Wadhwa, R. S., Chaudhari, M. S., Chandrasekhar, V., Saha, A., Mukhopadhyay, R., Geophysical investigations for deciding alignment of head race tunnel and location of lake tapping at Koyna hydroelectric project, Maharashtra, India.
International Symposium on the Fusion Technology of Geosystem Engineering, Rock Engineering and Geophysical Exploration
Seoul, Korea, Nov. 18-19, 2003

Geophysical investigations for deciding alignment of head race tunnel and location of lake tapping at Koyna hydroelectric project, Maharashtra, India

R. S. Wadhwa, M. S. Chaudhari, V. Chandrasekhar, A. Saha, R. Mukhopadhyay
Central Water and Power Research Station, Pune,411024, India

Abstract: Continuous seismic refraction, reflection and echo-sounder surveys conducted at Koyna Project site provided geotechnical information which helped in choosing the alignment for Head race tunnel and in designing and choosing the site for Lake Tap. Seismic refraction survey both on land and in shallow water determined depths to bedrock and helped in inferring the bedrock quality. Seismic reflection survey mapped the subsurface stratigraphy with high resolution. Reservoir-bed and bedrock contours drawn from the results of the survey helped in choosing the tunnel alignment and the lake tap position cost effectively. It was inferred from the results of the survey that the geology and the quality of rock do not change unexpectedly around the site for extension of Head race tunnel and the lake tapping. The bedrock levels evaluated by seismic survey agreed remarkably well with those inferred in boreholes having Rock Quality Designation 90 percent or more.

1. Introduction

Engineering geophysical methods are a useful site investigation tool in civil engineering provided applied by experienced geophysicist and in conjunction with geological and other geotechnical site investigation methods. Most Engineers for site investigations still rely on conventional tests such as drilling, trenching etc. The conventional approach to defining the geology of a particular site has been to use pattern drilling upon bedrock. Drilling requires several days and is quite expensive. Also, geotechnical tests including drilling provide informations from point to point and values are interpolated in between places. These interpolations may be misleading in situations where there are large undulations in the subsurface bedrock or in situations where buried channels exist. Also the geotechnical tests grossly under sample the subsurface and are frequently inadequate practice (Sarman and Palmer, 1990). Correctly applied geophysics can fill the information gap by sampling a much larger volume at a lower cost (Whiteley, 1990). The geophysical exploration will reduce the number of drill holes required to attain detailed subsurface geological information. Therefore, in any engineering geological site investigation, use of geophysical techniques based on correct geological model is essential. Thus, by mapping geological strcutures with geophysics, a major saving may be made and usually the limited drilling required for the site may be completed in a very short span of time. Geophysical techniques provide continuous scanning along lines and therefore, cost to knowledge ratio is clearly in favour of geophysical techniques. The logical and correct sequence for any major economical project planning should comprise a surface geological survey, a geophysical survey and test drillings.

It is proposed to utilise more quantum of water for irrigation purposes from existing Koyna reservoir in India. For this it is proposed to have a new lake tap at RL 589 m on the extension of the existing Head Race Tunnel (HRT). For deciding the alignment for extension of HRT and for fixing new lake tap position, one of the most important input parameter is the topography of the reservoir-bed which determines the size of the natural reservoir and the available storage capacity. Also, the ideal location for the lake tapping is where the rock is of good quality, overburden thickness is minimal and the geology and the engineering properties of the rocks do not change frequently or unexpectedly (Solvik 1983). The reservoir-bed and the bedrock topography at Koyna reservoir is very uneven, and any number of boreholes even drilled in grid pattern will not be able to provide the correct subsurface information. To derive these parameters economically and continuously with depth, continuous seismic refraction, reflection and echo-sounder surveys were carried out. This derived subsurface information will help in deciding the alignment for the extension of HRT and in designing and choosing the site for piercing of the tunnel. Fig.1 shows the site plan including the area both on land and underwater covered by seismic survey.

