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Deciphering of Weak Zones Using Cross-hole Seismic Tomography

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ABSTRACT
Low strain stiffness required for deciding the levels and for designing the foundations of nuclear reactors for dynamic analysis can be determined with depth by cross-hole, up-hole or down-hole seismic techniques utilizing boreholes and polarized or directional energy sources. Of these techniques because of the well defined wave paths, cross-hole technique is the most reliable to measure in situ dynamic properties. Cross-hole seismic studies conducted at a nuclear power plant helped in establishing the foundation level of nuclear reactors as well as for determining the fundamental period of the site. At the same atomic power project site, tomographic studies helped in deciphering the lateral and vertical extent of weak zones with depth.

The foundation level of nuclear reactor both from cross-hole and tomographic analysis was evaluated to be at 12 m depth from the ground surface. P-wave tomographic studies revealed that the large region between the boreholes has a compressional wave velocity over 5 km/sec which is indicative of good quality basalt, devoid of any major fracture zone or cracks. Three weak zones of limited lateral and vertical extent inferred from the P- wave velocity tomogram should be treated to avoid any adverse effect on the foundation of nuclear reactors particularly in case of earthquake. The velocity tomogram revealed that the velocity distributions in the horizontal and vertical directions are similar which indicated that stresses both in horizontal and vertical directions are of the same order. Small abnormal features observed on the tomogram should be ignored because both technique and data can not resolve the small features. These features were attributed to error in picking arrival times, less ray density both near source and receiver hole or scattering of waves from small inhomogeneities.

INTRODUCTION

Extensive investigations are required to be performed to verify the suitability of rock foundations for nuclear power plants. The ability of rock formation to support the load of a structure and the design of structural foundation are often based on laboratory tests performed on rock cores obtained during subsurface investigations. In order to confirm that the in situ rock over the whole of foundation excavation corresponds to the conditions determined from the core samples, seismic refraction and cross-hole seismic techniques can be employed in addition to visual observation.

Seismic refraction method provides information on top level of rock only. However, if inhomogeneities or weak/ shear zones exist at depth, the same can not be inferred or delineated by refraction method. For delineation of weak zones with depth cross-hole seismic technique is best suited for establishing their lateral as well as vertical extent.

The operation of nuclear reactors results in the generation of unbalanced dynamic forces and moments which are transmitted to the foundation and the underlying soil or rock, depending on the strata the nuclear reactors are founded. The foundations for reactors must therefore be designed to ensure stability under the combined effect of static and dynamic loads. The dynamic nature of the loads makes the problem of analysis and design of foundation somewhat complex. Even though the magnitude of dynamic load is small, it is applied repetitively over long periods of time. The vibration response of a reactor foundation-soil/ rock system is defined by it's natural frequency and the amplitude of vibration under normal operating conditions of the reactor. There are two most important parameters to be determined in designing the foundation for any reactor (Prakash 1981, Prakash & Puri 1988, Richart, Hall & Woods 1970). For static loads : The foundation should be safe against bearing capacity failure and it should not settle excessively.

For dynamic loads : There should be no resonance. That is the natural frequency of the reactor-foundation-soil/ rock system should not coincide with the operating frequency of the reactor.

The natural frequencies or periods of vibration of any dynamical system comprise a fundamental indicator of the dynamic response characteristics of the system. For a stratum of uniform thickness 'H' the period of vibration for any mode is given by (Dowrick 2003).

$$T_n = \frac{4H}{(2n-1)} \frac{}{V_S}$$

where 'n' is an integer and 'V_s' is the mean shear wave velocity in the layer and a function of stiffness and density. The average shear wave velocity of the layers is determined by

$$V_S = \sum_{i=1}^{n} \frac{d_i}{d_i / V_{si}}$$

Where d_i thickness of individual layer in metres and V_{si} is shear wave velocity in layers 'i' in m/s.

For determination of in situ shear wave velocity with depth, there are several seismic wave propagation tests, namely, seismic cross-hole test, seismic down-hole test and spectral analysis of surface waves (SASW) test. Among these tests, seismic cross-hole test is considered to be the most accurate for determination of in situ shear wave velocities (Boominathan & Gandhi 2001).

