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Seismic tomographic inversion for rock quality evaluation

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ABSTRACT
Assessment of the quality of the rock is important for ensuring stability of an underground power house, especially in the Himalayan region traversed by numerous faults and associated weak zones. The extent of weak zones around such locations can be deciphered from the in situ seismic velocity distribution with depth. A high resolution seismic tomographic study delineating weak zones in an underground power house site is presented. The study was conducted in ten boreholes situated along a line spaced 10 m apart each, taking two boreholes at a time. The rock type available at the power house site was dolomite.

A square grid of 1 m X 1 m was chosen for the tomographic inversion based on the compressional wave velocity of dolomite rock and the dominant frequency in the recorded waveform. The reliability of tomogram construction was ensured by i) comparing the travel time data obtained from field measurements with that generated by the model in the iteration process ii) by checking whether the velocity distribution obtained is consistent with the representative values of velocities of the rock type obtained at the site and iii) by suitably constraining the iteration process through prior knowledge of rock velocities at the site. In all, nine tomograms were obtained. In the combined tomogram, where velocities of individual cells are used, eight isolated weak zones of varying dimensions and orientations were inferred.

INTRODUCTION

Assessing the quality of bed rock prior to locating a civil structure is important to ensure its integrity and stability. Seismic tomography is a closely sampled, high resolution technique for delineating weak zones in bed rock (Iyer and Hirahara, 1993). Seismic transmission tomography can be a valid tool to detect mechanical discontinuities and the decay in structures and to aid rehabilitation (Cardarelli, 2000). Seismic wave tomography can generate a cross sectional picture of an object detecting the inner defects or material properties of the rock and filled materials (Hu Chih-Hsin et al, 2012). The advantage of the tomographic technique is that it yields in situ velocity distribution of the sample area with high resolution, at much lower cost and in much shorter time. Tomography has been used extensively in geophysical work (Dines and Lytle, 1979), e.g. for a dam site on Reunion Island (cotton et al., 1986), for research on buried voids, for shafts and tunnels (Lytle and Dines, 1980) and for Pre-and Post-excavation studies for a nuclear power plant (Wadhwa et al., 2005). In tomographic reconstruction, measurement of some energy which has propagated through a medium is made and from this energy, internal distribution of the medium's character is obtained by inversion process (Redington and Berninger, 1982; Jackson and Tweeton, 1994). Acoustic tomograms can be made using amplitude, phase shift or travel time observations. Generally, cross-hole seismic tomographic surveys use travel time data (Kevin, 1988) because of ease and convenience.

Rock quality with depth was to be evaluated at the proposed underground power house for Vishnugad Pipalkoti Hydroelectric Project (VPHEP), Uttarakhand on Alaknanda river. The project area forms part of Alaknanda valley and exposed rocks belonging to Garhwal and Central Himalayan Crystalline Group, Calcareous shale and dolomitic limestone / dolomite were observed at the dam site (Executive Summary, THDC, 2009). A 650 m long adit was made in the hillock at village Hut to assess the rock quality as well as to decide the exact location for the underground power house. As the adit was excavated using explosives, the top surface of the rock is shattered and it is difficult to infer the quality of exposed dolomite rock. To assess the quality of the rock with depth and also to delineate subsurface weak zones, tomographic studies in ten NX sized boreholes separated by 10

