TWO DIMENSIONAL VELOCITY FIELD OF THE IRANIAN PLATEAU

Alireza KHODAVERDIAN
School of Civil Engineering, college of Engineering,
University of Tehran, Tehran, Iran
a.khodaverdian@ut.ac.ir

Hamid ZAFARANI
International Institute of Earthquake Engineering and Seismology, Tehran, Iran
h.zafarani@iiees.ac.ir

Mohammad RAHIMIAN
School of Civil Engineering, college of Engineering, University of Tehran, Tehran, Iran
rahimian@ut.ac.ir

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ABSTRACT

Long-term crustal flow of the Iranian Plateau is computed using a kinematic model. Three independent data sets (geometry of the seismically active faults mapped in prior geological studies, geodetic benchmark velocities, and principal stress directions) are combined using a finite-element model to better understand regional geodynamics of the Iranian Plateau. We are successful to find the best kinematic model, in which all the data sets are fitted at a RMS level of 1.0 datum standard deviation. The best fitted model, for the first time, provides the velocity field over the Iranian Plateau from all available kinematic data. Spatial distribution of displacement rates within the plateau shows a mixed pattern, in which semi-rigid blocks (e.g. Lut Desert Block and South Caspian Block) are embedded in a deformation zone (e.g. the Zagros and Alborz Mountain Belt). Our estimated rates are consistent with the past earthquakes, and are in the range of previous published rates, in which geodetic benchmark velocities are merely analyzed using different modeling techniques. Sharp changes of displacement rates in some region (e.g. northeastern Iran) show high strain rates, and hence using elastic block modeling seems not to be suitable for fault slip rate estimation. Moreover, the obtained results are useful to calculate the strain rate field, which could be considered as an indicator for undiscovered or/and unmapped faults.

INTRODUCTION

The Iranian Plateau is located within the convergence zone of two rigid plates, the Arabian and Eurasian plates (Hempton, 1987). Neotectonics in the Iranian plateau is complicated by a mix of the various tectonic processes, including seismically active intra-continental collision (Zagros, Alborz, Kopet-Dag, Talesh) and subduction of the oceanic crust (Makran). Despite being highly seismic regions in the Iranian Plateau, seismotectonics and contribution of distributed seismic sources have remained largely unknown. In the recent studies (Djamour et al., 2010; Djamour et al., 2011; Mousavi et al., 2013; Walpersdorf et al., 2014), some parts of the Iranian Plateau are modeled using purely elastic micro-plates separated by only few plate boundary faults. The weakness of these modeling is that only major fault can be studied and distributed deformations resulted from minor faults are ignored. However, lots of minor faults exist in Iranian plateau and should be considered in any proper strain modeling.

In the present study, to have realistic estimates of all deforming zones in Iranian Plateau, the whole area of the plateau is modeled as a single system of faults (discontinuity) and continuum media. The primary purposes of this modeling is to estimate long-term distributed deformation by combining all kinematic data including geological slip rates, geodetic velocities, and stress directions. The kinematic model allows us to better constrain the fault slip rates and distributed deformations, and is finally used to produced long-term distribution map, which is independent of seismic catalogs.

1. ACTIVE TECTONICS OF IRAN

General characteristics of present day tectonics in the Iranian Plateau are broadly identified in numerous prior studies (see references below). Global or local GPS-based plate models (Kreemer et al., 2003; McClusky et al., 2003; Reilinger et al., 2006; Sella et al., 2002; Vernant et al., 2004b) all demonstrated an active convergence between the Eurasian and Arabian plates in similar patterns. The convergence rate also increases from northwest to southeast due to location of the Arabia–Eurasia Euler pole situated in North Africa (McClusky et al., 2000; McClusky et al., 2003; Sella et al., 2002; Vernant et al., 2004b). Margins of major deformation zone are defined based on the cutoffs in topography and seismicity. The eastern limit of deformation zone is considered at the political border between Iran and Afghanistan/Pakistan, roughly longitude 62°E, and northeastern and southwestern margins are formed by the Kopeh-Dagh and the Zagros belts, respectively (Jackson and McKenzie, 1988). The largest part of the shortening is accommodated by crustal shortening and strike-slip faulting in the Zagros and the Alborz and Kopeh Dagh mountains. Whatever shortening that is not taken in the Zagros causes an N-S right-lateral shear between central Iran and western Afghanistan.

In summary, Iranian Plateau consists of some deforming belts surrounding aseismic blocks (Central Iranian block (CIB), South Caspian block (SCB) and Lut Desert Block (LDB))(see Fig. 1) (Jackson et al., 1995; Walker and Jackson, 2004). In the following, the present-day kinematics of each zone is described.

