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Quantitative analysis of the Nepal earthquake on 25 April, 2015 in the perspective of future earthquake hazard

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ABSTRACT

The earthquake that occurred in Nepal on 25 April, 2015 was followed by about 256 aftershocks which continued for another 20–25 days. The Coulomb stress change due to the main shock has been estimated at depths 10 km, 15 km and 22 km which justify the occurrence of about 218 aftershocks of magnitudes 4 to 5 mostly at 10 km depth and the rest of magnitudes 5 to 7.3 mostly at 15–30 km depth. The western, southern and northern fringes of the fault plane that slipped on 25 April, 2015 show a high value of positive Coulomb stress change estimated at the above mentioned depths and yet these parts of the fault remained devoid of any aftershock epicentre and therefore must be treated as seats for possible future events. Co-seismic displacement of 5 GPS stations located in Nepal after the devastating earthquake of *M*w7.8 on 25 April, 2015 and its largest aftershock of *M*w7.3 on 12 May, 2015 have been separately estimated and analysed.

1. Introduction

On 25 April, 2015 an earthquake of *M*w7.8 occurred about 77 km northwest of Kathmandu in Nepal at a focal depth of 8.2 km (http://earthquake.usgs.gov/earthquakes). The fatal earthquake that caused huge loss of human lives occurred in the Himalayan thrust wedge near the basal decollement which defines the lower boundary of the thrust wedge and is referred to as the Main Himalayan Thrust Fault (MHT) [1]. The three main thrust systems in the Himalayas, branching off as ramps from MHT are the Main Central thrust (MCT), Main Boundary thrust (MBT) and the Main Frontal thrust (MFT) which respectively separate the Greater Himalayan, the Lesser Himalayan, the Sub-Himalayan Zones and the Indo-Gangetic Plains from one another [2,3]. The convergence rate of Indian plate under Tibet varies from west to east along the length of the Himalayas [4]. The convergence rate across Nepal is about 20 mm/yr [5]. As a result of the fast convergence across Nepal, a portion of Himalayan thrust wedge moved southward over the Indian Plate along the MHT and resulted in the devastating earthquake on 25 April, 2015. According to the slip distribution model proposed by the "finite fault" analysis of USGS (http://earthquake.usgs.gov), a maximum slip of 3.5 m occurred. According to Zhang et al. [6], however, the slip distribution resulted in a maximum slip of 4.5 m. The main shock of 25 April was followed by more than 250 aftershocks (Fig. 1), one aftershock of *M*w6.7 occurred at depth of 22 km on 26 April, 2015 and the largest one (*M*w7.3) occurred on 12 May, 2015 with its epicentre located about 30 km east of the 25 April earthquake. The variation of earthquake magnitude with their depth of occurrence is plotted in Fig. 2.

In this paper, we have estimated and analysed the Coulomb stress change at 10 km and 15 km and 22 km depths imparted due to the earthquake based on the slip distribution model and the fault plane geometry proposed by USGS. Abundance of aftershock locations in the areas showing positive Coulomb stress change and yet remaining devoid of any aftershock demarcated as probable locations for future events. The co-seismic displacement of 5 GPS stations located in Nepal after the main shock on 25 April, 2015 and the aftershock on 12 May, 2015 separately have also been estimated and analysed.

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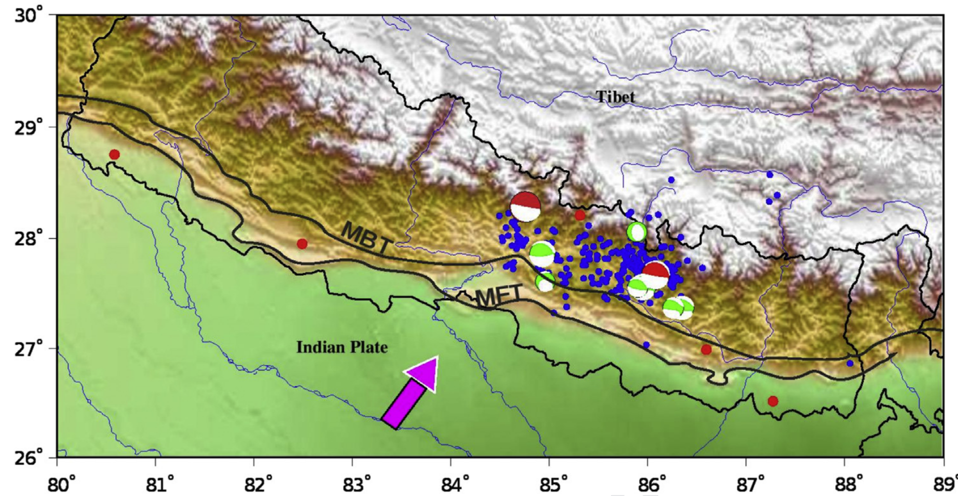

Fig. 1. Focal plane solutions of the main shock E1 and its largest aftershock E2 (red) and available focal solutions of other aftershocks (green) plotted on a topographic map of Nepal. Blue dots are epicentres of other aftershocks and red dots indicate the GPS stations. The magenta arrow shows the direction of convergence of Indian Plate under Tibet.

