CONTRIBUTION OF INTERNAL DEFORMATIONS OF EARTH'S CRUST IN TRIGGERING EARTHQUAKE INDUCED DISASTERS

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ABSTRACT: Landslides have been reported as the most devastating secondary effect (non-shaking) of deadly historical earthquakes in terms of the loss of lives, properties and disruption of communication facilities. Mid-Niigata Prefecture Earthquake of 2004 and Kashmir earthquake of 2005 are two of the most catastrophic earthquakes of last decade and have triggered numerous landslides and slope failures. Seismic stresses have been calculated for the epicentral areas of both of the aforementioned earthquakes in the interior of a laterally homogeneous layered half-space through the forward modeling. Distribution of landslides for both of the subject earthquakes are compared to the square root of the second principal invariant of deviatoric stress tensor and a remarkable correlation is observed. Comparison of the existing landslides and seismic stresses deduces development of a similar stress pattern in the past.

Key Words: Mid-Niigata Prefecture earthquake, Kashmir earthquake, seismic stresses, landslides

INTRODUCTION

Most of the moderate to large historical earthquakes triggered numerous landslides and slope failures which caused significant damages to seismically active areas. In addition to their direct impacts, landslides and slope failures cause long lasting geotechnical problems in the form of destabilized mountainous slopes due to rock weathering such as debris flows, temporal mass movements, etc. Some of the most catastrophic earthquakes in terms of landslide disasters in the last decade include the 1999 Chi-Chi Earthquake of Taiwan (10,000 landslides; Wang et al. 2003), the 1995 Hyogoken-nanbu Earthquake of Japan, the 1994 Northridge Earthquake in the USA (11,000 landslides; Harp and Jibson 1996), the 1989 Loma Prieta Earthquake in the USA (1,280 landslides; Keefer 2000), the 2004 Mid-Niigata Prefecture Earthquake in Japan (1,353; Sato et al. 2005a) and 2005 Kashmir Earthquake of Pakistan (2,424 landslides; Sato et al., 2006). Quantitative and geospatial study of global losses caused by the most deadly earthquakes in last 40 years (Marano et al., 2010) has shown that deaths from landslides have been the largest among those from other causes than shakes. We, therefore, need to rationally understand the triggering mechanism and thorough cause investigation for such landslide disasters.

Mid-Niigata Prefecture Earthquake jolted central Japan on October 23, 2004, and was followed by a large number of aftershocks. The epicenter of the earthquake was located in the low raised Higashiyama mountain terrain (Figure 1), which has a very clear active folding geological structure (Yoong and Okada, 2005). In common with other historical earthquakes in active folding regions, the Mid-Niigata Prefecture Earthquake also triggered thousands of landslides. The economic loss due to

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these landslides was initially estimated at 8 billion US dollars, making this one of the costliest landslide events in history (Kieffer et al., 2006).

Kashmir Earthquake, deadliest in the recent history of south Asia, struck northern areas of Pakistan and Pakistan administrated state of Jammu and Kashmir on October 8, 2005. The epicenter of the earthquake is located 100 km north of Islamabad, capital of Pakistan, in a rugged mountainous terrain. The source of the earthquake is about 75 km long NW-SE trending Balakot-Bagh reverse fault (Figure 2). Blind reverse separation of the causative fault has crushed and disintegrated dolomite slope surfaces. Different authors have detected several thousands of landslides triggered by this earthquake. The most worth mentioning is the massive Hattian-Bala landslide which flushed about four villages and blocked two tributaries of Jhelum River and created a huge landslide dam. Later this landslide dam was breached and caused flooding of the downstream reach.

In this paper, the authors have obtained the seismic stress distribution through forward modeling near the surface of a layered half-space and tried to develop a cause and effect relation between the landslide disasters and change in the state of stress induced by seismic stresses. The sources in terms of the dislocations across the fault rupture planes are determined by the inverse modeling in authors' previous work (Kazmi et al, 2013).

