Impact of topography and three-dimensional heterogeneity on coseismic deformation

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SUMMARY

Knowledge of deformation at plate boundaries has been improved greatly by the development of observational techniques in space geodesy. However, most theoretical and numerical models of coseismic deformation have remained very simple and do not include realistic Earth structure. 3-D material heterogeneity and topography are often neglected because simple models are assumed to be sufficient and available tools cannot easily accommodate complex heterogeneity. In this study, we demonstrate the importance of 3-D heterogeneity using a spectral element method that incorporates topography and 3-D material properties. Using a parabolic hill model and a topographic model of the 2010 Maule earthquake, we show that topographic features can alter the shape of observed surface deformation patterns. We also estimate the coseismic surface deformation due to a model of the slip distribution of the 2015 Gorkha earthquake using realistic topography and 3-D elastic structure, and find that the presence of topography causes changes in the shape of observed surface displacement patterns, while material heterogeneities primarily affect the magnitude of observed displacements. Our results show that the inclusion of topography in particular can affect predictions of coseismic deformation modelling.

Key words: Mechanics, theory, and modelling; Earthquake ground motions; South America; Asia.

1 INTRODUCTION

In recent years, developments in space geodesy have dramatically improved observations of coseismic deformation. Techniques that rely on global positioning systems (GPS) can measure the 3-D position of a receiver with centimetre-level precision. There are thousands of these stations worldwide, including many permanent stations at plate boundaries. Some of these stations have sampling rates of up to 5–10 Hz. Interferometric synthetic aperture radar (InSAR) provides global images of the Earth with the precision of a few millimetres. Data from two passes of SAR satellites are combined to produce an interferogram, which informs us about surface deformation that occurred along the line of sight (LOS) between the radar antenna and the Earth’s surface (Bürgmann & Thatcher 2013).

InSAR can be used to produce high-resolution images of large areas, but it generally fails to resolve areas with dense vegetation, steep topography or large deformation, such as the area close to a fault. Light detection and ranging (Lidar) data can be used to image areas with dense vegetation or extreme topography (Nissen et al. 2014). A laser is used to measure ground elevations from an aircraft. If Lidar scans from before and after an earthquake are available, one may take the difference between those scans to determine the change in elevation due to the earthquake (Oskin et al. 2012).

Aerial photographs may be used to observe deformation near the fault. This technique is also useful when studying less recent earthquakes for which satellite data are not available. Ayoub et al. (2009) successfully used aerial photography archives to image coseismic displacement for the 1992 Landers, California, event and the 1999 Hector Mine, California, event. Large deformations near the fault may also be observed with optical satellite images. Vallage et al. (2016) used optical satellite images to study near-field coseismic deformation generated by the 2013 Balochistan, Pakistan earthquake.

Time-variable gravity data from Gravity Recovery and Climate Experiment (GRACE) have also been used to observe coseismic deformation. This technique is particularly useful in oceanic areas, which are generally inaccessible to GPS and InSAR. GRACE consists of a pair of satellites that orbits the Earth. Global gravity models can be generated at the rate of one model every 2–4 weeks. This allows us to observe gravity fluctuations due to seismic deformation (Mikhailov et al. 2004).
Although geodetic observations of coseismic deformation have improved tremendously in the past few decades, coseismic deformation modelling techniques have not progressed as much and generally do not accommodate realistic Earth structure such as 3-D material heterogeneity and topography. Many studies of coseismic deformation continue to use homogeneous half-space models based on analytical solutions developed by Okada (1985, 1992). Okada (1985) presented analytical solutions for surface deformation caused by slip on a rectangular finite fault embedded in an isotropic homogeneous elastic half-space. Okada (1992) extended those results to include internal deformation. These solutions are still widely used in finite-fault inversions and seismic source modelling (McCaffrey et al. 2007; Sigmundsson et al. 2010; Yagi et al. 2016).

Okada’s results may be improved upon by incorporating stratified material properties into the half-space. This may be done via an analytical or semi-analytical technique (Pollitz 1996; Savage 1998). Zhu & Rivera (2002) derived solutions for a point source in a layered half-space using the Thompson–Haskell propagator matrix approach. Wang et al. (2003) presented a numerical approach that allows static displacements to be calculated for an unlimited number of isotropic layers.

