

# Seismic tomography as a vital tool in the preliminary stage of hydro plant studies: the cases of two large schemes in Ethiopia

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## Introduction

Geophysical investigations are essential in the design and construction of hydroelectric plants. They are used throughout the entire design and construction process, from basic design through to construction verification. Starting at the basic design phase, tomography is extremely useful given that it is:

1. fast
2. low cost
3. it does not require particular on-site conditions such as roads or special access routes

Since the only other investigations possible and available at such an early design phase are satellite imagery, aerial surveys and visual inspections, geophysical investigations are fundamental to identify the weak zones to be investigated during subsequent phases.

During the second phase, when boreholes are being drilled, geophysical investigations have two fundamental purposes:

- calibration of first phase investigations
- detailed local measurements (cross-hole)

Although the geophysical investigations in this phase are not as widespread as in the first, they are accurate.

In the third phase, characterized by the start of excavations, seismic investigations are used to study the weak zones in greater detail. Surface seismic investigations (MASW) are also performed in this phase.

During the fourth phase of activities this type of investigations may also serve the purpose of quality control of the foundation excavation or the construction embankment.

## 1. Methodology: from the first observation of refraction phenomena through the tomographies obtained from Eikonal Equations, such as the seismic route Path Finder

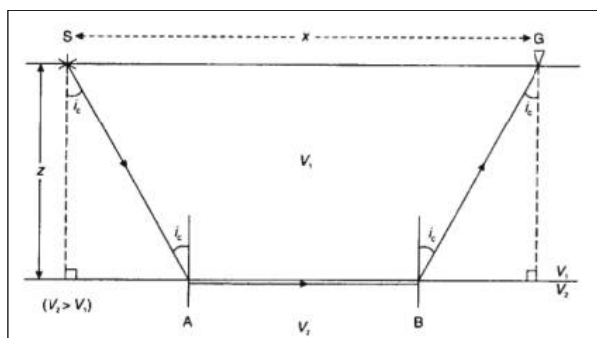


Figure 1 - Seismic wave refraction on a discontinuity plane between means at different velocities ( $V_1 < V_2$ )

The application of the physical principles of refraction to subsoil exploration engenders from modern seismology: indeed, even the observation of seism arrival times at different distances from the epicenter denotes that the increase of the arrival times does not follow a linear law commensurate with the increase of the distance. Generally, shorter time intervals occur whence covering equal space intervals located at longer distances.

Such observations and the analysis of the seismic wave velocity differences at different distances from the earthquake epicenter that in 1909 lead Andrija Mohorovic (1857-1936) to the definition of one of the most important discontinuities within the earth's crust, the so-called *Moho*,

separating the crust with an average velocity of 5.6km/s from the mantle with a 7.7km/s average velocity.

It was only a few years previously (1899) that *August Schmidt* formulated the mathematical treatment of the possibility to highlight subsol rock discontinuities by analyzing the refraction of the waves, but the technological aids of the period did not facilitate experimental demonstrations.

As portrayed in the simple scheme in figure 1, the seismic ray that starts at source point (S) and directly reaches the geophone point (G) covers the distance in the time indicated by the distance (x) divided by the Velocity ( $V_1$ ). In the case there be an increase of velocity ( $V_2$ ) at a certain depth (z), and even though the ray travelling along the trajectory S-A-B-G will cover a greater distance and exploit the higher velocity  $V_2$ , it will arrive at a specific critical distance  $X_c$ , the geophone G, at the same instance as the direct ray that only travelled through the layer of  $V_1$  velocity material.

Beyond the  $X_c$  critical distance, the first rays to reach the geophones will be those covering the longest trajectory. From thereon, the first seismic wave arrivals will be those with refracted waves and enveloping the first arrivals points as a function of the distance will result in a line with a  $1/V_2$  gradient, whilst the line joining the points of first arrival in the first stretch considered as a function of the distance had the gradient of  $1/V_1$ .

As to the definitions in these figures, the depth of the discontinuity between the two layers having velocities  $V_1$  and  $V_2$  may be calculated using the following equation:

$$D_1 = (T_i/2) (V_1 V_2) / (V_2^2 - V_1^2)^{1/2}$$

where  $T_i$  is the intercept time to be derived as set forth in figure 2.