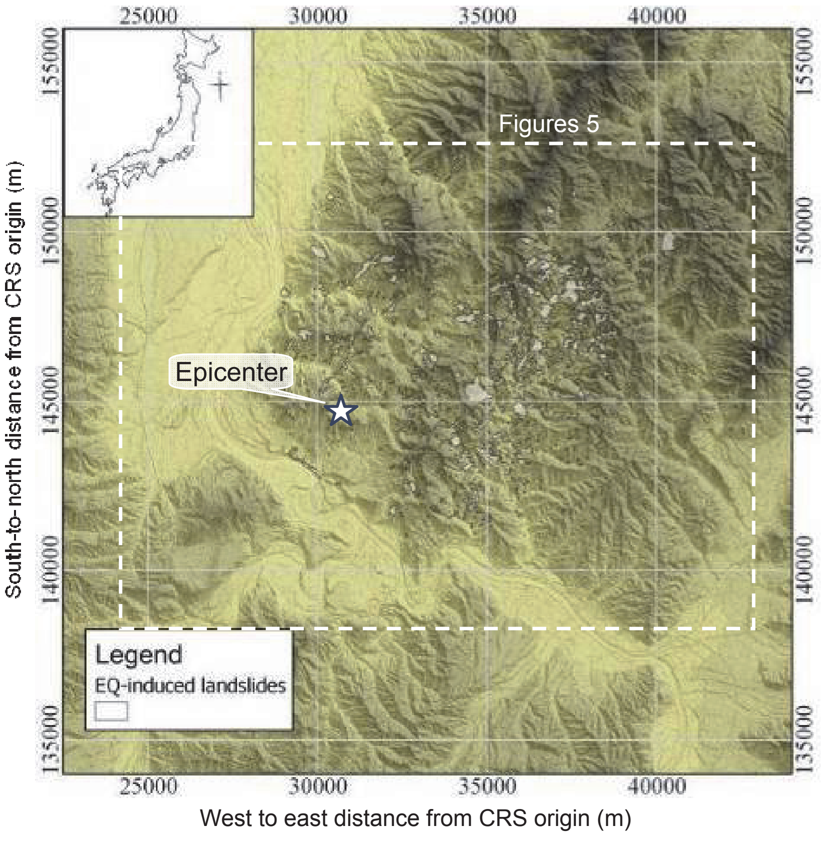

Figure 1. Epicentral area of the October 23rd 2004 Mid- Niigata-Prefecture Earthquake (37.2917°N, 138.8666°E): The terrain shown above is a digital representation of cartographic information (Digital Elevation Model) in a raster form with pixels arranged in $5\text{m} \times 5\text{m}$ square. Topographical mapping is on the JGD2000/ Japan Plane Rectangular Coordinate System VIII with its southwest corner located as the origin at 138°30′00"E, 36°00′00"N. White polygons show the distribution of landslides triggered by this earthquake mapped by Oyagi et al. (2008).

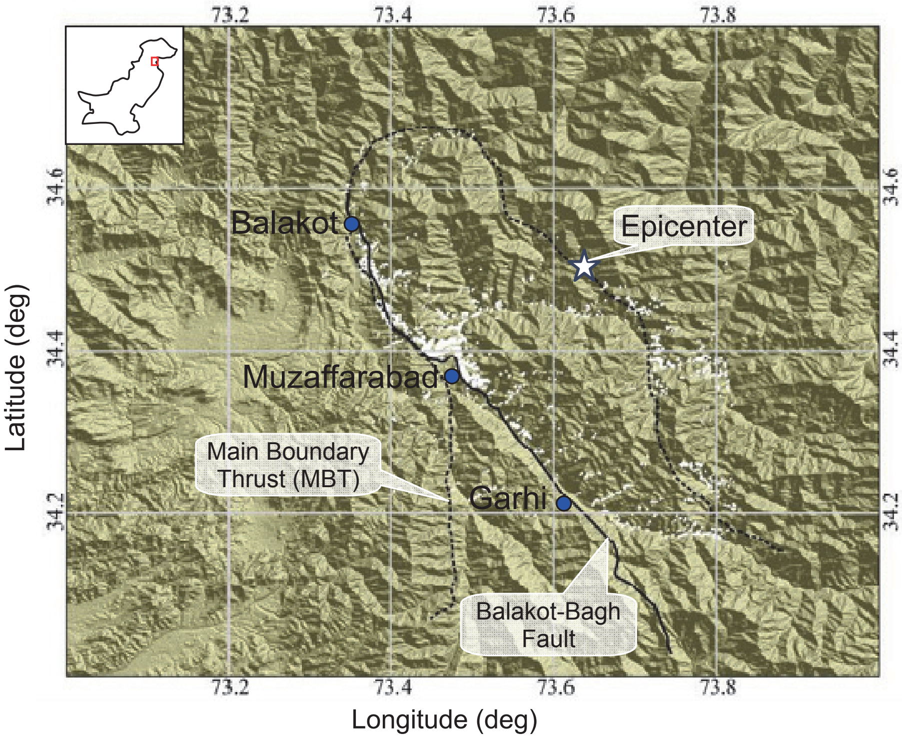

Figure 2. Tectonic map of 2005 Kashmir Earthquake with the causative Balakot-Bagh Fault overlaid the terrain map. White dots show the distribution of landslides triggered by Kashmir earthquake (extracted from the satellite data by Sato et al., 2007)

