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Pre and post-excavation cross-hole seismic and geotomographic studies for a Nuclear Power Project

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ABSTRACT

The foundation site response evaluation to earthquake forces requires determination of both compressional and shear wave velocities. This information allows less conservative safety margins and thereby helps in reducing the cost of building construction. Cross-hole seismic studies in NX size (~80 mm dia) boreholes to evaluate Compressional (P-) and Shear (S-) wave velocities upto 51 m depth from the surface (EL 100 m) were carried out at Reactor Building (RB) RB-3 and RB-4 sites. It was found that at RB-3 site, the P-wave velocity was 5400 m/sec while the shear wave velocity with depth ranged between 2900 m/sec and 3200 m/sec.

The RB-3 site was then excavated upto EL 79.4 m and the rock was grouted by cement slurry. To study the effect of removal of overburden and blasting on the quality of rock, as also to decide the exact value of shear wave velocity to be adopted for designing the foundation of reactor building, cross-hole seismic studies upto EL 62.4 m were carried out.

In addition to calculating the average wave velocities, the post-excavation cross-hole data were also analysed by seismic ray geotomography to evaluate velocity field distribution with depth. The pre and post excavation P- and S- wave velocity values were similar from which it was inferred that blast energy was contained and extension of fractures was not inferred. Also post P- and S-wave velocity tomograms revealed that the velocities in horizontal and vertical directions were same indicating that the distribution of stresses in both directions was of the same order and inhomogeneities have no preferential direction of orientation.

INTRODUCTION

Knowledge of any two of the five elastic constants of an isotropic material is enough to completely specify the material's elastic properties. The elastic constants most commonly used are Young's modulus 'E' and Poisson's ratio 'σ'. These are generally determined either in the laboratory or in the field by static testing. Static testing yields high precision results of a limited volume of material, but these values are seldom representative of the larger "field" volume that the civil engineer has to deal with as these are greatly affected by local inhomogeneities. Also, all geotechnical tests provide information from point to point and the values are interpolated in between places. These tests grossly under sample the subsurface and are frequently inadequate (Sarman & Palmer 1990).

Dynamic loading is applied to the ground by a variety of structures such as dams, tidal barriers, offshore platforms, wind power generators, nuclear reactors and large vibrating machines. In case of vibrating machines, such as electrical generators or nuclear reactors, which can at times vibrate within a relatively wide frequency range, the foundation block has to be designed in such a way so as to avoid resonance. Therefore, an important condition for designing the foundation of nuclear reactors is the correct estimation of elastic interaction between the host rock and the structure. Study of this interaction requires the knowledge of the dynamic rigidity moduli of ground, usually calculated from the shear wave velocities obtained from cross-hole, up-hole or down-hole logging and surface seismic refraction methods and corresponding bulk density values.

In contrast to static, up-hole and down-hole methods of testing subsurface strata, greater radius of investigation is provided by cross-hole technique. The region surveyed is the path between the source and detector boreholes. It provides greater measurement accuracy, as the seismic waves travel through a particular medium with less interference from nearby refracting horizons. Another advantage of cross-hole technique is that it can delineate underlying low velocity layers those remain masked in surface refraction survey. Therefore, the P- and S-wave velocities evaluated by cross-hole technique (and the elastic constants determined there from) can be used in (a) dynamic analysis of earthquake generated stress wave propagation in soils and rocks performed as part of safety evaluation of major structures such as nuclear reactors and dams (b) dynamic analysis of foundation and (c) dynamic finite element analysis of soil-structure interaction problem. The technique also helps in the detection of cavities, open fractures, zones of weakness or other discontinuities, with depth.

This paper describes the use of cross-hole seismic and geotomographic studies to evaluate the pre- and post-excavation dynamic moduli with depth required for designing the foundations of reactor buildings for a nuclear power project in Maharashtra.

It is proposed to increase the generating capacity of atomic power station at Tarapur, by 1000 MWe. For this, two reactors each of generating capacity 500 MWe alongwith other structures e.g. turbine buildings, cooling towers etc are to be constructed. The site for these reactor buildings is near the existing power plant.

To decide the location of the reactors and other structures, seismic refraction and electrical resistivity surveys were carried out. From the results of the geophysical investigations the site for these structures was fixed (Wadhwa et al. 1999). Geophysical survey was followed by drilling programme to check the profiles at points found to be critical for the project and to obtain samples or other details about the overburden and rock properties. Core drilling is one of the best methods for determination of rock quality but other cheaper and quicker drilling methods (percussion and hammer drilling) may also be used in conjunction with geophysical measurements in the drill hole itself to obtain the physical properties around the drill hole. One geophysical method used in recent years for such measurements in NX size holes is the seismic logging technique where the seismic velocities along the wall or between the drill holes can be measured.

The foundation site response is a special type of engineering survey, requiring the determination of both P- and S- wave velocities with depth. From these parameters Poisson's ratio and dynamic moduli (if bulk density values are determined) can also be evaluated. These are used in computer model studies to calculate the dynamic site response of a foundation. Thus, the response of the foundation to the earthquakes can be anticipated. This information is used in the structure design, often allowing less conservative safety margins and reducing the cost of building.

