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1-D velocity model delineated using dense seismic network in the Koyna-Warna region, Maharashtra, India

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ABSTRACT

For the first time in the Koyna-Warna region of Maharashtra state, India the CSIR-National Geophysical Research Institute, Hyderabad deployed a dense seismic network of 97 stations. They were operated for five months. A total of 499 earthquakes were located using SEISAN software. The Lithology indicator viz., the Vp/Vs ratio (Pickett 1963) was determined using the Wadati diagram and VELEST (Kissling et al. 1994). The results of the relationship established between Vp and Vs are then applied to delineate a 1-D P-wave velocity model using VELEST (Kissling et al. 1994) approach to solve hypocentral parameters. Analysis of data helped in delineating 1-D velocity structure, viz., 1) Exposed Deccan trap basalt of 1.2 km thickness with P-wave velocity (Vp) of 4.81 km/sec, 2) gneiss granitic basement layer with a thickness of 8.8 km and velocity (Vp) of 5.935 km/sec and 3) middle crust with velocity (Vp) of 6.355 km/sec. Middle crust is found to be extending to a depth of 25 km (thickness 15 km). Middle crust details have been taken from D.S.S derived velocity-depth model of Kaila et al (1979). Until , authentic teleseismic data from distances beyond ~50 km and extending to at least 100 km are utilized in building the velocity-depth model, we reiterate that it is not desirable to specifically use velocity- depth information (in the depth range10-25 km), from other studies for precise relocation of region`s earthquakes. The 1-D velocity (Vp) model, extending to 10 km, presently obtained significantly reduced RMS error and improved earthquake locations. We are confident about accuracy of improved earthquake locations, especially of the earthquakes having focal depths extending to not more than 10 km (The focii of Koyna- Warna earthquakes are generally found to lie between 3 to 7 km).

INTRODUCTION

The Koyna-Warna region of Maharashtra, India is the best example for reservoir triggered seismicity in the world. The largest earthquake occurred on December 10, 1967 of M 6.3 (Gupta et al. 1969; Langston 1976; Gupta & Rastogi 1976; Chander & Kalpna 1997; Mandal et al. 1998).Since then many earthquakes of low magnitude (< 4.5 M) occurred in this region. About 30 km south of the Koyna Reservoir, impoundment of a second reservoir (Warna Reservoir) started in 1985, and the reservoir was filled to a depth of 60 m by 1993.

The Geological and tectonic map (Figure 1) shows that the entire study region is covered by Deccan trap volcanic formations. Deccan traps thickness is about 2 km in the western part of the study area and reduced thickness of about 200 m is noticed near the eastern, southern, and northern fringes of the Koyna-Warna region (Lightfoot 1985; Kaila et al. 1981; Sarma et al. 2004). Both Koyna and Warna reservoirs lie on the elevated North-South trending Western Ghat Escarpment, parallel to the west coast of India. The escarpment is believed to be fault-derived (Pascoe 1964; Valdiya 1984). Several lineaments viz. L1 to L7 have been identified between Koyna and Warna Reservoir based on aeromagnetic data analysis. These lineaments are oriented along NW-SE direction (Dura-Gomez & Talwani 2010). A NW- SE trending lineament follows the course of the Warna River. It may correlate with a fault in the basement rocks below the Deccan Traps (Talwani 1997). Similarly, a NNE-SSW oriented lineament trends through the Koyna region and is referred to as the Koyna River Fault Zone (KRFZ) along which ground cracking was observed following the 10 December 1967 earthquake.

Previously in the study area, several crustal velocity models were derived using seismological data (Dube et al. 1973; Gupta et al. 1980; Rastogi & Talwani 1980; Bhattacharya 1981; Srivastava et al. 1984; Rai et al. 1999; Krishna 2006; Shashidhar et al. 2011). Dube et al. (1973) obtained a four layered crustal model from forty aftershocks of the main earthquake. Gupta et al. (1980) proposed a two layer model up to 40 km depth using twelve earthquakes of M ≥ 4.0 with foreshocks and aftershocks during the period 1973-76. For the first time Kaila et al. (1979) proposed a crustal model based on a deep seismic sounding survey along two profiles in the east-west direction in the Koyna region, one passing through the Koyna Dam and another to the north of the dam. Rastogi & Talwani (1980) adopted a three layer model from Kaila et al. (1979). Bhattacharya (1981) derived a three layer model based on surface wave dispersion studies, which is similar to Dube et al. (1973).