To illustrate the application of cross-hole seismic technique in actual practice, a case history of the cross-hole and tomographic investigations performed and the results obtained at Kakrapar Atomic Power Project site is presented. At the site the lateral and vertical extent of the weak zones in the bedrock up to 100 m depth were determined. It was concluded from the studies that the cross-hole tomographic measurements provide quantitative documentation to substantiate the geologist's and engineer's inferences from borehole data and serve to identify the exact dimensions of the possible anomalies.

CROSS-HOLE SEISMIC SURVEY

The procedure used for a shallow cross-hole survey (Stokoe & Woods 1972 and Michalopoulos et al.,1979) consists of drilling a source and a listening borehole to the desired depth. At each depth where measurements are to be taken, the shear wave source is clamped to the borehole wall and a vertical/ triaxial velocity transducer is wedged against the wall of the adjacent listening boring at the same depth. The borehole hammer is stuck both up and down though separately (for reversal of phase of shear wave) triggering a seismograph and sending an impulse down through. The impact is transmitted to the subsurface material and body waves are generated in the rock. The direct arrivals of the body waves are picked-up by the velocity transducer in the adjacent listening boring and are displayed on the recorder. Fig.1 shows the arrangement of source and receivers at a particular depth. The evaluated shear and compression wave velocities can be used to evaluate the possible effects of the unanticipated conditions on the foundation design parameters.

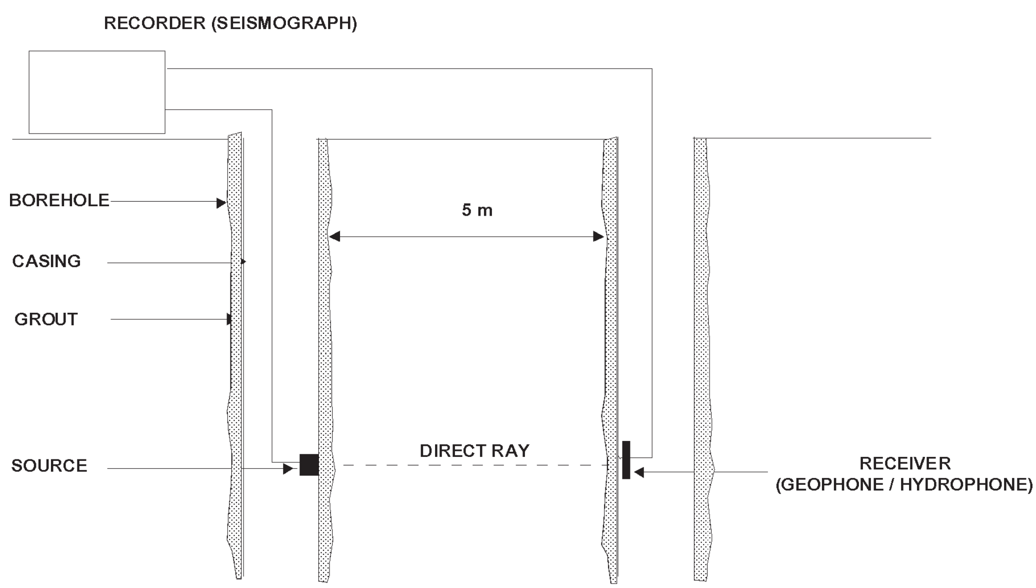

Figure 1. Cross-Hole Seismic Test Method.

SEISMIC TOMOGRAPHY

Tomography though developed in medical research where the path of rays is a straight line for making X-ray or NMR images, is comparatively more complicated for application to geophysics. This is because in acoustic propagation the ray paths become curved because of refractions which complicates the inversion significantly. However, within the past decade tomography has been used in geophysical work (Dines & Lytle 1979) for a dam site on Reunion island (Cotton et al., 1986), search for buried voids, shafts and tunnels (Lytle & Dines 1980), Pre- and post-excavation studies for a nuclear power plant (Wadhwa et al., 2005). A tomographic reconstruction requires that an integrated measure of some physical property be made along a path through an object, then an inversion of these measurements be made to obtain the distribution of material properties (Redington & Berninger, 1982). Acoustic tomograms may be made using amplitude, phase shift or travel time observations. Generally, geophysical surveys because of ease and convenience use travel time data (Kevin 1988).

