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Seismic hazard assessment of Koyna region, Peninsular India: using geospatial approach

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Abstract

Background: Earthquake-prone regions from the stable continental regions (like Peninsular India) warrant total seismic hazard estimation from possible sources — reservoir induced or tectonic. The Koyna region falls in the so-called stable continental region, though previously considered as aseismic because of its location in the Peninsular India, which was argued to be the continental Shield region; however, it is seismically active ever since the December 10, 1967, strong earthquake (M6.5) which killed around 200 people and damaged properties. The event was initially attributed to reservoir-induced seismicity. The present study aims at mapping the spatial distribution of hazard intensity in terms of peak ground acceleration and damage potential expressed as Modified Mercalli Intensity
(MMI) levels owing to the scenario earthquakes (M4.0 to M6.9) from the linear sources and background seismicity in the Koyna region. For the seismic source model, geospatial integration approach is used. To delineate the source boundaries we perform spatial analysis of seismicity attributes and assigning weights based on the geological information. In addition, spatial buffering of thematic layers of faults and lineaments is applied to truncate the spatial uncertainties. Thematic attribute layers are integrated over the SRTM-DEM-derived geomorphic features and spatial seismicity pattern to define the possible linear seismic source zones. We employ ArcGIS® to perform geospatial analysis and to integrate thematic spatial information finally to prepare the seismic hazard and damage potential zones for the Koyna region.

Results: We present the probabilistically estimated seismic hazard and damage potential estimates for the Koyna region. Spatial mapping of the hazard parameters is performed on Geographic Information System (GIS) platform. Along with the historical and instrumental earthquake data, we incorporate updated and relocated seismic events from circa 1618 to 2017 covering ~ 400 years period, for analyzing the mean annual rates of seismicity and earthquake recurrence intervals. The anticipated recurrence intervals of earthquakes ~ M5.5 is around 100 ± 10 years. The estimated peak ground acceleration (PGA) for 10% probability being exceeded in 50 years (i.e. 500 years of return period) is greater than 21% g is anticipated for the area located (~30 km radius) between the Koyna and Warna Reservoirs.

Conclusions: The hazard estimates for the 500 years return period earthquake scenarios (M4.0 to M6.9) are based on the bedrock level estimation. Estimated PGA-values are grouped into three categories that are relatively defined as high, moderate, and low hazard zones, respectively. Slightly damaging intensity (MMI-VII level) expected in 50 years has ~ 40% probability and PGA greater than 21% g for the area which is located between Koyna and Warna Reservoirs, which is identified as high hazard zone.

Keywords: Earthquake, Seismic hazard, Koyna, GIS, Probability, Stable continental region

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Background

It is evident from the recent devastating earthquakes that in many parts of the world that the existing seismic hazard maps frequently failed in making the predictions of expected seismic ground motions levels. This inadequacy can be attributed to imprecise and surmised identification/mapping of seismically active faults, inadequate paleoseismic data, and uncertainty in the fault slip rates estimations and other seismicity related information. Improvement of risk estimation methods and vulnerability assessment schemes is warranted whenever cutting-edge development of earthquake science and recent or updated earthquake data is available. Because reliable risk estimates are essential since it offers the primary information for risk management and mitigating agencies. The present study is carried out, by applying recently occurred earthquake events and the relocated seismicity in the Koyna seismic zone in Peninsular India, to map the damage potential probabilistically. We assume segmented linear seismic sources delineated based on geologic, morphotectonic characteristics and fault-slip rates.

Besides, primary seismic hazards (i.e. bedrock level ground motion) the amount of damage inflicted by earthquake events can also be attributed to heterogeneous geological material characteristics since unconsolidated surface deposits tend to amplify in the seismic ground motions. Earthquake scenarios represents a potential future earthquake by assuming a particular magnitude, location, and fault-rupture geometry and estimating ground shaking using a variety of approaches for the regions where the seismic sources are of tectonically active. In addition to the understanding of regional tectonic set-up, it is also important infer the dynamics of Reservoir Induced Seismicity (RIS) for a total seismic hazard assessment of a given region. RIS occurs only when the pre-existing stress, geologic, and hydrologic conditions at the site are suitable (Simpson, 1976). Seismicity in the Koyna region in Peninsular India, was initially attributed to the RIS, is still not well understood. Predominant geology of is basalt, about 1500 m to 1700 m thick of Deccan Traps basalt flow layers is reported from Koyna region (Kaila et al., 1981; Sarma et al., 2004).

