

# **Correlation between aspects of slope failures and surface displacement triggered by the 2005 northern Pakistan earthquake**

by

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## **ABSTRACT**

Northern Pakistan earthquake (Mw7.6) of October 8, 2005 occurred in the Kashmir region controlled by Pakistan. The previous studies reported 1) some uplift (on the northeast side) and dextral strike-slip crustal deformation occurred on the existing active fault (Balakot-Garhi fault), 2) 3-D crustal deformation map was produced using ENVISAT/Synthetic Aperture Radar (SAR) amplitude images, 3) the earthquake-induced 2,424 slope failures were identified from the interpretation using SPOT5 (System pour l'Observation de la Terre 5) stereo-images, almost all of them occurred on the hanging wall of the fault and near the fault. In this study area, which is 4km-wide zone from the fault on the hanging wall, we calculated 2-D (horizontal) deformation aspect from the 3-D crustal deformation map, we selected 979 large slope failures whose size is 15.8m by 15.8m and more, and we overlaid the large failures' slope aspect on the horizontal crustal deformation aspect. As a result, many large slope failures faced SW and S direction, and it was found that this anisotropic aspect is correspondent to that of planar crustal deformation. This fact infers that aspect of slope failures may be mainly controlled by the direction of the displacement of the earth surface.

**KEYWORDS:** SPOT5, ENVISAT, SAR, Pakistan, earthquake, slope failures, crustal deformation

## **1. INTRODUCTION**

Northern Pakistan earthquake (Mw7.6) of

October 8, 2005 occurred in the Kashmir region in the northwestern part of the Himalayas. The epicenter is north-northeast direction and 105 km away from Islamabad.

The crustal deformation was spatially mapped with Synthetic Aperture Radar (SAR) data from the European Space Agency's ENVISAT [1], and it was revealed that the newly deformed area occupies a 90-kilometer-long northwest-southeast trending strip. Heavily damaged area north of Muzaffarabad has the maximum deformation up to six-meter uplift as observed by the satellite. The detected crustal deformation was along the active fault and all observations were consistent with previously known directions of past fault movements.

There is the known active fault (Balakot-Garhi fault, Fig.1) stretching NW-SE direction near the epicenter, some uplift (on the NE side) and dextral (right-lateral) strike-slip activities were revealed [2]. According to the fault model optimal calculation in a homogeneous elastic half-space as formulated by [3], three planes of dip-slip reverse fault were reported [4].

Furthermore, many slope failures were triggered by the earthquake [5], and 2,424 slope failures were detected in the area of 55km by 51km including Muzaffarabad [6]. Almost all of the slope failures were located on the hanging wall of Balakot-Garhi fault.

Purpose of this study is to clarify the relation between the slope aspect of slope failures triggered by the earthquake and the direction of crustal movement by the earthquake.

## **2. STUDY AREA**

The study area is 4km-wide zone of the hanging wall from the Balakot-Garhi fault, whose area is 245.7km<sup>2</sup>. More than 4km away from the fault,

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the number of the slope failures is remarkably reduced.

### 3. METHODS

#### 3.1 SPOT5 image interpretation

After the earthquake, SPOT5 (System pour l'Observation de la Terre 5) panchromatic images were taken on October 20 and 27, 2005. The incident angle of October 20 and 27 images is at the left side of 26.4 degree and at the right side of 30.4 degree, respectively.

To delineate the interpreted slope failures and record their planar location, in advance, orthographic (ortho-) images were prepared. In other words, SPOT5 images were geometrically corrected using 34 ground control points (GCPs) and 90m-resolution Shuttle Radar Topography Mission- (SRTM-) digital elevation model (DEM). Next, we interpreted SPOT5 stereo-images in the study area, and delineated the slope failures on the orhto-image.

Before the earthquake, SPOT5 panchromatic images were taken on March 2, 2004. As referring it, the slope failures existed before the earthquake were removed, and the slope failures were selected.

#### 3.2 Calculation of slope aspect at the slope failure.

The slope failures were overlaid on the 15m-resolution DEM derived from TERRA/ASTER data [7]. The ASTER has a stereoscopic capability in the along-track direction mainly for DEM generation. To fit the size of slope failure in area with ASTER-DEM resolution, those whose area are less than 15.8m by 15.8 m were removed, and relatively large slope failures were selected. As a result, the number of the selected slope failures in the study area was 979.

#### 3.3 3-D crustal deformation analysis

Tobita et al (2006) [1] clarified the 3-D components of the crustal deformation by the earthquake using multiple SAR image matching [8]. Three pairs of ENVISAT/SAR images, i.e., those taken on 17 September 2005 and 22

October 2005 from descending orbit, which means the SAR sensor looked down on the study area from the east sky, taken on 19 September 2005 and 24 October 2005 and 3 September 2005 and 12 November 2005 from ascending orbit, which means the SAR sensor looked down on the study area from the west sky. The two components such as azimuth (longitudinal) and line of sight (crosswise) components of crustal deformation were independently calculated from the above three pairs of the SAR image, next, Cartesian (easting, northing, and upward) components were calculated by least square method, finally, horizontal and vertical components of the crustal deformation were obtained from the Cartesian components.