The seismic source used in tomographic studies was a 'Bison' borehole hammer with hydraulic clamping device. The compressional wave receivers were unclamped vertical component geophones (hydrophones) which were molded in a downhole cable with 1 m intervals and formed itself into a 12 station geophone cable. The hydrophone cable was lowered in one borehole from 6-17 m depth. By moving the hammer incremently (1 m) the region was spanned. After this recording, the hydrophone string was moved to the next position i.e.16 m to 27 m depth by keeping one hydrophone overlapping. The waves were then produced at 1 m interval from 17 m to 28 m depth by keeping the hydrophone cable at the same position and the waves were recorded. Fig.2 shows the actual observation pattern in which every source receiver pair is connected by a straight line. Thus the procedure of moving and clamping the hammer in the source hole from 6 m to 100 m depth at 1 m interval was repeated and the P-wave arrival times were recorded. Total 1296 rays (data) were used to reconstruct tomogram between two boreholes spaced 10 m apart.

'Terraloc Mark-6' seismograph was used for data acquisition with 40μ sec sampling A/D conversion for each channel. The frequency range of the first arrival waves was 500 to 1000 Hz. For generation of and recording of P- and S- waves, up to 30 m depth, Bison's borehole hammer with hydraulic clamping device and triaxial/ vertical borehole geophones with pneumatic clamping device were used.

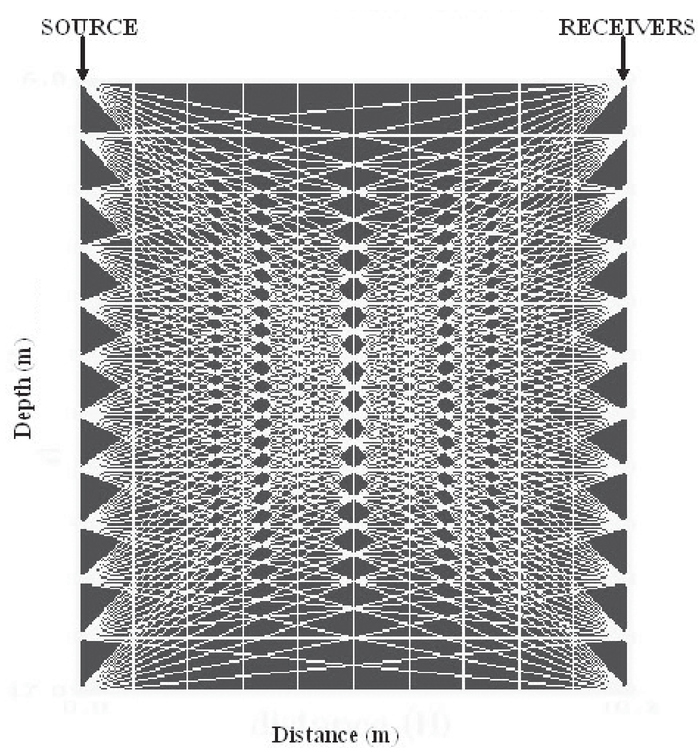

Figure 2. Ray Diagram for various positions of sources and receivers.

PROJECT SITE AND PROBLEM

Kakrapar atomic power plant is situated at Latitude 21° 14′ 6″ N and Longitude 73° 22′ E on the left bank of Tapi river. The generating capacity of the power plant is to be increased by 1400 MWe by installing two additional nuclear reactors each of generating capacity 700 MWe. General engineering design criteria for nuclear power plant requires that nuclear power plant structures, systems and components important to safety be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, tsunami and seiches without loss of capability to perform their safety functions. Therefore, the geologic, seismic and engineering characteristics of a site and its environs shall be investigated in sufficient scope and detail to provide reasonable assurance that they are sufficiently well understood to permit an adequate evaluation of the proposed site. In addition to describing the ground motion produced by safe shutdown earthquake, determination of the lithologic, stratigraphic, hydrologic and structural geologic condition of the site and the region surrounding the site, determination of static and dynamic engineering properties of the materials underlying the site is of great importance. Included should be properties needed to determine the behaviour of underlying material during earthquakes and the characteristics of the underlying material in transmitting earthquake induced motions to the foundation of the plant, such as seismic wave velocities, density, water content, porosity and strength.