Though the majority of coseismic deformation studies use homogeneous half-space models, several studies have explored the effects of 3-D heterogeneous elastic structure. Kyriakopoulos et al. (2013) studied the $M_w$ 9.0 2011 Tohoku–Oki earthquake to evaluate the effects of 3-D elastic structure on slip inversion. They compared inversion results from a homogeneous model with those obtained from a model that had a strong subducting slab and weak overriding plate. Both models had complex fault geometry and realistic topography and bathymetry. The inversion was performed using surface displacements from geodetic data. They found that inverting with a heterogeneous model yielded a smaller amount of slip, dispersed over a larger area. Duputel et al. (2014) used a Bayesian approach to account for uncertainty in elastic parameters when performing an inversion for a slip model. Ragon et al. (2018) used a similar technique to account for uncertainty in the fault geometry. The inclusion of these uncertainties resulted in a better constrained slip model.

However, in other settings, 3-D elastic structure was not found to have a strong effect. Lindsey & Fialko (2013) looked at the effects of 3-D structure on slip rates in the southern San Andreas fault system. They found that 3-D material properties did not have a significant effect on the inverted slip pattern. Complex fault geometry was required to explain geodetic observations.

Some studies have also considered the impact of topography. Li et al. (2016) computed gravity changes for the 2011 Tohoku–Oki earthquake. They found that the inclusion of topography improved the misfit of their model predictions with GRACE observations. Hsu et al. (2011) studied the 2005 $M_w 7.8$ Nias–Simeulue, Sumatra earthquake to determine how surface displacements in an elastic medium are affected by topography and 3-D material properties. They found that if topography was included when calculating surface displacements, the horizontal component was larger in magnitude, while the vertical component was greater on the oceanic side and smaller on the continental side of the trench. Their study separately examined the effects of 3-D material properties, and found that predicted surface displacements were greater in the heterogeneous model than in the homogeneous model due to a sediment layer in the heterogeneous model. In comparing these two effects, they found that topography caused changes in the shape of the displacement pattern, while material properties mostly caused changes in magnitude. Trasatti et al. (2011) considered the effects of both topography and 3-D elastic structure in an inversion for the slip distribution of the 2009 $M_w 6.3$ L’Aquila earthquake. Their findings were that topography had a very small effect due to weak topography in the area, but heterogeneous material properties caused significant changes in the shape of the inverted slip pattern.

These previous studies have shown that 3-D structure can affect predictions of coseismic deformation modelling. However, the majority of coseismic deformation studies continue to use simple models. The full effects of 3-D structure are still unknown, and it is not clear whether these effects can safely be neglected under most circumstances. This is because studies of this nature are difficult to perform with existing tools. Current methods are based on a lower order spatial discretization and are not fast enough or accurate enough to easily accommodate 3-D structure. Very often, elaborate meshes must be constructed with elements of varying size in order to guarantee accuracy near the fault while allowing the simulation to run in a reasonable amount of time. This imposes limits on the type of structure that can be implemented since the mesh is already highly complex. It also means that simulating coseismic deformation with 3-D structure is a very slow, laborious process, so studies are limited in scope.

In this paper, we demonstrate that our new software package, SPECFEM-X, which is very accurate and efficient, is able to simulate coseismic deformation in a domain with realistic Earth structure using relatively simple meshes that have nearly uniform mesh spacing. We explore the effects of 3-D heterogeneity in a variety of settings. To examine the effects of topography, we first consider a parabolic hill model and compare the resulting deformation patterns to those produced by flat meshes. Next, we generate a model of the 2010 Maule, Chile earthquake with realistic topography, including the Peru–Chile trench. Finally, we turn to Nepal, where we look at the effects of both topography and 3-D elastic heterogeneity.

2 TOOLS AND METHODS
In this study, we use a versatile software package called SPECFEM-X, which is based on the spectral-infinite-element method. The spectral-element method (SEM) is a type of finite-element method that uses Gauss–Legendre–Lobatto nodal quadrature (Patera 1984; Komatitsch & Vilotte 1998) based on a higher order spatial discretization. This method is widely used for simulations of seismic
wave propagation (Komatitsch & Tromp 1999; Lekić & Romanowicz 2011; Nissen-Meyer et al. 2014).

