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Final Technical Report

Testing the Quality of Geodetic Fault Slip Rates by Explicit Consideration of Spatial Correlations

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Summary

Although potentially minor in comparison to epistemic uncertainties, the inclusion of spatial correlations between data when solving for model parameters such as fault slip rate is important to consider. This is also particularly important as projects such as the Community Geodetic Model progress to produce dense geodetic solutions including both GNSS and InSAR velocities. With such a density of points, assumption of independence and lack of accounting for spatial correlations (a) inherent in the data and (b) as a consequence of physical phenomena that generate and perturb the observed velocities will over-average and under-estimate the formal uncertainties associated geophysical parameter estimates, which may lead to meaningful discrepancies with other methods or put too much confidence in . Just as temporal correlations between data points in a GNSS time series is known to increase the magnitude of velocity uncertainties by a several (e.g. 3–5) times, so accounting for spatial correlations between geodetic data points is likely to result in the uncertainties associated with geophysical parameters such as fault slip rates to increase by several times. Correlations between model parameters such as creep rate and locking depth are also likely to introduce a factor of up to three when estimating moment deficit accumulation rate; however, as the parameters are negatively correlated, this may still be a useful approach to estimating such a quantity, bearing in mind these limitations.

Correlations between data in geodetic solutions

Significant formal covariances already exist in geodetic velocity solutions, which may be seen in the full covariance matrix of GNSS velocity solutions, such as the ITRF2014 global solution. This demonstrates that the assumption of truly independent geodetic velocities, which is commonly implicit in current work, is not necessarily valid. The factor by which uncertainties are underestimated may also be understood by exploring the full variance space of geodetic solutions in comparison to common direct inversion techniques, such as fitting arc-tangent functions (e.g. Savage and Burford, 1973) to fault-perpendicular velocity profiles or block models. Using my GNSS velocity solution for the North San Francisco Bay Area (supported by USGS EHP Award G18AP00051), both these techniques produce fault slip rate sigmas for the three strike-slip faults in the region (San Andreas, Rodgers Creek and Green Valley) of around 0.1–0.2 mm/yr, which is equivalent to a 95% confidence interval of about 0.2–0.4 mm/yr. However, Figure 1 shows the results of a Monte Carlo Markov Chain estimation from the same cross-fault profile. Clearly the 95% confidence interval is more in the range of approximately 1 to 1.5 mm/yr, which is four to five times smaller than the direct inversions assuming independent data. Fully accounting for spatial correlations between the data is likely to provide a similar factor by which the uncertainties are underestimated.

