directions of particle motion generates large stresses in the hanging wall. The particle movement in the corner of the hanging wall behind the C wave can become very large and strong seismic motion can be experienced behind C. The P and S waves generated in the footwall upon fault surfacing appear to be relatively strong, but actually they are much weaker than the C wave in the hanging wall. Hence, the generation of the asymmetric seismic motion related to shallow dip-slip faulting may be mechanically well explained for an inclined fault plane [2, 6].

2.2. Asymmetric dynamic rupture in a symmetrically layered medium

In the above section, geometrical asymmetry is needed for the generation of the asymmetric seismic motion. In this section, it is shown that also a geometrically symmetric vertical fault model can cause asymmetric motion if the primary upward rupture can be deflected at a horizontal interface between layers of a stratified medium. Although the primary fault rupture in an ordinary seismological model is assumed to penetrate an interface between layers and move further into the adjacent geological layer without producing secondary ruptures along the interface, deflected ruptures are accepted in the field of fracture mechanics, numerically as well as experimentally. A simple experimental example is shown below.

In figure 3(a), in addition to a welded vertical interface modeling a fault plane, the polycarbonate plate (thickness 10 mm) has a horizontal interface between the top layer and the so-called seismic basement. The horizontal interface is unbonded but compressed by the gravitational force. The whole plate is fixed at the ends and a projectile impinges upon the bottom of the vertical fault plane. The snapshots (now 448 x 384 pixels) taken at a frame rate of 40,000 fps (figure 3(b)-(d)) with the same high-speed digital video camera show that first, strong I waves, induced by the primary rupture, propagate upwards (seen in figure 3(b) at relative time 0 μs). Then, at time 50.00 μs (figure 3(c)), on the dynamically compressive right side (rising hanging wall) of the vertical fault plane, one of the I waves is transmitted from the lower basement across the non-welded but contacting interface. On the other hand, on the dynamically tensile left side (relatively subsiding footwall), the other I wave is completely reflected at the possibly separated interface. At time 75.00 μs (figure 3(d)), the I wave in the top layer is recognizable also on the left side, but its amplitude is by far smaller than that of the I wave on the right side. Figure 3(d) also indicates that much of the kinetic energy originally conveyed by the incident upward I waves is reflected at the unbonded horizontal interface and the reflected downward I waves traveling along the ruptured fault plane as well as the outward I waves moving along the horizontal interface can be identified on each side of the vertical fault plane. Nevertheless, an asymmetric wave field can be generated in this geometrically simple symmetric model. The experimentally observed dynamic rupture pattern can be reproduced by finite difference calculations [6]. The combination of the mechanisms mentioned in the previous and current sections suggests that even a fault plane having a larger dip angle like the Kamishiro Fault can induce asymmetric motion.
3. Dip-slip faults consisting of damage zones with sets of smaller-scale parallel cracks

In the last chapter, each model is assumed to have a single large-scale fault plane that produces only one single seismic event at one time. However, with these models, it is hard to study the dynamics of an earthquake swarm or a cluster of earthquakes, or to understand, for example, the generation of the 2016 Kumamoto, Japan, earthquakes that virtually consist of two main shocks, the first one ($M_s$ 6.2 at 9:26 pm JST on 14 April) immediately followed by the stronger second one ($M_s$ 7.0 at 1:25 am JST on 16 April). Possibly more sophisticated dynamics and a more detailed local look at smaller-scale ruptures are required for comprehending the real complex seismic events. In this chapter, therefore, rupture development in a dip-slip fault damage zone with sets of pre-existing smaller-scale parallel cracks is traced.