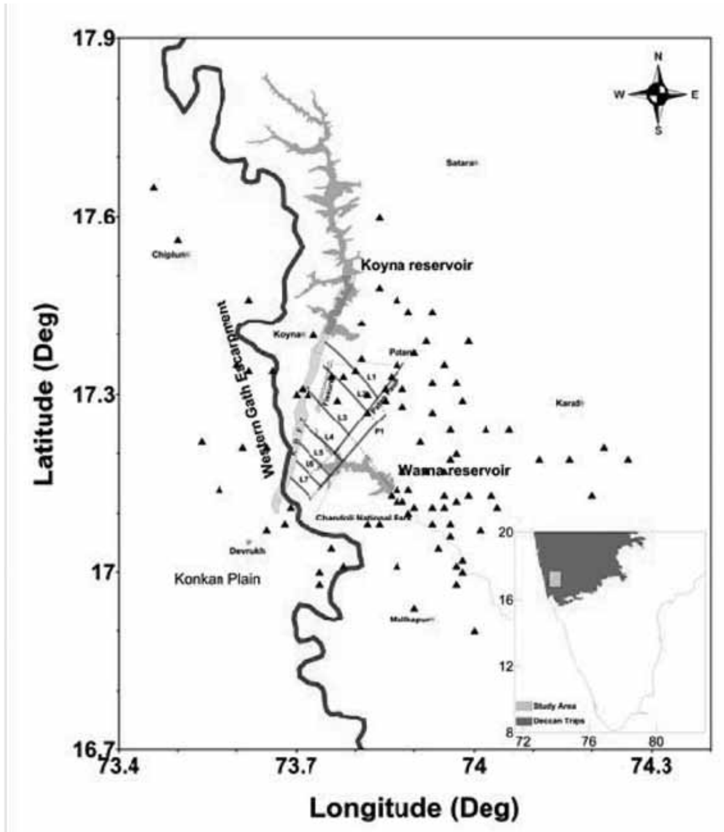

Figure 1. The Koyna-Warna region and lineaments L1 to L7, Patan fault (P1 fault and Koyna River Fault Zone (KRFZ). Blue line is Western Ghat Escarpment and Triangles are stations.

Srivastava et al. (1984) derived a velocity model utilising the data recorded by temporary IMD stations installed to record DSS active seismic detonations. These stations made use of shots detonated along the two DSS profiles. Krishna (2006), inferred a six-layered model including low velocity layers. Shashidhar et al. (2011) modified Kaila et al. (1979) model using data from11 digital seismograph stations. In this study, local earthquake data of 97 seismic stations was used to estimate a 1-D velocity model. As a part of this study, to start with, a reliable estimate of Vp/Vs ratio was determined using Wadati method (Wadati 1933) and VELEST program (Kissling et al. 1994). By incorporating this Vp/Vs ratio in Joint hypocenter determination (JHD), a 1-D P-velocity model has been obtained. The present study is useful not only for routine event location but also for studying the nature and pattern of region`s seismic activity. The information thus elicited has been used to better understand regional tectonics around the Koyna-Warna reservoirs.

DATA

The data used for the present study was recorded by 97 temporary seismic stations in Koyna- Warna region (Figure 1) ,operated by CSIR-National Geophysical Research Institute, Hyderabad, from January, 2010 to May 2010. Each station is equipped with three component 4.5 Hz geophone (Geospace Y-28 GS11-3D), a 12 volt 65 Ah battery, and a solar panel. The time base is provided by the Global positioning system (GPS) with a horizontal accuracy of about 5 to 10 meters. Both the solar panels and GPS units were placed on the roof tops. During data acquisition all the stations were installed inside the houses of local citizens, for security. Geophones were coupled to the ground within 0.3-m-deep holes. Geophones critically damped at 0.707, have a sensitivity of 32 V/m/s. To ensure data quality, only those events that were recorded at epicentral distances of about 50 km from the Warna seismicity zone, were used. During the preliminary data analysis, problems have been encountered in identifying reliable S-wave arrival information, as the onset of the S-wave arrival was either buried inside the coda of P waves or hidden by near-surface converted waves. As a result, identification of S-wave phases required special care. Figure (2) shows examples of events that were recorded on vertical- (BHZ) and horizontal-component (BHN) sensors from local earthquakes occurred on 12 January 2010.