GEOLOGY

Kakrapar atomic power project is situated on Deccan traps. The rock existing at site is hard grayish basalt underlying overburden comprising back filled soil, stiff silty clay and weathered rock. The groundwater level is at a depth of 3 m to 6 m below the ground surface.

RESULTS

Cross-hole Studies

All geotechnical ground investigations aim to determine stiffness, strength and other parameters in order to allow design calculations to be carried out. The small strain stiffness relevant to the design of civil engineering and building works, in general is similar to the very small strain stiffness (G_{max}). The same with depth is determined from cross-hole seismic methods.

P- and S- wave velocities determined up to 30 m depth in East and South directions at reactor building site are shown in Figs. 3a & 3b. Shear wave velocities range from 250 m/sec to 3270 m/sec. This wide range of velocities is indicative of different stiffness of overburden and rock. However, within each respective overburden unit or for that matter in the rock, the range of both shear and compressional wave velocities is much narrower (Figs. 3a & 3b). It can be seen from the figure that the bedrock i.e. the rock suitable for laying the foundation of the reactor occurs at 12 m depth. At this depth the rock quality designation (RQD) reported is 78 percent. The foundation with this shear wave velocity value can be treated as a rigid foundation. The average shear wave velocity for 30 m depth worked out to be 1050 m/sec and this yielded a fundamental period of the site to be 0.11 sec. This period should be kept in mind while designing the foundations of nuclear reactors, against design-basis-earthquake.

Tomographic Studies

The data of the borehole drilled at the centre of reactor building revealed that a weak zone in the rock exists at 89 m depth. This was inferred from the poor RQD's obtained at that depth. Though approximate vertical extent of the weak zone was established by drilling, its lateral extent could not be established. It was feared that this weak zone may adversely affect the foundation of the reactor especially in case of earthquake. Doubts were raised as to whether the poor RQD's obtained at 89 m depth were the result of faulty drilling. To resolve this problem P- wave tomographic studies up to 100 m depth were carried out in two boreholes spaced 10 m apart.

The P- wave arrival times in tomography were analysed using Simultaneous Iterative Reconstruction Technique (SIRT) by constraining the upper P- wave velocity to 6.5 km/sec and lower bound velocity of 1.0 km/ sec (Ghosh et.al., 2000). The velocity field between source and receiver boreholes was discretized on a square grid measuring 1m X 1m. Fig.4 is a tomogram of P- wave velocities from 6 m to 100 m depth. Three weak zones having lower P- wave velocities, of varying dimensions are seen in the tomogram. The first weak zone starting from 6 m depth from very close to the source hole extends up to 17 m depth in the bedrock close to the receiver hole. The width of this weak zone decreases with depth. As from cross-hole studies the foundation of the reactor has been recommended at 12 m depth; this weak zone must be treated to avoid the effect of weak zone.

