The Effects of Bulk Friction and Cohesion in 2D Dynamic Models of the 1971 San Fernando Earthquake

Guadalupe Bravo[1], David Oglesby[1], Élyse Gaudreau[2], Gareth Funning[1], Edwin Nissen[2], James Hollingsworth[3]
University of California, Riverside[1] University of Victoria[2] Universitè Grenoble-Alpes[3]
Contact: gbrav011@ucr.edu

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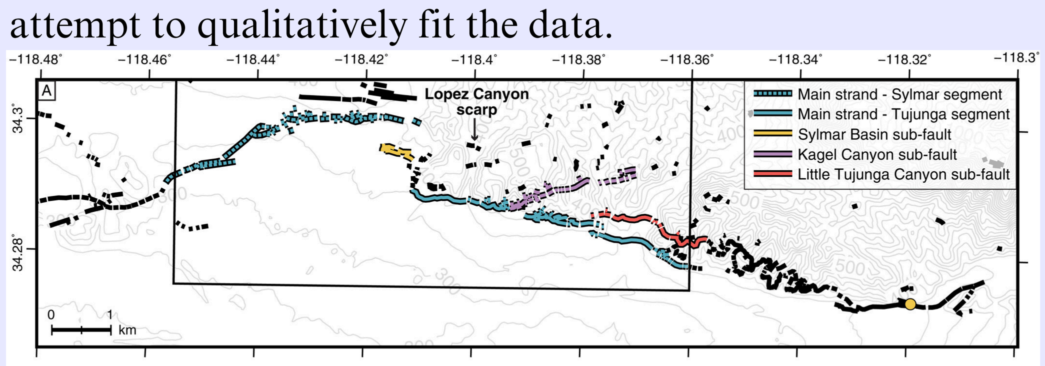
Off-Fault Deformation

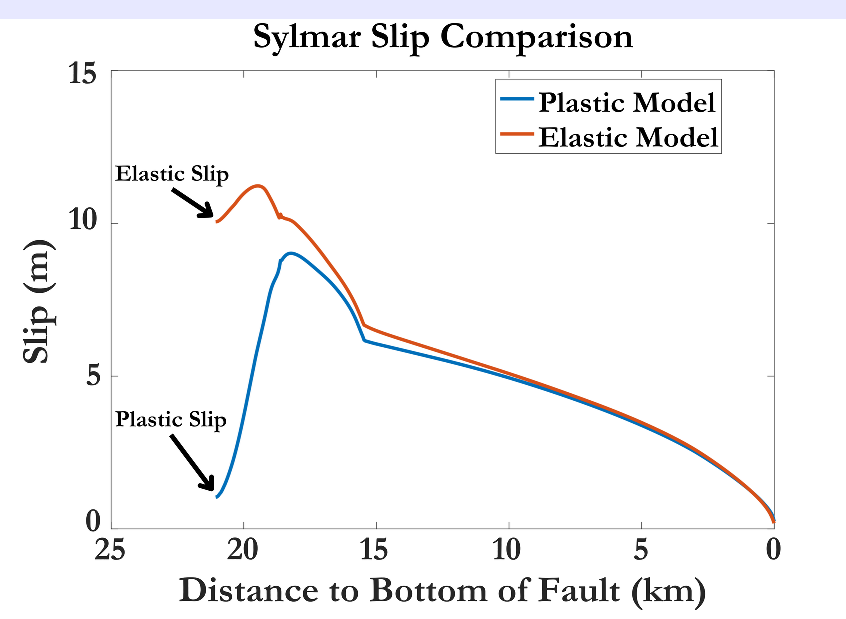
Off-fault deformation (OFD) is observed to varying degrees in all surface-rupturing earthquakes and may hold critical information about rupture processes. The 1971 San Fernando earthquake exhibits a particularly intriguing pattern of OFD where there was more vertical OFD in the Sylmar fault segment than the Tujunga fault segment, with such deformation typically concentrated on the hanging wall side of the fault. We explore the physical process underlying this observation via plastic material behavior. We perform a parameter study on the competing effects of bulk friction, cohesion, and fault geometry, and then attempt to qualitatively fit the data.