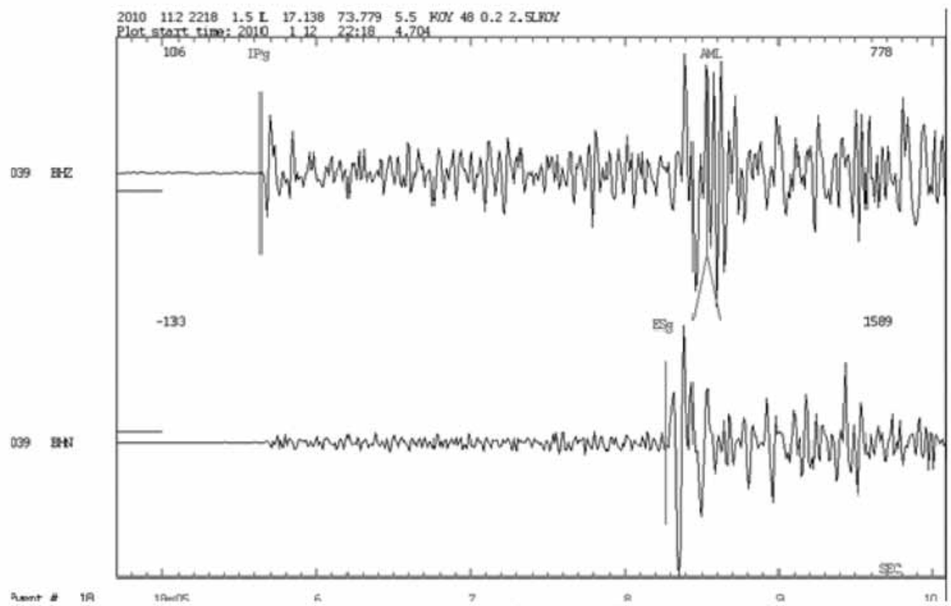

Figure 2. The seismic event recorded on vertical- (BHZ) and horizontal-component (BHN) sensors. Local earthquake occurred on 12 January 2010.

DATA ANALYSIS:

To start with the Wadati method (Wadati 1933) was used for getting model-independent estimates of travel times of P and S waves to various stations. The method was originally suggested to estimate the origin time of an earthquake and later used by many investigators for velocity-ratio estimates (e.g. Semenov 1969; Nersesov et al. 1971; Key et al. 2011; Oldrich Novotny et al. 2012). For this purpose, differences in arrival times of S and P phases were plotted against the P arrival time for each earthquake. This has yielded a linear relation between the time difference $t_s - t_p$ and the arrival time t_p (Figure 3a). We tried various V_p / V_s ratios in the range from 1.69 to 1.74 in the VELEST program for about 25 iterations, which gave us the average RMS error 0.12125 sec for the V_p / V_s ratio of 1.70 (Figure 3b).

In the second step, we used HYPO71 program (Lee & Lahr 1975) and a one-dimensional crustal model of Kaila et al. (1979) (Figure 4d). Figure (4a) shows majority of the recorded earthquakes are concentrated south of the Warna reservoir. Individual hypocentral depths (corresponding to each earthquake; with epicentral co-ordinates marked conventionally) could not be determined accurately, as majority of the recording stations were distributed along a specific direction, easterly, around the epicenters (Figure 1) .Such a distribution pattern led to generation of inadequate velocity model and less accurate hypocentral depth details.

In order to improve the earthquake location and 1-D velocity model we used Joint Hypocenter Determination (JHD) program (Kissling et al. 1994). This program iteratively determined the hypocenters as well as velocity model. The JHD equations used to determine the hypocenters, is written as:

$$r_{ij} = dT_j + \left(\frac{\delta t}{\delta x}\right)dx_j + \left(\frac{\delta t}{\delta x}\right)dy_j + \left(\frac{\delta t}{\delta x}\right)dz_j + ds_i$$

where,

$$r_{ij} = t^0_{ij} - t_{ij} = t^0_{ij} - \left(T_j + \tau_{ij} + s_i\right)$$

t^0_{ij} is the observed arrival time, t_{ij} is the computed arrival time based on 1-D velocity model. t_{ij} is written again as the sum of the initially estimated origin time of the j^{th} earthquake, T_j, the computed travel time from the j^{th} earthquake with estimated location (x_i , y_i ,z_i) for the i^{th} station, T_{ij}, and the station correction for i^{th} station, s_i. dT_j is the perturbation of the origin time for j^{th} earthquake.

