RAILWAYS PLATFORMS MONITORING USING LAND SURFACE WAVE ANALYSIS - DCOS.
PART ONE: PRINCIPLES, MEASUREMENTS AND RESULTS.

CONTRÔLE DES REMBLAIS DE PLATEFORME PAR L'ANALYSE DES ONDES DE SURFACE – DCOS (DETECTION DE CAVITÉS PAR ONDES DE SURFACE) PARTIE UNE : PRINCIPES, MESURES ET RÉSULTATS

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ABSTRACT – The detection of geological anomalies such as karstic caves in carbonate bedrock, near surface tunnels (from the First World War) or mine working constitute a main challenge for many structures or projects of the French Railways Company (SNCF). A non-usual approach of measurement by passive seismic and processing (DCOS) using the propagation properties of the Rayleigh is described. Results obtained on a full-scale test station are explained.

RÉSUMÉ – La détection "d'anomalies" géologiques telles que des cavités karstiques dans des niveaux de calcaire, des tunnels réalisés lors de la Première Guerre Mondiale, ou les cavités résultant de l'exploitation de mines, constitue un enjeu majeur pour l'exploitation du réseau ferré par SNCF. Seront présentés dans cet article une approche peu commune de mesures par sismique passive, le traitement associé (DCOS) basé sur les propriétés de propagation des ondes de Rayleigh ainsi que les résultats obtenus sur un site test mis en place par SNCF.

1. Introduction

The detection of geological anomalies such as karstic caves in carbonate bedrock, near surface tunnels (from the First World War) or mine working constitute a main challenge for many structures or projects of the French Railways Company (SNCF).

One way to characterize the shallow subsurface, is to determine the shear wave velocity [Vs] depth profile. This is now well recognized as a pertinent non-invasive method for the evaluation of the material properties (shear modulus) in soil and rock deposits. Multichannel Analysis Surface Wave [MASW] technique allows producing an easily understood velocity depth profile. Changes in the soil properties can be detected by a MASW profiling method. For large survey areas, a fast acquisition is obtained by using passive measurement (natural or anthropic noise called micro-tremor) as a seismic source.

Unfortunately, a classical direct use of the MASW processing does not permit easily and with a good success ratio to localize karstic features, voids. Some changes in the shear wave velocity can be shown but only if the size of the geological anomalies is big enough to produce a visible modification on the shear wave velocity.

In 2004, in order to bring a solution to this problem, we have developed, in collaboration with SNCF, an innovative analysis for the geological anomaly detection using the Rayleigh wave's properties. This processing, called DCOS (Détection de Cavités par Ondes de Surface) is based on signal processing (frequency domain) and statistical analysis. It has been patented in 2005 by SismOcean (SismOcean, 2005).The target of this analysis is to characterize the surface wave properties modification (dispersive pattern) before and after their interaction with the geological anomaly (void, local unconsolidated or stiffer materials…). The possibility to use micro-tremor allows us to acquire data in “noisy” conditions (urban areas, industrial plants, etc.) and to work on the railroad platforms (ballast) where it is too difficult to generate seismic signal with classical active sources. Results obtained by the DCOS analysis allow to localize the geological anomalies in distance along the railway and also to estimate their depth.

2. History, site and acquisition

On behalf of RFF, SNCF realized a full-scale test station to compare several geophysical methods capable of detecting cavities, essentially due to tunnels or underground galleries made during the First World War, which may be at the origin of collapses (subsidences) under the High Speed Railway. The tests included a "recognition" component to accurately assess the capacity of each geophysical method, to know the limits of use, to obtain calibrated signatures. The final aim of this project was to study possible coupling between methods, as well as a benchmark in order to define which method would permit a rapid and periodic scanning on certain sectors of the railroad to identify possible evolution and / or occurrence of voids in the vicinity of the platform (Grandsert, 2005, Nebieridze, 2009).

2.1. Chaulnes, full scale test station

The site test was composed of two tunnels reinforced by a wooden structure (Nebieridze, 2009). These cavities crossed a maintenance track for vehicles and a maintenance railroad (Figures 1 and 2). The tunnels characteristics were:
- Square section of 2 x 2 meters.
- The roof was 1 meter below the base of the ballast for the tunnel A, and 3.5 meters for the tunnel B.
- When our seismic operation has been performed the two tunnels has been half fullfilled of local ground. The void left in the tunnels had a high of 1 meter.

Figure 1. Chaulnes site, vehicle track

Figure 2. Chaulnes site, railway (maintenance and circulation)

2.2. Objectives and seismic measurements

The objectives of this survey performed in 2003 was to study the influence of the voids or local anomalies on the propagation of anthropic seismic noise. On this site, the main seismic sources are the highway located at 300 meters, and the train traffic at far distance (long time before or after their arrival on the site test location). For the rest of the article the passive seismic signal will be called micro-tremor.