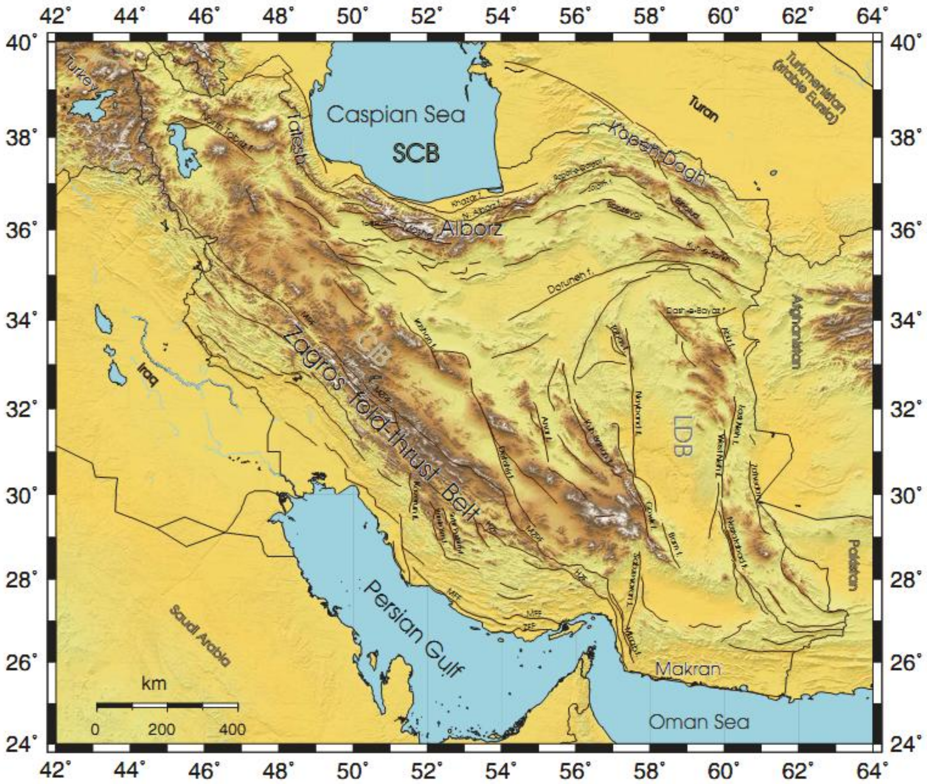

Figure 1. The Iranian Plateau, thick solid lines represent active faults

The Zagros fold-and-thrust belt, extending from eastern Turkey to the Strait of Hormoz, is one of the most seismically active belts in Asia. Seismicity of the Zagros shows that main portion of overall shortening is absorbed by the belt. The northeastern border of the deforming Zagros zone, which separates the Zagros

Mountain belt from CIB, is approximately coincided with a major thrust, the Main Zagros Reverse Fault (Fig. 1). In the central Zagros, numerous strike-slip faults also divide the two distinct structural domain; the region with strain partitioning in the northwest Zagros and the zone of orthogonal convergence in the southeastern (Talebian and Jackson, 2004).

The Alborz Mountains in northern Iran extends along the southern side of the Caspian Sea from the Talesh Mountains in the west to the Kopeh-Dag Mountains in the east. The Kopeh Dagh range is considered as the northeastern limit to the Arabia-Eurasia deformation zone. The SCB, as one of the thickest sedimentary basin in the world (Brunet et al., 2003), is an aseismic block surrounded by active belts (Priestley et al., 1994) (Fig. 1). Copley and Jackson (2006) also noted that the SCB is moving to the northwest with respect to the Eurasia. To the east, a sharp cut-off in seismicity and mountainous topography near to the eastern political border of Iran indicates that Arabia–Eurasia shortening is accommodated within the Iranian plateau. The low velocity of GPS stations, which lies west of the Afghanistan, also shows that east of the Lut block is a part of stable Eurasia. Approximately northward motion of central parts of Iran causes right-lateral shear in eastern Iran (Vernant et al., 2004b). The shear deformation is localized on an array of dextral faults dissecting Central and Eastern Iran, particularly on fault systems surrounding the aseismic Lut block, which is flat and behave as relatively rigid blocks (Fig. 1).