India has witnessed a number of devastating earthquakes in the past five decades. According to a joint World Bank–UN study, around 200 million people living in India will be exposed to seismic risk by 2050 (WB–UN, 2010). Virtually, India's 50% land is declared as seismically-prone. Considering the seismic risk and economic losses, seismic microzonation and hazard assessment at regular interval should entail as a part of disaster management processes for mitigating the hazard. In India, seismic microzonation studies on major cities that are vulnerable to the earthquake hazards have been carried out by Mohanty et al., 2007 (Delhi), kanth and Iyengar, 2006 (Mumbai), Sitharam and Anbazhagan, 2007 (Bangalore), Nath et al., 2008 (Guwahati), Ganapathy 2011 (Chennai), Mahajan et al., 2007 (Dehradun), Rao et al., 2011 (Jabalpur), and Pal et al., 2008 (Sikkim) on regional scales (MoES, 2011). GIS based application for estimating the seismic risk assessment of urban areas is developed and demonstrated for Mumbai city by Sinha et al., (2008). Available probabilistic seismic hazard assessments for peninsular India is performed based on the regional tectonic-setup by assuming one or two seismic source models on national scale (Jaiswal and Sihna, 2007; Nath and Thingbaijam, 2012).

The data gaps have been moderated in these exercises. At the same time, towns situated in proximity to urban areas are being developed to decongest the cities. Therefore, there is a need to prepare hazard assessment and mitigation plan for intended/ongoing areas of development. The earthquakes occurring in this part of stable continental region (SCR) emphasize the need for seismic hazard assessment and damage potential zonation for non-urban areas incorporating updated seismicity and spatial uncertainties of seismic sources.

GIS technology enables the storage of point and polygon information as geo-referenced spatial database and allows for further upgrading of new information. Geo-referenced information could be retrieved, analysed and results could be presented on geospatial mode for data dissemination for disaster management. This study demonstrate the effective use of limited (spatial and quantitative) information (seismological, geological and geomorphological) to a more accurate spatial variation of the seismic hazard that can be modelled, which will provide an improved basis for seismic (micro) hazard zonation.

The objective of this study is to assess the seismic hazard and demarcate the damage potential zones by incorporating the updated seismic events on geospatial mode for the Koyna region.

Methods

The steps that are followed in this study are:

1. Collection of earthquake, active tectonic, geological, geophysical and topographic data from different sources;
2. Creation of geospatial information database, from available thematic maps, by digitizing and geo-referencing the theme polygons, point information, and extrapolate on space using the ArcGIS®;
3. Analyze the spatial distribution of seismicity and buffer the lineaments/faults indicating potential spatial extension for defining the source zones;
4. Determining the return periods for potentially damaging earthquakes based on the complied earthquake catalogue;

5. By assuming many scenarios and identifiable seismic source zones calculation of probabilities of event parameters;
6. Computing the mean annual probability for expected return periods using hazard integral equation for 10Km X 10Km grid points covering the entire study area and its surroundings;
7. Zoning of probabilistically estimated seismic intensity using ArcGIS® for seismic risk analysis and mitigation strategy planning.

Data used in this study are — earthquake catalog information of ~400 years period to determine earthquake rates, high resolution geology maps, local soil maps supported by field-based data in establishing subsurface information of the site conditions, Landsat-7 ETM$^+$ satellite images (NASA Landsat Program, 2003) for maintaining the uniform spatial continuity and demarcation of lineaments/faults and SRTM data for deciphering landforms, elevation, natural slope classes.

Peninsular India

Peninsular India is considered as one of the largest Precambrian Shield areas of the world. This Shield area was described as the stable land mass associated with low or no seismicity. However, earthquakes events such as 2001 M7.7 (Bhuj), 1993 M6.3 (Killari), 1997 M5.7 (Jabalpur), and 1967 M6.5 (Koyna), stressed the need for the revisiting of the stable continent belief as manifested by intra-plate earthquakes. It is believed that, the bending of the Indian plate is due to the collision of the Indian plate with Tibet plate that generated the elastic stress build-up within the tectonic pockets. This results in consequent slip along the faults and cause seismic activity in the Peninsular India. Northwest striking faults under the Deccan Traps are believed to exist in this region (Chandra, 1977). Thermal springs are found to occur either near the contact of two geological units or along prominent tectonic units in the Peninsular Shield. The stored stresses are released by frequent micro to moderate earthquakes through the thermal spring areas located in the West Coast of India, whereas in the rest of the Peninsula the stress release is through less frequently occurring moderate earthquakes (Chadha, 1992).

Koyna-Warna region

Koyna-Warna region (Fig. 1) is part of Deccan Volcanic Province covered by basaltic lava flows of Cretaceous-Tertiary age (~65 Ma).The basement is occupied by migmatitic-gneiss that is normally found at mid crustal