RESULTS

We estimated the 1-D velocity model using 9,427clear P-arrivals and 8721 S-arrivals from 423 well identifiable earthquakes using JHD method (Kissling et al. 1994). We located earthquakes, which fulfil minimum requirement with respect to location quality, i.e events of at least six well recognisable P arrivals and three clear S-arrivals with a maximum azimuthal gap less than 180°. On an average 25 pickings were available for each event. In this process, we searched for the minimal RMS misfit at each and every station and rejected events with root mean square (rms) residual larger than .05 s. Finally a P-wave 1-D velocity model (Figure 5a; Table 1) was obtained on the basis of the minimum RMS misfit. However, the layer thickness

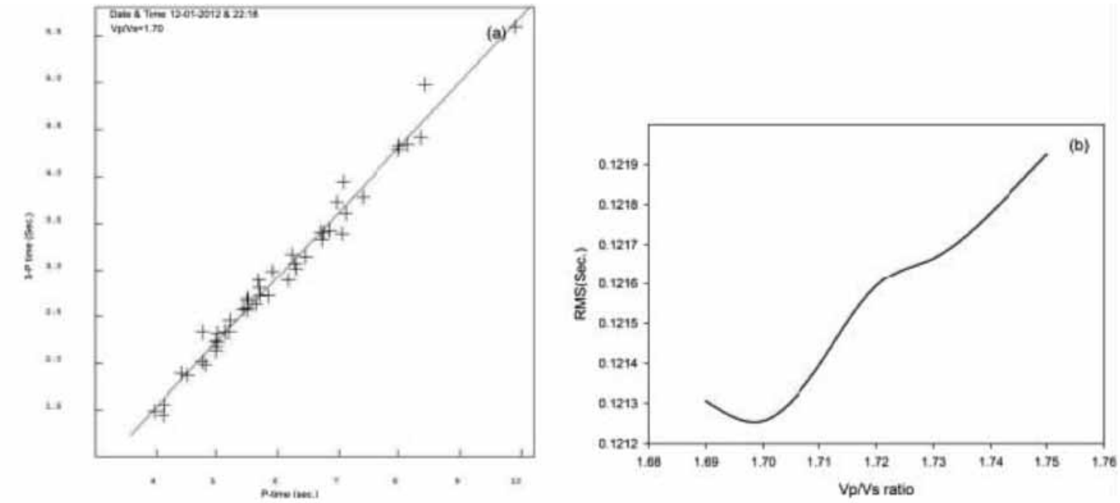

Figure 3. (a) Wadati plot showing P wave arrival times against difference in times of arrival of S and P waves , (b) Iterative process of different V_p / V_s ratio's using VELEST method.

