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Local interpolation of coseismic displacements measured by InSAR

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ABSTRACT

Coseismic displacements play a significant role in characterizing earthquake causative faults and understanding earthquake dynamics. They are typically measured from InSAR using pre- and post-earthquake images. The displacement map produced by InSAR may contain missing coseismic values due to the decorrelation of ASAR images. This study focused on interpolating missing values in the coseismic displacement map of the 2003 Bam earthquake using geostatistics with the aim of running a slip distribution model. The gaps were grouped into 23 patches. Variograms of the patches showed that the displacement data were spatially correlated. The variogram prepared for ordinary kriging (OK) indicated the presence of a trend and thus justified the use of universal kriging (UK). Accuracy assessment was performed in 3 ways. First, 11 patches of equal size and with an equal number of missing values generated artificially, were kriged and validated. Second, the four selected patches results were validated after shifting them to new locations without missing values and comparing them with the observed values. Finally, cross validation was performed for both types of patch at the original and shifted locations. UK results were better than OK in terms of kriging variance, mean error (ME) and root mean square error (RMSE). For both OK and UK, only 4 out of 23 patches (1, 5, 11 and 21) showed ME and RMSE values that were substantially larger than for the other patches. The accuracy assessment results were found to be satisfactory with ME and RMSE values close to zero. InSAR data inversion demonstrated the usefulness of interpolation of the missing coseismic values by improving a slip distribution model. It is therefore concluded that kriging serves as an effective tool for interpolating the missing values on a coseismic displacement map.

1. Introduction

Coseismic displacements on the Earth's surface arise due to the energy released by earthquakes. Coseismic displacements play a key role in understanding their source mechanism (Leprince et al., 2007; van Puymbroeck et al., 2000). For example earthquake causative fault characterization and modeling depends on accurate measurement of them. Conventionally they are measured in the field using a total station or a GPS. Field methods provide accurate measurements but allow only sparse sampling. They are sometimes not feasible due to problems in accessing the area. Moreover, they may be time consuming and laborious (Kaneda et al., 2008).

Remote sensing can be used as an alternative, as both optical and radar data from space and aerial platforms allow the detection and measurement of coseismic displacements in earthquake hit areas (Avouac et al., 2006). Pre- and post-earthquake images are compared by using specialized remote sensing techniques (Taylor et al., 2008). A comprehensive database of images is available almost worldwide. Coseismic displacements can be measured from remotely sensed data as soon as a post-earthquake image of the area is available (Pathier et al., 2006).

Synthetic aperture radar interferometry (InSAR) is an often used technique for detecting and measuring coseismic displacements. InSAR exploits the phase difference of pre- and post-earthquake data and yields the displacement vector, which is sensitive mainly in the vertical direction. This technique has centimeter precision. InSAR, however, fails if the gradient of change is high. For generating an interferogram, the gradient of displacements should not exceed half a fringe per pixel size of the images (Michel et al., 1999). The gradient of change more than half a fringe per pixel would cause a loss of coherence between the images (Sarti et al., 2006). Such a loss of coherence may also be caused by several other factors, such as topography, vegetation, water bodies, agricultural practices and man-made changes. This factor is a major obstacle to estimate coseismic displacement measurements near the earthquake causative fault (Fialko et al., 2005; Funning et al., 2005). As a consequence, an InSAR derived displacement map has missing values (gaps), mainly due to temporal changes, topography and earthquake induced damages. Keeping in view the importance of coseismic displacements for fault characterization, there is a need to calculate these missing values.

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This study addresses the displacement map of the 2003 Bam earthquake. The produced displacement map has major gaps in the urban areas of Bam and Baravat, the river passing near Bam and the surrounding streams and vegetation. For this earthquake missing values also occur along the earthquake causative fault. Interpolation of the missing values is, therefore, useful for its characterization.

The Bam earthquake area was selected due to the following reasons. To our knowledge, interpolation of missing coseismic displacement values has not previously been applied to such data. Bam was severely damaged and the earthquake causative fault is directly passing under the city (Stramondo et al., 2005). In order to estimate the coseismic displacements interpolation is necessary. The Bam area is dry and flat with little vegetation and topography, hence the number of missing values in the displacement map, is expected to be limited. Finally, there is an extensive literature and interest in the area.

Typical interpolation techniques available in a geographical information system (GIS) are inverse distance weighting (IDW) and trend surface analysis (Burrough and McDonnell, 1998). A trend surface is based on regression of measurements on the coordinates, whereas IDW interpolation is based on a weighted combination of the surrounding measurements with weights depending upon the distance to observations. Geostatistical methods are preferred over trend surfaces and IDW because they build an explicit model of the spatial dependence and use it to interpolate at un-sampled locations and minimize the interpolation error variance (Addink and Stein, 1999).