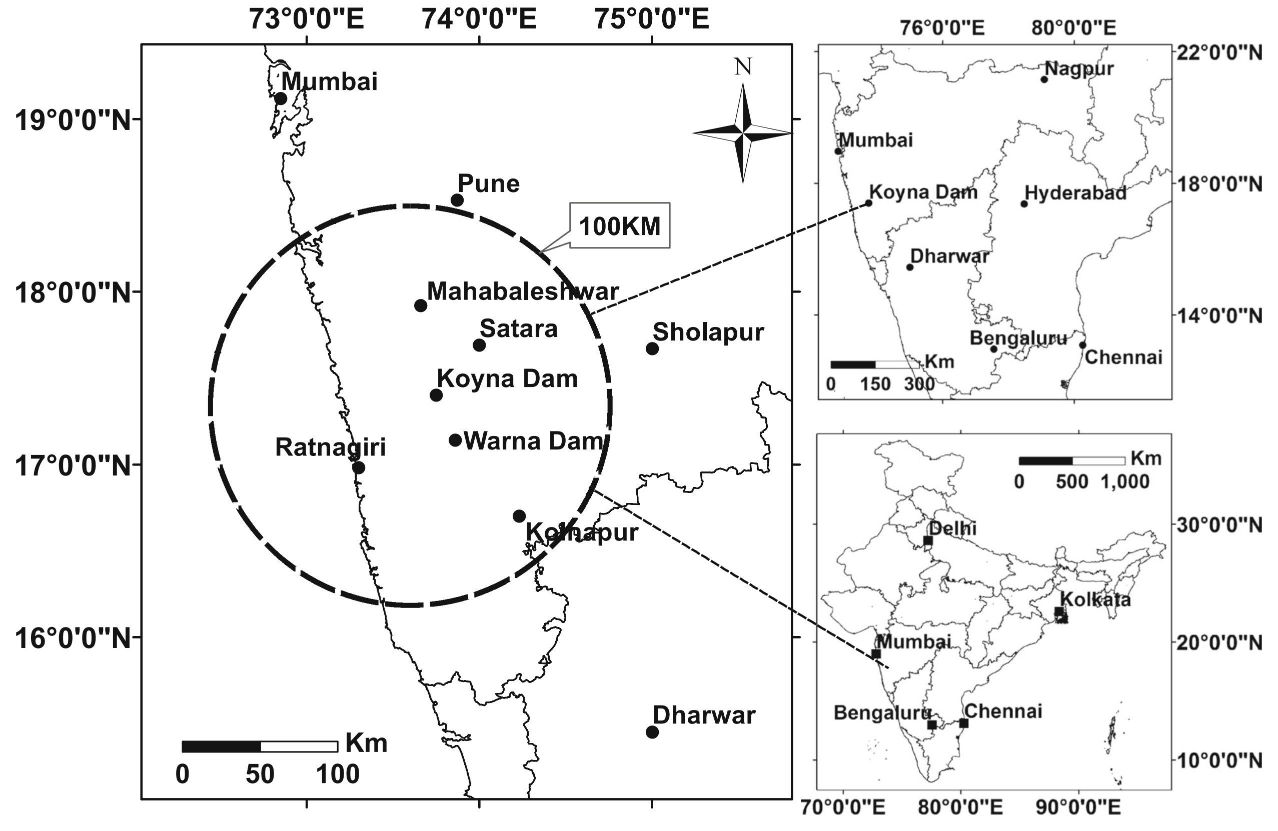

Fig. 1 Location of Koyna region and the Peninsular India

levels. The focal depth of the events occurs at depths of around 6–9 Km below the surface. The maximum thickness of the Deccan Traps is around 1500–1700 m and source of the any seismic events need to be within the Deccan Traps basaltic pile. Fault-plane solutions and allied geophysical modelling have yielded results that are not consistent with each other. Earthquakes do not elucidate an entire fault-zone structure in the near surface; it is difficult to assess the overall tectonic structure from seismicity alone (Catchings et al., 2015). The ductile basaltic layer conceals the surface expression of the underlain seismogenic faults if any. Fractures and cooling joints are seen on the surface. The reported seismicity near Koyna and Warna reservoirs is on the eastern side of the escarpment from the focal depth of 7–9 Km below the surface (Figs. 3 and 6). Moho geometry in the Koyna-Warna region varies from 37 Km to 42 Km, with a slight dip towards SE. The average velocities in Koyna are higher than in Warna indicating a fractured setting in the latter. The seismicity event distribution in Koyna region is along the NNE-SSW trending fault zone coincides with a low velocity zone between two competent zones with a very high velocity > 4.0 Km/s. It is believed that the diffusion process and not the reservoir load effect, is the dominating mechanism in triggering earthquakes in Koyna.

Earthquakes are occurring in a 20 × 30 Km area around Koyna since the impoundment of Shivajisagar Reservoir (Koyna Dam) in 1962, including the largest triggered earthquake of M6.5 on December 10, 1967, and 21 earthquakes of > M5.0 occurred since 1962 (Figs. 7 and 1). These events were further enhanced by the impoundment of the nearby Warna Reservoir in 1993 (Gupta, 2011). The earthquake of April 25, 1997, was located close to Koyna and February 11, 1998 earthquake was close to the Warna Reservoir. The microearthquake activity close to the source region was found to increase before the occurrence of the main shocks and continue up to a month before reaching a background level (Ramana et al., 2007).

The western margin of India has a nearly straight NNW-SSE trending coastline that gradually rises in a step-like pattern and all of a sudden a drastic change in elevation could be observed. It is an elevated rift-flank generated by the lithospheric mechanics of continental rifting phenomenon. There is a lack of evidence of block-faulting as the Western Ghats escarpment is well--adjusted to rock type and crustal structure (Fig. 3).