2. Geology

The area around the proposed project mainly comprises compact and non-vesicular amygdaloidal and chlorophaeitic basalt, red or black tachylytic basalt and volcanic breccias of different kinds. Compact basalts are jointed rocks while the amygdaloidal basalts are mostly unjointed. The joint pattern is quite variable. The volcanic breccias with normal basalt lava matrix are sound rocks while those with matrix of red or black tachylytic basalt or chlorophaeitic basalt may be weak. The breccias and black tachylytic basalt are sound rocks when in situ, but deteriorate on exposure to the atmosphere. Some basalt flows are weakened by hydrothermal alteration which is responsible for changes of the normal grey colour of basalts to brown, pink or shades of red and purple.

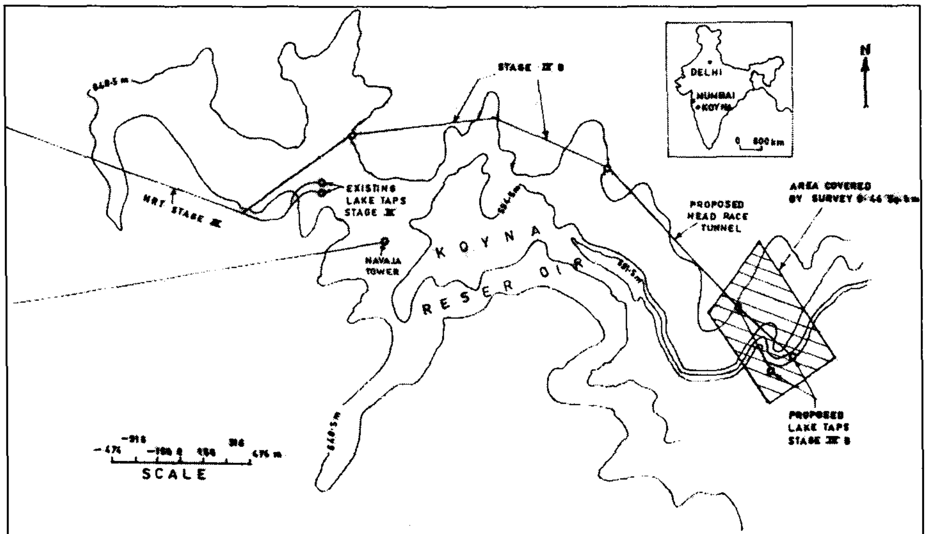

FIG. 1 SITE PLAN SHOWING AREA COVERED BY SEISMIC SURVEY

3. Methods Employed

Based on field conditions, to complete the engineering geology investigations for the project at the lowest cost and with the highest speed, integrated geophysical surveys were conducted . The methods applied include, continuous seismic refraction soundings both on land and in shallow water, hydrosonic sounding in deep water and echo-sounder soundings.

3.1 Seismic Refraction Method

Continuous profiling technique was used for field data collection and the 'Generalised Reciprocal Method' using 'Gremix' software was used for data interpretation (Palmer, 1980).

3.2 Seismic Reflection Method

Hydrosonic sounding is the most efficient of the geophysical methods. The technique provides very high resolution of the subsurface and a profile averaging 5 km length can be completed every day. Continuous underwater seismic profiling was carried out using a sub-bottom profiler system with 'boomer' seismic source. The technique requires a ship, a towed device that emits acoustic pulses at regular intervals, a detector (hydrophone) that detects the reflected signals, and a chart paper recorder to print the output of the hydrophone for a permanent record (Dobinson, A. and Mc Cann D.M., 1990).

3.3 Echo-sounder

Echo-sounder survey provides water depths by measuring elapsed time between transmission of supersonic sound pressure waves and the return of echo from the reservoir-bed. The echo-sounder survey provides continuous water depth with an accuracy of 15 cm in 30 m depth of water.

4. Equipment Employed

The instrument employed for refraction survey was a ABEM Terraloc, 24 – channel signal enhancement seismograph. Small explosive charges (130 gm to 800 gm) buried in 1.5 m deep holes were used as a source of seismic energy. Five or more recordings were made for each spread to provide reverse refraction from each seismic boundary. 4 Hz geophones were used for picking up refracted arrivals on land while the same in shallow water were detected by 10 Hz hydrophones.

Continuous underwater seismic profiling was carried out using a single channel sub-bottom profiler system manufactured by M/s EG&G, USA. The seismic source used was boomer with 300 Joules input energy. The 100 Hz hydrophone was an 8 element array with preamplifier. The hard copy of the record, depicting various subsurface layers including rock topography was printed on a EPC thermal chart paper recorder with paper width of 50 cm.