CRUSTAL DEFORMATIONS AND SOURCE INVERSION ANALYSIS

Mid-Niigata Prefecture Earthquake

The authors have extracted three dimensional Lagrangian ground displacements from accurate digital elevation models of an 11km x 7.5km low-rising mountainous epicentral area (Higashiyama Mountains). Mathematical formulation of the numerical model to extract Lagrangian ground displacements, its application to the subject earthquake and comparison of obtained displacement components with field measurements and/or observations is discussed in authors' previous paper (Kazmi et al., 2013). Based on the theory of elastic dislocation, linear inversion of available geodetic data has been performed for a multi-segment fault model, embedded in a laterally homogenous layered half space. Figure 3 shows the results of spatial distribution of fault slips (Kazmi et al. 2013).

2005 Kashmir Earthquake

Different authors have obtained crustal deformations associated with the 2005 Kashmir earthquake using different data sources and data techniques. All of them have revealed high later and vertical components of crustal deformations in a wide belt along the total stretch of causative Balakot-Bagh fault. Linear geodetic data inversion analysis has been performed to reveal spatial distribution of slip on a 90km x 30km fault rupture plane having strike and dip angles of 320^o and 29^o, respectively (Figure 4). The largest simulated value of slip has reached 7.6 meters. Slips are mainly concentrated in the shallower depth of the rupture plane (Figure 4) and the slip vectors close to the ground surface are closely matching the crustal deformation pattern.

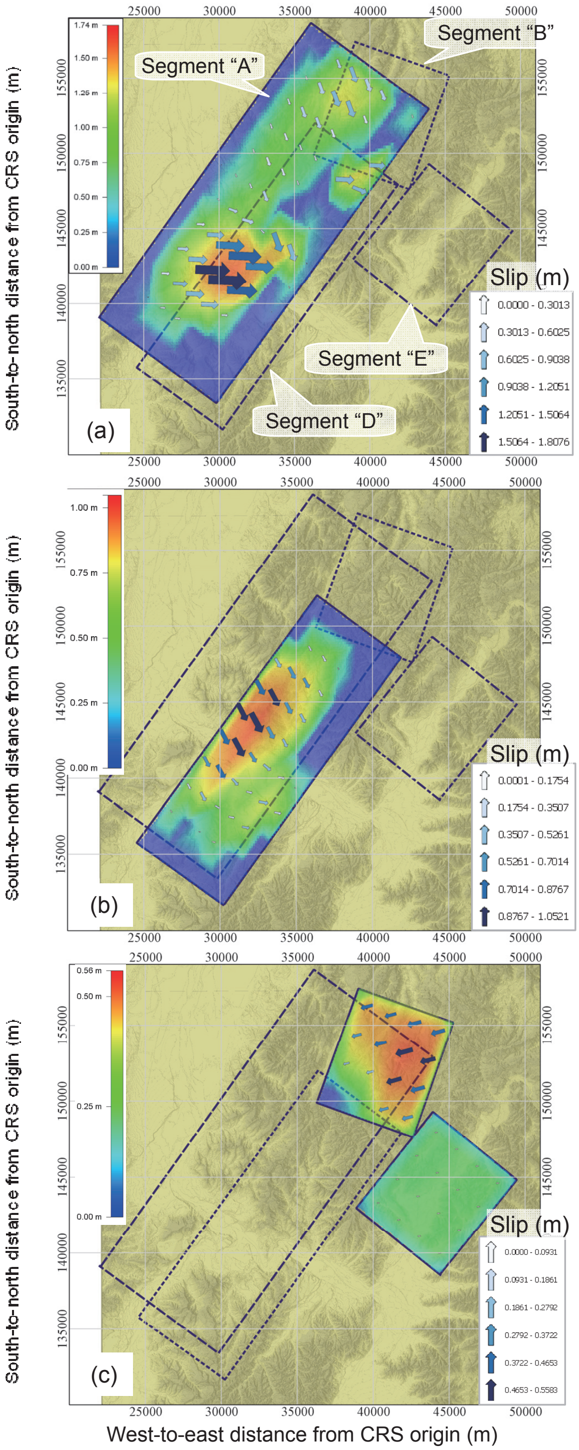

Figure 3. Surface projections of fault slip distribution obtained by the inverse modeling (Kazmi et al. 2013). The detailed geometry of the multi-segment fault model is available in authors' previous paper.

