SCEC Project 21168 – Final Technical Report
Rupture Propagation Around the Big Bend of the San Andreas Fault:
A Dynamic Rupture Modeling Case Study of the Great Earthquake of 1857
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The 1857 Earthquake

The Great San Andreas Fault/Fort Tejon Earthquake of 9 January 1857, estimated to have been ~M7.8 to M7.9 (Wallace, 1970; Sieh, 1978; Zielke et al. 2010), may have been California's largest historic earthquake. Its mapped surface rupture extends from Cholame in the north to Wrightwood in the south, for a total length of ~350 km (Wallace, 1970; Sieh, 1978; Zielke et al. 2010). Shaking from this earthquake lasted between 1 and 3 minutes, was felt as far north as Yuba City, as far south as northern Baja California, and as far east as Las Vegas (Agnew and Sieh, 1978; Stover and Coffman, 1993). In addition to strong shaking, the 1857 earthquake caused liquefaction and other hydrological effects as far away as the Santa Clara Valley and the Sacramento Delta (Agnew and Sieh, 1978; Stover and Coffman, 1993). Despite the widespread effects, due to the sparseness of California's population at the time, property loss was minimal and only two people died. Nonetheless, a modern repeat of the 1857 event would cause considerable loss of life, property, and infrastructure over a large section of California. As such, an 1857-type event is generally considered the maximum likely event for hazard calculation and earthquake preparedness in southern California (e.g., Olsen et al., 2006; Field et al., 2015).

The 1857 rupture propagated around the Big Bend of the San Andreas – a ~35° compressional bend. Previous studies of dynamic rupture around simplified bent faults suggest that compressional bends of this angle can pose a significant barrier to rupture (e.g., Kase and Day, 2006; Kame et al., 2003; Lozos et al., 2011). Consistent with this idea, paleoseismic studies show that the Carrizo Plain section of the San Andreas to the north of the bend, and the Mojave section to the south, both rupture more frequently – and out of sync with each other – than they do at the same time as each other and as the hinge of the Big Bend (Scharer et al., 2017). This suggests that the Big Bend may, along with Cajon Pass and San Gorgonio Pass to the south, also be an earthquake gate along the San Andreas Fault – and, in turn, that the 1857 earthquake may have been an exceptional event, rather than a common or characteristic earthquake, as it is sometimes considered (e.g. Schwartz and Coppersmith, 1984; Grant, 1996).

In 2017, as part of another project, I conducted some preliminary dynamic rupture simulations in which I have tried to get rupture to propagate around the Big Bend (Lozos, 2017). The concept of the Big Bend as a barrier or earthquake gate holds true in these results as well (Figure 1). I was not able to get rupture to propagate through the hinge of the bend from any direction. I therefore proposed to use dynamic rupture simulations to address the question of which conditions are necessary to replicate the rupture length and mapped surface slip of the 1857 rupture through the Big Bend of the San Andreas Fault.

