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# In Situ Geophysical Investigation to Evaluate Dynamic Soil Properties at the Ilarionas Dam, Northern Greece

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ABSTRACT

Seismic geophysical methods have long been used by geologists and geophysicists to delineate subsurface features. These techniques work because different types and strengths of soil and rock transmit energy at different velocities. The Crosshole-Downhole tests (CH-DH) and seismic refraction survey (RS) are among the most used methods in engineering applications to obtain the elastic properties of subsurface layers. As a result, seismic methods have evolved into a cost-effective tool for rapidly determining depth to bedrock in engineering and construction projects. The seismic methods are best suited to sediment thickness analysis, bedrock quality determination and detection of the presence of weaknesses in the bedrock before the erection of any civil engineering structures such as bridges, tunnels, dams and portals.

Seismic methods are also useful in estimating the rippability of bedrock ahead of construction. These methods are particularly useful for large-scale projects that require a significant number of drill holes, resulting in a substantial investment of time and costs for drilling. The CH-DH and RS methods are typically comparable in total cost to drilling, but provide significantly more information in 2-D and 3-D and therefore reduce the likelihood of conceptually oversimplifying the subsurface conditions.

The above mentioned methodologies were considered to be the most appropriate geophysical methods for investigating the shallow structure and the dynamic soil properties of the area where the Ilarionas Dam is scheduled to be constructed. The main target of this work was to prove the potential of geophysical methods in providing accurate information to the civil engineer and to obtain information on the dynamic soil and rock properties for earthquake design analyses for the dam construction. Specifically, nine refraction seismic profiles and three crosshole-downhole seismic tests were implemented to determine the subsurface conditions of the study area. The tests determined the shear and compression wave velocity profiles versus depth and other crucial parameters such as Young and Rigidity modules. Furthermore, they allowed the detailed 2-D mapping (along several profiles of the study area) of the subsurface variation of the soil and rock dynamic moduli.

## 1. INTRODUCTION

The seismic method is a powerful geophysical exploration technique that has been widespreadly used in geophysical engineering for more than 40 years and has been increasingly applied since the 90s in geotechnical and environmental applications, usually for investigation depths shallower than 40 meters. The applicability of seismic methods depends on the presence of acoustical contrasts in the subsurface. In many cases the acoustical contrasts occur at boundaries between geological layers, although man-made boundaries such as tunnels and mines may also create such contrasts.

Seismic survey is the geophysical method, which is most closely related to identify rock

