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Chirp Sonar and Electrical Resistivity Imaging survey for integrity of concrete lining in a Hydel Channel

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ABSTRACT
Underwater geo-engineering survey, deploying chirp sonar system (frequency modulated signal 500 Hz to 12 KHz) along with dual frequency echo-sounder from a precisely positioned vessel was carried out along one traverse of about 1.0 km length. The survey was aimed to assess the quality of concrete lining at the bed of Nangal Hydal Channel, which is an integral part of Bhakra Nangal dam located in border of Himachal Pradesh and Punjab. The channel has a bed width between 17 m and 24 m with a 2 m/sec velocity of water flow. The integrity of channel lining was identified by measuring reflection coefficient (R) values between water and channel bed interface. Different values for the reflection coefficient are obtained for concrete lined channel bed and the channel bed where concrete lining is disturbed. At the channel bed, the R value greater than 0.69 has been inferred to represent good to very good quality concrete and the places with R value less than 0.48 have been inferred as inferior quality concrete. Compressional wave velocities have been estimated from reflection coefficients and used to infer the quality of concrete. The reflection coefficient values of 0.48 and less observed in the seismic records from channel RD 2830 m to 2920 m revealed zones of inferior quality. Electrical resistivity imaging survey conducted along two profiles on the banks of the channel revealed a few zones of comparatively higher resistivity (205 Ω m - 700 Ω m). These zones located from channel RD 2898 m to 2948 m, with varying dimensions, are attributed to the zones prone to excessive seepage. It is inferred that water is getting leaked due to inferior quality of the concrete in the channel bed and is coming out from the adjacent banks of the channel, where the same is observed in ERI sections as high resistivity zones.

INTRODUCTION

The 61 km long concrete lined Nangal Hydel Channel commissioned in 1954 is an integral part of Bhakra Nangal dam located in border of Himachal Pradesh and Punjab (Fig. 1).It has almost completed its life span, which normally is about 50 years for a concrete lined channel. In general, the depth of channel is about 6-7 m. It has a bed width between 17 m and 24 m and velocity of flow of water is 2 m/sec. The side slope of the channel is 1.25 H: 1V. The channel system, which is 6 decades old has been supplying water continuously for a fertilizer plant and a thermal power station, besides irrigation. All the maintenance and repair works of the channel have been carried out with the water flowing in the channel. To provide a new lease of life to channel and to ensure its trouble free running for the next 3-4 decades, in depth high resolution shallow sub surface imaging study of the channel bed is required. The quality of concrete at the bed of channel can be evaluated by collection of concrete core samples and testing them in the laboratory. The collection of concrete samples from high speed gushing waters is not only difficult but also the information derived will correspond to the isolated points only. Also, the sample will cover only a small volume of the concrete and the sampling procedure may affect the quality of concrete at the bed of the channel. On the other hand, geophysical methods cover larger volume and also provide continuous information of quality of in situ concrete. Of the geophysical methods, chirp sonar technique deploying wide frequency band (500 Hz to 12 KHz) provides high horizontal and vertical resolution and the measured reflection coefficient can be related with the in situ quality of concrete. Considering this, Chirp sonar survey along with dual frequency echo-sounder survey was carried out between RD 2100 m (Reduced Distance which is the distance measured from the beginning of the channel) and RD 3100 m i.e. in 1 km vulnerable stretch of the channel, to decipher the lateral extent of patches of poor quality concrete. Electrical Resistivity Imaging survey was also conducted on the bank of the channel very close to Chirp Sonar survey for delineating zones prone to seepage. The schematic site plan and layout map of chirp sonar and ERI traverses are shown in Fig. 2 and Fig. 3, respectively.