SPECFEM-X primarily solves quasi-static problems. It has been used to solve several problems in geomechanics, such as background gravity (Gharti & Tromp 2017), gravity anomalies (Gharti et al. 2018), magnetic anomalies (Gharti & Tromp 2019), coseismic and post-earthquake deformation (Gharti et al. 2019a) and earthquake-induced gravity perturbations (Gharti et al. 2019b).

SPECFEM-X solves the (un)coupled elastic-gravitational equations. In this study, we focus only on coseismic deformation. Therefore, we neglect the influences of the background and perturbed gravity fields, so that the governing equations are reduced to

\[ \nabla \cdot \mathbf{T} + \mathbf{f} = 0 \quad , \]

where \( \mathbf{T} \) is the incremental Lagrangian Cauchy stress and \( \mathbf{f} \) denotes the external forces. Although SPECFEM-X is capable of using any order of elements, we use second-order elements, that is, three GLL points per dimension for all of the examples in this paper. All examples in this study have elastic material properties.

The fault is implemented via a grid of moment–density tensor patches, where each patch has an associated elastic tensor \( \mathbf{C} \), normal vector \( \hat{n} \), slip direction \( \hat{s} \) and slip magnitude \( \Delta s \), so that the moment-density tensor \( \mathbf{m} \) is given by (Dahlen & Tromp 1998)

\[ \mathbf{m} = \Delta s \mathbf{C} : \hat{s} \hat{n} \quad , \]

where \( : \) denotes the double inner product.

In this study, we implement faults with fixed strike, dip and rake, such that \( \hat{s} \) and \( \hat{n} \) are the same for all patches as shown in Fig. 1. The slip magnitude \( \Delta s \) may vary between fault patches. In a non-homogeneous domain, \( \mathbf{C} \) is given by the material properties at the location of the patch.

Trelis Pro 16.3 (www.csimsoft.com/trelis.jsp) and MeShAssist (Gharti et al. 2017) were used to generate all of the meshes used in this study. All meshes consist entirely of hexahedral elements. For the parabolic hill example, we used infinite elements, an outer layer of elements that simulates far-field boundary conditions. The meshes for the Nepal and Maule examples are sufficiently large that they do not require infinite elements. Boundary conditions for those models include a free top surface, fixed bottom and sides held fixed in the outward direction.

3 COSEISMIC DEFORMATION ON A PARABOLIC HILL

We first tested the effects of topography with a synthetic model consisting of a rectangular block with a parabolic hill-shaped surface. A similar example in a 2-D domain was presented by Tinti & Armigliato (2002). That study used a finite-element code to compute earthquake-induced deformation on the surface of a 2-D mesh with a Gaussian hill-shaped surface. They imposed an earthquake on a finite fault and compared the resulting deformation with results obtained based on the analytical solution of Okada (1992) for a flat domain. Significant differences were observed between the topographic and flat solutions. Here, we present the results of our experiment in a 3-D domain.

We computed displacements with our parabolic hill-shaped mesh and compared those results with displacements computed in three different flat meshes with elevations at the top, bottom and centre of the hill. The hill is 3 km tall, and the flat meshes have elevations at 0, 1.5 and 3 km.

The model domain is 30 km × 30 km × 15 km (not including the hill) with 400 m average mesh spacing. All meshes have identical resolution. We used hexahedral elements and infinite element boundary conditions as described in Section 2. All simulations have a Poisson’s ratio of 0.25 and a Young’s modulus of 104.8 GPa. Fig. 2 shows the topographic mesh used in this simulation. Notice that the elements in the topographic mesh vary in size and shape to accommodate the topography of the hill. The mesh has a total of 227 468 elements and runs on 40 processors in approximately 7.4 min.

A right-lateral strike-slip fault with 10 m of slip was imposed at a depth of 3 km on a fault plane parallel to the \( x \)-axis. The fault is 500 m × 500 m, and is comprised of 1600 moment tensor patches. Slip is uniform across the entire fault. We did two tests, one with the fault in the centre of the mesh at \( x = 0 \) km, \( y = 0 \) km (directly below the centre of the hill) and one with the fault in the upper right-hand corner of the mesh at \( x = 2.5 \) km, \( y = 2.5 \) km.

