Geoscience Frontiers 8 (2017) 81–91

Contents lists available at ScienceDirect

China University of Geosciences (Beijing)

Geoscience Frontiers

journal homepage: www.elsevier.com/locate/gsf

Research paper

Finite element models to represent seismic activity of the Indian plate

S. Jayalakshmi*, S.T.G. Raghukanth

Department of Civil Engineering, Indian Institute of Technology, Madras 600036, India

ARTICLE INFO

Article history:
Received 7 November 2014
Received in revised form
3 December 2015
Accepted 20 December 2015
Available online 14 January 2016

Keywords:
Indian plate
Plate driving forces
Finite element model
Seismicity
Cratons

ABSTRACT

Quantification of seismic activity is one of the most challenging problems faced by earthquake engineers in probabilistic seismic hazard analysis. Currently, this problem has been attempted using empirical approaches which are based on the regional earthquake recurrence relations from the available earthquake catalogue. However, at a specified site of engineering interest, these empirical models are associated with large number of uncertainties due to lack of sufficient data. Due to these uncertainties, engineers need to develop mechanistic models to quantify seismic activity. A wide range of techniques for modeling continental plates provides useful insights on the mechanics of plates and their seismic activity. Among the different continental plates, the Indian plate experiences diffused seismicity. In India, although Himalaya is regarded as a plate boundary and active region, the seismicity database indicates that there are other regions in the Indian shield reporting sporadic seismic activity. It is expected that mechanistic models of Indian plate, based on finite element method, simulate stress fields that quantify the seismic potential of active regions in India. This article explores the development of a finite element model for Indian plate by observing the simulated stress field for various boundary conditions, geological and rheological conditions. The study observes that the magnitude and direction of stresses in the plate is sensitive to these conditions. The numerical analysis of the models shows that the simulated stress field represents the active seismic zones in India.

1. Introduction

The estimation of seismic hazard due to future earthquakes is one of the most challenging problems faced by earthquake engineers. The starting point in the estimation of hazard is to assemble all the past events that occurred in the region. This catalogue is routinely used by several investigators to explain the seismic potential of various active regions. Based on the earthquake catalogue, empirical relations between magnitude and frequency are derived to quantify the seismic activity in a given region. This relation, popularly known as Gutenberg-Richter recurrence law, is associated with large number of uncertainties that are statistically accounted to evaluate hazard. The uncertainties arise mostly due to lack of sufficient data at that particular site. On the other hand, there have been several attempts in the last three decades to develop mechanistic models for tectonic plates by geophysicists, to understand seismic activity in various continental plates. These models have provided useful insights into the motion of plates and forecast plate velocities (DeMets et al., 1990; Bird, 2003).

Based on the understanding of driving mechanisms of plates, forces and tectonic stress fields, the modeling of tectonic plates by mechanistic approaches are attempted on both global and regional scales (Bird, 1978, 1998). DeMets et al. (1990) used a global model to describe the current plate motion between 12 assumed rigid plates by inverting plate motion data. However, with advanced instrumentation, it has been made possible to measure the present day stress field in the crust (Zoback, 1992). These measurements provide useful insights into the mechanism driving the plates and the tectonic processes. The WSM 2008 release contains numerous new data and updates on the stress indicators (Heidbach et al., 2008, 2010). There are almost 145 stress measurements in the Indian plate and this data is indicated in Fig. 1. The stress indicator at a given location points the direction of maximum horizontal compressive stress (σ_{hmax}) in that region. It is observed that most of stress indicators in Indian subcontinent are obtained from the focal mechanism of past earthquakes. The stress measurements are widely used in modeling continental plates to understand the boundary conditions and lateral strength of the plates. Sargent

* Corresponding author.
E-mail address: jayalakshmi.s@mechyd.ac.in (S. Jayalakshmi).
Peer-review under responsibility of China University of Geosciences (Beijing).

http://dx.doi.org/10.1016/j.gsf.2015.12.004
1674-9871/

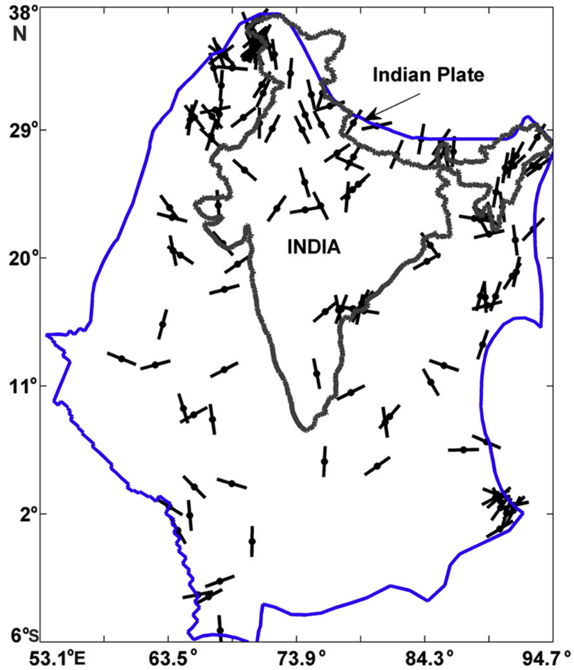

Figure 1. Directions of maximum horizontal compressive stress in the Indo-Australian plate (after Zoback, 1992).

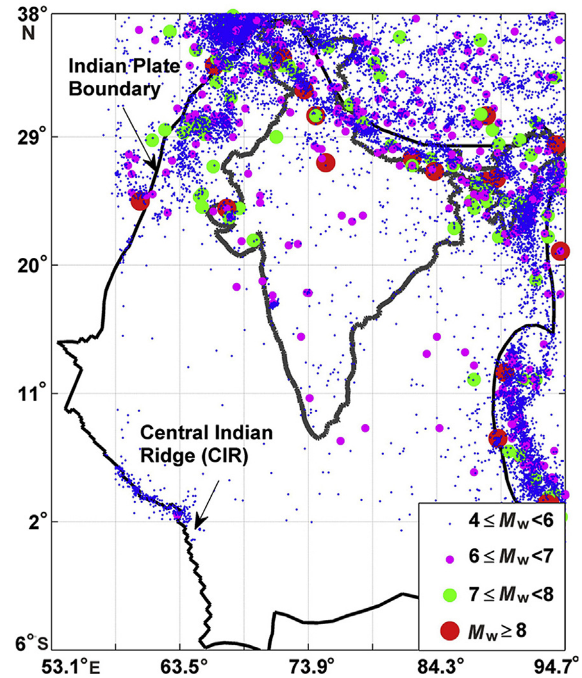

Figure 2. Earthquake catalogue of India (2474 BC–2011 AD).

(2004) modeled entire Eurasian plate using finite element and compared the lithospheric stress fields using the reported stress data on Eurasia. Dyksterhuis et al. (2005) modeled the Indo-Australian plate for understanding the present day and palaeo-stress field to study evolution of stresses in Australia and tectonic reactivation in many parts of the continental shelf. However, in the Indian context, Cloetingh and Wortel (1985) developed finite element model for Indo-Australian plate based on plate driving forces to study regional stress field in India. Although the predicted stress regimes from this model imparted awareness on the present day dynamics of Indian plate, not much instrumental data was available to validate these conclusions. Recently, Müller et al. (2015) studied the evolution of stresses in various regions of Indian lithosphere based on palaeo-stress modeling by considering three geological time scales namely Oligocene (33 million years ago), Miocene (20 million years ago) and present. The modeling has shed light on formation of various tectonic structures in Indian subcontinent based on the simulated directions of maximum compressive stresses (σ_{hmax}). All these mechanistic models have provided numerous insights on long term plate velocities, formation of plate boundaries, faults and are routinely used by geophysicists to predict seismicity and identify active regions.