Cross-hole seismic studies in NX size (~ 80 mm dia) holes to evaluate compressional and shear wave velocities upto 51 m depth from the surface (EL 100m), were carried out at the proposed Reactor Building (RB) RB-3 and RB-4 sites. The RB-3 site was later excavated upto the foundation level (EL 79.4m) and the exposed hard rock was further grouted by cement slurry. To study the effect of removal of overburden/weathered rock and blasting (as weathered rock had to be blasted for removal) on the quality of rock as also to decide the exact value of the shear wave velocity to be adopted for designing the foundation of reactor building, cross-hole seismic studies again upto EL 62.4m were carried out.

GEOLOGY

The proposed site is situated in the Deccan traps basalt. The common rock types are amygdaloidal basalt, volcanic breccia/brecciated basalt. At some places, fresh basalt rock is encountered below the overburden while elsewhere it is overlain by weathered rock. The overburden including weathered rock upto about 20 m depth has been removed at the RB-3 site to lay the foundation on the fresh rock.

CROSS-HOLE SEISMIC TECHNIQUE

The cross-hole seismic technique for measuring average Compressional (P-) and Shear (S-) wave velocities comprises generating both these waves at a particular level in a borehole and recording them at the same elevation in one or more adjacent holes. By this, the times of travel, for both P- and S- waves, of a known distance within the media are measured. Average P- and S- wave velocities at that level are then calculated from the corresponding travel times and distances.

PREPARATION OF BOREHOLES

The holes used for cross-hole studies should be of NX size. However, boreholes in the overburden at the site drilled were of SX size (100 mm dia). To make them suitable for cross-hole studies, NX size PVC casing (density 1.4 gm/cc) was lowered into the boreholes. The space between the PVC casing and the borehole wall was pressure grouted with bentonite clay (density 1.4 gm/cc) so that the strata, the grout material and the PVC casing become homogeneous mass and there is no refraction at the casing and the surrounding material. The use of cased holes does not significantly affect the value of shear wave velocities as long as the casing is firmly grouted into the surrounding medium throughout its length. The use of casing is usually mandatory for sandy and gravely sites in order to eliminate the caving of borehole walls. To keep the effect of casing to the minimum, the thickness of grout should not exceed one percent of the distance between the boreholes (Auld 1977). A thicker grout section will affect the travel time, and unless the grout thickness and its velocity are known, a travel time correction cannot be applied.

Since shear waves cannot be transmitted through liquid and are highly attenuated in semi liquid drilling mud, it is necessary to position the recording geophones in firm contact with the material. To achieve this, geophones must be clamped to the borehole wall to avoid the effect of borehole fluid on the system. Under these circumstances the borehole may be either dry or filled with water or drilling mud but with no effect on shear wave velocity measurement. Yet another advantage of holding geophone against the borehole wall is that it does not introduce any error in distance measurements because of caving etc. particularly in soft rock conditions.

The advantage of recording shear waves, in addition to being the true representative of rock quality (as these are not affected by fluids in pores) is that it provides better resolution of weak zones and inhomogeneities. This is because the S-wave velocities in a particular strata are significantly less than P- wave velocities, therefore S-waves with comparable frequency content result in much shorter wavelengths. This helps in achieving better resolution especially of smaller fractures and cracks.

EQUIPMENT EMPLOYED

24- channel signal enhancement engineering seismograph 'Terraloc' was used for data acquisition and recording. Borehole hammer with clamping facility was used for generation of predominant shear waves and weak compressional waves at various depths. The shear waves were picked up at various depths by borehole triaxial/vertical geophones fixed against the borehole wall by pneumatic clamping facility.

It was observed during the field study that below the water table in the borehole, a lot of high frequency noise was produced by the hammer while raising or lowering it to generate the shear waves. Different filters with several bandwidths to eliminate the noise and get the clean record were attempted. These included: no filter (noisy record), 0-250 Hz, 0-500 Hz, 0-1000 Hz. It was observed that the filter having bandwidth of either 0-500 Hz or 0-1000 Hz provided the noise free records with well defined P- and S-arrivals.

PRE EXCAVATION STUDIES

Fig. 1 shows the site plan of the Reactor Building (RB)-3 alongwith the locations of three boreholes used for cross-hole studies. Borehole BH-4 was used as source hole for lowering hammer and for generation of P- and S- waves. The recording boreholes were located at distances of 5 m and 10 m respectively from the source hole. Recordings were made starting from a depth of 6 m upto a depth of 51 m at an interval of 3 m. Though not necessary, the advantage of using more than one hole for recording is that it eliminates any error in judging the correct instant of the impact, which may arise due to the delay in triggering the equipment.

