

## Details of surface displacement of the 1990 Rudbar earthquake (Iran) using optical images

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### ABSTRACT

The June 20th Mw 7.3 Rudbar earthquake happened on a left-lateral strike-slip fault with 80 km length along three main discontinuous right-stepping segments in western Alborz mountain belt. The sparse field measurements showed a horizontal and vertical displacement of ~60 cm and ~95 cm, respectively. The reported surface slip displacements are surprisingly low given the high moment release of the shallow event, coupled with the pure nearly vertical left-lateral fault. To fully resolve the coseismic displacement, we calculate the surface displacement field associated with the event using optical image correlation of satellite and aerial photos. The measured maximum fault parallel horizontal displacement of ~5.5 m in the eastern part of the fault, Zard-Geli segment, is in agreement with the macroseismic isoseismal curves. The minimum displacement happened on the beginning of Kabateh (~50 cm) and the end of Zard-Geli (~1.2 m). The average magnitude of surface slip is about 2.2 m which is in agreement with the reported moment of the event provided that the width of the fault plane be ~15 km. The larger surface displacement measured by the optical image processing method is due to the distribution of deformation over a wide fault zone with a width of ~300 m to ~1600 m. Moreover, we identify a new surface rupture of ~23 km length expanded from Sefid-Rude to the NE of Zard-Geli fault segment.

**Keywords:** Rudbar earthquake, Satellite imagery, SPOT, Aerial photo, Optical Image correlation

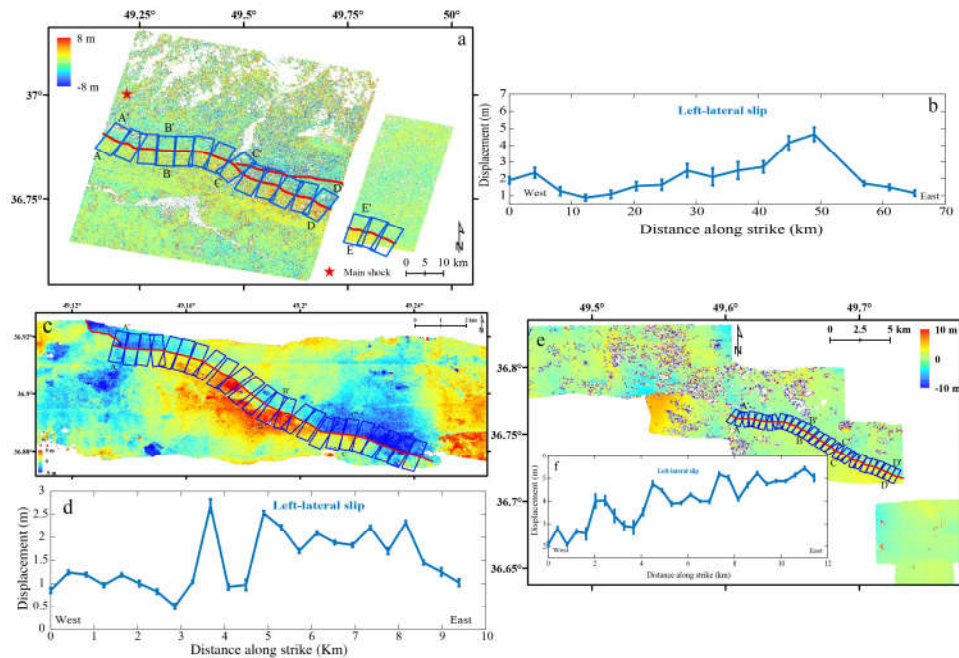
### INTRODUCTION

The 1990 June 20th Rudbar earthquake (Mw7.3) was a devastating event killed ~15000 people (Presidency Islamic Republic of Iran Plan and Budget Organization, <https://www.mporg.ir>), left approximately half a million people homeless and destroyed three cities and 700 villages in North of Iran (Berberian *et al.*, 1992). The earthquake happened on previously unknown left-lateral strike-slip fault in the west of Alborz Mountain belt. The fault length is about 80 km on an almost near-vertical fault plane with a strike of 95°N to 120°N (Berberian *et al.*, 1992). According to seismological studies, due to pure left-lateral strike-slip behavior of fault, we expect a much larger horizontal displacement on fault rupture than that of observed. The maximum horizontal displacement reported by field studies is ~60 cm (Gao, Wallace and Jackson, 1991; Berberian *et al.*, 1992; Gao and Wallace, 1995; Berberian and Walker, 2010). Considering a seismic moment of  $\sim 8.8 \times 10^{19}$  N (Gao and Wallace, 1995); a maximum depth of fault plane of 20 km (Tatar and Hatzfeld, 2009), a fault length of 80 km (Berberian *et al.*, 1992) and assuming a rigidity of 30 GPa, the expected left-lateral slip for the almost pure strike-slip fault is about 183 cm, a value significantly different than the reported horizontal displacement.

