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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 helpful comments and have responded in line below.

The authors used ABAQUS -a commercial finite-element software package- to simulate postseismic deformation on the self-gravitating earth model. They have benchmarked their results for both coseismic and postseismic deformations with semianalytical solutions. The article's subject matter is interesting and relevant to the journal of Geoscientific Model Development (GMD). The results for the given examples look excellent. I have the impression that the overall content of the article could be improved. I have a

few concerns.

- The authors used the finite-element method, which is also clearly implied from the title. However, I do not see any related finite element formulations. I expect at least the strong and weak forms of the governing equations with necessary boundary conditions so that the work is entirely reproducible. For example, implementing full gravity and solid-fluid coupling is known to be challenging for global problems. I am curious about how those aspects are implemented. In my view, a proper section for appropriate formulations would make this article complete.

We have not included the governing equations for the finite element formulation as this part of the study is not new work. The model is based on the finite element formulation of Wu (2004) and equations therein, as referenced on line 84. Instead, we focus the paper on describing the new aspects of this model – incorporating a fault plane and prescribing slip. To make the work more reproducible we will add further references to Wu (2004) including signposts to the relevant sections or equations of that study.

- The most basic and widely used Earth model is the Preliminary reference Earth model (PREM, Dziewonski, A. M. & Anderson, D. L., 1981). I wonder why authors chose to use a simple three-layered model instead of the PREM. Furthermore, they mention in the abstract "the model can be easily adapted to include different rheological models and lateral variations". In this context, at least one example with the lateral variation of viscosity (e.g., Latychev et al., 2005) would be interesting.

We chose the same simple three-layer structure for this benchmarking exercise as that used by Pollitz (1997) (line 186). Since we were undertaking some benchmarking tests with the same fault geometry as those in Pollitz (1997) it was essential to keep the Earth model consistent with that study. Using the Preliminary Reference Earth Model (PREM) instead would not add anything to the results in our opinion, and only complicate reproducibility of the results for others. Our study does not include lateral variations in viscosity as the primary aim was to benchmark the model against other existing models and there is no open-source spherical model that we are aware of with which to benchmark these results. Using the model for case studies that require lateral variations in viscosity will be the subject of future work.

- Although not explained in the article, it seems that the mesh contains the nonconforming elements when transitioning from course to fine elements as shown in Figure 1. But then in Section "2.1 Model Geometry and Mesh" the authors mention, "The element type used is an 8-node linear brick element"! How is it possible to use an 8-node brick element for nonconforming elements? Do you use a discontinuous Galerkin method? Please clarify.

We thank the reviewer for bringing to our attention this lack of detail. ABAQUS provides a useful way to join together meshes of different resolutions to aid mesh refinement problems. The two separate meshes are joined together by a "tie constraint" on a surface where they have non-conforming elements relative to each other. Using a tie constraint ensures there is no relative movement between the surfaces and that displacement and stress are continuous through the boundaries. Nodes on one mesh are tied to nodes on the other mesh. Tie coefficients are generated and used to interpolate quantities from nodes on one side of the mesh to nodes on the other side of the mesh. We will expand the text in Section 2.1 to include further description of this method.

- Authors have frequently used the term "flat earth." I think "homogeneous halfspace" or "layered halfspace" is probably a more appropriate term.

We will change this term to "layered halfspace" but will also note on first use that it is also referred to as "flat-Earth" in other literature (e.g. Wu, 2004) so as not to cause confusion to the reader.

Given the above comments, I would recommend this article for a moderate to major revision. Minor comments follow. In the comments below, P refers to the page number, and L refers to the line number.

P4L29: "..on the likely Earth structure..." What do you mean by "likely Earth structure"?

We mean Earth structure inferred by the model. We will change this to "inferred Earth structure".

P2L34: "flat-Earth." "Homogeneous halfspace" or "layered halfspace"?

We will change this term to "layered halfspace".

P3L92: "a fault plane within the mesh." Given that you use the brick elements, accommodating the realistic and complex faults may be very difficult with this approach. Alternatively, one can use the so-called moment-density tensor approach.

We acknowledge that a limitation of the model is that it is currently restricted to a single fault plane, due to the difficulties in constructing a mesh around a complex fault structure, as discussed on line 246. The moment-density tensor approach suggested by the reviewer is an alternative method of representing a fault within a spectral-element mesh (e.g. Gharti et al. 2019) whereby the mesh geometry is not required to conform to the geometry of the fault plane. However, our current knowledge is that this method cannot be implemented in a finite-element mesh in ABAQUS due to the restrictions of defining loads and forces on elements or surfaces within the mesh. The focus of our study is far-field deformation which is not sensitive to the details of the fault plane and slip distribution (Khazaradze et al., 2002, Tregoning et al., 2013, Zhou et al. 2012), rather it is the overall moment magnitude that is important, which can be represented on a single plane.