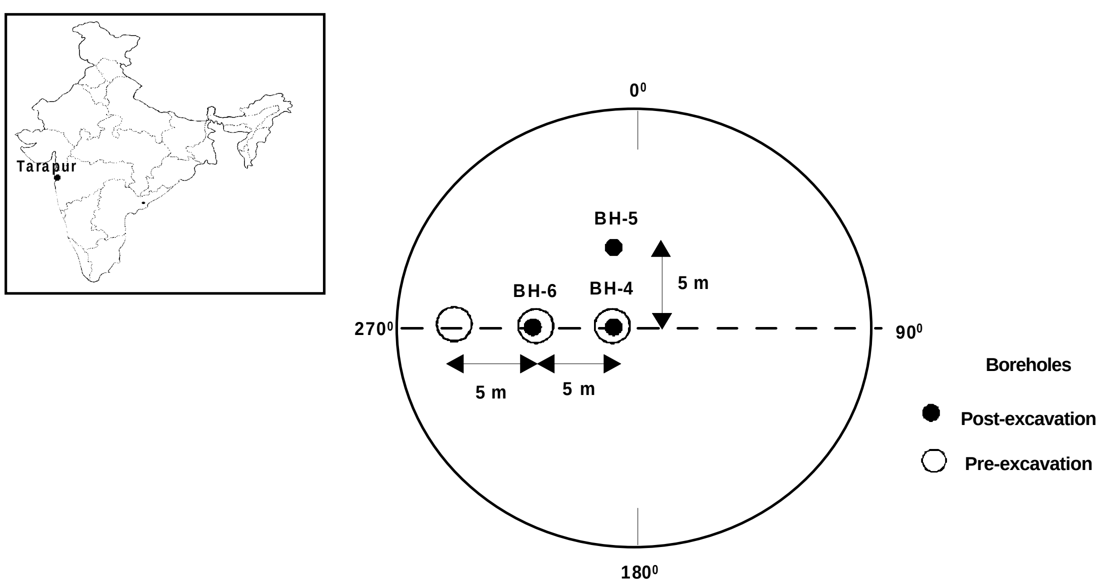

Figure 1. Schematic location plan of the Reactor Building (RB-3) area.

Table 1. Compressional and Shear Wave Velocities, Poisson's Ratio, Young's and Shear Moduli at various depths (Pre-excavation)

Depth m	Compressional wave velocity (m/sec)	Shear wave velocity (m/sec)	Density gm/cc	Poisson's ratio	Young's modulus X 10^5 kg/cm^2	Shear Modulus X 10^5 kg/cm^2
6	5400	2970	2.8	0.28	6.52	2.52
9	5400	2900	2.8	0.3	6.19	2.4
12	5400	2980	2.8	0.28	6.52	2.54
15	5400	3000	2.8	0.28	6.52	2.57
18	5400	3120	2.8	0.25	6.94	2.78
21	5400	3120	2.8	0.25	6.94	2.78
24	5400	3170	2.8	0.24	7.07	2.87
27	5400	3180	2.8	0.23	7.19	2.89
30	5400	3200	2.8	0.23	7.19	2.93
33	5400	3200	2.8	0.23	7.19	2.93
36	5400	3130	2.8	0.25	6.94	2.80
39	5400	2970	2.8	0.28	6.52	2.52
42	5400	3200	2.8	0.23	7.19	2.93
45	5400	3000	2.8	0.28	6.52	2.57
48	5400	3140	2.8	0.24	7.07	2.82
51	5400	3140	2.8	0.24	7.07	2.82

Table-1 shows the values of P- and S- wave velocities, Poisson's ratio, Young's and Shear moduli of elasticity as evaluated from these studies at RB-3 site before excavation. At RB-3 site, the P-wave velocity from 6 m to 51 m depth is 5400 m/sec. The shear wave velocity for the same depth ranges between 2900 m/sec and 3200 m/sec.

POST EXCAVATION STUDIES

The RB-3 site was then excavated for about 21 m upto the hard rock (EL 79.4 m) where the foundation of the reactor building was to be laid. Cross-hole studies were carried out at this site to evaluate P- and S- wave velocities upto 17 m depth. The purpose of the survey was to study the effect of blasting on the quality of rock as also to evaluate the S- wave velocity, which would be used for designing the foundation of reactor building to take into account the rock and structure interaction in case of an earthquake.

For cross-hole studies, three NX (~ 80 mm dia) size holes in two mutually perpendicular directions i.e. North and West (BH-5 and BH-6) spaced 5 m apart were drilled upto 17 m depth (Fig 1) by percussion drilling (as this drilling technique is cheap and fast). The borehole BH-4 was used for generating seismic waves while remaining two boreholes were used for lowering triaxial/vertical geophones. Both these geophones are equally efficient in recording S- waves. Systematic travel time measurements were made with hammer located at 1 m, 3 m, 5 m ...... 15 m, 17 m depth. Geophones clamped against borehole wall were accordingly positioned at these depths in receiving holes for recording P- and S- wave arrivals. Thus, the holes to record P- and S- waves were logged at 2 m depth interval starting from 1 m below the foundation level as the holes were metal cased upto that depth. The hammer blows at each level were stacked 5 to 6 times to increase signal-to-noise ratio especially for S- waves. These time measurements yielded average P- and S- wave velocities with depth. Table- II shows the values of P- and S- wave velocities, Poisson's ratio, Young's and Shear moduli of elasticity as evaluated from these studies at RB-3 site after excavation.

Fig 2 shows a comparison between average P- and S- wave velocities in the depth range of 21-35 m before and after excavation. It is seen from Fig 2 that post-excavation P-wave velocities are slightly higher than those of the pre-excavation values while the trend is just opposite for S-wave velocities. The reason for this could be that the post–excavation holes for the cross-hole studies were percussion drilled. The percussion drilling must have induced some cracks in the rock

