California State University, Northridge

Surface Displacement and Ground Motion from Dynamic
Rupture Models of Thrust Faults with Variable Dip Angles and
Burial Depths

A thesis submitted in partial fulfillment of the requirements for
the degree of Master of Science in Geology - Geophysics

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May 2020

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Acknowledgements

I would like to thank my loving and patient family, with special thanks to my husband, Jason Ulloa, for his unwavering support.

I would also like to thank the Southern California Earthquake Center (SCEC) for funding this project under SCEC award # 18218, and scholarship donors Marilyn Hanna, and the Coast Geological Society, Pacific Section of the American Association of Petroleum Geologists (CGS-PSAAPG) for their generosity.

I would like to thank the entire CSUN Geoscience department, including my fellow graduate students, for their encouragement and support. I am especially grateful the members of my committee: Doug Yule, who is always approachable and knowledgeable, and was my first contact in CSUN's Geoscience department, and Dayanthie Weeraratne, who gave me a tour of the department during my first visit to campus, and is always ready with invaluable advice.

Most of all, I would like to thank my advisor, Julian Lozos, for his teachings, patience, encouragement, and willingness to lend an ear.

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Abstract

Surface Displacement and Ground Motion from Dynamic Rupture Models of Thrust Faults with Variable Dip Angles and Burial Depths

By

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Master of Science in Geology - Geophysics

Thrust fault earthquakes are particularly hazardous in that they produce stronger ground motion than normal or strike-slip events of the same magnitude due to a combination of hanging wall effects, vertical asymmetry, and higher stress drop due to compression. Two examples of strong motion thrust earthquakes are those of Northridge 1994 ($M_w = 6.7$, $PGA = 1.82g$) and Christchurch 2011 ($M_w = 6.2$, $PGA = 2.21g$), which both ruptured on blind thrust faults, with burial depths of 5 km and 5.9 km, respectively. Surface displacement occurs in both blind and emergent thrust ruptures, and can potentially damage lifelines such as gas lines and water pipes, and infrastructure such as roads, high-rise buildings, residences, and hospitals.

Our 3D dynamic rupture modeling parameter study focuses on planar thrust faults of varying dip angles and burial depth, in order to establish a physics-based understanding of how ground motion and displacement depend on these geometrical parameters. We vary dip angles from 20° to 70° , and burial depths from 0 km to 5 km. We conduct rupture models on these geometries

using different dynamic stress drops, fault strengths, and homogeneous initial stresses versus stresses tapered with fault depth.

As we steepen dip angle, peak particle velocities in the homogeneous stress case generally increase in emergent faults, but decrease in blind thrust faults. Meanwhile, ground motion increases with steepening dip angle under the stress gradient. Both horizontal and vertical ground motion decrease more drastically as we bury the fault under homogeneous initial stresses. Under tapered initial stresses, ground motions increase in blind thrust faults as we bury the fault, but are highest in emergent faults. We find that varying dynamic stress drop has a considerable scalar effect on both ground motion and surface displacement, whereas changing fault strength has a negligible effect.

Due to the simple geometry of a planar fault, our results can be applied to understanding basic behavior of specific real-world thrust faults. They may be useful for assessing ground motion and displacement hazard for thrust earthquakes, and possibly also for determining offset and shaking risk to structures and lifelines.

Introduction

Thrust faults are compressionally driven dip-slip faults which are found in compressional tectonic settings all over the world, sometimes in densely populated areas. The geometry and compressive nature of thrust faults make them highly destructive, generating more powerful ruptures than other kinds of faults of the same size. Since the walls are compressed, they have a higher yield stress for initial shear stress to overcome. This leads to a large stress drop and higher energy release. A compression zone is a geographical area subject to tectonic shortening, such as Los Angeles and the Himalaya Mountains, which contain thrust systems and numerous faults (Herren, 1987; Davis et al., 1989; Argus et al., 1999; Shaw et al., 2002). Thrust faults are responsible for such earthquakes as Northridge 1994 ($M_w=6.7$); Chi Chi, Taiwan 1999 ($M_w=7.6$); and Lushan, China 2013 ($M_w=6.6$), where seismic stations recorded strong ground motions that caused extensive damage (Celebi, 1995; Ma et al., 2001; Liu et al., 2013). While emergent thrust faults reach the surface, blind thrust faults are buried in the shallow subsurface. Without surface expression, we cannot see the top edge of a blind thrust fault with the naked eye, though some may have more subtle expression in the form of anticlines. Blind thrust faults often go undetected until rupture, as was the case with the Northridge Thrust, discovered in 1994, and the Puente Hills Thrust, part of which ruptured in the Whittier Narrows earthquake of 1987.

During a thrust rupture, compression causes the hanging wall of the fault to move up relative to the footwall. The walls of a thrust fault can also undergo decoupling, which leads to increased ground motion (Brune et al., 1996). The angle of a dip-slip fault affects directivity, as the seismic rupture front propagates updip and amplifies at the surface (Nielson, 1998).

Moreover, geometric spreading and seismic wave attenuation can decrease ground motion and surface displacement with upward propagation in blind thrust ruptures (Chang et al., 2004), especially on deeply-buried faults. Slip on a thrust fault, even without surface expression, can cause both uplift and subsidence in a single event (Ellis and Densmore, 2006). Thrust earthquakes also have strong hanging wall effects (Shabestari and Yamazaki, 2002), in which particle velocity and peak ground acceleration (PGA) measured on the hanging wall are greater than those on the footwall (Campbell and Bozorgnia, 1994; Celebi, 1995; Somerville et al., 1996). Although the Northridge earthquake had a magnitude of only M6.7, peak ground accelerations (PGA) recorded during the rupture were as high as 1.82 g (Jones et al., 1994). In New Zealand, the Christchurch earthquake of 2011 ($M_w=6.2$), high levels of shaking caused liquefaction and substantial structural damage (Bradley et al., 2014; Li et al., 2014) and PGA recorded were as high as 2.21 g (Wood et al, 2011).