In India, the active regions include Himalaya, north-east India and the subduction zone along the Indo-Burmese and Andaman border. The recently compiled Indian earthquake catalogue (Raghukanth, 2011) is shown in Fig. 2. It is observed that there are other regions like Indo-Gangetic basin, Gujarat and Peninsular India that pose challenge in hazard estimation due to lack of available data. Jayalakshmi and Raghukanth (2015) developed the first engineering model for Indian plate to estimate seismic activity in India. The model performed reasonably well in identifying active regions of India. The model used elastic plate with applied ridge push force at the Central Indian ridge of Indian plate. Moreover, there are number of approximations used in the model which include fixing the Himalayan boundary and neglecting continental collision force, slab pull and mantle drag without examining the long term behavior of the plate. Thus, it will be interesting to study the effect of all the plate boundary forces and complex rheologies on the stress field of Indian plate. It is expected that such mechanistic models can overcome the difficulties faced by engineers due to lack of available data to estimate seismic hazard in a given region. Since seismic hazard depends on distribution of earthquakes with large and small return periods, both long term and short term tectonic behavior of Indian plate needs to be explored. Therefore, the focus of the present study lies on various aspects of modeling Indian plate by exploring the effects of different boundary conditions, lateral strength variations and material rheology on the stress field. A finite element model for Indian plate is developed based on the available information on plate driving forces (Forsyth and Uyeda, 1975; Turcotte and Schubert, 2002) and the recently available stress orientations from WSM Release 2008. Although three dimensional models are more desirable, it is difficult to incorporate complexities such as topography, bathymetry and material properties of different layers of the crust due to lack of available data. The Indian plate is composed of numerous heterogenous features such as cratons, fold belts and sedimentary basins, which need to be considered in the model. The material rheology of lithosphere also plays an important role in the lithospheric stress field of India. Therefore, the effects of boundary conditions, lateral strength of the plate and rheological properties on the stress field are studied by considering the long term behavior of the plate. However, for most of the engineering purposes, it is important to understand the short term behavior of the plate since design periods for structures range between 50 and 500 years. Since the earthquake catalogue is available for this duration, the model must represent this data by indicating active regions in India. Therefore, the analysis of Indian plate by considering both long term and short term plate behavior is also present in this study.

2. Geological setting of India

India broadly consists of three distinct geological units namely the Himalaya, the Indo-Gangetic plain and the Indian shield. These geological features are shown in Fig. 3. The historic collision of Indian plate with the Eurasian plate about 50–60 million years ago led to the formation of the Himalayan mountain chain (Valdiya, 1998). The Indian plate is continuously under-thrusting beneath the Eurasian plate, and stresses are increasing and accumulating progressively in the Himalayas. This makes the Himalaya seismically active compared to other geological units. Some of the notable earthquakes that have occurred in the Himalayan region are the 1897 Shillong earthquake ($M_w = 8.1$), 1905 Kangra earthquake ($M_w = 7.8$), 1934 Bihar-Nepal earthquake ($M_w = 8.3$), 1950 Assam earthquake ($M_s = 8.7$) and the 2005 Muzaffarabad earthquake ($M_w = 7.6$). The epicenters of past earthquakes compiled from various sources (Raghukanth, 2011) are shown in Fig. 2. The seismic activity in various regions of India is explained based on the focal mechanism of past earthquakes (Kayal, 2008). There are also reports of three major gaps in Himalayan region namely Kashmir gap, Garhwal gap and the Assam gap where large events have not occurred in the past 500 years (Khattri and Tyagi, 1983, 1987; Bilham et al., 2001). These gap regions have generated a lot of interest among seismologists and earthquake engineers because of the huge seismic potential to produce future damaging earthquakes. The Chaman fault in the west and Sagaing fault in the east cut the Himalayan mountain chain at its two extremities. These faults are further linked with the longer plate boundary faults of the Indian Ocean including Central Indian ridge, Southeast Indian and the Ninety east ridge towards the eastern boundary thrust. The Indus Tsangpo Suture Zone (ITSZ) is considered to be the plate boundary where the Tethys Ocean was consumed by the subduction process (Valdiya, 1998).

The Indo-Gangetic Plain is composed of the alluvial plains and embodies the southern side of the Himalayas. The seismicity in this region is moderate compared to that of Himalayas (Quittmeyer and Jacob, 1979). The Son-Narmada-Tapti zone (SONATA) has been episodically active since the late Archean. The Jabalpur earthquake of 22nd May, 1997 is associated with the activity of this fault. The Indian shield is a land mass that lies far away from the collision zone and is believed to be relatively stable. The shield region is further subdivided into five rigid blocks known as cratons namely Dharwar (DHC), Bastar (BAS), Bundelkhand (BUC), Singhbhum (SIC) and the Meghalaya craton (MC). The boundaries of craton as given by Valdiya (2010) are also shown in Fig. 3. Cratons are generally composed of granite and metamorphic rocks and are often bounded by a shear zone or a major fault line along its periphery. Bundelkhand craton, also named as Aravalli/Rajasthan craton constitutes the north-western part of the Indian shield. It covers an approximate area of 1.4×10^6 km^2. Dharwar craton occupies 1.1×10^6 km^2 area and is one of the oldest cratonic blocks comprising of granitic rocks of age 3.40 Ga. Tectonically, the Bundelkhand craton is separated from the Bastar and Singhbhum cratons by the long Son-Narmada rift zone. Further, the Singhbhum craton is separated from the Bastar craton by the Mahanadi graben. The Godavari rift valley demarcates the boundary between the Bastar and Dharwar cratons. The southern boundary of the Dharwar craton has a system of shear zones in the north south. The cratons accommodate regions known as 'sedimentary basins' which are created by long term subsidence infilled by sediments.

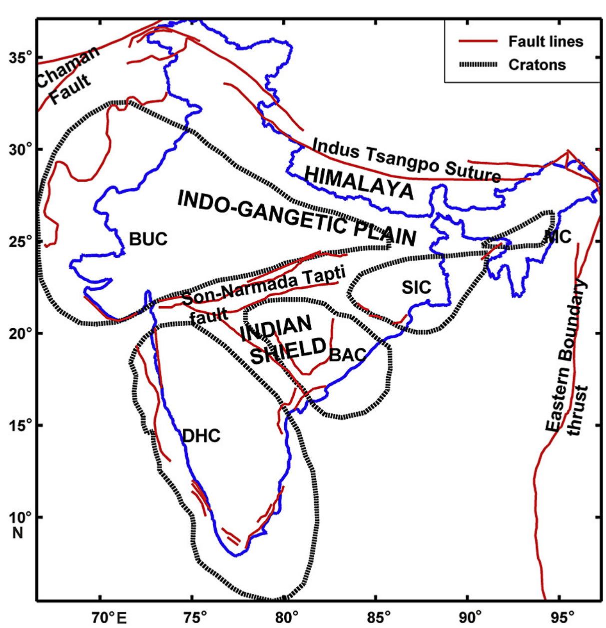

Figure 3. Geological features in Indian subcontinent with plate boundary faults and tectonic boundaries of cratons. BUC–Bundelkhand craton; DHC–Dharwar craton; BAS–Bastar craton; SIC-Singhbhum craton; MC–Meghalaya craton.

3. Finite element model for Indian plate

The geometry and the boundaries of the Indian plate being known, the next step is to develop a mechanistic model of Indian plate. The dimensions of the Indian plate are not subject to much variation when going from earth's spherical geometry to a flat surface. Thus, the latitudes and longitudes are converted to Cartesian coordinates in km, giving a total area of 12×10^6 km^2 for the Indian plate. The thickness of the plate is approximately 60 km which is relatively smaller than the maximum in plane dimension of the plate which is about 5000 km. Since, the geometry and loading on the edges of the plate are restricted to this plane, two-dimensional plane stress elements are used to model Indian plate.

Next important step is to identify the relevant boundaries of the plate on which the plate driving forces act. The northernmost part of the Indian plate is marked by the Main Boundary Thrust (MBT) by Bird (2003). Although this boundary is regarded as most seismically active and visible on the surface, the Indian plate underthrusts beneath Eurasian plate beyond MBT. Therefore, the actual boundary of Indian plate is the ITSZ zone, which is considered in the engineering model developed by Jayalakshmi and Raghukanth (2015). Therefore, the boundaries of Indian plate include the divergent margins along the Central Indian ridge, continental collision boundary along the Himalayas and the subduction zones along the Indo-Burmese and Andaman Arc. All these boundaries are indicated in Fig. 4a.

