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Crustal velocity models for Koyna earthquakes based on DSS explosions (NGRI *vs* IMD)

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सार — हाइपो-71 कम्प्यूटर प्रोग्राम द्वारा परिमाण ≥ 4 के अच्छी तरह से अभिलेखित भूकंपों के अधिकेन्द्र प्राचलों की तुलना द्वारा भारत मौसम विज्ञान विभाग (श्रीवास्तव इत्यादि 1984) और एन.जी.आर.आई. (कैला इत्यादि 1981) द्वारा डी.एस.एस. विस्फोटों पर आधारित कोयना क्षेत्र के लिए भूपर्पटी वेग के मॉडलों का मूल्यांकन किया गया है। इन दो मॉडलों द्वारा 4 बड़े विस्फोटों की अवस्थिति का भी आकलन किया गया। दिसम्बर 1967 के मुख्य कोयना भूकम्प के अवकेन्द्रीय प्राचलों का भी विवेचन किया गया जिसकी उद्गमकेन्द्री गहराई केवल पी-तरंग आगमन समय पर आधारित लगभग 2 कि.मी. (श्रीवास्तव और दूबे 1982) बताई गई थी। यह परिणाम निकलता है कि कोयना जलाशय के आसपास सूक्ष्म भूकम्प गतिविधि और उनके स्रोत तंत्र का मॉनीटरन करने में पी और एस तरंग वेगों/संरचनाओं सहित भारत मौसम विज्ञान विभाग के मॉडल अच्छे परिणाम उपलब्ध करायेंगे।

ABSTRACT. Crustal velocity models have been evaluated for the Koyna region based on DSS explosions by IMD (Srivastava *et al.* 1984) and NGRI (Kaila *et al.* 1981) by comparing the epicentral parameters of well recorded earthquakes of magnitude ≥ 4 through HYPO-71 computer programme. The location of 4 large explosions has also been computed by these two models. The hypocentral parameters of the main Koyna earthquake of December 1967 have also been discussed whose focal depth was reported about 2 km (Srivastava and Dube 1982) based on P-wave arrival time only. It is inferred that IMD's model with P and S wave velocities/structures will provide better results in the monitoring of micro-earthquake activity and their source mechanism in the vicinity of Koyna reservoir.

1. Introduction

Seismic activity in the Koyna region after the damaging earthquake of 11 December 1967 ($M=6.5$) is still continuing, although the frequency and the intensity of tremors in the region have substantially decreased over the last two decades. Also, the occurrence of earthquakes of magnitude 4.5 or larger immediately attracts the attention of the geo-scientists throughout the world in view of their proximity to the Koyna dam. Thus, the seismic activity needs to be monitored continuously for which an appropriate crustal velocity model is needed.

Since 1972, National Geophysical Research Institute (NGRI) has been conducting 'Deep Seismic Sounding Surveys' independently in different parts of the country after initial collaboration of 3 years with the U.S.S.R. in the Kavali–Udipi profile in the Peninsular India. India Meteorological Department has also been participating in the programme by deploying high gain fast speed recording seismographs in the vicinity of the profiles for which special arrangements are made by NGRI to record the origin times of DSS explosions. Different techniques are made use of by NGRI and IMD to work out the crustal structures in the region. The results of NGRI show variations of the seismic wave velocities of P-waves and the layer thickness along the profiles; faults and discontinuities in underlying layers are interpreted in detail. But S-wave velocities and structure cannot be evaluated. The stations set up by IMD do not generally lie along the profile but enclose the area within a radius of 40 to 50 km which provide direct calibration of the region in terms of averaged seismic wave velocities and crustal structure over a larger area. Of late, NGRI is also providing an averaged crustal structure along the profiles. This velocity model, however, need not necessarily agree with the results of IMD.

The object of this paper is to compare the errors in the hypocentral parameters of earthquakes and explosions based upon the models by IMD and NGRI. Also, the results of the main earthquake and one of the large aftershocks have been briefly discussed by comparing with the better estimates of focal depths of these two shocks available from synthetic wave form modelling (Langston 1976, Langston and Franco Spera 1985).