A thrust fault rupture can generate enough surface displacement to shift roads and structures (Xu et al., 2013), and permanently change the topography of a region (Jones et al., 1994; Allen et al., 1998). Intense shaking during a thrust rupture can launch heavy objects into the air (Allen et al., 1998), trigger landslides (Roback et al., 2018), and cause building collapse (Wald et al., 1996; Kircher et al., 1997). Permanent ground displacement (PGD) increases the likelihood that an earthquake will damage lifelines, such as water pipes and gas lines (Rofooei et al., 2012; Rojhani et al., 2012), as did the San Fernando earthquake of 1971 ($M_w=6.6$) (Bonilla et al., 1971).

There have been many studies on thrust faults, but most are empirical or lab simulated. For example, Abrahamson and Somerville (1996) derived laws from modeling hanging wall effects based on observations from the Northridge rupture of 1994. Shaw and Shearer (1999) used local seismic data, such as reflection profiles, to locate and understand a system of blind thrust faults in the Los Angeles area. Brune (1996) used elastic foam rubber models of thrust faults in a laboratory to offer a better understanding decoupling and hanging wall effects on thrust faults with a 25° dip angle in the field. He affirmed that effects such as decoupling and trapped seismic wave energy generate vastly higher levels of ground motion on the hanging wall than the footwall. Shi et al. (1998) used a two-dimensional lattice model to gain a numerical understanding of hanging wall effects, and to corroborate with the Brune model.

Previous works have played an important role in improving our knowledge regarding the physics of thrust faults. Dynamic rupture models have been used for geometrical parameter studies for decades, but most of these studies have been performed on strike-slip faults , and address rupture propagation rather than particle velocity and surface displacement (Harris and Day, 1993; Ely et al., 2010; Duan and Oglesby, 2012; Lozos et al., 2011). Some 3D dynamic rupture models relate to specific ruptures or faults (e.g. Mikumo and Miyatake, 1992; Oglesby and Day, 2001). Dynamic rupture models using 3D finite elements can have edge effects, causing distortions in some of the mesh elements. The elements nearest the fault plane and at the tip of the hanging wall need to fit the triangular form of the model, but rectangular elements are less taxing on a computer due to simplicity. Therefore, the user must have access to a computer which can run models in high-resolution. As a result, there are relatively few dynamic rupture modeling studies on dipping faults. For example, Magistrale and Day (1999) ran models on tear

faults to discern the effect of segmenting on rupture propagation through thrust fault systems. Oglesby et al. (2000) modeled particle velocity and surface displacement of simple, planar, dipping faults, comparing the ground motion and surface displacement of both thrust and normal faults. Our study differs from this one in that all of their faults are emergent and they test fewer dip angles. Peshette et al. (2019) modeled the dynamics of jumping ruptures between emergent dipping faults while varying dip angle, distance between faults, and stress drop. They found that fault geometry and stress drop are important variables in the intensity of thrust fault ruptures. Our study differs from this one as well, in that our focus is on ground motion and surface displacement, rather than the ability of rupture to jump between two faults.

While all of these studies improve our understanding of thrust faults, here, we aim specifically to address the physics of how dip angle and burial depth affect ground motion and surface displacement. Though individual real faults have more complexity than the faults in our models, our parameter study will be useful for understanding broad behaviors of real world faults. Our results may be a good starting point for site-specific studies and probabilistic hazard calculations.

Methods

For this parameter study, we varied the dip angle θ , and burial depth b , of a simple, planar thrust fault, combining these two parameters within a set of models (Figure 1). We generated tetrahedral meshes of 30 km long (along strike) x 15 km wide (along dip) thrust faults, which we placed in a 39 x 48 x 30 km fully elastic half space using the commercial software Cubit. We gave each fault the same dimensions in order to eliminate rupture size as a factor (Gutenberg and Richter 1956, Aki 1966b, Hanks and Kanamori, 1979). Within each set of models, we tested burial depths of $b = 0, 1, 2, 3, 4$, and 5 km, combined with dip angles of $\theta = 20^\circ, 30^\circ, 40^\circ, 50^\circ, 60^\circ$, and 70° , for a total of 36 meshes. Throughout this work, we do not distinguish between thrust and reverse faults; rather, we refer to all compressionally driven dip-slip faults as thrust faults regardless of dip angle. Since fault burial depth and dip angle vary, but fault dimensions do not, the basal depth of the fault varies from model to model. We generate ground motion plots in the form of spatially distributed peak particle velocities, and surface displacement plots in the form of spatially distributed vertical ground displacements.

We ran the models in FaultMod (Barall, 2009), a fully dynamic, 3D finite element method, which performed well in the SCEC dynamic rupture code validation exercise (Harris et al, 2009). We forced nucleation under linear slip-weakening friction (Day 1982b), by raising the initial shear stress σ_o above the yield stress σ_y over an area larger than the critical patch size required for self-sustained rupture (Table 2). We set the nucleation point 3 km from the left edge of the fault and 3 km updip from the bottom of each fault. We set the run time at 30 seconds to ensure that the entire fault ruptured.

We varied dynamic stress drop $\Delta\sigma$ and fault strength S to determine what effects they have on ground motion (Oth et al., 2017) and surface displacement. Dynamic stress drop, $\Delta\sigma$, is the amount of stress the fault releases during rupture, and is defined by the difference between the initial shear and final stresses.

$$S = \frac{\sigma_y - \sigma_o}{\sigma_o - \sigma_f} = \frac{\sigma_y - \sigma_o}{\Delta\sigma}.$$

The fault strength, S , is a unitless quantity which represents a fault's resistance to rupture.

$$\sigma_y = \mu_s \sigma_n.$$

$$\sigma_f = \mu_d \sigma_n,$$

where σ_n is initial normal stress, μ_s is the static coefficient of friction, μ_d is the dynamic coefficient of friction, and σ_f is the final shear stress acting on the fault (Das and Aki 1977, Day 1982b) (Table 1).