The echo-sounder used for measuring water depths precisely was Atlas Deso – 10 having output frequency of 200 kHz and with facility to print output on a 23 cm wide chart paper. The position fixing and navigation of the survey vessel was carried out using two laser operated electronic theodolites.

5. Details Of Investigations

5.1 Seismic Refraction Survey on Land and in Shallow Water

Four seismic traverses the lengths of which varied between 55 m and 115 m were taken on land. Seismic spreads with 12 or 24 geophones (depending on the spread lengths available) kept at 5 m interval were deployed. Shots were fired at 50 m interval. The traverses were aligned parallel to the shore of the reservoir to avoid large undulations in the surface topography. Fig.2 shows the locations of these traverses marked as P1, P2, P3 and P4 alongwith the proposed site for lake tapping.

Two refraction profiles marked as P5 and P6 were conducted in shallow water. For refraction profiles in shallow water, seismic cable having twelve hydrophones at 10m interval was floated on the water surface to get a spread length of 110m. To correct for the time taken for the waves to travel through water, water depth below each hydrophone was measured using portable digital echo-sounder.

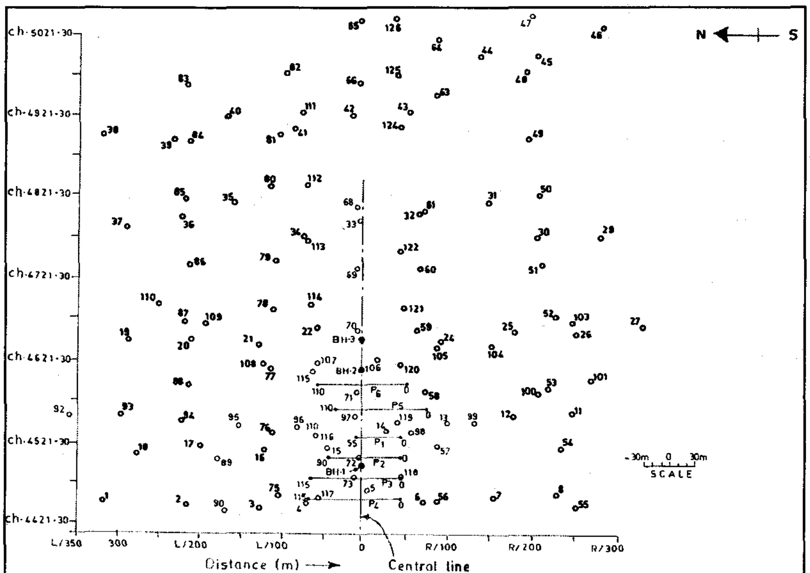

FIG.2. SITE PLAN SHOWING SEISMIC REFRACTION AND REFLECTION TRAVERSES ALONGWITH THEIR FIX NUMBERS

5.2 Seismic Reflection Survey

Underwater reflection survey using boomer seismic source having 300 Joules input energy was conducted along 14 traverses. The lengths of these profiles varied between 480 m and 740 m. Of these traverses, 7 were conducted nearly parallel to the reservoir shore while the remaining 7 were taken across these traverses. The location plan of these traverses is also shown in Fig.2.

The position co-ordinates of the survey boat as it moved along pre-marked traverses were taken every one minute using a pair of laser operated electronic theodolites. To correlate the position co-ordinate of the boat with the seismic records the fixes every one minute on the seismic record were marked. The fix numbers along each traverse are shown in Fig.2. The depths of the subsurface reflectors deciphered on the seismic records were then calculated at those fixes.

6. Results

6.1 Seismic Refraction Survey

All first arrival times were picked manually from the seismograms to the nearest quarter of a millisecond. These arrival times were tabulated and time-distance plots were constructed and interpreted using the software programme 'GREMIX' – developed by Interpex limited. This interactive data processing routine allowed plotting of each travel time plot, selection of velocity slopes, and identification of forward and reverse shot pairs. With known ground level of each geophone, the programme calculated the subsurface layer thicknesses at shot points as well as below all geophones. The depth section as inferred along traverse P1 of length 60 m taken at Chainage 4526 m is shown in Fig.3. Three subsurface layers representing loose overburden, compact/saturated overburden and rock are identified. The compressional wave velocity of loose overburden varied between 400 m/sec and 550 m/sec while the same for compact overburden was 1150 m/sec. The velocity of bedrock was evaluated to be 5800 m/sec. Near zero chainage, of this traverse, the rock is overlain both by loose and compact overburden while at Chainage 45 m, compact overburden thins out and the rock is overlain by loose overburden only. Similarly, the data for other refraction traverses also yielded two/three subsurface layers.