2. Techniques for crustal structure

2.1. *DSS technique* (*NGRI*)

In this technique, shot points are located at 30 to 40 km intervals along the profile. Two Soviet seismic stations of type POESK 1-48 KMPV-OV are used in time, each with 30 out of a total of 48 seismic channels connected to seismic calls with an interval of 200 m. The 30th channel of the first seismic station is kept common on the ground with the 1st channel of the second seismic station for the purpose of correlation of waves on the adjacent records. Thus, the total length of a single seismic spread is 11.6 km. Refracted and reflected arrivals are picked up by following correlation from records to record, and are plotted in the form of travel time distance curves for each shot point. The average velocity depth function is determined by using refraction data for shallow depth ranges and reflection data from reciprocal shot points for intermediate depths. For larger depths, where reciprocal shot point data is not available, single sides reflection data is used.

Four geophones bunched in a group are used for a single seismic channel. The geophones are placed inside pits of about 1 to 2 ft depth in ground to decrease the wind generated noise. The DSS field recording is done during the night when the background noise level is lowest. The instant of explosion is radioed by a H.F. transmitter at the shot point, received at the seismic station and radioed on one of the auxiliary seismic channels.

The DSS field recording is done on the magnetic tape which is started just a few seconds before the expected time of first arrivals. A record is also taken on a photographic paper from the oscillograph on which the instant of explosion is recorded. The magnetic tapes are played back using appropriate filter and gain settings depending upon the distance from the shot point, progressively lowering the high cut filter as the recording is carried farther and farther from the shot points. The NGRI-DSS method, so far gives only P-wave velocities and crustal structure along the profile.

Sometimes attempts are made to record near vertical reflections through a special arrangement but, in general, near vertical reflections are very weakly recorded.

2.2. *IMD method*

The technique used by IMD makes use of deployment of 4 to 5 high gain fast speed (10 mm = 1 sec) seismographs of electromagnetic type on either side of the DSS profile. Timings are impinged on the records after clock corrections which is done by comparison of crystal clocks with BBC or ATA radio signals for which NGRI provides special arrangement. The coordinates of the shot points are also given by NGRI. The seismic phases, *i.e.*, P_g, P^*, P_n and corresponding S-phases are recorded by IMD stations depending upon the distance and gain of instruments.

The various seismic phases, P_g, S_g, P_n, S_n, P^*, S^* and the reflected phases are picked up from the records and plotted on a graph between time and distance for each phase. The least square technique is used to determine the velocity of these waves. By assuming a two layered crust, the thickness of granitic and basaltic layers are determined. The crustal structure is evaluated by known equations. The interesting results from IMD's data are as follows :

(*i*) From the Kavali-Udipi DSS profile, it is found that there is relatively greater attenuation in P-waves in Cuddapah basin as compared to Western Ghats (Chaudhury *et al.* 1984). Also, P_g wave velocity is largest in Cuddapah region which decreases towards Western Ghats.

TABLE 1

Comparison of IMD (Srivastava *et al.*) and NGRI (Kaila *et al.*) crustal velocity models from DSS blasts

Model (Srivastava *et al.* 1984)		Model (Kaila *et al.* personal communication 1983) I		II	
Depth (km)	Velocity (km/sec)	Depth (km)	Velocity (km/sec)	Depth (km)	Velocity (km/sec)
0.0	4.60	0.0	4.950	0.0	4.900
4.20	5.82	1.0	5.535	1.0	5.335
17.30	6.61	2.0	6.125	2.0	5.765
36.30	8.23	6.5	6.175	4.0	5.095
		11.0	6.220	6.0	6.025
		15.5	5.275	8.0	6.155
		20.5	6.530	10.0	6.380
		23.5	6.595	13.0	6.470
		26.5	6.670	16.0	6.560
		30.0	6.900	19.0	6.600
		37.0	8.263	25.0	6.805
		41.0	8.289	28.0	6.895
				31.0	6.985
				34.0	7.105
				38.0	8.100

NOTE : A model by Kaila *et al.* (1979) which was taken by Dube (1985) to compare the models based on DSS and earthquakes is as follows :

4.80 (km/sec)	0.0 (km)
5.67	1.2
6.49	10.0
7.01	25.0
8.05	42.0

It may, however, be mentioned that the above model has since been discontinued in view of low P_n values. Model I and II have hence been used for comparison with IMD's model (Kaila personal communication 1983) in this paper.

