Particle motions in a physical model of shallow angle thrust faulting

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Abstract. A physical model of thrust faulting has been constructed out of elastic foam rubber. The thrust wedge has an angle of 25°, and is forced from the back by a steel-hydraulic system of effectively infinite rigidity, analogous to the force exerted by tectonic plates. The observed particle motions show many features different from those commonly assumed in dislocation models of subduction thrusts. Interface waves associated with fault opening propagate along the thrust plane (from the back) and temporarily decouple the overlying hanging wall plate from the foot wall. Because of the geometry of the reflecting fault boundary, and the free surface (also reflecting), energy is trapped in the wedge and, as a consequence, the particle motions and energy in the hanging wall are much greater than in the foot wall. The interface wave and the energy trapped in the upper plate propagate up the wedge and break out at the toe of the thrust with a spectacular increase in motions.

If this model is analogous to the real earth, it suggests that some common assumptions in dislocation modeling may be incorrect. The model may explain apparent missing energy radiated to teleseismic distances, the anomalously low number of empirical Green's functions needed to model teleseismic *p* waves, and the evidence of intense shaking on the hanging wall toe of some thrust fault earthquakes. The results support the suggestion that interface waves may explain the lack of high frictional heat generation from thrust faults, and may explain the 'paradox of large overthrusts'. The results also suggest that the seismic hazard of great subduction thrust earthquakes and continental shallow angle thrust faults might in some cases be seriously underestimated.

Keywords. Seismic hazard; thrust faults; strong motion.

1. Introduction

Shallow angle thrust faults are responsible for by far the greatest amount of energy and moment release of all the earth's fault types. These great earthquakes are caused by convergence of tectonic plates. In most cases, the thrust faults outcrop under the ocean and can cause devastating tsunamis. Only around India do great subduction thrusts outcrop on land. In numerous other regions of the world relatively shallow angle thrusts cause major damaging earthquakes on land.

Puzzling from a mechanical point of view is the geological evidence of large nearly horizontal continental overthrusts which have moved more or less coherently hundreds of kilometers. The mechanical explanation for these has been the source of much speculation, since the coefficient of friction would seem to prevent such movements. The force necessary to overcome friction would result in crushing of the overlying plate (Oldham 1921; Hubbert and Rubey 1959; DeBremaecker 1987; Price 1988). Several authors seized on the explanation that, if the whole plate could not move at once, then it must move in wrinkles or dislocation bands so that only a small band of the plate was being moved at any one time (Oldham 1921; DeBremaecker 1987; Price 1988) but no clear mechanism for accomplishing this was described. Oldham (1921) thought that

wrinkles might exist on the underlying footwall plate. Price 1988 thought that geological evidence indicated dislocation bands fracturing the overlying footwall plate.

Hubbert and Rubey (1959), on the other hand, suggested that the friction force was reduced by fluid pressure on the fault, in effect lifting the upper plate with water under super-hydrostatic pressure (near lithostatic). Birch (1961) criticized this solution, and Birch's statements were critically analyzed by Raleigh and Griggs (1963) who concluded they were not fatal criticisms. Although the Hubbert-Rubey explanation became widely accepted, it is nearly impossible to directly test, and others have tried to revive the dislocation band hypothesis (DeBremaecker 1987; Price 1988). A related paradox is that there is evidence of low frictional heat generation by subduction thrusts (Ziagos *et al* 1985; Furukawa and Uyeda 1989; Molnar and England 1990, 1995; Kao and Chen 1991; Tichelaar and Ruff 1993; Hyndman and Wang 1995), in spite of the fact that subduction thrusts represent such huge amounts of geologic slip.

There is essentially no accelerogram data base for predicting ground accelerations for major shallow angle thrust faults which outcrop on land (e.g., in India). There are indications from non-instrumental observations that accelerations from thrust faults can be very high. Oldham (1899) reported observations of boulders and fence posts being ejected out of their seats, and argued that this implied that ground accelerations must have exceeded 1 g. Nason (1973) used observations of strong ground shattering to suggest that energy was trapped in the hanging wall of the 1971 San Fernando earthquake.

Energy estimates from major earthquakes have been problematical, and the amount of energy estimated to be radiated to teleseismic distances has been much less than expected, based on current modeling using the dislocation theory (Winslow and Ruff 1995; Choy and Boatwright 1995). Similarly, Heaton and Hartzell (1989) found that they needed only about one-third the expected number of empirical Green's functions to explain the teleseismically radiated high frequency energy.