Seismic Reflection Method

The reflection of waves at the boundary between two media is a function of the change in acoustic impedance, which is a product of density and velocity (Ewing and Ewing, 1970). The quantum of reflected energy, decides whether a particular layer will be detected and recorded. The reflected energy is a function of the nature, quality and compactness of the strata existing at the channel bed. The reflection

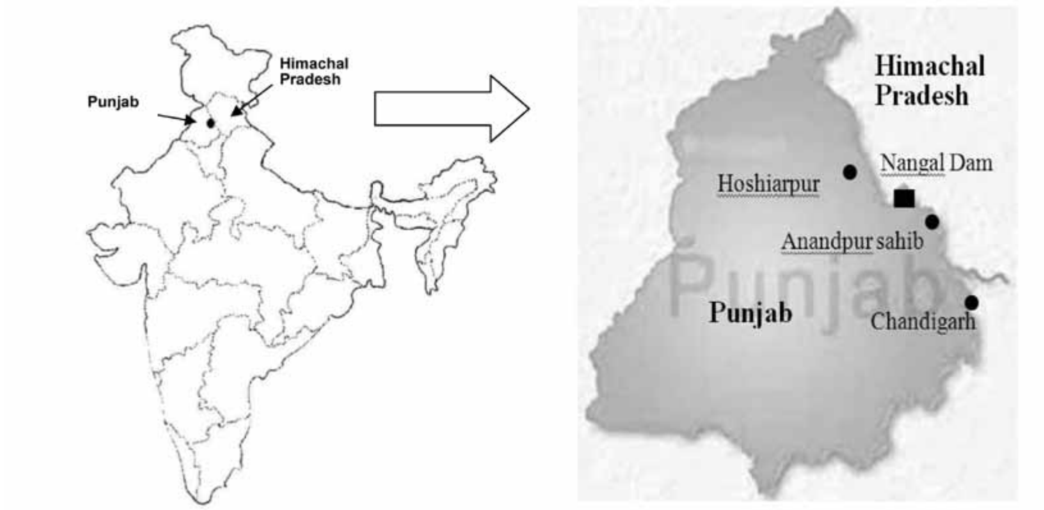


Figure 1. Location of Nangal Dam

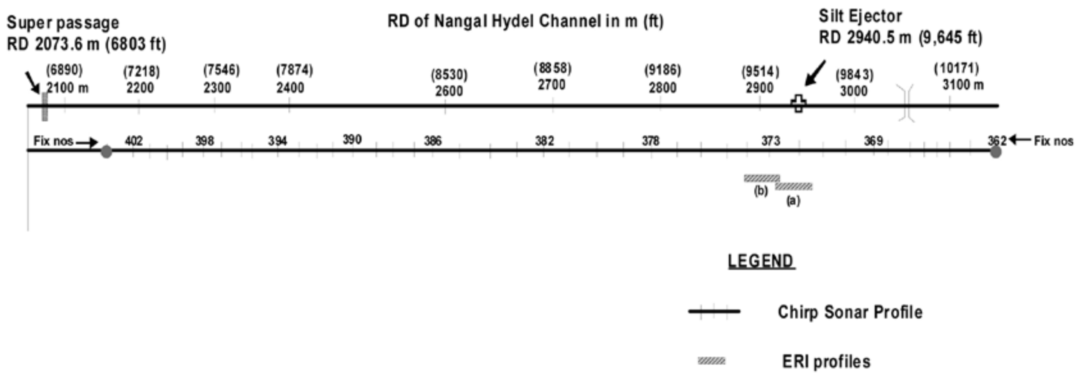


Figure 2. Schematic plan showing chirp sonar and ERI traverse

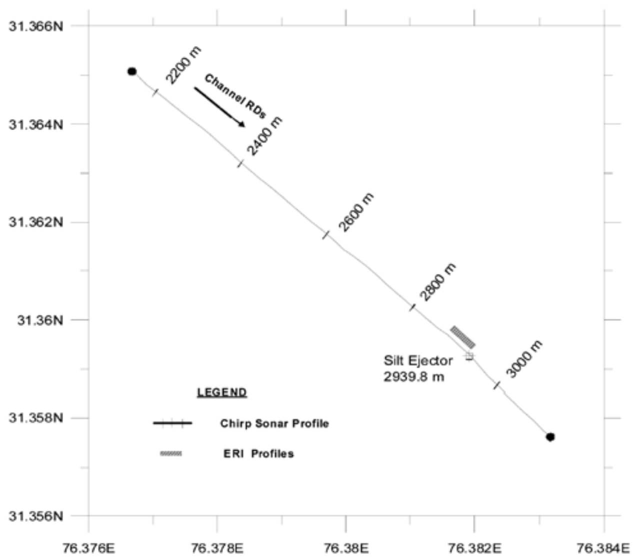


Figure 3. Layout of chirp sonar and Electrical Resistivity Imaging Profile

coefficient (R) for normal incident ray at the boundary of the interface is given by

$$R = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1} = \frac{E_2}{E_1} \qquad (1)$$

where 'ρ' and 'V' are the bulk densities and velocities on either side of the interface. 'E_1' is the incident energy and 'E_2' is the reflected energy. The order of value of 'R' provides information about the quality and compactness of the interface between the water and channel bed strata; in this case, it is concrete. The value of 'R' evaluated either using densities or compressional wave velocities or measured by the ratio of reflected and incident energy . With Chirp sonar system, the reflection coefficient of the first interface is measured by the ratio of reflected to incident energy is exactly the same.

Higher value of reflection coefficient 'R' at the bed of channel can be attributed to the compactness of the in situ concrete. The physical and elastic characteristics of the water column and underlying solids comprising channel-bed, determine the amount of wave energy that will be absorbed and thus attenuated.

Chirp Sonar Survey

Chirp sonar uses a digital calibrated linearly swept Frequency Modulated (FM) pulse that provides nearly constant resolution with depth. It uses wide band FM pulses that cover the range of frequencies from 500 Hz to 12 kHz. This wide band width ensures that sediment layers as close as 7 cm thick can be distinguished. The energy of the transmitted FM pulses can be varied from 100 to 2000 Joules by adjusting gain of the power amplifier or by selecting pulse length from 5 to 200 milliseconds.