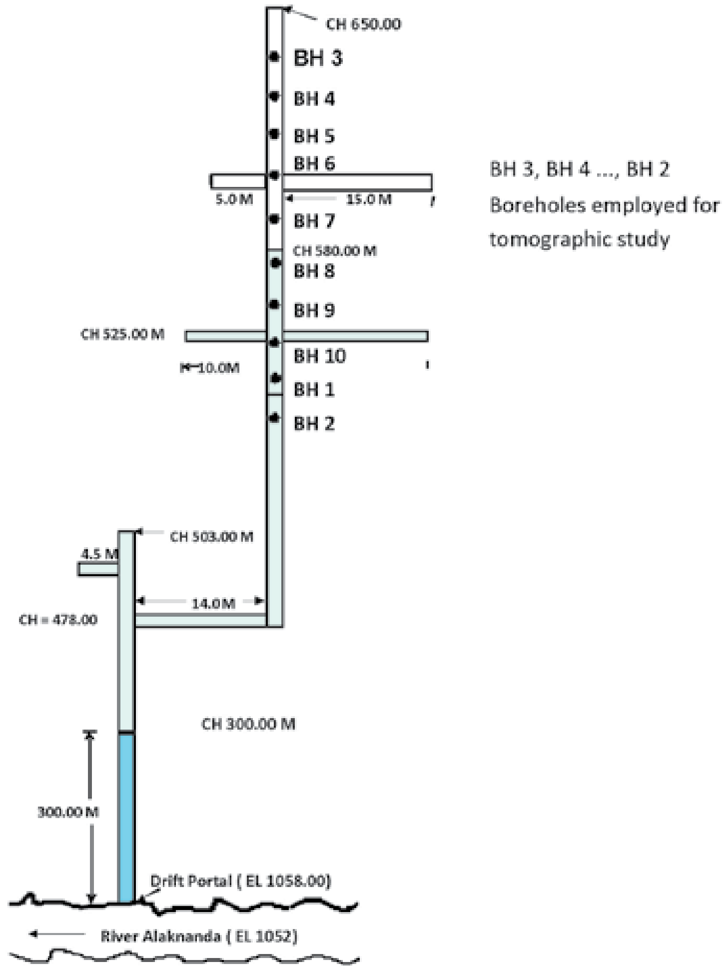

Figure 1. Location of Boreholes for Tomography Studies.

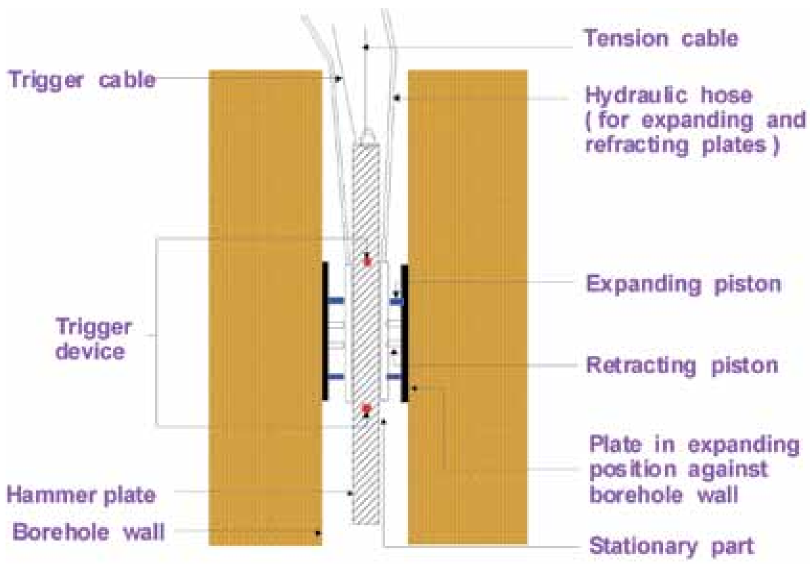

Figure 2. Schematic diagram showing details of borehole hammer

Table – I. Compressional and shear wave velocities on dolomite rock samples

Sl.No.	Depth of Sample	Bore-hole No.	Density gm/cc	Compressional wave velocity m/sec
1.	29-30m	3	2.82	4970
2.	25-26m	4	2.88	5160
3.	23.5-24.5m	9	2.82	4710
4.	14 – 15m	2	2.70	4320

m in the adit up to 46 m depth were carried out. In the area studied, P-wave velocity of good quality dolomite rock varied from 3500 m/sec to 6000 m/sec and zones having velocity less than 3500 m/sec were inferred as weak rock.

