SEISMIC TOMOGRAPHY FOR INTERNAL CONDITION INVESTIGATION AND ASSESSMENT OF QUANTITY OF GROUTING FOR CONCRETE AND MASONRY DAMS

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ABSTRACT

Engineering geophysics is regularly used to augment geotechnical data for site characterization. Despite being essentially same as engineering geophysics, dam geophysics is relatively new entrant to the field of applied geophysics. Dams, like any civil structure, require regular monitoring and maintenance. The size and complexity of dams does not permit conventional invasive inspections. Geophysical surveys on a number of dams have provided extremely useful information about internal condition of the dams. Improvements in geophysical equipment and processing software have made it possible to interpret and display results with better precision. This has made dam geophysics extremely useful to dam owners.

Choosing a cost effective methodology for specific problems in dams is critical for success of a dam rehabilitation and improvement program. To date, grouting remains technique of choice for rehabilitation of concrete and masonry dams. Use of seismic tomography (with electrical resistivity tomography) provides detailed information about zones of deterioration inside the dam body. This information can provide reasonably accurate estimates of grouting which can be used for a targeted rehabilitation and prioritization in case of time and budget constraints.

Present paper demonstrates application of seismic tomography for mapping internal condition of dams for assessing optimal grouting quantity estimation.

1. INTRODUCTION

Sub-surface imaging by geophysical surveys is an extensively used tool for subsurface mapping. Continuing improvements in survey equipment performance and advances in processing and imaging software have made it possible to detect, display, and interpret small geological features with greater accuracy.

Geophysical methods are sensitive to contrast in the physical properties in the subsurface. Different methods respond to different physical properties, like material strength, material conductivity (linked to water saturation), fluid movement (seepage), change in density etc. The application of geophysical methods to dams enables detection of problems in early stages and hence can become part of dam safety surveillance program. Geophysical techniques, by virtue of their non-invasive and non-destructive nature, offer an excellent solution for investigation or regular monitoring of dams, and detection of anomalous conditions which might snowball into major problems if left untreated.

Once a problem has been detected and zones/areas requiring repair have been identified, the selection of right rehabilitation technique and associated costs need to be decided. Grouting remains a preferred method of choice for rehabilitation of concrete and masonry dams. However, best possible results from grouting can be expected when a rehabilitation program is properly designed, methodically executed and equitably rewarded. By using a combination of geophysical techniques (electrical resistivity imaging and seismic tomography), it is possible to map zones of deterioration in dam body. It is also possible to assess the quantity of grouting required. Armed with this vital information, dam owners can plan and budget for dam rehabilitation program. It is also possible to prioritize zones which require urgent repairs if the time and budget are do not permit undertaking repairs of entire dam in one go.

2. DAM GEOPHYSICS METHODS

The appropriate techniques for investigations should be chosen based on factors such as objective of investigations, resolution required, depth of investigation required, physical property to be defined, eometry and construction of dam and ature of target & host material. Table 1 provides a matrix of capabilities and applicability of various techniques:

Table 1 : Capabilities and Applicability of Various Techniques

Geophysical Surveys for Dam Investigations				
Method	**Sensitive To...**	**Typical Applications**	**Advantages**	**Suitable Dams**
Resistivity Imaging	Moisture content variations, conductivity, water table, porosity	Detection of Saturated Zones, Phreatic line	Ability to detect seepage zones, weak zones, cavities and voids	Earthen (Excellent), Masonry (Excellent), Concrete (Marginal)
Streaming Potential	Water flow through porous medium	Detects seepage paths and quantum of seepage	Ability to differentiate between 'saturated' and 'Seepage Zones'	Earthen (Excellent), Masonry (Excellent), Concrete (Marginal)
Seismic Refraction	Changes in strata type based on P Wave velocity (Elastic Property)	Determination of strength of dam material, foundation condition assessment, Phreatic line	Ability to determine P wave velocities, which can be converted to density of material	Earthen (Excellent), Masonry (Excellent), Concrete (Marginal)
ReMi (Refraction Micro-tremor)	Change in shear properties of medium, based on S Wave velocities	Determination of strength of dam material, foundation condition assessment	Determines shear wave profile without any boreholes. More advanced and easier than MASW/SASW	Earthen (Excellent), Masonry (Excellent), Concrete (Excellent)
Seismic Tomography (Cross-face or cross-hole)	Difference in elastic properties. Variations in P Wave velocity.	Detailed assessment of strength of dam material	Very high resolution, weak zones readily idenfiable	Concrete(Excellent), Masonry (Marginal
Ground Penetrating Radar	Change in dielectric properties	Detection of buried pipes and cables, voids, cavities	High resolution mapping of shallow features	Earthen (Marginal), Masonry (Marginal), Concrete (Excellent)