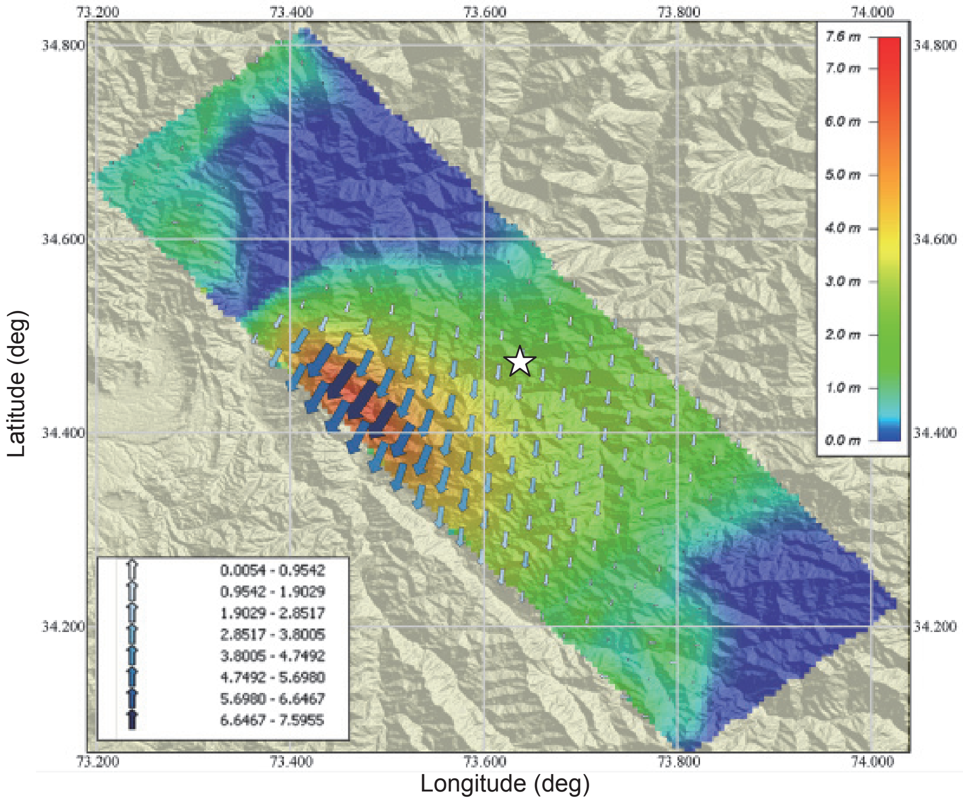

Figure 4. Surface projection of the fault slip distribution obtained by the linear geodetic data inversion. The color shows the scale for slip while the vectors are to show the direction of slip. White star shows the location of hypocenter

SEISMIC STRESSES IN THE INTERIOR OF SOIL

The analytical solutions for surface and internal deformations generated by shear and tensile faults in a homogenous half-space were derived by Okada (1985, 1992) and are widely used as the forward model for inversion. However, a homogeneous half-space model may oversimplify the real earth, and a model of horizontally layered half-space is considered to be a workaround. To solve for elastic deformation in the layered half-space, there was a progressive development in the numerical techniques and most of them are based on wavenumber integration method (e.g. Sato, 1971; Sato and Matsu'ura, 1973; Sing, 1971 etc.). However, the wavenumber spectra or kernel functions for the layered half space can only by integrated numerically or approximated. The problems of limited number of layers due to exponential growth of the calculation for kernel functions and numerical instability were dealt rationally more recently by Wang (1999), who considered the problem from its physical point of view. Following Wang (Wang, 2003), seismic stresses/strains are calculated in the interior of soil by considering a similar layered half space as was used in inverse modeling.

The partial differential equation governing static deformation in an elastic medium in combination with Hooke's law is given by:

$$(\lambda + 2\mu)\nabla(\nabla \cdot \mathbf{u}) - \mu\nabla \times (\nabla \times \mathbf{u}) = \mathbf{f} \quad (1)$$

where λ and μ are the two Lame constants, u is the displacement vector, and **f** is the body force.