We ran sets of models with homogeneous initial stresses, where $S = 1, 1.5$, or 2 ; and $\Delta\sigma = 5, 10$, or 15 MPa. We refer to the case where $S = 1.5$ and $\Delta\sigma = 10$ MPa as our “basic case.” We also ran a set of models in which the shear and normal stress on the fault vary with depth, which we call the tapered stress model. In this case, at a depth of 19095 m—the lowest basal depth of all of our model faults—we set stresses to be equal to twice the stresses of the basic case, then tapered the shear and normal stress to 0 MPa at the free surface. At the midpoint—a depth of 9547.5 m—we set the initial stresses equal to those of the basic case. The initial stresses on the fault itself therefore depend on its orientation and depth within this stress gradient. We included the tapered stress scenario because stresses acting on a fault generally increase at depth and can therefore relate ground motion to depth of the fault plane within the earth/stress field, thus a

deeper blind rupture could lead to increased ground motion at the surface, as observed by Pitarka et al. (2009).

Figure 1.

A simple, planar, blind thrust fault, at burial depth (b) in relation to the free surface, and dip angle (θ).

Table 1.

Stresses used in the cases of model sets with varying parameters, with shear stress σ_o , normal stress σ_n , dynamic fault strength S , and stress drop $\Delta\sigma$.

Stresses used in Cases Modeled with Variable Parameters			
S (unitless)	$\Delta\sigma$ (MPa)	σ_o (MPa)	σ_n (MPa)
1	10	20	50
1.5	5	11.25	31.25
1.5	10	22.5	62.5
1.5	15	33.75	93.75
2	10	25	75

Table 2.

Parameters held constant for all models.

Physical and Computational Parameters		
<i>symbol</i>	<i>name</i>	<i>constant value</i>
μ_s	Coefficient of Static Friction	0.6
μ_d	Coefficient of Dynamic Friction	0.2
d_c	Critical Slip Weakening Distance	0.4 m
v_p	P-wave Velocity	6000 m/s
v_s	S-wave Velocity	3464 m/s
ρ	Density	2700 kg/m ³
	Element Size (Fault and Surrounding Media)	200 m
	Element Size (Buffer Zone)	600 m
r_c	Forced Nucleation Zone Radius	3000 m

Table 3.

Depth of fault base per model in kilometers.

burial depth b (km)	dip angle θ	depth of fault base (km)	hypocentral depth (km)
0	20°	5.130	4.1042
0	30°	7.500	6.0000
0	40°	9.642	7.7135
0	50°	11.491	9.1925
0	60°	12.990	10.3923
0	70°	14.095	11.2763
1	20°	15.095	5.1042
1	30°	13.990	7.0000
1	40°	12.491	8.7135
1	50°	10.642	10.1925
1	60°	13.990	11.3923
1	70°	15.095	12.2763
2	20°	7.130	6.1042
2	30°	9.500	8.0000
2	40°	11.642	9.7135
2	50°	13.491	11.1925
2	60°	14.990	12.3923
2	70°	16.095	13.2763
3	20°	8.130	7.1042
3	30°	10.500	9.0000
3	40°	12.642	10.7135
3	50°	14.491	12.1925
3	60°	15.990	13.3923
3	70°	17.095	14.2763
4	20°	9.130	8.1042
4	30°	11.500	10.0000
4	40°	13.642	11.7135
4	50°	15.491	13.1925
4	60°	16.990	14.3923
4	70°	18.095	15.2763
5	20°	10.130	9.1042
5	30°	12.500	11.0000
5	40°	14.642	12.7135
5	50°	16.491	14.1925
5	60°	17.990	15.3923
5	70°	19.095	16.2763

Results

Ground Motion

Ground motion in the basic case.

In this study, we show the results of each case in the form of 36 figure panels, where dip angle increases from left to right, and burial depth increases from top to bottom (Figure 2). We will compare ground motion in the basic case to that of the tapered stress case for both horizontal (Figures 3, 4; 5, 6) and vertical (Figures 7, 8; 9, 10) components. Here we examine horizontal (Figure 3) and vertical (Figure 7) particle velocities for the basic case, where $S = 1.5$ and $\Delta\sigma = 10$ MPa. In general, ground motion decreases with deeper burial depth for all dip angles. In terms of the maximum horizontal particle velocity, as dip angle increases, ground motion decreases in faults with burial depths of 0 to 2 km, while faults of burial depths of 0 and 1 km increase at 60° , and those with a depth ranging from 3 to 6 km show more of a linear decrease with the least particle velocity at a burial depth of 5 km and a dip angle of 70° . In most models, there is a larger area of stronger horizontal ground motion on the hanging wall than on the footwall. However, peak horizontal particle velocity is greater on the footwall in steeper, more shallow-buried faults (Figure 3). The mean horizontal particle velocity decreases with steepening dip angle from 20° to 40° , but increases at dip angles steeper than 40° . Maximum vertical particle velocity is consistently higher on the hanging wall than on the footwall (Figure 7). In blind thrust models, peak vertical particle velocity increases slightly, then decreases as we steepen the dip angle. However, in our models of emergent faults, peak vertical particle velocity steadily

increases with steeper dip angle (Figures 7, 9). For burial depths ranging from 0 to 3 km, the mean vertical particle velocity decreases slightly, then begins to increase between 40° and 50° and continues to increase as we steepen dip angle. The change in all particle velocities is more pronounced in models of faults with shallower burial depths. In models of faults with burial depth of 3 km, the change in mean vertical particle velocity is almost unvarying as the dip angle steepens (Figure 10). The cases with burial depths of 4 and 5 km have a slight decrease in mean vertical particle velocity with progressively steeper dip angles, but then at 40°, particle velocity continues to decrease, with a near-linear downward trend.

