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Critical Jump Distance for Propagating Earthquake Ruptures Across Step-Overs

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Abstract—The geometry of a strike-slip fault system is an important component that influences the kinematics and interactions of the various faults within the system. Discontinuities and bends in the fault geometry not only determine the types of structures and the physiography that we observe along the fault system but also have a significant influence on the propagation of earthquake ruptures. A precise knowledge of the fault geometry, especially how it is segmented and other physical parameters, is essential for seismic hazard analysis. It is known that earthquake ruptures sometimes propagate over multiple faults by jumping from one segment to the next. A fault jump is a sudden dynamic coalescence of two faults separated by a step-over. Field observations suggest that a step-over width of 5 km is an appropriate maximum jump distance. Our study shows that between 2.5 and 6.5 km of step-over width, the probability of fault jump, for both releasing and restraining step-overs, decreases significantly from 100 to <10 %.

1. Introduction

Step-overs are important geometric features that separate two fault segments and cause segmentation of fault systems. Based on the stepping and the slip direction of the fault, step-overs generate tensional or compressional forces that result in subsidence or uplift of the region between the two faults (Fig. 1). Step-overs that are under tensional forces are referred to as releasing, or dilatational, step-overs, whereas those under compression are called restraining, or compressional, step-overs. These discontinuities usually mark regions of deceleration and termination of earthquake rupture, but there are cases in which a propagating rupture jumps from one fault segment to the next across these gaps (Aki 1979; Segall and Pollard 1980; Lindh and Boore 1981; Sibson 1985; Barka and Kadinsky-Cade 1988; Wesnousky 1988). The 1992 Landers earthquake was a typical example of an earthquake rupture that jumped across several releasing step-overs, propagated along five different faults, and became an Mw 7.3 event (Sieh *et al.* 1993; Wald and Heaton 1994; Aydin and Du 1995). It is important in seismic hazard analysis to know whether a rupture can jump across these discontinuities, since the length of rupture determines the size of the earthquake and the area affected by it. Although the initial stress distribution, strength, and stress drop along the fault affect rupture propagation, it has been shown that fault geometry plays a dominant role in the rupture process.

Geologic observations and laboratory and numerical experiments over the years have shown that the width of a step-over controls the probability of a jump. Barka and Kadinsky-Cade (1988) studied the fault geometry along the North Anatolian Fault (NAF) in Turkey and suggested that large earthquake ruptures generally do not propagate past individual step-overs that are wider than 5 km. Wesnousky (1988), in addition to the NAF, studied the San Andreas, Garlock, Whittier-Elsinore, Calaveras, Green Valley, San Jacinto, and Newport-Inglewood fault zones in California and argued that step-overs impede or arrest the propagation of earthquake ruptures. His work suggested 1–5 km step-over widths for rupture arrest. Knuepfer (1989) compiled worldwide observations along strike-slip faults and proposed a critical step-over width of 5 km for restraining and 8 km for releasing step-overs. In a more recent study, Wesnousky (2006) studied 22 historical strike-slip earthquakes from different locations of the world and showed that around a step-

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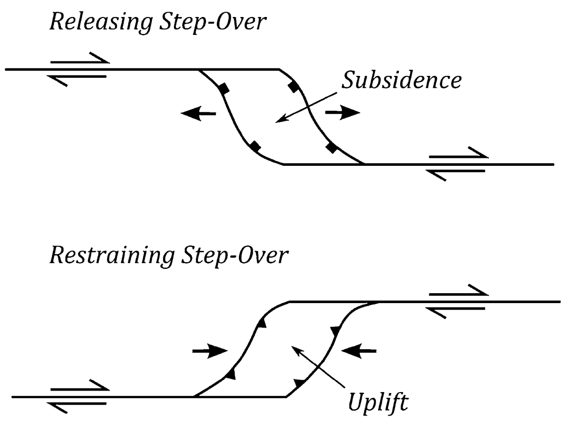

Figure 1
Types of step-overs and associated structures generated in response to tectonic stresses

over width of 3–4 km, a transition exists above which ruptures have not been observed to propagate. He also noted that for step-over widths that are smaller, ruptures appear to cease propagating only about 40 % of the time.