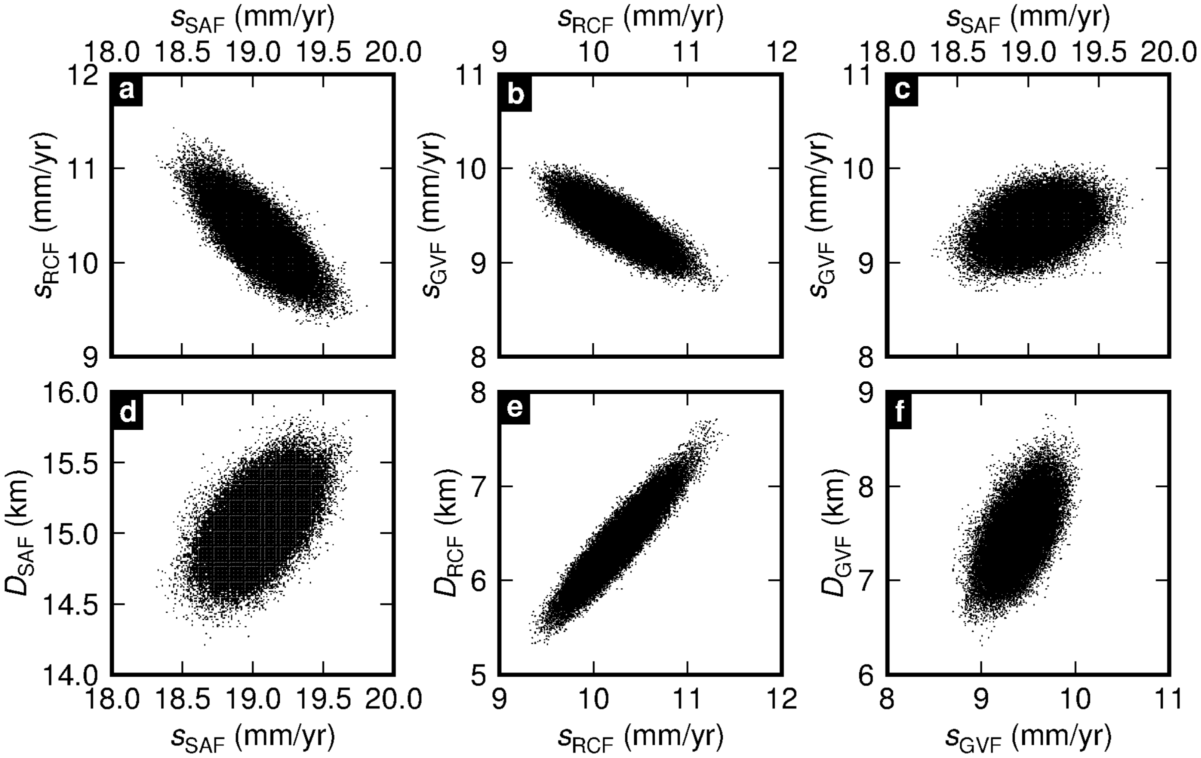

Figure 1: Results of Monte Carlo Markov Chain analysis for three parallel strike-slip faults in northern California (San Andreas, Rodgers Creek and Green Valley), showing both the confidence intervals and trade-offs (correlations) between the model parameters when the range. Direct inversion by a least-squares method or block model yields slip rate sigmas of 0.1–0.2 mm/yr (i.e. 95% confidence interval of 0.2–0.4 mm/yr), whereas the confidence interval for slip rates here is about 0.8–1.5 mm/yr for all three faults.

As part of the exploration of the data space, I also investigated the relationship between different geophysical parameters (fault slip rate, locking depth and creep rate) to understand how these interactions may also relate to their formal uncertainties versus their our estimates, and affect our confidence regarding quantities that are carried forward to derivative products such as probabilistic seismic hazard assessments.

Correlations between creep and locking depth in geophysical inversions

Correlations between the data points are not the only ones to have an effect on meaningful geophysical parameters. The correlations between model parameters and information gained about the physical phenomena, including often-sought and cited quantities such as moment deficit accumulation rate and earthquake recurrence interval, is also important. This is particularly true in the case where common models, such as the Savage and Burford (1973) arc-tangent formulation commonly employed for strike-slip faults, are violated by what we know about the solid Earth, for example the physical meaning of "locking depth" and inference about creep rate at various depths in the crust. To this end, I explored the impact of creep rate (or coupling coefficient) on estimates of slip rate and locking depth using arc-tangent formulation.

Intuitively, it is clear that a fault that is creeping fully at the long-term slip rate will produce a step-function of velocity across the fault. If this is nevertheless modeled using the arc-tangent formulation, the solution is the limit where locking depth goes to