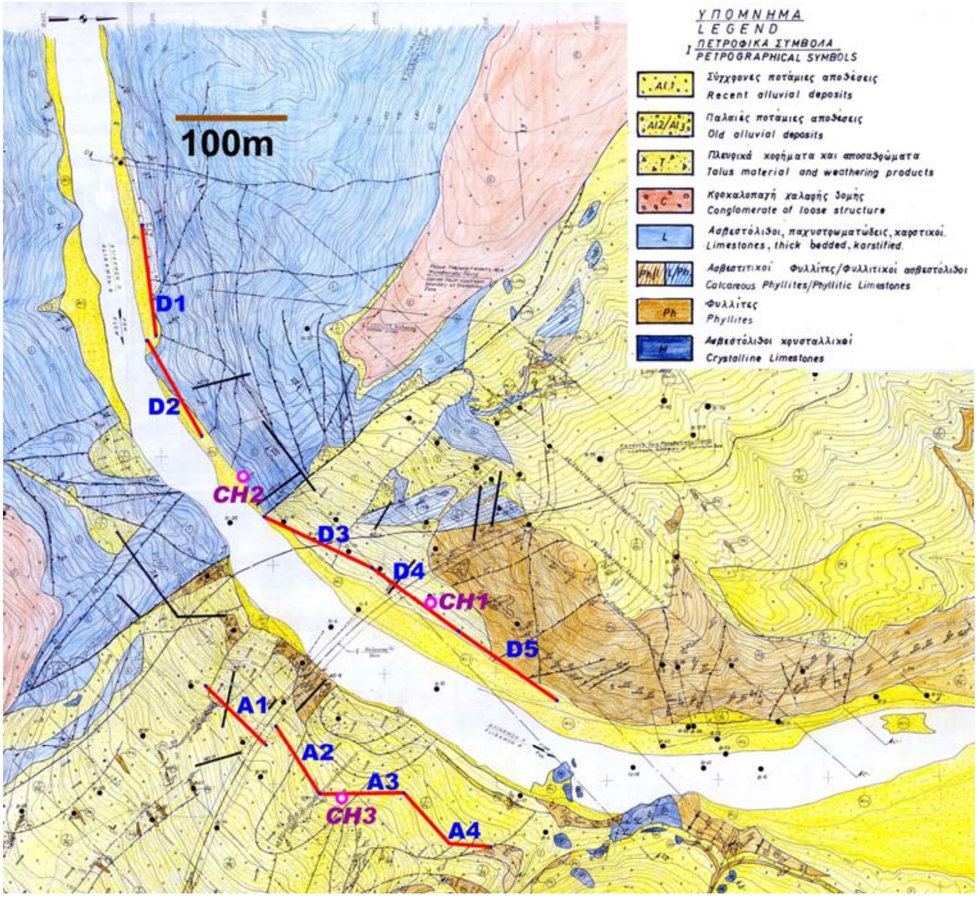


Figure 1. Geological map of the broader area under investigation (Foti, 2002). The nine seismic refraction profiles are presented with thick lines and codes (A# and D#). The location of the three CH-DH experiments are also shown with solid circles and codes (CH-#).

and soil mass properties, since seismic wave velocity varies with the main mechanical properties, such as Poisson's ratios and others modules. The earliest applications of the method primarily concern the determination of the depth to bedrock beneath a soil cover. Later, the same method was used successfully for the location of "weak" zones, such as shear zones and faults. Nowadays, seismic methods have been used in connection with planning of dams, tunnels and portals (Klimis et. al., 1999; Savvaidis et al., 1999; Soupios et al., 2005; Othman, 2005; Venkateswara et al., 2004).

The field measurements can be carried out on the surface, in boreholes, or even on the seabed. The necessity of a borehole controls the overall geophysical cost which is increased unless boring is also needed for other geotechnical purposes (CPT/SPT tests, etc). Recently, most scientists prefer to apply all the available seismic methods, such as, Refraction Seismics as well as, Crosshole and Downhole Seismics tests, since they are highly accurate methods for determining material properties of rock and soil sites (Neep et al., 1996; Rechtien, 1996; Luna and Jadi, 2000; Soupios et al., 2001). Thin low-velocity layers lying between high velocity layers can be detected with these methods, which may not be possible with surface methods. In addition, the accuracy and resolution of the CH and DH methods is almost constant for all test depths, whereas the accuracy and resolution of the surface methods decreases with depth. A limitation of these methods is to generate adequate energy without damaging the borehole casing.

For the study region refraction seismic were acquired in nine selected areas and CH and DH measurements were performed in three selected places in the area where the Ilarionas Dam is scheduled to be situated, in order to obtain information on the dynamic soil and rock properties for earthquake design analyses for the Dam construction. Those tests allowed the determination of shear and compression wave velocity profiles versus depth and other important elastic parameters such as Young and Rigidity modules.

The results of both geophysical methods were in a good agreement with the geological formations of the study area and the final velocity models were used to: a) produce two-dimensional images of the subsurface variation of the dynamic moduli and, b) to correlate the determined velocity models with the four main geological/geotechnical formations of the area.

