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Estimating coseismic ground displacement during the 2015 Gorkha, Nepal, earthquake from accelerometric data at KATNP station

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ABSTRACT

This paper presents an investigation into the residual ground displacement during the 2015 Gorkha, Nepal earthquake. The available accelerometric data recorded from a near field recording station (KATNP) are processed using two different techniques. The techniques include a method based on pulse identification after low pass filtering and modifications to an empirical regression method to remove some of the subjectivity. The results are compared to both high-rate (5 Hz) global positing system (GPS) coseismic displacement data and interferometric synthetic aperture radar (InSAR) satellite imaging. Since the GPS sensors are not collocated with the acceleration sensors, the InSAR data is used to determine displacement trends to facilitate comparison. It is shown that both methods investigated in this paper provide similar coseismic displacement waveforms matching those of the high-rate GPS. In addition, the vertical and east displacements derived from accelerometric data match well to the quasi up-down and quasi east-west displacement trends from InSAR.

1. Introduction

Near field ground motions may contain substantial low frequency content resulting from coseismic (residual) displacement or forward directivity effects. Although the ability of modern digital sensors to record reliable low frequency content is superior to their analog predecessors, recordings may still suffer from low frequency contamination from a variety of sources. Some sources include instrument and background noise, baseline offsets due to ground tilt or rotation, and the electrical/mechanical behavior of the sensor [1]. Ground motion processing schemes using filtering to remove low frequency noise will also remove the content corresponding to the coseismic displacement [2–6]. Researchers in this field attempt to recover the coseismic displacement by various techniques. These techniques focus on ways to identify and remove the noisy portion of the low frequency content and retain the signal corresponding to the coseismic displacement. Ideally, the exact physical phenomena responsible for the low frequency noise could be identified for a sensor, and a correct processing procedure implemented to address the phenomena, but this is rare [1].

Ground motion processing with high pass filtering [2] generates zero baseline waveforms which do not retain the coseismic displacement component. Thus, alternative methods to extract the residual displacement were developed as early as 1976 by Bogdanov and Graizer [7]. In Graizer [8] a polynomial adjustment technique was proposed which subtracts a third order polynomial from the raw time series. The polynomial coefficients are determined by minimizing the sum of the square of the adjusted velocity. In the author's literature review it appears this method has been seldom used beyond [8]. Graizer [8] states that, as one of the conditions for use of this method, “the influence of rotations and tilts should be minor”. Since there is evidence of tilting around Kathmandu during this earthquake [9] the method will not be used. However, the minimum square of the velocity as selection criteria will be adopted for one of the methods discussed in this paper.

Perhaps the most widely used method is that of Iwan et al. [10] which has been subsequently modified by various researchers including [11–15]. [10] suggested using two constant acceleration adjustments, a_m over the time from t_1 to t_2 and a_f over the time from t_2 to t_f, with t_f usually taken as the end of the record (t_d), to correct for linear velocity trends. Some of the recommendations in Iwan et al. [10], such as time instant selection based on a threshold acceleration (50 cm/sec.^{2}), are based specifically on the response of the sensors studied. The subsequent widespread use of this method, with modifications, indicates that it is versatile and adaptable to many different ground motion recordings and sensor behaviors. It was stated by [10] that “the final results are fairly insensitive” to the selection of t_1 and t_2, based on their research. It was later shown that, to the contrary, the displacement results are sensitive to the time instant selection for other recorded ground motions. Boore [11] proposed the “v0 correction” which finds t_2 using the time when a line fit to a portion of the raw velocity waveform becomes zero. The method of [11] still retains considerable subjectivity since the criteria for selecting t_1 and the time instants for line fitting are based on subjective descriptions. Numerous modifications have been

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proposed based on the method of [11], mainly to help reduce the level of subjectivity in selecting the time instants. Akkar and Boore [12] added two more time instants, based on the times used to fit a linear regression to raw velocity and used Monte Carlo simulations to generate a suite of corrected waveforms. Wu and Wu [13] identified physical phenomena to assist in the time instant selection and added a third time instant t_3. Rupakhety et al. [14] uses a third time instant t_3 like [13] and added a procedure to select t_2 based on the flatness of the low frequency portion of the Fourier amplitude spectrum of velocity. The method of [14] still retains subjectivity in the selection of t_1. Chao et al. [15] used the model of [13] and selected time instants t_2 and t_3 based on certain values of the ratio of energy distribution in the acceleration time history.

Other techniques based on empirical mode decomposition (EMD) [16] and discrete wavelet transform (DWT) [17] have been introduced. These techniques use two different methods of decomposing the raw acceleration time series into numerous nonstationary time series. Each of these decompositions identifies a unique component of the raw time series and can be identified as noise, or can be attributed to the coseismic displacement. The adjusted time series is then constructed by summing the appropriate decomposed time series to remove the noise. In both EMD and DWT based methods, the decomposed time series have varying frequency content with lower modes containing generally higher frequency than the higher modes. The highest modes contain the lowest frequency content, and since this frequency content contains the baseline drift and low frequency noise, the highest modes are eliminated from the system. The downside is the complex processing schematic and a level of subjectivity is still involved in determining the appropriate time series to retain.