Experimentally, using a digitally controlled laser cutter, transparent birefringent polycarbonate specimens having smaller-scale parallel cracks located in a staggered fashion are prepared. Quasi-static tension acting parallel to the free surfaces of each specimen is externally applied by a tensile testing machine at a prescribed constant strain rate. By changing the distribution patterns of the initial cracks and their dip angles, the evolution of the primary ruptures as well as the initiation and development of the secondary and further ruptures are observed with the high-speed digital video camera at a frame rate of 50,000 fps (440 × 192 pixels). Figure 4 shows typical results for a specimen of thickness 2 mm with a set of vertically dipping smaller-scale cracks (figure 4(a)). In this case, after surfacing of the primary upward rupture, which means after a total split of the specimen into two by the primary rupture, the rupture jumps on the top free surface and the secondary downward ruptures start moving from remote positions. Then, the secondary ruptures abruptly stop propagating. However, one of them is astonishingly reactivated and resumes its dynamic propagation, here, after 200 μs of arrest (figure 4(b)). As seen here, the rupture development in this vertically dipping fault damage zone is basically composed of three distinct stages (figure 4(c)): (1) Propagation of the primary upward rupture; (2) initiation and arrest of the secondary downward ruptures at remote places; and (3) reactivation of (one of) the secondary downward ruptures after a temporal interval. Since no additional external load is exerted to the totally split specimen after the penetration of the primary rupture, the secondary and ensuing delayed ruptures, or a cluster of ruptures, are apparently owing to the dynamic, primary rupture-induced waves [7, 8].

![Figure 3](image-url)

**Figure 3.** (a) Dimensions of a layered specimen [unit: mm]. (b)-(d) Experimentally obtained isochromatic fringe patterns are totally asymmetric although the geometry and loading conditions for the dynamic rupture are (anti-) symmetric (modified after [6]).
Figure 4. (a) Dimensions of a typical specimen with a set of pre-existing smaller-scale cracks that models a vertically dipping fault segment with a damage zone near a free surface [unit: mm]. (b) Rupture development in the specimen subjected to uniaxial tension with a constant strain rate $1.3 \times 10^{-2}$ /s. (c) Dynamic rupture behavior. (d) Numerical simulations indicate the crucial roles played by the primary rupture-induced waves in the evolution of a cluster of ruptures (modified after [8]).

Figure 5. Rupture development in specimens having multiple smaller-scale inclined but parallel cracks and subjected to quasi-static uniaxial tensile loading with a constant strain rate $1.2 \times 10^{-2}$ /s. Normal faulting with a dip angle of (a) 60 or (b) 40 degrees is modeled (modified after [8]).
The important roles of the primary rupture-induced waves in the dynamic rupture development may be confirmed again by numerical finite difference simulations. For instance, for visual clarity, figure 4(d) shows the influence of the waves induced by the primary rupture in a geometrically plain specimen having smaller-scale cracks only on the line of the primary rupture. The analysis is performed by setting $1,201 \times 361$ orthogonal grid points with uniform grid spacing $\Delta x = 0.125$ mm and time step equal to $\Delta t/(2V_p)$ for a homogeneous, isotropic and linear elastic polycarbonate specimen used here (now, mass density $1,200 \text{ kg/m}^3$, shear modulus $820 \text{ MPa}$ and Poisson’s ratio 0.37, i.e. $V_p \approx 1,820$ m/s, $V_s \approx 830$ m/s and $V_R \approx 780$ m/s). The primary rupture propagates at an experimentally recorded sub-Rayleigh speed of 563 m/s from the bottom free surface to the top one. In figure 4(d) where contours of the maximum in-plane shear stress, normalized with respect to the quasi-statically applied constant uniform tensile stress, are shown, the rupture front waves can be clearly recognized. Also, the reflection of the primary rupture-induced body waves gives regions of amplified stresses near the top horizontal free surface at remote positions from the primary rupture. In these regions of stress amplification, the secondary rupture may be initiated. Additional simulations indicate that upon a total split of the specimen by the primary rupture, outward $R$ waves traveling along the top free surface are produced. Once these $R$ waves reach the edges of the specimen, they are reflected and then diffracted to generate further ruptures at a later stage. More precisely, the $R$ waves can propagate along the already broken surfaces of the secondary ruptures and control the reactivation of the arrested secondary ruptures [7]. In this way, the rupture development is dynamically governed by the rupture-induced waves.