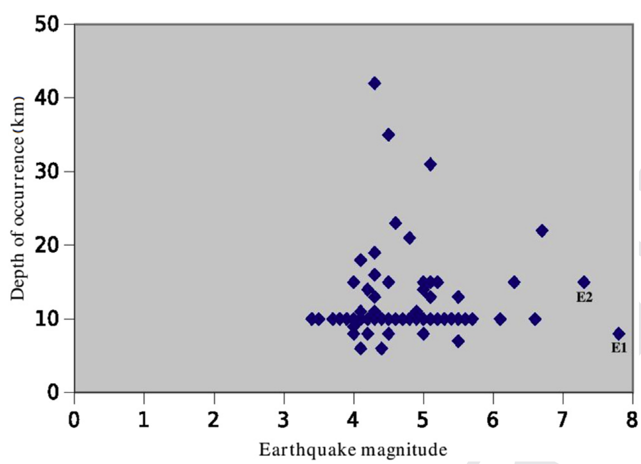

Fig. 2. Earthquake magnitude plotted against their depth of occurrence.

2. Earthquake and GPS data source and processing

Earthquake epicentre location data have been downloaded from USGS (http://earthquake.usgs.gov/earthquakes) and the focal solutions of the main event and few aftershocks have been obtained from CMT Harvard (http://www.globalcmt.org) and processed with GMT ver. 5.1.1 [7]. SOPAC Data Archive (http://sopac.ucsd.edu) has provided GPS data from 5 stations in Nepal. GPS data have been processed with GAMIT/GLOBK ver. 10.6 [8,9]. Topographic data for Fig. 1 have been obtained from http://www.ngdc.noaa.gov/mgg and Figs. 1 and 6–8 have been processed with GMT ver. 5.1.1.

3. Coulomb stress change after earthquake

3.1. Theory

Estimation and analysis of Coulomb stress change is very useful in understanding how one earthquake can trigger another as stress increase results in further earthquakes [10]. Failure of rocks in a brittle manner is a function of both shear and confining stresses formulated as Coulomb failure criterion (CFC) which is independent of regional stress but depends on fault geometry, sense of dip and co-efficient of friction. CFC requires both shear and normal stress on an incipient fault plane satisfy conditions analogous to those of friction on a pre-existing surface. Mathematically CFC is obtained from Eq. (1).

Failure occurs on a certain fault plane when the Coulomb stress σ_f exceeds the specific value given by

$$\sigma_f = \tau_\beta - \mu\left(\sigma_\beta - p\right) \tag{1}$$

where τ_β is the shear stress on the failure plane oriented at angle β with the σ_1 axis, σ_β is the normal stress, p is the pore fluid pressure and μ is the co-efficient of friction. τ_β is always taken to be positive in this expression, though in the usual process of resolution of stress τ_β can be positive or negative giving rise to right-lateral or left-lateral slip.

The Coulomb stress change (CSC) is given by Eq. (2) [11],

$$\Delta\sigma_f = \Delta\tau_\beta - \mu\left(\Delta\sigma_\beta - \Delta p\right) \tag{2}$$

Because of the tendency of Δp to counteract σ_β, the above equation is sometimes written as,

$$\Delta\sigma_f = \Delta\tau_\beta - \mu'\left(\Delta\sigma_\beta\right) \tag{3}$$

where μ' is "effective" reduced coefficient of friction given by:

$$\mu' = \mu\left(1 - \Delta p / \Delta\sigma_\beta\right) \tag{4}$$

Negative value of $\Delta\sigma_f$ in Eq. (2) would imply that failure threshold has not yet been reached, while a positive value of $\Delta\sigma_f$ would indicate that the failure threshold has been exceeded. An earthquake reduces the average value of the shear stress on the fault that slipped, but the shear stress rises at the fault tips and elsewhere also. Stress increase of less than 1.5 bar appears sufficient to trigger an earthquake and stress decrease of similar amount are sufficient to suppress them [10].

3.2. Results

The 25 April, 2015 earthquake (E1) occurred at a depth of 8.2 km when a fault plane with strike = 295°, dip = 10° slipped along MHT according to the "finite fault" analysis of USGS. The main shock E1 was followed by a large number of aftershocks (about 256) which

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