(*ii*) From the profiles in the Koyna region during Phase I and Phase II experiments, S_g velocity is found to be lowest as compared to other parts of the Peninsular India (Srivastava *et al.* 1984).

3. Crustal velocity models in Koyna region

The crustal velocity models in the Koyna region are given in Table 1. It may be noted that there is a significant difference between the two models in the P-wave velocities given by Kaila *et al.* (1981) for the Koyna region. From these, abridged models have also been worked out. It would, thus, appear that inspite of useful applications of NGRI-DSS results for detailed structure, the averaged models along the profile may not be representative for micro-earthquake locations which occur over a larger area. Combining the data of Koyna Phases I and II, an averaged model has been reported by IMD (Srivastava *et al.* 1984). A surficial layer for the traps of 1.2 km thickness was also added

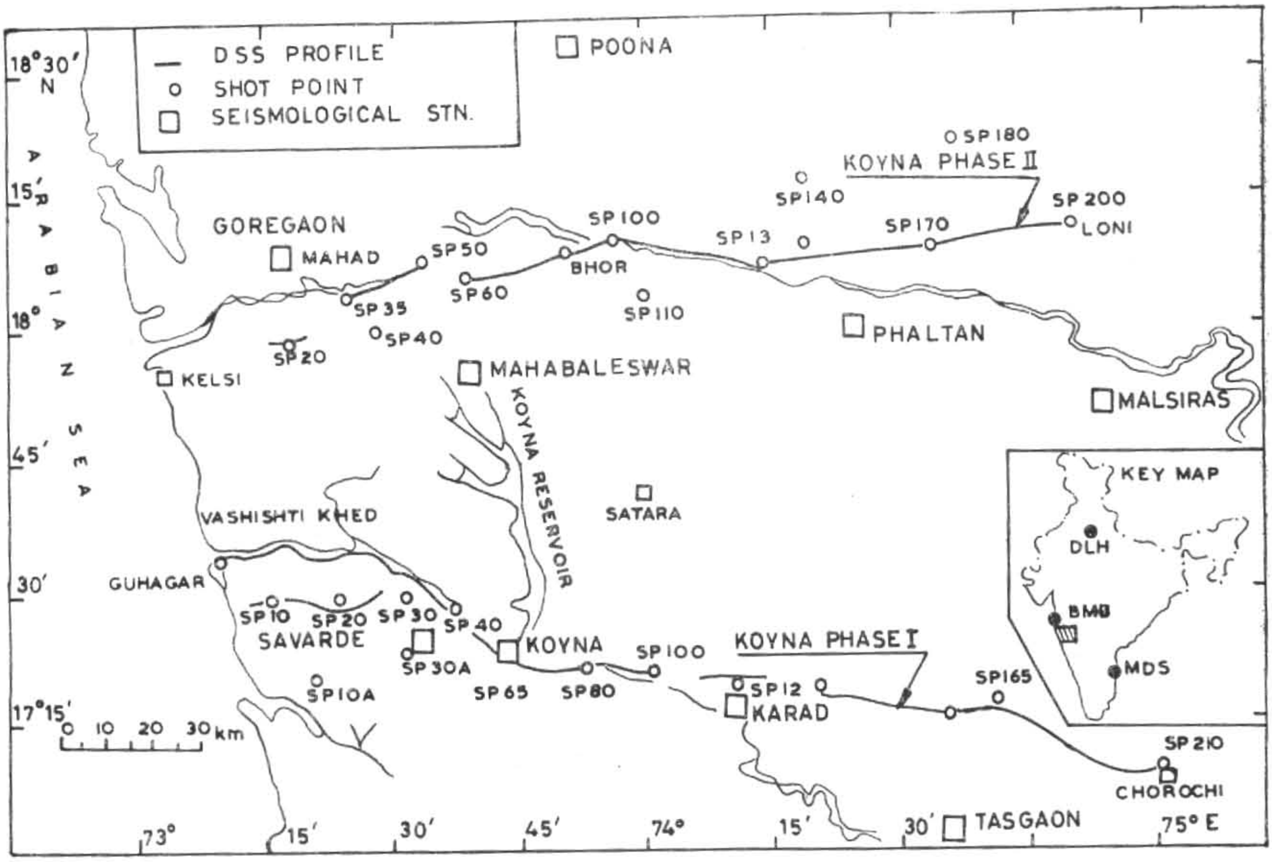

Fig. 1. Koyna region showing phases I & II

to the IMD's two layered model using the results of Tandon (1973) and Bhattacharya and Srivastava (1973). The spread of seismological stations set up by IMD around both these profiles (I and II) makes it applicable over the entire reservoir area in the Koyna region (Fig. 1). Occasionally, the short period seismographs also record very short period dispersed surface waves which can be used to estimate the thickness of the traps/ sedimentary layer (Bhattacharya and Srivastava 1973). Thus, the experiments enable us to determine the averaged crustal velocity model over the area enclosed by the seismograph stations.

Since 1982, IMD has also deployed high frequency micro-earthquake seismographs during the DSS field season to detect the micro-earthquakes whose parameters are determined to the best possible accuracy making use of the local crustal velocity model deduced by IMD for that region from DSS explosions (Srivastava *et al.* 1984).

The following differences between NGRI and IMD crustal models may be noted :