DATA ACQUISITION

A hydraulically clamped borehole hammer, a hydrophone string of 12 elements spaced 1 m apart and a 24-channel signal enhancement seismograph, 'Terraloc model MK6' were used for data acquisition. Fig.1 shows the site plan of the ten NX (76 mm inner diameter) size boreholes spaced 10 m apart drilled up to 48 m depth. Travel time data was acquired up to 46 m depth only due to length of the borehole hammer being 1.5 m. To begin with, travel time data were acquired between two consecutive boreholes i.e. BH-2 and BH-1. Hydraulically clamped borehole hammer manufactured by M/s Bison, USA was used for generating P- waves and was initially clamped at 2 m depth in the source hole. The borehole hammer consisted of a stationary part and a moving part. The stationary part comprised a hydraulic cylinder block with six horizontal pistons, three pistons for expansion (clamping) and retraction (releasing) and the other three pistons to act as a guide for smooth movement of the hammer plate (Fig.2). A trigger switch is embedded into the cylinder block and is connected to the seismograph for recording the shot instant (i.e. zero time of seismic record). The movable part of the hammer, can be lifted above or lowered below for upward or downward hitting (Ravendra Nath et al., 1992). Seismic records were taken with a sample interval of 40 micro seconds and the arrival times of the P-waves were read manually. The generated seismic waves propagate through the medium and reach the receiver borehole where the same are picked up by hydrophone chain consisting of 12 hydrophone elements placed from 2 m to 13 m depth in the adjacent borehole located 10 m away and the 12-channel record depicting the times of arrivals of P-waves was obtained. The hammer was lowered further by 1 m and was clamped at 3 m depth. P-waves produced at this depth were also recorded by keeping the hydrophone string at 2-13 m depth. Similarly, the hammer was successively lowered to depths of 4, 5, … 13 m and travel time data collected.

Similarly, the travel time data for the remaining stretches i.e. 13-24 m, 24-35 m and 35-46 m for one pair of boreholes was collected. Fig. 3 shows the actual observation pattern for 12 receiver locations and 12 source locations in which every source-receiver pair is connected by a straight line. Initially, travel time data was collected by lowering borehole hammer in BH-1 and hydrophone chain in borehole BH-2. Then, borehole hammer was retained in borehole BH-1 and hydrophone chain was lowered in the adjacent borehole BH-10 and travel time data for this borehole pair was collected. In this way tomographic data for all ten boreholes, using a pair of boreholes at a time were acquired. For one pair of borehole up to 46 m depth, total number of P-wave travel time data for all source and receiver locations was 576. These travel times were then inverted to get the velocity distribution with depth yielding nine tomograms.

P- wave ultrasonic velocities on 4 dolomite core samples collected at site were determined using non destructive ultrasonic technique using 52 KHz transducer. Portable Ultrasonic Non-Destructive Testing (PUNDIT) equipment was used in the laboratory for P- wave velocity measurements on rock samples. Table-I gives the details of laboratory studies conducted on core samples.

It is seen from the table that the compressional wave velocity of dolomite rock cores varies between 4320 m/sec and 5160 m/sec. Therefore, an upper velocity constraint of 6,000 m/sec is used for the tomographic inversion. The velocities evaluated on rock samples differ from those measured in situ and