## 2. STUDY AREA – GEOLOGICAL SETTINGS

The investigated area is located in the western part of Greece, twenty kilometers from the town of Kozani and eleven kilometers South-Southwestern of the village of Aiani. The main geological formations of the area are shown in Figure 1. The general geology of the area consists of gravels, coarse sand, moraine overlying a weathered/transition layer/zone consisting of calcareous phyllites and phyllitic limestones. The basement consists of fractured phyllites, thick bedded and karstified limestones and crystalline limestones. The sedimentary layers become thicker and more cohesive with depth. The free ground water level is normally located fifteen meters below the ground surface (due to the adjacent Aliakmonas River) and the pore water pressure is hydrostatic from this level.

## 3. SEISMIC REFRACTION MODELING

The selection of the location of the profiles was planned according to the geology and the accessibility of the study area.

### 3.1 Data Acquisition - Processing

Seismic refraction data were acquired along nine profile lines, using a Geometrics R-24 Strataview digital seismograph and signals were recorded by 24 12Hz OYO-Products geophones deployed at 10m and, occasionally, 7m intervals along the refraction lines. A 7kg sledgehammer striking a metal plate was used as the seismic source. Geophones were almost buried just beneath the surface to reduce interference from the ground-coupled sound wave.

Selected shots were used to build velocity profiles for each line using the SIP family of routines (Rimrock Geophysics, 1995). Picking of first arrivals proved to be a difficult task due to their very low frequency content and their “emergent” character. These attributes of the first breaks resulted in a higher likelihood of having systematic error of a few milliseconds in the selected arrival times and can result in a less precise final model.

Each of data files included precise positions for each geophone and shot point and all of the first arrival picks and appropriate static corrections were applied to the picked arrival times. Each pick was typically assigned to a specific subsurface layer in the data file in order to produce the Time-Distance (T-D) plot. The interpretation code (SIPT-2) is based on the assumption of discrete layers that are laterally continuous and have constant velocity.

### 3.2 Interpretation

T-D plots were constructed in order to assign the refractors (layers) and finally an iterative non-linear algorithm was applied to estimate a cross section of the resulted velocity model (figure 2).

For the interpretation of the selected data sets, each arrival was correlated to a layer where the corresponding refraction of the seismic wave has been recorded.

The final interpretation of each profile contains the morphology of the discontinuities (refractors) and the velocities of the body (P and S) waves within each layer. In figure (2) a typical velocity cross-section for P-waves (profile A4) is presented, where three layers have been identified. The first velocity layer (520 m/sec) corresponds to the surface cohesive quaternary sedimentary formations. The second layer exhibits a much higher velocities (1200 m/s) and corresponds to the massive and possible tectonically fractured limestone. The third layer is a high velocity (2400 m/s) which probably consist of weathered phyllites.

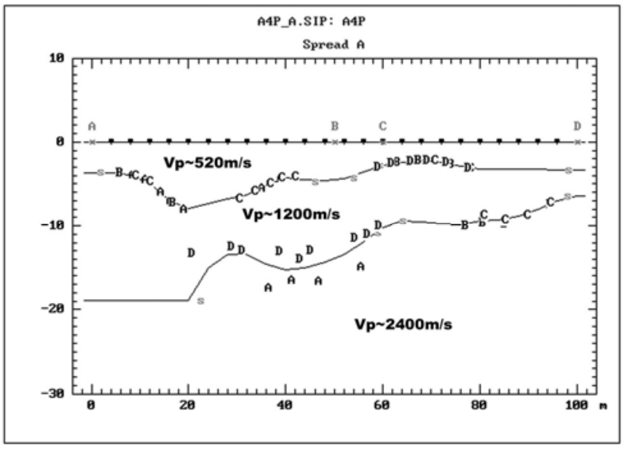


Figure 2. Final P-velocity structure for A4 seismic profile.

Superposition and/or joint interpretation of continuous seismic profiles (e.g. D3, D4 and D5 as shown in figure 1) allowed the determination of 2D velocity models, from which cross-section images of the velocity distribution could be easily compiled. An example is presented in figure (3), where the finally composed velocity model as determined from the refraction seismic survey is correlated with the final velocity distribution of CH-1.