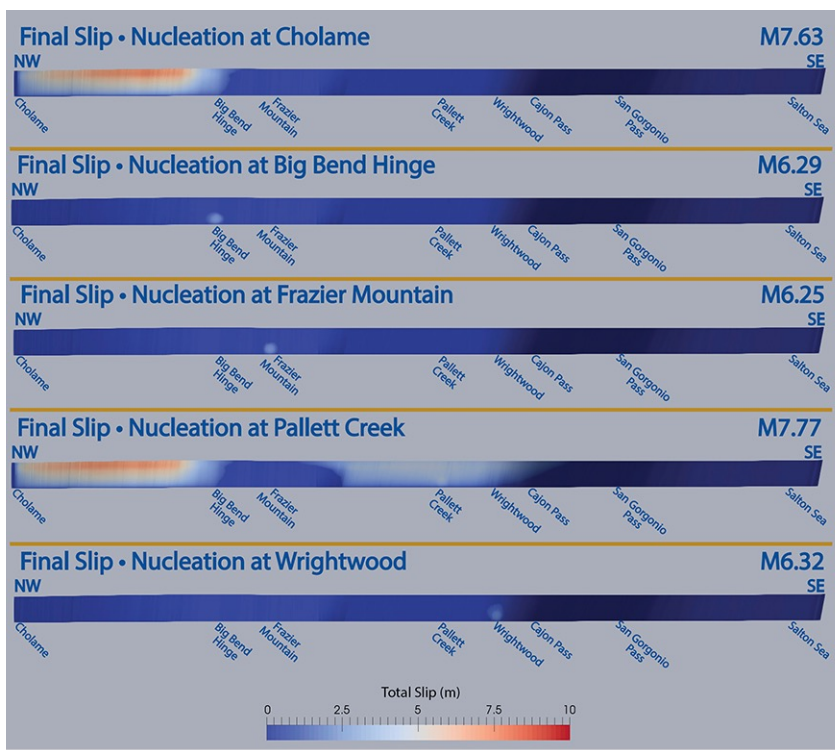

Figure 1. Slip distributions from preliminary dynamic rupture simulations in the vicinity of the Big Bend of the San Andreas Fault. Notice that, regardless of nucleation point, none of these ruptures propagate around the bend.

About This Report

When I submitted my interim report for this project in 2022, I described how the setup process for this detailed, CXM-based project required me learning to use several new tools, on top of the usual time-consuming nature of this type of project setup.

Since then, I have learned how to use many of these tools, but have also run into some other scientific/conceptual questions I needed to consider and answer about my setup before I could really answer the questions I put forth in the proposal. Additionally, given the teaching-focused nature of our department at CSUN, I also have had less time to focus on this complex project than I initially anticipated I would. For these reasons, I still have not gotten to the point where I have made a satisfactory model of the 1857 San Andreas earthquake, and have instead been focused on answering the more general questions that I will need to understand before I can properly interpret my eventual results on this work.

I still fully intend to complete these proposed models of the 1857 earthquake, and I will update the SCEC publications database once that work is done. For the rest of this Final Report, I will go through the points I made in the 2022 Interim Report, and will describe the progress I have made on them and how this sets me up better for the 1857 project.

Community Fault Model (CFM)-Based Fault Meshes

Since 2022, I have learned how to make finite element meshes using SCEC CFM geometries. I owe many thanks to Scott Marshall here, who shared his scripts that convert CFM geometries into a format that the commercial finite element meshing software Cubit can use. I am also grateful to Roby Douilly, who shared some his own approaches to using external fault geometry files in dynamic models.

I successfully used CFM fault geometry for my recent work on the Sierra Madre Fault (see report for SCEC project #22158). Especially after working with four discontinuous thrust fault segments in that project, I feel confident about making CFM-based meshes of a single continuous strike-slip fault. Additionally, from recent CFM workshops and focus groups, I know there has been some discussion of which version of the San Andreas Fault (SAF) is the best one to treat as the primary/preferred interpretation. With this in mind, I plan to mesh several SAF geometries from the CFM and see if any are better or worse at reproducing the characteristics of the 1857 earthquake.

The results of one of my other SCEC-funded projects (#18209) will also be extremely helpful for interpreting how the specific geometry of the SAF controls the rupture behavior. Some parameterizations of the SAF have several changes in dip, even in places where the strike seems linear. The most significant one is in Cajon Pass (which inspired project #18209), but there may be another smaller one as the Carrizo Segment connects into the Big Bend segment proper (e.g., Fuis, 2012). My simulations of linear-strike faults with changes of dip at depth showed that down-dip nonplanarity can affect rupture propagation in similar ways to along-strike nonplanarity, though the more planar fault surface closer to the ground surface can allow the rupture to propagate around some of these knots and kinks (Lozos, 2021). Now that I have quantified this effect over a large simplified geometrical parameter space, I will be in a better position to interpret how much the along-strike Big Bend versus the down-dip angle changes affected the 1857 rupture process and path.

Using a Newer Community Velocity Model (CVM) Version

I had already learned how to use the updated CVM-H (Shaw et al., 2015) in a general sense by the time I wrote the interim report for this project, but I had not completed any simulations with this in place yet. Now I have used the CVM-H in a completed project (Sierra Madre Fault rupture simulations, SCEC project #22158), and I know the velocity structure setup aspect of the 1857 project will be even easier with the CVM-H than it was with the old CVM-S (Magistrale et al., 2000).

Including Ground Surface Topography

Previous numerical modeling studies on other parts of the San Andreas Fault show that ground surface topography next to the fault can affect the rupture process by acting like a lens that focuses waves back onto the fault and affects the state of stress (Kyriakopolous et al., 2021). Because there are large mountains along most of the 1857 rupture trace, I think it is important to consider topographic effects as a possible factor in allowing rupture to propagate around the hinge of the Big Bend. This comes with two issues, though: first, building a fault mesh with a nonplanar ground surface; and second, determining some non-site-specific rules about how ground surface topography can affect rupture propagation.