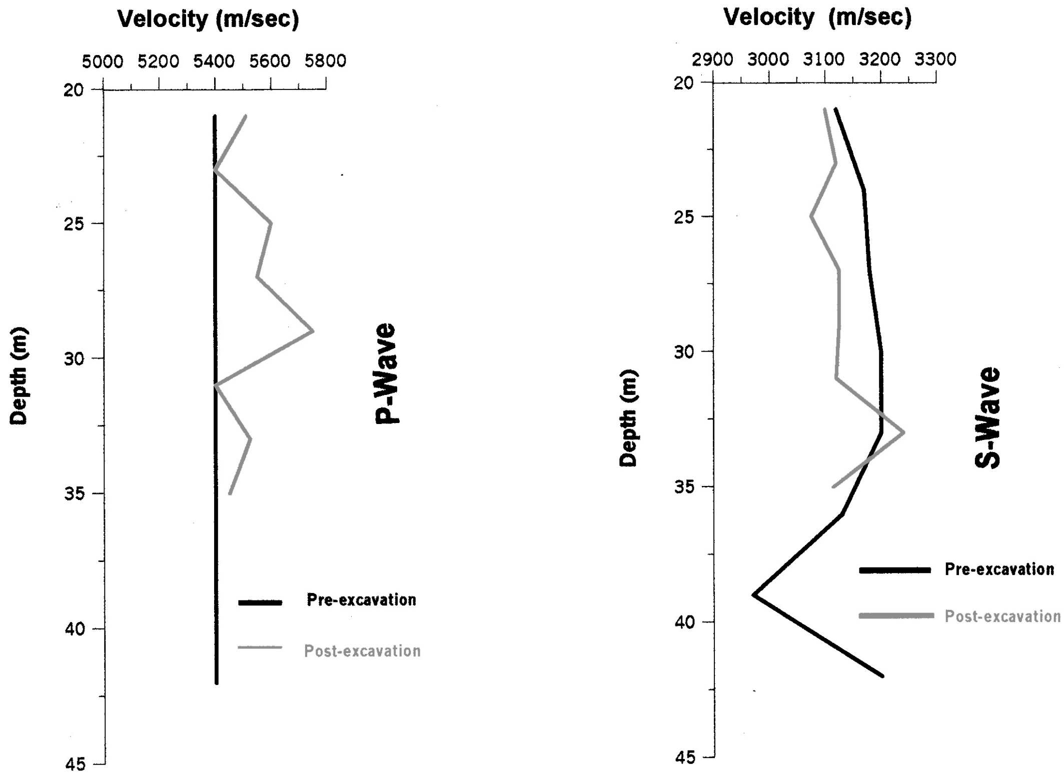

Figure 2. Comparison between average P- and S- wave velocities before and after excavation.

near the holes. Since the S-wave velocities have lower wavelengths the resolution achieved is better. Therefore, the effect of drilling induced cracks is more pronounced on S-wave velocity as compared to the P-wave velocity values. Grouting contributed to increased P-wave velocity but drilling induced cracks lowered the S-wave velocity. Almost similar velocity values for P-wave and S-wave before and after excavation indicate that blast energy was contained, neither new fractures were developed nor the extension of the existing ones took place.

TOMOGRAPHIC ANALYSIS

Velocity determination as described above is a measure of average quality of the rock strata along the line of wave propagation, but it fails to provide information on the distribution of quality (inferred from change in velocity) along that line (Ivansson 1985; Stewart 1991). If a sufficient number of measurements are made for a section of rock between the boreholes, inversion technique can be used to reconstruct a two-dimensional image of the distribution of velocity. Such a technique was applied to the post- excavation cross-hole data for the reactor building site.

Tomography involves reconstructing a slice or cross-section through an object using energy measurements taken through the object. Computerised tomography has been used with great success since 1970's in diagnostic medical imaging but civil engineering applications have difficulties like complex wave propagation (e.g. diffraction, ray bending), sensitivity to transducer coupling and performance and limited data sampling (Williamson 1991). These factors contribute to limitations in resolution and defect detection.

DATA ACQUISITION

For recording of post-excavation cross-hole data for tomographic studies, three triaxial/vertical transducers in each receiver hole in north and west directions were lowered and were clamped initially at 1 m, 3 m, and 5 m depths. The hammer, in the source hole, was fixed at 1 m depth and the P- and S- waves generated at 1 m depth were recorded by three transducers in each hole. The whole waveform data recorded at three depths provided direct arrival times for P- and S- waves at those depths. Then by keeping the receivers fixed at those levels (i.e. 1 m, 3 m, 5 m) the hammer in