Lack of GNSS and InSAR geodetic data at the time of the Rudbar earthquake, dense vegetation and rough topography along the rupture plane, possible slip accommodation within a wide shear zone (Binet and Bollinger, 2005; Taylor *et al.*, 2008), accessibility to the great archive of optical images, motivated us to use Optical image Correlation (OIC) method to study the surface deformation associated with the Rudbar event. Knowledge of variation of surface displacement along the Rudbar rupture plane can provide critical information required to understand the variability of the recorded macroseismic damage in the earthquake-stricken region and also estimate the width of shear zone along the rupture place required for seismic hazard map.

## Methodology and Data

In this work we measured the horizontal displacements associated with the Rudbar earthquake utilize OIC processing tools such as Co-registration of Optically Sensed Images and Correlation (COSI-corr) (Leprince *et al.*, 2007) and Ames Stereo Pipeline (ASP). We use COSI-Corr to investigate the magnitude and distribution of coseismic ground displacement by retrieving continuous 2D correlation maps of the ortho-Images. ASP helps us to generate DEM from pre/post stereo-pairs and orthorectification of aerial photos to produce 2D displacement maps. To determine the surface deformation associated with Rudbar coseismic fault rupture, we use SPOT satellite imagery and aerial photos (Zinke, Hollingsworth and Dolan, 2014; Milliner *et al.*, 2015, 2016; Zinke *et al.*, 2019). We use eight SPOT images spanning eight years from 1989 to 1996 (Table 1), covering ~71 km of the rupture mapped by Berberian *et al.*, (1992). These images cover the center and eastern part of the Rudbar fault, namely Kabateh and Zard-Geli segments. To study in more detail the rupture, we use aerial photos of 1968 (49 photos), and 2001-2003 (39 photos) (Table 1) to retrieve continuous 2D maps of the surface deformation associated with Rudbar fault rupture (Zinke, Hollingsworth and Dolan, 2014; Milliner *et al.*, 2015, 2016; Zinke *et al.*, 2019).



**Figure 1.** Ground displacement field obtained from SPOT images. (a), (c) & (e) East-west displacement map. Red solid lines are the rupture traces extracted from OIC of SPOT images, and aerial photos in Kabateh and Zard-Geli segments, respectively. The red star indicates the epicenter of the mainshock and the blue rectangles are stacked profiles illustrating offset in fault parallel direction. (b), (d) & (f) shows slip distribution along Rudbar rupture trace obtained from OIC

**Table1.** Specifications of Images used in this study.

|      | Pre-earthquake                 |                                   |                 | Post- earthquake                   |                                  |                                   |                                   |                 |
|------|--------------------------------|-----------------------------------|-----------------|------------------------------------|----------------------------------|-----------------------------------|-----------------------------------|-----------------|
|      | SPOT                           |                                   | aerial<br>photo | SPOT                               |                                  |                                   |                                   | aerial<br>photo |
| Time | 24 <sup>th</sup><br>July, 1989 | 29 <sup>th</sup><br>July,<br>1989 | 1968            | 21 <sup>th</sup><br>April,<br>1994 | 9 <sup>th</sup><br>Oct.,<br>1994 | 18 <sup>th</sup><br>Oct.,<br>1994 | 26 <sup>th</sup><br>Aug.,<br>1996 | 2001-<br>03     |
| Type | push<br>broom                  | push<br>broom                     | Frame<br>camera | Push<br>broom                      | Push<br>broom                    | Push<br>broom                     | Push<br>broom                     | Frame<br>camera |

## CONCLUSIONS

We measured an average displacement of ~220 cm along ~71 km Rudbar rupture which is in agreement with the expected average displacement (i.e. ~240 cm) for a rupture plane with width of 15 km (Berberian *et al.*, 1992). We have found a new rupture strand associated with the Rudbar event not reported in the previous works. The rupture branch has a length of 23 km and lies to north of Zard-Geli segment. The fault parallel horizontal displacement have partially included the displacement along the new strand into our calculation of the average displacement along the fault. The distribution of the rupture displacement along the fault shows a peak (with maximum displacement of 5.5 m about 40 km east of the epicenter) towards east of the rupture plane, ~12 km east of the Rudbar city and ~ 8 km east of Jirandeh. The pattern of along the fault slip distribution fully explains the widening of the macroseismic isoseismal intensity (Berberian *et al.*, 1992). The slip distributions profiles along the fault strike are in agreement with the displacement retrieved from the inverted source model using body waves of the mainshock (Campos *et al.*, 1994).