The use of refraction seismics for the exploration of the subsol, and in particular for the identification of saline domes (known as excellent traps in hydrocarbon research characterized by high seismic wave propagation velocities with respect to surrounding rocks) became a widespread exploration method only after the 1920's.

Since then, research ventures have contemplated data processing methods developing procedures to enable the reconstruction of the subsol model even in complex contexts where the velocity of propagation differ within the same layer or the surface and subsol discontinuity morphology is very complex, as in the case of the

technologies known as *Delay-Time* and *Plus-Minus*.

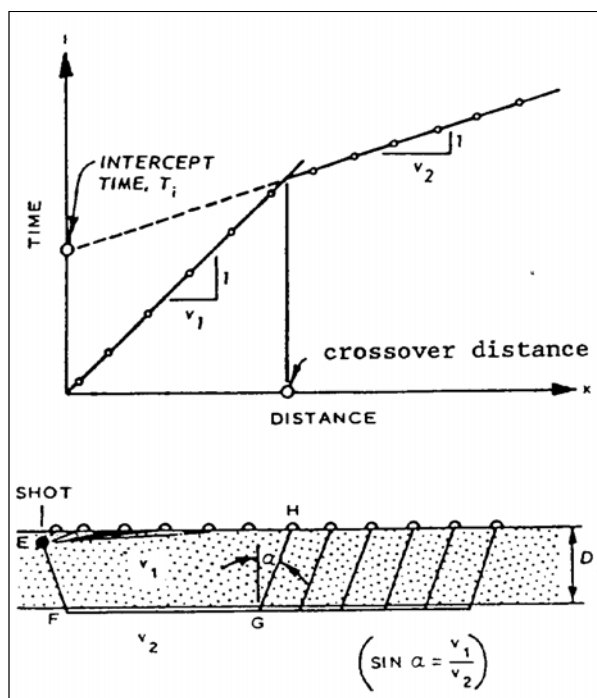


Figure 2 - Refraction of seismic wave on a plane of discontinuity between means. Determination of the presence and depth of a surface of discontinuity, analysis of the functions *space /travel time* of the vibrations (*dromocrone*) - from U.S. Army - geophysical exploration for enginee-ring and environmental investigations.

Moreover, one of the more important and realistic mathematical procedures for subsol model reconstruction is owed to D. Palmer, (The Generalized Reciprocal Method of Seismic Refraction Interpretation, Society of Exploration Geophysicists, Tulsa, OK, 1980), who introduced the sophisticated data processing method known by the acronym GRM that reconstructs the seismic velocity sequences per each geophone position along the profile explored.

This method foresees the existence of profile stretches where the trend of the discontinuity originated seismic signal under study be generated from two opposite positions in order to analyze the reciprocal times of seismic signals that have travelled along equal paths in the two opposite directions.

Figure 3 exemplifies the restitution of the results obtained with this processing technique. The semicircles under each geophone indicate the probable area of origin of the refracted wave, whilst their envelope identifies the probable surface of the discontinuity.

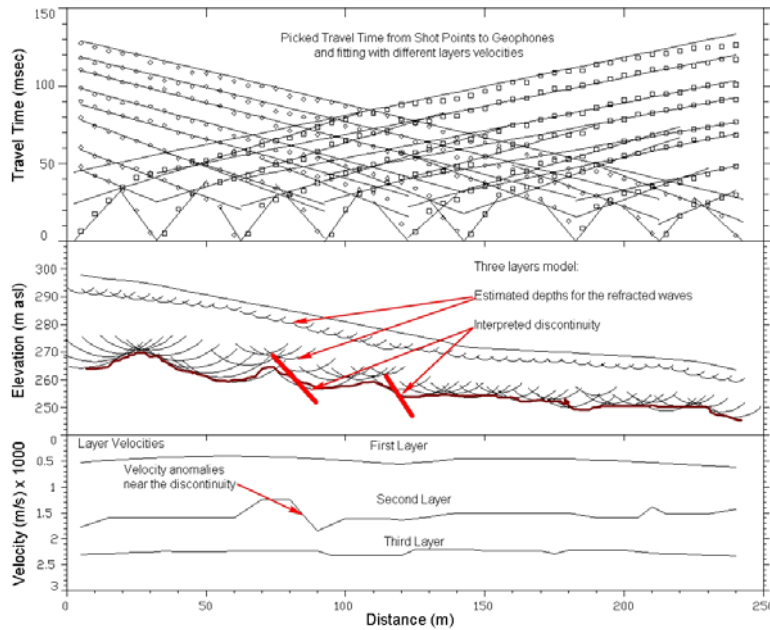


Figure 3 - Example of restitution of the data processing with GRM to highlight structural and stratigraphic discontinuities (GEORISORSE ITALIA - Technical Report unpublished)