Geomorphic information

Geomorphologic features are grouped into hilly uplands and Western Ghats Escarpment (WGE) that rise to an elevation greater than 1390 m a.s.l. The WGE divides the eastern Deccan Plateau; where the lowest elevation (around Karad and Kolhapur) is about 550 m a.s.l. The Deccan Plateau has the step-like topographic of alternating steep and flat slopes (Fig. 2). Their elevation range groups are: <300 m, 550–600 m; 800–900 m; 950–1000 m a.s.l. The elevation of Konkan Coastal Belt (KCB) is less than 250 m a.s.l.; extends about 30–40 km further westwards till the shoreline of the Arabian Sea. It has steep-sided, flat-topped hill ranges, interspersed with flat-bottomed valleys (Fig. 3).

SRTM data having three arc-second (~90 m) ground resolutions is used to produce the spatial distribution of elevation and slope. They are grouped into <40 m, 40 to 360 m, 360 to 660 m, 660 to 960 m and >960 m a.m.s.l. classes (Fig. 3). These class intervals roughly indicate laterite, colluvium and black soil deposits, and deeply weathered basalts/highland laterite.

Regional geomorphic features such as valleys and steep slope hilly landforms — forming high relief terrain can alter the direction of propagating seismic waves. Amount of natural slope contributes to the angle of reflection and diffraction of seismic waves and can also influence the site response parameters. Steep terrain

Fig. 2 Field photo showing basalt flow layers

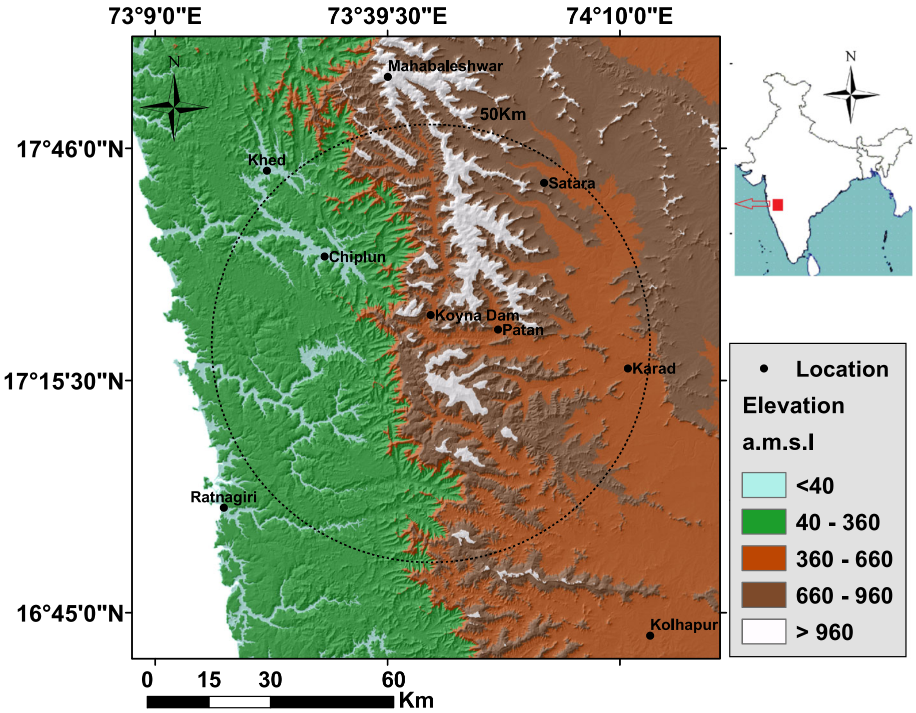

Fig. 3 Spatial distribution of elevation in and around Koyna region (100 Km radius)

slope tends to focus the reflected seismic waves at the slope crest, whereas gentle slopes scatter the diffracted seismic wave (Ashford et al., 1997). The spatial distributions of natural slopes (Fig. 4) are grouped into <3°, 3°-10°, 10°-20°, 20°-30° and >30°. It approximately designates the domination of soil, soil and weathered rock/laterite, laterite and fresh/hard rock and hard rock in the sub-surface (~30 m down to the engineering bedrock) that affects the shear wave velocity.

Rock and soil types

There are more than 11 volcanic flow basalt layers and they consist of massive and vesicular basalt, amygdaloidal basalt, agglomerate, tuff breccia and red bole. The individual flow varies between 45 m to 61 m thickness. Red bole layer up to a thickness of 2 m is found persistently along the contact between the individual flows. Lateritization is a process of low-temperature weathering associated with mineralogical breakdown and the degree of weathering diminishes with depth. Laterites that are found capping the elevated basalt mesas of Western Ghats is termed as high-level laterite (900–1500 m a.s.l.) and semi-continuous belt lying west of Western Ghats Escarpment as low-level laterite (30 to 100 m a.s.l.).

Coarse-textured shallow reddish soils occur on the foothill slopes, deep soils are found along river banks/valleys. Besides, low-level laterite deposits, coastal alluvial soils are found along the Konkan Coast it consists of deep sandy loam soil deposits.

