Updating HTDP for two recent earthquakes in California

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Abstract This paper describes the National Geodetic Survey (NGS) process for selecting and validating models for two recent earthquakes prior to their inclusion in the Horizontal Time Dependent Positioning software (HTDP v 2.9), the 28 September 2004 Parkfield, California earthquake with a magnitude of 6.0 and the 22 December 2003 San Simeon, California earthquake with a magnitude of 6.5 . The process of modeling and correcting for deformation can be well illustrated by utilizing the data from these earthquakes because they represent contrasting styles of deformation; Parkfield exhibited strike-slip motion and San Simeon was predominantly a blind-thrust earthquake. Also, while both earthquakes were relatively small, they produced significant displacements (though restricted to a relatively small area near the epicenter). The Parkfield earthquake in particular produced an unusually high proportion of post-seismic deformation. This deformation can accumulate during a period of a few months after the earthquake compared to co-seismic deformation that occurs suddenly during an earthquake. Quantifying and characterizing deformation at these disparate time scales represents a major challenge to developing the accurate models of deformation that are required to support modern high-accuracy surveying in tectonically active areas like California.

We found that the best dislocation models for this purpose are determined from inverting a combination of GPS vectors and InSAR data as opposed to ones derived from seismic body waves. This is because including direct measurements of the deformation field provides a more faithful estimate of changes in relative position than would otherwise be the case. This study also shows the importance of including separate dislocation models of the co-seismic and post-seismic deformation, which is important because the post-seismic deformation can be comparable in magnitude to the co-seismic deformation, as it was for the Parkfield earthquake.

Introduction

Since the 1960’s geologists have known that the surface of the Earth is broken into a series of large plates which are in constant motion relative to each other at rates which are typically greater than 0.1 m/yr. These plates generally move as rigid blocks; however, at their edges there is a zone (often called a plate boundary) where they move against each other, causing geologic phenomenon such as earthquakes. The contiguous United States is divided into two tectonic plates. The North American Plate contains all of the contiguous states except for a small part of western California which resides on the Pacific Plate. The plate boundary zone between these two plates passes offshore north of San Francisco and continues northward slightly offshore along the Pacific coast all the way to Alaska. In the ITRF and WGS84 reference frames, all points on both the Pacific and North American plates have non-zero velocities (Snay and Soler 2000). The NAD83 reference frame, however, is defined so that all points on the North American Plate located away from this plate boundary zone will have (on average) zero horizontal velocities. Points located within the Pacific-North American plate boundary zone will have NAD_83 velocities that are transitional between the respective velocities of these two plates and as a result have nonzero NAD_83 velocities with magnitudes of up to 5 cm/yr. Accurate surveying in the western US requires a model describing crustal velocities and earthquakes to allow survey measurements to be corrected for differential movement so that surveys conducted at different epochs may be compared. The National Geodetic Survey (NGS) has developed the HTDP (Horizontal Time Dependent Positioning) software that enables its user to make these corrections (Snay 2003, 1999). As a result of its proximity to this plate boundary a zone a few hundred km wide-- including most of California, Nevada, Oregon Washington and Alaska-- is deforming. This deformation causes the relative position of points on the Earth to change with time. Consequently, survey measurements taken at different times will differ and we must have some method to compensate for this change or the resulting coordinates will contain biases.

Two quite different processes are responsible for the deformation in the western states. The first of these, known as the secular field, represents the response of the crust in the plate boundary zone to the differential movement of the two tectonic plates. The crust accommodates this motion by slowly deforming which means that the velocity vectors in the plate boundary zone are transitional between the velocity vectors in the two plates. While the deformation is continuous, the effect of the rates (which exceed 5 cm/yr in some places) accumulate with time and are large enough that they cannot be ignored. The secular velocities are thought to be relatively constant so that once this field is mapped, it need not be changed although periodic updates may be needed to reflect our growing knowledge of crustal dynamics. The second process we have to model is the sudden large displacement associated with earthquakes. In this case, quite large displacements can happen during a period of few minutes or less. The co-seismic portion of the deformation field is therefore different because earthquakes happen in an unpredictable way and each time a new earthquake occurs the HTDP software must be updated to address the displacements caused by the earthquake. Because these two processes are very different both temporally and spatially, two quite different methodologies are required to correct for them. The secular field is represented by an interpolation scheme of the velocity field that to provide an estimate of the velocity difference between any two points on the plate boundary zone while earthquakes are represented using dislocation models that define the slip on related geologic faults.