Inversion of coseismic displacements is a commonly applied procedure to calculate the earthquake source parameters, in particular the slip magnitude and its distribution on the fault plane in the subsurface. This slip model can give a spatial insight into dislocation properties like the depth of the locked fault segment and the location of major asperities. The accuracy of a slip model depends upon the near-field (near the fault) spatially dense coseismic displacements. If a slip model is prepared using only the far-field displacements then details may be lost as compared to using near-field displacements (Elliott et al., 2007). As InSAR does not provide the near fault displacements, interpolation can help in obtaining these near fault displacements. The present study aims to compare the inversion models for both the original and the interpolated datasets in order to appraise the usefulness of the kriging.

The objective of the study is to interpolate the missing coseismic displacements by applying kriging. The accuracy of interpolation was evaluated by validation and cross-validation. The results from the geophysical modeling, obtained through inversion of the displacements, were compared for the original and the interpolated datasets. This was necessary in order to assess the utility of the interpolation.

2. Study area

Bam is an ancient city that lies in Kerman province, south-east Iran. Large parts of Iran are located in a tectonically active area. Central Iran accommodates approximately 14 mm yr^{-1} motion due to the northward convergence of Arabian plate into relatively stable Eurasia plate (Gonzalez et al., 2009; Peyret et al., 2007). Tectonically the study area (Fig. 1) is a part of a rigid Lut block bounded by two fault systems (Funning et al., 2005).

The study area is flat with a partially cemented alluvial fan system from the southern Jebal Barez Mountains. The cities of Bam and Baravat are separated by a ridge, 1520 m above mean sea level, which is actually a scarp of the Bam fault. It starts 9 km southeast of the Bam city and is oriented into the north–south direction.

On 26 December 2003, a devastating earthquake of magnitude 6.5 at the Richter scale struck the area, killing more than 30,000 people and causing severe damage to the city of Bam infrastructure. A preliminary study suggested that this earthquake was along the Bam fault (Fu et al., 2004). Subsequent field investigations and preliminary interferometric studies (Talebian et al., 2004), however, showed that the earthquake occurred along a previously unknown fault (Jonsson et al., 2004; Perski and Hanssen, 2006). The InSAR studies revealed that the major part of this fault is south of the city and that it may have extended toward the north, passing under the city (Peyret et al., 2006; Stramondo et al., 2005).

3. Data and pre-processing

The pre- and post-earthquake SAR images (ENVISAT ASAR) are dated 3 December 2003 and 11 February 2004 respectively, with a difference of 70 days. The perpendicular distance between orbits of the two scenes (the baseline) is 4 m. The images are in IS2 mode and have an incident angle of 23°, VV polarization and single look complex format. The generation of displacement map was carried out using SARscape 4.2 utility in the ENVI® 4.7 software. A post-earthquake ASTER image dated 2 January 2004 was used for the visual classification of landcover of the study area.

3.1. Modeling displacements using InSAR

An interferogram shows the phase-difference of two co-registered SAR images of pre- and post-earthquake. Each fringe in the interferogram represents a 2π change. The phase-difference measurements (φ) are the summation of several effects; namely, ground deformation (φ_{def}), topography (φ_{topo}), atmospheric delay (φ_{atmp}), flat Earth (φ_{flat}), temporal changes (φ_{temp}) and other unknown sources of noise (φ_{noise}) (Wang et al., 2009):

$$\varphi = \varphi_{def} + \varphi_{topo} + \varphi_{atmp} + \varphi_{flat} + \varphi_{temp} + \varphi_{noise} \quad (1)$$

In order to measure φ_{def}, the other effects of phase contribution have to be removed. To remove φ_{topo}, an SRTM DEM of 3″ was used. It was assumed that φ_{atmp} is negligible for this study, because of the dry and stable meteorological conditions in the area. The flat Earth phase (φ_{flat}) is compensated by using orbital information. Also, φ_{temp}, which represents temporal environmental changes, is negligible due to the arid environment of the study area. Finally, φ_{noise}, is assumed to be small. A Goldstein filter was applied (Goldstein and Werner, 1998) to improve the quality of the interferogram. It is an adaptive filter that reduces the phase noises and preserves the local fringe rate in the interferogram. The filter significantly improves the fringe visibility in the decorrelated areas (Baran et al., 2003).

Phase unwrapping of the interferogram converts the 2π cyclic fringes into a continuous signal using a region growing algorithm (Baldi, 2003; Costantini, 1998; Fornaro and Sansosti, 1999). Phase unwrapping provided the surface displacements projected onto the radar LOS (line of sight). A coherence image, giving the measure of the stability of the phase, was produced as well. The unwrapped interferogram was geocoded using GCPs and SRTM DEM to have the map coordinates projected to UTM zone 40-North and datum WGS-84.

3.2. Coseismic displacement map

The interferogram is of good quality (Fig. 2(a)) due to very dry conditions on the ground, relatively flat area and short baseline (Gonzalez et al., 2009). The cities of Bam and Baravat show major incoherent areas (Fig. 2(b)) in the main deformation site due to vegetation and the collapse of buildings.