At the time of pulse transmission, the chirp computer generates a FM signal that contains pre-determined phase corrections and amplitude correction to compensate for anomalies in the frequency response of the transducers and transmitting and receiving electronic gadgets. This compensated FM signal prevents source ringing. The Gaussian pulse spectrum is chosen for the transmitted pulse so that loss in band-width due to sediment attenuation is minimum. As the Gaussian- shaped spectrum is attenuated by sediment, energy is lost but its band-width is nearly preserved. This preserves temporal or vertical resolution of the pulse and increases sub-bottom penetration. Upon receipt of a key pulse from the deck unit, the output of the power amplifier is applied to wideband piezoelectric ceramic transducers mounted on the tow fish, which produce acoustic pulses. Sub-bottom reflections are measured at the hydrophone receiving array, the output of which is amplified by a programmable gain amplifier before being digitized by a 16-bit A/D converter. This digitized signal is processed by signal processing chip. Signal processing includes i) compression of the FM reflections to band limited impulses, ii) calculation of envelop of the compressed data by Hilbert transformation, iii) correction for the amplitude losses caused by spherical spreading and sediment attenuation losses, iv) calculation of reflection coefficients and v) perform dynamic range compression for displaying the data on terminals or hard copy recorders.

To achieve the theoretical temporal resolution predicted by the inverse of the bandwidth, chirp pulse is compressed using a matched filter. Matched filter is optimum filter for detecting a known signal in white noise. Matched filter correlates the measured sub-bottom reflections with the outgoing pulse. If reflections or noise do not resemble the outgoing pulse, the matched filter efficiency attenuates the unwanted signals. During pulse compression the matched filter improves the ratio of signal to in-band noise by

$$SNR_{input} - SNR_{output} = 10 \log t\ BW \qquad (2)$$

where t and BW are effective pulse length and bandwidth of the transmitted FM pulse respectively.