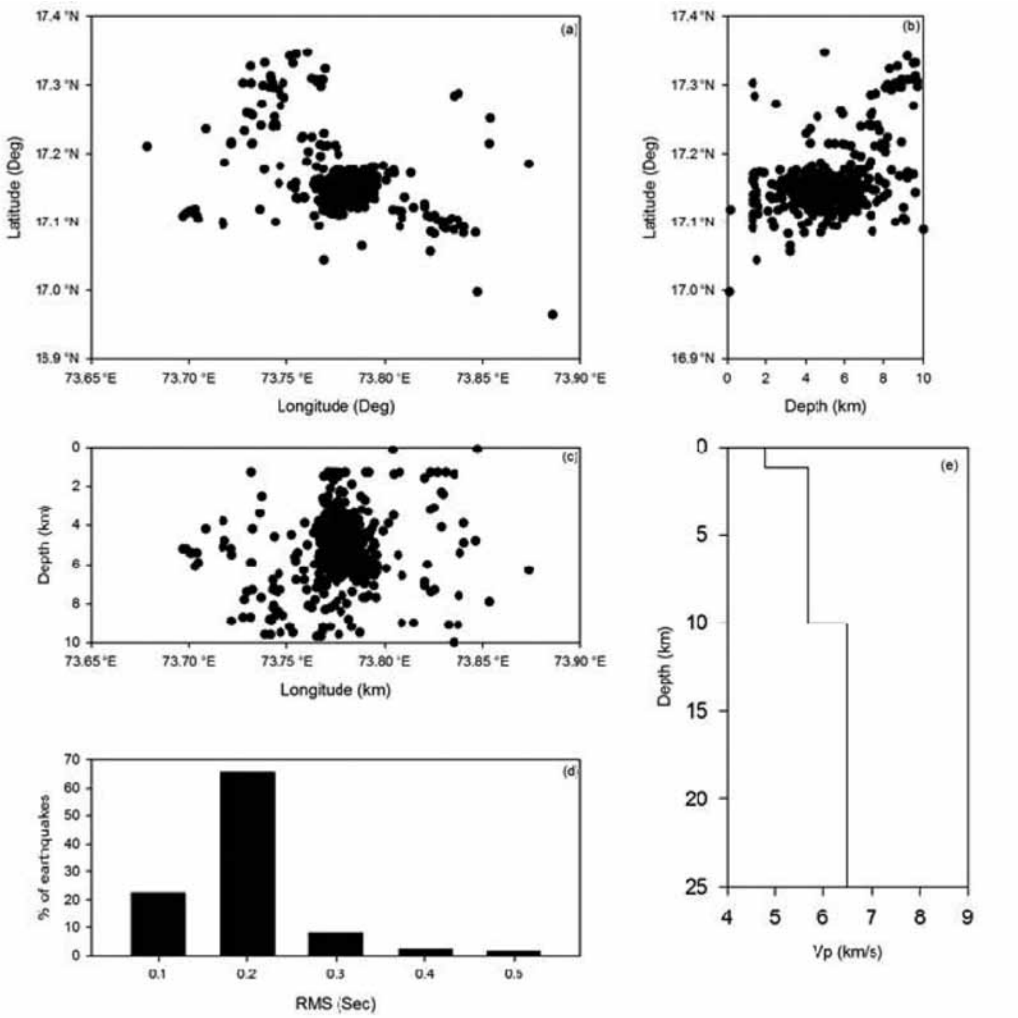

Figure 4. (a) Earthquake hypocenter location map of Koyna-Warna region, (b) Latitude Depth distribution of earthquake hypocenters, (c) Longitude depth distribution of earthquake hypocenters (d) RMS error Vs % of earthquakes, (e) velocity model of Kaila et al., (1979).