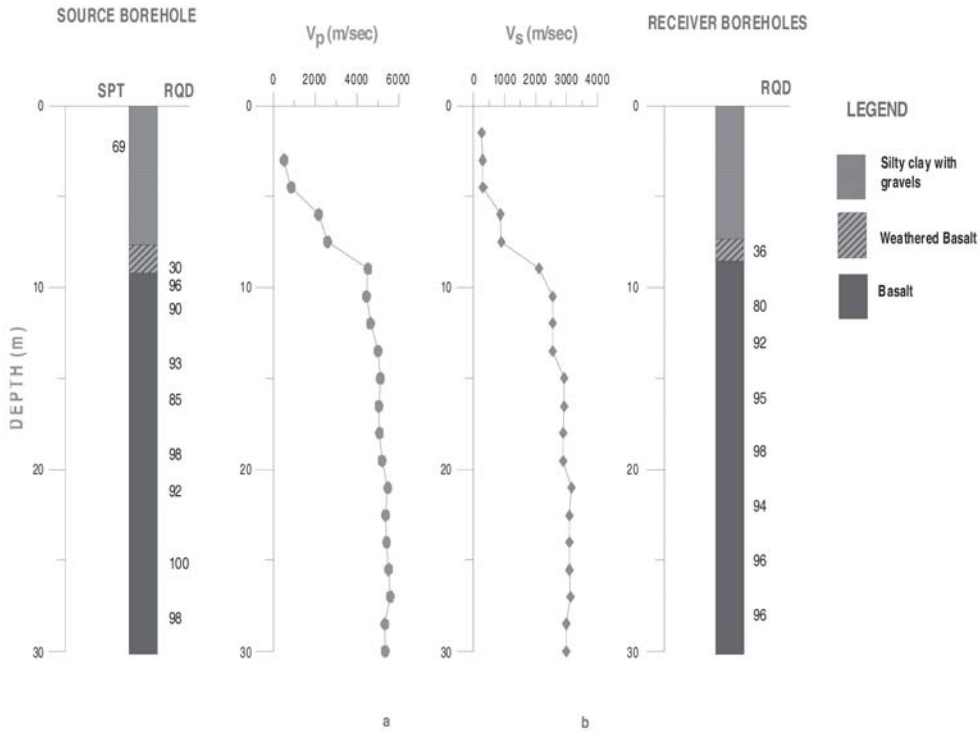

Figure 3a. Wave Velocities in east direction along with source and receiver hole logs. a) Compressional b) Shear

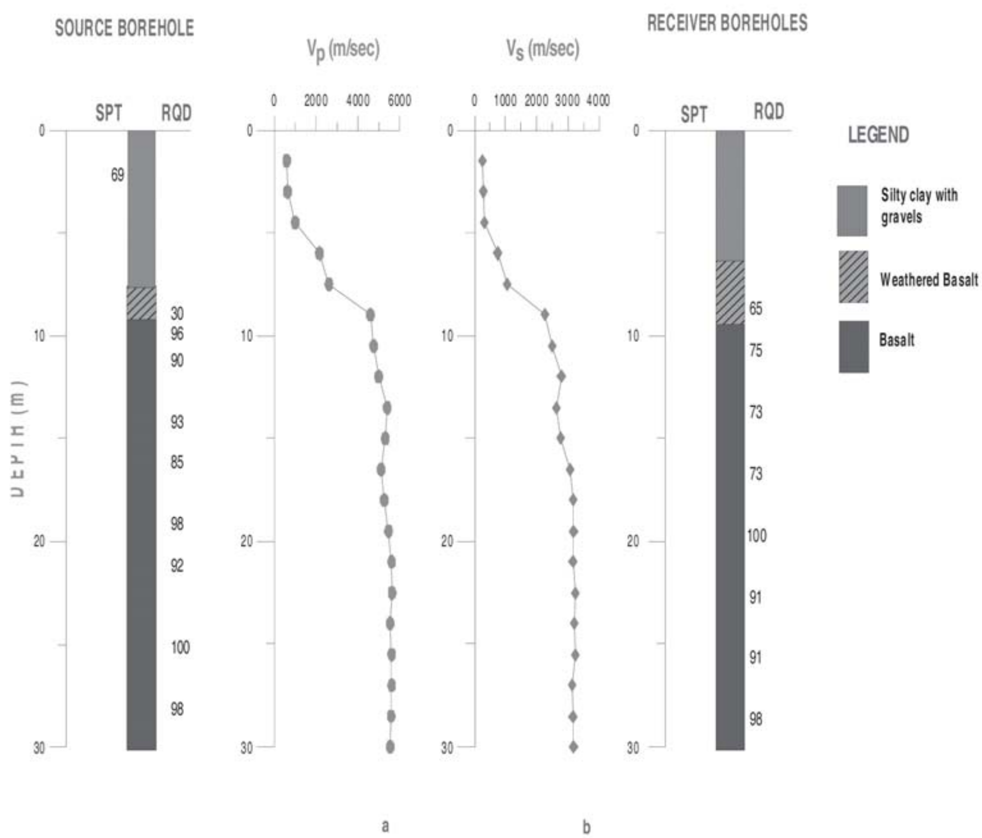

Figure 3b. Wave velocities in south direction along with source and receiver hole logs. a) Compressional b) Shear