2. Foam rubber model

To better understand the dynamics of thrust faulting, we have constructed a foam rubber model with thrust fault geometry (wedge angle 25°, figure 1). Foam models of fault slip have been constructed in several previous studies (Brune *et al* 1990, 1993; Anooshehpour and Brune 1994). The main characteristic of these models which makes them important for earthquake modeling is that they can represent whole-fault-scale dynamic and geometrical effects, which obviously cannot be modeled with small samples of rocks.

One of the most interesting discoveries to come from foam rubber modeling was the existence of interface waves which reduce the normal stress and cause local fault opening (Brune *et al* 1993; Anooshehpour and Brune 1994). Brune *et al* (1993) suggested that interface waves could explain the heat flow paradox, the anomalous radiation of *p*-wave energy, and the paradox of large overthrusts. Anooshehpour and Brune (1994) confirmed that interface opening significantly reduced frictional heat generation on the fault surface. Mora and Place (1994, 1995) modeled the geometry of the foam block experiment using a numerical lattice model and confirmed that such interface opening waves could exist in the lattice model. Brune *et al* (1993) found that when an upper rectangular foam block was pushed from the end, and the upper surface left free

Figure 1. Diagram of the foam rubber thrust model. Dimensions are given in text. Photographs of motion of the interface and toe of the model are shown in figures 2 -5 (from the opposite side).

(asymmetric model), the upper fault surface moved much farther than the lower. They suggested that since this geometry was similar to that expected for thrust faults, similar motions might be characteristic of thrust faulting, and might explain the paradox of large overthrusts.

2.1 Description of the foam rubber thrust model

The intent of the present study was to investigate the large scale dynamic and geometrical effects in a foam rubber model with the geometry close to the expected for shallow angle thrusts. The geometry of the foam thrust model is shown in figure 1. The wedge angle of 25° is close to that typical of many shallow angle thrusts (as distinct from steeper angle reverse faults). The dimensions of the lower block are $97''L \times 73''W \times 34''H$, and those of the upper block $73''L \times 72''W \times 32''H$. The plate force is approximated by a stiff plywood board at the back of the wedge forced by a steel hydraulic piston, which is effectively infinitely rigid compared to the rigidity of the foam model, so that there is no dynamic interaction between the model and the piston. Fault slip (dislocation) typically initiates near the back of the fault surface and propagates to the front. A distribution of sizes of events occurs, but most of the slip is accomplished by periodic large events which result in the forward part of the upper block bounding forward a few centimeters.

2.2 Particle motions

Near the back of the thrust, near the forcing board, the initial rupture characteristics appear to be similar to those reported earlier for the pure shear-strike slip case, the slip pulse accelerating from the nucleation point and developing fault opening during slip. However, rather than maintain approximately the same dimensions, the opening slip pulse grows in dimension and amplitude (both opening and shear amplitude), primarily by increased motion in the upper block. Thus the fault motion rapidly becomes asymmetric. The effect of the fault opening is to make the fault surface opaque to seismic energy, and thus trap the energy released in the upper plate, and concentrate the

Figure 2. Superimposed video frames, 1/30 second apart, of interface wave on the fault surface passing from right to left. Lines and dots are 5 cm apart. The opening of the fault is indicated by the dark space between surfaces.

energy as the rupture moves forward towards the toe of the thrust. This results in a strong increase in the amplitude of motion of the upper plate, and spectacular breakout motions as the rupture reaches the free surface.

These effects are shown in figures 2 through 5. In each of these figures two successive frames of a video are superimposed (1/30 sec apart), so that the difference in position approximately corresponds to the particle velocity. The dimensionless volume shear strains away from the fault are about 10^{-2} , whereas-corresponding strains in the earth are about 10^{-4} . Thus only relative strains are strictly comparable to thrusting in actual earthquakes (since the strains in the model are greatly amplified relative to those in the earth). The block markers with coloured dots at the fault surface are 5 cm apart.