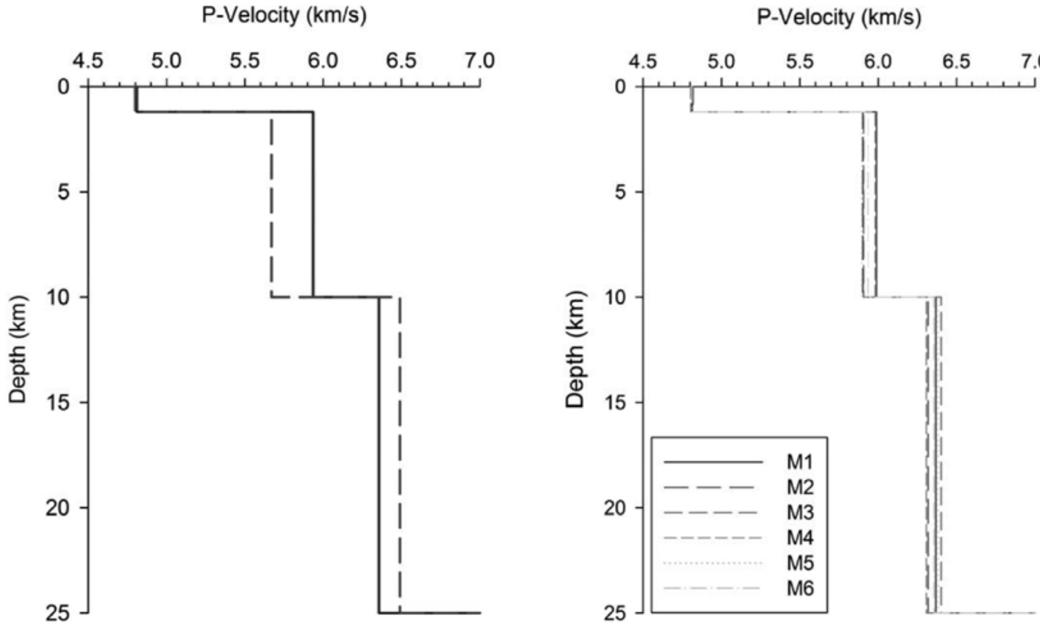

Figure 5. (a) Initial and final velocity models derived using VELEST. The dashed line indicates the initial velocity model of Kaila et al., (1979) and Solid line is the final velocity model, (b) Stability test. M1 -M5 line indicates the different initial models with higher and lower velocity. M6 line is the estimated model.

information below 10 km depth is not firmly resolved, as we have used basically data from earthquakes located up to ~50 km. Even though the middle crust is found to be extending to a depth of 25 km (15 km thickness), we are not advocating its use in precise analysis of earthquakes falling beyond 50 km distance.

It is suggested to make use of teleseismic data of distances beyond 50 km to conclusively fix thickness particulars of middle crust (a detailed study using both active and passive sources and recorded by broadband and presently used stand alone systems , with data extending to 100 km and beyond would yield crustal velocity structure extending to middle and lower crust).

Stability was tested after running five times the VELEST program for five different data sets (M1-M5) of about100 local earthquakes recorded south of the Warna Reservoir. The output velocity models are very close to average velocity model shown in Figure (5b).To avoid any ambiguity, we have decided to confine thickness particulars to top two layers, viz. Deccan Trap formation and Granitic basement. The middle crust thickness, as shown in the final model (15km) could be only used (as of now) for academic purpose, until reliable teleseismic information (extending to distances beyond 100 km) is taken in to consideration, in building the velocity-depth model. Since we have good confidence regarding data up to 50 km, it is decided to confine our model details to depths not beyond 10 km. The velocity information pertaining to middle crust is retained, due to confirmed accuracy from iterative procedure. So, in nutshell we reiterate that the velocity-depth model delineated up to 10 km depth could be used, without any ambiguity in dealing with near earthquakes (distance of ~50 km) of less than 10 km focal depth.

Table 1. Depth Vs Velocity

Depth (Km)	Velocity (km/s)
0	4.8108
1.2	5.9352
10	6.3558

The estimated 1-D velocity model reduced the RMS residual from 0.20 to 0.1 sec. As shown in the event distribution versus RMS residuals (Figure 6), the estimated velocity model is much better than the earlier model. The first layer of 1.2 km thickness, with P-wave velocity (Vp) of 4.81 km/sec is identified as the Deccan trap basaltic rock. Upper crustal layer of 8.8 km thickness (Vp 5.935km/sec) underlying Basaltic layer is the gneiss granitic basement. It is underlain by mid crustal layer of velocity of (Vp) 6.355 km/sec. This layer could be extending to a depth of about 25 km.

DISCUSSION AND CONCLUSIONS

Presently seismic activity in the Koyna-Warna region is concentrated south of the Warna Reservoir. Relocation of seismic events by using the estimated 1-D velocity model revealed the depth range of earthquakes between 3 and 7