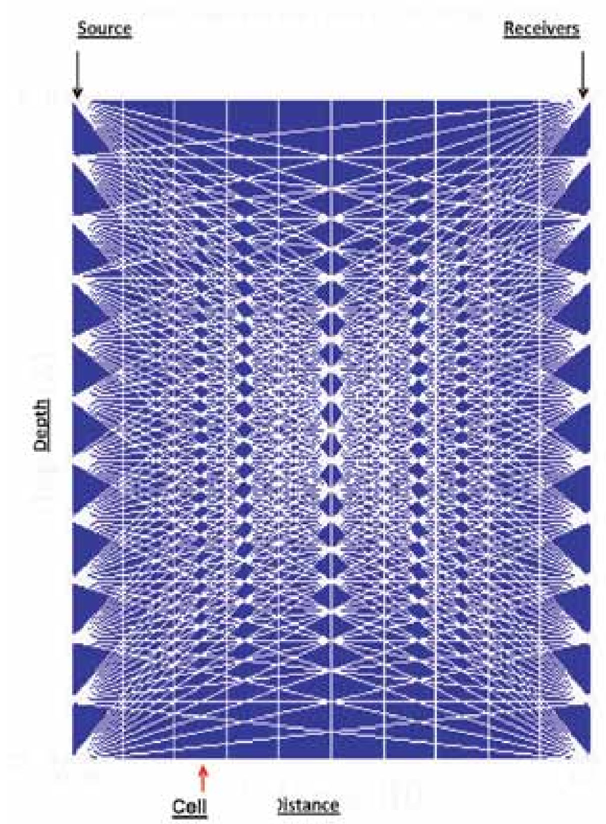

Figure 3. Ray diagram for various positions of sources and receivers

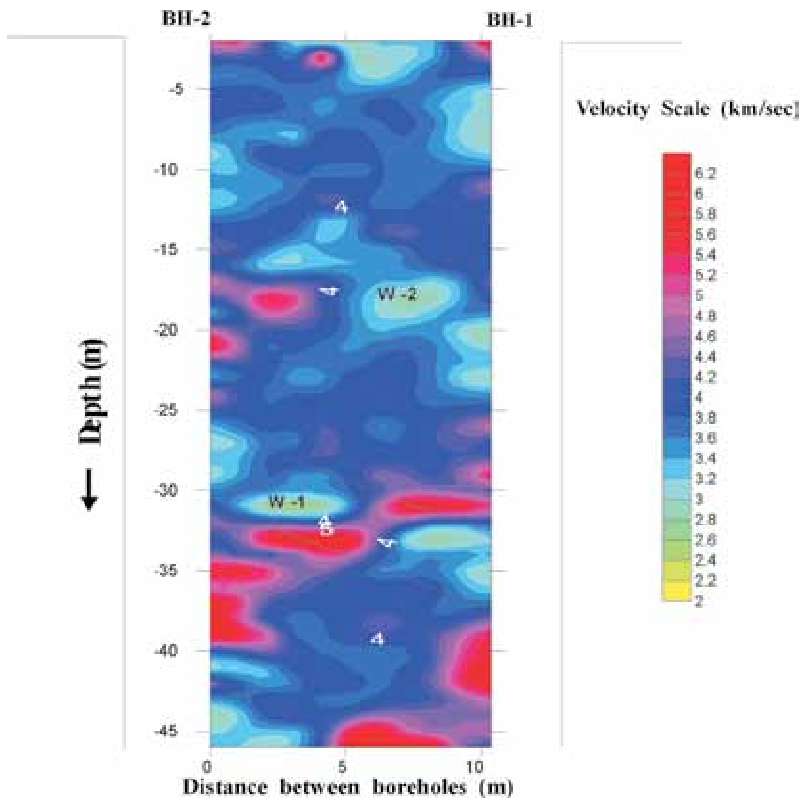

Figure 4. Contoured P- wave velocities between boreholes BH-2 and BH-1

they represent only a small volume of rock close to the borehole. As such, the P- wave velocity of 3500 m/sec and above was interpreted to be good quality intact dolomite rock while velocity below 3500 m/sec was inferred to be weak zone (Mavko, 2009, Barton, 2007).

DATA ANALYSIS

In cross-hole tomography, the zone between two boreholes is divided into small cells. The choice of number of cells depends on the total number of P-wave arrivals recorded in the field experiment. The two dimensional plane between boreholes BH-2 and BH-1 was descretised using square cells of 1m X 1 m, 44 in the vertical direction and 10 in horizontal direction, resulting in a total of 440 cells. Therefore, total 576 rays and as many equations were obtained for the various positions of sources and receivers. Therefore, in this set up, a near unique inversion is possible as the number of equations (576) is much larger than the number of unknowns (440 cell velocities). Once the cell size is decided, tomographic inversion begins with an assumption of initial model of the compressional wave velocity between two boreholes (source and receiver). With these initial average velocities, first arrival times of the rays for all possible positions of sources and receivers are calculated using straight ray tracings. These synthetic travel times are compared with the field measured travel times and the differences or residuals are inverted to obtain perturbations to the velocity model using algorithm of Jackson et al. (1992). The procedure is repeated and the velocity model is perturbed until, either there are no differences between the model travel times and the measured arrival times or RMS error is within the set limit (Singh and Singh, 1991).