Fig. 3 shows the surface deformation generated by each of the four meshes for a fault at the centre of the domain. The elevation profiles for each of these meshes are shown in Fig. 4(a). Note that the three flat meshes produce deformation patterns that have a similar shape, which decreases in magnitude as the height of the mesh surface increases. The mesh with the hill (far left-hand column) produces a deformation pattern that has a different shape from the flat meshes. The \( x \) and \( y \) components have large lobes that are farther apart than in the flat mesh results, with additional small lobes appearing at the
Figure 3. Three-component surface displacements generated with each of the meshes used in the parabolic hill study. Columns from left to right: mesh with a parabolic hill 3 km high, flat mesh at 0 km elevation, flat mesh at 1.5 km elevation and flat mesh at 3 km elevation. The flat meshes yield a displacement pattern that has the same shape for all of the meshes. The magnitude of the displacement decreases as the mesh surface is raised farther from the fault. The topographic mesh yields a deformation pattern that has a different shape from the other three, with additional lobes appearing in the $x$ and $y$ components, and distortion of the lobes in the $z$ component.

Displacement profiles for the topographic and flat meshes are shown in Fig. 4(b). These plots show surface displacements along a line perpendicular to the fault. The plots in the left-hand column of Fig. 4(b) show results for an earthquake directly under the hill, and the plots in the right-hand column show results for an earthquake in the centre of the model where the hill is located. The $z$ component has lobes that are more rounded at the centre of the domain. In general, the displacement pattern appears to be dispersed and broadened at the location of the hill.
the upper right-hand corner of the model domain. The profiles are located at $x = 2.5$ km for the centred fault and at $x = 0$ km for the off-centre fault.

In both cases, the flat meshes generate displacement patterns that have a similar shape, which changes only in magnitude as the height of the surface is increased. The topographic model, however, generates a displacement pattern that appears dispersed over the hill. All components show flattening of the displacement pattern at the centre of the model, where the hill is located. Note that when the earthquake is not located directly under the hill, the topography causes asymmetry in the displacement pattern. In both models, the shape of the observed deformation pattern is significantly altered by the presence of the hill. This could have a substantial impact on our interpretation of this event. Given geodetic data about the surface displacements, one would be apt to draw the wrong conclusions about the focal mechanism and slip distribution if topography was not accounted for.

The topographic profile in Fig. 4 appears to generally match most closely with the 3 km profile at the centre of the hill and with the 0 km profile at the edges of the mesh. This suggests that we may be able to reproduce the topographic profile using a flat mesh with a correction for receiver elevation. Okada calculations may be corrected for receiver elevation by raising or lowering the fault to the appropriate depth relative to the surface at each point along the profile. We compared the result of this calculation to the SEM topographic surface displacement for both strike-slip and dip-slip events using an off-centre fault at $x = 2.5$ km, $y = 2.5$ km. Profiles of surface displacement perpendicular to the fault at $x = 0$ are shown in Fig. 5. For the strike-slip event, shown in the left-hand column of Fig. 5, the $z$ component is nearly identical, but the $x$ and $y$ components have significant differences. For the dip-slip event, shown in the right-hand column of Fig. 5, the most significant differences are also in the $x$ and $y$ components, but here the $z$ component is larger in the topographic solution. This makes sense because a dip-slip event has a very strong vertical component of motion. The differences between the profiles are due to the fact that surface displacements in a topographic domain are influenced by the shape of the surface as well as its height (Segall 2010).

4 COSEISMIC DEFORMATION WITH TOPOGRAPHY FOR THE 2010 MAULE EARTHQUAKE

To investigate the impact of topography more thoroughly, we looked for topographic effects using a real-world event: the 2010 Maule, Chile earthquake. The main topographic feature in this region is the Peru–Chile trench, which is 6 km deep at its deepest point inside our study region. Our mesh surface has a topography range of $-6.0$–$5.8$ km. This region is well instrumented and has been extensively studied with GPS (Vigny et al. 2011).
Figure 5. Profiles perpendicular to the fault for a strike-slip earthquake (left) and a dip-slip earthquake (right). The blue curve is the Okada calculation corrected for receiver elevation, and the red curve is the SEM calculation with a topographic mesh.

Figure 6. (a) Topography of the Maule region from ETOPO1. The study region is outlined in red, and the fault is outlined in orange. (b) Our slip model, a smoothed version of the Sladen (2010) slip model from the SRCMOD data base. The fault is dipping 18° southeast.

