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Geoscientific Model Development Discussions

Interactive comment on "A global,spherical,finite-element model for postseismic deformation using ABAQUS" *by* Grace A. Nield et al.

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We thank the reviewer for these suggestions and have responded to the detailed comments in line below.

-Review of "A global, spherical, finite-element model for postseismic deformation using ABAQUS" by Nield and co-authors.

-The manuscript represents an implementation of postseismic viscoelastic relaxation problems in a widely used finite-element commercial package. The study addresses common problems associated with meshing the domain, which is difficult around

faults, and benchmarks the results against semi-analytic solutions attained with another widely used, but open-source, package. The study is accompanied with supplementary material that allows the community to reproduce and expand on these results quickly.

-The study makes a number of simplifying assumptions about the rheology of the Earth that permits direct comparison with the semi-analytic code visco1d. However, once the code is benchmarked, these assumptions should be relaxed and more realistic constitutive laws that include a power-law stress/strain-rate relationship at steady state and a similar power-law constitutive behavior for transient creep - all compatible with laboratory observation of olivine creep - should be implemented and described. More realistic distributions of physical properties associated with thermal activation of viscoelastic flow in a realistic thermal field should follow.

Power-law and transient power-law rheology have not been included in this study as the primary aim is to benchmark coseismic and postseismic displacement results against those produced by existing models with linear rheology. The implementation in ABAQUS of the rheologies mentioned by the reviewer is straight forward and has been done in other studies as mentioned on line 108. We will add more detail and references such as those suggested by the reviewer to section 2.2 to expand on this. However, using our model with more complex rheology will be the subject of future work and we feel that this is outside of the scope of our benchmarking study.

-A remaining issue is the meshing around more complex fault assembly that include multiple surfaces is not included in the model. As many earthquakes are now imaged to such a level of accuracy that these details are often well constrained, including complex fault geometry would be a relevant addition.

We agree this remains a limitation of the model due to the difficulties in constructing a mesh around a complex fault structure with brick elements. However, we are focusing on the far-field postseismic displacement which is less sensitive to simplifications made to the fault geometry than near-field displacement (Khazaradze et al., 2002, Tregoning et al., 2013, Zhou et al. 2012). Representing complex fault geometry with a single plane geometry can provide a useful way of modelling far-field postseismic deformation. This method has been used by Takeuchi and Fialko (2013), and we will include a reference to this study on line 251. When applied to case studies, fault and slip properties in the model can be adjusted so that model output matches observations of coseismic displacements which provides further confidence in modelled far-field deformations (e.g. Sun et al., 2018).

-Finally, the iterative procedure to include self-gravity should be replaced by directly solving the appropriate equations based on advection of pre-stress.

This approach is not possible for a spherical model in ABAQUS, please also see more detailed response to comment below.

-I follow with a few detailed remarks.

-55: An example of finite-element modeling of post-seismic relaxation with a spherical geometry is Agata, R., Barbot, S.D., Fujita, K., Hyodo, M., Iinuma, T., Nakata, R., Ichimura, T. and Hori, T., 2019. Rapid mantle flow with power-law creep explains deformation after the 2011 Tohoku mega-quake.ÂaNature communications,Â ËŸ a10(1), pp.1-11. ËŸ

This additional reference will be included.

-105: Since it seems so easy to add more realistic rheology with the method, it should actually be done in this study. More realistic rheology involves a power-law stress/strain-rate relationship, see

Hirth, G. and Kohlstedt, D.L., 2003. Rheology of the Upper Mantle and the Mantle Wedge: A View from the Experimentalists: Inside the Subduction Factory, v. 138. Karato, S.I. and Wu, P., 1993. Rheology of the upper mantle: A synthesis. Science, C2 GMDD Interactive comment Printer-friendly version Discussion paper 260(5109),

pp.771-778. Recent development include the inclusion of transient creep compatible with nonlinear steady-state creep: Masuti, S., Barbot, S.D., Karato, S.I., Feng, L. and Banerjee, P., 2016. Upper-mantle water stratification inferred from observations of the 2012 Indian Ocean earthquake. Nature, 538(7625), pp.373-377.

-Inclusion of realistic rheology seems more important and relevant than including self-gravitation.

We feel this is outside the scope of the benchmarking study, please also refer to our earlier comment.

-130: It is unfortunate that Abaqus cannot simply solve the appropriate governing equations for self-gravitation and that these iterations are necessary. How can that be improved? Is there a way to solve a user-defined set of equations? Are the governing equations with self-gravitation not readily included in Abaqus? How is advection of pre-stress included?

The governing equations solved in ABAQUS cannot be changed. A gravity load can be included directly within ABAQUS as a uniform acceleration in one fixed direction, therefore it is not easily applied to a spherical model. We choose instead to use the iterative approach as this has been shown by others (Wu, 2004) to correctly represent self-gravitation for a spherical viscoelastic Earth.

Advection of pre-stress is included via the elastic foundations described in section 2.3. We will add additional text to this section to clarify.

-180: The horizontal and vertical resolutions of the mesh seem inadequate to resolve the near field. The fault is 200x20 km and the mesh size around it is 10x5 km, representing just 20x4 mesh elements along the fault. It is actually surprising that the numerical result match the analytic solution so well with such a coarse mesh. This is perhaps an area of improvement.

We are focusing on the far-field postseismic deformation within a global setting, which requires a mesh with a very large number of elements. It is therefore computationally expensive to have a very high-resolution mesh in the near-field and we are forced to trade off the mesh resolution (and hence more accurate near-field results) against computation time. To provide further justification for our choice of mesh resolution we will perform extra sensitivity tests for one of the fault cases and discuss the results in the text.

-215: We need to see a convergence test in terms of mesh resolution for these cases. This may not necessitate more figures, but this needs to be discussed. I suspect that the resolution of the mesh in the near field can be improved, with valuable gains on the misfit. I suspect that the discrepancies that accumulate at long period during postseismic relaxation may be reduced with a more appropriate mesh in the near field.

As per our response to the previous comment, we will perform extra sensitivity tests for mesh resolution and discuss the results in the text. We will pay particular attention to improvements in misfit and the trade of in computation time.

-250: If linear rheology models are assumed, several simulations can be run with separate parts of a complex fault geometry model - each fault at a time - and the results subsequently combined.

This is an approach that could work for modelling complex faults with linear rheology, we will amend the text to include this point.

——————- Additional References:

Khazaradze, G., Wang, K., Klotz, J., Hu, Y., and He, J., Prolonged post-seismic deformation of the 1960 great Chile earthquake and implications for mantle rheology, Geophys. Res. Lett., 29(22), 2050, doi:10.1029/2002GL015986, 2002.

Sun, T., Wang, K. & He, J., 2018. Crustal Deformation Following Great Subduction Earthquakes Controlled by Earthquake Size and Mantle Rheology, Journal of Geophysical Research: Solid Earth, 123, 5323-5345.

Tregoning, P., Burgette, R., McClusky, S. C., Lejeune, S., Watson, C. S., and McQueen, H. (2013), A decade of horizontal deformation from great earthquakes, J. Geophys. Res. Solid Earth, 118, 2371– 2381, doi:10.1002/jgrb.50154.

Zhou, X., Sun, W., Zhao, B., Fu, G., Dong, J., and Nie, Z. (2012), Geodetic observations detecting coseismic displacements and gravity changes caused by the Mw = 9.0 Tohoku-Oki earthquake, J. Geophys. Res., 117, B05408, doi:10.1029/2011JB008849.

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