3. ELECTRICAL RESISTIVITY IMAGING

The method uses pairs of electrodes to inject current into the ground and measure the resulting electrical potential distribution. For field data acquisition, ERI profiles are conducted on dam crest. The length of profile and electrode spacing are selected based on the depth of investigation. Typically the maximum depth of investigation is in the central portion of the dam which reduces towards the abutments. As the depth of investigation by ERI reduces at the ends, the profiles can be extended farther away from abutments. To plant electrodes into dam crest, holes of 18-20mm diameter and 250-300mm are drilled using a portable drilling machine.

Fig. 1 : Electrodes planted on dam crest

Fig. 2 : ERI profile on dam crest

If sufficient width is available, two ERI profiles (one towards upstream and other towards downstream) can be planned. It is not practically possible to plant electrodes in spillway portion. To overcome this, electrodes can be planted on the crown of galleries. Many dams have spillways in major part of their alignment. In such cases, ERI is not advisable.

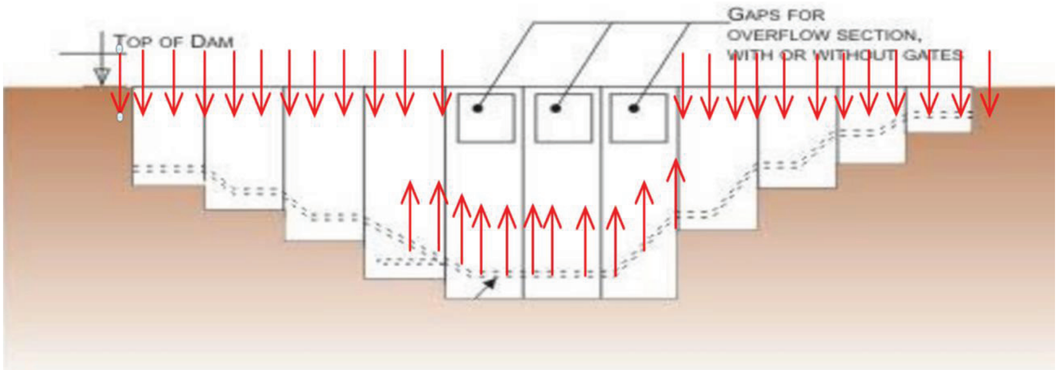


Fig. 3 : Alternate arrangement for ERI in dam with spillways

The results of electrical surveys carried out on the crest of a dam are presented as vertical sections showing the electrical properties of the dam materials. Electrical currents travel along preferential pathways in the most conductive materials such as dam core composed on fine grained materials. The method provides picture of internal resistivity distribution of the dam structure, identifying areas of water saturation in the dam body, and thus identifying the zones of water accumulation and wetting.

2D Resistivity Imaging uses an array of electrodes (typically 40-60) connected by multicore cable to provide a linear depth profile, or pseudosection, of the variation in resistivity both along the survey line and with depth. The modelled results are displayed as scaled resistivity-depth pseudosection as illustrated below in Fig. 1. Blue zones represent areas of low resistivity whilst reds are relatively higher. The wedge shape of the plot illustrates the gradual reduction in the amount of data acquired as the current and potential electrode spacing are increased.