Later on during the '80s, the continuing development of numerical data processing methodologies with ever faster and more powerful systems lead to the development of inverse numerical modeling methods foreseeing the verification of a pre-established model based firstly on experimental data thence modified consistently with subsequent iterations.

Such systems comprise of an iteration process which, step after step and subsequent small modifications on the model, lead to results that may be defined as “the best adaptation of the model to the unknown reality of the subsoil” as the comparison between the experimental and theoretical data calculated on the model is acceptable.

Practically, the interpretation phase envisages an initial, layered subsoil model characterized by specific seismic velocities that may also be derived from prior stratigraphical modeling with one of the previous methods (Intercept Times, GRM, Plus Minus, etc.) and its subsequent step-by-step progressive modification so that the travel times measured between each shot point and the various geophones reach a minimum Root Mean Square (RMS) value defined according to the following equation:

$$x_{rms} = \sqrt{\frac{1}{n} (x_1^2 + x_2^2 + \dots + x_n^2)}$$

where  $\{x_1, x_2, \dots, x_n\}$  represent the deviations between the experimental travel times read on the various seismograms and those calculated for the same routes on the numerical model. However, many section zones may seem to have “low seismic ray coverage” owing to the position of the shot points and geophones and therefore be less reliable with respect to those having higher seismic ray route density.

The numerical model optimization process leads to the modification (increase or decrease) of the model element velocities crossed by the various seismic routes as the time measured per each specific route may be higher or lower than that calculated on the model.

This intervention is repeated numerous times whilst the subsequent modifications are carried out in small steps (percentage variation of the velocities or modification of the discontinuity depth) and generally within the margins defined by the operator maintaining the minimum and maximum values within a preset range.

Nevertheless, these “Ray Tracing“ techniques do have some limits in terms of detailed subsoil model reconstruction: in fact, there may be velocity contrasts owing to velocity variations in one specific element in one part of the model which highly influence the results (i.e. in high velocity zones) while far less influence may be exerted by other elements (i.e. in the low velocity zones of the model).

Starting from these optimization methods applied to stratigraphies obtained by other interpretation methods, the advancement of data processing and interpretation methods has lead to finite elements modeling where the simplest base model could even be represented by a small element mesh, be they square or rectangular, characterized by variable velocities having regular progression from surface downward within predefined ranges based on seismic velocity evidence or according to a regular gradient of increasing velocity.

The optimization of the model therefore still takes place according to an iterative process with modification sequences, increasing or decreasing the velocities of the single elements according to the positive or negative difference characterizing the various seismic rays they have been crossed by during the analytical verification and the paths taken by the seismic waves between the shot points and the various geophones.

The theoretical transit time verification procedure in the ray tracing systems analyses the rays with refraction-due different trajectories occurring on the interfaces of the various elements causing the initially downward ray to resurface. The final comparison is therefore still expressed numerically using the RMS value and portrayed graphically by the comparison of the experimental drone trends observed during the survey and the theoretical ones calculated on the model (see figure 4).