Matched filter processing also effectively attenuates side lobes. The wide bandwidth of the FM sweep has the effect of smearing the side lobes of the transducer and thus achieving a beam pattern with virtually no side lobes. The compressed pulse resulting from the signal processing procedure has a time duration approximately equal to the inverse of the bandwidth of the chirp pulse.

In pulse type sonar systems (boomer and sparker source) higher frequency content was invariably associated with an increase in resolution and decrease in penetration. Chirp technology as explained earlier reduces the trade-off between signal range and image resolution.

The resolution of an imaging system is measured by its ability to separate closely spaced objects. In a conventional single frequency system, the limit of resolution is determined by the pulse length of the transmitted waveform. However, in a multi-frequency system like chirp sonar, it is the bandwidth of the transmitted pulse that sets the limit for the system's theoretical resolution.

In conventional pulse type sonar, vertical resolution is calculated by multiplying pulse length by the speed of sound in water and dividing the product by two to account for the ping's round trip travel time.

$$\text{Resolution} = (\text{Pulse length X Speed of Sound in water}) / 2 \qquad \ldots (3)$$

Whereas, in chirp sonar vertical resolution is controlled by the bandwidth alone.

$$\text{Resolution} = \text{Speed of Sound in water} / 2 \text{ X bandwidth} \qquad \ldots (4)$$

Since the transmitted chirp pulse is highly repeatable and its peak amplitude is precisely known, it is possible

Figure 4. Chirp Sonar system (a) Topside processor (b) SB-0512i Tow fish

to estimate reflection coefficient values between water and concrete interface at every ping (pulse transmission point) from the peak pulse amplitude measurements of the bottom returns.

Some of the advantages of Chirp sonar over conventional short pulse sonar for quantitative measurements are, i) High pulse repeatability, ii) Noise free reflection data, iii) No source ringing and iv) High vertical resolution (LeBlanc et al, 1992; Schock et al, 1989, 1992).

An echo sounder essentially provides water depths from which bathymetric contour maps are prepared. Echo sounder consists of one or multiple transmitters and receivers. Transmitter generates sound waves which travel through the water and the waves reflected back from water bottom are recorded by the receiver. The depth of water "D" is calculated using the relation,

$$D = V\,T / 2 \qquad \dots (5)$$

where, V is the velocity of sound in water and T, the two-way recorded travel time. Dual Frequency Echo Sounder used in the survey operates at two frequencies of 200 kHz and 38 kHz. In this system the higher frequency i.e. 200 kHz provides precise water depth while low frequency i.e. 38 kHz gives thickness of soft sediments, if present. Penetration achieved with lower frequency is a function of geology and may vary from 1 m to 5 m depending on whether subsurface strata are sediment or clay. Bar check was carried out before the start of the survey to calibrate the echo-sounder. With echo-sounder, continuous water depths can be obtained with an accuracy of 15 cm for water depths up to 30 m (Trabant, 1984).

Chirp Sonar survey was conducted with model X-star and SB 0512i Tow fish manufactured by M/s Edge Tech (Fig.4), dual frequency echo-sounder with output frequencies 38 kHz and 200 kHz manufactured by M/s Kongsberge and a Differential Global Positioning System (DGPS) manufactured by M/s Sokkia with position accuracy of ±2 m for the moving boat.

Electrical Resistivity Imaging (ERI)

ERI is a surface geophysical method which provides a virtual cross-section of subsurface soil and rock layers in terms of resistivity values. The application of ERI in the field consists of two steps i) measuring the apparent (weighted average) electrical resistivity of the ground over numerous stations and ii) computerized processing of the measured apparent resistivity data to obtain a virtual cross-section of the subsurface showing the estimated true resistivity and thickness values. For resistivity imaging survey in the field, a large number of electrodes at fixed intervals in a line are deployed. An electric current is passed between two electrodes and the potential difference developed is measured between a second pair of electrodes. From the measured potential difference and knowing the relative disposition of current and potential electrodes, the apparent resistivity is calculated. In resistivity imaging, multiple electrodes and a computerized switching system are used to speed-up data acquisition and to choose the desired electrode configuration for field surveys automatically. The apparent resistivity values thus measured are inverted to obtain true resistivity depth section. The electrical resistivity imaging survey was conducted by `Scintrex Automatic Resistivity Imaging System' (SARIS) manufactured by M/s Scintrex. In the present study, Wenner- Schlumberger configuration was deployed.

