Plasticity and Off-Fault Deformation in the 1971 M_w 6.6 San Fernando Earthquake

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Abstract

Slip and off-fault deformation both occur during an earthquake, with the former measured on the fault and the latter away from it. Significant off-fault deformation was measured for the 1971 San Fernando Earthquake, in which the steeply-dipping Sylmar segment, which passes through soft near-surface sedimentary layers, experienced a higher percentage of vertical off-fault deformation compared to the shallower-dipping Tujunga fault segment, which passes through firmer sedimentary rocks (Gaudreau et. al 2023). Our aim is to learn about what may have caused this off-fault deformation and its heterogeneity by performing dynamic rupture modeling and analyzing the effects of the different fault geometries and material properties. We compute 2D dynamic finite element models using the FaultMod code (Barall 2009), varying parameters such as stress, material properties, friction, cohesion, and fault geometry to understand how they affect slip and ground motion. We find that bulk friction and cohesion and their interaction with nonplanar, dipping fault geometry can significantly impact the generation of off-fault failure and deformation, in some cases producing higher slip in models with plasticity than in otherwise equivalent elastic models. In addition, we observe qualitatively more vertical off-fault deformation within 1 km of the fault trace in our models for the Sylmar Segment than in our models for the Tujunga Segment, in agreement with observations.

Introduction

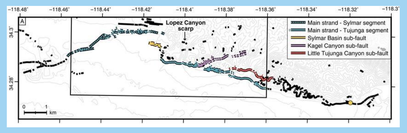


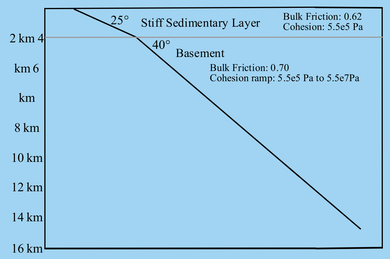
Fig 1. Surface rupture of the 1971 San Fernando earthquake. (Gaudreau et al. 2023).

- There was significant off-fault deformation (OFD) for the 1971 San Fernando Earthquake.
- There was more vertical OFD in the Sylmar fault segment (81%) than the Tujunga fault segment (64%), with such deformation typically concentrated on the hanging wall side of the fault.

Question

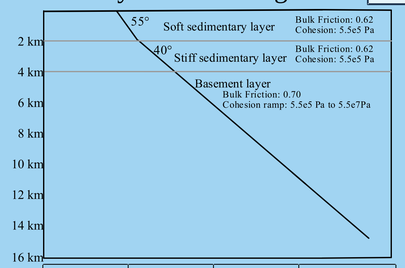
What may have contributed to the difference in OFD for the Sylmar and Tujunga Fault Segments?

Tujunga Fault Segment



	Vp (m/s)	Vs (m/s)	Density (kg/m³)
Stiff sed. layer	3100	1600	2300
Basement	6000	3464	2670

Sylmar Fault Segment



	Vp (m/s)	Vs (m/s)	Density (kg/m³)
Soft sed. layer	2400	1200	2000
Stiff sed. layer	3100	1600	2300
Basement	6000	3464	2670

Finite Element Model

We use the 2D dynamic finite element method (Barall 2009) to model the Sylmar and Tujunga fault segments separately. In our models, we use Drucker-Prager plasticity and observe changes to fault slip and surface deformation as we vary cohesion and bulk friction both in high and low friction scenarios.

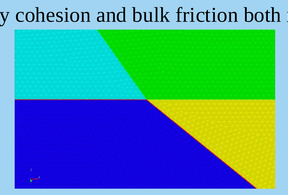


Fig 2. Example of the mesh used for the finite element models.

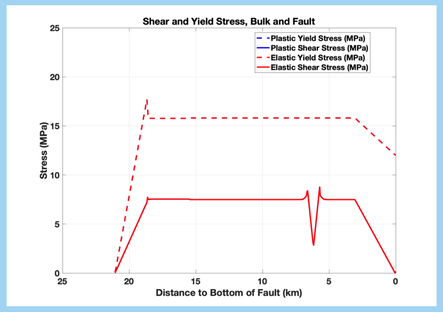
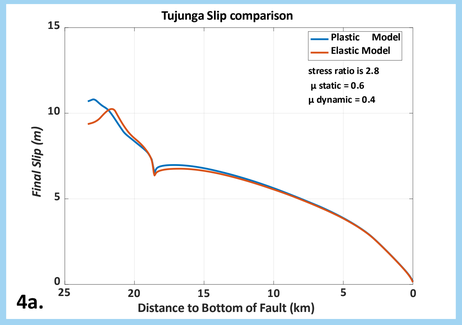
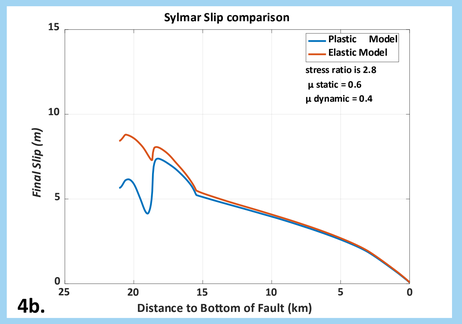
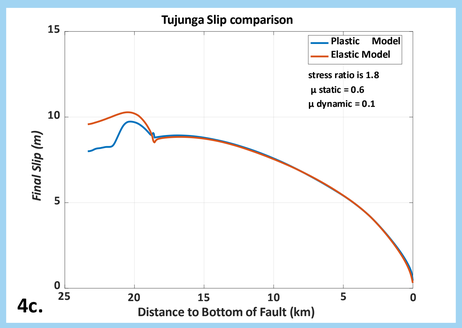