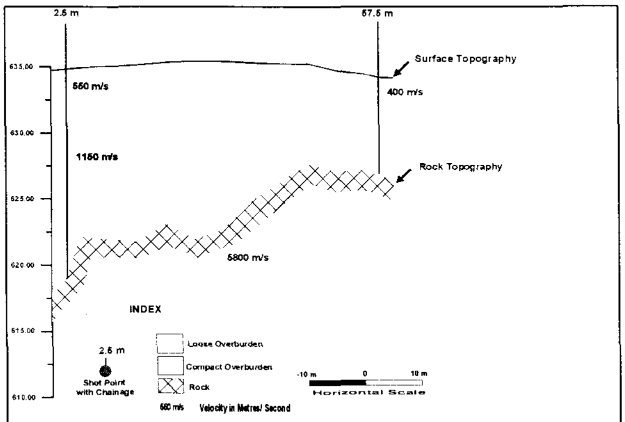

Fig. 3 : Depth- Section Along Traverse P1 (Chainage 4526 m

Results of the seismic refraction survey indicate a two/three layer model of the subsurface. The near surface seismic layer has velocity ranging from 360 m/sec to 600 m/sec and a thickness varying between 3.5 m and 9.5 m. The compact layer has velocity between 800 m/sec and 1500 m/sec with thickness of about 10m.

The depth to bedrock varied from RL 600.5 m to RL 632.0 m. The velocity of rock ranged between 4700 m/sec and 6000 m/sec which for basalt indicates good quality of rock.

Along refraction traverses P5 and P6 conducted in shallow water two layer model representing saturated overburden and bedrock was inferred. The depth-section along traverse P5 shown in Fig.4 revealed that the reservoir-bed level varies from RL 628 m to RL 623 m. The thickness of overburden ranges between 11 m and 16 m. The rock level along this traverse was inferred to be between RL 611 m and RL 616 m (Fig.4).

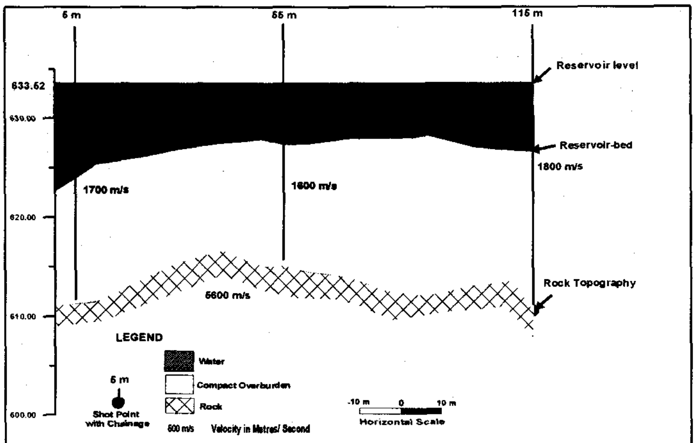

Fig. 4: Depth- Section Along Underwater Refraction Traverse P5 (Chainage 4559 m)

6.2 Seismic Reflection and Echo-Sounder Survey

In the area surveyed, on seismic reflection records, two subsurface reflectors were identified. The first reflector matched with the reservoir-bed while the second represented bedrock topography.