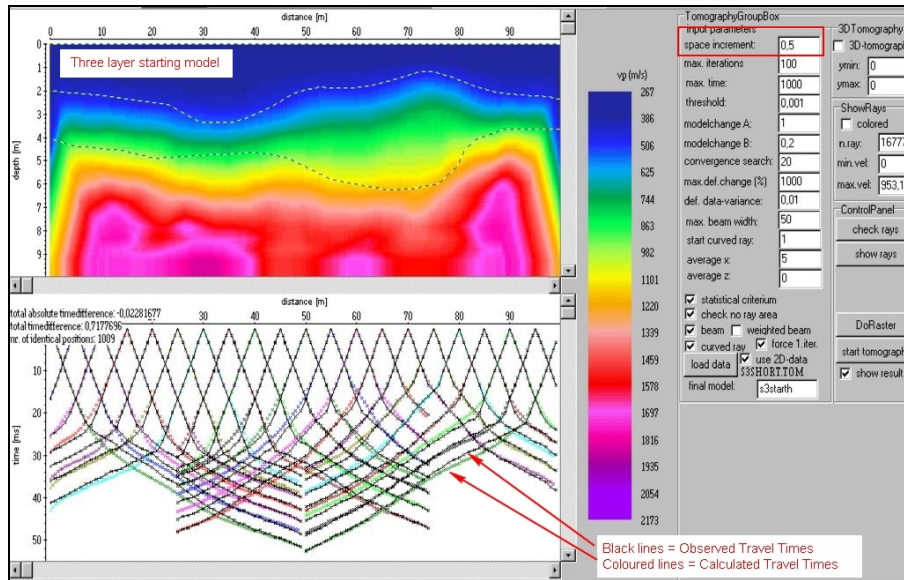


Figure 4 - Finite element model of small size (0.5m) obtained after 100 iterations with analyzing a patterns of 16,777 seismic rays, starting with a 3-layer model. The differences between the experimental and those calculated dromocrone show the goodness of the modeling. (Software ReflexW)

The results of this calculation methodology already supply a numerical model of the subsoil which is very close to reality. However, the modeling of zones with velocity inversions or, rather, with low velocity layer insertions in higher velocity layers, is still very difficult. These situations are very frequent and extremely important in the geotechnical explorations for large works. A further step ahead in the processing methodologies, that we can define as “tomographical” in so far as it supplies a genuine images of the subsoil parameterized by the velocity of propagation of the seismic waves (be it P or S), was accomplished with the introduction of the “Eikonal equations” consisting in optimal trajectory research functions for the propagation of signals such as, in this case, seismic signals. Such functions are essentially based on the propagation of the wave fronts according to Snell’s Law and Fermat’s Principle: **“Of all the possible paths through a medium between two points, the seismic ray follows the path with the shortest travel time”** (Pierre Fermat, 17<sup>th</sup> century French mathematician).

In practice, therefore, one may affirm that the seismic signal tends to travel through zones characterized by higher velocities and to propagate first therein and subsequently in the surrounding zones. As the seismic refraction survey analyzes the paths taken by the signals generated in various positions arriving first to the geophones, the survey may indeed be considered an analysis of the signals whose paths travel through the higher velocity zones.

This statement goes beyond the very concept of “refraction” that does not take into account the analysis of situations involving velocity decreases surface downwards. In fact, in the case of above circumstances with further velocity increases in the lower layers, the reconstruction of the wave front trajectories with the Eikonal equations will highlight the first arrival signals and relate them to paths within the more superficial high velocity layer up to a certain distance, whereas at greater distances the first arrival signals will refer to those propagated in the deeper high velocity layer. The intermediate layer between the two higher velocity layers will appear uninvolved by the wave fronts and be characterized by lower seismic velocities. Therefore, instead of non seismic path tomographic processing (Ray-Tracing) one may refer to tomographic reconstructions obtained with the **“Wave-path Eikonal Tomography” (WET)** technique.

Figure 5 portrays the seismic tomography obtained from a seismic profile executed in the Grand Ethiopian Renaissance Dam area in order to highlight the development of a cavity intercepted by the dam foundation excavations.