Harris *et al.* (1991) and Harris and Day (1993, 1999) modeled the effects of fault step-overs on dynamic rupture processes. Their 2D and 3D dynamic simulations of strike-slip faults indicated that releasing steps delayed rupture jumps relative to restraining steps. They found that the speed of rupture and the amount of overlap played important roles in the rupture jump process. Without an overlap, the rupture was unable to jump a releasing step-over as narrow as 0.5 km wide. They concluded that a strike-slip earthquake was unlikely to jump a fault step wider than 5 km. Kase and Kuge (1998, 2001) examined the effects of fault geometry on fault jump between two parallel and perpendicular strike-slip faults. Their 2D and 3D models showed that the geometry (strike and step direction; parallel faults were jumped more easily), the location of the edge of the first fault, and the depth of the upper edge of the two faults (especially whether the faults reach the Earth's surface or not) influenced the rupture propagation. Duan and Oglesby (2006) combined a viscoelastic model for stress accumulation and an elastodynamic model for the rupture process to explore the dynamics of two parallel strike-slip faults. They found that heterogeneity in fault stress due to geometrical parameters such as step-over width and along-strike overlap, and the rupture history of the fault system, can affect the distances a rupture can jump. They concluded that ruptures can jump a 4 km step-over width for a restraining case and an 8 km or more for a releasing step-over if the fault system has historically experienced many earthquakes. A young step-over with more homogeneous stress state allowed ruptures to jump smaller step-over widths. More recently, Lozos *et al.* (2012) studied the effect of an intermediate fault within the step-over region using 3D finite element modeling. They observed that for a restraining step-over, existence of an intermediate strike-slip fault that is longer than 7 km always aided rupture propagation. Intermediate fault lengths <5 km had no effect on the rupture propagation. In contrast, for releasing step-overs, an intermediate fault at various lengths mostly hindered rupture jump rather than helped it. Their results suggested that rupture propagation through releasing step-overs was more difficult than restraining ones.

In this paper, we examine these observations using the Virtual California (VC) earthquake simulator (Rundle 1988; Rundle *et al.* 2006). VC is a boundary element, three-dimensional earthquake simulation code that includes static interactions of stress (Green's functions) between fault segments using dislocation theory. Stress accumulation is by means of "backslip" (Savage 1983); a linearly increasing displacement is applied across each fault segment at a constant prescribed velocity in the opposite direction of the sense of motion of the fault. In other words, model faults slide backwards during the interseismic period to accumulate stress. This has important implications for our model results that we will explore further in the discussion section. A model earthquake occurs when the increasing stress on the fault segment exceeds the prescribed static coefficient of friction of the segment. This is a quasi-steady-state model in that faults do not grow or die. The backslip model applied to a single fault results in periodic earthquakes. But because of the interactions between faults in the VC model, the behavior of each fault is complex, not periodic. We study both releasing and restraining step-overs, but put more emphasis on releasing ones since they are six times more likely to occur in nature than restraining step-overs (Wesnousky 2006).

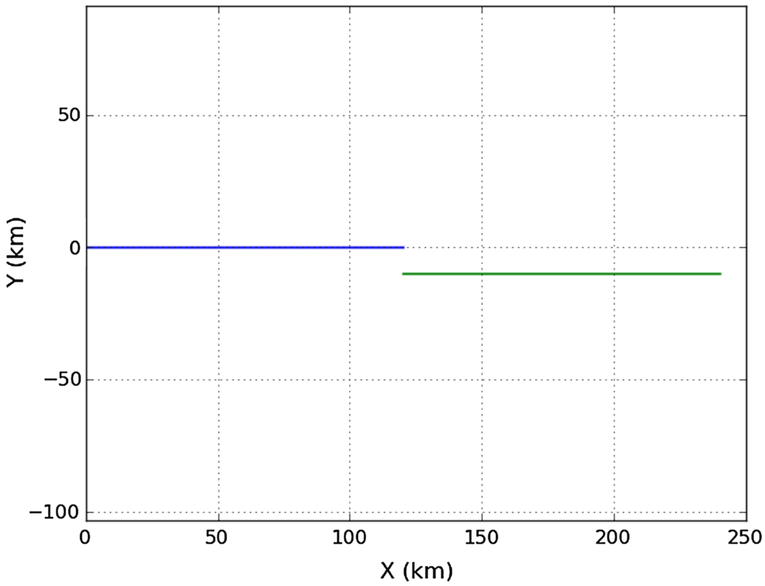

Figure 2
Plan view of jump model. Both faults have a length of 120 km and have uniform and identical physical characteristics. The case shown above represents a 10 km step-over width.