For any given dip angle, peak particle velocities for buried ruptures generally vary less than 0.20 m/s per 1 km difference in burial depth. However, there is a much larger difference in ground motion between the emergent fault models and all of the blind fault models, with a difference in peak particle velocities of up to 3.06 m/s between the emergent rupture and that which is buried 1 km (Figure 5, 6, 9, 10).

How tapered vs. homogeneous initial stresses affect ground motion.

The tapered stress case has considerably different results than the basic case (with uniform initial stresses). The patterns in horizontal ground motion are opposite between the two cases. Where there is an overall decrease in ground motion with both steepening dip angle and deeper burial depth in the basic case, the same variations increase peak horizontal particle velocity in the tapered stress case (Figures 3, 4). Peak vertical particle velocity has a similar spatial distribution in both the homogenous and tapered stress cases, but overall ground motion is

reduced in the tapered stress case in models of shallow-dipping and shallow-buried faults, and increased in steeper and deeply-buried fault models.

In the homogenous stress case, models of emergent faults have much higher peak particle velocities than the blind thrust models. In the tapered stress case, however, the ground motion in emergent faults is not always higher than that of buried faults. When it is, the difference in ground motion between ruptures on surface and buried faults decreases as we increase burial depth (Figures 7, 8). There is a pattern of increasing peak vertical particle velocities with steepening dip angle and deeper buried faults in the tapered stress case (Figure 8). Moreover, where the uniform stress cases exhibit an overall decrease in ground motion with increased burial depth, those with a stress gradient show the strongest ground motion from surface-rupturing cases, but the next highest from faults with a burial depth of 5 km, and progressively lower ground motion from faults with progressively shallower burial depth. The stress gradient also has an effect on ground motion as we vary dip angles. Both maximum horizontal and mean vertical particle velocities increase with higher dip angle in the uniform stress case (Figures 9, 10).

Figure 2.

Key to figure panels throughout this text, including Appendix.

Figure 3.

Horizontal particle velocity in the homogenous stress case, $S = 1.5$ and $\Delta\sigma = 10$ MPa. Each panel in this grid represents one rupture model.

Figure 4.
Horizontal particle velocity in the tapered stress case.

Figure 5.

Maximum Horizontal Particle Velocity

0 km 1 km 2 km 3 km 4 km 5 km

Homogeneous

Tapered

Figure 6.

Mean Horizontal Particle Velocity

0 km 1 km 2 km 3 km 4 km 5 km

Homogeneous

Tapered

Figure 7.

Vertical particle velocity in the homogenous stress case, $S = 1.5$ and $\Delta\sigma = 10$ MPa. Each panel in this grid represents one rupture model.

Figure 8.

Vertical particle velocity in the tapered stress case.

Figure 9.

Maximum Vertical Particle Velocity

0 km 1 km 2 km 3 km 4 km 5 km

Homogeneous

Tapered

Figure 10.

Mean Vertical Particle Velocity

0 km 1 km 2 km 3 km 4 km 5 km

Homogeneous

Tapered

How varying S with a fixed stress drop affects ground motion.

Varying the fault strength (S) has little effect on ground motion, though maximum particle velocities are affected more than mean particle velocities. With dynamic stress drop fixed at 10 MPa, the greatest difference in particle velocity is in the horizontal maximum component between $S = 2$ and $S = 1.5$ in the surface fault dipping 20° , where the difference is 0.15 m/s. When we take the difference in average particle velocity between $S = 2$ and $S = 1.5$; $S = 1.5$ and $S = 1$; and $S = 2$ and $S = 1$; across geometries for each component of particle velocity—maximum vertical, maximum horizontal, mean vertical, and mean horizontal—the average of those values is only 0.02 m/s (Figure 11).

Figure 11.

Maximum and mean particle velocity from models of faults with burial depths of 2 km and homogeneous initial stress conditions, while varying S and dynamic stress drop $\Delta\sigma$ (MPa). The example of this burial depth is representative; these patterns are consistent in all blind thrust fault models.

—◆— $S=1, \Delta\sigma=10$ —■— $S=1.5, \Delta\sigma=10$ —▲— $S=2, \Delta\sigma=10$ —×— $S=1.5, \Delta\sigma=5$ —*— $S=1.5, \Delta\sigma=15$

How varying stress drop with a fixed S affects ground motion.

Particle velocity increases considerably with increased dynamic stress drop ($\Delta\sigma$) in all cases (Figure 11). With increased dynamic stress drop where $S = 1.5$, and $\Delta\sigma = 5, 10$, and 15 MPa, respectively, we see a jump in both horizontal and vertical particle velocities. The strongest ground motions come from emergent faults in all cases. For all burial depths, particle mean velocities and maximum horizontal particle velocities, levels of ground motion decrease with steepening dip angle. However, mean particle velocities are similar at angles of 40° and 50° , then increase with steeper dip angle. However, maximum vertical particle velocities increase with dip angle for models of emergent faults. The ground motion of blind thrusts in this case begin to increase, then decrease with steepening dip angle. The highest peak vertical particle velocity values of the surface-rupturing fault models for the are at the 70° dip angle. However, models of faults with a 20° dip angle produce a higher particle velocity value than those with a 70° dip angle combined with a lower stress drop (Figure 9).

Surface Displacement

How tapered vs. homogeneous initial stresses affect surface displacement.

Spatial distributions in the tapered stress case of both uplift and subsidence are similar to those of the homogenous stress case, but the stress gradient causes the amount of surface displacement between models to fit within a smaller range (Figures 12, 13). The amount of surface displacement in emergent faults increases with steeper dip angle in both the homogeneous and tapered stress cases. Although the amount of surface displacement in these models is greater in the homogeneous stress models than in those of the tapered stress case, Figure 13 illuminates the location of the broken surface at the tip of the hanging wall in surface ruptures. This illumination appears as the distribution of uplift abruptly terminates at the tip of the hanging wall in all dip angles, as does subsidence at the edge of the footwall in steeper emergent faults. At 20°, the amount of subsidence in blind thrusts increases as we bury the fault. However, as we steepen dip angle, amounts of subsidence between models decreases as we bury the fault, and are similar at 30°. The amount of uplift is higher in deeper-buried faults than shallow-buried blind faults when angles range from 20° to 50°, but is higher in shallow-buried blind faults at steeper dip angles (Figure 14). As we bury the fault deeper or steepen dip angles, the amount of uplift in the tapered stress case increases steadily while the amount of subsidence decreases (Figures 13, 14, 15). With deeper burial depth, the difference between the amount of surface displacement in the homogeneous and tapered stress models decreases until they reach similar values.