An earthquake with moment magnitude $M_w = 8.8$ struck central Chile on 2010 February 27. The earthquake occurred at a depth of 35 km (Moreno et al. 2010) on a section of the fault that is dipping approximately 18° southeast. The high energy and shallow location of this event generated large surface displacements, making it an ideal choice for a study on the effects of surface topography.

Fig. 6 shows the region used for our study of the Maule earthquake. The mesh is 671 km long and 436 km wide with 6 km average mesh spacing. We used hexahedral elements and fixed boundary conditions as described in Section 2. The slip model, shown in the left-hand corner inset, is the Sladen (2010) slip model from the SRCMOD database. It is a rectangular fault with fixed strike of 18°, dip of 18° and rake of 112°. The fault is 570 km long and 180 km wide. Its shallowest point is 11.3 km deep, and its deepest point is 62.3 km deep. There is a large asperity at the northern end of the fault and smaller asperities in the centre and at the southern end. We interpolated the model’s original 228 patches to obtain a total of 3706 patches.
4.1 Topographic effects

The surface of the mesh uses topography and bathymetry supplied by ETOPO1 (Amante & Eakins 2009), resampled to 6 km resolution. The elastic properties are the same for both meshes: Poisson’s ratio is 0.25 and Young’s modulus is 100 GPa. Fig. 7 shows the topographic mesh used in this simulation. This mesh has a total of 106,288 elements and runs on 16 processors in approximately 3 min. The flat mesh has an elevation of 21 m, which was chosen by calculating the average elevation in a $0.1^\circ \times 0.1^\circ$ square around the epicentre of the earthquake. The main topographic feature in our simulation is the Peru–Chile trench, which is visible as a curved line running along the upper portion of the topographic mesh. A small section of the fault that slipped is not under the mountains, so their presence has only a minor influence on the calculated surface displacements.

A coseismic model of this event that is produced using a flat mesh will have significant errors. If Green’s functions produced by that model are then used in a finite-fault slip inversion, errors in the displacement pattern’s shape are likely to be mapped onto the slip distribution.

The topography of the Maule region is relatively simple: it consists of an oceanic section that is at the depth of the ocean floor and a continental section that is above sea level. This might imagine that it would be possible to replicate most of the effects of the topographic mesh using two flat meshes at different elevations. This would be equivalent to correcting for receiver elevation. To test if this would work, we used a flat mesh at the elevation of the seafloor, approximately 5.1 km below sea level. The results of this calculation are shown in Fig. 9. The surface displacements calculated with this mesh are significantly greater than the displacements from the topographic and flat meshes in Fig. 6 since the surface is closer to the fault. However, the additional lobes on the oceanic side of the domain that are seen in the topographic case are not recovered by this mesh. In light of the tests that we did with the receiver elevation correction in Section 3, we can surmise that these additional lobes are due to the shape of the surface, not its height. This is reasonable because the Maule region has an extreme topographic change at the trench.

5 COSEISMIC DEFORMATION FOR THE 2015 GORKHA, NEPAL EARTHQUAKE

To further investigate the impact of topography, we studied the April 2015 Gorkha, Nepal earthquake. This region is a great location for a study of topography because the Himalayan mountain range has extreme variations in elevation. Our study region has an elevation range of 0.98–7.35 km. Nepal’s topography is very different from Chile’s; it is rougher and has more small-scale features. Because this region is entirely contained on land, it has been extensively studied with high-quality GPS and SAR (Grandin et al. 2015).

An earthquake with magnitude $M_w$ 7.8 occurred in the Gorkha region of Nepal on 2015 April 25. It ruptured an area approximately 120 km long $\times$ 80 km wide (Yagi & Okuwaki 2015). The earthquake’s hypocentre was located at 15 km depth on a shallowly dipping fault plane that forms part of the subduction zone between the Indian and Eurasian plates (Goda et al. 2015). The high energy and shallow depth of this event generated strong shaking throughout central Nepal, which makes this event an ideal candidate for a study of the effects of surface topography.