(*i*) NGRI gives more details of crustal structure but restricted along the DSS profiles. As such, the averaged velocity structure is related to that profile only. On the other hand, IMD's model gives an averaged model covering a much larger area.

TABLE 2

Comparison of errors of IMD and NGRI models

(Based on 28 well recorded Koyna shocks, Mag. ≥4.0)

Error	Srivastava *et al.* (km)	Kaila *et al.* Model I (km)	Kaila *et al.* Model II (km)
Mean ERH	4.89	5.94	5.514
Mean RMS	0.430	0.455	0.432
Mean ERZ	6.43	4.91	6.91

(*ii*) NGRI model is restricted to P-wave velocities while IMD's model gives P and S velocities of different crustal phases which are needed in the computer programmes of HYPO-71 and HYPO-ELLIPSE of U.S. Geological Survey.

(*iii*) IMD's participation also enables to study the attenuation of seismic waves over different regions. On this basis, local Richter magnitude scale can be calibrated.

4. Results and discussion

4.1. *Earthquake parameters in Koyna region*

A comparison of the crustal models of IMD and NGRI is made through the determination of epicentral parameters of 28 well recorded earthquakes of magnitude 4 or more using HYPO-71. The results are given in Table 2. It may be noticed that RMS, ERH and ERZ values are comparable for both these models taking

TABLE 3

Explosion co-ordinates (focal depth restrained to zero)

Date (Mar 76)	O-time			Location		Depth (km)	Gap	RMS (km)	ERH (km)	ERZ (km)	Model
	h	m	s	Lat. (°N)	Long. (°E)						
24	18	13	59.48	17°17.58′	74.43.31′	0.00	234	0.22	1.4	2.3	IMD
24	18	14	00.75	17°16.32′	74.42.98′	0.00	231	0.34	2.7	4.6	NGRI
24	18	14	00.73	17°17′-18.75″	74.41′-14.35″	—	Location out		—	—	SP 165
						NGRI (1′S, 1.7′E)		IMD (0.58′N, 2′E)			
22	17	33	26.66	17°19.36′	74°42.09′	0.00	242	0.30	0.3	0.7	IMD
22	17	33	27.51	17°19.24′	74°40.64′	0.00	240	0.17	0.4	0.6	NGRI
22	17	33	28.6	17°17′-18.75″	74°41′-14.35″	—	Location out		—	—	SP 165
						NGRI (2′N, 0.6′W)		IMD (2′N, 0.5′E)			
13	17	54	53.03	17°51.95	73°18.15′	0.00	346	0.36	9.5	4.7	NGRI
13	17	54	52.85	17°48.69′	73°18.49′	0.00	347	0.57	13.0	5.8	IMD
13	17	54	56.25	17°28′-40.00″	73° 16′-12.92″	—	—			—	SP 10
						Location out					
						NGRI (23.2′ N, 2′E)		IMD (30′ N, 2′E)			