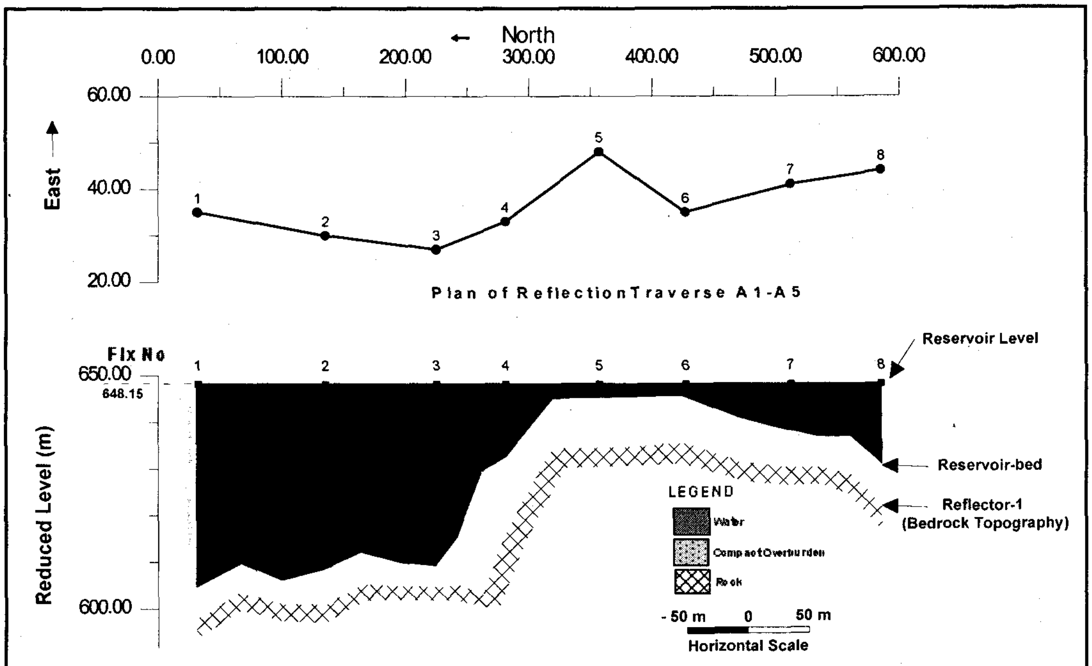

Fig. 5 : Depth-Section Along Reflection Traverse A1- A5

Depth-section with respect to reservoir level (RL 648.15 m) along traverse A1-A5 is shown in Fig.5. Along the traverse reservoir-bed is very uneven with a lot of undulations. The reservoir-bed level varies from RL 604.6 m to RL 646 m. The reservoir-bed level is at RL 604.6 m below fix 1, shallows to RL 646 m. below fixes 5 and 6 and then again deepens towards fixes 7 and 8 (Fig.5). The bedrock level along this traverse ranges between RL 597.8 m and RL 635 m; it being shallowest below fixes 5 and 6 and is the deepest below fix 1. The bedrock topography generally follows reservoir-bed levels except near fix 4 where a local depression in the bedrock is inferred. It can be inferred from this figure that any number of boreholes would not be enough to decipher reservoir-bed and bedrock topography precisely. From the boreholes drilled later to verify and calibrate the seismic results, it was seen that the bedrock levels inferred in reflection survey matched with those in the boreholes wherever the Rock Quality Designation (RQD) was more than 90 percent and continued to increase with depth. It was inferred from the results of reflection and echo-sounder surveys that the reservoir-bed levels in the area varies from RL 588.6 m to RL 645.2 m while the same for bedrock ranges between RL 575.2 m and RL 638.0 m.

7. Correlation Between Borehole Data and Seismic Results

Locations of one borehole BH-1 drilled on land and of two boreholes drilled underwater for calibration and verification of seismic results are shown in Fig.2. The correlation between subsurface stratigraphy as inferred from refraction results and those inferred in borehole BH-1 are shown in Fig.6. The level of rock with RQD greater than 90 percent is at RL 619.87 while that evaluated below shot at Chainage 57.5 m of traverse P2 is at RL 620 m. This shows the perfect match between the bedrock levels evaluated by refraction survey and that inferred in borehole results.