This paper describes the NGS process for modeling earthquakes, focusing on two recent earthquakes in California (figure 1), which were the largest to occur in the contiguous United States in the last 3 years. Characterizations of the co- and post-seismic motion of these earthquakes were included in HTDP V 2.9 released in January 2007. Updating HTDP was a necessary component for the incorporation of GPS-observations that have been made pre- and post-earthquakes into the National Horizontal Re-Adjustment undertaken by NGS recently (Pearson 2005).

Displacements caused by earthquakes

The deformation associated with an earthquake is caused by a fault or fracture in the earth that slips suddenly due to the stress in the surrounding rocks. Sometimes the break extends to the surface in which case the displacement will change very suddenly as one side of the fault will move one way while the opposite side moves in the opposite direction. More commonly though the break does not reach the surface. Even in this case, however, the earthquake will cause surface displacements because slip on the fault will cause sympathetic movement in the surrounding rocks and this deformation will propagate through the Earth to the surface. Slip on the fault also has the effect of allowing the material surrounding the fault to rebound as the stress stored in the rocks in the surrounding rocks is released. This allows the rocks to regain their un-deformed shape resulting in the deformation associated with the earthquakes extending a considerable distance from the fault. In large earthquakes, measurable displacement can extend hundreds of km from the earthquake.

In regions where the fault is cool enough to be fully solid, the deformation associated with an earthquake will be complete within a few minutes and is called co-seismic deformation. However in large earthquakes, the rupture may extend deep enough so that he rocks are partly molten and deformation is much slower, typically lasting for several months. This slow deformation is not associated with noticeable seismic waves or shaking and is called post-seismic deformation. The final deformation field associated with the earthquake is the sum of both the co-seismic and post-seismic components.

Dislocation models

Predicting the effect of an earthquake on positional coordinates utilizes relatively simple mathematical equations provided by dislocation theory (Okada 1985). The equations predict the elastic response of a uniform half-space to slip on a rectangular patch embedded in the half-space. Each dislocation represents a rectangular patch in the Earth where one side slips relative to the other by a uniform amount. The name, dislocation, is used because of the slip displacement is uniform over the rectangle thereby producing a discontinuity along the edges of the patch. The model is shown conceptually in figure 2. A dislocation model is obviously very similar to what happens during an earthquake where one side of the fault slips relative to the other. A single dislocation can model an earthquake. However the requirement that the slip be uniform and that the slipped region be shaped like a rectangle are serious limitations since real earthquakes are much more complex. These difficulties are overcome by breaking the fault into a series of small rectangular dislocations which, taken together, can map the complexity associated with a real earthquake. In the earthquakes discussed below, as many as 300 dislocations were required to map each earthquake.

Dislocations are determined by varying the properties of the dislocations such as the amount of slip and the geometry of the rectangular patch until the predictions of the dislocation models provide a satisfactory match with observations made during and after the earthquake. There are two main types of observations that are used to constrain dislocation models, surface measurements of displacements measured with Global Positioning System (GPS) data sometimes augmented with InSAR (Interferometric Synthetic Aperture Radar) data and the seismic-wave data generated by the earthquake.

Post earthquake slip

Along with the very sudden co-seismic displacements, earthquakes can be followed by slow displacements which continue for a few months. This motion is called post-seismic slip. Post-seismic slip follows an exponential decay with a time constant of about 1 month for the earthquakes discussed here. The post-seismic slip (s_{ps}(t)) at any given time after the earthquake is represented by the equation:

$$s_{ps}(t) \quad = \quad A_{ps}\left(1-e^{\frac{t}{\tau}}\right) \qquad \textbf{(1)}$$

where A_{ps} is the total post-seismic slip on the rectangular patch, t is the amount of time that has ellapsed since the earthquake (that is, the amount of time between the earthquake and the date in question) and τ represents the decay time constant. Since the decay time constant has a value of 0.087 years in the two earthquakes discussed here (Johanson et al 2006), the exponential in the equation above rapidly approaches 1 in value, and the post-seismic slip distribution approaches the values of the post-seismic dislocation coefficients (A_{ps}). The values of s_{ps}(t), for a unit value of A_{ps} are plotted as a function of t in figure 3. Note that if 100 days or more have elapsed since the earthquake, the slip on the fault is for all intents and purposes equal to the coefficient A_{ps}.