TABLE 4

Location parameters of explosions (depth unrestrained)

Date (Mar '76)	O-time (GMT)			Location		Depth (km)	Gap	RMS (km)	ERH (km)	ERZ (km)
	h	m	s	Lat. (°N)	Long. (°E)					
				(a) *India Meteorological Department*						
13	17	54	53.51	17°51.98′	73°25.04′	1.63	340	0.82	15.4	6.5
22	17	33	28.93	17°2.28′	74°32.24′	26.15	174	0.68	28.9	8.3
24	18	14	00.75	17°13.03′	74°42.26′	17.61	224	0.56	10.3	14.1
				(b) *NGRI Model*						
13	17	54	53.48	17°41.93′	73°12.26′	11.36	353	0.85	38.2	4.9
22	17	33	29.37	17°2.28′	74°32.46′	25.29	173	0.77	34.3	9.5
24	18	14	02.10	17°4.12′	74°36.43′	23.46	188	0.79	28.5	4.6

the velocity (V_p/V_s) ratio of 1.70 based on IMD's model (which also gives S-wave velocities).

4.2. *Relocation of DSS explosions*

An attempt was made to further test the applicability of models through a comparison of the coordinates of three well recorded large size DSS explosions by using the P and S-wave arrival times in the local network and restraining the focal depth to zero in the Hypo-71 programme. The results are given in Table 3. It may be seen that the order of errors in both the models is broadly similar. However, if the depth of the explosions is unrestrained as shown in Table 4, the following results are found :

Origin time

The origin times for two explosions near SP 165 showed an error of $\pm$ 0.33 and 0.02 sec for IMD model as compared to 0.77 and 1.35 sec for NGRI model. Relatively larger errors were noted for the explosion near SP 10. The results are similar to the case when the focal depth of the explosions was restrained to zero (Table 3).

RMS

Lower values of RMS were found for IMD model as compared to NGRI model for explosions near SP 165 while errors were similar for explosions near SP 10. For the restrained focal depth, almost similar errors were noted for the two models for explosions near SP 165 but larger errors were obtained for SP 10 which were attributed to large azimuthal gap as compared to explosions near SP 165.

ERH

ERH errors were least with IMD model for all the three explosions as compared to NGRI model. Almost similar result was obtained when the focal depth was restrained except for slightly larger error for SP 10 in IMD model.

ERZ

The error in focal depth was lesser in two cases in NGRI model as compared to IMD model. In the case of restrained depths, errors were similar for explosion of 22 March 1976 while, lesser errors were noted with IMD model for explosion of 24 March 1976. Errors were much larger for the explosion near SP 10 with both models.

4.3. *Main Koyna earthquake,* 11 *December* 1967

Table 5 gives the parameters of the main Koyna earthquake. It may be mentioned that Srivastava and Dube (1982) reported the focal depth of the main earthquake as 2 km using P-wave onset times only based on velocity model from DSS explosions (Srivastava *et al.* 1984). A question, therefore, arises whether such a shallow focus of an earthquake of magnitude 6.5 (which was also found by Kaila DSS velocity models I and II) can be attributed to errors in the model. A recent study using synthetic seismograms by Langston (1976) for the main Koyna earthquake has shown the focal depth as 4.5 km. Dube (1986) compared different velocity models used so far from DSS data as well as earthquakes (Tandon and Chaudhury 1968, Rastogi and Talwani 1980, Gupta *et al.* 1980, Dube *et al.* 1983). Of the two abridged DSS models by Kaila *et al.* (1979), it is seen that Dube (1986) included only one velocity model with low P_n value as 8.05 km/sec which gave the focal depth of the main shock as 4.88 km using this DSS model. The focal depths by other models ranged from 4.20 to 8 km with the exception of 1.78 km as the focal depth by model of Srivastava *et al.* (1984.) Of the two NGRI models I and II, the model II with lower P_n values gives lesser RMS, ERH and ERZ for the main shock as compared to model I. However, least errors are found in the India Met. Dep. (IMD) model. Reanalysis by Kaila has shown preference for the velocity model with the P_n velocity as 8.2 km/sec (Rastogi *et al.* 1986) whose results also give a shallower focal depth of 1.87 km for the main shock, supporting the results of Srivastava *et al.* (1984). It is also noticed that the trial velocity models also limit its utility to P-wave observations only similar to that from NGRI-DSS data. For monitoring micro-earthquakes which are generally confined close to the vicinity of the Koyna reservoir and were well within the seismological stations operated by IMD during DSS experiments, the directly calibrated velocity model given by Srivastava *et al.* (1984) based on known origin time and location would be thus preferable. Including the S-wave velocity of Koyna observatory the focal depth of the main earthquake increases to 7.65 and 5.06 km by IMD and NGRI models respectively. The focal depth of 7.65 km as found by IMD's model is slightly more than that deduced from wave form modelling but agrees with Tandon and Chaudhury (1968). Since the correct velocity model is supposed to arrive at the same parameters whether based on P or S alone or both together further studies based on a local network of larger number of stations are needed for this region with more accurate timing system such as through telemetery networks.