Figure 4 illustrates spatiotemporally complex rupture evolution in a fault damage zone with multiple smaller-scale cracks. The observed local up-/downward and instantaneous/delayed ruptures cannot be imagined simply by following the global stress-strain curve with one sharp stress drop that is obtained by a testing machine. Further experiments show that in the case of a larger dip angle, the rupture development may be dynamic and akin to the vertically dipping case while in the case of smaller dip angles the primary rupture tends to evolve rather quasi-statically, linking pre-existing smaller-scale cracks gradually one after another. The former case with all smaller-scale parallel cracks having a dip angle of 60 degrees except for the vertical slits on the free surfaces is depicted in figure 5(a). First, the primary upward rupture (1) dynamically connects the pre-existing inclined cracks and then, the secondary downward rupture (2) propagates in the hanging wall, followed by the third downward rupture (3). The rupture development looks similar to the vertically dipping case in figure 4, but here, both primary and secondary ruptures are arrested halfway and only the third rupture reaches the free bottom surface of the specimen. That is, all three ruptures may dynamically radiate seismic waves into the far-field. In the latter case with a smaller dip angle of 40 degrees, the rupture evolution is totally different. In figure 5(b), the primary upward rupture (1) moves relatively slowly in a quasi-static fashion, connecting the pre-existing cracks intermittently and possibly causing an earthquake swarm with smaller magnitudes. This gradually evolving primary rupture is arrested well below the top free surface. Then the system loses its mechanical stability and the secondary downward rupture (2), initiated in the hanging wall, can propagate dynamically. In light of seismic waves, the secondary rupture emits much more kinetic energy into the far-field in a temporarily shorter period and will be practically more important than the slowly evolving primary one with a much less amount of wave radiation [8].

As mentioned here, the primary rupture development can be either quasi-static or dynamic. According to the additional experimental investigations, whichever occurs seems to be more largely governed by the initial crack distribution pattern, but the criticality of the existence of sets of smaller-scale cracks in generating a cluster of subsidiary ruptures or an earthquake swarm remains unchanged.

4. Conclusions
In order to clarify the mechanics related to the asymmetric dip-slip seismic motion in the two-dimensional framework, the techniques of experimental dynamic photoelasticity and numerical finite
difference simulations are employed. First, dynamic rupture of a relatively large, vertical or inclined fault plane is investigated near a horizontal free surface in a monolithic linear elastic medium. It is shown that upon surging of the primary fault rupture, not only the Rayleigh surface waves moving along the free surface to the far-field but also Rayleigh-type interface waves traveling back downwards along the ruptured fault plane may be generated. If the fault plane is inclined and the geometry considered is asymmetric, the mechanical interaction of Rayleigh surface and interface waves is possible in the hanging wall, which can induce a corner wave with intense energy and larger dynamic disturbances only in the hanging wall. As a result, the asymmetric seismic motion is found. The symmetry of seismic motion can be more simply broken, even in geometrically symmetric cases, if rupture takes place in a layered medium and the secondary interface rupture is allowed between layers. Then, rupture of more realistically complex dip-slip faults with damage zones is investigated. The damage zones consisting of sets of smaller-scale parallel cracks are subjected to quasi-static horizontal external tensile loading. The photoelastic experimental photographs taken for different dip angles show that the primary upward rupture can develop either quasi-statically or dynamically, but normally the secondary downward rupture is initiated at a distant position from the primary one on the top free surface of the hanging wall. Surprisingly, for a larger dip angle, the initiation, arrest and resumption of dynamic movements of the secondary and ensuing ruptures occur even without additional external load, and apparently the dynamic waves induced by the primary upward rupture cause this cluster behavior.

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