2. *Model Setting*

Our relatively simple model consists of two parallel strike-slip fault segments that are separated from each other with a step-over (Fig. 2). We vary the width of the step-over (the separation distance between the two segments) and calculate the percentage of events that jump from one segment to the next. Both fault segments have a length of 120 km and share identical physical properties. They are embedded in an elastic half–space, composed of 3 × 3 km elements and extend to a depth of 12 km (4 elements deep, see Fig. 3). There are, in total, 320 elements in the model. A backslip velocity of 2 cm/year and a mean recurrence interval of 200 years are applied to each fault element. The recurrence interval in our model determines the static coefficient of friction for a given fault element. Higher recurrence intervals result in higher static coefficients of friction. We employed a dynamic triggering value of 0.05 (high dynamic triggering) to make rupture propagation as easy as possible. Dynamic triggering is our method of modeling the stress singularity at the rupture tip. When an element fails on a fault, the difference between the static failure stress and the dynamic failure stress is reduced by the dynamic triggering factor F which takes any value

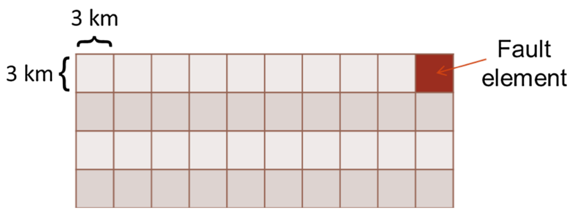

Figure 3
Cross-sectional view of a vertical model fault plane

between 0 and 1. If we define the Coulomb failure function (CFF) as;

$$\mathrm{CFF} = \tau - \sigma = 0$$

Dynamic triggering can be written as

$$F = \frac{\mathrm{CFF}_0 - \mathrm{CFF}}{\mathrm{CFF}_0}$$

where CFF_0 is the value before stress transfer. With dynamic triggering, failure occurs at a reduced value of CFF <0. When $F = 1$ there is no enhanced failure; when $F = 0$ any stress leads to failure (Rundle 1988; Rundle *et al.* 2006; Yikilmaz *et al.* 2010, 2011).

We studied both releasing and restraining step-over settings by changing the slip direction from right lateral to left lateral without changing the geometry. The model fault stepped to the right in both cases. A right lateral fault pair in this setting will generate a releasing step-over, and a left lateral fault configuration will result in a restraining step-over. We ran each model for 100,000 years, counted the number of events that involved both faults, and divided this into the total number of events to obtain a rate of step-over jumps.

3. Simulation Results

We first present results of the releasing step-over model. We systematically varied the step-over width from 1 to 20 km and observed the ratio of events that involved both faults to the total number of events during the 100,000-year simulation time. We observed that for up to 2.5 km separation distance, all events jump across the step-over. At around 3 km, the two faults start to decouple. Above 3 km of step-over distance, the number of successful jumps decreases significantly (Fig. 4). At 3.5 km, ∼84 % of all events result in rupture jump. At 4 km, the number of successful rupture jumps goes down to ∼42 %. At 5 km, only ∼17 % successful rupture jumps are observed. Above 5.5 km, the curve stays relatively flat. From this point onward the percentage of successful rupture jumps is around a few percent.

Figure 5 gives a simulated earthquake catalog of rupture jumps for a period of 3,000 years. Each half of the plot represents a model fault. A straight line going through indicates a rupture jump from one fault to the next.

Although the restraining step-over model shows a similar trend, it is clear that rupture jump is more likely in this setting. At 3 km step-over width, all events end with a rupture jump. At 4 km, 88 % of events jump. At 5 km, it's 41 %, and at 5.5 km 30 % of all events result in a successful jump. These findings are in contrast with the proposition that restraining step-overs are better barriers at stopping rupture propagation, however, it should be noted that there are only very limited observations and data sets on this matter.