Surface cover features

False colour composites (bands 5, 3, 1) of Landsat-7 ETM+ of November 14, 1999 and November 25, 2000, having 30 m spatial resolution are used for extracting the lineaments and land cover features — water bodies (WB), natural vegetation (F), floodplain (FP), settlement (R) etc. (Fig. 5).

Structural information

Cooling of lava flow causes shrinkage and results in formation of cooling joints. Long, linear/gently curvilinear joints that extending continuously across several metres and occur parallel to each other with a uniform spacing are found in the Deccan Traps of the Koyna area. Fracture planes are occurring sub-parallel to each other. Fracture zone is a narrow linear zone along which several close-spaced. Shear zone is a linear zone along which the fracturing of the basalt is very close-spaced (Kale et al., 2016). Due to deeply weathered bedrock, soil cover, thick shrub vegetation, the areal extension and intensity of fracturing cannot be determined (Kale et al., 2014). Considerable regional fracture lineaments in the study area are N-S (strong geomorphic and geophysical expression), NW-SE (strong geomorphic and geophysical expression), NE-SW (moderate Geomorphic and geophysical expression) and E-W (not clear). Majority of reported events are associated with NW-SE and NE-SW trending lineaments/faults. Figure 6 shows the linear features that represent fractures/faults demarcated and

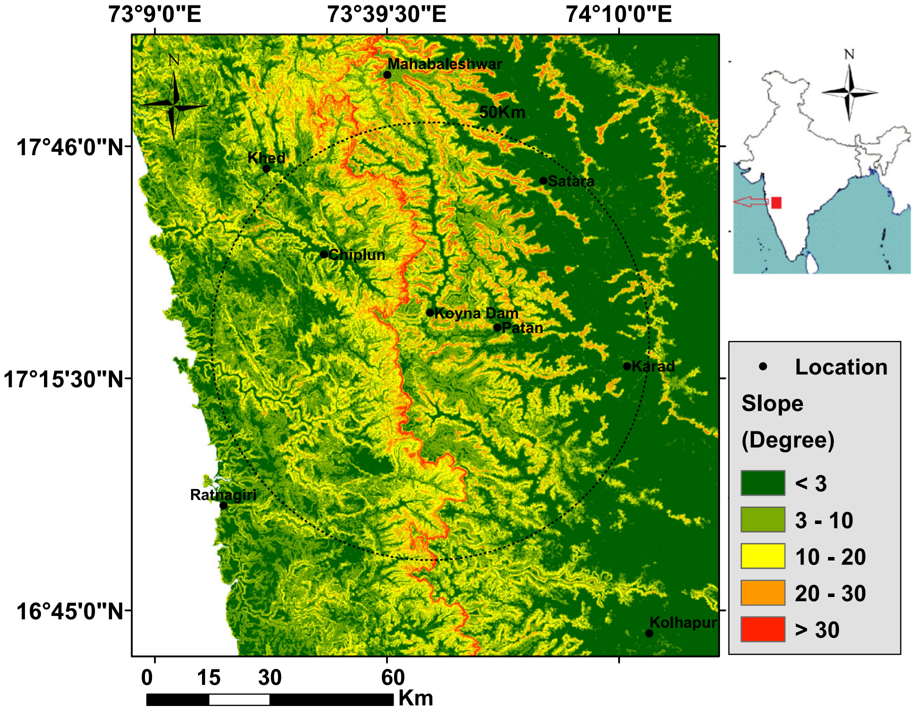

Fig. 4 Spatial distribution of natural slope derived from the SRTM data

the reported seismic events and lineaments and concealed faults. In addition to NNW-SSE, N10^0E to N30^0E lineaments are also present.

The potential activity of faults are grouped as — active faults — characterized by current activity (movement or event) /associated with surface-rupturing earthquakes in the past 11,000 years; capable faults having ability for movement; and potential capable of being or becoming active. It is associated with surface-rupturing earthquakes occurred in the Quaternary age (~1.6 m years).