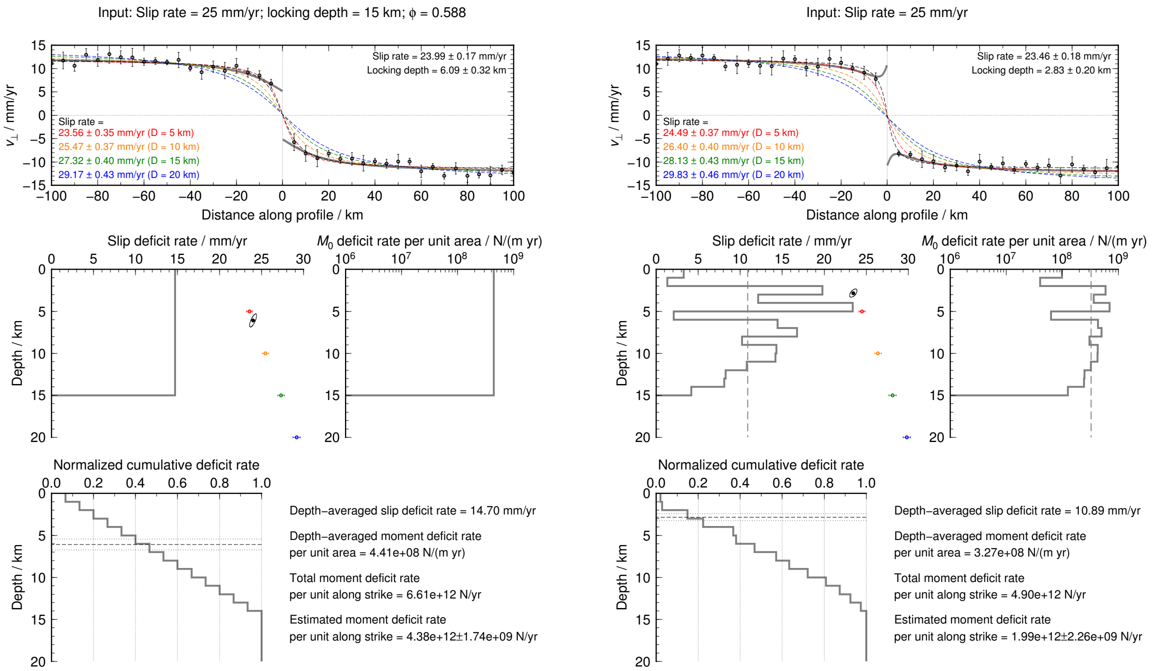

Figure 2: (Left) One synthetic setup from the 100 uniform creep rate experiment described in the main text. The grey line represents the true surface velocity profile expected based on the slip rate deficit depth profile shown in the middle-left plot. Red, orange, green and blue dashed lines in the top plot and points in the middle-left plot are slip rate estimates when locking depth is fixed to 5 km, 10 km, 15 km and 20 km, respectively; the black dashed line is the solution when locking depth is also estimated as a free parameter. (Right) One synthetic setup from the 100 variable creep rate experiment described in the main text.

zero. It follows that locking depth is correlated with creep rate, or the proportion of the long-term slip rate that is not accumulating to be released in a future earthquake.

Given the ubiquitous nature of fitting arc-tangent functions to profiles of geodetic velocity across faults, I explored the impact of this assumption on the geophysical parameters of slip rate and locking depth; I then extended the analysis, hypothesizing that there nevertheless may be a useful relationship to moment accumulation and recurrence interval, given that these rely on area of the fault, which is related to the estimated locking depth.

I performed two synthetic experiments, one in which the creep rate was uniform between the surface and the locking depth (e.g. Figure 2), and one in which the creep rate was allowed to vary with depth (e.g. Figure 3), which is likely to be more realistic. The former experiment is known in the UCERF models as the "coupling coefficient" and the latter is somewhat of a hybrid combination of UCERF's "coupling coefficient" and "aseismic factor". For each experiment, one hundred iterations of synthetic inputs were generated at random distances from the fault, with velocity perturbations assigned by random noise, and fit using a non-linear least-squares approach to solve for slip rate and locking depth.

The maximum slip rate for each experiment was 25 mm/yr and the maximum allowable locking depth was 15 km. In the case of the uniform creep rate, the coupling coefficient is defined as $1 - c/s$, where c is the creep rate and s is the long-term fault slip rate; in the case of the variable creep rate, c is defined as the depth-averaged creep rate (integrated creep rate over depth).

The correlation between locking depth and slip rate for both uniform and variable creep rate is seen most readily in the middle-left plots of Figure 2. As locking depth is increased, either artificially by fixing the locking depth while or as a result of trying to imitate the high localized strain rate induced by creep on the fault, the slip rate also increases. However, slip rate, in general, is still estimated within about 10–15% of its input value, although this is mostly determined by the far-field data, which has the most control over this quantity but is greatly affected by the influence of other, parallel faults in the region. In this synthetic experiment, only one fault is considered but it is important to note that this situation is unrealistic for southern California and this work should be extended for the case of multiple faults with overlapping (and interacting) fields of deformation to more fully assess the influence of model parameter correlations.

The correlation between creep rate and locking depth is most readily seen in the upper plots of Figure 3. As the coupling coefficient decreases (creep rate increases), so does the locking depth that is estimated assuming that the fault is fully locked, as is implicit in a lot of modeling approaches. Again, the slip rate estimate is seen to vary little around its true input value.

This intuitive yet often overlooked trade-off between fault model parameters led me to investigate whether or not such correlations and uncertainties ultimately would