P3L96: "...using surface-to-surface tie constraints. . ." Please write appropriate equations for these constraints.

The equations used by ABAQUS to define the tie constraints are integrated into the software so it would not be appropriate to reproduce them in this paper. The information we have included with regards to ABAQUS key words and input files is sufficient to allow other to use these methods.

P4 Section 2.3: These boundary conditions are best to be represented by appropriate equations!

We will include a more specific reference to the Wu (2004) study that this model is based on so that the reader can refer to the original source for the equations.

P6L165: "...as the fault is not allowed to open." Realistic faults may have some opening as well. How do you accommodate that kind of scenario?

At present we do not accommodate opening faults although we appreciate this is a realistic fault scenario. We recognise that this is a limitation of our model and will include a further comment in the discussion section to acknowledge this.

P6L181: "500 km." Given that the total depth of the model is 670 km, how does this large element behave?

The total depth of the model is 2891 km – from the surface down to the lower mantle-core boundary. The elements of 500 km size are present only within the lower mantle layer and the global mesh that surrounds the region of refined mesh where the fault lies. We ensure that the majority of coseismic and postseismic displacement occurs in the inner part of the model where elements are much smaller, so that the large elements should be deforming by only a negligible amount.

P7L185: "... simple Earth structure". Why not use a more common Earth model PREM?

Please see response to earlier comment about the use of PREM.

P7 Section 4.2 Coseismic Results Can you show the snapshots of the surface displacement?

We will add 3 new figures to supplementary information showing coseismic surface displacement and postseismic surface displacement at the 3 times shown in profiles on figures 3-5. The 3 new figures will correspond to the fault geometries tested.

P7 Section 4.3 Postseismic Results Can you show the snapshots of the surface displacement at selected time steps?

Please see response to previous comment.

P7L214: "...less coseimic dispalcemetn from the ABAQUS. . ." What is the reason for less coseismic displacement for ABAQUS?

We attribute this to mesh issues, as detailed on line 205. We propose to include more details on mesh resolution tests as suggested by reviewer 2, which will provide further justification.

P9L251: "...an approximation of all the fault planes into a single geometry would be required.." I don't think this is a reliable way. A better alternative is to use the moment density tensor approach.

Please refer to our earlier comment regarding the moment-density tensor approach. We agree that in the near-field results would not be as reliable as fully representing the structure, however, 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.

Figure 1: This figure may be sharper and better in black and white.

When outputting graphics from ABAQUS in black and white the quality is worse. We will keep the colour but output at higher resolution.

Figures 3-5: Showing the depth only to 100 km is confusing. Either show the full depth or explain it in the captions.

We show the upper 100km as these material properties are those that primarily govern the Earth's response, but we agree this could be confusing. We will explain in the captions that the lower mantle is not shown, but material properties given in Table 2.

Figures 3-7: Figures look low in quality. It may be better to save those figures in vector graphics, if possible.

We will increase the resolution of these figures.

Finally, the following references are worth citing. References: Al-Attar, D. & Tromp, J., 2014: Sensitivity kernels for viscoelastic loading based on adjoint methods Geophysical Journal International, Oxford University Press, 196, 34-77

Dziewonski, A. M. & Anderson, D. L., 1981: Preliminary reference Earth model Physics of the Earth and Planetary Interiors, 25, 297-356

Latychev, K.; Mitrovica, J. X.; Tromp, J.; Tamisiea, M. E.; Komatitsch, D. & Christara, C. C., 2005: Glacial isostatic adjustment on 3-D Earth models: a finite-volume formulation Geophysical Journal International, Blackwell Science Ltd, 161, 421-444

Zhong, S.; Paulson, A. & Wahr, J., 2003: Three-dimensional finite-element modelling of Earth's viscoelastic deformation: effects of lateral variations in lithospheric thickness Geophysical Journal International, 155, 679-695

We thank the reviewer for suggesting further references and will include them as appropriate in the text.

Additional References: Gharti, H. N., Langer, L., and Tromp, J., 2019. Spectral-infinite-element simulations of earthquake-induced gravity perturbations, Geophysical Journal International, 217, 451-468. DOI:10.1093/gji/ggz028.

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.

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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