Figure 2 shows the opening slip pulse at about the middle of the wedge. The opening of the fault surface is clearly visible. The first frame shows the pulse coming in from the right, and the second frame shows it leaving the frame to the left. It is obvious from the difference between the two video frames that the upper fault surface has moved a much greater distance than the lower fault surface. Figure 3 shows the slip pulse approaching the free surface. It has raised the free surface (i.e., ground surface) away from the fault surface, but has not yet ruptured to the edge. The slip from the previous event left the surface slightly displaced (hanging wall over foot wall). Figure 4 shows an amplified view of the upper block leaping forward between the two frames. Point 2 (blue dot) on the upper block has moved about 8 cm forward and up, while points 9 and 10 on the lower block have rebounded about 1 cm (backward and up). Figure 5 shows an example of the spectacular particle motion as the fault breaks out at the surface.

Figure 3. Like figure 2, but showing rupture approaching the free surface.

Numerous reruns of the experiment were carried out. In each case there was a distribution of event sizes, but most of the slip was accomplished by the large characteristic events with particle motions similar to those shown in figures 2–5. The main characteristics of the particle motion important to understanding the slip mechanism are: (1) The slip starts more or less symmetrically with a form similar to that reported in previous studies of stick slip in symmetric (strike slip) models; (2) As the dislocation moves forward, the amplitude of motion of the upper fault surface increases rapidly, both for fault parallel motion, and opening motion; (3) The relative amount of motion of the upper block becomes much greater than that in the lower block, so that a relatively small amount of energy is radiated downward; (4) The energy in the upper plate becomes highly concentrated near the tip of the upper plate, resulting in intense shaking at the tip.

2.3 Comparison with dislocation theory

Essentially all of the recent studies of earthquake energy radiation and seismic hazard have assumed the dislocation theory as the basic mathematical framework (e.g.,

Figure 4. Like figure 2, but showing the toe of the fault leaping forward and upward about 8 cm.

Figure 5. Like figure 2, but showing snapping of the toe of the fault as the rupture intersects the free surface.

Heaton and Hartzell 1989; Cohee *et al* 1991; Winslow and Ruff 1995; Choy and Boatwright 1995). There are drastic differences between the pattern of strains and particle motions found in the foam rubber model and those assumed for dislocation modeling. In the dislocation theory: (1) The same dislocation time function is assumed for the lower plate as for the upper plate (e.g., Heaton and Hartzell 1989); (2) The fault plane is assumed transparent, so that waves reflecting off the free surface pass through the fault to teleseismic distances; (3) The point source response immediately above and below the fault surface is assumed the same, i.e., the Green's function is assumed to be continuous across the fault surface (see Aki and Richards 1980). The motions in the foam rubber model are so different than those typically assumed in dislocation modeling that if the foam model is analogous to the real earth, the consequences for earthquake hazard might be quite severe.

3. Discussion

3.1 Energy radiation and ground motions

Although rough estimates of energy from earthquakes are provided by the classic results of Gutenberg and Richter (Gutenberg 1956), only with the advent of modern instrumentation has a relatively accurate estimate of energy been available from teleseismic records. Results from many earthquakes suggested that the energy radiation estimated from teleseismic recordings was considerably smaller than predicted by the Gutenberg-Richter energy relationship (Winslow and Ruff 1995; Choy and Boatwright 1995). On the other hand, estimates of energy based on near-source recordings tended to give radiated energy estimates comparable to or larger than expected from the Gutenberg-Richter relationship (Smith *et al* 1991; Zuniga 1993; Haddon 1996). In the Choy and Boatwright (1995) study the apparent stress, proportional to the ratio of energy (determined teleseismically) to moment, was found to be about ten times lower for thrust faults than for strike slip faults. They suggested that their results indicated a fundamentally different mechanism for thrust faults and strike slip faults. Heaton and Hartzell (1989) found that in modeling large subduction zone earthquakes using smaller earthquakes as empirical Green's functions, that they needed only about one third the number that would be necessary for the sum of the moments of the smaller events to match the moment of the larger event. These observations may be explained by the foam rubber model, since the fault slip and fault slip velocity in the lower block is much less than for the upper block. Conversely, more energy is trapped in the upper block to contribute to strong ground motion.