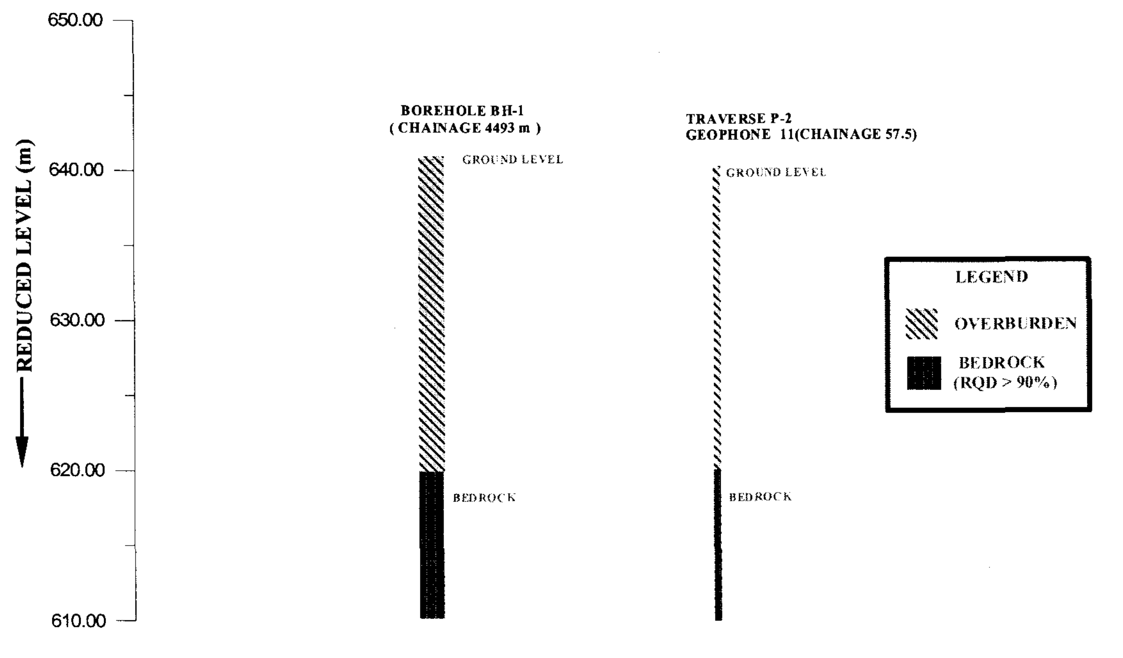

FIG.6 COMPARISON BETWEEN SEISMIC REFRACTION AND BOREHOLE RESULTS

Fig.7 shows the comparison of bedrock levels evaluated in reflection survey with those inferred in boreholes drilled underwater. The level of rock in borehole BH-2 with RQD more than 90 percent is at RL 599.98 m while below fixes 107 and 115 (Fig.2) existing near this hole the bedrock level is inferred at RL 599.6 m and at RL 600.13 m respectively. This shows the perfect match between underwater reflection and borehole results. The correlation between borehole BH-3 data and the seismic results is also shown in Fig.7.

8. Reservoir-Bed and Bedrock Contours

Using all the data from these three methods the depth contours of reservoir-bed and bedrock, at 2 m interval were drawn and are shown in Figs 8 and 9 respectively. It is seen from Fig.8 depicting reservoir-bed contours, that in the middle area surveyed there is a prominent depression tending North-Northwest. The reservoir-bed is shallowest in the West and this high is gently dipping in East and North directions. The eastern part of the area surveyed is also elevated.

The bedrock contours follow the reservoir-bed contours. The sediment thickness in South varies from 5 m to 10 m while in North the same ranges between 10 m and 15 m and is more or less uniform (10 m) in East and West.