The Indian plate is constantly moving northward from the Central Indian ridge to the subduction zones. The state of dynamic equilibrium of the plate can be mathematically defined as

$$\nabla \cdot \sigma + f = \rho \ddot{u} + c\dot{u} \quad (1)$$

where σ is the stress tensor and f denotes the body force, ρ is the density of the plate, c is the coefficient of damping, $\ddot{u}$ and $\dot{u}$ are the plate accelerations and velocities. The terms on the right-hand side of Eq. (1) represent the forces due to inertia and damping. However, geologically, plates accelerate at very slow rates of few centimeters per year (Harada and Hamano, 2000; Bowin, 2010). Thus, the inertial effects due to plate accelerations can be assumed negligible in the analysis of Indian plate. The damping force is the resistance induced by the plate due to mantle drag force which is caused by the viscous coupling between the plate and the mantle beneath. Sargent (2004) has included the effect of this force by introducing dashpot elements in Eurasian plate model assuming that the basal drag resists plate motion on a large scale. At any point, the resistive

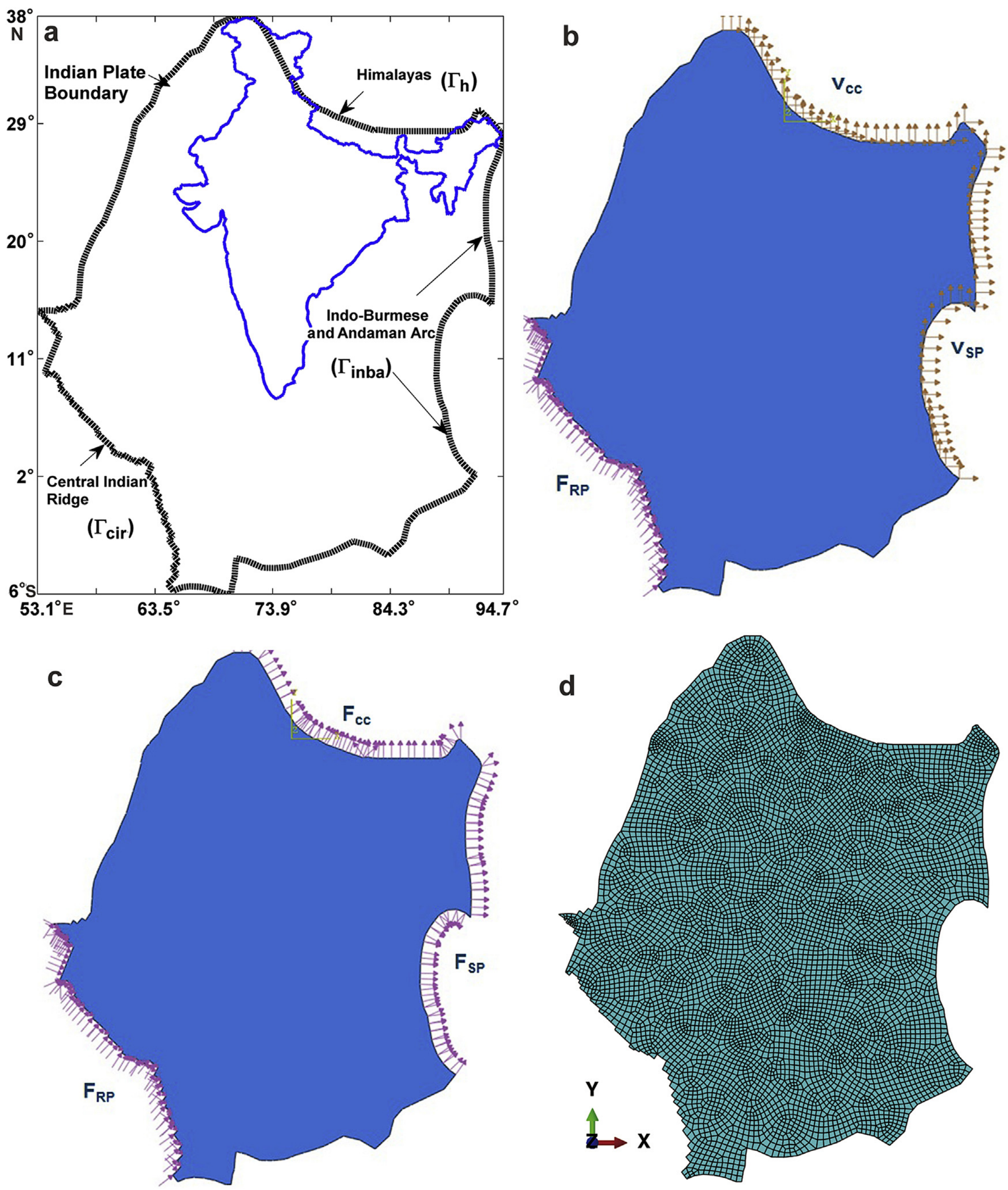

Figure 4. (a) Indian Plate boundary. (b) Model with velocity boundary conditions: known plate velocities applied at Himalaya and Indo-Burmese border. (c) Model with force boundary conditions: known plate forces applied at Himalaya and the Indo-Burmese border. (d) Finite element mesh used to discretize the Indian plate.

force exerted by the dashpot is proportional to the plate velocity at that point. The input that needs to be estimated for the dashpot element is the coefficient of friction relating the force and the velocity. Turcotte and Schubert (2002) gave a relation to estimate the value of shear stress τ between lithosphere and upper mantle.

$$\tau = \frac{-2\eta v_{avg}}{h}\left(2+3\frac{h_L}{h}\right) \tag{2}$$

where η is the viscosity of the upper mantle (10^{19}–10^{20} Pa s), h is the thickness of the upper mantle ($\sim$220 km), h_L is the thickness of the lithosphere and v_{avg} is the average plate velocity. The coefficient of friction for the dashpot element can be obtained by dividing the shear force on the element by the average plate velocity ($\sim$5 cm/yr for Indian plate). The shear force is computed from the known shear stress and the element area. The solution of the boundary value problem in Eq. (1) requires the definition of appropriate boundary conditions at all the boundaries of the plate. However, these boundary conditions are available in terms of plate velocity data and the plate driving forces.

As a first step, one needs to understand the appropriate boundary conditions acting on the Indian plate. Current plate velocities are available from the work of DeMets et al. (1990). The possible driving forces on the Indian plate are described as follows.

First, a ridge push force F_{RP} is applied along the Central Indian ridge between the borders of Somalia and Indian plate. The expression for the ridge push is given by the relation (Turcotte and Schubert, 2002).

$$F_{RP} = \rho_m g \alpha_v (T_m - T_0)\left[1 + \frac{2\rho\alpha(T_m - T_0)}{\pi(\rho_m - \rho_w)}\right] \quad (3)$$

where ρ_m is density of the mantle (3300 kg/m^3), g is the acceleration due to gravity (10 m/s^2), α_v is the thermal expansion coefficient (3×10^{-5}/K), ($T_m - T_0$) is the temperature difference between mantle and surface (1200 K), ρ_w is the density of water (1000 kg/m^3), thermal diffusivity (k_d) can be taken as 1 mm^2/s and t is the age of lithosphere in seconds. The magnitude of this force is calculated based on the mean age of 20 Ma for this oceanic lithosphere. This force is applied as pressure of magnitude 7.5×10^{12} N/m distributed along the entire oceanic lithosphere and acts normal to the strike of the ridge. Next important force is the continental collision force F_{cc} along the Himalayan pate boundary where the Indian plate converges with Eurasia. Coblentz et al. (1998) estimated a force of 2×10^{12} N/m for the Himalayas and hence applied as pressure along this boundary. Lastly, a slab pull force F_{sp} is applied along the subduction zone towards the eastern side of the plate. This force drives the plate towards the subduction zone in the Andaman Sea and the Border between Indian plate and Burma plate. The force is estimated based on age, subduction rate and dip of the subducting slab and applied as pressure of magnitude $\sim 3.6 \times 10^{13}$ N/m (Khan, 2011).

Although several authors have published estimates of many of these plate driving forces, exact computation of these forces is difficult. Among all the driving forces, only ridge push is a numerically well-known force that depends on the age of lithosphere. However, the estimates of slab pull and collision forces are subjected to large number of uncertainties in the subduction zones (Scholz and Campos, 1995).