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

Calculating the difference between Elastic and Plastic models

We explore 2D elastic and plastic models, which are two different models for how materials behave when you apply forces to them.



To calculate the percentage difference between the two models , we take the difference between the two models' slip at the surface, divide by the elastic slip at the surface, then multiply by 100.

$$\frac{\text{Elastic Slip} - \text{Plastic Slip}}{\text{Elastic Slip}} \times 100$$

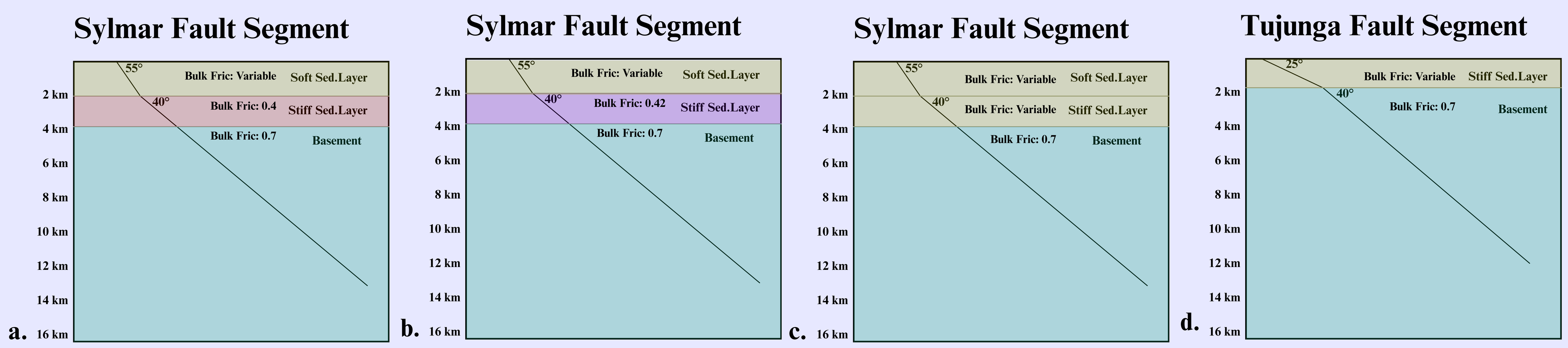
To calculate the vertical displacement we take the slip at the surface for each of the models and multiply it by the sin of the dip angle.

Research Questions

1. How do bulk friction and cohesion interact to modify fault slip and vertical displacement relative to perfectly elastic models?
2. What range of parameters are qualitatively consistent with observations of OFD in the San Fernando Earthquake?

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 in different scenarios. Our models also incorporate depth-dependent stress with fluid overpressure below 2 km depth to avoid artificially high slip.



a.

	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

b.

	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

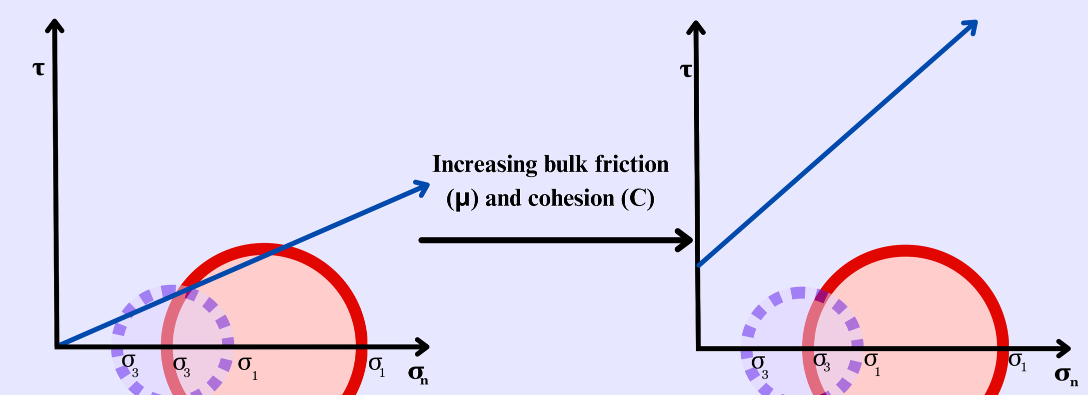
c.