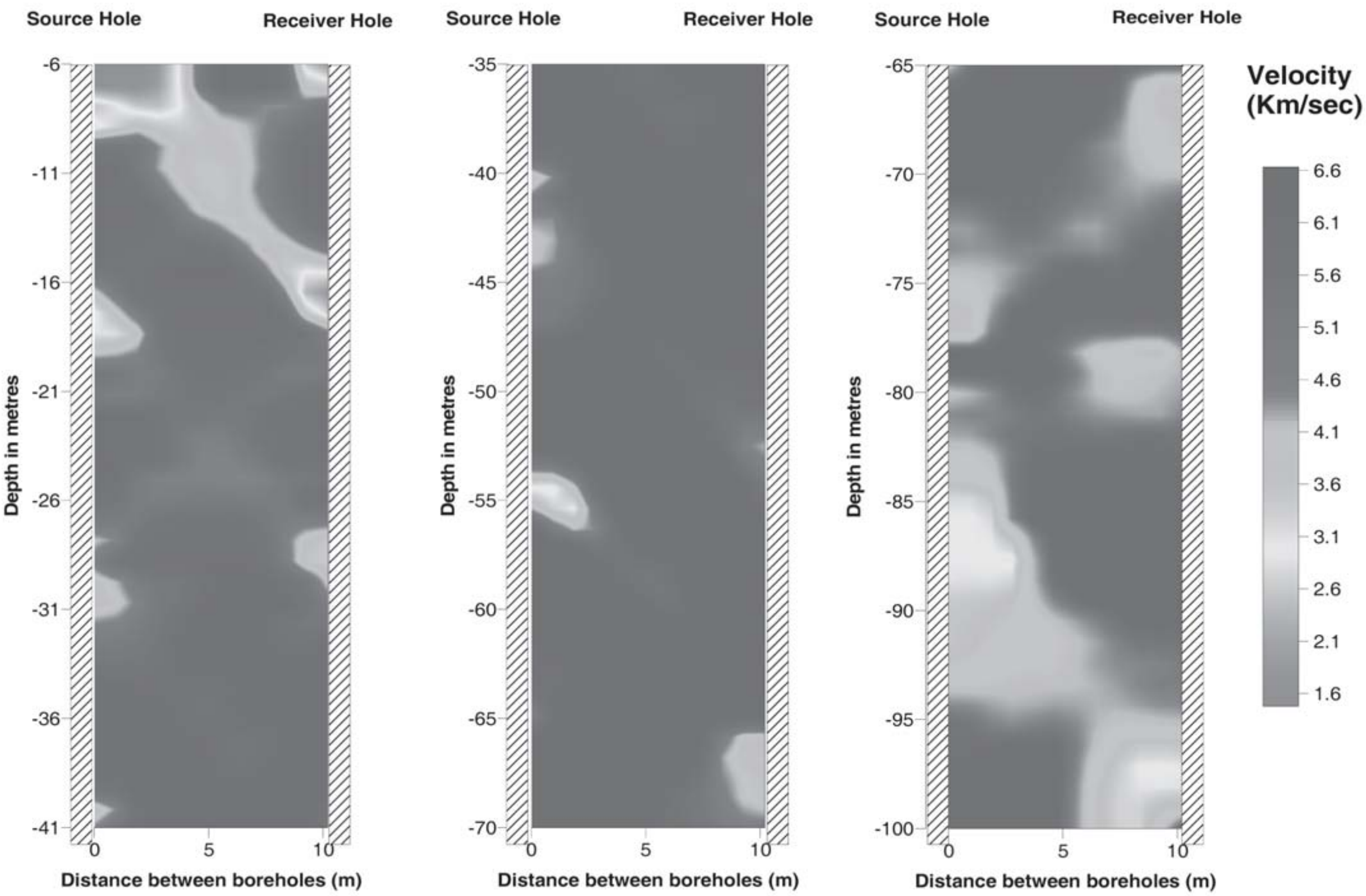

Figure 4. P-wave velocity Tomogram at reactor building-4 site.