While developing models for tectonic plates, one may use the relevant plate boundary forces as boundary conditions to simulate stress field in the plate. Since the current plate velocity data is quite well known, one may also prefer to use them as boundary conditions at these boundaries. It is observed that at the collision boundary along Himalayas, the Indian plate converges at an average rate of 50 mm/yr (Bilham et al., 1998) and the collision force reported is 2×10^{12} N/m (Coblentz et al., 1998). In the subduction zone, the plate velocity is 36 mm/yr (DeMets et al., 1990) whereas the slab pull force 3.6×10^{13} N/m drives the plate towards the trench (Khan, 2011). While forces are more associated with mechanics of the plate and the mantle, the velocities prescribe the motion of the plate. For example, in spite of high velocities, the collision forces in Himalayas are lower than the slab pull force in the subduction zone. The stress field in the interior of the plate varies depending on the type of boundary condition applied in the model. Therefore, one can mix both force and velocity boundary conditions in the respective plate boundaries. In the present study, the ridge push force along the Central Indian ridge boundary τ_{cir} is applied as one of the force boundary conditions.

For the remaining boundaries along Himalayas and Indo-Burmese Andaman arc, the known plate velocities can also be applied. To explore the effects of different kinds of boundary conditions on the plate, two models are developed in the present study. First, a model with velocity boundary conditions is analyzed with the corresponding plate velocities applied at these boundaries of the Indian plate. The second one is a model with the plate driving forces acting on these boundaries. In both cases, the models assume uniform thickness (60 km) and homogeneous elastic material properties (E = 75 GPa, $\upsilon = 0.25$) for the plate.

In the first case, velocity boundary conditions v_{cc} and v_{sp} are applied along the boundaries τ_h and τ_{inba} respectively. The model is shown in Fig. 4b. The second model holds force boundary conditions along these boundaries which are indicated by F_{cc} and F_{sp} in Fig. 4c.

In all cases, plane stress conditions are assumed, thus avoiding the possibility of out-of-plane normal and shear stresses. Hence, the models presented in this study do not explain evolution of mountains or formation of basins and compare them with the actual topography. In the present study, the Indian plate is modeled in ABAQUS 6.10.1 and the plate is discretized using 4-noded quadrilateral elements with a mesh resolution of 35 km over the entire plate. The finite element mesh used in the models is shown in Fig. 4d.

4. Results and discussion

To perform dynamic analysis of the elastic plate, a computation time period has to be chosen in such a way that the material nonlinear effects do not affect the stresses in the plate. Therefore in the present study, the models are analyzed for a time period of 47,000 years with a time increment $\Delta t = 0.25$ years. The Von-Mises stress, which is a measure of stress intensity often used in engineering, is obtained for both the models (Popov and Balan, 1998). The results of the analysis with different boundary conditions, lateral strength and rheology are discussed in the following section.

4.1. Effect of boundary conditions

Models A1 and A2 are analyzed and stress fields are simulated over the entire plate. The results are shown in Fig. 5. Fig. 5a shows the stress contours in the model with relative plate velocities applied as boundary conditions. The contours indicate that maximum stresses occur in the northeast Himalayas and low stresses in the remaining part of the plate. However, the spatial distribution of epicenters of past earthquakes reveals that the subduction zones and other Himalayan zones are highly potential regions (Fig. 5a). The contours do not represent stress concentrations in these regions. For the Model A1, compressive stresses are observed on most regions in the plate, except near the CIR boundary as shown in Fig. 5b. The directions of maximum principal stresses are oriented north-south, almost throughout the plate. However, along the CIR boundary, the directions are east-west oriented. It is also observed that tensile stresses are dominant over the length of CIR boundary. The magnitude and directions of simulated stress field for Model A2 is shown in Fig. 5c and d. In this case, maximum stresses are observed in parts of Himalayas and the subduction zones on the trench side. The variation of stress field is largely influenced by the forces applied in the boundaries of Indian plate compared to the velocities. The applied slab pull is almost an order higher than ridge push and the collision force and hence, the stresses are more concentrated towards the eastern trench side of the plate as shown in Fig. 5c. The maximum horizontal principal stresses due to force boundary conditions are indicated in Fig. 5d. The dominant components are tensile stresses over most regions of the plate. While the stresses are oriented E–W in Himalaya, Central and Peninsular India, they tend in north-south direction in western, eastern and ridge boundaries of the plate.

4.2. Effect of lateral strength variations

The models developed in the previous section assume uniform thickness and homogeneous material properties for the entire plate. However, the plate is composed of numerous geological provinces with rocks of differing age. Among these provinces, cratons form the old and stable parts of the crust, and their boundaries are demarcated by faults and lineaments as shown in

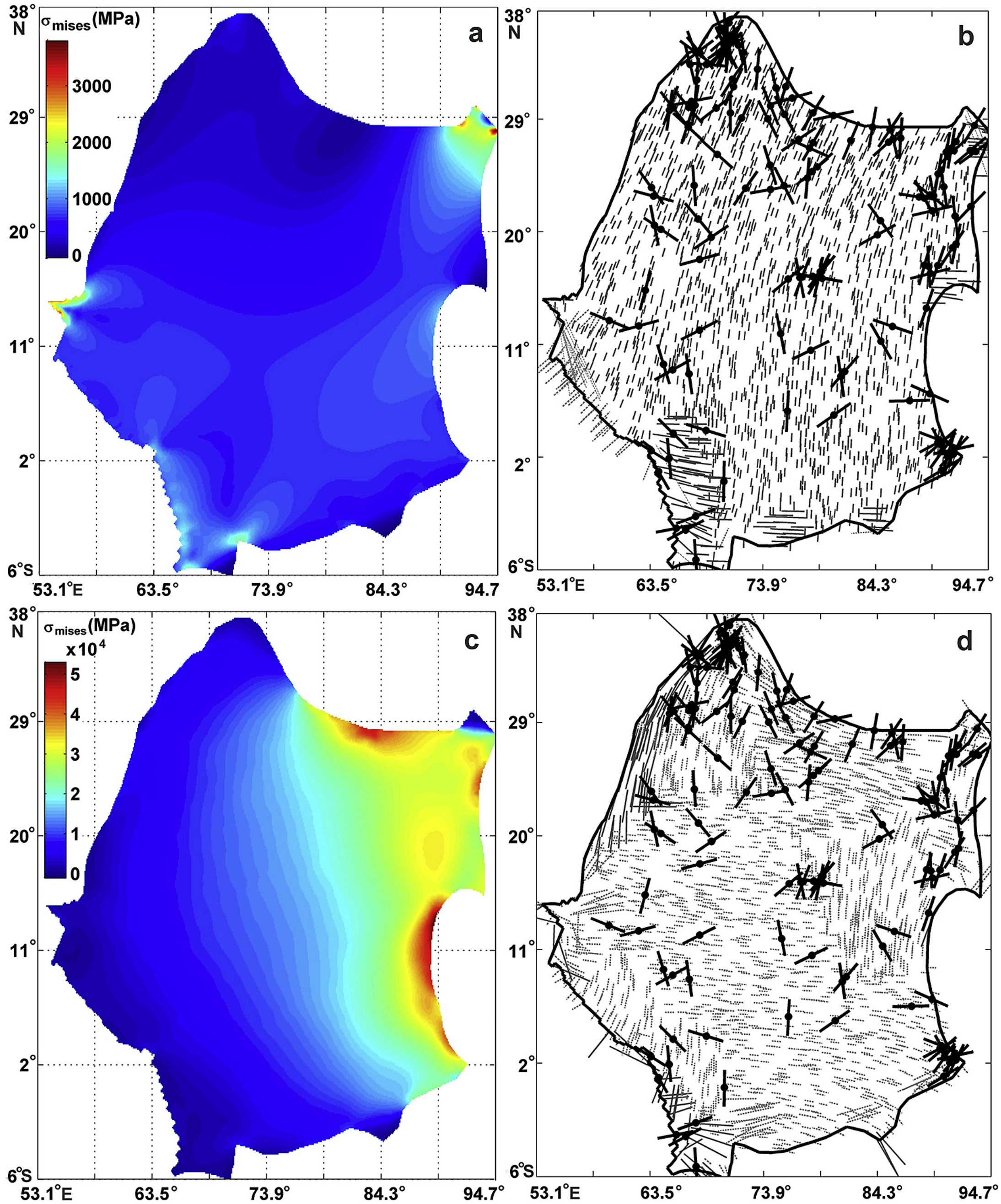

Figure 5. (a) Contours of Von Mises stress obtained for Model A1. (b) Orientation of maximum horizontal principal stress for Model A1. (c) Contours of Von Mises stress obtained for Model A2. (d) Orientation of maximum horizontal principal stress for Model A2. Dark lines indicate compressive stress and light lines indicate tensile stress. Thick black lines with circles indicate stress data from WSM, 2008.