	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

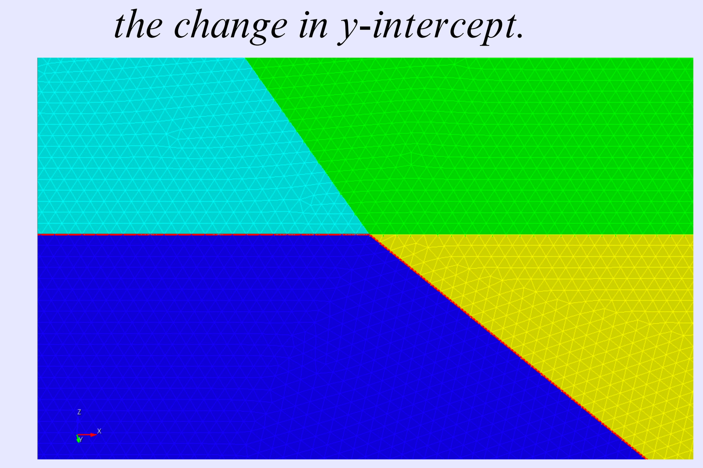
d.

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

We ran models for different combinations of bulk friction and cohesion. For panel a (Sylmar), the top layer varied in bulk friction while we had a constant bulk friction of 0.4 for the stiff sedimentary and 0.7 basement layer. For panel b (Sylmar), the top layer varied in bulk friction while we had a constant bulk friction of 0.42 for the stiff sedimentary and 0.7 basement layer. For panel c (Sylmar), the top two layers varied in bulk friction while the basement layer stayed constant at 0.7. For panel d (Tujunga), the top layer varied in bulk friction while the basement layer stayed constant.