Surface displacement in the basic case.

In the homogenous stress case, the amount of surface displacement decreases overall as we bury the fault deeper, while distributions of peak uplift and subsidence do not shift. The area of subsidence is concentrated near the rear of the hanging wall (opposite the fault tip) in the shallow angle faults, and shifts to the leading edge of the footwall in faults with dip angles of 40° and greater (Figure 12). The amount of subsidence decreases slightly as dip angle steepens, then at 40° , increases steadily. The amount of subsidence is also greatest at the surface, and decreases with deeper burial depth (Figures 12, 15). As we steepen the dip angle, the area of uplift on the hanging wall increases, and the amount of uplift from ruptures with on emergent faults increases, while the amount of uplift in the blind thrusts increases slightly, then decreases (Figures 12, 14).

Figure 12.

Surface displacement in the homogenous stress case, $S = 1.5$ and $\Delta\sigma = 10$ MPa. Positive values represent uplift; negative values represent subsidence.

Figure 13.

Surface displacement in the tapered stress case.

Maximum uplift in the homogenous and tapered stress cases.

Maximum subsidence in the homogeneous and tapered stress cases.

How varying S with a fixed stress drop affects surface displacement.

Varying the fault strength S has no discernible effect on surface displacement (Figure 16). In all three cases where $\Delta\sigma$ is fixed at 10 MPa, numerical plots consistently follow a pattern where the amount of subsidence decreases then increases as dip angles become steeper, while the amount of uplift increases then decreases. Their plotted values overlap to the where they are nearly indistinguishable. Spatial distribution plots also show minute variations in surface displacement when comparing cases where only S varies (Figure 11; Appendix, Figures A3, A6). The average difference between surface displacement values for the same geometries across stress cases was 1.49 cm for uplift and 0.323 cm for subsidence across the three cases where S varies while $\Delta\sigma = 10$ MPa. This negligible effect shows that other parameters, such as dip angle and stress drop, control surface displacement, as opposed to fault strength S .

Figure 16.

Maximum surface displacement from faults with burial depths of 2 km and homogeneous initial stress conditions, while varying S and dynamic stress drop $\Delta\sigma$ (MPa).

How varying stress drop with a fixed S affects surface displacement.

Both uplift and subsidence consistently increase with higher stress drop for all three scenarios where S is fixed at 1.5 (Figure 16). Surface displacement between the emergent fault cases is greater than in the 1 km buried faults. As we bury the faults deeper, surface displacement gradually decreases with steepening dip angle (Figures 14, 15). As we steepen dip angle, maximum subsidence decreases, then at about 40° , steadily increases.

Discussion

Ground Motion

The tapered stress models yield less overall ground motion than those in the basic homogeneous stress case. Overall, the values of peak horizontal and vertical particle velocities in the tapered stress case average 74% and 73% of those in the homogeneous stress case, respectively (Figures 5, 9). Given the stress gradient, stresses near the free surface are reduced, resulting in a lower yield stress and subsequent stress drop, and therefore generating less ground motion from the surface ruptures. In contrast with the homogeneous stress case, peak particle velocities in the tapered stress case increase in blind thrust faults as we bury the faults deeper (Figures 5, 9). This opposing behavior is a result of stress drop controlling ground motion and increasing with depth (Figure 17). Faults buried deeper in the tapered stress case have increased overall stress drop, releasing more energy. However, greater distance from the surface causes this energy to dissipate more between the top of a buried fault and the surface due to attenuation and geometric spreading. Comparing Figure 3 to Figure 4, and Figure 7 to Figure 8, we can see that ground motion distribution between the basic and tapered stress cases is similar in models of faults with 40°, 50°, and 60° dip angles, combined with burial depths of 3 km and 4 km. These faults are placed with intermediate burial depths and dip angle, so their positions give rise to less influence by the stress gradient (Table 3).

Fault geometry systematically drives the variations in ground motion from model to model. As we bury faults deeper, ground motion decreases due to wave attenuation and geometric spreading. Moreover, a steeper fault has geometry closer to that of a vertical fault and

thus, there is less asymmetry between the fault walls. While the fault base is consistently farther from the surface than those of shallow-dipping faults of equal burial depth, these fault models also have a smaller ground area above the fault plane (Figure 18). Therefore, the spatial distribution of strong peak particle velocity is much greater on the hanging walls in models with shallow dip angles than in faults with steeper dip angles (Figures 3, 4, 7, 8).

In the basic case, while we see a slight decrease in vertical ground motion as we bury the fault deeper, most of the measurable change in ground motion is an increase on the footwall for steep dip angles at 0 and 1 km burial depth relative to other footwalls in our models, due to fault geometry (Figure 7). Horizontal ground motion is controlled by along-strike directivity, as we can see in Figure 3 from the broadening area of ground motion from the nucleation point on the left to the end of the fault on the right.

Linear scaling is clear between cases with different S and dynamic stress drop. Varying S has little to no effect on ground motion, while varying dynamic stress drop has a larger influence on ground motion. Because we use the equation $S = \frac{\sigma_y - \sigma_o}{\sigma_o - \sigma_f} = \frac{\sigma_y - \sigma_o}{\Delta\sigma}$, there is a linear relationship between initial stresses and S as we hold $\Delta\sigma$ constant, and between the initial stresses and $\Delta\sigma$ as we hold S constant. Although varying dynamic stress drop causes considerable changes in particle velocity, this is only a scalar effect where output variations are dependent on arbitrary input. These systematic variations are most evident in the patterns of both the mean and maximum particle velocities (Figure 11). However, they are also apparent when comparing spatial distributions between cases of uniform initial stresses (Appendix, Figures A1, A4, A7 and A10; A2, A5, A8 and A11; A3, A6, A9, and A12).