Fig. 10 shows the study region. The model region is contained in the red box, and the outline of the fault is shown in orange. Our mesh is 214 km long and 152 km wide, with 3 km average mesh spacing. The smaller mesh spacing was necessary to capture the small-scale features of the region’s topography. We used hexahedral elements and fixed boundary conditions as described in Section 2. The slip model, shown in Fig. 10(b), is the Yagi & Okuwaki (2015) slip model, obtained from the SRCMOD database. This model is a rectangular fault with fixed strike of 285$^\circ$, dip of 10$^\circ$ and rake of 58.6$^\circ$. The fault is 160 km long and 88 km wide. Its shallowest point is 4.6 km deep, and its deepest point is 18.5 km deep. There is one asperity at the centre of the fault, with decreasing amounts of slip at the edges. The original model has 220 patches, which we interpolated to obtain 1456 patches.
Figure 8. Three-component coseismic surface displacements for the Maule earthquake. Displacement differences (bottom row) were found by subtracting the displacement generated in a topographic mesh (top row) from displacement generated in a flat mesh (centre row).

5.1 Topography

The surface of the topographic mesh has real topography from ETOPO1 (Amante & Eakins 2009), resampled to 3 km resolution. The elastic properties are the same for both meshes: Poisson’s ratio is 0.25, and Young’s modulus is 82.4 GPa. These values were chosen because they are the material properties at the location of the fault (i.e. the top of the mesh) in Chen et al. (2015)’s tomographic model of the region. See Section 5.2 for more information about this model.

Fig. 11 shows the topographic mesh. This mesh has a total of 95,112 elements and runs on 16 processors in approximately...
Figure 9. Surface displacements for the 2010 Maule event with the mesh surface at $-5.1$ km, the approximate depth of the ocean floor.

Figure 10. (a) Topography of the Nepal region from ETOPO1. The study region is outlined in red, and the fault is outlined in orange. (b) Our slip model, a smoothed version of the Yagi & Okuwaki (2015) slip model from the SRCMOD data base. The fault is dipping $10^\circ$ northeast.

Figure 11. Mesh for the Nepal event with ETOPO1 topography.

2.9 min. The flat mesh has an elevation of 1.36 km, which was calculated by taking the average elevation in a $0.1^\circ \times 0.1^\circ$ square around the epicentre of the earthquake. The main rupture zone for this earthquake was in the valley near Kathmandu. Significant deformation also occurred in the mountains nearby. Our flat model has higher elevation than the valley and lower elevation than the mountains flanking it.

Fig. 12 shows three-component surface displacements for our simulations. The maximum difference between the results calculated by the flat and topographic meshes is about 10 per cent. The magnitude of the difference is not as great in this case as it was for the Maule event, where we saw differences of up to 30 per cent. This is likely due to two factors. The Maule mesh has an elevation range of 11.8 km, while the Nepal mesh only has an elevation range of 8.33 km. Also, and perhaps more significantly, the elevation of the Maule mesh changes sharply at the trench, where the largest coseismic deformation takes place. This results in a very large topographic effect.
Figure 12. Three-component surface displacements (viewed looking down at the top of the mesh). Displacement differences (bottom row) were found by subtracting the displacement generated in a topographic mesh (top row) from displacement generated in a flat mesh (centre row).

Figure 13. Vertical cross-section of the tomography model used to study the effects of 3-D elastic structure. The model is primarily stratified. The green circle indicates the location from which material properties were taken for the homogeneous model.

In the Nepal simulation, larger differences are observed directly under the fault, with smaller differences at the edges of the mesh. Differences are also greatest at areas of extreme topography, where the mountains are highest or the valleys are lowest. For all components, the flat result has a smaller magnitude than the topographic one in the centre of the domain and a larger magnitude in the north.
and south. This leads to a change to the displacement pattern calculated by the flat mesh. If an inversion were to be done with a flat mesh, that pattern difference would probably be mapped onto the inferred slip distribution, leading to an incorrect interpretation of the nature of this earthquake.

5.2 3-D elastic properties

Chen et al. (2015)’s tomography model of Asia was used to explore the effects of 3-D elastic structure. An image of the model is shown in Fig. 13. The model has 8 km horizontal resolution and 5 km vertical resolution. It is primarily stratified. We used the properties at the top of the tomography model for our homogeneous model. These properties were chosen because they correspond to the elastic properties at the location of the fault. The same flat mesh with zero elevation was used for both simulations. This mesh has a total of 94146 elements and runs on 16 processors in approximately 2.3 min.