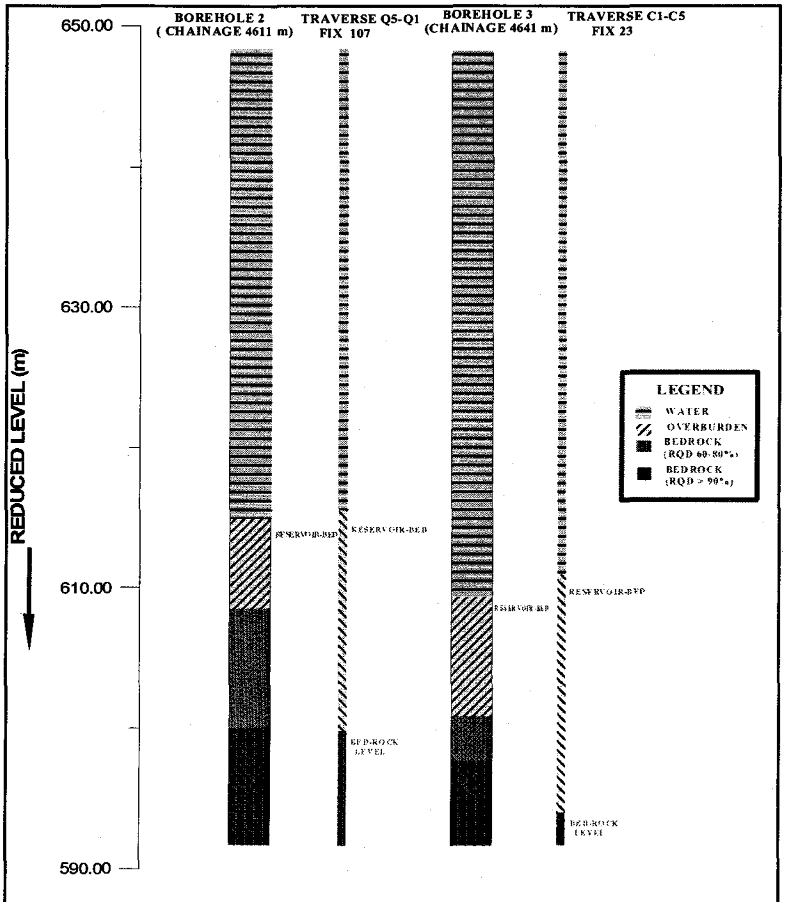

FIG.7: COMPARISON AMONG SEISMIC REFLECTION AND BOREHOLE RESULTS

9. Economics Of Survey

Geophysical surveys are intended to minimise the number of boreholes for an adequate definition of the subsurface thus saving both on cost and time. The total area of the engineering geological investigation at Koyna project covers 0.45 sq. km. To get the subsurface geological information of this area from boreholes placed 50 m apart on a grid of 100 m, the cost of drilling 120 holes will be about Rupees 2 crores. The accomplishment of drilling work would take more than 300 days. Using the integrated geophysical methods, the field data collection was completed in 15 days and at much less cost.

10. Conclusions

The refraction survey both on land and in shallow water as well as echo-sounder and seismic reflection survey successfully investigated the depth of bedrock, reservoir bed levels and thickness of overburden. In reflection survey two subsurface reflectors matching reservoir-bed and very good quality rock were inferred. The bedrock depths evaluated by seismic surveys matched with good quality rock having RQD 90 percent or more.