RESULTS AND DISCUSSIONS

Reflection coefficient (R) can be found by taking the ratio of reflected energy and incident energy or by using density and compressional wave velocity. For example, a very good quality concrete will have compressional wave velocity `V_2'

Table-1. Quality of Concrete and Reflection Coefficient
(after Leslie and Cheeseman, 1949)

Sl. No.	Quality Of Concrete	P-wave Velocity in Concrete (m/sec)	Density of Concrete (Assumed) (kg/m^3)	P-wave Velocity in Water (m/sec)	Density of Water (Assumed) (kg/m^3)	Reflection Coefficient
1	Very good	4570 and above	2400 and above	1500	1000	0.76 or above
2	Good	3660 - 4570	2100-2200	1500	1000	0.69-0.74
3	Questionable	3050 -3660	2100-2200	1500	1000	0.62-0.69
4	Poor	2130 -3050	2000	1500	1000	0.48-0.62
5	Very Poor	2130 or below	2000	1500	1000	0.48 or less

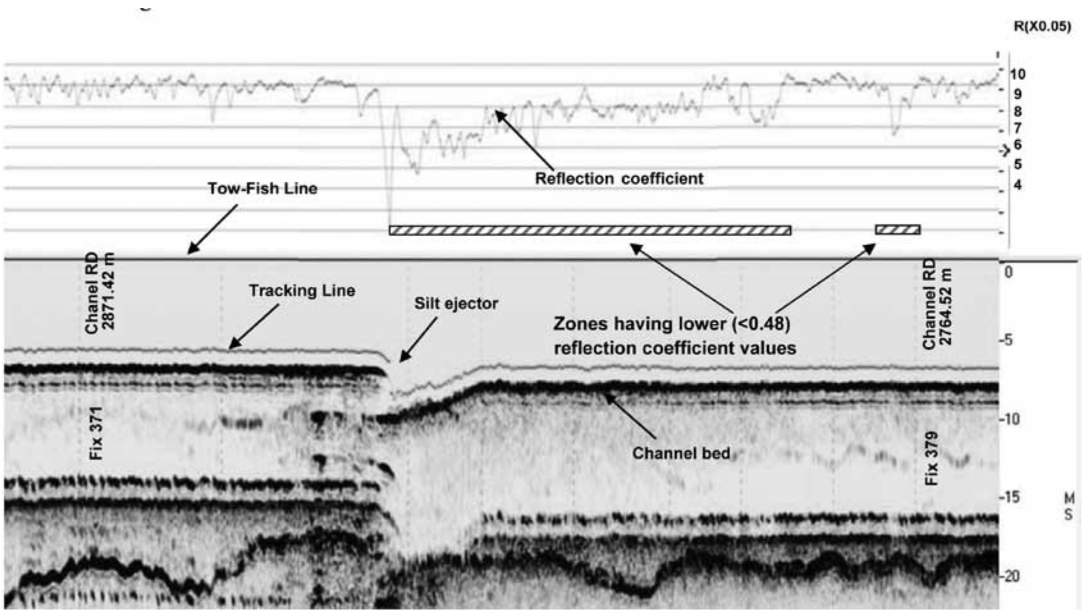


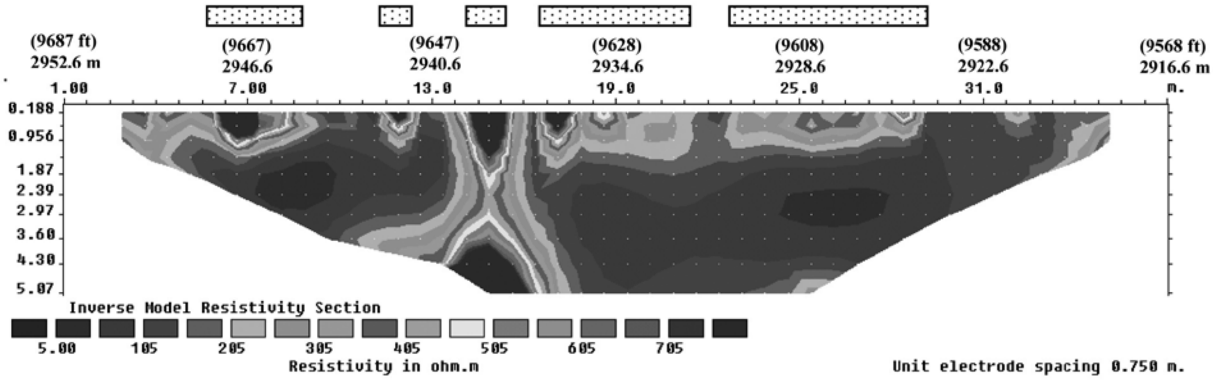
Figure 5. Typical Chirp Sonar Record Showing continuous graph of Reflection Coefficient values

= 4570 m/sec and bulk density 2400 kg/m^3. The fresh water has compressional wave velocity `V_1' = 1500 m/sec and density = 1000 kg/m^3. Substituting these values in equation (1), the reflection coefficient for very good quality concrete works out to be 0.76. Thus, a reflection coefficient of 0.76 implies a good quality concrete with velocity of 4750 m/sec. A correlation between compressional wave velocity in concrete, reflection coefficient of water and concrete interface and quality of concrete as defined by Leslie and Cheeseman (1949) is given in Table-I. This velocity criterion can be converted into reflection coefficient criterion by assuming the density of concrete and water.