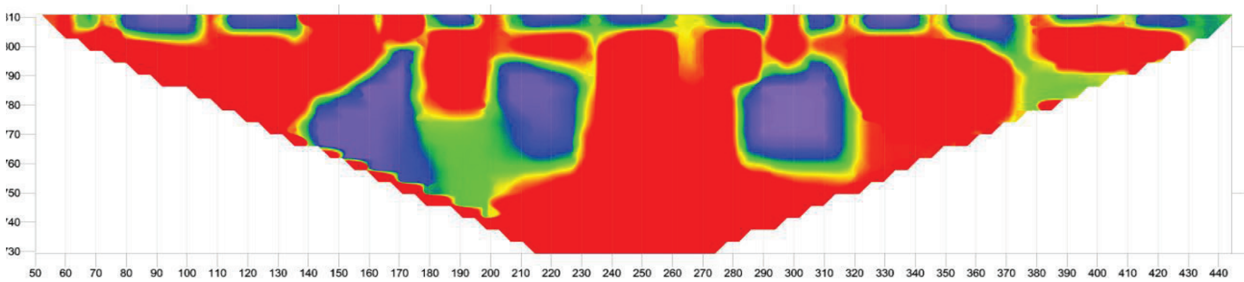


Figure 4 : Electrical Resistivity Section Showing Zone of Saturation (Blue)

4. SESIMIC TOMOGRAPHY

Seismic Tomography is conducted between a pair of receivers and transmitters. The seismic method is based on generation of elastic energy using various sources which is propagated through the investigated structure following different modalities and tracks depending on elastic properties variations of particular material crossed. The elastic waves are recorded by specific sensor in the form of electric signals.

Velocity analysis consists of an estimation of time needed by the elastic impulse to cover the distance between the transmitter-receiver couple. Therefore the second step consists of time-distance processing of data set to calculate sonic velocity distributions and to estimate a tightly linked parameters with elastic properties of investigated area. Seismic tomography survey provide maps (called tomograms) that show the velocity distributions of elastic waves along plane sections. This process starts from measuring the travel time of longitudinal waves along high number of ray tracks which reciprocally cross each other within the area between transmitter and receiver position. Tomography resolution and then the final results accuracy are determined by numbers of ray paths acquired and with their angular covering.

Seismic survey is performed in two configurations- L-section tomography and Cross face or cross section tomography. L-section tomography is performed between dam crest and dam gallery. In case of multiple galleries, L-section tomography is conducted between dam top and first gallery, between first gallery and second gallery and so on. Cross face tomography is conducted between upstream and downstream faces of the dam.

For L-section tomography, multiple receivers (24-48 geophones of suitable type) are planted on gallery crown and seismic hammer is used as energy source. Depending upon gam geometry and height difference between dam top and gallery, geophone spacing and hammer shot point spacing is decided.