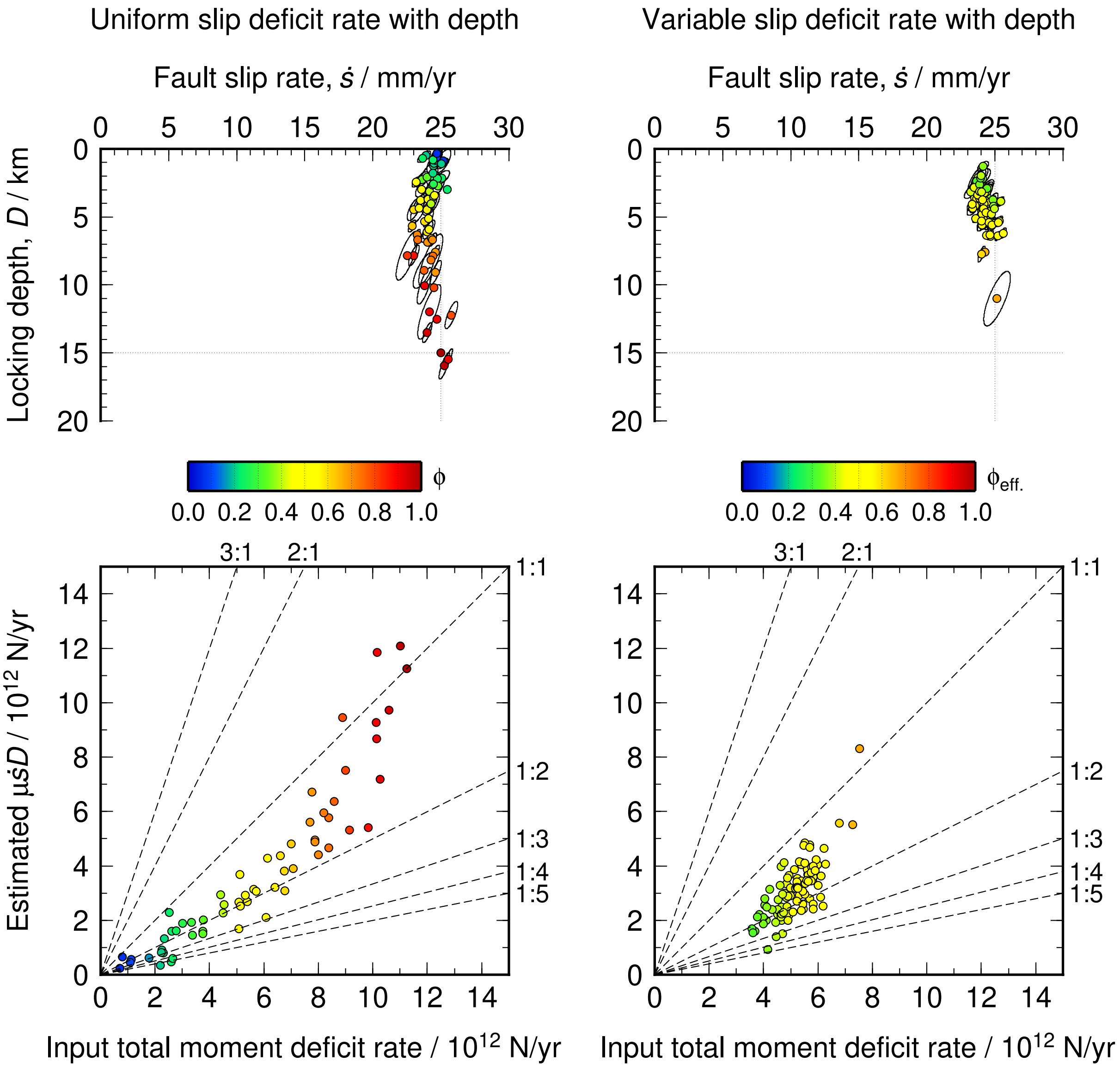

Figure 3: Estimates of slip rate and locking depth (top row) for the 100 uniform creep rate (left column) and 100 variable creep rate (right column) experiments. For the uniform creep rate experiment, the input slip rate is 25 mm/yr and locking depth is 15 km. Equivalent comparison of input versus estimated moment accumulation rate (per unit length along strike) is shown in the bottom row for both experiments.

have a meaningful impact if viewed from the perspective of moment accumulation. First, the negative correlation between creep rate and locking depth (estimated assuming full coupling) effectively means that lower slip deficit accumulation rates are manifest as smaller areas over which the estimated fault slip rate is occurring, given the common approach of Savage and Burford (1973) or block models with full coupling. Moment (or potency) accumulation rate includes both the slip deficit accumulation rate and the area over which that is occurring. The ultimate effect of the correlations