2. PREVIOUS QUANTITATIVE MODELS FOR NEOTECTONIC CRUSTAL FLOW

In the first attempts to quantify tectonics of the region using GPS data (Masson et al., 2007; Masson et al., 2005; Nilforoushan et al., 2003; Vernant et al., 2004b), several models without any discrete faults, at best only presented a large-scale view of the present-day kinematics of the Iranian Plateau. Active deformation in various key areas such as the Alborz, Zagros, and Zagros–Makran transition also studied based on the GPS measurements (Bayer et al., 2006; Hessami et al., 2006; Masson et al., 2006; Tatar et al., 2002; Vernant et al., 2004a; Walpersdorf et al., 2006). Bayer et al. (2006) constrained the motion on the transition zone between the Zagros collision and the Makran oceanic subduction using a simple block model. Tavakoli et al. (2008) estimated the strike-slip motion on the Kazerun fault system in the Central Zagros from local profiles.

Elastic block modeling has been used for several years to decipher the active deformation in a given region (McCaffrey, 2002; McCaffrey, 2005; McClusky et al., 2001). General assumption in this modeling technique is that most deformation is localized near the major faults, while little strain is left inside the fault-bounded blocks. In other words, slip on secondary faults is neglected. Djamour et al. (2010) interpreted GPS velocities with an elastic block model of the Alborz mountain range and found that the left lateral motion in the Alborz range is resulted from clockwise rotation of the SCB relative to Eurasia. Mousavi et al. (2013) evaluated kinematics of major fault zones in NE Iran, as well as the motion of the SCB relative to the surroundings. Adding the new geodetic measurements as constrain in the elastic block model showed that location of the South Caspian Euler pole with respect to Eurasia is further east away than that calculated by Djamour et al. (2010). In other study, Walpersdorf et al. (2014) suggested the current fault slip rates in eastern Iran. Results revealed that some blocks were poorly represented by the rigid block model, because of existence of small faults in region. Moreover slip rate of one major fault (Doruneh) was found to be significantly different depending on the used approach.

3. MODELING METHOD AND INPUT DATA

The kinematic finite element program was used to merge all kinematic data including geological offset rates, GPS measurements, and principal stress directions. In the modeling technique, the domain is divided into 2D triangle finite elements. Seismically active faults within the Iranian Plateau have been included in our model from various sources. most of the geometric properties and mechanisms of faults are from Hessami et al. (2013). Traces of active faults are shown in Fig. 2. We also collect long-term geological offset rates, which are provided in the literature. Less than 20% of active faults have geological slip rate since relative displacement of geologic features or their date of commencement are not studied well. Some geological fault slip rates incorporated in the model are listed in Table 1.

Table 1. Geological offset rates used in the modeling. Key: Right-Lateral (RL), left-Lateral (LL)

Fault	Geological slip rate (mm/year)	Citation
Gailatu-Siah Chesmeh-Khoy	2~4 (RL)	(Copley and Jackson, 2006)
Mosha	1.9~2.1 (LL)	(Ritz et al., 2003)
Ipak	1 (LL)	(Bachmanov et al., 2004)
Doruneh	2.1~2.7 (LL)	(Fattahi et al., 2007)
West_Neh	1~5 (RL)	(Meyer and Le Dortz, 2007)

Combination of interseismic velocity benchmarks over the whole Iranian Plateau (e.g. Tavakoli et al. (2008), Djamour et al. (2010, 2011) and Mousavi et al. (2013)) are modified to show the velocity vectors in the reference frame of stable Eurasia, and then used for modeling. Principal stress directions are also collected from various sources and interpolated to be used as third restrains in the modeling. Finally, the relative weights of geological data and of area-based stress direction to the geodetic data are tuned, so that misfit errors are minimal. We are successful to find the best kinematic model, in which all the data sets are fitted at a RMS level of 1.0 datum standard deviation.