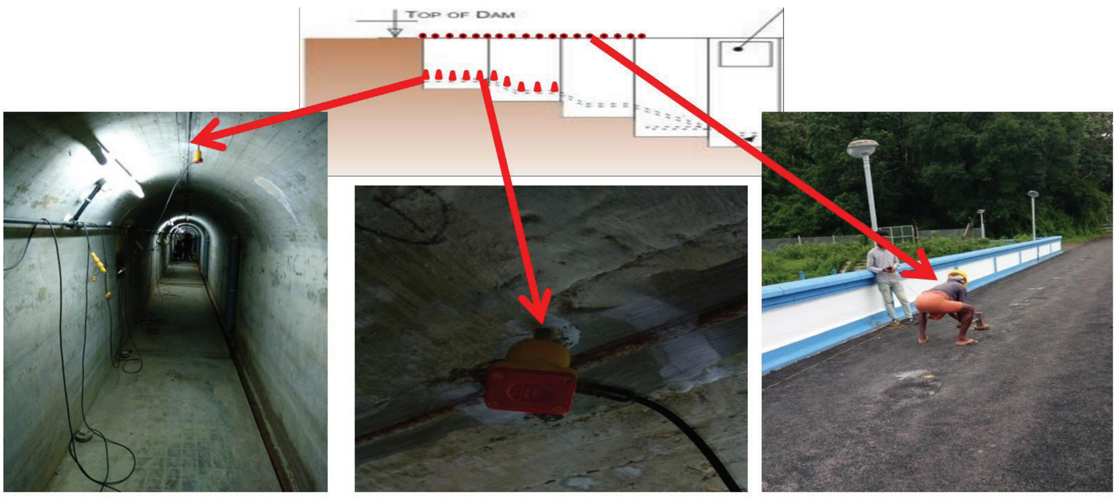


Fig. 5 : L-section tomography arrangement

Typically 50-100m length can be covered in one L-section tomography. Depending on the length of the dam, profiles are repeated till full length of the dam is covered. For covering spillway part of the dam, hammering is done on spillways with additional safety arrangements.

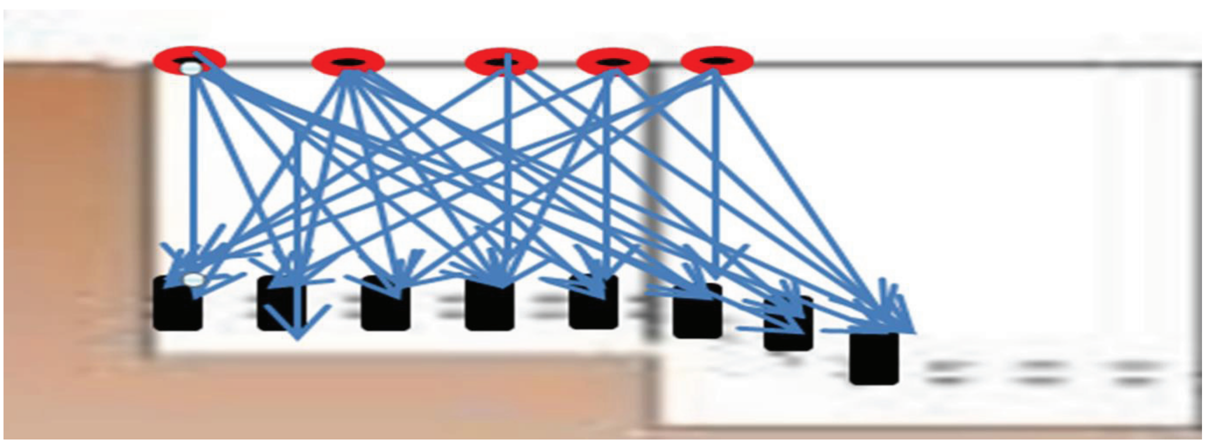


Fig 6 : L-section tomography ray path coverage

Based on the anomalous zones identified in L-section tomography, cross face tomography between upstream and downstream face is conducted. Cross face tomography requires more elaborate arrangements and is more expensive and therefore should be done selectively.

For underwater portion on upstream side, two options are available- use of a hydrophone string as receiver on upstream face and hammering on downstream side with a seismic hammer or use of sparker on upstream face and geophones/ accelerometers on downstream face.