My current Masters student, Nicholas Madera, is working on a project that approaches both of these questions. He is conducting a geometrical parameter study of how different heights and widths of fault-adjacent positive topography (hills/mountains) control rupture propagation through fault bends of different angles. So far, he is finding the same wave-focusing effects and normal stress perturbations as in Kyriakopolous et al.'s (2021) Cajon Pass work, and he is working on untangling how much of this effect comes from topography height versus width, and at what point the fault geometry matters more than the topography, and vice versa (Madera and Lozos, 2023). Nicholas is on track to complete his thesis in Summer of 2024. His results put me in a much better position to interpret which effects I might see in my 1857 models are specifically related to the presence of the Transverse Ranges.

Teaching Nicholas how to make fault meshes for his thesis work required that I also learn how to set up meshes with bumpy surfaces, and how to adjust the FaultMod input files to handle them. This luckily turned out to be much more straightforward than I expected; I am no longer concerned that having a highly complex ground surface will prevent the model from running. I have not yet tried to use the topographic high points encoded in the CVM to build a mesh surface that includes mountains and valleys. However, as part of a non-SCEC project I am working on about interactions between the Marlborough Fault System and the Alpine Fault on the South Island of New Zealand, I am building a mesh using a DEM to define the ground surface. I expect that I will be able to use the workflow from this project for building my San Andreas mesh as well.

More Complex Initial Stresses

Many of my previous studies approached incorporating stress complexity in a way that is ultimately still simple: by resolving a uniform stress tensor onto a nonplanar fault geometry at observation-based maximum horizontal compressive stress (S_{Hmax}) angles, which results in heterogeneous on-fault stresses. In my Interim Report for this project, I said that I wanted to learn how to use the much more heterogeneous and realistically-complex SCEC Community Stress Model (CSM; Yu et al., 2013) S_{Hmax} and stress amplitudes (where available) in my model setup. I learned how to do this in the course of my Sierra Madre Fault models (SCEC project #22158). I got SHmax orientations and local principal and differential stresses from Luttrell and Smith-Konter (2017), then assigned these directly to each node of the fault (Figure 2). Getting this to work in my dynamic simulations was complicated, both from a sign conventions standpoint, and from the more philosophical standpoint of what scale of heterogeneity is actually realistic to consider. I did eventually get this to work, though, and I now have the scripts and workflow in place to use CSM stresses in future simulations (including those for the 1857 earthquake).

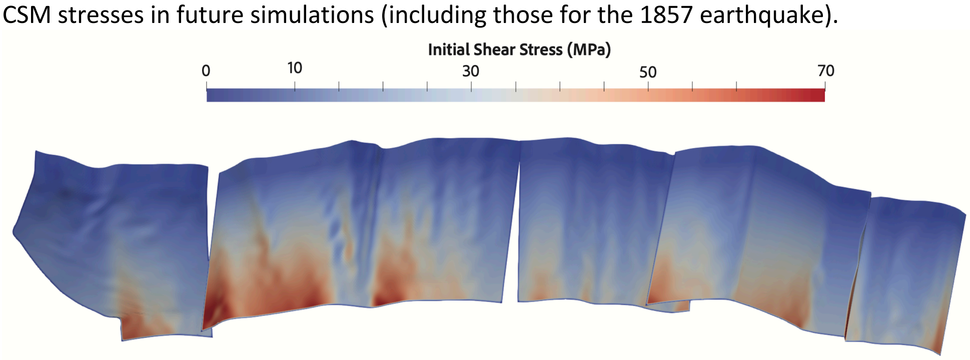

Figure 2. Example of CSM-based initial stresses on the CFM geometry for the Sierra Madre Fault Zone. My eventual models of the central/southern San Andreas Fault will have similarly complex initial stresses from using this method.

During my preliminary work on the 1857 earthquake (Lozos, 2017), I found that a regional stress field alone did not allow rupture to propagate through the Big Bend. While it remains to be seen how a CSM-based stress field will change this, my preliminary models were still consistent with paleoseismic evidence that the Carrizo section and the Mojave section of the SAF, on either side of the Big Bend, rupture separately about as often as they rupture together (Scharer et al., 2017). Together, this implies that an 1857-style rupture may be more uncommon than it is characteristic, and that stress accumulations from multiple earthquake cycles may be necessary to promote this type of event. In the course of my current collaboration with GNS Science on ruptures through a nonplanarity in the center of the Alpine Fault in New Zealand, I have developed scripts to take the final stresses from one dynamic rupture simulation, increment the shear stress based on long-term slip rate, and calculate which spots on the fault are closer to failure based on slip-weakening and Coulomb friction criteria. This means my modeling can now span multiple earthquake cycles, and incorporate both coseismic and interseismic stresses into the initial conditions for each subsequent dynamic model in a set (Figure 3). Now that I have made these scripts, I will easily be able to adapt them to the 1857 project, and to incorporate stresses from the SAF's longer-term rupture history (on top of CSM-based and topography-related stresses).