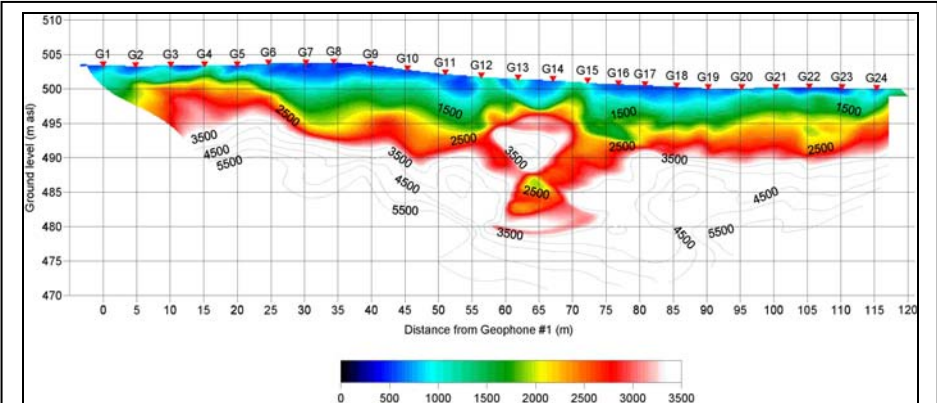


Figure 5 - Seismic tomography of P-wave velocity for the profile SL\_CV\_06 located in the dam foundation area, on the right bank of the Grand Ethiopian Renaissance Dam. Between geophones 13 and 14, approximately 485 m asl has been highlighted an area with decrease of the seismic velocity up to values lower than 2,500 m/sec respect the surrounding areas where values of 3500-4500 m/sec are presente in the tomography.

The representation of the wave front distribution confirms the prior definitions, i.e. that the trajectories of the wave fronts that first reach the various sensors lower velocity zones do tend to avoid or go round the low velocity zones.

Indeed, figure 6 shows how the wave front density in the same low velocity zone is generally lower than 10 wave fronts/element whilst in the surrounding areas the maximum values reached indicate over 80 wave fronts/element.

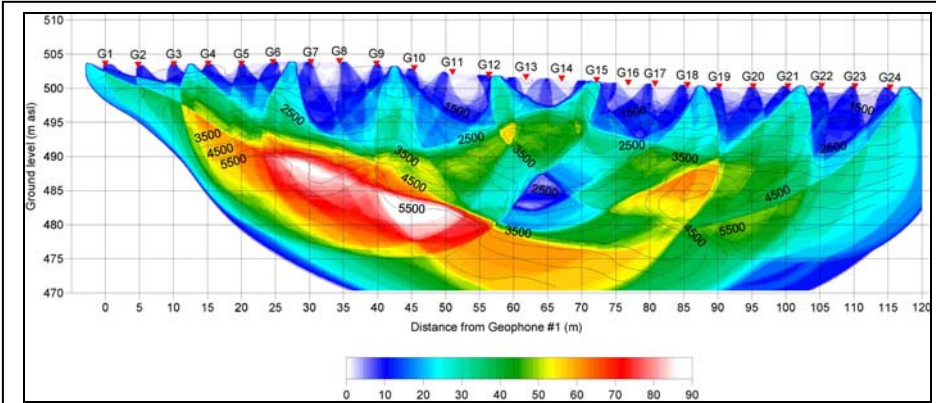


Figure 6 - Tomography of the Wave front density (Coverage) for the same Seismic Line of the Figure 5. The total number of wave front analysed is 216 and it possible to see that in the high velocity zones the density is very high (more than 80 wf/pixel) while in the low velocity zones the density is very low (20 or less).

**2. Advancement of prospection devices and data processing software.**

The advancement of prospection equipment is related to the general progress of electronic devices that has allowed to reduce to a minimum the overall bulk, weight and transport fragility of the collection systems. Twenty years ago, a quality seismograph equipped with 24 channels weighed even 25-30Kg, was very sensitive bumps and required high power supply. Today, they can be easily transported in waterproof and shock resistant

containers and weigh only a few kilos. Moreover, the control and data collection system can be fully detached from the seismograph and connected to it via wi-fi, whilst the operator may remain at safety distance even when the profile involves impassable or difficult access zones.

The following photograph portrays a wireless system connected to a notebook used to collect data during the detailed study of the Gibe III dam foundation bottom.



Fig. 7 - Wireless Seismograph

The use of the wireless function was particularly convenient as the operator was often distant from the seismograph that was positioned in the various work zones by expert rock climbers. Noticeably, technological progress was not limited to weight reduction and wireless applications, but has also and mainly involved the considerable sensitivity of the devices characterized, in this case, by a 24 bit resolution with continuing sampling at a frequency range from a few hertz to some thousand Hz. The 24 bit resolution enables operations without data amplification set up as it is possible to transform the signals originating from the geophones into digital information within a very ample range in so far as the 24 bit do allow to discriminate 16.777.206 potential difference levels. If the peak-peak maximum value acquired by a geophone close to the shot point is 10V, then the minimum value of the signal legible by the instrument will be 0.0000006 V, or 0.6 microVolt.