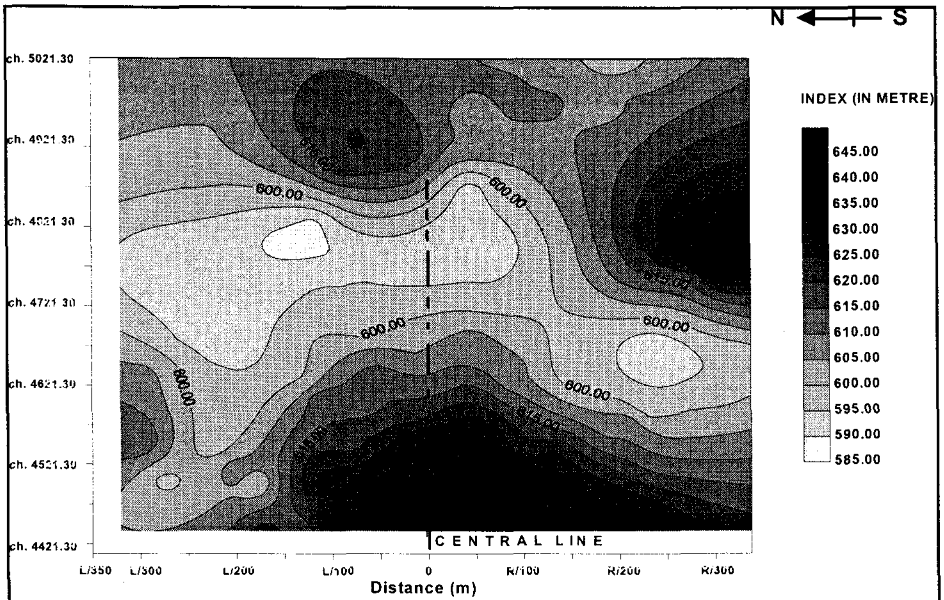

Fig.8 : Depth Contours of Reservoir-bed

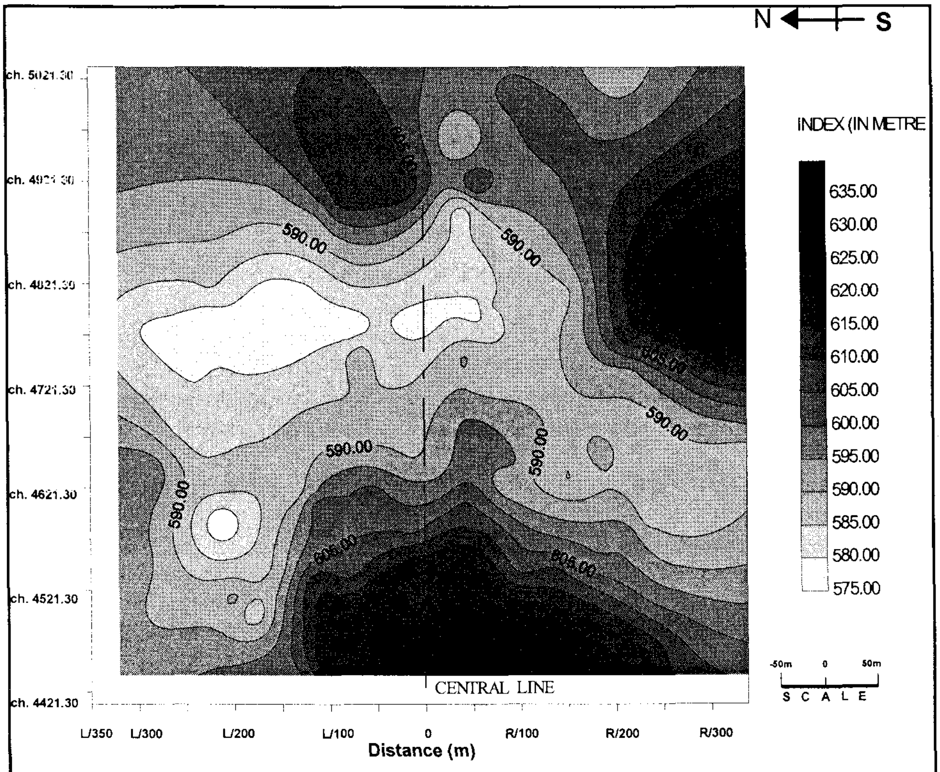

Fig.9 : Depth Contours of Bedrock (Reflector-R1)

Though there is no substitute for information that is derived by drilling holes, the seismic survey independently and cost effectively provided information about possible structures and the continuity of various layers that otherwise could not have been obtained by any amount of drilling. The drilling program with just three holes was effectively planned and better utilized in conjunction with the results of a geophysical survey to decide the extension of HRT and to locate the position for lake tapping.

Acknowledgement

The authors are grateful to Mrs. V.M. Bendre, Director, Central Water & Power Research Station, for her constant encouragement and for according permission to publish this paper. Authors are also grateful to Dr. N. Ghosh, Additional Director for useful discussions for planning the survey and in interpretation of data.

References

Dobinson, A. And Mc Cann D.M. (1990). Application of marine seismic surveying methods to engineering geological studies in near shore environment, Quarterly Journal of Engineering Geology, 23, 109-123.

Palmer, D. (1980). The Generalised Reciprocal Method of seismic refraction interpretation, Society of Exploration Geophysicists Monograph, Tulsa, OK 1 – 104.

Sarman Rakesh and Donald F. Palmer (1990). Engineering Geophysics : The need for its development and application, 6th International IAEG Congress, Rotterdam, 1017-1024.

Solvik, O., (1983). Underwater piercing of Tunnel Publication No.3, Norwegian Hydropower Tunneling, Norwegian Soil and Rock Engineering Association, Tapir Publishers/ University of Trondheim, The Neitherland, 111-114

Whiteley, R.J., 1990, Advances in engineering seismics, 6th International IAEG Congress, Rotterdam, 813-825.