### 4. RESULTS AND DISCUSSION

Ratio of the aspect of the slope failures is shown as black solid bold line in Fig.2(a), indicating concentration of S and SW aspect. Black solid thin line in Fig.2(a) shows the ratio of the aspect of all slopes of the mountain in the study area. In general, SW, W, and NW facing slopes exist in this area. By comparing these, it is recognized that the slope failures occurred prominently on the S and SW facing slopes.

Fig.2(b) shows the ratio of the direction of the horizontal component of the crustal deformation in the study area., which concentrates in S and SW direction. The similarity of prominence of aspect of slope failures and direction of horizontal crustal deformation suggests that the failures were triggered by not the ground motion but the displacement of the earth surface by the crustal movement itself.

The crustal deformation detected by the SAR technology [1][4] shows the mixture of the deformation triggered by the main shock but also by the aftershocks and aftereffect, but according to the interview for afflicted people living near the Balakot-Garhi fault, main crustal deformation was formed at a burst (Prof. Takashi Nakata, Hiroshima Technology University, Japan, personal communication). This suggests that almost all amount of surface displacement occurred at the main shock and the

slope failures were triggered.

Earthquake-induced slope failures are often explained as follows: when driving force derived from seismic acceleration in unit area exceeds sediment shear stress on the slope, they occur [9], and it is valid that many slope failures were triggered by the acceleration of S-wave, which is transverse wave and almost all of the seismic-wave energy is occupied by S-wave energy. However, the seismic wave directivity by the 2005 north Pakistan earthquake is not reported because an installed strong-motion seismograph network is not known in the study area. Even if the strong motion were recorded, the result would show that the motion oscillated from one direction to the opposite direction, but black solid bold line in Fig.2(a) does not show the prominent slope ratio of both S-SW and N-NE. In the case of Mikawa earthquake (M6.8) occurred on 13 Jan 1945 in SE Japan, the houses built on the hanging wall of low-angle reverse fault were heavily damaged, and it was reported that direction of the collapsed houses coincided with the direction of the horizontal crustal deformation [10]. It infers that the prominent aspect of many slope failures in this study may be controlled not by the ground motion of S-wave but by some other factors such as the decline of friction by the rapid displacement of the ground toward the particular direction.

## 5. CONCLUSIONS

Digital elevation model was able to be directly produced by satellite remote sensing image, and slope aspects in wide area were able to be effectively calculated compared with existing topographic map. In a wide study area, neither had it been possible until crustal deformation was mapped by the SAR technology at uniform resolution, nor had it been possible to correlate slope aspect of failures to direction of horizontal crustal deformation.

There is scarce example to correlate them, but if many example of the correlation between them will be stocked, it will be revealed whether the prominent aspect of slope failures has relation to

horizontal direction of crustal deformation or not. In the case that the correlation is approved, this knowledge may be useful information to reduce earthquake-induced slope failure disaster against human-related facilities by considering slope aspect and the past crustal deformation directions triggered by the past earthquakes.

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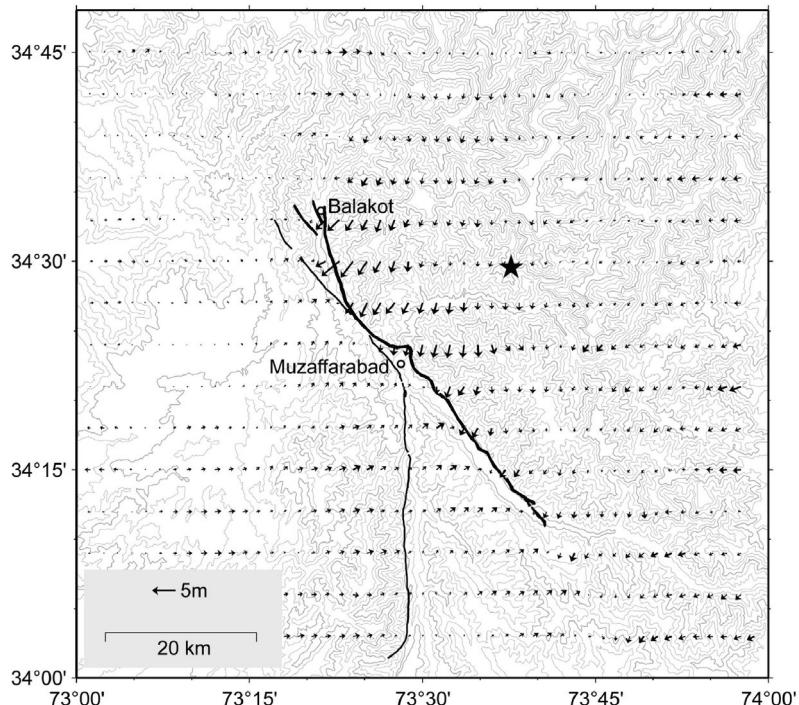


Fig.1 Detected crustal deformation using ENVISAT/SAR data (wavelength of 5.6 cm, C-Band) [1]. The star means epicenter of the earthquake. Arrow indicates 2-D (horizontal) deformation (amount and direction). Black solid bold and thin lines are Balakot-Garhi fault and Jhelum fault [2], respectively.