By applying Hankel transforms (Aki and Richard, 1980), the partial differential equation of static deformation is transferred to a set of ordinary differential equations which are decoupled from each other, and represent P-SV and SH modes. The resulting set of ordinary equations for P-SV mode is given by:

$$\frac{d}{dz} y_m = A y_m \tag{2}$$

where y_m and A are the generalized displacement vector and coefficient matrix for P-SV mode, respectively, given by:

$$y_m = (U_m \quad E_m \quad V_m \quad F_m)^T \tag{3}$$

$$\mathrm{A} = \begin{bmatrix} 0 & 1/(\lambda+2\mu) & \lambda k/(\lambda+2\mu) & 0 \\ 0 & 0 & 0 & k \\ -k & 0 & 0 & 1/\mu \\ 0 & -\lambda k\,/\,(\lambda+2\mu) & 4k^2\mu(\lambda+\mu)/(\lambda+2\mu) & 0 \end{bmatrix} \tag{4}$$

Similarly for the SH mode, the resulting equation are;

$$\frac{d}{dz} x_m = B x_m \tag{5}$$

with the generalized displacement vector, x_m, and the coefficient matrix, B, given as;

$$x_m = (W_m \quad G_m)^T \tag{6}$$

$$\mathrm{B} = \begin{bmatrix} 0 & 1/\mu \\ k^2\mu & 0 \end{bmatrix} \tag{7}$$

The surface of the layer (z = 0) is traction-free and the laterally homogeneous layers making up a semi-infinite half space are in welded contact along their boundary planes. The fault planes are modeled by superimposing double couples, single forces, inflations, etc.

Thomson-Haskell propagator algorithm is applied to get the solution of complete boundary value problem. Chain rule property of the Thomson-Haskell Propagator Matrix Method helps to conveniently relate the solutions across different depths. The detailed mathematical formulation of the numerical technique is given by Wang et al. (2003).

The second principal invariant of deviatoric stress tensor, J_2, can be considered as an index for rocks and soils deformability in the absence of reliable rock failure criterion and spatial coverage of soil/rock properties. Although the slip surfaces for different landslides will have large variability, seismic stresses are calculated at a representative depth of 5 meters below the ground surface to discuss the landslide triggering mechanism and its relation with the seismic stresses.

Figure 5(a) shows spatial distribution of the square root of the second principal invariant of deviatoric stress, $\sqrt{J_2}$, for the epicentral area of Mid-Niigata Prefecture Earthquake at 5 meters below the ground surface. Parallel belts of large $\sqrt{J_2}$ values are observed at an about 4km regular interval. All the landslides triggered by this earthquake are found concentrated along the stripes of large $\sqrt{J_2}$ values (white polygons in Figure 5(a)). This highlights the importance of the seismic stresses in triggering and/or reactivation of landslides. It is also noted that all the existing landslides that had been identified as of 2000 (National Research Institute for Earth Science and Disaster Prevention, 2000) are even more precisely clustered along the higher values of $\sqrt{J_2}$ (white polygons in Figure 5(b)). It can be deduced from the concordant behavior of higher $\sqrt{J_2}$ values and landslides existing before that earthquake that a similar pattern of stress distribution might have repeated in the past.