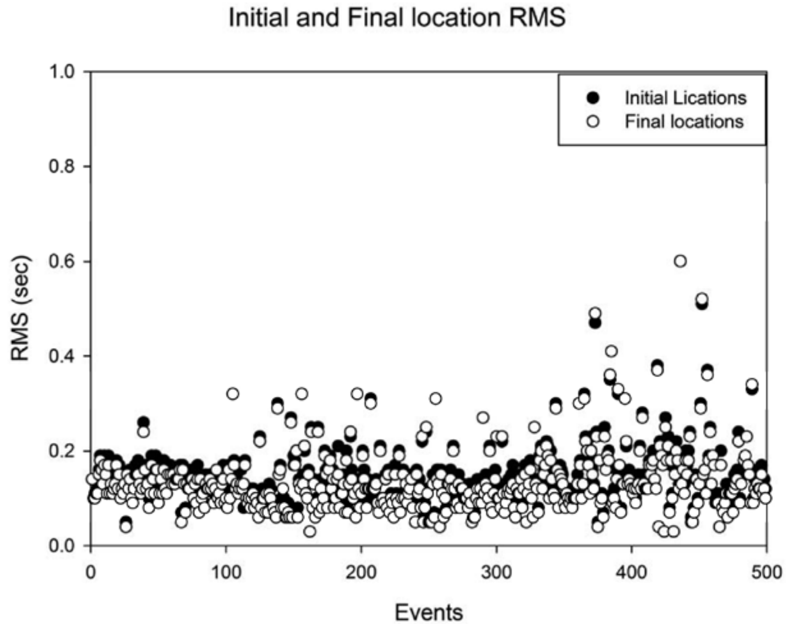

Figure 6. RMS residual errors in 499 earthquake locations during January 2010-May 2010 in the Koyna-Warna region using the VELEST approach. Improvement of the residual errors over the model of Kaila et al. (1979) (black circle) can be seen in the new model (White Circles)

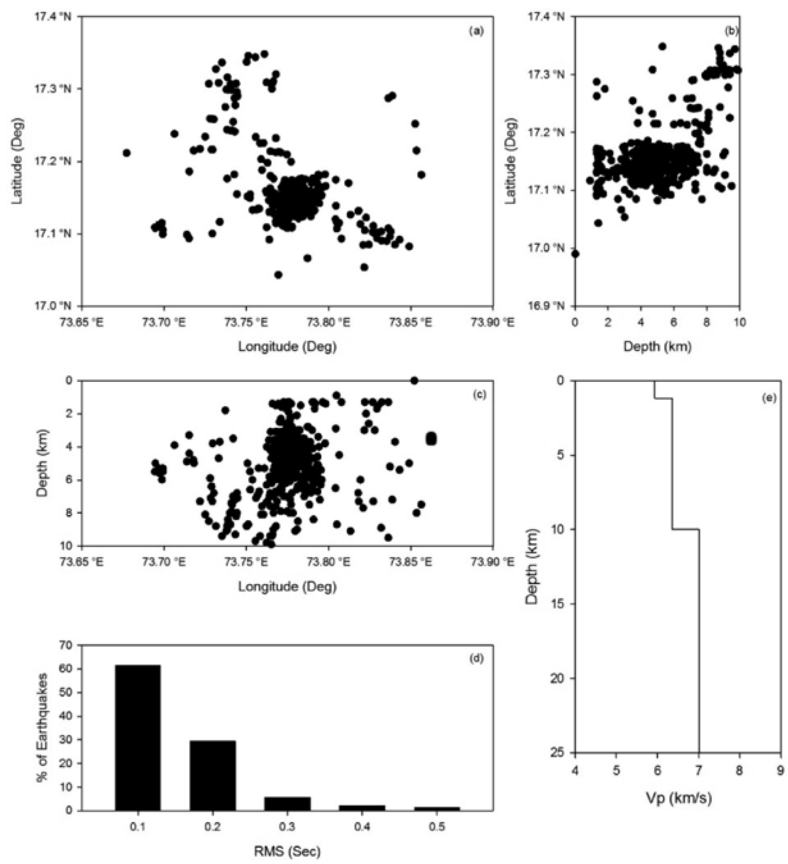

Figure 7. (a) Earthquake hypocenter location map of Koyna-Warna region, (b) Latitude Depth distribution of earthquake hypocenters, (c) Longitude depth distribution of earthquake hypocenters, (d) RMS error Vs % of earthquakes, (e) New Velocity model.

km (Figure 7). The P-wave velocity model, generated in the present study, improved the routine earthquake locations recorded by the dense seismic network of 97 stations, as shown by considerable reduction of RMS misfit from 0.20 to 0.10 sec. Earlier derived models come under the category regional (since they used travel time data from larger epicentral distances), while the present model is area specific, as it has been delineated by using data from shorter distances i.e. stations were installed nearer to source region. A new 1-D velocity model obtained using VELEST approach for the Koyna-Warna region has Deccan trap basalt of thickness 1.2 km with Vp-velocity 4.81km/sec, underlain by gneiss granitic basement of 8.8 km thickness with Vp-velocity 5.935 km/sec. The model also shows presence of Middle crust of velocity (Vp) 6.355 km/sec. The generated model can be successfully used in precise analysis of earthquakes of less than 10 km focal depth.

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