Second weak zone in the tomogram is observed from 65 m to 75 m depth. This weak zone as opposed to the weak zone at 6 m depth occurs from source to receiver hole. Third weak zone starting from 85 m depth extending up to 100 m depth is inferred. The lateral extent of this weak zone is limited (Fig.4). The vertical extent of the weak zone is a little more than that inferred in source hole through drilling. This may be due to smoothing effect inherent in tomography. Small low velocity anomalies close to source or receiver hole seen in the tomogram, where ray density is less as also in the zones affected by drilling induced cracks can be ignored. Also narrow features observed in the tomogram should be omitted because neither technique nor data are capable of resolving such narrow features. Perhaps these are the results of either errors in picking travel time or strong scattering etc. Large velocity gradients in the tomogram lead to the reconstruction method misplacing some features because of refraction. In the remaining area, the P- wave velocity inferred is 5 km/sec and it can be inferred that the host rock is of very good quality and devoid of any fractures.

CONCLUSIONS

Having been accepted by engineers that low strain stiffness plays an important role in dynamic analysis of structures, cross-hole seismic technique provides this information with depth. Shear and compressional wave velocities evaluated from cross-hole technique can be deployed to establish the level of foundation and to evaluate the fundamental period of site. Simultaneous Iterative Reconstruction Technique produced a tomogram that was found to be consistent with a large number of observed travel-time data and drilling results. The most significant result of tomographic analysis of data was confirmation of level of foundation established using cross-hole technique as well as establishment of lateral and vertical extent of three weak zones at varying depths. Narrow features observed on tomograms should be ignored because neither technique nor data could have resolved such small features. These features result from error in picking travel time, less density of rays both near source and receiver holes as also from scattering.

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REFERENCES

Boominathan, A. & Gandhi, S.R., 2001, Summary of Geotechnical investigation and characterization and evaluation of design parameters of PFBR site Kalpakkam. Report submitted to Department of Atomic Energy, Kalpakkam by IIT Madras.

Cotton, J.F., Deletie, P., Jacquet-Francillon, H., Lakshmanan, J., Lemeine, Y. & M.Sanchez, 1986. Curved ray seismic tomography: Application to the Grand Etang Dam (Reunion Island), First break, 4, 25-30.

Dines, K.A. & R.J.Lytle, 1979. Computerized geophysical tomography, IEEE Proc., 67, 1065-1073.

Dowrick, D., 2003. Earthquake Risk Reduction, John Wiley and Sons, New York

Ghosh, N., Wadhwa, R.S.& Mukhopadhyay, R., 2000. Seismic tomography of synthetic models and a masonry dam, 3rd International R&D Conference, Central Board of Irrigation and Power (CBIP), Jabalpur, India.

Kevin T. Kilty, 1988. Acoustic tomography in shallow geophysical exploration using transform reconstruction, SAGEEP, 823-829.

Lytle, R.J. & Dines, K.A., 1980 Iterative ray tracking between boreholes for underground image reconstruction, IEEE trans. Geosci, Remote sensing, V. GE-18, 234-240.

Michalopoulos, A.P., Hanson, K.R.,.Raynand, D.A. & Arias, R.P. 1979. Measurement, selection and use of dynamic soil properties in design, Proceedings of the Seventh European Conference on soil mechanics and Foundation Engineering.

Prakash, S., 1981. Soil Dynamics, McGraw-Hill book Co, New York.

Prakash, S. & Puri, V.K., 1988. Foundations for Machines : Analysis and Design, John Wiley and Sons, New York.

Redington, R.W. & Berninger, w.h., 1982. Medical Imaging Systems, Physics Today, 34 (8), 36-46.

Richart, F.E., Jr, J.R.Hall, & Woods, R.D., 1970. Vibrations of Soils and Foundations. Prentice-Hall, Englewood, Cliffs, New Jersey.

Stokoe, K.H. & R.D.Woods, 1972. In situ shear wave velocity by cross-hole method, Journal of Soil mechanics and Foundation Division, ASCE, 98 (5), 443-460.

Wadhwa, R.S., N.Ghosh, M.S.Chaudhari, Ch. Subbarao and Raja Mukhopadhyay, 2005. Pre- and Post- excavation cross-hole seismic and geotomographic studies for a nuclear power project, J. of Ind. Geophys. Uni., 9 (1), 137-146.

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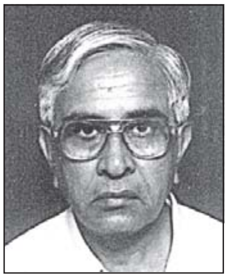

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