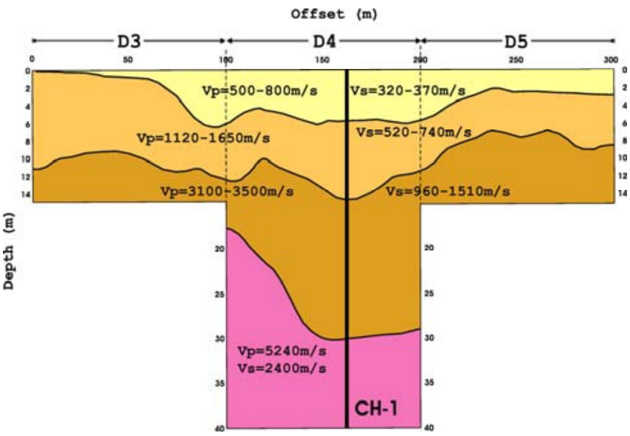


Figure 3. Velocity cross section of the unified D3, D4 and D4 refraction profiles.

## 4. CROSSHOLE – DOWNHOLE SEISMIC SURVEY

For the CH and DH seismic tests, eight boreholes were constructed using a water drilling machine. The borehole setup is shown in Figure 1.

In CH-1 and CH-2, three boreholes are used in order to obtain an accurate estimation of the attenuation model with depth, whereas in for CH-3 where two boreholes were constructed and used only for the estimation of the final P and S velocity model.

The boreholes were 4.5 inches in diameter, PVC cased and grouted according the American Standards (ASTM D4428/D4428M-84) to ensure good transmission of the wave energy. The holes were cased and grouted in order to prevent the soil from caving in during the testing and to allow good source-soil coupling. The distances between adjacent boreholes were of the order of 5-6 meters.

### 4.1 Data Acquisition - Processing

The source and receiver boreholes were drilled to the total depth of investigation. The seismic source was lowered to the measurements depth and one or two receivers were lowered to the same depth in the other boreholes. To generate shear and compression wave energy, we have used the BGS Cross-hole shear-wave electromagnetic hammer with an inflated tube clamping system. The recording of the generated pulse was performed with two similar tri-axial GEOSTUFF geophones (BHG-2 model) clamped to the borehole wall by means of motor-driven bow-springs.

The vertical component of the receiver was used to capture the vertically propagating shear waves (SV), while the two horizontal components recorded the propagating compression waves (P) and the horizontally propagating shear waves (SH). The hammer input and the receiver outputs were recorded by a Geometrics seismograph (StrataView-24bit, 24 channels). At the same time, the one of the geophones was also used to acquire DHS data set, bu generating compressional and shear waves at the surface by the use of a sledgehammer with a triggering system. The source and receivers were then moved to the next measurement depth and the process was repeated until all desired depths were sampled.

The SAC freeware interactive software (Seismic Analysis Code, developed by Lawrence Livermore Laboratory, University of California, 11/6/2000, Version 00.59.2) was employed for the picking of the arrivals times. Picking of P arrivals was much easier than S-arrival identification since it is always the first wave usually sharply arriving at the geophone (Figure 4a).