Post-seismic slip is important to surveyors because it contributes to the total deformation field on the surface that will affect the relative position of points causing them to change from the relationships measured during earlier surveys. Unlike the co-seismic deformation, it accumulates with time over a period of a few months, or longer for large earthquakes. The post-seismic deformation at any given time can be estimated using equation 1 but HTDP v 2.9 does not have this capability. We include the post seismic deformation in our model by adding the dislocation model containing the post seismic coefficients (A_{ps} from equation 1) and the dislocation model associated with the co-seismic displacements together to produce a single model that will estimate the total deformation (both co and post seismic) which are assumed to occur at the time of the earthquake. Because the post seismic deformation is assumed to occur instantaneously rather than following the power law in equation 1, this model will not be able to follow the gradual increase in post-seismic deformation for the first 100 days or so after the earthquake. Hence, for a few months after an earthquake, some small inconsistencies may be observed near the epicenter.

The Parkfield Earthquake

The magnitude 6.0 Parkfield Earthquake occurred on, 28 September 2004 at 10:15 AM PDT near the small town of Parkfield CA. It was a strike-slip earthquake on the San Andreas Fault. Maximum displacement vectors for this earthquake were generally less than 0.1 m but, because this was a strike-slip event, where vectors on opposite sides of the fault point in opposite directions, the resultant would be up to 0.2 m of relative motion on GPS baselines or other survey measurements that cross this fault (see figure 4). This earthquake was very unusual in that the post-seismic deformation around the fault was comparable in magnitude to the co-seismic movement (also shown in figure 4). For this reason, it is essential that both co-seismic and post seismic motion be included in our model because neglecting the post-seismic component of the deformation will cause of the corrections that we apply to survey data to be significantly underestimated.

Because of the large post seismic displacement associated with this earthquake we used two dislocation models, one for the co-seismic deformation and one for the post-seismic deformation. Both models were provided by Johnson et al (2006). They were constrained by surface deformation measurements (both GPS and InSAR data) without using seismic body waves. The parameters of the post seismic dislocation model are different from the co-seismic model because they represent coefficients of the post-seismic "slip" which are the amplitude of an exponential function describing decaying slip rather than estimates of slip on the fault plane (s_{ps}) that are representative of any particular time. They must be multiplied by a function of time as in Eq 1 to provide a model that can be used to predict the deformation at a given time. However as shown in figure 2, the exponential function in Eq 1 rapidly approaches 1 in value once the elapsed time since the earthquake exceeds a value about three times the characteristic time, which in this case is 0.087 years. As a result, when at least 100 days have elapsed the post-seismic deformation is essentially complete and the post-seismic dislocation coefficients can be treated as a dislocation model which will predict the total post-seismic deformation field. Because HTDP currently lacks the ability to predict the slow accumulation of post-seismic deformation after an earthquake, we combined the co and post seismic dislocations into a single model that will predict the total (co- and post-seismic) deformation associated with the earthquake but not to follow the gradual development of the post-seismic displacement in the first few months after the earthquake because the post seismic component is assumed to occur instantaneously.

San Simeon Earthquake

The San Simeon earthquake occurred on 22 December 2003 within the coastal ranges of central California, about 60 km west of the epicenter of the Parkfield earthquake. The earthquake had a magnitude (Mw) of 6.6 and was significantly larger than the Parkfield earthquake. While the earthquakes occurred in relatively close proximity, in some ways they couldn't be more different. In contrast to the Parkfield earthquake which was a strike slip earthquake, the San Simeon earthquake was a blind thrust event, which means that the two sides of the inclined fault plane moved toward each other. Because this was a blind thrust, the fault plane did not reach the surface. As a result, even though the San Simeon earthquake was larger that the Parkfield earthquake, the displacement vectors are smaller but were spread over a larger area.