The three basic steps in data analysis and processing are: (1) picking the arrival time of each recorded seismic trace, (2) inverting these travel times using tomographic software to produce an image of the compressional velocity distribution, and (3) to assess the reliability of tomograms with respect to the subsurface geology. The reliability and uniqueness of the velocity tomograms were improved by putting the lower (1800 m/sec) and upper (6000 m/sec) limits on the velocities. Analysis of synthetic model studies suggests that upper and lower velocity limits are helpful in obtaining a distribution that is unique and matches more closely with the model data (Ghosh et al., 2000). These constraints were based on the velocities of dolomite rock reported in literature (Flavio et al, 1993) and also from laboratory measurements of velocities on rock samples collected at site.

From the frequency spectrum of most of the seismic wave records, the dominant frequency of compressional waves was observed to be about 900 Hz. Taking typical compressional wave velocity of dolomite rock to be 4000 m/sec, dominant wavelength of the waves works out to be 4.4 m. The maximum allowable resolution being a quarter of the wavelength, the resolution achieved in tomographic studies was about 1 m. Therefore, in tomographic inversion of the arrival time data, in keeping with the achievable resolution, a grid size of 1m x 1m was used.

RESULTS AND DISCUSSION

The nine tomograms depicting lateral and vertical variations of P-wave velocities for the planes between two successive boreholes were obtained by inverting the arrival times using 'GEOTOM' software package. Fig. 4 is a contoured image of the P-wave velocities between boreholes BH-2 and BH-1. The lower velocities observed either very close to source or to receiver holes were ignored as they could be due to lesser ray density.

It is seen from this tomogram (Fig. 4) that there are two dipping linear strips from 8 m-14 m in BH-2 towards 18 m-25 m in BH-1 and from 26 m-31 m in BH-2 towards 33m-37m in BH-1 having lower P- wave velocities between 2000 m/sec and 3500 m/sec. It is seen from the tomogram that the velocity distributions in the horizontal and vertical directions are of the same order indicating that there is no anisotropy.

The tomogram between boreholes BH-5 and BH-6 showing P- wave velocity distribution is shown in Fig. 5. One strip of weak zone having low P- wave velocity (below 3500 m/sec) is inferred. The lower boundary of this zone starts from BH-5 at 15 m depth and extends to 25 m depth in BH-6 and upper boundary starts from 9 m in BH-5 and extends up to 17 m depth in BH-6.

In all, nine tomograms were obtained. A combined tomogram was obtained by taking velocities of individual cells from the nine individual tomograms