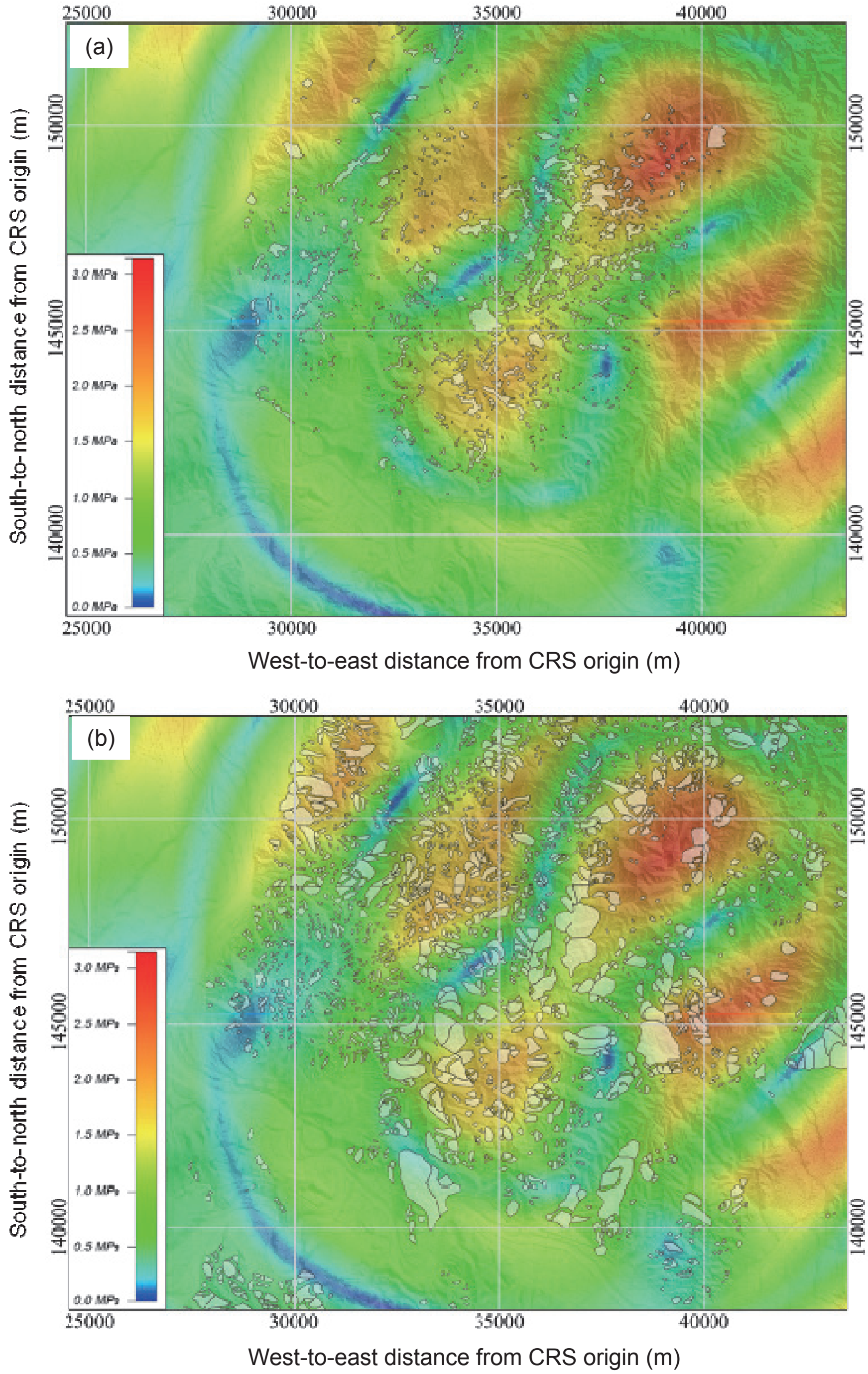

Figure 5. Distribution of the square root of the second invariant of deviatoric stress tensor at 5 meters below the ground surface along with the (a) landslide distribution triggered by the earthquake (white polygons) and (b) landslides existing before the earthquake (white polygons). All the landslides are found remarkably consistent with the stripes of large $\sqrt{J_2}$ values.

Figure 6 shows the spatial distribution of $\sqrt{J_2}$ values for the whole epicentral area of 2005 Kashmir earthquake. Higher values of $\sqrt{J_2}$ are aligned along the causative Balakot-Bagh fault and extend in a wider brush towards the hanging wall. It is also worth mentioning that almost all landslides triggered by the Kashmir earthquake (extracted by Sato et al. 2005 from the satellite data) are concordant with the higher values of $\sqrt{J_2}$ (white dots in Figure 6).

The above mentioned discussion, about two of the most devastating earthquakes in last decade, elaborates the importance of the seismic stresses and their relation to the soils and rocks deformability. In a separate work, the authors have also observed that the damages to underground facilities are also located at the higher values of $\sqrt{J_2}$. For a given scenario earthquake, seismic stress distribution can be used to delineate potentially hazardous areas and to carry out protection works for the important and unavoidable locations. It also highlights the importance of monitoring crustal deformations, which will allow us to calculate spatial stress distributions that have been appearing over and over during a long period of geological time. Assuming that the similar events will be occurring continually, the information will be crucial for taking necessary measures to protect our lives and properties.