Fig. 3. Cratons occupy almost 25% of the plate area and significantly affects the lateral strength of the plate. Therefore, the Indian plate with all the five cratons is modeled with the forces applied at the respective boundaries. For incorporating the cratons in India, the plate is partitioned into five different blocks based on the boundaries illustrated in Fig. 3. The effect of cratons on the stress field can be studied by varying the material properties in these regions of the plate. Since elastic models are developed in the present study, the parameters that affect the lateral strength of the plate include Young's Modulus (E), Poisson's Ratio (υ) and thickness (t_c) of the craton. The complexity of the problem increases when there are more number of unknowns that significantly affect the stress field. However, this difficulty can be resolved by adopting a simpler approach to model cratons. Therefore in the present study, the method of 'transformed cross section' is used for analysis of plate with cratons (Popov and Balan, 1998). Using this concept, the cross section of the plate is transformed into an equivalent cross section of an imaginary plate composed of only one material. The equivalent cross section is obtained by varying the thickness at the cratons. Therefore, two models are developed (Model B1 and Model B2) by varying the thickness of the craton relative to the plate.

Model B1 is first analyzed by increasing the thickness of the cratons relative to the plate. The cratons are assigned a thickness of 120 km which is double the thickness of the surrounding continental crust. The Von-Mises stress contours are shown in Fig. 6a. The contours reveal the structure of cratons and the magnitude of

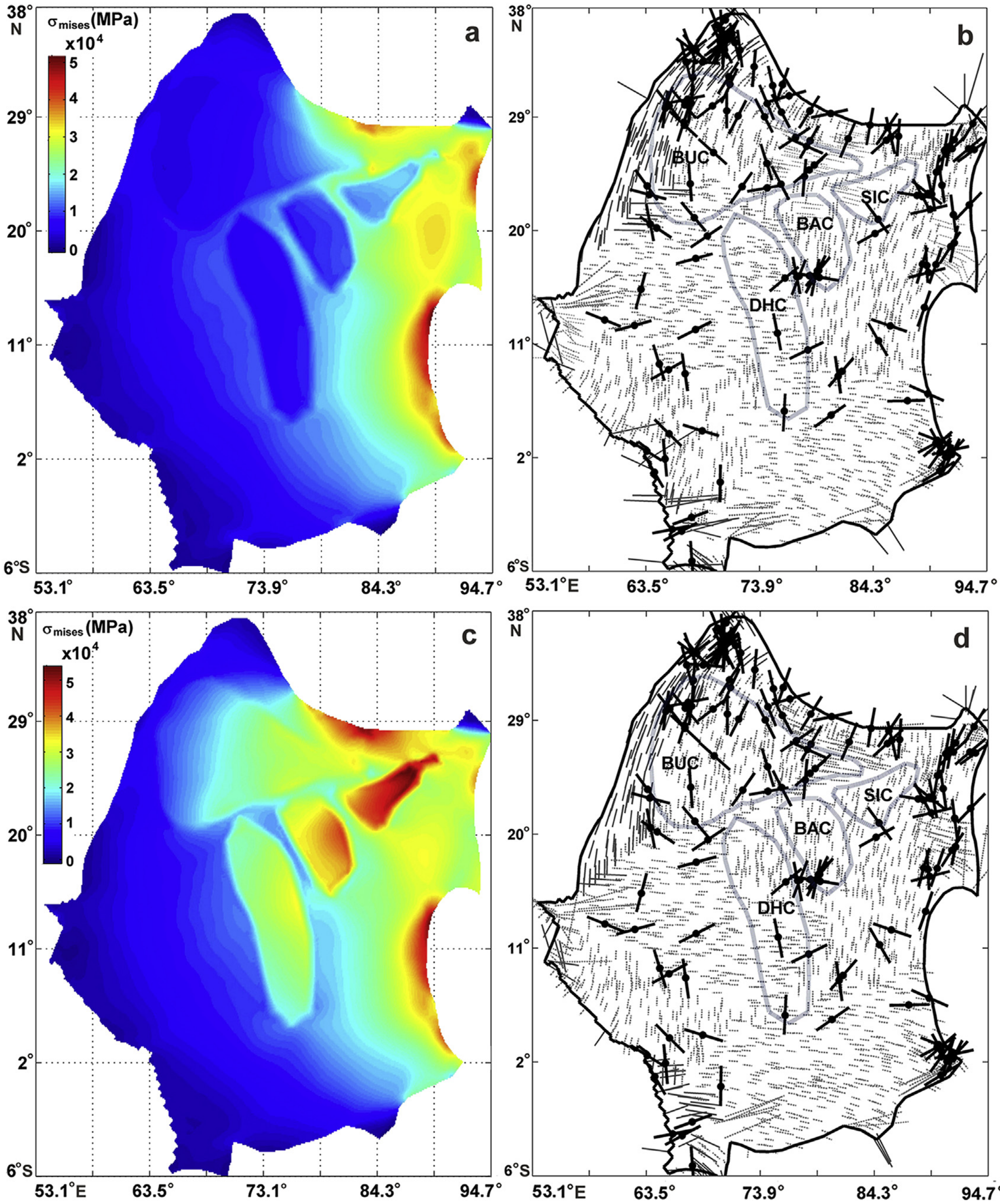

Figure 6. (a) Contours of Von Mises stress obtained for Model B1. (b) Orientation of maximum horizontal principal stress for Model B1. (c) Contours of Von Mises stress obtained for Model B2. (d) Orientation of maximum horizontal principal stress for Model B2. Dark lines indicate compressive stress and light lines indicate tensile stress. Thick black lines with circles indicate stress data from WSM, 2008.

stresses are lowered within the cratons compared to the surrounding regions of the plate. The region between each craton exhibits relatively higher stresses compared to those within the cratons. The magnitudes of stress increase towards the eastern trench side of the attributing to the large slab pull force acting at this boundary. Fig. 6b shows the direction of maximum horizontal principal stress. The stress distribution is similar to that observed for Model A2. In this case, significant variations are obtained near the cratonic blocks. Along Himalaya, the vectors rotate by almost 90° which make them transversely aligned to most of the thrust faults (MBT, MCT) in this region. In the Son-Narmada rift zone between BUC and the remaining cratons, significant rotations in tensile stresses are observed towards the eastern side. Significant earthquakes such as Son-Valley (*M* 6.5, 1927), Satpura (*M* 6.3, 1938), Balaghat (*M* 5.5, 1957), Broach (*M* 5.4, 1971) and Jabalpur (*M* 6.0, 1997) earthquakes have occurred in this zone. The focal mechanisms of these events indicate faulting along the plane of Son Narmada fault (Kayal, 2008). In general, not much perturbation of stresses occurs in the remaining boundaries and within the cratons.

So far in the study, no physical constraints are observed for the thickness of the cratons and hence the effect of thinner cratons is also explored. Model B2 is developed by assigning a thickness of 25 km to all the cratons. The contours of Von-Mises stresses are shown in Fig. 6c. It is observed that the stresses in the cratons are higher than the stresses in the surrounding plate. In the region between the cratons, the stresses are lower than those within the cratons. Maximum stress is observed in the north-east cratons (SIC, MC). The stress directions observed in Himalaya are similar to those observed from Model B1. However, on the eastern side of Son-Narmada rift zone, the directions are oriented E–W as against the observations in Model B1. Significant rotations are also observed in northern parts of DHC, BAS and SIC compared to the stress directions from Model B1.