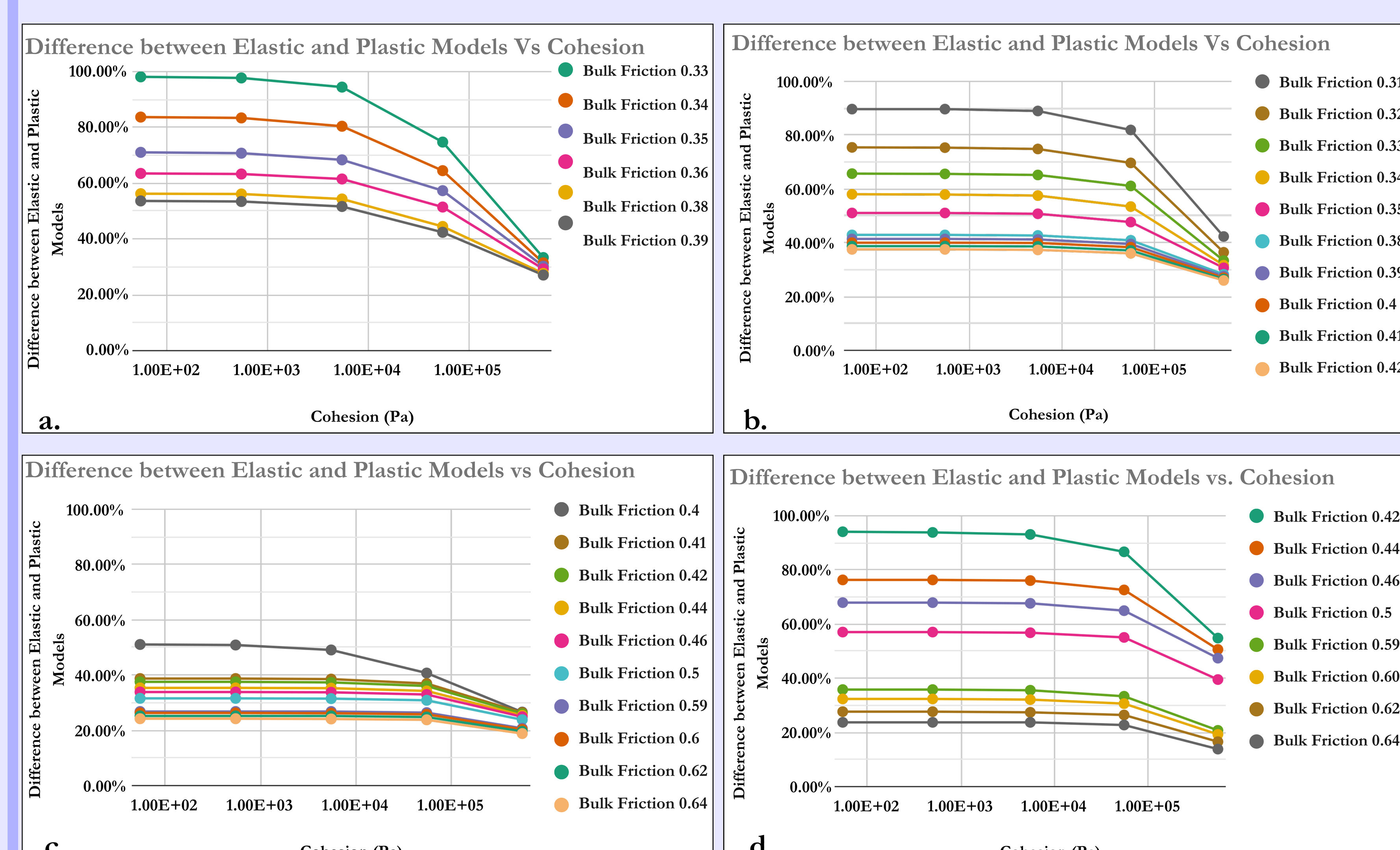


Above is an example using mohr circles. We can decrease plasticity by increasing bulk friction, shown by the change of slope in the figure above, or increasing the cohesion, shown by the change in y-intercept.



Example of the mesh used for the finite element models.