Figure 17.

Initial shear stresses acting on 40° dipping thrust faults with burial depths of 0, 2, and 4 km. Initial stresses in our homogeneous stress models are uniform, whereas those in our tapered stress models are not. The panels each show the fault tilted for ease of viewing, with the downward direction aiming into the subsurface.

Figure 18.

Cross section of the hanging wall for each dip angle θ , regardless of depth. The dashed purple line represents the area over the hanging wall, and the solid red line represents the fault.

When considering the horizontal component, we see much stronger ground motion at the surface in the basic case than we do in the tapered stress case. In models with steeper dip angle,

more horizontal ground motion is distributed on the footwall in both the uniform and tapered stress cases than in those with shallow dip angles, as directivity is influenced by the geometry of the faults. The effect of directivity is prominent in the horizontal component of ground motion, as in our models, the spatial distributions of these velocities widen outward from the point of nucleation. Directivity affects horizontal peak particle velocity, in that shallower-dipping faults lie in a direction closer to true horizontal than steeper faults, and the rupture front is damped by material above the hanging wall. When considering the vertical component, while most of the strong ground motion is on the hanging wall in both cases, we see less overall in the tapered stress case due to decreased stress drop at the top of the fault.

Surface Displacement

As shown in Figures 12, 13, 14, and 15, there is more surface displacement overall in the basic case than in the tapered stress case. The overall values of subsidence and uplift in the tapered stress case average 72% and 73% of those in the homogeneous stress case, respectively. This is because fault slip influences surface displacement, and the stress gradient generates less stress drop and therefore less slip at the surface. As we bury the faults deeper, nucleation is more energetic than with faults of shallow depth, but wave attenuation and geometric spreading cause this energy to decrease with distance. In our tapered stress case, stress drop is lower near the surface, while ruptures that nucleate deeper in the subsurface begin with higher stress drop. There is a balance between high energy release in deeper ruptures and energy loss due to geometric spreading and wave attenuation. In the case of both homogeneous and tapered initial

stresses, regions of uplift and peak vertical ground motions correlate, as they are both controlled by fault geometry and stress drop.

Surface displacement in the basic case consistently decreases as we bury the fault deeper, as surface displacement is influenced by slip and fault geometry. Slip causes upward motion on the hanging wall, resulting in uplift. The dip angle of the fault affects the distribution of surface displacement (Figure 18), and those set at a burial depth of 0 km break the surface (Figures 12, 13). Models of emergent faults show far greater surface displacement than those buried at 1 km, while the difference in surface displacement between blind thrust faults at 1 km increments (e.g. 1 and 2 km, 2 and 3 km, etc.) is far less (Figures 14, 15). The distribution of subsidence is controlled by the width of the hanging wall (Figure 18), where the rear of the hanging wall subsides in shallow angle faults, which have more area above the hanging wall, but the entire hanging wall uplifts in more steep, narrow faults. As in Figure 12, uplift abruptly terminates at the tip of the hanging wall in models of emergent faults. This is where the fault tip breaks the surface. Subsidence is distributed on the rear of the hanging wall in 20° and 30° dipping faults, but on the leading edge of the footwall in steeper fault models. As the hanging wall of a shallow-dipping faults uplifts, it pulls the surface toward the footwall, stretching and spreading it thin behind it, resulting in subsidence. In steeper faults, compression forces the edge of the footwall to descend flank to the uplifting hanging wall. Since we generated our models to have the same slip regardless of fault geometry, those with steeper dip angles have more uplift than shallower-dipping faults, since the motion in these cases is closer to pure vertical. In blind thrust faults, spatial distributions of both uplift and subsidence across geometries in one set of models

are consistent, but uplift and subsidence decrease as we bury the faults deeper, due to increased amount of material above the fault plane.

In the tapered stress case, varying S has a negligible effect on surface displacement. As with particle velocity, varying dynamic stress drop yields a larger, scalar effect on surface displacement in both the basic and tapered stress cases. Increased stress drop generates a more energetic rupture front and therefore more slip, which in turn increases surface displacement.

While surface displacement in the homogeneous stress case decreases as we bury the fault deeper, tapered stresses causes relatively more surface displacement when faults are buried deeper at shallow angles, due to higher initial stresses, (Figure 13). When comparing the basic case to the tapered stress case, we see consistency in the distribution of surface displacement with burial depths of 3 km and 4 km and dip angles of 50° , 60° , and 70° (Figures 12, 13). The stress gradient has less of an effect on surface displacement of steeper faults with intermediate depth because initial stresses are similar between cases at the hypocentral depth.

In each of the cases where we varied S , $\Delta\sigma$, and added the stress gradient, the pattern of maximum vertical particle velocity is consistent with the pattern of uplift, while the pattern of maximum horizontal ground motion correlates with subsidence. Ground motion and surface displacement correlate because stress drop and fault geometry are controlling factors for both. The distributions of uplift and subsidence relate to whether the peak ground motion is vertical or horizontal, respectively. Increasing the stress drop on a fault increases the slip on the fault, increasing uplift on the hanging wall. Directivity controls horizontal ground motion, which also

affects fault slip, pulling the hanging wall forward, and pushing the adjacent edge of the footwall to subside. Therefore, increasing the stress drop also increases subsidence.