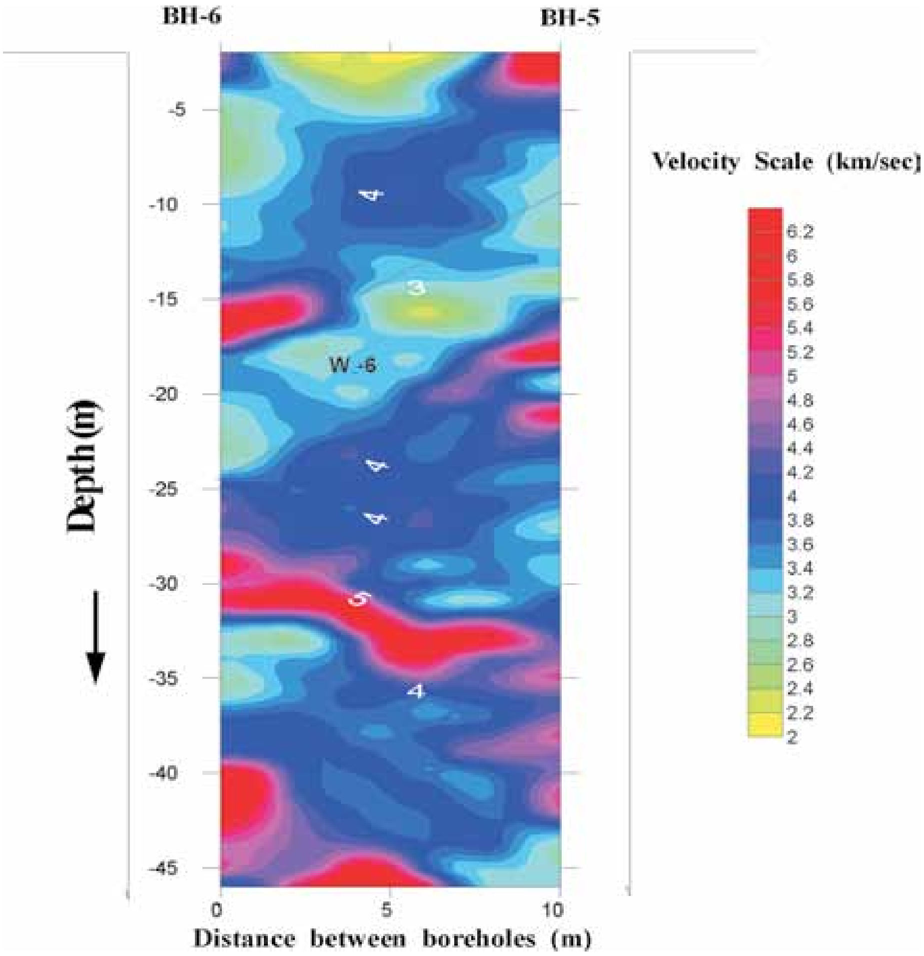

Figure 5. Contoured P- wave velocities between boreholes BH-6 and BH-5

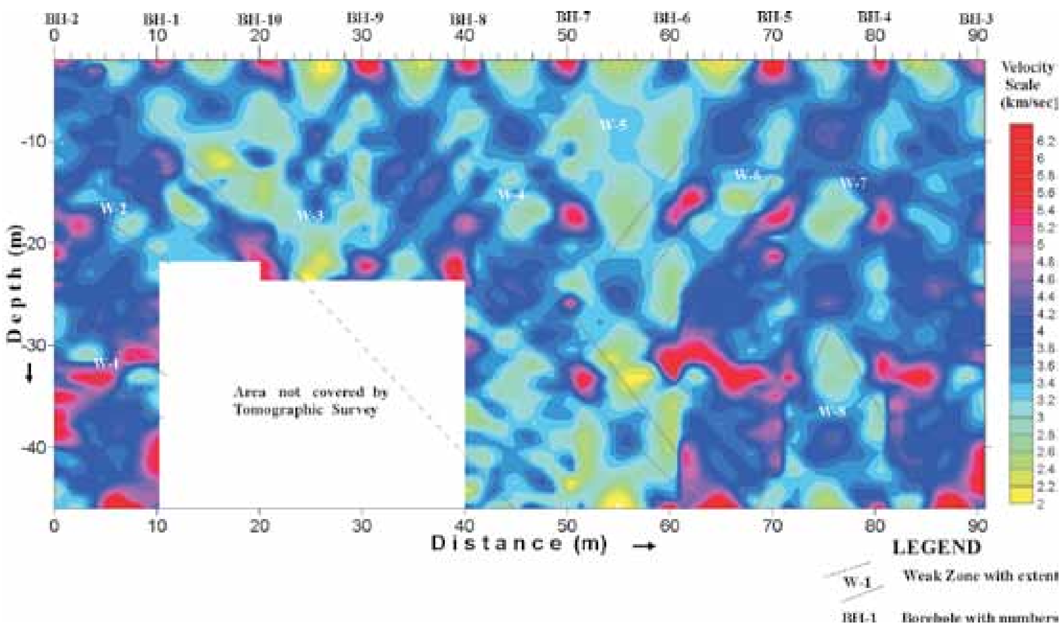

Figure 6. Contoured P-wave velocities between pairsof Boreholes 2-1, 1-10, 10-9, 9-8, 8-7, 7-6, 6-5, 5-4 & 4-3.