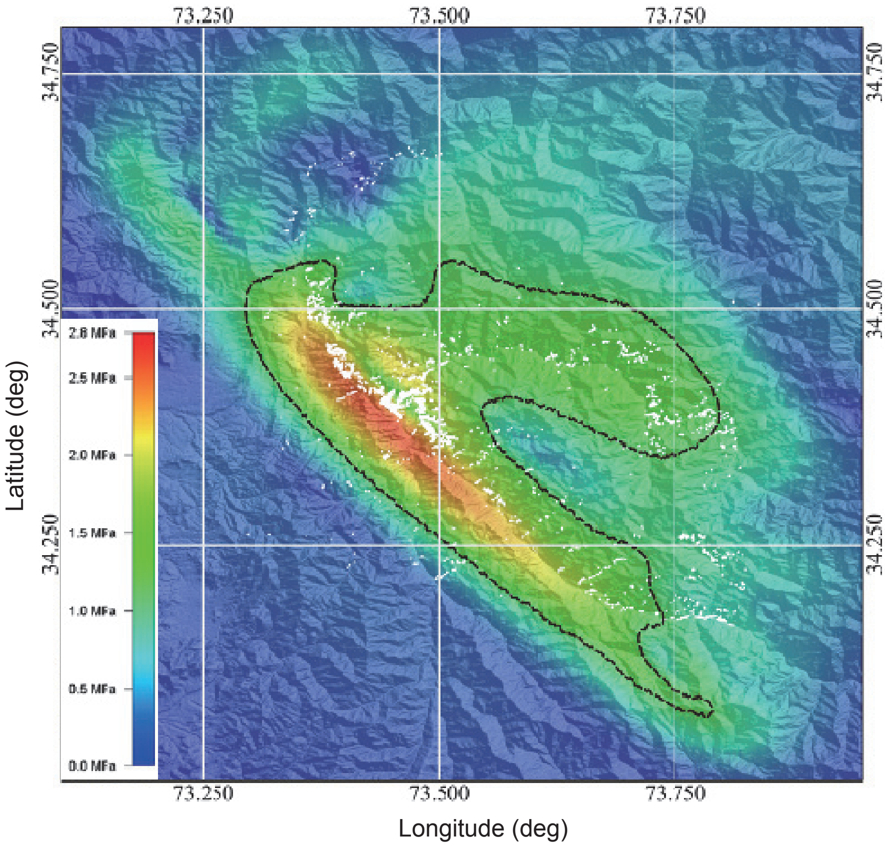

Figure 6: Distribution of the square root of the second invariant of deviatoric stress tensor at 5 meters depth below the ground surface along with the distribution of landslides triggered by the Kashmir Earthquake. All the landslides are found remarkably consistent with the large $\sqrt{J_2}$ values.

CONCLUSIONS

Large earthquakes can trigger numerous landslides, which are very often the most devastating secondary effect of an earthquake in terms of all kinds of losses. Estimation of co-seismic stress changes from geodetic data was taken for investigating the causes and triggering mechanisms of landslide disasters.

Based on the theory of elastic dislocation, a source inversion analysis has been performed to obtain spatial distribution of slips on fault ruptures planes for two of the most devastating earthquakes of the last decade, namely Mid-Niigata Prefecture Earthquake (2004) and the Kashmir Earthquake (2005). Through a forward modeling, the seismic stresses were evaluated in the interior of a latterly homogeneous layered half-space. In the absence of reliable yield criterion and spatial coverage of soil/rock properties, square root of second principal invariant of deviatoric stress tensor $\sqrt{J_2}$, is taken as an index of rock/soil deformability. It was observed that the spatial distribution of landslides triggered by both of the aforementioned earthquakes were found consistent with those of the large values of $\sqrt{J_2}$.

For the Mid-Niigata Prefecture Earthquake, a set of digital data was also available for the locations, sizes and shapes of landslides which existed before the earthquake (mapped in 2000). Spatial pattern of existing landslide clusters were also found concordant with those of large values of $\sqrt{J_2}$, suggesting that the active folding epicentral area of the Mid-Niigata Prefecture Earthquake might have been experiencing similar stress pattern in the past.

Assuming that the similar events with those in the past will be occurring continually in many earthquake-prone zones, the information of co-seismic stress distribution will be important for taking rational measures to protect our lives and properties. Though the method is yet imperfect often with unavailability of important geological and geotechnical data, it is considered to hold great promise to be used in both disaster mitigations and land conservations.

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