4.3. Effect of non-linear material rheology

The elastic models analyzed with different boundary conditions and thickness variations shed light on their importance in stress modeling. However, the material properties of rock are subject to change over geological time spans during the motion of a continental plate. Non-linear effects including viscosity and plasticity play a role in the stress state of tectonic plates. Several models incorporating such effects are developed for long term stress modeling (Regenauer-Lieb and Petit, 1997; Lithgow-Bertelloni and Richards, 1998). In the present study, plasticity is introduced in Model B1 and a new Model C is developed by defining a yield stress $\sigma_y = 100$ MPa. A computation time period of 1.5 million years is chosen to investigate the effect of plasticity on the stress field. Von Mises stress contours and directions of maximum horizontal principal stress are obtained after analysis of Model C (Fig. 7a and b). It is observed that a large portion of the plate reach the limiting yield stress of 100 MPa after the computation time. Except for BUC, DHC, SIC and western parts of Himalaya, the remaining part of the plate has yielded. In the other regions of the plate, the magnitudes of stress are comparatively lower than those observed for Model B1. The decrease in stress is attributed to the low plastic strains due to flow of material (ABAQUS, 2011). Deformations are highly localized in the eastern trench side and equilibrium is attained by propagating the yield stress in the surrounding regions. Zones of high stress concentrations are observed in the Son-Narmada region and the Godavari basin between DHC and SIC. The directions of maximum horizontal principal stresses are indicated in Fig. 7b. Due to the high magnitudes of slab pull and collision forces, the nature of stresses observed is tensile over most regions as obtained for Model B1. There are few regions where significant variations in stress directions are seen. In Himalaya, the stress directions are aligned transverse to the observed data The Son-Narmada zone exhibits north-south stress orientations on the eastern side which is similar to the observations for Model B1. The simulated compressive stresses in few regions in the shield further south, are in good agreement with the observed stress data.

4.4. Short term behavior of Indian plate

The effect of boundary conditions, thickness and nonlinear rheology on the stress fields are discussed through Models A1, A2, B1, B2 and C. In all these models, the plate driving forces are applied for a long time span ranging from 43,000 years to 1.5 million years. However, in engineering practice, the mean probable design life of a structure ranges between 50 and 100 years depending on the importance of the structure (IS: 875, Part 3, 1987). Since the complete earthquake catalogue is available for shorter time spans that range from 50 to 500 years, it will be of interest to investigate whether this data can be represented by the model. It is observed that the stress fields simulated by Models B1 and C are consistent with the seismic activity and the observed stress data in India. Therefore, a Model D1 is developed with the same properties as that of Model B1 (Table 1) and analyzed for a shorter computation period of 50 years, which is a commonly adopted design life period for buildings, using $\Delta t = 0.025$ years. The Von Mises stress contour and the directions of maximum horizontal principal stress obtained from the analysis of short term behavior of elastic plate is shown in Fig. 8a and b. It is observed that the magnitudes of short term stresses are same as those of long term stresses. Similar to the results obtained for Model B1, the potentially active zones in India are demarcated by regions of high stress. The directions of maximum horizontal stresses from Model D1, also exhibit similar pattern of those observed for Model B1 in Fig. 6b. The regions of tensile

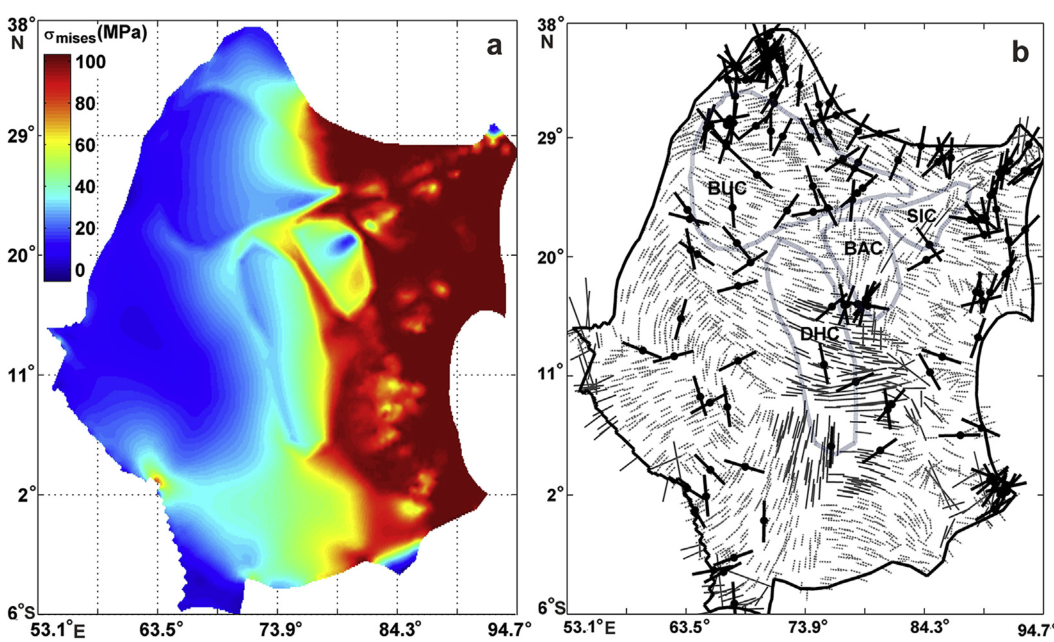

Figure 7. (a) Contours of Von Mises stress obtained for Model C. (b) Orientation of maximum horizontal principal stress for Model C. Dark lines indicate compressive stress and light lines indicate tensile stress. Thick black lines with circles indicate stress data from WSM, 2008.

Table 1
The different models and their properties used in the analysis of Indian plate. Values of $F_{RP} = 7.5 \times 10^{12}$ N/m, $F_{cc} = 2 \times 10^{12}$ N/m, $F_{sp} = 3.6 \times 10^{12}$ N/m, $\upsilon_{cc} = 50$ mm/yr and $\upsilon_{sp} = 36$ mm/yr.

Properties		Model							
		A1	A2	B1	B2	C	D1	D2	E
BCs	CIR	F_{RP}	F_{RP}	F_{RP}	F_{RP}	F_{RP}	F_{RP}	F_{RP}	F_{RP}
	Himalaya	υ_{cc}	F_{cc}	F_{cc}	F_{cc}	F_{cc}	F_{cc}	F_{cc}	fixed
	Subduction	υ_{sp}	F_{sp}	F_{sp}	F_{sp}	F_{sp}	F_{sp}	F_{sp}	F_{sp}
Thickness (km)	Plate t_p	60	60	60	60	60	60	60	60
	Craton t_c	60	60	120	25	120	120	120	120
Elastic Properties	E (GPa)	75	75	75	75	75	75	75	75
	υ	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Yield Stress (MPa)		–	–	–	–	100	–	100	–
Computation time period (years)		47,000	47,000	47,000	47,000	1.5 million	50	50	50