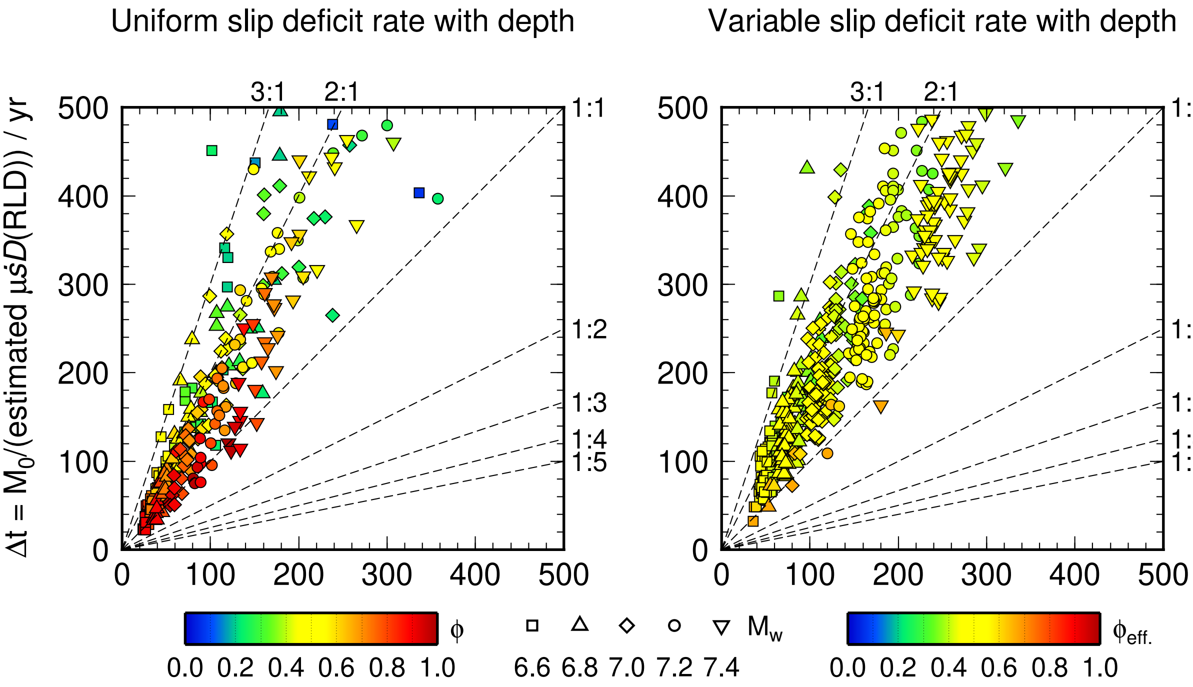

Figure 4: Uncertainty of earthquake recurrence time, based on the Wells and Coppersmith (1994) relationships between moment magnitude and rupture length at depth for strike-slip faults to convert estimated moment accumulation per length along strike to seismic moment.

between each of these model parameters when considered in the framework of moment accumulation (per unit length along strike) is seen in the lower plots of Figure 3. Expressed this way, it becomes evident that moment accumulation rate, even under the influence of competing and implicitly neglected geophysical parameters described above, generally is accurate to less than a factor of two, i.e. the estimated moment accumulation rate may be underestimated by up to a factor of approximately two. Although the coupling coefficient (creep rate) relates to the overall moment deficit rate, it does not appear to have much of a correlation with this underestimation factor.

Finally, I present this same information in terms of earthquake recurrence time, assuming full release of the accumulated seismic moment during the intervening period in an earthquake of a given size (from M_w6.6 to M_w7.4). I use the Wells and Coppersmith relationships between moment magnitude and rupture length at depth for strike-slip faults to convert my estimates of moment accumulation rate per unit length along strike to seismic moment, given a particular moment magnitude of earthquake. From there, the recurrence interval of that magnitude of earthquake is simply the seismic moment divided by my estimated moment accumulation rate per length along strike. When compared to the input (known) fault parameters used to generate the data that is then inverted (e.g. Figure 2), again the impact of competing and implicitly neglected geophysical parameters on the estimated recurrence interval is seen. Figure 4 shows that, independent of coupling coefficient (creep rate) or moment magnitude of eventual earthquake, the recurrence interval from my synthetic experiments is generally overestimated by up to a factor of three.

Conclusions

The results of these real-data and synthetic experiments demonstrate that estimates of common geophysical parameters, such as fault slip rate and locking depth, when based on incomplete covariances matrices and/or physical models (such as those that should include an explicit estimation of coupling coefficient or creep rate), have uncertainties that are likely to be underestimated by a factor of at least two to three.

References

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Wells, D. L., and K. J. Coppersmith (1994), New Empirical Relationships among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement, *Bull. Seismol. Soc. Amer.*, *84*, 974–1002.