Other important advancements have occurred in the data processing and pre-processing softwares, e.g. filtering, despiking, multiple files assembly, muting and picking, allowing rapid obtainment of results after a few processing sequences that is however performed by an operator with the necessary experience and methodological preparation.

### 3. Examples of WET seismic application in the great hydroelectric projects in Ethiopia

Since 2006, our undertakings in Ethiopia have focused on two great hydroelectric projects foreseeing the following impressive hydraulic works of which some have already been built:

- The GIBE III project on the Omo river in south-west Ethiopia, involving the construction of a 240m high RCC dam with a 600m crest length. The installed capacity will be approximately 1.950 MW.
- The Grand Ethiopian Renaissance Dam (GERD) on the Abay river (Blue Nile) in the western area bordering Sudan, for a total installed capacity of 6.000 MW approx. involving the construction of two large dams: the Main Dam in RC Cover the afore river will be 160m high and have a crest length of 2.000 m approx. as well as the rockfill Saddle Dam with a 50m maximum height and a 6.000 m crest length.

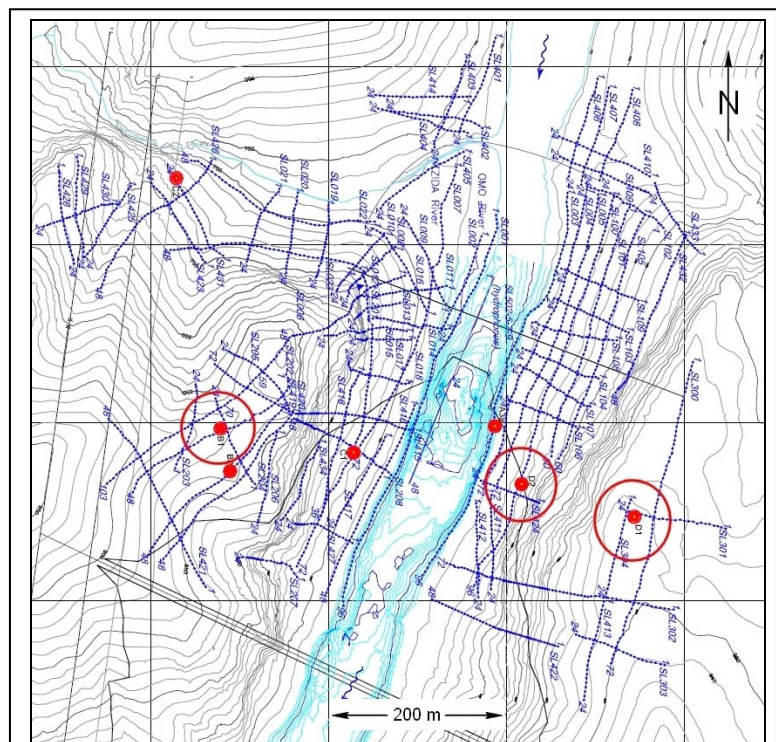


Figure 8 - GIBE III Hydroelectric Project - Seismic lines

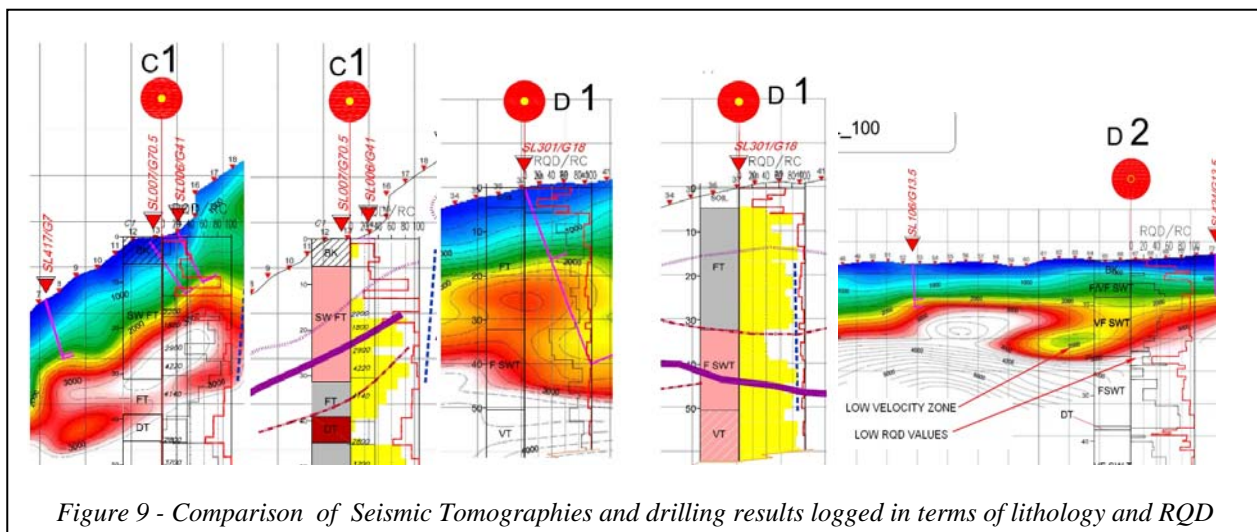
### 3.1 The GIBE III Dam

Several interventions have been realized in this area for various scopes during different design phases involving over 30 km of seismic profiles which were all processed using the WET technique resulting in the restitution of interpretation sections both in parallel to and in direction of the mountain side maximum slope. The main operational difficulties were represented by the particular morphology of the Valley distinguished by stretches of vertical escarpments, some over one hundred meters high (surveyed with the assistance of expert rock climbers), characterized by trachytic rock which only gave an impression of high consistency and compactness. The direct observations and the drilling results subsequently confirmed what initially indicated by the seismic investigations: the trachyte was almost always highly weathered, often very fractured and characterized by very low seismic wave velocities.