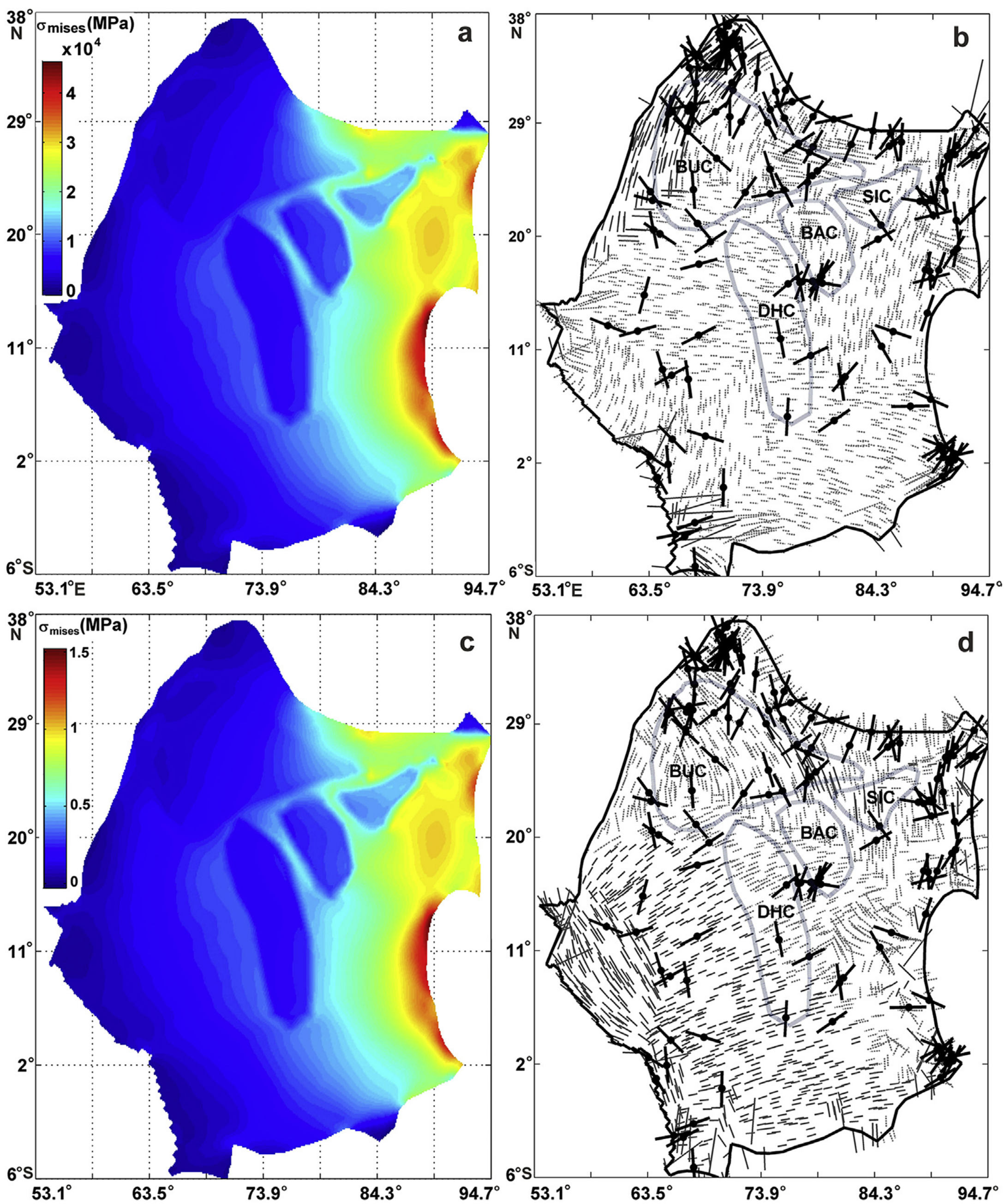

Figure 8. (a) Contours of Von Mises stress obtained for Model D1. (b) Orientation of maximum horizontal principal stress for Model D1. (c) Contours of Von Mises stress obtained for Model D2. (d) Orientation of maximum horizontal principal stress for Model D2. Dark lines indicate compressive stress and light lines indicate tensile stress. Thick black lines with circles indicate stress data from WSM, 2008.

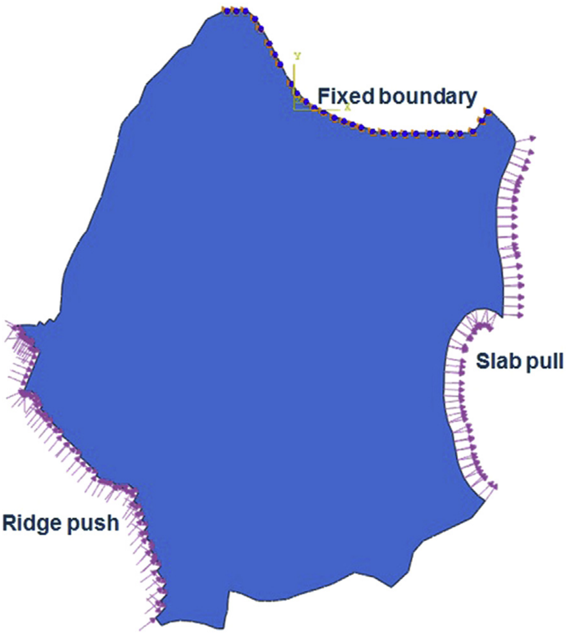

Figure 9. Model E with applied ridge push and slab pull force, fixed at Himalaya.

stresses can be interpreted as regions exhibiting minimum compressive stresses. The reason for dominance of tensile stresses in these regions is due to the effect of large slab pull applied on the trench side of the plate.

In order to study the effect of plasticity in short term stresses, a Model D2 is developed with the same properties as that of Model C (Table 1) and analyzed for a shorter computation period of 50 years, using $\Delta t = 0.025$ years. In this case, it is observed that no region of the plate has yielded when the forces are applied for 50 years. The spatial distribution of stresses shown in Fig. 8c is similar to that of the elastic model in Fig. 8a. However, the magnitudes are almost four orders less than those observed in the elastic model. The overall decrease in stress is due to the time dependent plastic strain in the plate. Plastic strain increases with increase in time and at the end of 50 years, yielding is not initiated in the plate. The observed stresses are relatively lower in the interior of the plate. The high stress concentrations in the Himalayas and the subduction zones also qualitatively agree with the seismicity database. The directions of maximum horizontal stresses observed for Model D2 is indicated in Fig. 8d. Significant variations in directions of stresses are observed, compared to those of Model C in Fig. 7b. In Himalaya, the stress directions are oriented north-south, transverse to the thrust faults. In BUC, the stress directions are rotated by 90° and are aligned transverse to many faults in this region. The Son-Narmada region exhibits stresses that are inclined in north-south direction. The compressive stresses observed near CIR boundary and other regions in BUC are in good agreement with the WSM stress data.

Among the different models studied to simulate stress fields, most of the models use plate driving forces as applied boundary conditions (Table 1). However, except with ridge push force (Eq. (3)), the uncertainties associated with other forces including mantle drag, collision force and slab pull are quite high. These uncertainties increase the number of unknowns in the model parameter space and complexities in estimating stresses in India for a short time scale. To overcome this difficulty, a Model E is analyzed with a fixed boundary condition along Himalaya. The collision force and mantle drag are taken into account by enforcing all the resistance to plate motion along Himalaya. Model E with the fixed boundary condition and other plate driving forces is shown in Fig. 9. The simulated stress contours and directions of maximum horizontal stress are obtained for the plate which is analyzed for 50 years. The results are shown in Fig. 10a and b.

Fig. 10a shows high stress concentrations in various regions of Himalaya, which are consistent with the intense seismicity. There have also been several reports on existence of seismic gaps with huge potential strains in Himalaya (Khattri, 1987; Bilham et al., 2001). Lower stresses are observed in other regions of the Indian shield and are in good agreement with the moderate seismicity

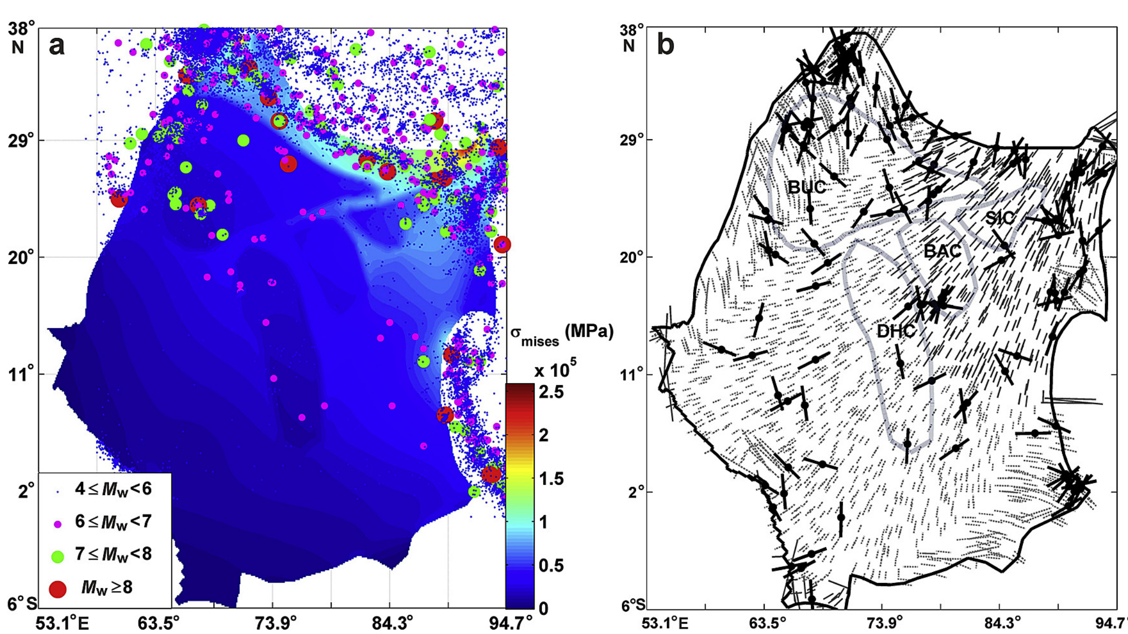

Figure 10. (a) Contours of Von Mises stress obtained for Model E superimposed with epicenters of past earthquakes. (b) Orientation of maximum horizontal principal stress for Model E. Dark lines indicates compressive stress and light lines indicate tensile stress. Thick black lines with circles indicate stress data from WSM, 2008.