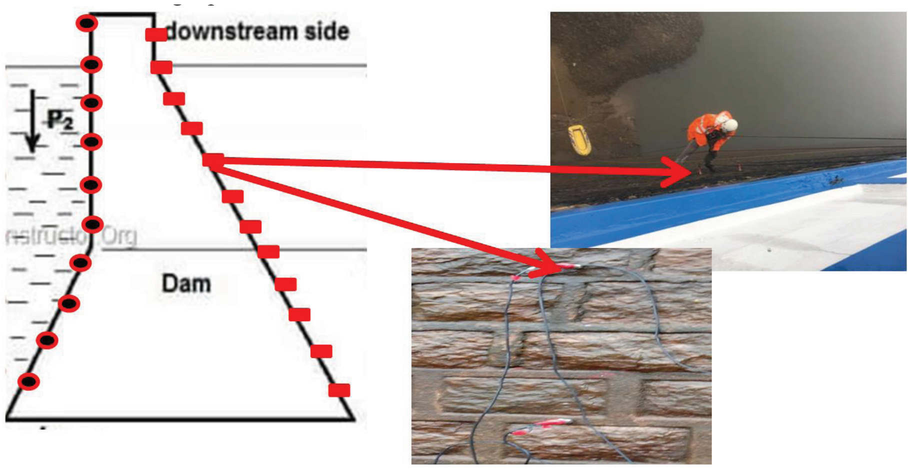


Fig. 7 : Cross face tomography arrangement

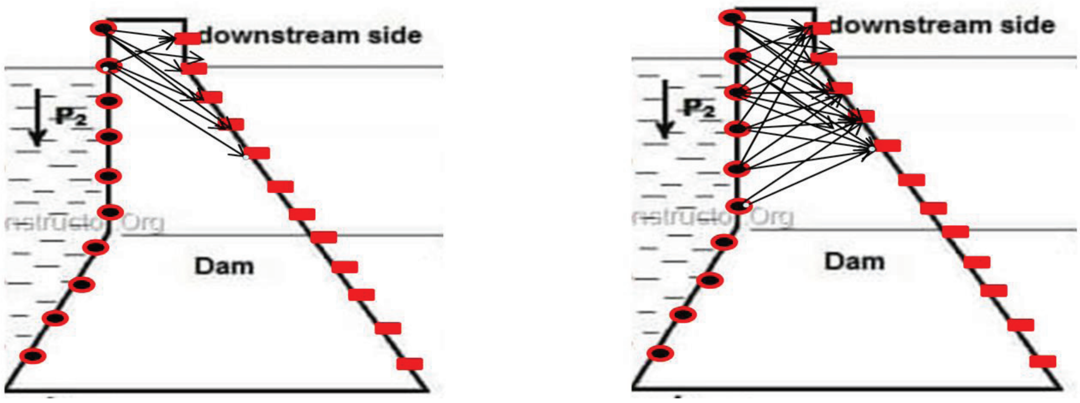
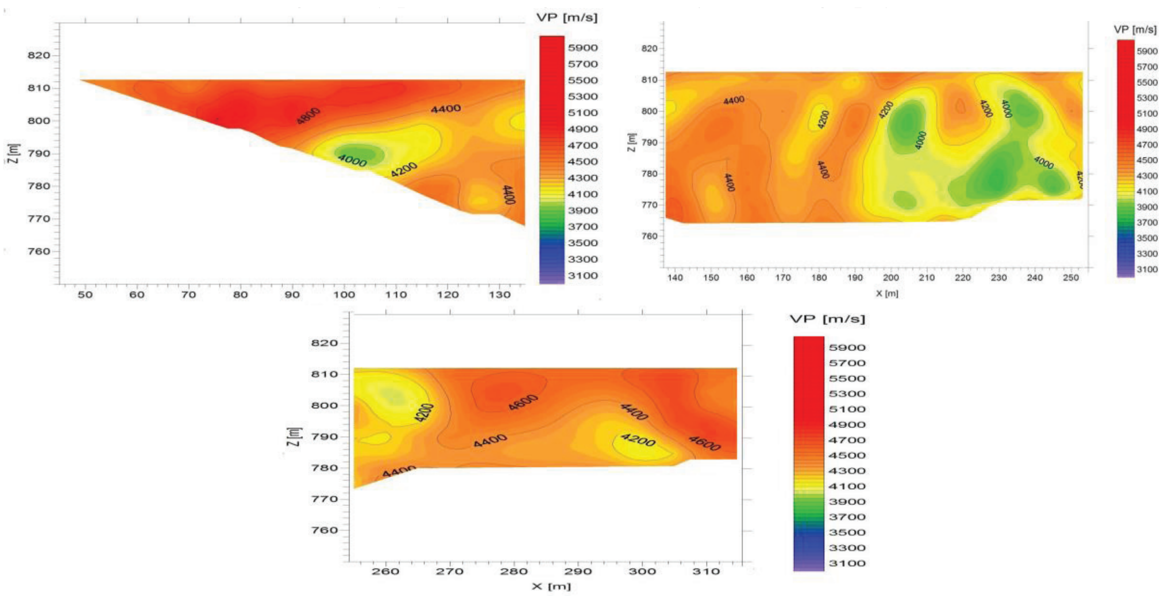