Higher seismic wave velocities suggesting high rock compactness were only encountered in the deep mountain sides and under the river level, although, even in this case, the frequent lateral variations did suggest the presence of important fractures or tectonic lineaments.

The investigations were performed to study three dam hypotheses: the first hypothesis involved an arch dam, the second a rockfill dam and the final selection of the approximately 240m high RCC dam with a straight axis. Furthermore, the explorations also involved the diversion tunnel inlet and outlet zones, the powerhouse area and the power tunnel intake, as well as the foundation zone of the bridge over the Omo river downstream the dam. The following figures exemplify some tomographic sections which are particularly interesting in view of the actual situations encountered during the subsequent phases.

Figure 9 hereafter exemplifies the reliability of seismic prospection with WET tomographic processing in which three tomographies, identifying low velocity layer alternations with higher velocity layers, are compared to the results of the relative boreholes, that identified low RQD values. In this case, the comparison is made between tomographies SL\_006, SL\_301 and SL\_100 with BHs C1, D1 and D2.



### 3.2 The Grand Ethiopian Renaissance Dam

The preliminary explorations for the GERD project started in September 2010 with a series of seismic profiles covering an over 31 km distance in the main dam and saddle dam zones.

Further profiles covering some 4 km in the saddle dam area were realized in 2011 and 2012 and another 6 km in the gated spillway area. Detailed explorations were also realized over a 1 km area in the main dam zone.

On the whole, the project area was explored with the aid of 42 km of seismic refraction profiles processed with the WET tomographic technique.

Due to space limitations herein, figure 10 portrays the seismic profiles plan for the main dam and main (gated) spillway areas and the results obtained from one of the more important seismic lines of the entire investigation, line SL\_203 located along the dam axis on the right side embankment.