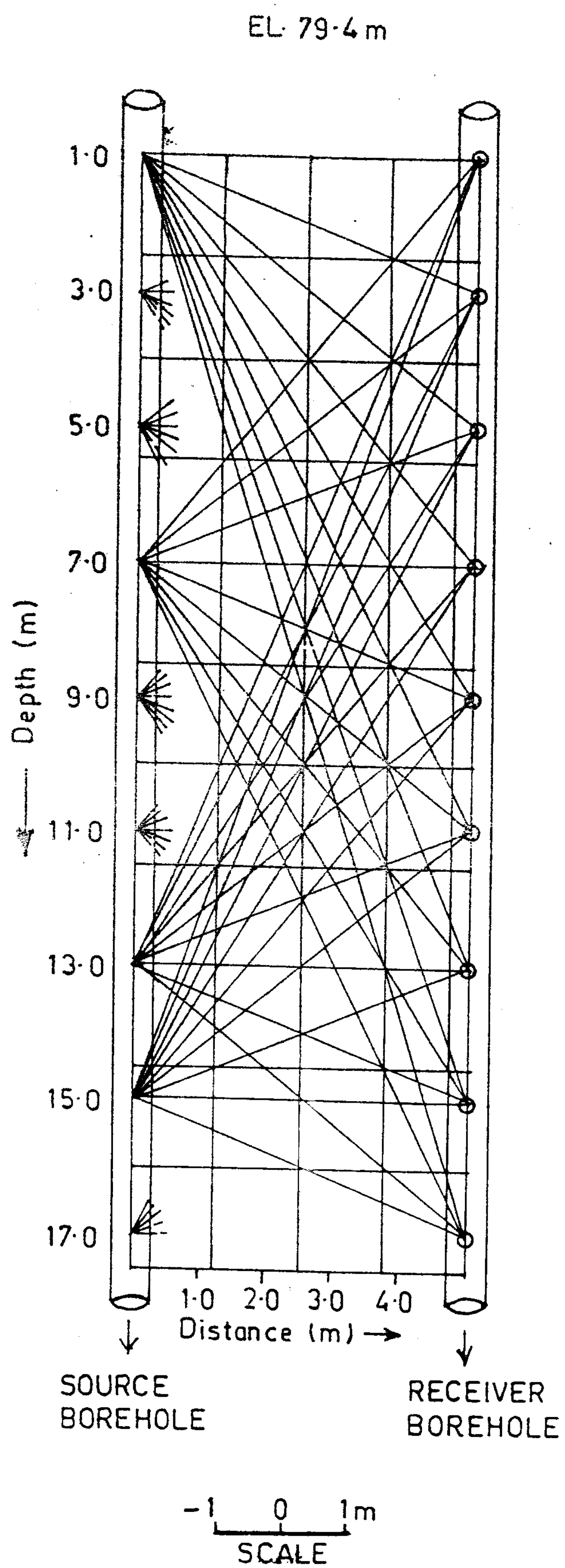

Figure 3. Ray diagram for various positions of sources and receivers.

the source hole was progressively lowered from 1 m to 17 m depth so that the seismic waves are recorded at every 2 m depth interval. The receivers were then moved to the next positions i.e. 7 m, 9 m and 11 m in both the receiving holes and clamped at those depths. The procedure of moving and clamping the hammer in the source hole from 1 m to 17 m depth at 2 m depth interval was repeated and the P- and S- wave arrival times were recorded at 7 m, 9 m and 11 m depth. The procedure of moving the hammer and the receivers in their respective holes was repeated until all the wave paths, for various combination of source and receiver positions were recorded. Fig 3 shows the ray diagram for complete set of source and receiver locations for one borehole. Complete data recording for tomographic studies in each direction comprised 9 hammer locations and for each hammer location there were 9 receiver positions. This yielded 81 ray paths covering various levels in boreholes and the corresponding 81 time measurements for P- and S- waves separately.

TOMOGRAPHIC DATA ANALYSIS

The cross-hole velocity distribution was computed using the Simultaneous Iterative Reconstruction Technique (SIRT) (Gilbert, 1972; Peterson, Paulsson & McEvilly 1985; Tweton et al. 1988). This involved modification of a specified initial model by repeated cycle of three steps : forward computation of model travel times; calculation of residuals (differences between model and experimental times); and application of velocity perturbances or corrections. The initial velocity model in the study consisted of same velocity for each pixel, which was calculated from the recorded arrival times of waves when the source and receiver were at the same level in their respective boreholes. The data were analysed on a personal computer using algorithm of Jackson, Tweeton & Fridel (1992). The tomographic reconstructions for P- wave velocity were constrained by limiting the upper velocity to 6.0 km/sec and a lower bound velocity of 4.5 km/sec. Analysis of studies performed on models in the laboratory suggest that upper and lower velocity limits are helpful in obtaining a reconstruction that matches more closely the model data (Ghosh, Wadhwa & Mukhopadhyay 2000). Similarly, for construction of S-wave velocity tomograms the upper and lower velocity limits of 3.4 km/s and 2.5 km/s respectively were assumed. These upper and lower limits for velocities are based on the measured pre-excavation velocity values of basalt rock as also the velocities of basalt reported in the literature.