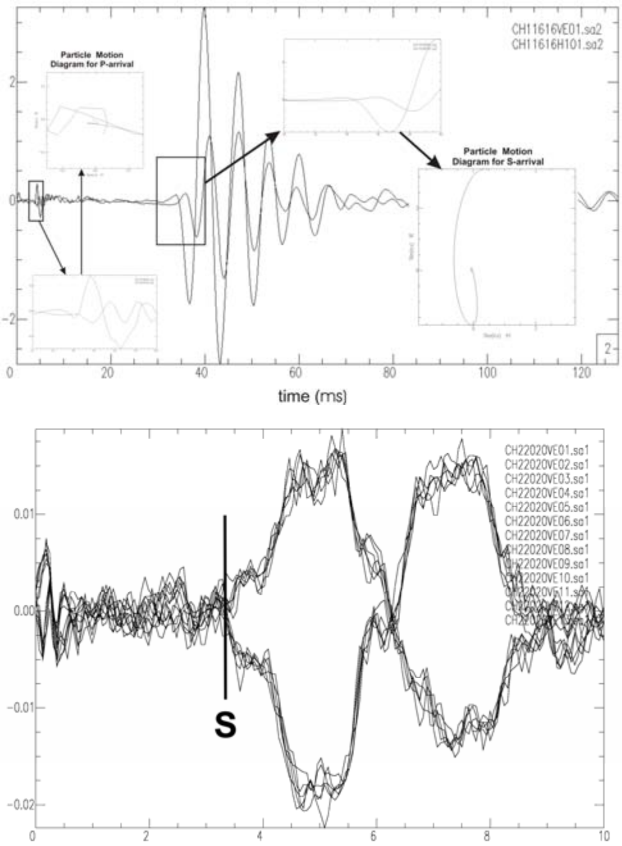


Figure 4. Picking of P and S-waves for cross-hole measurements: a) (Top) Picking of P waves (first clear onset) and S arrivals (application of particle motion diagrams). b) (Bottom) Picking of S arrivals using the standard "positive-negative deviation" approach

For the S-waves, the picking of the onset of shear-wave motion in the presence of source generated noise (later cycles of P-motion or tube waves) can sometimes be challenging. Two methods of identification were applied: a) The conventional method of overlapping waveforms (from the "positive" and "negative" source polarity records) for each of the geophones components (usually the vertical which clearly records the SV wave) is often adequate to obtain a crossover onset of shear-wave energy (figure 4b) and, b) alternatively we used the change of polarization direction of the wave field using particle motion diagrams. In practice for the P-wave arrival a linear particle motion along the direction of propagation is observed, whereas the S-wave arrival is associated with particle motion almost perpendicular to the direction of propagation. Using this method we could distinguish the component which "received" the S-wave motion by plotting component pairs, as is shown in Figure 4b, since the orientation of the horizontal components of the recording geophones was unknown.

### 4.2 Data Interpretation

For the interpretation of the DH measurements, a second order polynomial numerical derivative approach was used (eq. 1):

$$V_i^{downhole} = \frac{\left(2L^{i+2} + L^{i+1} - L^{i-1} - 2L^{i-2}\right)}{\left(2t^{i+2} + t^{i+1} - t^{i-1} - 2t^{i-2}\right)} \qquad (1)$$

where L is the depth of the receiver, t is the measured traveltime and i is the position of the receiver into the borehole.

For the CH data interpretation, when one receiver was available, the travel time from source to the receiver was measured and used for velocity estimation In the case that two receiver boreholes were used, the travel time between the receivers was measured, usually referred to as interval travel time measurements. Note that interval travel times are much more accurate than source-receiver (direct) travel times, since the later suffer from source timing errors caused by differences in seismic triggering, variations in source impulse characteristics and errors arising from variations in borehole size or mud-cake thickness near the transmitters. On the other hand, from the triple borehole measurements (CH1 and CH2) it was easy to estimate this error, which for our seismic source was of the order of 0.5ms, which was added to the raw traveltime data. The final velocities for the compressional and shear waves at each depth were easily determined by dividing the travel distances by the measured travel time. The travel-time distances were measured along the surface at the begging of the survey, assuming that the boreholes were nearly-vertical.

The finally picked traveltime and estimated velocity data for both types of data 1(CH and DH) are presented for two indicative locations (CH1 and CH3) in Tables 1 and 2.