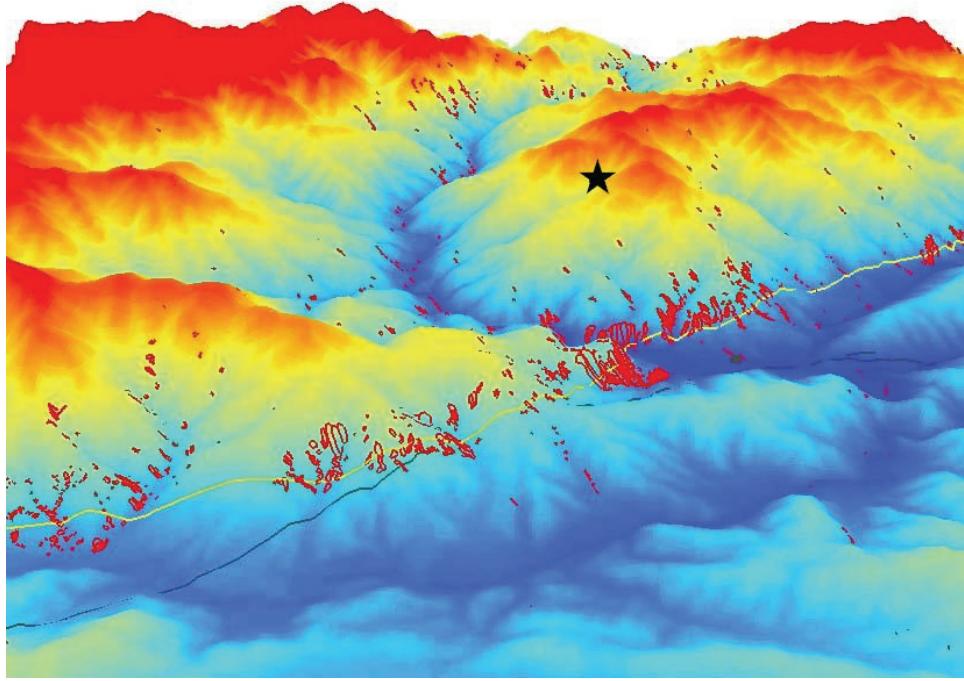


Fig.2 Bird-eye view from the east direction around the epicenter (black star). Polygons are slope failures interpreted using SPOT5 stereo-images. Pale and dark lines are Balakot-Garhi fault and Jhelum fault [2], respectively.

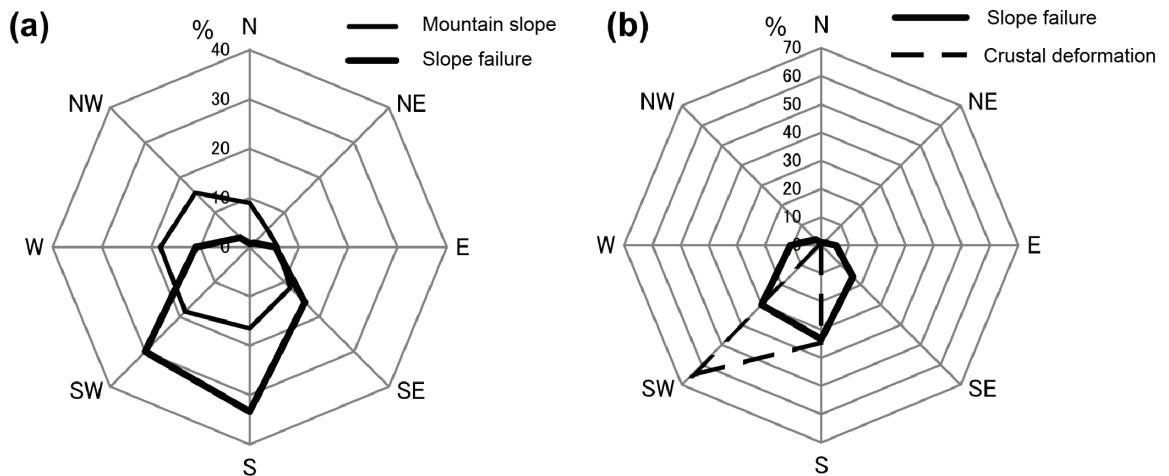


Fig. 3 (a) Relation of slope aspect count ratio between mountain slope and large slope failures on the hanging wall within 4 km from Balakot-Garhi fault, (b) Relation of slope aspect count ratio between slope failures and horizontal crustal deformation.