(Fig. 2). The directions of maximum horizontal principal stress are shown in Fig. 10b. It is observed that compressive stresses are simulated over the many regions in India towards Himalaya and eastern boundary. These directions tend northward and compare well with the observed stress directions from WSM data. However, there is dominance of tensile stresses in western regions of Himalaya, BUC, DHC and Son-Narmada region. These directions are generally aligned towards the eastern subduction zone. The reason for this can be attributed to the effect of large slab pull and the fixed boundary condition.

5. Summary and conclusions

This article is motivated by the desire to develop a finite element model of Indian plate to represent its seismic activity. The need of the finite element model to overcome the difficulties due to lack of available data in hazard estimation is discussed. The important parameters that need to be considered in modeling are explored and this includes boundary conditions, lateral strength variations and rheology. The recently available stress data from WSM, release 2008 are obtained for Indian plate and comparisons are made with the simulated stress field in the plate. Different models are developed with properties listed in Table 1 and analyzed in ABAQUS 6.10.1.

Firstly, the effect of velocity and force boundary conditions on the stress field is studied from Models A1 and A2. The magnitude of stress field simulated from Model A2 varies within the plate, consistent with the seismic activity. Secondly, the lateral strength of the plate is varied at the cratons and stress fields are simulated for Models B1 and B2 with thick and thin cratons. The stresses relatively vary within the cratons compared to the surrounding plate stresses. Although constraints are not obtained for the cratons in the present study, it is interpreted that thickness is a parameter that is sensitive to the stress field in the plate. The third important study is the effect of plasticity on the stress field (Model C). When Model C is analyzed for a computational time of 1.5 million years, many regions in the plate reach yield stress. However, the yielding is closer to the regions with dense seismicity as seen from earthquake catalogue in Fig. 2. The fourth stage of modeling is to understand the effect of all these parameters in the short term behavior of the plate.

Since most of the engineering designs use a design span ranging from 50 to 100 years for different types of structures, Models D1 and D2 are developed with elastic and plastic properties listed in Table 1. The distribution of stresses simulated by both models is same. However, the magnitudes are lowered in the case of Model D2 due to the slow built up of plastic strains. The general observation in all the models with force boundary condition is that there are dominant tensile stresses in the plate. The reason is attributed to the assumptions made in the magnitude of applied and resistive forces. Therefore, as a last step, Model E is developed by applying fixed boundary condition at Himalaya, along with ridge push and slab pull forces on the remaining boundaries. Stress concentrations are observed in most of the potential regions in India and are agreement with the earthquake catalogue. The simulated directions of compressive stresses are in good comparison with the observed stress data.

However, there are few limitations that need to be addressed within the scope of the present study. All the models used in the present study are two dimensional and do not explain the implications on topography or effects like gravitational spreading. The models developed are not calibrated against quantities such as seismic strain rates, GPS measurements and stress drops. Further improvements in the result are possible if the model constraints are decided optimally using these known measurements.

Acknowledgments

The authors thank the anonymous reviewers for their careful reading and the constructive criticisms. The reviewers' suggestions have made a lot of improvement to the contents of the article.

References

ABAQUS, 2011. ABAQUS Documentation. Dassault Systèmes, Providence, RI, USA.
Bilham, R., Blume, F., Bendick, R., Gaur, V.K., 1998. Geodetic constraints on the translation and deformation of India: implications for future great Himalayan earthquakes. Current Science 74 (3), 213–229.
Bilham, R., Gaur, V.K., Molnar, P., 2001. Himalayan seismic hazard. Science 293 (5534), 1442–1444.
Bird, P., 1978. Finite element modeling of lithosphere deformation: the zagros collision orogeny. Tectonophysics 50, 307–336.
Bird, P., 1998. Testing hypotheses on plate-driving mechanisms with global lithosphere models including topography, thermal structure, and faults. Journal of Geophysical Research: Solid Earth 103 (B5), 10115–10129.
Bird, P., 2003. An updated digital model of plate boundaries. Geochemistry, Geophysics, Geosystems 4 (3).
Bowin, C., 2010. Plate motion conserves angular momentum. eEarth 5, 1–10.
Cloetingh, S., Wortel, R., 1985. Regional stress field of the Indian plate. Geophysical Research Letters 12 (2), 77–80.
Coblentz, D.D., Zhou, S., Hillis, R.R., Richardson, R.M., Sandiford, M., 1998. Topography, boundary forces, and the indo-australian intraplate stress field. Journal of Geophysical Research: Solid Earth 103 (B1), 919–931.
DeMets, C., Gordon, R.G., Argus, D.F., Stein, S., 1990. Current plate motions. Geophysical Journal International 101 (2), 425–478.
Dyksterhuis, S., Albert, R., Müller, R., 2005. Finite-element modelling of contemporary and palaeo-intraplate stress using abaqus. Computers & Geosciences 31 (3), 297–307.
Forsyth, D., Uyeda, S., 1975. On the relative importance of the driving forces of plate motion. Geophysical Journal International 43 (1), 163–200.
Harada, Y., Hamano, Y., 2000. Recent progress on the plate motion relative to hotspots. In: The History and Dynamics of Global Plate Motions. Geophys. Mono., 121, pp. 327–338.
Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeß, D., Müller, B., 2008. The World Stress Map Database Release 2008. http://dx.doi.org/10.1594/GFZ.WSM.Rel2008.
Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeß, D., Müller, B., 2010. Global crustal stress pattern based on the World Stress Map database release 2008. Tectonophysics 462. http://dx.doi.org/10.1016/j.tecto.2009.1007.1023.
Jayalakshmi, S., Raghukanth, S.T.G., 2015. An engineering model for seismicity of India. Geomatics, Natural Hazards and Risk 6 (1), 1–20.
Kayal, J.R., 2008. Microearthquake Seismology and Seismotectonics of South Asia. Capital Publishing Company, New Delhi.
Khan, P., 2011. Role of unbalanced slab resistive force in the 2004 off sumatra megaearthquake(Mw > 9.0) event. International Journal of Earth Sciences 100 (7), 1749–1758.
Khattri, K., 1987. Great earthquakes, seismicity gaps and potential for earthquake disaster along the Himalaya plate boundary. Tectonophysics 138 (1), 79–92.
Khattri, K., Tyagi, A., 1983. Seismicity patterns in the Himalayan plate boundary and identification of the areas of high seismic potential. Tectonophysics 96, 281–297.
Lithgow-Bertelloni, C., Richards, M.A., 1998. The dynamics of Cenozoic and Mesozoic plate motions. Reviews of Geophysics 36 (1), 27–78.
Müller, R., Yatheesh, V., Shuhail, M., 2015. The tectonic stress field evolution of India since the Oligocene. Gondwana Research 28 (2), 612–624. http://dx.doi.org/10.1016/j.gr.2014.05.008.
Popov, E.P., Balan, T.A., 1998. Engineering Mechanics of Solids. Pearson Education Inc., New Jersey, USA.
Quittmeyer, R.C., Jacob, K.H., 1979. Historical and modern seismicity of Pakistan, Afghanistan, northwestern India, and southeastern Iran. Bulletin of the Seismological Society of America 69 (3), 773–823.
Raghukanth, S., 2011. Seismicity parameters for important urban agglomerations in India. Bulletin of Earthquake Engineering 9 (5), 1361–1386.
Regenauer-Lieb, K., Petit, J.-P., 1997. Cutting of the European continental lithosphere: plasticity theory applied to the present alpine collision. Journal of Geophysical Research: Solid Earth 102 (B4), 7731–7746.
Sargent, M.T., 2004. Dynamics of the Eurasian Plate (Master's thesis, Department of Physics of the Swiss Federal Institute of Technology Zurich).
Scholz, C.H., Campos, J., 1995. On the mechanism of seismic decoupling and back arc spreading at subduction zones. Journal of Geophysical Research: Solid Earth 100 (B11), 22103–22115.
Turcotte, D., Schubert, G., 2002. Geodynamics. Cambridge University Press.
Valdiya, K., 1998. Dynamic Himalaya. Universities Press, India.
Valdiya, K., 2010. The Making of India: Geodynamic Evolution. Macmillan Publishers, India.
Zoback, M.L., 1992. First- and second-order patterns of stress in the lithosphere: the worldstress map project. Journal of Geophysical Research 97, 11703–11728.