In the study at Nangal Hydel Channel, as given in Table- I, the reflection coefficient greater than 0.69 (corresponding to velocity of concrete = 3660 m/sec or above) has been inferred to represent good to very good quality concrete. The reflection coefficient less than 0.48 (corresponding to concrete velocity less than 2130 m/sec) has been inferred to represent poor to very poor quality concrete. A direct correlation between reflection coefficient and quality of concrete for a specific site can be established by sampling and testing the concrete core samples in the laboratory. In the present study, the criterion given in the Table-I has been used to predict the quality of concrete at the bed of Nangal Hydel Channel.

The reflection coefficient `R' value along the traverse varied from 0.15 to 0.8. Adopting the criterion for defining the quality of concrete (given in Table-I), start and end RD's of the patches with 'R' values of 0.48 or less were found. These patches represented the location where the quality of concrete has deteriorated. The lateral extent of these zones having bad / inferior quality of concrete is shown in Fig. 7.

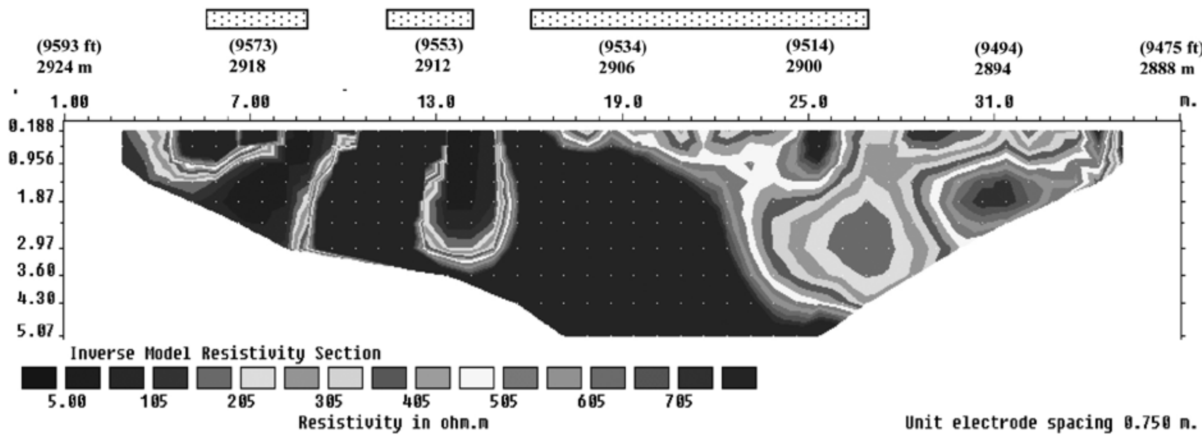
Chirp sonar record from channel RD 2764.52 m to 2871.42 m depicts continuous graph of reflection coefficient value along with channel bed (Fig. 5). The green line above channel bed is bottom tracker line. Bottom tracker