## REFERENCES

- Berberian, M. *et al.* (1992) 'The Rudbar-Tarom earthquake of 20 June 1990 in NW Persia: preliminary field and seismological observations, and its tectonic significance', *Bulletin of the Seismological Society of America*, 82(4), pp. 1726–1755.
- Berberian, M. and Walker, R. (2010) 'The Rudbr Mw 7.3 earthquake of 1990 June 20; seismotectonics, coseismic and geomorphic displacements, and historic earthquakes of the western "High-Alborz", Iran', *Geophysical Journal International*, 182(3), pp. 1577–1602. doi: 10.1111/j.1365-246X.2010.04705.x.
- Binet, R. and Bollinger, L. (2005) 'Horizontal coseismic deformation of the 2003 Bam (Iran) earthquake measured from SPOT-5 THR satellite imagery', *Geophysical Research Letters*, 32(2), pp. 1–4. doi: 10.1029/2004GL021897.
- Campos, J. *et al.* (1994) 'Faulting process of the 1990 June 20 Iran earthquake from broadband records', *Geophysical Journal International*, 118(1), pp. 31–46. doi: 10.1111/j.1365-246X.1994.tb04673.x.
- Gao and Wallace, T. C. (1995) 'The 1990 Rudbar-Tarom Iranian earthquake sequence: Evidence for slip partitioning', *Journal of Geophysical Research: Solid Earth*, 100(B8), pp. 15317–15332. doi: 10.1029/95jb00320.
- Gao, Wallace, T. C. and Jackson, J. A. (1991) 'Aftershocks of the June 1990 Rudbar-Tarom earthquake: Evidence for slip partitioning', *EOS, Trans. Am. geophys. Un.*, 72, p. 44.
- Leprince, S *et al.* (2007) 'Automatic and precise orthorectification, coregistration, and subpixel correlation of satellite images, application to ground deformation measurements', *IEEE*

- Transactions on Geoscience and Remote Sensing*. IEEE, 45(6), pp. 1529–1558.
- Leprince, S. *et al.* (2007) ‘Co-Registration of Optically Sensed Images and Correlation (COSICorr): an operational methodology for ground deformation measurements, in: Geoscience and Remote Sensing Symposium, 2007’, *IGARSS 2007. IEEE International*, pp. 1943–1946.
- Milliner, C. W. D. *et al.* (2015) ‘Quantifying near-field and off-fault deformation patterns of the 1992 Mw 7.3 Landers earthquake’, *Geochemistry, Geophysics, Geosystems*. Wiley Online Library, 16(5), pp. 1577–1598.
- Milliner, C. W. D. *et al.* (2016) ‘Comparison of coseismic near-field and off-fault surface deformation patterns of the 1992 Mw 7.3 Landers and 1999 Mw 7.1 Hector Mine earthquakes: Implications for controls on the distribution of surface strain’, *Geophysical Research Letters*. Wiley Online Library, 43(19), pp. 10–115.
- Shean, D. E. *et al.* (2016) ‘An automated, open-source pipeline for mass production of digital elevation models (DEMs) from very-high-resolution commercial stereo satellite imagery’, *ISPRS Journal of Photogrammetry and Remote Sensing*. Elsevier, 116, pp. 101–117.
- Tatar, M. and Hatzfeld, D. (2009) ‘Microseismic evidence of slip partitioning for the Rudbar-Tarom earthquake (Ms 7.7) of 1990 June 20 in NW Iran’, *Geophysical Journal International*, 176(2), pp. 529–541. doi: 10.1111/j.1365-246X.2008.03976.x.
- Taylor, M. H. *et al.* (2008) ‘Detecting co-seismic displacements in glaciated regions: An example from the great November 2002 Denali earthquake using SPOT horizontal offsets’, *Earth and Planetary Science Letters*, 270(3–4), pp. 209–220. doi: 10.1016/j.epsl.2008.03.028.
- Zinke, R. *et al.* (2019) ‘Three-Dimensional Surface Deformation in the 2016 MW 7.8 Kaikōura, New Zealand, Earthquake From Optical Image Correlation: Implications for Strain Localization and Long-Term Evolution of the Pacific-Australian Plate Boundary’, *Geochemistry, Geophysics, Geosystems*. Wiley Online Library, 20(3), pp. 1609–1628.
- Zinke, R., Hollingsworth, J. and Dolan, J. F. (2014) ‘Surface slip and off-fault deformation patterns in the 2013 MW 7.7 Balochistan, Pakistan earthquake: Implications for controls on the distribution of near-surface coseismic slip’, *Geochemistry, Geophysics, Geosystems*. Wiley Online Library, 15(12), pp. 5034–5050.