TABLE 5

Epicentral parameters of the main Koyna earthquake of 10 December 1967

Date (Dec '67)		O-time (GMT) *h m s*	Lat./Long.	Depth (km)	RMS (sec)	ERH (km)	ERZ (km)
			(i) IMD Model				
10	(a)	22 51 19.48	17°25.70′N, 73°44.12′E	1.68	0.31	3.1	4.8
	(b)	22 51 19.16	12°23.95′N, 73°45.10′E	7.65	0.52	11.5	6.0
			(ii) NGRI Model I				
10	(a)	22 51 19.58	17°25.81′N, 73°45.10′E	1.87	0.60	5.7	6.6
	(b)	22 51 19.84	17°23.95′N, 73°45.10′E	5.05	0.61	6.0	2.9
			(iii) NGRI Model II				
10	(a)	22 51 19.73	17°25.37′N, 73°43.75′E	0.74	0.48	5.2	6.6
	(b)	22 51 19.64	17°23.45′N, 73°45′E	6.02	0.60	5.5	6.5

Parameters based (a) only on P wave (b) from P wave and Koyna S wave observations

TABLE 6

Epicentral parameters of the Koyna aftershock of 12 December 1967 (Mag. 5.2, ISC, 5.4 USCGS)

Model	Epicentre Lat. (°N), Long. (°E)	Origin time (GMT) *h m s*	Focal depth (km)	RMS (sec)	ERH (km)	ERZ (km)
Kaila Model I	17°16.27′N, 73° 40.39′E	06 18 34.59	1.12	0.57	6.9	16.1
Kaila Model II	17°17.65′N, 73° 41.03′E	06 18 35.36	5.15	0.59	7.0	7.0
IMD Model	17°17.56′N, 73° 4.51′E	05 18 34.86	5.43	0.48	6.3	6.4
IMD	17.28° N, 73.66° E	06 18 34.0	8	—	—	—
USCGS	17.6° N, 73.9° E	06 18 37.9	29	—	—	—
ISC	17.30° N, 73.85° E	06 18 36.8	29	—	—	—

4.4. *Larger aftershock* (12 *Dec 1983*) *of main event*

Table 6 gives the epicentral parameters of a large aftershock of the Koyna main event using Kaila models I, II and IMD model. It may be noted that similar to the main shock RMS errors are least with IMD model

Kaila model I gives a very shallow focal depth of 1.12 km. The focal depth of 5.4 km is in closer agreement with the results of Langston and Franco Spera (1985) who modelled short period and near regional long period wave forms and then identified $_pP$ and $_sP$ phases on the short period wave forms to yield a well constrained sources depth of 3.5 to 4.0 km.

5. Conclusions

The study brings out the following conclusions :

(*i*) The crustal structure and velocity models from P-waves by IMD and NGRI using explosion data give almost similar results. Such models have known advantages over those derived from earthquake data.

(*ii*) Wherever S-wave velocities are needed, IMD model is to be preferred since it was deduced from the network of stations deployed during DSS phases I and II which covered the area around the Koyna reservoir where aftershocks activity is continuing.

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