The results for these simulations are shown in Fig. 14. Displacement differences were calculated by subtracting the displacements calculated with a homogeneous model from those calculated with the 3-D tomography model. The differences are up to 10 per cent in magnitude. The horizontal components have greater differences than the vertical component. For the horizontal components, the differences are mostly in the magnitude of the result and minimal shape differences are observed. This is due to the fact that the tomography model has little lateral variation. However, the vertical component shows a difference in shape that corresponds to the difference in material properties at the northern and southern sides of the surface.

We find that the effects due to topography and heterogeneous elastic properties are of similar magnitude. This differs from the findings of Wang & Fialko (2018), who found that heterogeneous...
material properties had a significantly stronger effect than topography on their coseismic model of the 2015 Gorkha earthquake. Their result may be due to the homogeneous model that they chose. In our study, we examine the effects of elastic heterogeneity by comparison with a homogeneous elastic model, which corresponds to the elastic properties near the fault. This ensures that the effect that we see is, in fact, due to the heterogeneity, and not due to overall differences in elastic properties between the two models. If another homogeneous model is chosen, the difference between the two simulations can become much larger because of overall differences in elastic properties. This is equivalent to introducing a direct current (DC) offset that dominates the result.

6 CONCLUSIONS

We examined the impact of topography and 3-D elastic structure on modelling coseismic deformation in a variety of settings.

Using a 3-D heterogeneous elastic model, we studied the effects of 3-D elastic structure on a coseismic deformation model of the Gorkha event. We compared the surface deformation produced with this model to the deformation produced with a homogeneous elastic model, and found that the differences were primarily in the magnitude of the deformation pattern, not the shape. Changes in magnitude are less consequential because this would have a smaller impact on the inferred slip pattern. However, our elastic model for this region is smooth and does not have abrupt changes in elastic properties. Differences in the deformation pattern’s shape might be observed in regions that have stronger heterogeneities.

We investigated at a synthetic example of topography by comparing the deformation patterns produced by flat meshes and a mesh with a topographic hill. We found that the flat meshes produced similar shaped deformation patterns regardless of the elevation of the mesh surface, but the topographic mesh produced a deformation pattern that was dispersed at the location of the hill. This suggests that the presence of topography may alter the shape of the observed deformation pattern, which has implications for inferences made about the slip that took place.

We also calculated surface displacements for this example using an Okada calculation with a correction for the receiver elevation, and found that the predicted displacements did not completely recover the displacements generated in the topographic mesh. The remaining difference is due to the shape of the topographic mesh.

To study the effects of topography on a real-world model of coseismic deformation, we chose the 2010 Maule earthquake. Here, too, we found that the topographic mesh produced a surface displacement pattern that had a significantly different shape than the one produced by a flat mesh, with differences of up to 30 per cent between the flat and topographic surface displacements. We also tested whether the topographic results could be recovered by a flat mesh at the correct elevation. In this case, the shape of the topography was found to dominate the topographic effect, and a flat mesh at the elevation of the sea floor failed to recover the displacements on the oceanic side of the topographic model.

As a final example, we studied the impact of topography on a simulation of the 2010 Gorkha earthquake. In this region, the flat mesh underestimated the surface displacements at the northern and southern edges of the domain and overestimated in the centre, again causing changes in the shape of the observed displacement pattern.

In all of our examples, we found that the presence of topography caused changes in the shape of the simulated surface deformation pattern. Thus, a simulation performed in a flat domain will produce a deformation pattern that does not have the correct shape if the study region has significant topography. If a finite-fault slip inversion is then performed using Green’s functions generated with the flat model, the resulting slip model may be incorrect. We plan to investigate the effects of topography on slip models in a future study.

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2-D snapshots were created using the open-source Python plotting library Matplotlib (www.matplotlib.org). Most of the model sketches were created using the open-source vector graphics editor Inkscape (www.inkscape.org). The open-source spectral-element software package SPECFEM-X used for this paper is freely available via the Computational Infrastructure for Geodynamics (www.geodynamics.org). This research was supported by NSF grant 1644826. We thank Hugo Sanchez-Reyes, an anonymous reviewer, and editor Jean Virieux for insightful comments that helped improve the manuscript.

REFERENCES