A streamer composed of 24 geophones (4.5Hz) was used with different spacing between the receivers (0.5, 1, 2 meters). For every configuration and all along the area, seismic shots and micro-tremor acquisition between the train circulations were performed.

The geophones spacing were as follow:

- 0.5 m on the road track above the cavity B, one seismic profile.
- 1 m on the road track and the railway (ballast) for train maintenance. Eleven seismic profiles equally spaced of 12 meters.
- 2 m on the railway (ballast). Five seismic profiles equally spaced of 24 meters.

2.3. Acquisition example

The two figures presented below (figure 3 and 4) illustrate the micro-tremor acquisition performed for a seismic spread with the tunnel B located at its middle. On these figures, the horizontal axis represents the distance (geophones) and the vertical ones the acquisition time in second. On both figures, it can be seen that for the time distance representation, and with the use of passive measurement, it is not possible to evaluate the soil parameters, and to identify a possible influence of the cavity on the signal propagation.

On the figure 3, there is no singular seismic wave which attenuates the global record. This kind of record can be considered homogeneous in term of energy received by all the geophones.

On the figure 4, the seismic signal generated by the train traffic is clearly visible and constitutes the main part of the energy received by all the geophones. Due to the large amplitude of this seismic signal, the other components of the micro-tremor are not visible with this kind of visualization.

In order to be able to get more information carried by the signal, it is necessary to work with the phase velocity and frequency.

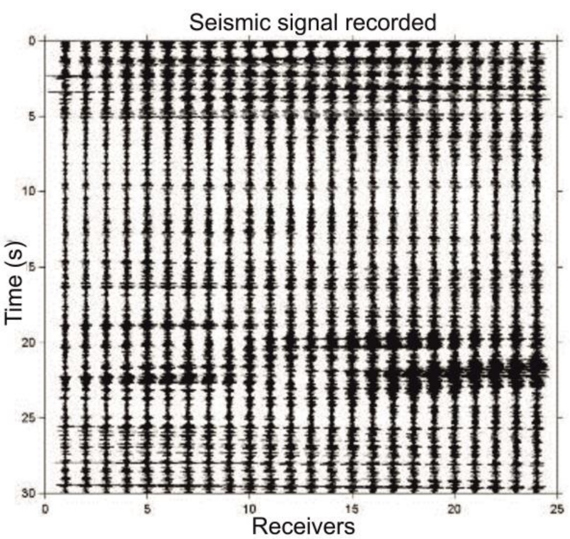


Figure 3. Passive acquisition, road way circulation (without train circulation)

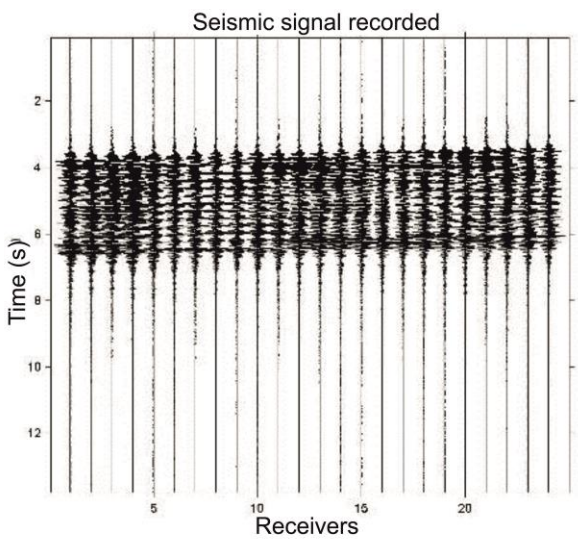


Figure 4. Passive acquisition, train circulation

3. Classical passive measurement processing

We based our approach on the MASW analysis (Park and al., 1999) giving access to the dispersive pattern of the surface wave propagating in the soil. The MASW processing uses a transformation from (distance vs time) to (phase velocity vs frequency). Our seismic spread is linear and the micro-tremor signal components (isotrope seismic source) are supposed to be measured by all the receivers with all the incident angles. The surface wave apparent phase velocity (V_{app}) of the micro-tremor depends on the real phase velocity (V_{re}) and of its incident angle α with the seismic spread:

$$V_{re} = V_{app} \cos(\alpha) \qquad (1)$$

The incident angle α is the angle between the propagating vector of the incident waves and the oriented axis defined by the seismic spread (from geophone 01 to geophone 24). The (V_{app} / V_{re}) ratio is represented on figure 5 where the vertical axes limits of the graph have been adapted for readability reason. The left axis corresponds to the difference, in percent, between V_{app} and V_{re} in function of α (Adamy, 2003).