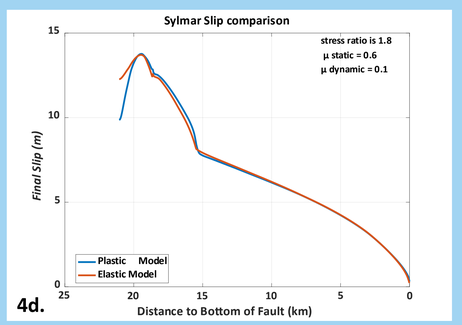
Fig 3. Shear and yield stress at 0.5 seconds for the Sylmar Fault Segment. Note constant effective stress below the fault bend.

Fault Slip



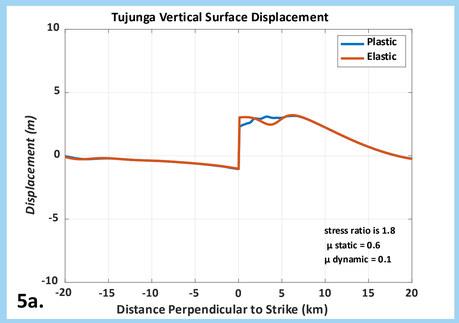


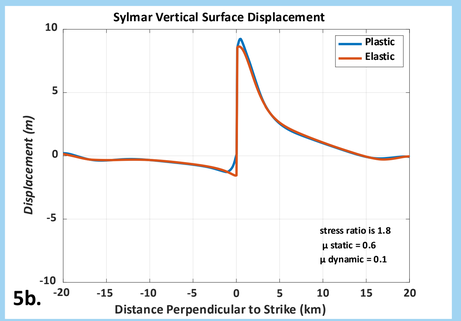


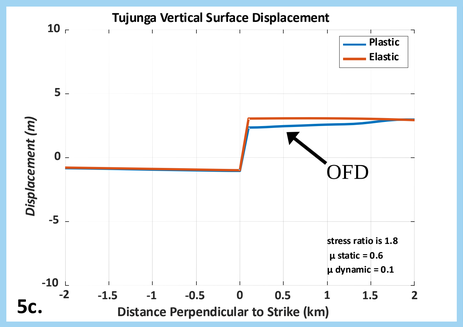


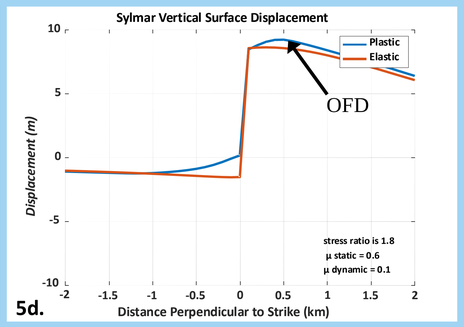
We compare fault slip for the elastic and plastic models of the two fault segments. In all cases, we see a difference in the amount of slip between the elastic and plastic models. Our elastic models tend to have more pull back at the surface, especially in our high friction models (i.e. Fig 4a).

Vertical Surface Displacement Including Off-Fault Deformation









The figures above compare the vertical displacement including off-fault deformation for the Sylmar and Tujunga fault segments. We use our low friction friction models to observe the vertical surface deformation for the Sylmar and Tujunga fault segments. Figures 5a and 5b show a zoomed-out comparison while figures 5c and 5d show the comparison zoomed in at 2 km away from the fault, where the data from Gaudreau et. al (2023) was taken. Qualitatively, we are observing more OFD in the Sylmar fault segment however, we are still tuning our models to more closely fit the data that was measured.

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Discussion

- The bulk friction and cohesion can make a difference in how plastic our models behave.
- We observe pull back at the surface, most noticeable in our elastic models.
- Qualitatively, we can see more vertical off fault deformation in the Sylmar segment than the Tujunga segment.
- In the future, we plan to use 3D finite element models to further study the difference in off-fault deformation between the two fault segments by viewing both the vertical and horizontal displacement.

References

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