Fig. 8 : Ray path coverage with cross face tomography



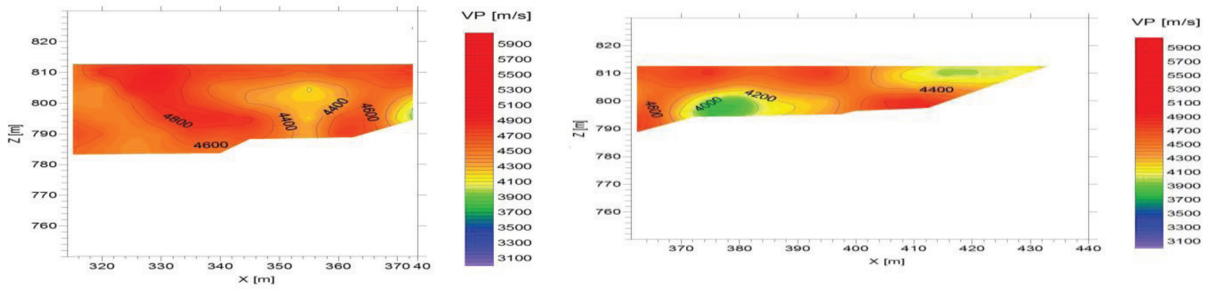


Fig. 9 : Results of L-section tomography

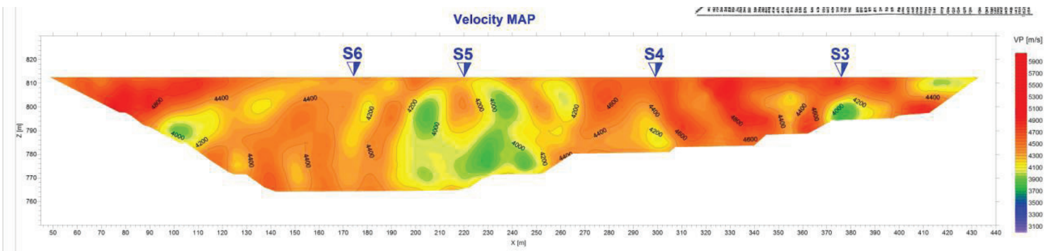


Fig 10 : Combined results of L-section topography

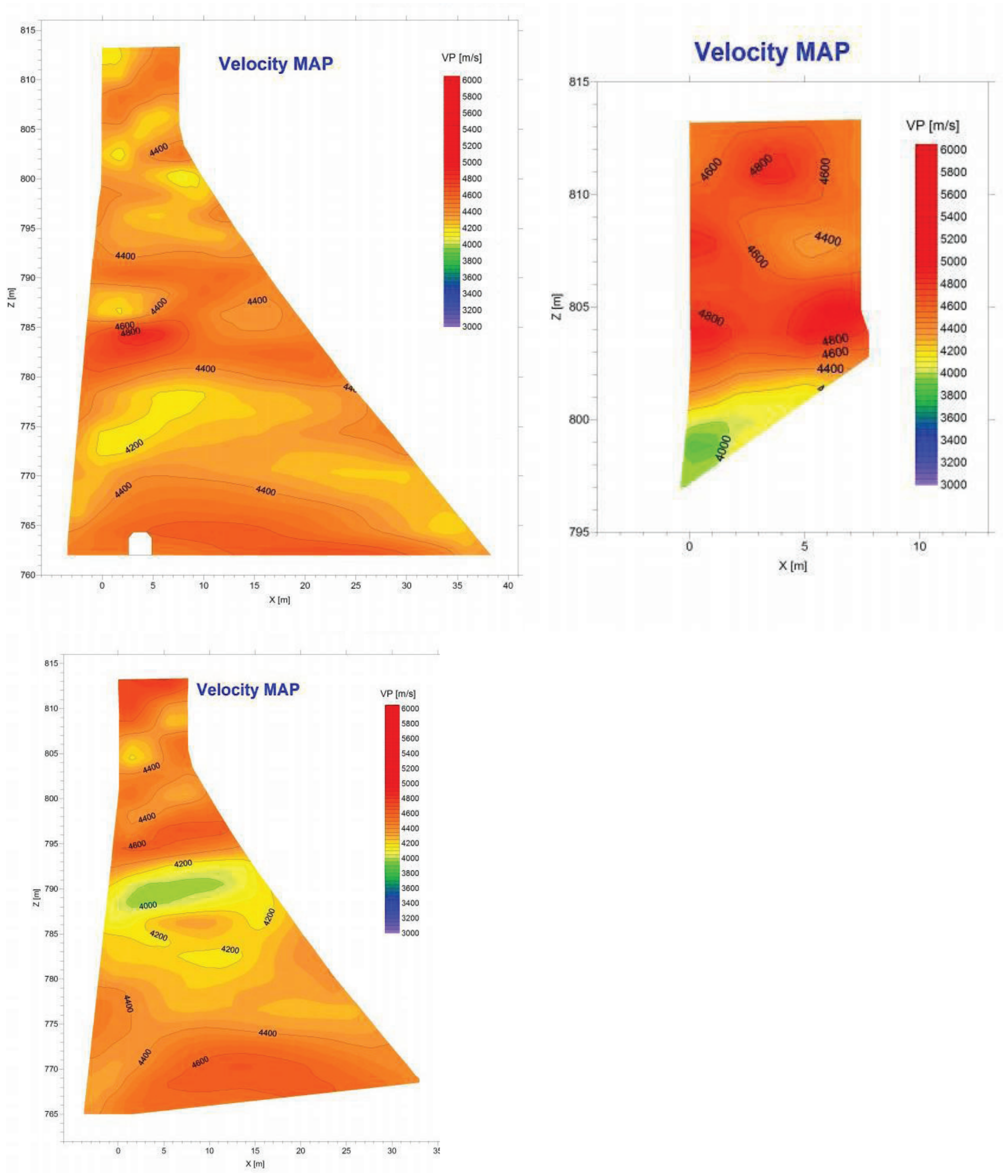


Fig 11 : Results of cross face topography

It may not be possible to assess number of cross face tomography surveys to be conducted while estimating cost and time. For budget and time estimates one cross face tomography for every 100m of dam length can be used.

5. DENSITY RESULTS

Seismic tomography results provide Vp distribution in dam body. By using following Gardner's equation, Vp can be converted to density