In this paper two methods are used to estimate the coseismic ground displacement from the Mw 7.8 2015 Gorkha, Nepal earthquake on April 25, 2015. The author has tried some of the existing methods with varying degrees of success, mainly due to their inherent subjectivity. Thus, two new methods have been used which are based on objective criterion. The first method uses filtering to extract the low frequency component and identify a "step pulse" which generates the step (fling) displacement. The second method is another modification to the procedure of [10] to make it semi-automatic, and to which a procedure to adjust for linear displacement drift is added. In the interest of retaining time series compatibility, all adjustments are made to the acceleration data. The electronic supplement of this paper provides the adjusted acceleration time series which can be integrated by the user to velocity and displacement.

The strong motion array in Nepal provided sparse coverage of the Gorkha earthquake and was recorded by only six near-field stations. The Kanti Path (KATNP) station operated by the United States Geological Survey (USGS) is installed in a one-story reinforced concrete building in Kathmandu. KATNP is located at a soil site, with approximate sediment thickness of about 550 m and shear wave velocities in the range of 170–300 m/s (NEHRP Site Class D soil) [18,19]. The recordings at this station are the focus of the work presented in this paper. The KATNP site is part of the NetQuake program which uses a Geosig-GMS recorder. However, the sensor type is unknown since the data files do not contain any identification. According to Luetgert et al. [20] the sensor typically employed with the NetQuake program is a Colibrys SF-2005 MEMS accelerometer. Both Geng et al. [21] and Rupakhety et al. [22] have also recovered approximate coseismic displacements from the KATNP recording. Rupakhety et al. [22] has used the method of [14] while Geng et al. [21] used the method of [11]. The methods of [11,14] have some level of subjectivity in their application while the two methods explored in this article are more objective. The v0 correction of [11] is highly subjective since it relies on fitting a line between two points on the velocity trace "well after the strong shaking has subsided". This line fitting allows the determination of t_2 based on the time where this line becomes zero. Further, time instant t_1 is found by estimating a time near the initiation of strong shaking. As discussed in [11], it is often difficult to estimate t_1 based on a subjective description, and the resulting waveforms are highly sensitive to the selection. The method of [14] is less subjective, but it uses "t_1 as the time when the displacement starts to move from its initial position", which is still subjective. Section 3 of this paper will show that the two methods used in this work are more objective. Complete processing details of both methods are presented herein, along with the acceleration time series, which are not provided in [21] and [22]. Hence this paper provides a necessary contribution to the literature on this earthquake event and discusses two new objective methods for extracting approximate coseismic displacements.

The Nepal Department of Mines and Geology (DMG) operates a sensor close to KATNP which also captured the mainshock and aftershocks [23]. Four sensors were installed and operated by a collaboration of Hokkaido University and Tribhuvan University at KTP, TVU, PTN and THM stations [9]. KTP is a rock site, while TVU, PTN and THM are sedimentary sites. The raw acceleration data from DMG, KTP, TVU, PTN and THM does not show evidence of coseismic displacement. This has been attributed to the instrument response for KTP, TVU, PTN, and THM [9]. Published coseismic displacements have been presented for KTP only, after deconvolution to remove the sensor response by [9]. To the author's knowledge, an analysis on the DMG data has not yet been published regarding the possibility of recovering residual displacement from that record. Table 1 lists the type of sensor for each station along with the epicentral and rupture distances.

In addition to the accelerometric data, coseismic displacement recordings are available from two high-rate GPS (5 Hz) installations at KKN4 and NAST sites, operated by UNAVCO [24]. There were no collocated GPS sensors at any of the six accelerometer sites. Hence, the high-rate GPS displacement records will only allow limited comparison to the accelerometric data. KKN4 is a rock site and located 10.5 km North of KATNP while NAST is a sedimentary site and located 6.2 km South of KATNP. The locations of the six strong-motion recording sites along with the two high-rate GPS sites are shown on Fig. 1. Crustal displacements have also been detected from the ALOS-2 [25] and Sentinel-1a [26] satellites using interferometric synthetic aperture radar (InSAR). Since the InSAR scans occur sometime after the earthquake event, they may be considered to capture the postseismic displacement since it will be shown that the GPS records show evidence of relaxation after the coseismic displacement. However, the InSAR data will be used to infer some of the coseismic displacement patterns, rather than attempt to match the magnitudes.

2. Step pulse identification – Method 1

High pass filtering removes low frequency instrument noise in addition to permanent displacement and baseline offsets. If the signal to noise ratio is high in the low frequency range, then it may be assumed that the low frequency component is predominantly composed of the permanent displacement and baseline offset components. This method relies on both high pass (or band pass) and low pass filtering to generate a zero baseline time series and low frequency time series, respectively. A bandpass filtered time series ($a_0(t)$) will have zero baseline [2], which can be expressed as the raw acceleration with high ($a_{HF}(t)$) and low frequency ($a_{LF}(t)$) time series removed:

Table 1
Epicentral, rupture distances and sensor type for each station.

Station	Sensor	R_{epi} (km)	R_{rup} (km)
KATNP	Geosig-GMS (NetQuake)	81	14.1
DMG	Geosig-AC23	81	14.4
KTP	Mitsutoyo JEP-6A3-2	81	13.7
PTN	Mitsutoyo JEP-6A3-2	84	13.1
THM	Mitsutoyo JEP-6A3-2	88	13.5
TVU	Mitsutoyo JEP-6A3-2	82	13.6