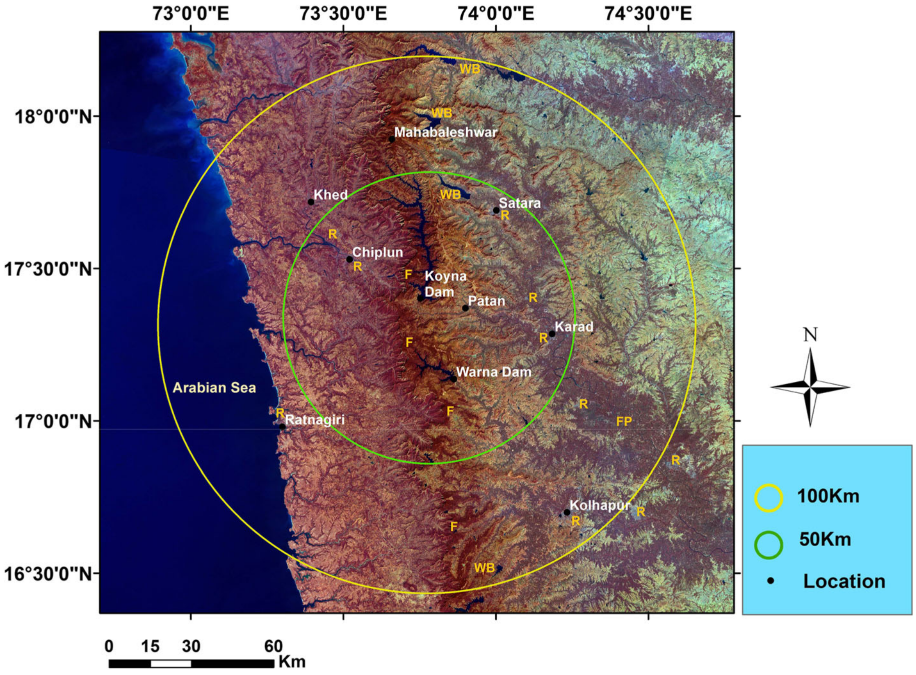

Fig. 5 False colour composite of the Landsat-7 ETM+ image 20th October 1999 showing the land cover features

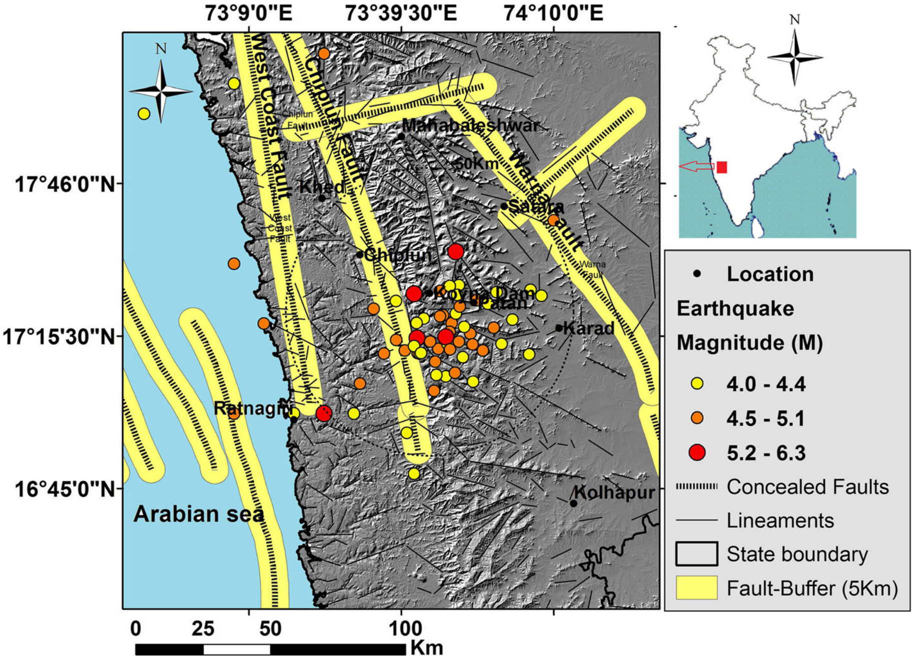

Fig. 6 Seismic events, concealed faults and lineaments

The said classification is used for identifying the seismic source zones and to define the potential faults, for estimating fault-to-site-distance probabilities, based on the published literature. Talwani (1997) inferred the Koyna-Warna fault system as Patan Fault — trending NE-SW by a dip of about 45° and NW-SE trending fractures extending from near-surface to hypocentral depths. Apparent, NNE-SSW and NNW-SSE striking seismicity patterns attributed to normal faults have been reported from the Koyna region and Warna region, respectively (Talwani, 1997; Srinagesh and Sharma, 2005).

Five linear seismic sources zones (NEZ, SEZ, WSZ, WCF, and WF), defined based on the focal mechanism parameters and fault slip rates (Dixit, 2014; Catchings, 2015) are employed in hazard assessments (Fig. 7).

Results and discussion

Hazard estimation

Estimation of the tendency of seismicity is derived from the time series analysis of historical and instrumental earthquake catalogue and other local sources. Source characterization is derived from (i) five linear source model — epicentre, fault orientation (or bearing), and type of fault, and (ii) an area source model — epicentre locations and hypocentral depths, for considering the background seismicity. Assessment of the probability of occurrence of various hazard levels, within the next 50 years, from the potential sources is computed from the probabilistic seismic hazard assessment (PSHA) hazard-integral Eq. (2) by assuming that the rate of earthquake occurrence in time is governed by the Poisson law.