Table 1. Final P and S velocity model determined from the CH measurements for the CH-1 borehole.

| Recording | Depth(m) | 1st Borehole | | 2nd Borehole | | $V_S^1$ | $V_S^2$ | $V_P^1$ | $V_P^2$ |
|---|---|---|---|---|---|---|---|---|---|
| | | $t_P$(ms) | $t_S$(ms) | $t_P$(ms) | $t_S$(ms) | m/s | | | |
| CH10202 | 2 | 6.5 | 15 | | | 374 | | 835 | |
| CH10404 | 4 | 5.7 | 10.5 | | | 527 | | 943 | |
| CH10606 | 6 | 3.85 | | | | | | 1349 | |
| CH10808 | 8 | 3.05 | 7.5 | | | 725 | | 1657 | |
| CH11010 | 10 | 2.8 | 5.65 | | | 943 | | 1785 | |
| CH11212 | 12 | | | | 9.2 | | 1093 | | |
| CH11414 | 14 | 2.2 | | | 10.2 | | 991 | 2189 | |
| CH11616 | 16 | | | 3.95 | 10.2 | | 991 | | 2409 |
| CH11818 | 18 | | | 4.2 | 9.5 | | 1060 | | 2280 |
| CH12020 | 20 | | | 3.4 | 8.1 | | 1233 | | 2753 |
| CH12222 | 22 | | | | 7.5 | | 1325 | | |
| CH12424 | 24 | | | | 6.8 | | 1452 | | |
| CH12626 | 26 | | | | 7.7 | | 1293 | | |
| CH12828 | 28 | | | 2.25 | 7.1 | | 1395 | | 3926 |
| CH13030 | 30 | | | 2.2 | 7.2 | | 1377 | | 4000 |
| CH13232 | 32 | | | 2.15 | 7.1 | | 1395 | | 4077 |
| CH13434 | 34 | | | 2.05 | 7.3 | | 1359 | | 4240 |
| CH13636 | 36 | | | 2.2 | | | | | 4000 |
| CH13838 | 38 | | | 1.8 | | | | | 4711 |
| CH14040 | 40 | | | 1.9 | | | | | 4511 |

Table 2. Final P and S velocity model determined from the DH measurements for the CH-3 borehole.

| Depth(m) | $t_P$ (ms) | $t_S$ (ms) | Distance(m) | $V_P$ (m/s) | $V_S$ (m/s) | |
|---|---|---|---|---|---|---|
| 2 | 5.97 | | 3.48 | 583 | | Borehole 1 |
| 4 | 6.8 | 12.5 | 4.91 | 723 | | |
| 6 | 10.34 | 14.8 | 6.64 | 834 | 434 | |
| 8 | 12.82 | 17.2 | 8.49 | 927 | 766 | |
| 10 | 13.4 | | 10.40 | 1167 | 804 | |
| 12 | 15.3 | 22.2 | 12.33 | 1421 | 772 | |
| 14 | 17.3 | 24.2 | 14.29 | 1340 | 797 | |
| 16 | 17.7 | 27.5 | 16.25 | 1561 | 810 | |
| 18 | 19.5 | 29.4 | 18.22 | 1974 | 684 | |
| 20 | 20.5 | 31.75 | 20.20 | 2242 | 790 | |
| 22 | 20.9 | 36.5 | 22.18 | 2948 | 825 | |
| 24 | | | 24.17 | 2683 | 1079 | |
| 26 | 22.3 | 39 | 26.16 | 2542 | 1540 | |
| 28 | 23.5 | 39.7 | 28.14 | 2594 | 1326 | |
| 30 | 23.9 | 42 | 30.14 | 2620 | 1266 | |
| 32 | 24.7 | | 32.13 | 2490 | 1328 | |
| 34 | 25.5 | 45 | 34.12 | | | |
| Depth(m) | $t_P$ (ms) | $t_S$ (ms) | Distance(m) | $V_P$ (m/s) | $V_S$ (m/s) | |
| 2 | 4.5 | 10 | 2.72 | 605 | 272 | Borehole 2 |
| 4 | 6 | 10.5 | 4.41 | 948 | 462 | |
| 6 | 8.25 | 17.7 | 6.28 | 727 | 581 | |
| 8 | 12.1 | 21.7 | 8.21 | 743 | 650 | |
| 10 | 14.3 | 20.5 | 10.17 | 1008 | 864 | |
| 12 | 16 | 24 | 12.14 | 1402 | 823 | |
| 14 | | 27.9 | 14.12 | 1651 | 619 | |
| 16 | 18 | 30 | 16.11 | 1968 | 689 | |
| 18 | 19.3 | 33.5 | 18.09 | 2229 | 737 | |
| 20 | 19.9 | | 20.09 | 1861 | 844 | |
| 22 | 20.4 | 38.5 | 22.08 | 1862 | 1166 | |
| 24 | 22.8 | 39.3 | 24.07 | 2258 | 1202 | |
| 26 | 23.2 | 40 | 26.07 | 2813 | 1558 | |
| 28 | | 42.7 | 28.06 | | 1576 | |
| 30 | 23.8 | 43.2 | 30.06 | | 1507 | |
| 32 | 24.5 | | 32.05 | 2852 | | |
| 34 | | 45.3 | 34.05 | | | |