For this earthquake we tried dislocation models from two sources. The first model, developed by Ji et al. 2004, was developed primarily by inverting seismic body waves augmented with a small number of displacements measured at Continuous GPS (CORS) stations, all of which were located to the north east of the epicenter. As a result the model provided limited constraints on the surface deformation field, particularly near the epicenter. In addition, , these data provided insufficient information for representing the post seismic motion. For these reasons, while the model did a good job determining the essential parameters of the fault plane, it did not provide a sufficiently accurate model of the surface deformation field for the purposes of correcting survey measurements. Later Johnson, (pers. com. 2007), developed a second model for this earthquake. As with the Parkfield earthquake the models were constrained by surface deformation measurements (both GPS and INSAR data) without using seismic body waves. We again combined the co and post seismic dislocations into a single model that predicts the total (co- and post-seismic) deformation associated with the earthquake.

Effect of the HTDP update on the National Adjustment

HTDP fills a critical role in facilitating the success of the National Adjustment in the western United States because the GPS baselines being adjusted were collected over 15 years and some mechanism for estimating and correcting for the effects of crustal deformation must be utilized. If not, the unmodeled deformation will cause vectors measured at different times to not fit. This project also provides an opportunity to demonstrate the importance of having a correct model of crustal deformation while adjusting survey measurements in tectonically active areas.

Future plans

A new model of the secular velocity field is being determined and will be incorporated in into the HTDP software within the next year. This model is based on DEFNODE (McCaffrey 2004). As part of this process, an analytical model representing horizontal crustal motion in the western contiguous states is being developed which will incorporate all of the major active faults in the region into a single model. The model will then be checked every year or so against all stations with well determined velocity vectors and any residual differences between the model vectors and the latest observed vectors will be modeled separately for the purpose of updating HTDP as needed. For HTDP users, the result will be a significantly more accurate model of crustal deformation in the western United States. In the future, we also hope to expand the geographic scope of HTDP to include Alaska and the western coast of Canada.

Conclusions

The Horizontal Time Dependent Positioning (HTDP) software has been updated to include dislocation models for the San Simeon and Parkfield earthquakes, the two largest earthquakes to occur in California since 2000. The revised software has now been released as HTDP Version 2.9. Including these models has significantly improved the ability to actually model and correct historical surveying measurements impacted by crustal motion in central California.

The growing use of seismic body waves as a constraint for dislocation modeling provides challenges to organizations such as NGS that use dislocation models to estimate surface deformation fields for the purpose of correcting for crustal motion between surveys of different periods. This is because, unless significant constraints from surface deformation measurements are included, the model will not faithfully replicate surface displacements. In addition, seismic body wave derived dislocation models include only the co-seismic portion of the earthquake slip but the earthquakes examined in this paper, particularly the Parkfield earthquake show that post-seismic slip on a fault can significantly add to the total earthquake-related deformation. The models we included were both derived from GPS vectors and InSAR measurements which directly measure surface deformation. They also both contained explicit models of post-seismic deformation. Our experience with the San Simeon earthquake shows that this type of model can provide estimates of the deformation significantly improved from estimates that are based on seismic body wave data.

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Figures

Figure 1 Map showing central California. Diamonds identify location of the San Simeon and Parkfield earthquakes