Implications

Our results are consistent with those of previous studies in regards to the effects of fault geometry and stress drop on ground motion, surface displacement, and a stress gradient. Our results are consistent with other dynamic rupture modeling studies of ground motion in dip-slip faults (Oglesby, 2000), as the distribution of peak ground motions are considerably higher on the hanging wall than the footwalls of most of our models. They are also consistent with empirical analysis showing that more ground motion is distributed on the hanging wall of a thrust fault than on the footwall due to hanging wall effects (Abrahamson and Somerville, 1996). Our 3D surface displacement results are also consistent with Ellis and Densmore's (2006) 2D kinematic models of surface displacement over a blind thrust fault. The topographic features they found in their study, such as the foredeep at the edge of the footwall, and the fold hinge above the hanging wall, coincide with geometric distributions of both subsidence and uplift in our models, respectively (Figure 19). Pitarka et al. (2009) discuss the "shallow-weak zone," where ground motion in shallow-buried faults is relatively weak and slip is low when compared to deeper ruptures due to reduced stress drop at a shallow depth. We see this in our results as well, as the stress gradient in our tapered stress models affects ground motion in the same manner.

We now compare our results to real-world scenarios by using two end members: the Northridge earthquake of 1994, and the San Fernando earthquake of 1971. The observed peak

ground velocities are higher for the Northridge fault, which has a deeper burial depth and deeper hypocentral depth. This trend of increasing peak ground velocity with deeper burial depths is consistent with our numerical model results. Given a wide range of observations, the Northridge earthquake of 1994 occurred at a hypocentral depth of approximately 18 km on a 15 km long section of a 20 km wide blind thrust fault, with a dip angle of 40° , and laying at a depth between 5 and 20 km (Davis and Namson, 1994; Wald et al., 1996). Maximum uplift from the rupture was about 52 cm (Hudnut et al., 1996), with a peak ground velocity (PGV) of .98 m/s (USGS CISCN website). In our tapered case, the 40° dipping fault buried at 5 km has a peak uplift value of 137.3 cm and peak horizontal and vertical velocities of 0.49 and 0.75 m/s, respectively. The numerical values do not correlate, as our initial conditions are arbitrary and do not necessarily match regional conditions. However ground motion distribution patterns correlate well with PGV contours (Figure 20), as do surface displacement patterns with those modeled from the rupture (Figure 21). Peak particle velocities are highest along the edge of the hanging wall while following the path of directivity along strike due to horizontal motion. Peak uplift is highest near the edge of the hanging wall, and the distribution of values in the model radiates with the pattern of the contours.

The San Fernando earthquake of 1971 ruptured a 15 km x 15 km area (Trifunac, 1974) of an emergent fault with a dip angle of 52° (Whitcomb, 1971), with a hypocentral depth of 13 km, so we compare the rupture with our 50° emergent fault. In the tapered case, this fault has a peak uplift value of 190.6 cm, and peak horizontal and vertical velocities of 0.64 and 0.98 m/s, respectively. The rupture of 1971 resulted in recorded uplift as high as 80 – 90 cm (Kamb et al., 1971), with a PGV of 1.4 m/s (USGS CISCN website). While the numerical values do not

correlate here either, for the same reasons as in the case of the Northridge rupture, the distribution patterns do correlate in the same manner (Figures 22, 23).

Figure 19. An example of how fault geometry affects surface displacement.

After Ellis and Densmore, 2006

Figure 20.

Our ground motion models of a 5 km buried, 40° dipping fault in the tapered stress case superimposed upon peak ground velocity (PGV) contours from the 1994 Northridge earthquake. Our models are rotated 212° to best conform to the strike of the fault. We have scaled our models to the size of the source earthquake in order to make a more direct qualitative comparison between real world and model ground motion.

Horizontal

Vertical

Contour maps from USGS CISEN website

Figure 21.

A relief map of southern California showing uplift contours from the Northridge earthquake of 1994, superimposed upon our surface displacement model of a 5 km buried, 40° dipping fault. Our model is rotated 212° to best fit the strike of the fault. We have scaled our models to the size of the source earthquake in order to make a more direct qualitative comparison between real world and model displacement.

Contour map after Jones et al., 1994

Figure 22.

The ground motion models of our emergent 50° dipping fault in the tapered stress case, superimposed upon peak ground velocity (PGV) contours from the 1971 San Fernando earthquake. The models are rotated 5° to best conform to the strike of the fault. We have scaled our models to the size of the source earthquake in order to make a more direct qualitative comparison between real world and model ground motion.

Contour maps from USGS CISE website

Figure 23.

Contours representing vertical geodetic controls—consistent entities, such as buildings—from the 1971 San Fernando earthquake superimposed on the surface displacement model of our emergent 50° dipping fault in the tapered stress case. The model is rotated 10° to best conform to the strike and dip of the fault plane in the contoured image. We have scaled our models to the size of the source earthquake in order to make a more direct qualitative comparison between real world and model displacement.

Contour image after Alewine and Jordan, 1973

Ground motion prediction equations (GMPEs) are essential in hazard science and engineering, in that they help to determine particle velocity at a given distance from the source fault of an earthquake of a given size. However, GMPEs are based largely on empirical data, which inherently has gaps in records for some magnitudes and some distances from the fault.

Our results can potentially help improve on GMPEs by providing examples of how ground motion changes at a wide range of distances from the source fault. Understanding the spatial distribution of ground motion associated with thrust fault ruptures is important for determining risk from secondary effects, such as landslides and liquefaction. Others can also use our results to estimate the distribution of permanent ground displacement associated with a thrust fault rupture, as this displacement also has the capacity to damage infrastructure.

Conclusion

This parameter study is unique in that we have shown the systematic effects of fault strength S , dynamic stress drop $\Delta\sigma$, dip angle θ , and burial depth b , in addition to a stress gradient applied to thrust fault models. We have modeled the surface displacement and both horizontal and vertical ground motion on 216 simple, planar thrust faults in a fully elastic half space, each with its own set of initial conditions. Each set of models combined burial depth in increments of 1 km, and dip angle in increments of 10° , as our parameters.