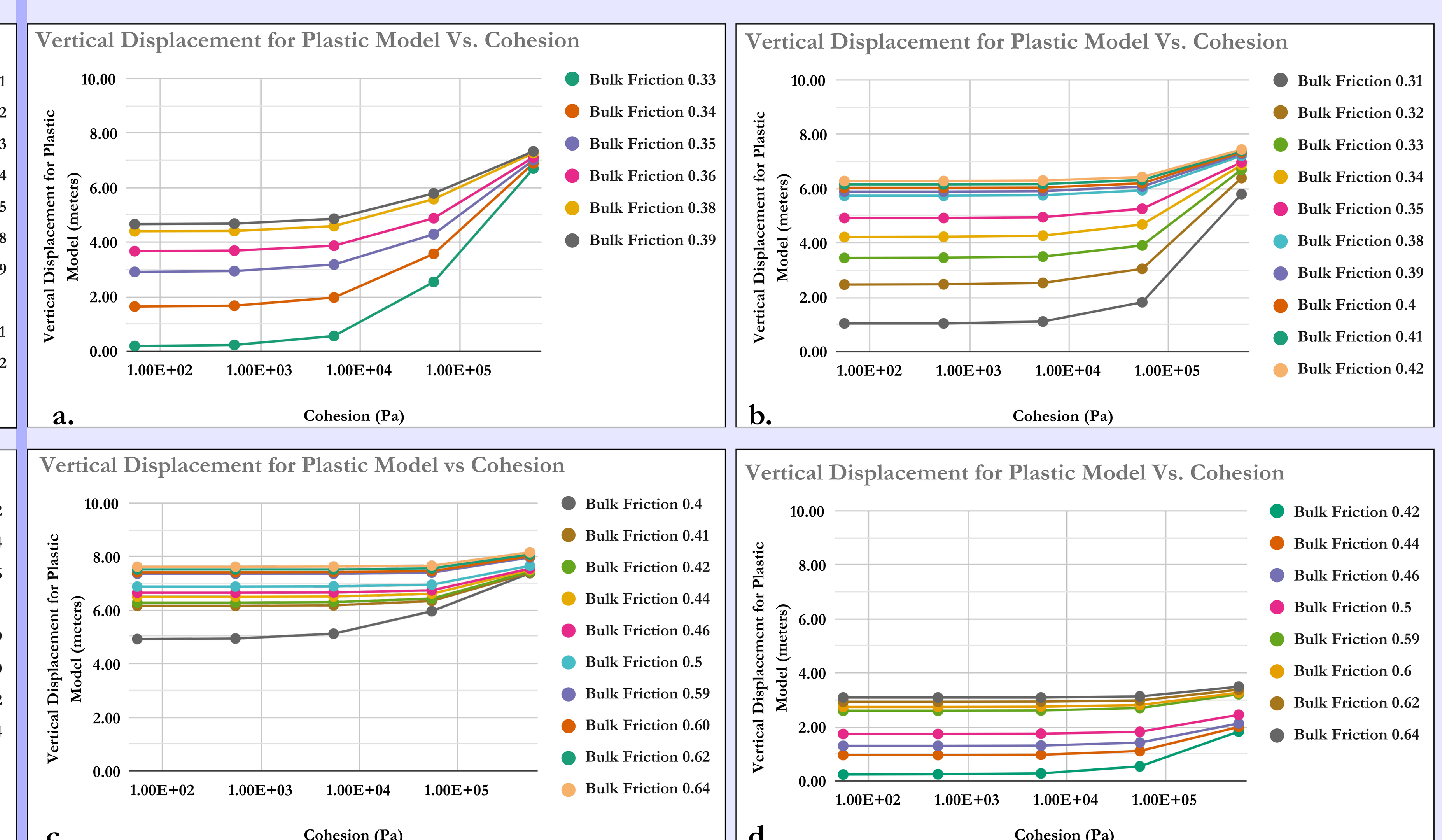
Difference between Elastic and Plastic Model



The figures above compare the difference between our elastic and plastic models where the closer the percentage is to 100%, the more plastically our model behaves. Panels a, b, and c correspond to models for the Sylmar Fault Segment while panel d corresponds to the Tujunga Fault Segment.

For each case, we tested the bulk friction with the following cohesion in the top layers: 5.5e1, 5.5e2, 5.5e3, 5.5e4, and 5.5e5 and a ramp going down to 5.5e7 in the basement layer.

Vertical Displacement for Plastic Models



The figures above compare the vertical displacement for each of the different cases. Panels a, b, and c correspond to models for the Sylmar Fault Segment while panel d corresponds to our Tujunga Fault Segment model. We observe less slip on the fault and more off-fault deformation in the plastic models with lower values of bulk friction and cohesion, qualitatively fitting the data better.

References

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Discussion

- As we decrease the bulk friction and cohesion parameters, our models diverge from our elastic models for both the Sylmar and Tujunga fault segment models.
- For low values of bulk friction, the cohesion takes on increased importance near the surface
- Our models with smaller bulk friction and cohesion values have less slip and more off-fault deformation at the surface than those with larger bulk friction and cohesion.
- For low values of bulk friction and cohesion, the surface slip and deformation are extremely sensitive to the change in bulk friction making the fitting of observations in this case challenging.