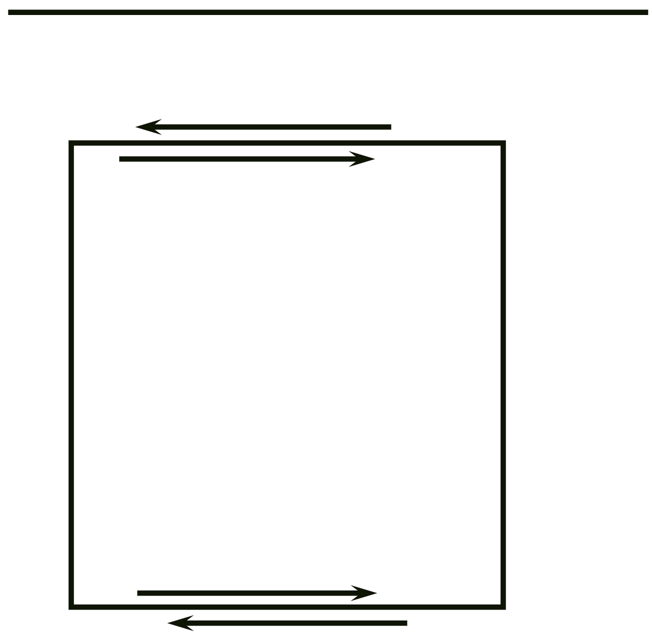

Figure 2 Schematic of a dislocation. The rectangle represents the slipping patch of the fault. Arrows represent the shear applied on the edge of the dislocation and the horizontal line above the rectangle represents the surface of the earth.

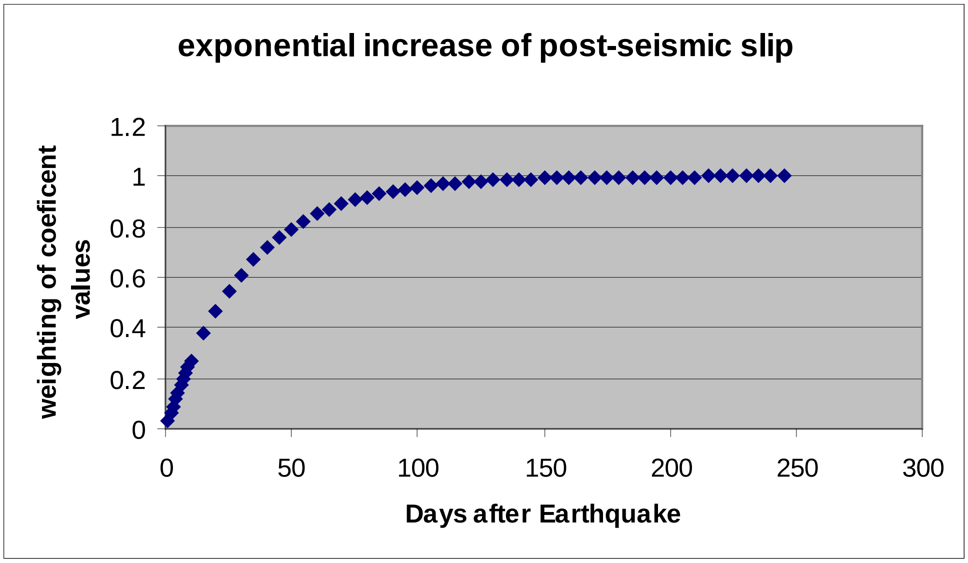

Figure 3 Exponential increase in post-seismic slip for the Parkfield earthquake

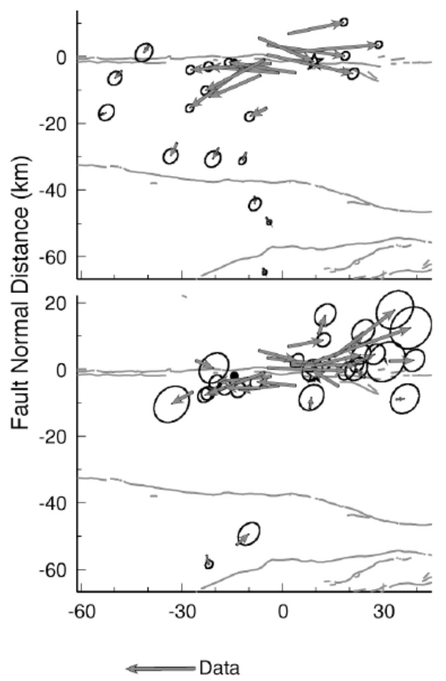

Figure 4
Displacement vectors for the co-seismic (above) and post-seismic (below) deformation associated with the Parkfield earthquake (after Johanson et al 2006)

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