Occurrence of seepage zone with channel RD m

2948.0-2944.7	Surface to 1.5m
2942.2-2941.0	Surface to 1.5m
2939.2-2938.0	Surface to 5.1m
2936.7-2932.2	Surface to 1.9 m
2930.6-2924.2	Surface to 1.5m

Figure 6a. Resistivity imaging section showing susceptible seepage zones at Silt Ejector site (Channel RD 2952.6 m – 2916.6 m)



Occurrence of seepage zone with canal RD

2920.3-2916.9	Surface to 1 m
2914.2-2911.1	Surface to 3.6 m (maximum depth probed)
2909.3-2899.3	At varying depths (maximum 5.07 m)

Figure 6b. Resistivity Imaging section showing susceptible seepage zones near Silt ejector site (Channel RD 2924 m - 2888 m)

line indicator confirms that reflection coefficient data is calculated from the water and channel bed interface. For proper recording of the reflection coefficient values, the system calibration factor as suggested by the manufacturer is adjusted before conducting the survey. The zones having reflection coefficient values lower than 0.48 were also marked in Fig. 5.

Two Electrical Resistivity Imaging (ERI) profiles using Wenner-Schlumberger configuration were taken on the bank of the channel. For ERI survey, 50 electrodes in a line at 0.75 m interval were deployed. Two resistivity imaging sections from channel RD 2952.6 m to 2916.6 m and 2924 m to 2888 m of 36.75 m length each near silt ejector site were taken. These profiles were taken in the opposite direction of the channel flow. Electrical resistivity imaging survey revealed 8 zones of varying dimensions, having comparatively higher resistivity values from 205 Ω m to 700 Ω m (Fig. 6a and 6b). These electrical resistivity zones are marked and are also shown in Fig. 7.

Curtis (1988, 1990) studied the relationship between hydraulic conductivity and electrical resistivity of fresh waters for evaluating the potential for artificial recharge. He showed that hydraulic conductivity increased as resistivity of the vadose zone sediments increased. Based on this observation, it can be inferred that as resistivity of the saturated zone increases the seepage rate can be expected