We have shown that fault geometry and stress drop systematically drive variations in both ground motion and surface displacement. We have found that when initial stresses acting on a fault are homogeneous, burying the fault systematically decreases particle velocity, while steepening the dip angle decreases peak particle velocity in blind thrust ruptures. We also see a pronounced increase in ground motion in surface ruptures relative to blind thrust ruptures due to wave amplification. Our spatial distributions also clearly demonstrate hanging wall effects. Peak particle velocities reside mainly on the hanging wall across geometries, with the exception of the horizontal component of steep-angle, shallow buried faults. Peak horizontal particle velocity is also controlled by directivity, stress drop, and fault geometry. We have also shown that varying the fault strength S yields negligible effect on ground motion, while varying the stress drop $\Delta\sigma$ has a more prominent yet scalar effect on ground motion.

Our models demonstrate how fault geometry and stress drop are controlling factors in surface displacement. Surface displacement under homogeneous initial stresses also

systematically decreases as we bury the fault due to increased material above the fault. As we steepen dip angle, the area of peak uplift dominates the front of the hanging wall, while the area of peak subsidence shifts from the edge of the footwall to the rear of the hanging wall. In our models where burial depth = 0 km the location where the fault breaks the surface is illuminated in map view.

We have also shown the relative changes in ground motion and surface displacement when we add a stress gradient to our basic case, since tapering the initial stresses can generate results more fitting to real-world faults. We ran 5 sets of models with homogeneous initial stresses, where we combined faults strengths of $S = 1, 1.5$, and 2 with stress drops of $5, 10$, and 15 MPa. We then added a stress gradient to our middle case, where $S = 1.5$ and $\Delta\sigma = 10$ MPa for our tapered stress case. We found that peak particle velocity in blind thrust ruptures in the tapered stress case steadily increases as we steepen dip angle or bury the fault. It also increases in surface ruptures as we steepen the dip angle, but the amounts of peak particle velocities in surface ruptures are inconsistent relative to the pattern following burial depth in blind thrust ruptures as a result of wave amplification at the surface.

Surface displacement in the tapered stress case steadily increases as we bury the fault or steepen dip angle, where the amounts of those at intermediate burial depths and dip angle are similar to those in the homogeneous stress case. Spatial distributions between the homogeneous and tapered stress cases were similar, but the amounts varied as a result of wave attenuation and geometric spreading counteracting stress drop. Deeply buried faults in the tapered stress case nucleate with a higher stress drop than faults nearer to the surface. However, the seismic waves

of ruptures that nucleate deeper in the subsurface also have a longer travel distance. Therefore, although they begin more energetically than shallow-buried ruptures and those on emergent faults, but much of this energy diminishes due to wave attenuation and geometric spreading.

Given the combination of parameters in this study, and the geometric simplicity of our models, others can apply these results to site-specific studies. Our spatial distribution plots can help to improve on GMPEs, and hazard scientists and engineers can also use our spatial distributions to better determine the potential locations of peak ground motion and surface displacement relative a thrust fault. Ground motion prediction equations are empirical, and are limited by a data set based on real-world ruptures. Regional stresses, style of faulting, and magnitude are all contributing factors in the amount and spatial distribution of both ground motion and surface displacement. Our results provide a physics-based representation of ground motion and surface displacement due to rupture on thrust faults. They can therefore be incorporated into GMPEs where said combination of contributing factors on a real-world thrust fault is unknown.

We can see variability of particle velocities and surface displacements due to thrust fault ruptures over a parameter space, and this can fill gaps in observational data. Our results can also be used to help determine areas on a map likely to experience the most shaking, and endure landslides, liquefaction, and damage to infrastructure as a result of surface displacement and ground motion.

Future studies can expand on our results to answer questions we have broached. Such studies can question the effects of oblique thrusting on ground motion on surface displacement, model more complex, non-planar dipping faults as technology advances, or determine the effects of material properties on thrust fault ruptures.

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Appendix

Figure A1.

Horizontal particle velocity in the homogenous stress case, $S = 1$ and $\Delta\sigma = 10$ MPa. Each panel in this grid represents one rupture model.

Figure A2.

Vertical particle velocity in the homogenous stress case, $S = 1$ and $\Delta\sigma = 10$ MPa. Each panel in this grid represents one rupture model.

Figure A3.

Surface displacement in the homogenous stress case, $S = 1$ and $\Delta\sigma = 10$ MPa. Positive values represent uplift; negative values represent subsidence.

Figure A4.

Horizontal particle velocity in the homogenous stress case, $S = 2$ and $\Delta\sigma = 10$ MPa. Each panel in this grid represents one rupture model.

Figure A5.

Vertical particle velocity in the homogenous stress case, $S = 2$ and $\Delta\sigma = 10$ MPa. Each panel in this grid represents one rupture model.

Figure A6.

Surface displacement in the homogenous stress case, $S = 2$ and $\Delta\sigma = 10$ MPa. Positive values represent uplift; negative values represent subsidence.

Figure A7.

Horizontal particle velocity in the homogenous stress case, $S = 1.5$ and $\Delta\sigma = 5$ MPa. Each panel in this grid represents one rupture model.

Figure A8.

Vertical particle velocity in the homogenous stress case, $S = 1.5$ and $\Delta\sigma = 5$ MPa. Each panel in this grid represents one rupture model.

Figure A9.

Surface displacement in the homogenous stress case, $S = 1.5$ and $\Delta\sigma = 5$ MPa. Positive values represent uplift; negative values represent subsidence.

Figure A10.

Horizontal particle velocity in the homogenous stress case, $S = 1.5$ and $\Delta\sigma = 15$ MPa. Each panel in this grid represents one rupture model.

Figure A11.

Vertical particle velocity in the homogenous stress case, $S = 1.5$ and $\Delta\sigma = 15$ MPa. Each panel in this grid represents one rupture model.

Figure A12.

Surface displacement in the homogenous stress case, $S = 1.5$ and $\Delta\sigma = 15$ MPa. Positive values represent uplift; negative values represent subsidence.