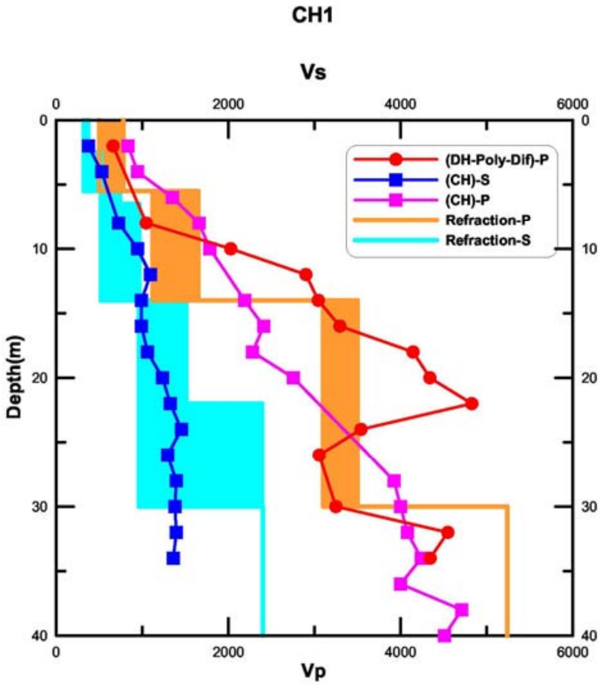


Figure 5. P and S velocity model as resulted from the CH (squares) and DH (circles) measurements as site CH-1. The velocity distribution as estimated from refraction measurements for P and S waves with depth is also given in the shaded areas.

In figure 5 we present the correlation of the various seismic velocity model for one (CH-1) of the sites under investigation using RS, CH and DH seismic measurements. A good correlation of the variation with depth identified from the different techniques was generally found. Using the obtained values it was possible to estimate several additional elastic moduli, such as, Young modulus, E, (eq. 2) and rigidity values, G, (eq. 3) for all depths for which data were available, in order to provide additional information for the calculation of the final dynamic response of the structure (dam) to be built.

$$E = 2 \cdot \rho \cdot (1+\sigma) \cdot V_s^2 \quad (2)$$

$$G = \rho \cdot V_s^2 \quad (3)$$

where ρ is the average density of each geological unit.

## 5. CONCLUSIONS - RESULTS

Using the results of the geophysical survey, a detailed correlation of geophysical parameters with the available geological information (surface mapping and borehole logs) was performed. A typical example is presented in figure (6), where the geological cross-section based on surface and borehole information is presented for a profile which practically runs along the D3-D4-D5 refraction lines (see figure 1 and 3).

In general, the velocity structure and the main layer characteristics of all the principal geological/ geophysical units have been well defined in both abutments of the dam. Moreover, results from refraction seismics (RS) were in a good agreement with the crosswell seismic (CH and DH) experiments.