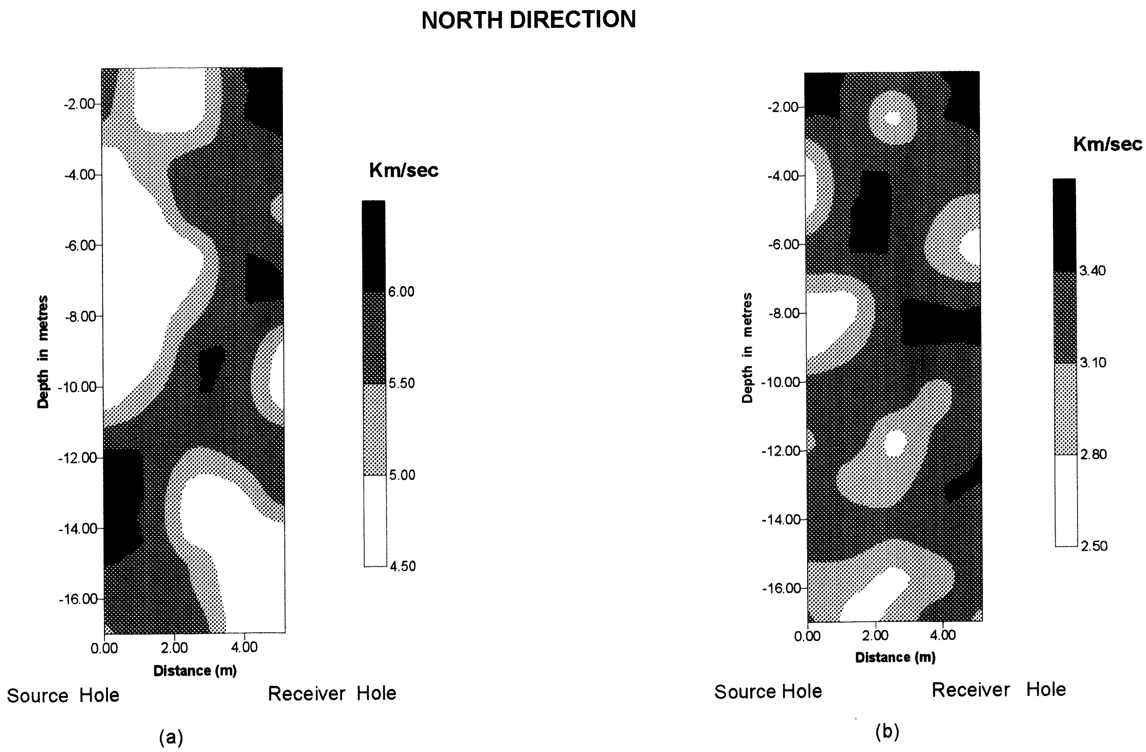

Figure 4. Tomograms of velocity field (a) P- wave velocity (b) S- wave velocity

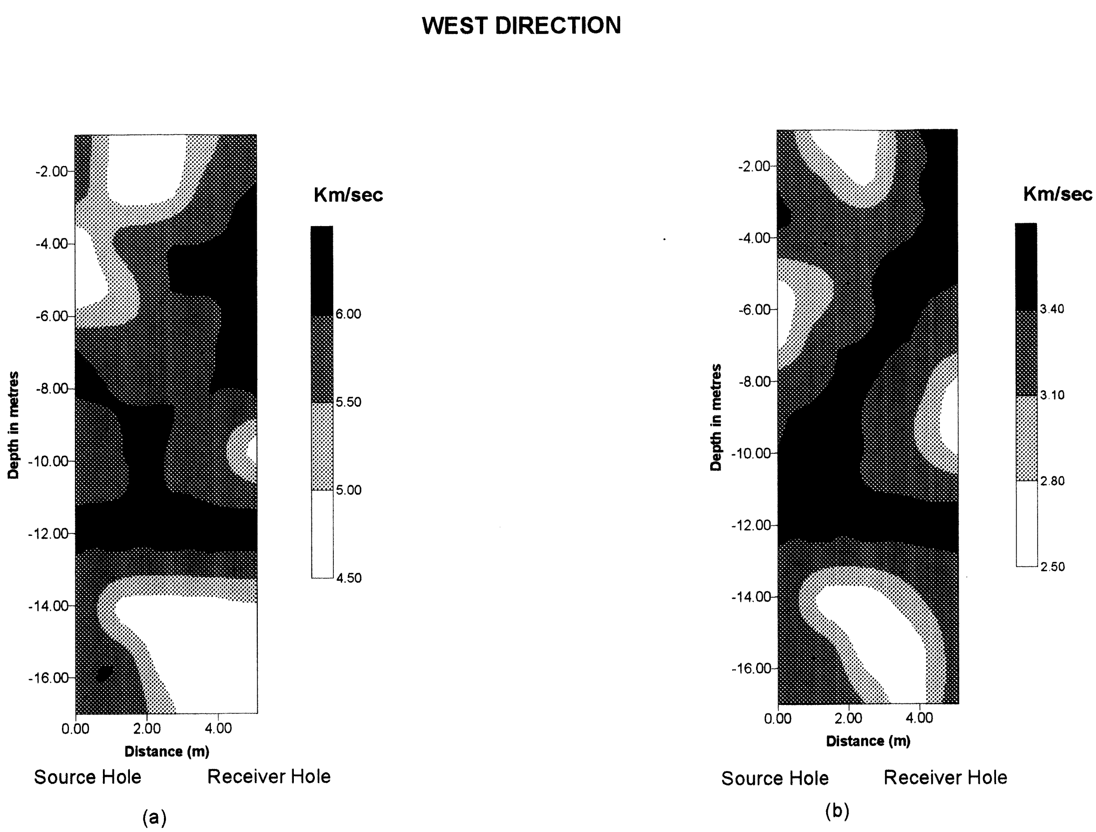

Figure 5. Tomograms of velocity field (a) P- wave velocity (b) S- wave velocity

The velocity field between the source and receiver boreholes was discretized to 44 cells each measuring 1.46 m x 1.27m. Therefore, there were 81 equations and 44 unknown parameters for this set-up of sources and receivers which were further constrained by upper and lower velocity values for each pixel. The velocity distribution from the corresponding arrival times of P- wave and S- wave for various pixels in between two boreholes was then calculated by straight/curved ray tomography. The velocity contours drawn are shown in Figs 4 and 5 for north and west directions respectively.

RESULTS

It is seen from Tables-I and II that the shear wave velocities do not necessarily increase uniformly with depth, even for strata that are reasonably uniform. The assumption of uniformly increasing shear wave velocity with depth is usually made in the absence of in situ velocity data and is not always correct.