PSHA integrates the probabilities of all possible magnitudes (m), all fault-to-site distances (r), rate of seismicity (α) of all the seismic sources, and the ground motion attenuation to produce hazard curves in terms of different level of ground motion and an associated annual frequency of being exceeded for 500 years (10% exceedance in 50 years), 2500 years (2% exceedance in 50 years) of return periods respectively. The attenuation relationship for the stable continental region (Toro et al., 2002) is employed for predicting PGA in terms of acceleration due to gravity is

$$\ln Y = C_1 + C_2(M-6) + (1) C_3 \; (M-6)^2 - C_4$$
$$\ln R_M - (C_5 - C_4) \; \max[\ln(\frac{R_M}{100}), 0] - C_4$$
$$R_M + \varepsilon_e + \varepsilon_a$$

(where) RM $= \sqrt{R^2 - {C^2}_7}$

In the above Eq. (1), lnY = PGA, M = magnitude, R = hypocentral distance, ε_e = epistemic uncertainty, and ε_a = aleatory uncertainty, C_1 to C_5 are regression coefficients.

The mean annual rate of PGA level for 10% probability being exceeded in 50 years is calculated by means of the hazard integral Eq. (2) (McGuire, 2004).

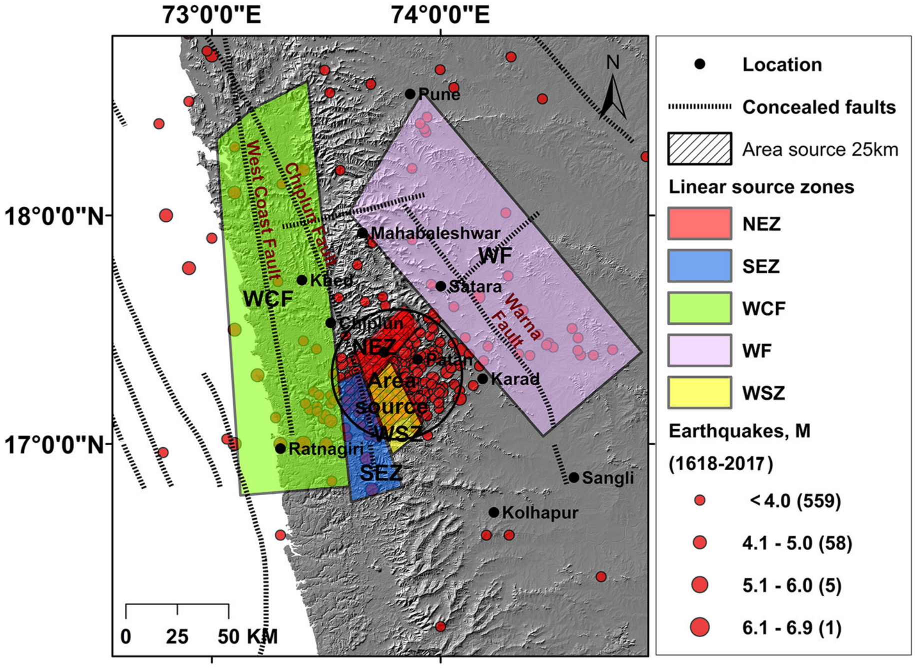

Fig. 7 Seismic source zones of Koyna region (compiled after: Dixit, 2014; Catchings, 2015). NEZ – North escarpment zone, SEZ – South escarpment zone, WCF – West coast fault, WF – Warna fault, WSZ – Warna seismic zone (Fig. 7)

$$E_i(Y \geq y_0) = \alpha_i \int_R \int_M f_R(r) f_M(m) P \left[Y(m,r) \geq y_0 | m, r\right] dm dr \tag{2}$$

where Y = PGA, y_0 = target PGA, m = magnitude, r = fault-to-site distance (~200 km radius), α = seismicity rate (0.01 for >M5.5 and 0.0025 for > M6.5), Ei ($Y > y_0$) = annual probability of being exceeded for target PGA levels.

The annual rates of PGA-values (10% exceedance probability) are calculated for around 300 point locations which make up the grid of 10 Km X 10 Km covering entire study area and its surroundings. Extractions of characterized parameters are on grid cell basis. Characterized parameters are used to describe the grids such as number of faults, their intersection and maximum and minimum events and their numbers. These grids characterized parameters can be extracted automatically through spatial interpolation. Using ArcGIS® estimated PGA-values gridded data are interpolated by means of geostatistical Kriging method to obtain the spatial distribution of hazard levels.

Results

Figure 8 shows the distribution of hazard levels expressed as peak ground acceleration (PGA) for 10% probability of exceedance in 50 years, contoured from high (>21% g) to low (<16% g) for rock site conditions. Earthquake ground shaking varies from place to place and it depends on the properties of the rocks and weathered or soil column that earthquake waves travel through.

In order to map the severity of ground shaking, Modified Mercalli Intensity (MMI) is estimated from the mean annual rate of PGA using the PGA – MMI relationship (equation-3) given by Shebastari and Yamazaki (2001):

$$\ln\,(\mathrm{PGA}) = 0.2545\ \mathrm{MMI} + 0.2977 \tag{3}$$

For damage potential estimates, MMI levels are obtained for various return periods (Fig. 8).