The performed geological-geophysical correlation showed that both P and S wave velocities increase significantly with depth, showing clearly the transition from the sedimentary layer (low velocity – poor mechanical behavior in static loads) to the (locally weathered) crystalline bedrock formations (high velocity – good mechanical behavior). Moreover, a good correlation between the defined geophysical units and the two main bedrock geological formations (limestones and phyllites) was established.

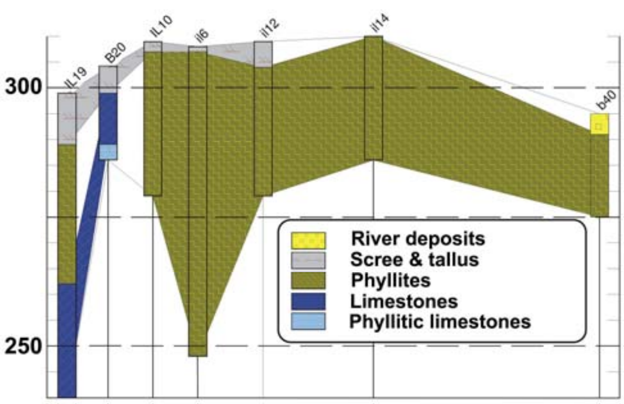


Figure 6. Geological cross-section parallel to the D3-D4-D5 refraction profile (see fig.1 and 3.), used for the correlation of geophysical and geological information.

When examining the results in detail and attempting to classify the final velocity models in the basis of the various formations, we have separated the velocity models in three different groups of layer velocities corresponding to the three main geological formations, as presented detail in the following section:

- Unit A ($V_P$=440-800 m/s, $V_S$=140-410 m/s)

  This unit consists of recent and old alluvial deposits. All measurements on this formation show very strong velocity variations, which are considered to be a result of the existing inhomogeneity in the unit. The average velocity Vp=620m/s, Vs=275m/s and the typical density for this geological formation (d=2.15gr/cm$^3$), correspond to $E_0$≈450MPa and $G_0$≈160MPa for the elastic modulus for this unit.
- Unit B ($V_P$=4200-4700 m/s, $V_S$=1230-1560 m/s)

  This unit consists of weathered and healthy limestone. At shallow depths, refraction seismics gives typical velocities around Vp=3450m/s and Vs=720m/s, which probably corresponds to fractured and weathered limestone. Down to 30 meters, a high velocity layer (Vp=5600m/s and Vs=2300m/s) is identified, which corresponds to healthy limestone, an interpretation which is also supported by the results obtained from geological and geotechnical information. For these depths, the corresponding elastic moduli values, using a typical density for this geological formation equal to d=2.65gr/cm$^3$, are $E_0$≈32500MPa and $G_0$≈11500MPa.
- Unit C

  This unit consists of weathered and healthy phyllites. From the surface up to the depth of 12 meters, average velocities of about Vp=1320m/s and Vs=630m/s have been estimated, indicative of a weathered and fractured phyllites layer. Using the aforementioned velocities and a density equal to d=2.5gr/cm$^3$, the average elastic modulus are, $E_0$≈2700MPa and $G_0$≈1000MPa, respectively. The deeper phyllite unit is characterized by the transition from the weathered phyllites to healthy phyllites and is identified bu its higher velocities (Vp=3000m/s and Vs=1200m/s). Using these velocities, the corresponding estimated elastic modulus are $E_0$≈10000MPa and $G_0$≈3700MPa.

The obtained results clearly suggest that the use of a combined surface-borehole seismic survey allowed the detailed and accurate correlation of geological-geotechnical and geophysical information, in order to provide average formation properties (elastic moduli, etc.), as well as 2D geophysical-geological cross–sections, which can be used for the seismic design and construction of the proposed Ilarionas Dam. The correlation of the results obtained from the different geophysical techniques (RS, CH, DH), as well as between geophysical and geological information is in all cases satisfactory, verifying the applicability of such techniques for in-situ dynamic soil properties determination.

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