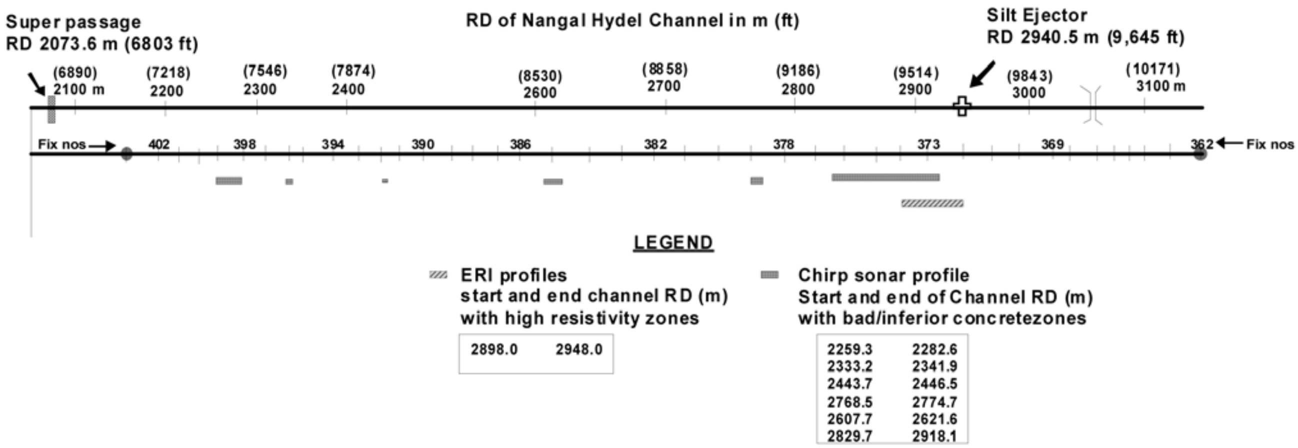


Figure 7. Nangal Hydel Channel RDs showing patches of bad and inferior quality concrete

to increase. This is because seepage of water through a saturated zone leads to replacement of finer particles (clay) by coarser material (sand), which increases the resistivity of the saturated zone. Butler and Llopis (1990) categorized geophysical methods in primary that are directly sensitive to seepage and secondary that are indirectly sensitive to a phenomenon that is a consequence of seepage. The direct detection method is based on the fact that the seepage water brings a seasonal resistivity variation, whereas the indirect detection method is based on the changing electrical properties of the soil that may be caused by internal erosion. Internal erosion is the reason why weak zones can take the form of high-resistive anomalies. When internal erosion occurs, the fine particles of the soil are washed out. This process affects the resistivity in two aspects, each working against the other. Firstly, the porosity of the core increases, which leads to a decrease of the resistivity due to higher water content. Secondly, the reduction of the fine content in itself increases the resistivity (Sjödahl, 2006, 2008). Laboratory test performed by Bergström (1998) on some Swedish glacial tills used for sealing layers on waste deposits indicate a significant increase in resistivity when the fine content is removed. The inset tables in Fig. 6a and 6b show lateral and vertical extent of seepage zones close to the channel as inferred from ERI sections.

Inset tables in Fig. 7 depict start and end RDs of bad/ inferior concrete zones and high resistivity zones. Along remaining RDs of the channel covered by the survey good to very good quality concrete has been inferred.

It can be seen that at the locations where concrete quality is poor (R <0.48, channel RD 2830 m to 2920 m), the resistivity of the strata on the channel banks is relatively high, (205 Ω m - 700 Ω m, Channel RD 2898 m – 2948 m). There is an overlap between channel RDs 2898 m to 2920 m in these two findings (Fig.7). It is therefore inferred that water is getting leaked due to inferior quality of the concrete in the channel bed and is coming out from the adjacent banks of the channel where the same is observed in ERI sections as high resistivity zones.

CONCLUSIONS

The values of reflection coefficient at the interface of water and concrete evaluated using Chirp sonar are utilized to find out the compressional wave velocity of concrete ,which can be attributed to the quality of concrete. Reflection coefficient above 0.69 is inferred to be representing good to very good quality concrete. The reflection coefficient less than 0.48 is interpreted to be relatively inferior quality of concrete. Based on these criteria, the lateral extents of patches having bad / inferior quality concrete are inferred. However, this relationship is generally site specific and hence cannot be applied to other locations. Electrical resistivity imaging survey conducted at two locations revealed 8 zones of varying dimensions, having comparatively higher resistivity (205 Ω m - 700 Ω m) values from channel RD 2898 m to 2948 m with varying dimensions, attributed to the zones prone to excessive seepage. The reflection coefficient values of 0.48 and less observed in the seismic records from channel RD 2830 m to 2920 m are identified as the zones prone to excessive seepage. These findings are helpful in identifying the seepage areas scientifically and further to restrict the treatment to the seepage portions of the channel, thereby saving on cost and time.

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