In 50 years, the estimate of 10% probability of exceedance reveal that the mean ground acceleration is greater than 0.21 g in the Koyna-Warna region and it is shown as the red zone, whereas PGA ranging from 0.18 g to 0.19 g is expected to experience by the towns located within 50Km radius are: Patan, Satara, Karad, and Chiplun shown in orange to yellow shades. The low accelerations (<0.16 g to 0.17 g) are found to be expected in Kolhapur, Mahabaleshwar, Rantagiri, Khed and their proximities (Fig. 8).

Slightly damageable ground motions are expected from the 100 ± 10 years return period earthquakes (~M5.5). For rock sites conditions, estimated total hazard attributable to ~500 years return period earthquakes is greater than 0.21 g, however at surface level

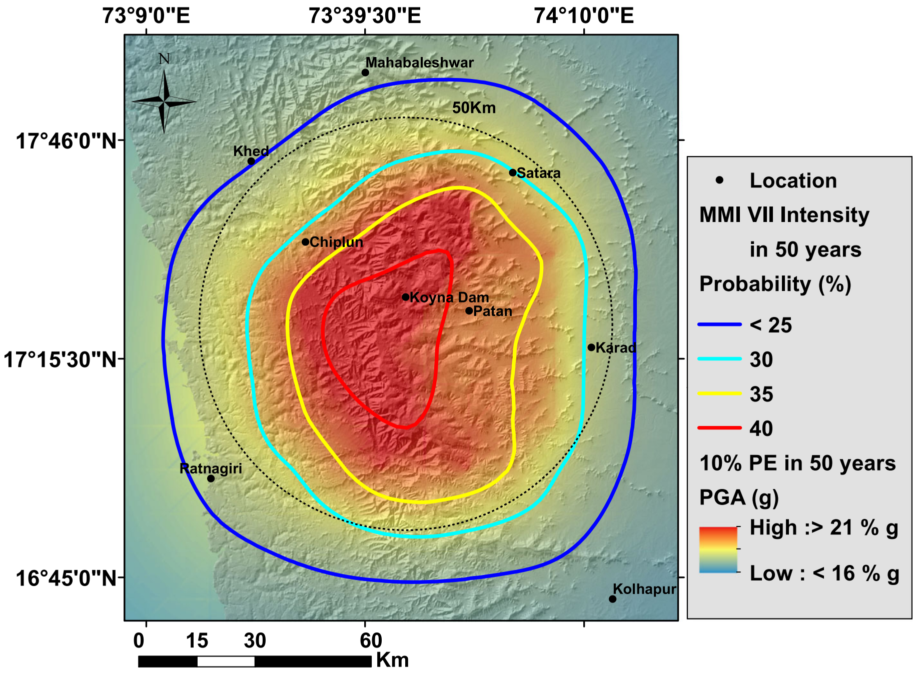

Fig. 8 Spatial distribution of estimated PGA (% g) as hazard levels and MMI –VII as damage potentials in 50 years

PGA is expected to amplify due to the unconsolidated material which make up soil-regolith formation in the Koyna-Warna region. Figure 8 shows that the expected intensity levels (MMI-VII or lesser) in 50 years expressed as probability (%) for the earthquake scenarios. Damaging intensity (MMI-VII level) expected in 50 years has ~ 40% probability for the area is located between Koyna and Warna Reservoirs.

Conclusions

Seismic risk and damage potential can modify with the occurrence of fresh events. These events throw a new light on the dynamics of seismic sources in the stable continental regions, therefore the necessity of installing earthquake monitoring networks is warranted, which is neglected previously due to its aseismic label, particularly in the other parts of Peninsular India in addition to Koyna.

In this paper, probabilistic seismic hazard is estimated for the 500 years return period earthquake scenarios (M4.0 to M6.9) for bedrock level conditions in the Koyna seismic zone. For hazard estimation, seismic events are collated till early 2017 and total hazard from the five linear sources are presented as spatial distribution of PGA and hazard potentials. The following derived conclusions would give an opportunity for reinforcement options if needed.

- The estimated PGA for 10% probability being exceeded in 50 years (i.e. for 500 years return period) ranging from less than 0.16 g to greater than 0.21 g for Koyna-Warna area (radius of 50Km area).
- The hazard estimates can the grouped into three relative categories for bedrock level accelerations greater than 0.21 g, 0.19 g, less than 0.16 g defining high, moderate, and low hazard levels, respectively.

Slightly damaging intensity (MMI-VII level) expected in 50 years has ~ 40% probability for the area which has PGA >21% g that is located between Koyna and Warna Reservoirs. There are surface transport alignment with more than 3 m to 5 m of cutting, tunnels and high bridges located in the study area; therefore seismic site response based microzonation is indispensible.

Abbreviations

GIS: Geographical Information System; MMI: Modified Mercalli Intensity; PGA: Peak Ground Acceleration; PSHA: Probabilistic Seismic Hazard Analysis; RIS: Reservoir Induced Seismicity; SCR: Stable Continental Region; SRTM: Shuttle Radar Topography Mission; WGE: Western Ghats Escarpment

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Authors' contributions

Both the authors have equal contributions in preparing the manuscript. Both authors read and approved the final version of the manuscript.

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