It is seen from Fig 4a that the P-wave velocity for the basalt rock, in general, varies with depth between 5.0 km/sec and 6.0 km/sec except at few places where it is evaluated to be little lesser (4.5 to 5.0 km/sec). The lower value of P- wave velocity is inferred at places where the ray density is less (at the edges of velocity tomogram) and in the area near the borehole wall most affected by drilling induced cracks and therefore can be ignored. Shear wave velocity tomogram upto 17 m depth in north direction indicates that this velocity in the area studied varies between 2.5 km/sec and 3.4 km/sec(Fig 4 b). In the S-wave velocity analysis also the velocities between 2.5 km/sec and 2.8 km/sec have been observed at the corners of tomogram near the source and receiver boreholes. It can be inferred from the velocity distributions in this figure that the basalt rock is of good quality and there is no weak zone or inhomogeneity present, which might have required treatment like grouting etc. Also, it is seen from P- and S- wave velocity tomograms (Fig 4) that the velocity distribution in horizontal and vertical direction is similar indicating that distribution of stresses in both directions was of the same order.

The wave velocity distributions for the same site in the west direction are shown in Fig 5. Fig 5a depicts P- wave velocity distribution with depth while shear wave velocity field has been shown in Fig 5 b. It is seen from this figure that in the west direction also the rock is of good quality and no weak zone having lower velocity is present. The P- and S- wave velocities at various depths in north and west directions are of the same order. It was inferred from this that inhomogeneities have no preferential direction of orientation and the average of two velocities at each depth can be adopted as the true velocity of rock at that depth.

RELIABILITY OF TOMOGRAM CONSTRUCTION

Determining the reliability of construction of wave velocity distribution though easy on models where initial values are known, is difficult for field data as no controls are available. Reliability of field tomogram construction can only be confirmed indirectly by measuring the discrepancy of reconstruction, which is the Root Mean Square (RMS) departure between the measured and calculated travel times from reconstruction. To avoid large discrepancies and to obtain reliable velocity field, constraints in terms of higher and lower velocity values are applied to tomogram construction. The number of pixels is kept much less than the number of measured data points (here it was 44 versus 81). Also, for minimum discrepancies the data collected for tomographic analysis must be precise and of very high quality. A final approach is to subjectively determine whether the

Table 2. Compressional and Shear Wave Velocities, Poisson's Ratio, Young's and Shear Moduli at various depths (Post-excavation)

Depth m	Compressional wave velocity (m/sec)	Shear wave velocity (m/sec)	Density gm/cc	Poisson's ratio	Young's modulus X 10^5 kg/cm^2	Shear Modulus X 10^5 kg/cm^2
21	5510	3100	2.8	0.27	6.96	2.74
23	5400	3120	2.8	0.25	6.95	2.78
25	5600	3075	2.8	0.28	6.94	2.70
27	5550	3125	2.8	0.26	7.06	2.79
29	5750	3125	2.8	0.29	7.19	2.79
31	5400	3120	2.8	0.25	6.95	2.78
33	5525	3240	2.8	0.24	7.43	3.00
35	5450	3115	2.8	0.25	6.97	2.77