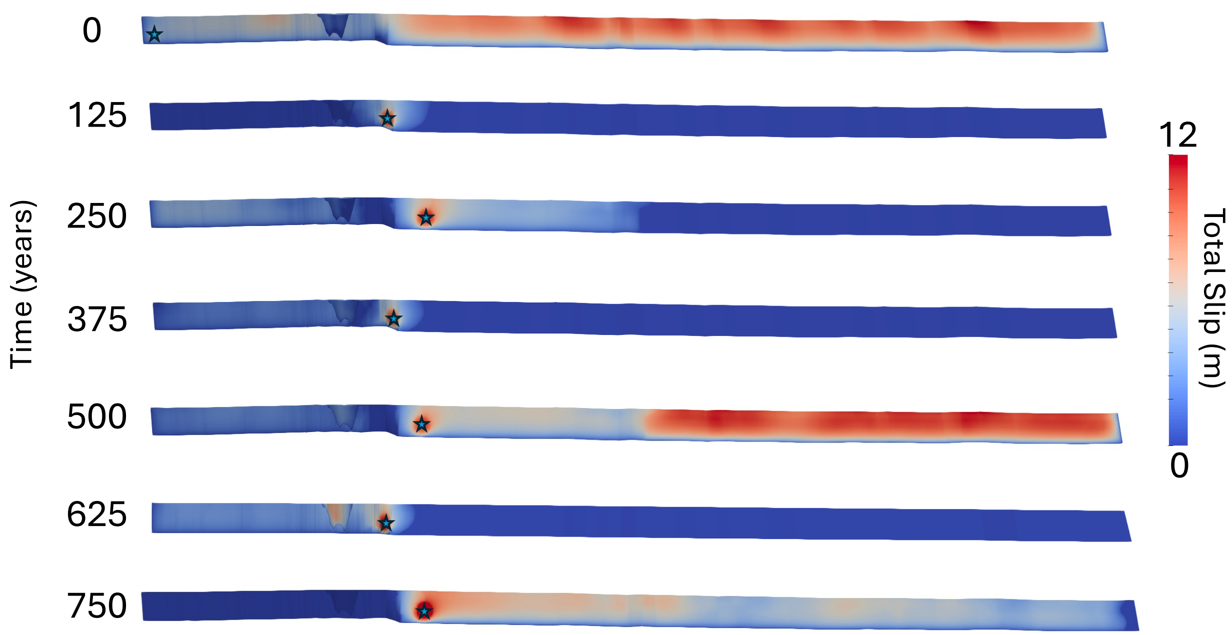

Figure 3. A series of slip distributions for multiple-cycle dynamic rupture simulations on the Alpine Fault, New Zealand. The star marks the hypocenter. Notice how the geometrical complexity about a third of the way along the fault behaves as an earthquake gate – letting ruptures through at some times and stopping them at others. I will be able to set up San Andreas Fault simulations using the same scripts that I used for these Alpine Fault models.

What's Next?

When I originally submitted this proposal to SCEC, I thought I was in a better position in terms of having the time to develop the new skills I needed to set these simulations up in the way I wanted. It quickly became apparent that this was not the case, and that I needed to address learning new tools and isolating factors that might eventually make or break a plausible simulation of the 1857 San Andreas earthquake on more of a one-by-one basis, and not all at once in a big project like this. Now that several years have passed, though, I actually am at a point where I have the required tools, skillsets, and additional understanding of how generalized geometrical details can affect rupture behaviors, to do what I proposed in for this project. Since I am now well past the end of the official project period, I am going to focus on finishing up several other late-stage projects before I return to the 1857 earthquake. I do, however, fully intend to pick this project back up, and to eventually have a publication about it to add to the SCEC database. Thank you for being patient with me on this project that has not at all gone as planned.

Publications Based On This Work

Since this work is still very unfinished, I do not yet have any publications based on it. Once this project has reached the point of a manuscript submission, I will enter it into the SCEC database, and will update it as the paper progresses through the peer review process.

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