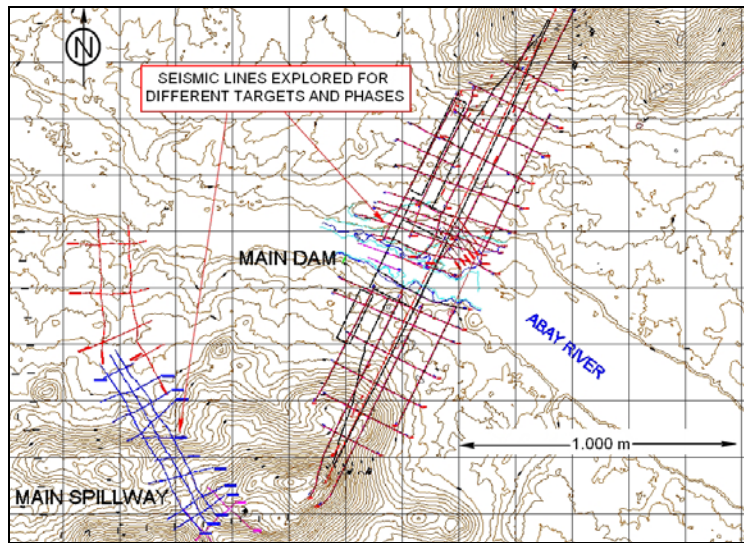


Figure 10 - Grand Ethiopian Renaissance Dam (GERD) Hydroelectric Project - Plan of the surveyed Seismic Lines in the Main Dam Area and Main Spillway area .

As noted in figure 11, this line highlights a very normal trend with only two anomalies that were initially interpreted as clues of fault lines or fractures.

Later on during the excavation, the left side anomaly (at ch 260 approx.) was found in close proximity of a cavity zone, while the right side anomaly located mid-slope seemed related to the presence of an intensely weathered fracture zone.

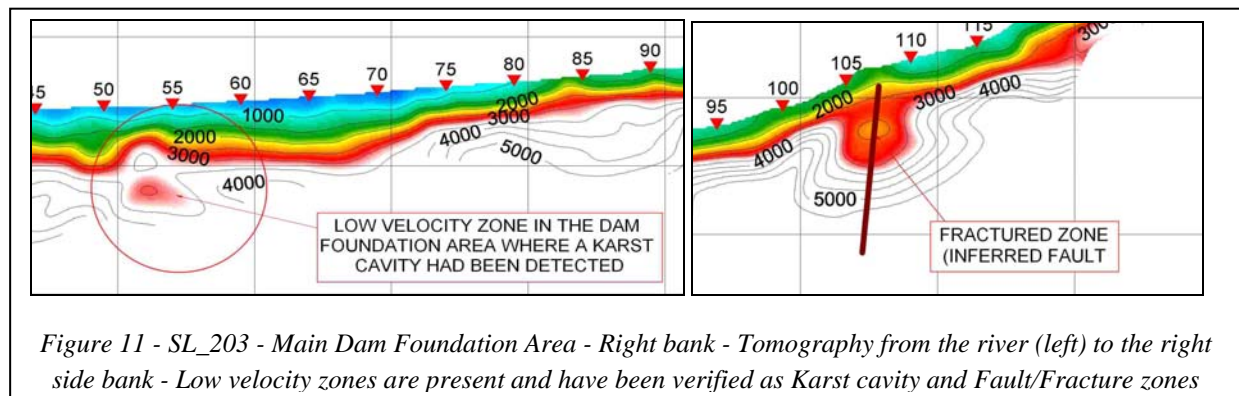


Figure 11 - SL\_203 - Main Dam Foundation Area - Right bank - Tomography from the river (left) to the right side bank - Low velocity zones are present and have been verified as Karst cavity and Fault/Fracture zones

#### 4. Conclusions

After the brief description of traditional seismic refraction surveying, we have illustrated the tomographic processing method with the Wave path Eikonal Tomography (WET) procedure that allows to surpass some of the limits of seismic refraction prospecting as it exploits Eikonal Equations to reconstruct mathematical subsoil models.

Such procedure produces a finite elements model of materials characterized by different seismic propagation velocities, or fast pathfinders between the signal source and the various signal reception points.

This leads to the definition of the subsoil models where higher velocity zones are preferred by signal propagation and lower velocity zone are encircled by the wave fronts as otherwise each wave front would be slowed down.

Moreover, this methodology allows to intervene in very irregular morphological conditions, as long as the coordinates of all points taken into account be precisely known.



The addition of the noteworthy versatility and manageability of the new data collection systems make this investigation methodology very highly useful, especially in the initial phases of large projects which are generally located in remote and not easily accessible areas.

One must especially recall and draw attention to the aspects of traditional seismic refraction prospecting that have been surpassed:

- ✓ Impossibility to highlight low velocity zones inter-layered or alternating with higher velocity layers;
- ✓ Difficult data collection and processing in morphologically complex zones.

Besides emphasizing that morphological conditions are no longer an issue, the two examples evidence that the low velocity zones identified on the tomographies have in numerous cases been confirmed by subsequent detailed investigations and/or the project excavation works.

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