and is shown in Fig. 6. In the combined tomogram eight isolated weak zones of varying dimensions and orientations were inferred. The P- wave velocity of good quality dolomite rock varied between 3500 and 6000 m/sec while the velocity less than 3500 m/sec was interpreted as weak zone in dolomite. In the combined tomogram two sets of weak zones are observed. One set of weak zones i.e. weak zones W-1, W-2, W-3 and W-4 dip from top to bottom and from left to right. The second set of weak zones i.e. weak zones marked as W-5, W-6 and W-7 dip from top to bottom but from right to left. The weak zone W-8 is triangular in shape. This zone exists between boreholes BH-5 and BH-3 and extends from 30 m depth to 46 m depth.

CONCLUSIONS

The results of tomographic studies helped to map subsurface geological conditions such as weak zones between boreholes. In the combined tomogram of ten holes, eight isolated weak zones of varying dimensions and orientations were inferred. The P-wave velocity of good quality dolomite rock varied between 3500 m/sec and 6000 m/sec. The rock with velocity greater than 3500 m/sec was interpreted as intact rock, without significant fractures. However, some zones having P- wave velocities less than 3500 m/sec were inferred. These low-velocity anomalies were interpreted as weak zones. Low velocities evaluated in the regions very close either to source or to receiver boreholes are ignored as the ray density there is less. These tomographic studies indicated that the selected site would be suitable for the power house after treatment of the weak zones.

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REFERENCES

Barton Nick, 2007. Rock quality, seismic velocity, attenuation and anisotropy, Taylor and Francis group, London, U.K. p.12

Cardarelli E., 2000. Seismic transmission tomography: determination of the elastic properties of building structures (some examples), Annali Di Geofisica, Vol, 43, N.6.

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.

Executive Summary, 2009. Environmental Studies for Vishnugad Pipalkoti Hydro Electric Project, Tehri Hydroelectric Development Corporation (THDC) India Limited, P-9

Flavio S. Anselmetti and Gregor.P. Eberli, 1993, Controls on Sonic Velocity in Carbonates, PAGEOPH, Vol. 141, No. 2/3/4 287-323

Ghosh, N., Wadhwa, R.S. and Mukhopadhyay, R., 2000. Seismic Tomography of synthetic models and Masonry dam. Third International Research and Development Conference on Sustainable Development of Energy Resources, 87-95.

Hu Chih-Hsin, Hsieh Sheng-Hsung, Hsieh Chih-Hsien, Jen Kai Huang, and Chao-Ming Lin (2012), Application of Elastic Wave Tomography for Dam Safety, SAGEEP, Vol. 25, Issue 1

Iyer, H.M and Hirahara ,K.., 1993, Editors, Seismic tomography Theory and Practice, Chapman & Hall, London, p.803

Jackson, M.J., Tweeton, D.R. and Fridel, M.J., 1992. Approaches for optimizing the use of available information in cross-hole seismic tomographic reconstruction, Proc. Geotech., Geocomputing Conference, Denver, 130-143.

Jackson M. J. and Tweeton D. R., 1994, MIGRATOM-Geophysical tomography using wavefront migration and fuzzy constraints, ISSN 1066-5552, Bureau of mines, United States department of the interior

Kevin, T. K., 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.

Mavko Gary, 2009. Introduction to Rock Physics, Stanford Rock Physics Laboratory, p. 74.

Ravendra Nath, Wadhwa, R.S., Chaudhari, M.S. and Seetharam, K., 1992. Assessment of liquefaction potential of soil by cross-hole seismic technique at the proposed Kayamkulam Super Thermal Power Station, Kerala. Proc. of the Indian Geotechnical Conference, Vol. 1, 31-34.

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

Singh, R.P. and Singh, Y.P., 1991. RAYPT A new inversion technique for geotomographic data, Geophysics, 56, 1215-1227.

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; Journal of Indian Geophysical Union, 9 (1), 137-146

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