We also briefly investigated how a region of overlap between two strike-slip faults, separated by a releasing step-over, affected the jump process (Fig. 6). We varied the overlap length systematically for a given step-over width and observed the ratio of successful jumps over the step-over. In general, an overlap enhances the jump process and allows earthquakes to jump further distances than a non-overlapping case. However, longer overlaps seem to be less effective in helping rupture jump than shorter ones, especially for wider step-overs (Fig. 6).

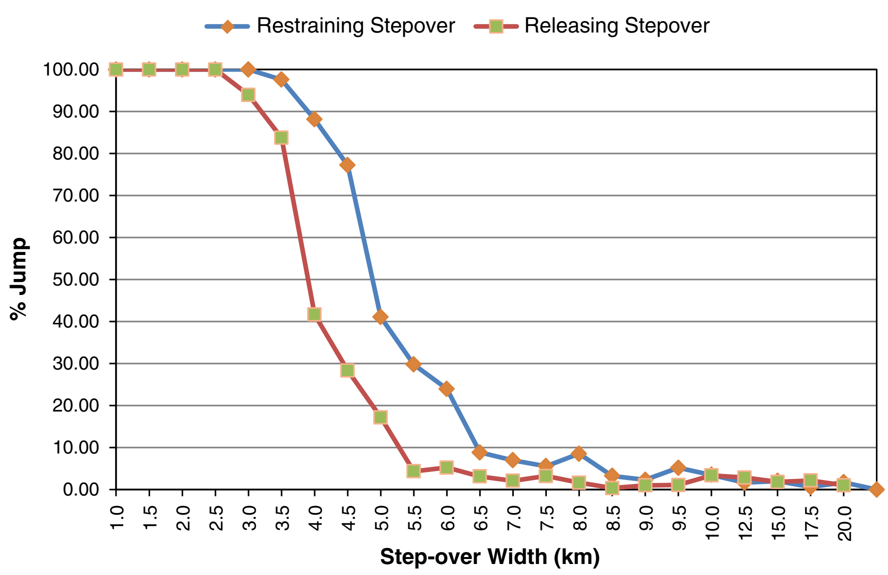

Figure 4
Percent of successful rupture jumps as function of step-over width. *Blue* and *red lines* represent restraining and releasing step-overs respectively

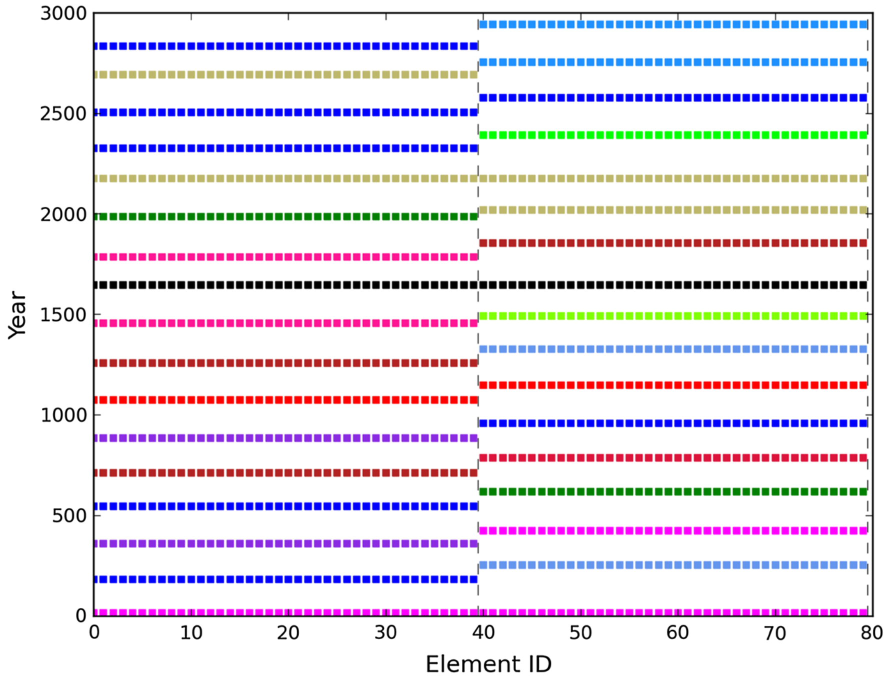

Figure 5
Simulated catalog of earthquake ruptures over a 3,000-year period. Elements 0 through 39 and elements 40 through 80 represent the two faults. A *straight line* (of the same color) between the two faults represents a fault jump. Rupture jump occurs at $t = 0$, 1,650 and 2,200. All other events occur on individual faults