$$\rho = 0.31\mathrm{v}_{\mathrm{p}}^{0.25}$$

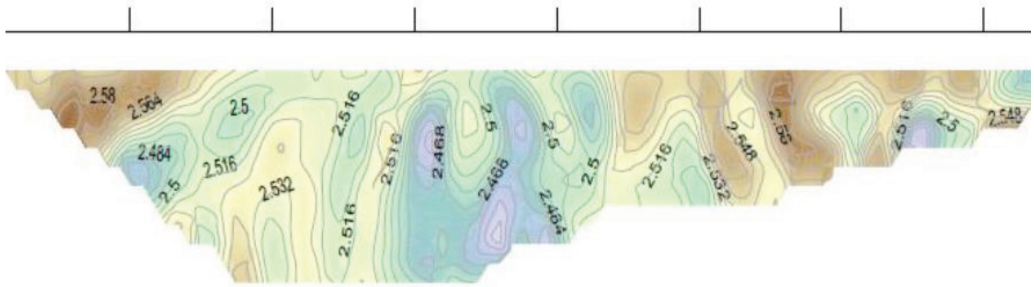


Fig 12 : Density map of dam

6. COMBINED RESULS OF ERI AND SEISMIC TOMOGRAPHY

Seismic tomography determines P wave velocity in the dam body, which is linked to strength of the dam material. A compact material will have higher velocities, whereas material with pore spaces and lesser strength will have lower velocity. Electrical resistivity imaging presents 2D distribution of electrical resistivity (reciprocal of conductivity) which is linked to moisture content in the material. Earth materials by themselves are resistive, and presence of moisture/ water increases the conductivity. In dams, therefore, low resistivity zones are associated with zones having higher moisture/ water content. There are various possible scenarios based on the above explanation:

1. Zones having lower material strength but dry in nature will have lower P wave velocities with corresponding high resistivity.
2. Zones having lower material strength and wet in nature will have lower P wave velocities with corresponding low resistivity.
3. Zones having significant strength and dry in nature will have high P wave velocity and high resistivity
4. Zones having significant strength and wet in nature will have high P wave velocity and low resistivity

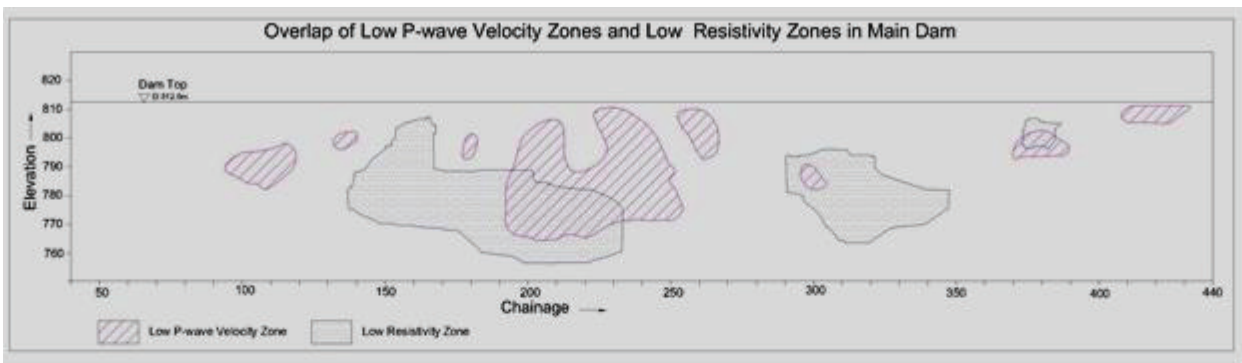


Fig. 13 : Interposing results from ERI and seismic tomography

7. ASSESSMENT OF GROUTING QUANTITY

Based on the dimension of zones having low P wave velocities, the volume of affected areas can be calculated. For approximation and ease of calculation, the areas can be taken having regular geometry. With known volume of anomalous zones and difference of density between sound concrete/masonry, the amount of grout material can be calculated.

Amount of grout = Volume of affected zone x difference in density

In addition to the amount of grout this calculated, additional 20-25% can be added to arrive at quantity of grout required.

8. CONCLUSION

The application of geophysical techniques (ERI and seismic tomography) provides detailed information about location and extent of affected zones in dam body. This type of detailed information is not possible through any other dam investigation technique. Using the methodology suggested, it is possible to assess the amount of grout material required. In case of budget and time constraints, it is also possible to repair and rehabilitate zones showing more distress. With known affected zones, it is possible to direct grout in targeted zones for more focused repairs. Geophysical investigations should be repeated after repair and rehabilitation to assess efficacy of repairs.

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