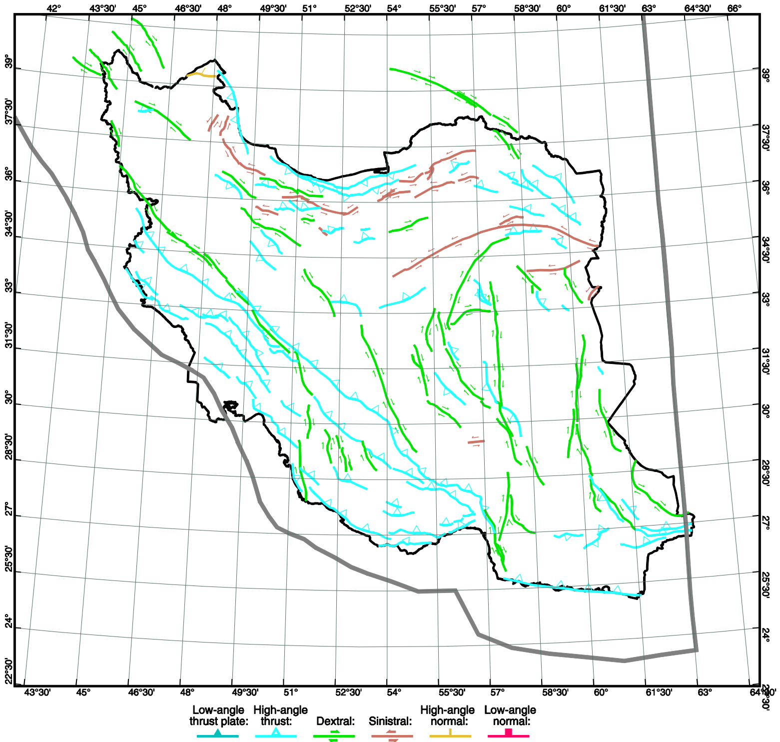

Figure 2. Traces of active faults within the Iranian Plateau

4. RESULTS AND DISCUSSION

Using the best fitted model, long-term velocity field in the Iranian Plateau is estimated and shown in the Fig. 3. In general view, the Arabian-Eurasian convergence rate, as expected, is estimated to decrease from east to west because of situation of the Arabia-Eurasia Euler pole. West of 57°E, different motion of the Zagros belt and central Iran shows the overall convergence motion principally accommodated by up by the Zagros belt in western Iran. East of 57°E, main portion of convergence of the Arabian and Eurasian plates absorbed by subduction of oceanic lithosphere beneath Iran Plateau in eastern Iran (Makran). The change of displacement rates in SCB and LDB is negligible; these regions therefore have little internal deformation and can be approximated as relatively rigid blocks that are bounded by seismically active belts. Hence, the remainder of the relative motion to Eurasia is distributed across the active belt of Iran (e.g. Alborz and Kopeh Dagh ranges and faults surrounding the Lut Desert). Long-term average velocity finally drops to almost zero at northeastern and eastern border of Iran. Hence, the adjacent regions to the northeast (Turan platform) and the east (western Afghanistan) seem to be aseismic. Epicenters of M>5 earthquakes from a unified seismic catalog for the Iranian plateau during 1900-2012 (Shahvar et al., 2013) are illustrated in Fig. 4. It is obvious that above mentioned results are consistent with the past earthquakes. For instance, seismicity of Zagros mountain belt is utterly different from CIB, and quasi-rigid behavior of SCB and LDB are apparent.

In the north of Iran, motion of the SCB is doubtful since all GPS stations are located at its boundaries. Incorporating GPS data and accurate estimates of slip rate for faults bounding the SCB are thus extremely efficient in evaluating kinematic of SCB. As shown in Fig. 3, the SCB approximately moves NW at rate of 7±1 with respect to Eurasia, which is similar to 7ـت10 mm/yr at an azimuth of 300ځN and 6±2 mm/yr at an azimuth of 300ځN proposed by Jackson et al. (2002) and Vernant et al. (Vernant et al., 2004a), respectively.

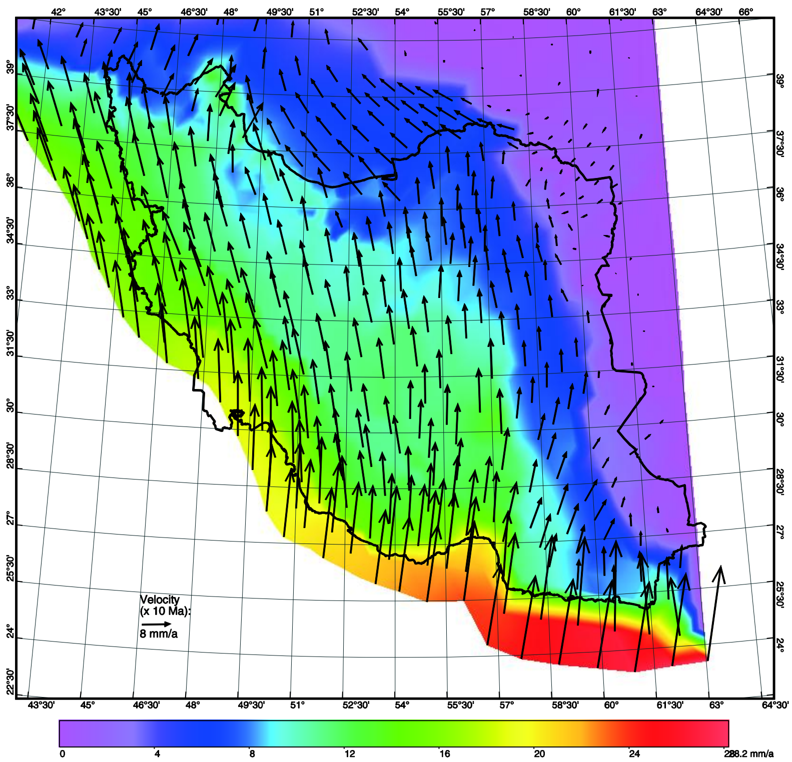

Figure 3. long-term average velocity field relative to stable Eurasia. Only 1/3 nodal velocities are shown as vectors.