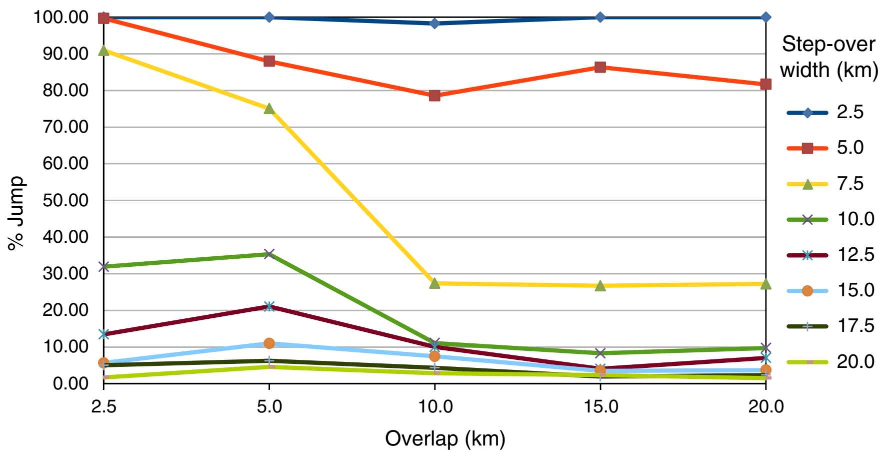

Figure 6
Percent of successful rupture jumps as a function of overlap length for the case of a releasing step-over. *Colored lines* represent different step-over separation values.

4. Discussion

In this paper we have studied the role of step-over width in arresting propagating earthquake ruptures. Our results indicate that step-over widths that are greater than about 5 km are rarely jumped. These results are in good agreement with geological field observations and other numerical and laboratory models. Although previous work suggested that releasing step-overs are more easily jumped than their restraining counterparts, in our models we find that restraining step-overs can be jumped more easily than releasing step-overs. This is most likely due to the stress accumulation method we employ in our models. Back-slip during the interseismic period reverses the sense of motion along our model faults, creating an opposite tectonic regime around the step-over region. In other words, a releasing step-over behaves as restraining during the interseismic period. We would also like to note that the hypothesis that releasing step-overs are jumped more easily is plausible, but there is not currently enough data to support it fully. Also, in all real-world cases studied to date, stepping strike-slip faults are linked together through a dipping fault (normal or reverse depending on the configuration). In our models we did not include such a link; rather, we aimed to see if the rupture would be capable of jumping over a gap without a connecting fault. OGLESBY (2005), through 3D finite element modeling, shows that releasing step-overs with linking normal faults are more prone to through-going rupture than compressional step-overs with linking reverse faults. A linking dipping fault is expected to be influential on the rupture propagation and this will be modeled in future work.

These relatively simple models can clearly be extended to study various other geometric configurations. For instance, in addition to the step-over width, the strike of one fault segment can be varied with respect to the other to see if obliquity has any influence on the jump process. Fault length and strength are other parameters that can be modified to study their influence on rupture propagation.

Another important case is stepping strike-slip faults with an overlapping region. Overlapping strike-slip faults are common in nature, and how the size of overlapping regions affects jumping is equally of interest for seismic hazard analysis. HARRIS and DAY (1999) concluded that, with no overlap, the rupture was not capable of jumping over a dilatational step-over width of 0.5 km. In our models we were able to get the rupture to propagate across step-overs with no overlapping regions. Our study into overlapping shows that a region of moderate overlap between two faults allows ruptures to jump longer step-over widths than a non-overlapping model. But increasing the length of the overlap reduces the probability of rupture jump.

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