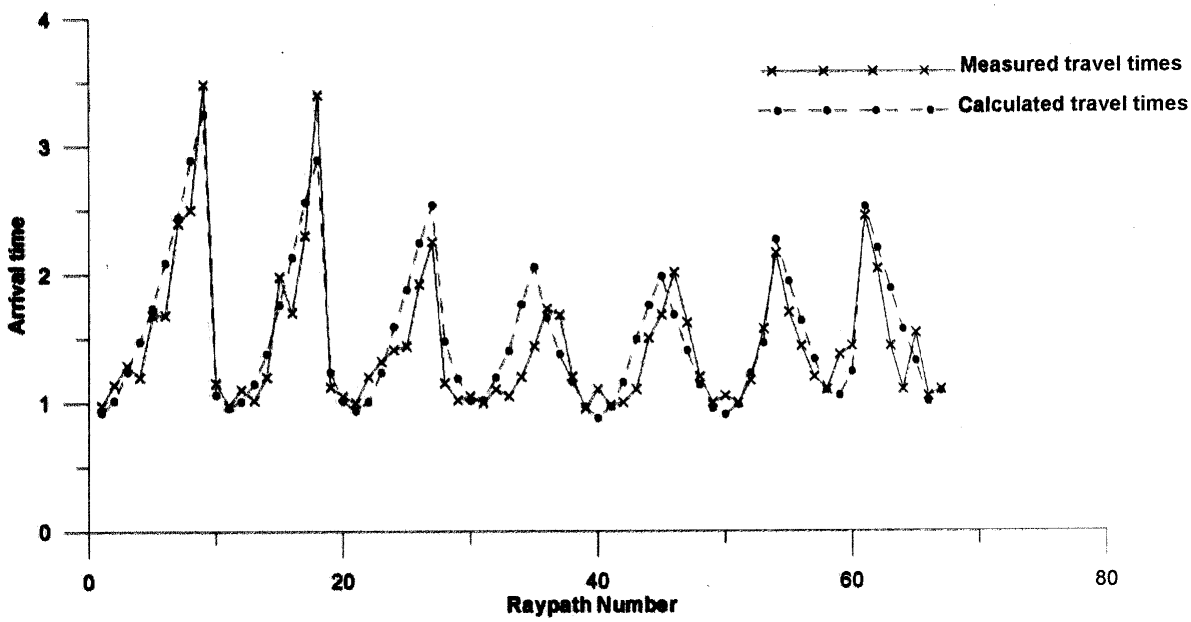

Figure 6. Comparison between measured and calculated travel times

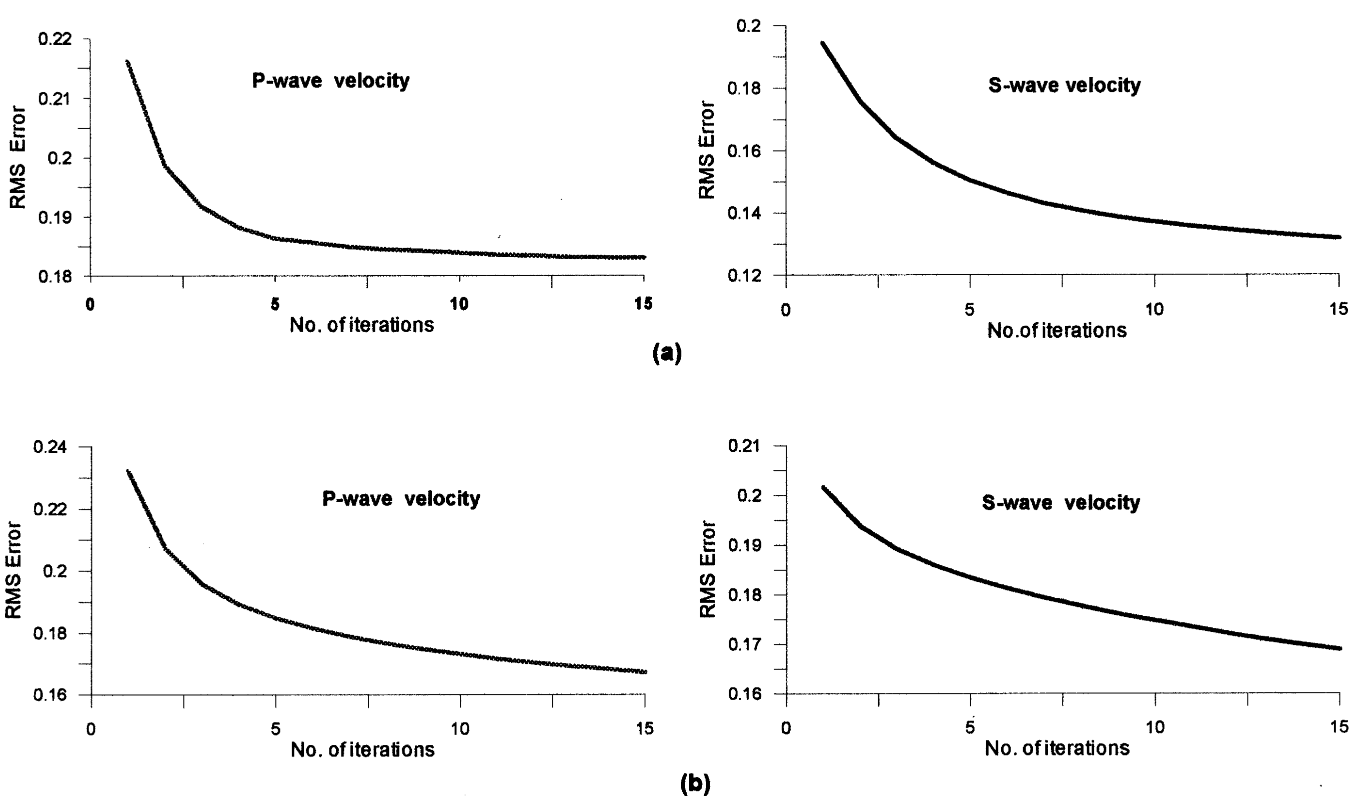

Figure 7. Matching between estimated and measured travel times with iterations (a) North direction (b) West direction.

reconstruction is reasonable and the velocities obtained through reconstruction are representative values of the strata and its quality. By taking all these factors into consideration, it was noticed that the tomograms obtained were reliable as very little discrepancy in the measured and calculated timings was observed. The comparison of the input timings for sixty five rays and the corresponding output timings for final velocity model using the same software package is shown in Fig 6. The perfect match between the two timings indicated that velocity tomogram was reliable. Also Fig 7 shows the RMS error for calculated (for final velocity model) and input timings after fifteen iterations. It is seen from the figure that both in north and west directions, the RMS error is about 0.17 percent, thus confirming again that the tomograms obtained were reliable.

CONCLUSIONS

The pre and post-excavation cross-hole studies at a reactor building site indicated that P- and S- wave velocity distribution, with depth, before and after the excavation is of the same order. It was inferred from this that the blast energy was contained and neither the existing fractures have extended nor new fractures have developed.

The tomographic analysis of post-excavation cross-hole data indicated that the velocity distribution in north and west directions (directions covered by cross-hole survey) is of same order. It was, therefore, inferred that inhomogeneities have no preferential direction of orientation. The average of two velocity values at any depth can be adopted to be true velocity of rock at that depth.

The velocity tomograms show that velocity distributions (both P- and S-velocities) in horizontal and vertical directions are similar indicating that the distribution of stresses in both horizontal and vertical directions was of the same order. Post-excavation studies revealed that P- and S- wave velocities varied from 5400 m/sec to 5750 m/sec and from 3100 m/sec to 3240 m/sec respectively. No weak zones having lower velocity values, which might have required treatment, were deciphered.

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