Displacement rates in regions located on each side of North Tabriz fault are severely different. That is showing a large part of the deformation in NW Iran is absorbed by the right-lateral strike-slip Tabriz fault in agreement with GPS results presented by Djamour et al. (2011).

The obtained results are very useful in calculation of strain rates over the Iranian plateau. Regions, which experience the sharp change of displacement rates, show large strain rates. In other words, strain rates can be considered as indicator to find the undiscovered and/or unmapped faults. A big zone with the large strain demonstrates the existence of many minor faults, which absorbed significant portion of the active deformation in the regions. Hence, off-fault seismicity should be taken into account in earthquake hazard assessment of the region. Moreover, large-scale elastic block model of these regions (e.g. northwestern Iran) is not suitable to interpret the present-day kinematics of the region from GPS data.

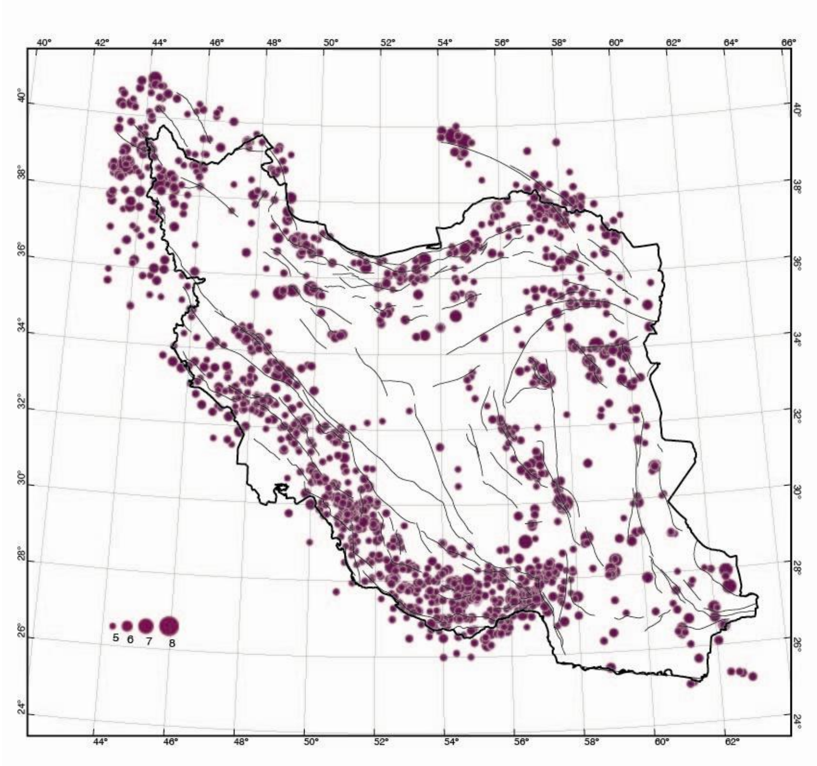

Figure 4. Epicenters of shallow M>5 earthquakes from a unified seismic catalog for the Iranian plateau during 1900-2012 (Shahvar et al., 2013)

CONCLUSIONS

In this paper, based on iterated weighted least square method, we presented a long-term kinematic model of the Iranian Plateau. The model of the plateau is fit to a data set including geometry of the seismically active faults mapped in prior geological studies, geologic fault offset rates, geodetic benchmark velocities, principal stress directions. The best model that fits all data within their uncertainty levels was selected, which allows us to better decipher the kinematics of regions. Our results are also consistent with past earthquakes as well as the published studies, in which geodetic benchmark velocities are merely analyzed using different modeling techniques. Spatial distribution of displacement rates within the plateau shows a mixed pattern, in which semi-rigid blocks (e.g. LDB and SCB) are embedded in a deformation zone. The obtained results are useful to calculate the strain rate field, which could be consider as an indicator for undiscovered or/and unmapped faults. Moreover, sharp changes of displacement rates in some region (e.g. northeastern Iran) show high strain rates, and hence using elastic block modeling seems not to be suitable for kinematic modeling.

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