3.2 Intense shaking and damage on the upper plate of thrust faults

Oldham (1899) in his classic study of the 1897 Indian earthquake, documented evidence of extreme shaking, including pebbles bouncing around on the ground "like peas on a drumhead," posts shot out of their holes, and boulders lifted out of the ground without cutting the edges of their former seats (see Richter 1958). Oldham (1899) argued that this was convincing evidence that the ground acceleration exceeded that of gravity. Although many have been skeptical of this conclusion, there has never been a clearly established alternate explanation. Nason (1973) noted that the San Fernando earthquake

of 1971 produced very strong seismic shaking on the hanging wall block of the fault. This evidence included accelerations of over 1 g recorded on the Pacoima Dam station and marked surface geologic effects such as landslides, soil cracking, and shattered earth (Barrows *et al* 1971; Nason 1973). Nason (1973) suggested that the wedge of the upper thrust block “might partially ‘trap’ seismic wave energy and cause a concentration of seismic energy near the tip of the wedge”. It appears that the foam rubber model displays precisely the mechanism suggested by Nason (1973), although the effects are probably considerably more pronounced in the model because of the shallower dip (25° vs. 45°). Several strong motion records with ground accelerations of over 1 g have now been obtained from thrust faults. It seems quite likely that the mechanism observed in the foam rubber model may have contributed to these high accelerations.

In many cases the ‘toe’ of the thrust is either buried by sediments (blind thrusts) or covered by water. Also, for many geological overthrusts the toe of the thrust fault steepens near the point of outcrop, and this can effect the dynamics of rupture (Raleigh and Griggs 1963). The effect of overlying sediment cover in typical blind thrusts could damp the spectacular breakout phase observed in the foam rubber, but it is not clear what the combined effect of sediment attenuation and ground motion amplification would be.

3.3 *The paradox of large overthrusts*

The mechanism observed in the foam rubber model may be important in explaining the paradox of large overthrusts. These overthrusts occur on very nearly horizontal thrust planes. To verify that the mechanism for reducing friction would be operative in this type of geometry, a strip of foam rubber 5.5 inches thick, 82 inches long, and 12 inches wide was forced by the piston to slide horizontally over a large block of the same material. The slip was accomplished by a series of buckle-like plate waves similar to those observed in the 25° thrust model. It was a regularly repeating mode of slip which allowed the upper block to move steadily to the limits of the model. The force required was much less than would have been required to slide the strip if the upper block had been forced to slide in complete contact. Since most of the geological evidence for large thrusts which have moved the upper plate hundreds of km comes from faults that are now seismically dead and exhumed, it is not certain whether most of them were seismically active or slipped quasi-statically (perhaps because of high pore pressure on the fault), or whether they slipped in large earthquakes, or numerous smaller ones. It seems quite possible that the paradox of large overthrusts might be in part explained by a combination of either wrinkle-like fault openings or reductions in normal stress in analogy with this long thin foam rubber block model.

3.4 *Heat flow from shallow angle thrusts*

Most studies of heat flow above shallow angle thrusts at continent-ocean boundaries indicate low frictional heat generation by the seismogenic part of the thrust fault (Ziagos *et al* 1985; Furukawa and Uyeda 1989; Molnar and England 1990, 1995; Kao and Chen 1991; Tichelaar and Ruff 1993; Hyndman and Wang 1995). Implied coefficients of friction are typically less than 0.1. Dynamic effects seen in the foam rubber model could in part explain this. Another commonly suggested explanation is

that high pore pressure water is trapped on the fault. (For a collection of recent articles, see AGU special section: Mechanical involvement of fluids in faulting, Hickman *et al* 1995). Since there appears to be a wide range of behaviour of subduction zone thrusts from region to region (e.g., Tichelaar and Ruff 1993), it is likely that a number of factors determine the behaviour in any particular case.

4. Conclusion

A physical model of thrust faulting has been constructed out of elastic foam rubber. The observed particle motions show many features different from those commonly assumed in dislocation models of subduction thrusts. Interface waves associated with fault opening propagate along the thrust plane and temporarily decouple the overlying hanging wall plate from the foot wall, trapping energy in the wedge and, as a consequence, causing the particle motions and energy in the hanging wall to be much greater than in the foot wall. The energy trapped in the upper plate breaks out at the toe of the thrust with a spectacular increase in motions.

If this model is analogous to the real earth, it may explain a number of puzzling and important features of thrust earthquakes, and suggests that the seismic hazard of thrust earthquakes might, in some cases, be seriously underestimated.

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