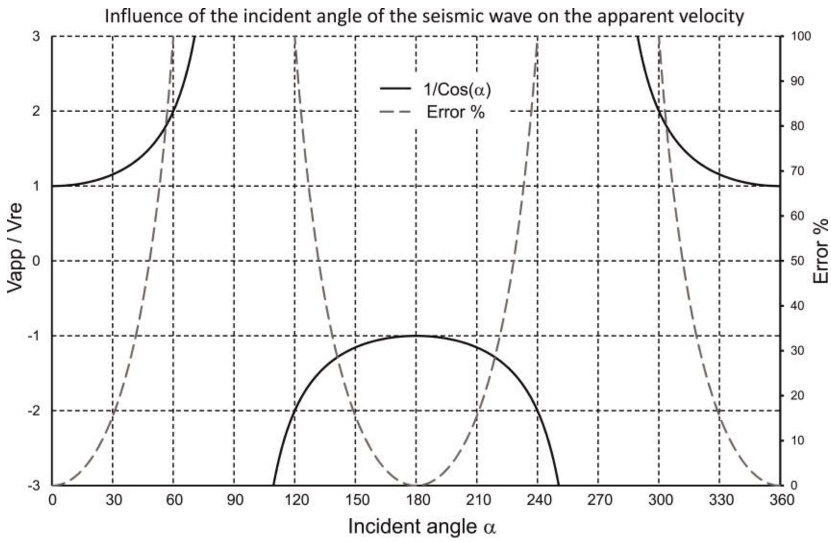


Figure 5. Influence of the incident angle on the phase velocity.

An asymptotical behaviour is observed for the incident angles of 90° and 270°, which correspond to the seismic waves arriving with a perpendicular direction to the streamer. The (V_{app}/V_{re}) ratio will be equal to 1 for arrivals in the axis of the streamer. If the wave field is correctly sampled by enough receivers, the relation $|V_{app}/V_{re}| < 1$ is always false for any value of the incident angle α. Thus, it will never be possible to measure apparent phase velocity slower than the real phase velocity.

On a diagram representing the dispersive pattern of the surface wave computed from micro-tremor signal (which corresponds to the energy distribution as a function of the apparent phase velocity and the frequency), a limit will be visible between areas with strong energy where $|V_{app}/V_{re}| > 1$ and weak or null energy where $|V_{app}/V_{re}| < 1$ (Figure 6).

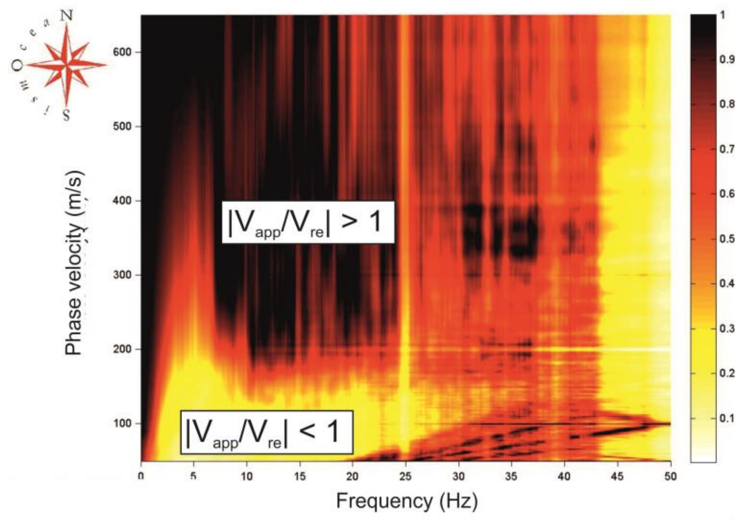


Figure 6. Influence of the incident angle on the phase velocity.

In comparison with an active acquisition where the streamer is aligned with the seismic source, the diagram will show the main part of the energy concentrated on the limit where the apparent phase velocity is equal to the phase velocity: $V_{app}=V_{re}$.

4. DCOS (Geological Anomalies Detection Using Surface Wave - GADUSw)

4.1. DCOS principles

DCOS analysis uses the surface wave propagation properties and their interaction with any kind of geological anomalies. Figure 7 shows a case without any geological anomaly.
The geological anomalies or heterogeneities are considered in term of their dimensions regarding to the streamer geometry that is to say with a significant dimension. These anomalies can be:

- voids (gypsum dissolution, karstic area, natural or handmade cave, underground gallery)
- voids partially or full of water
- local under compressed soil
- …

On the figure 7, the triangles represent the receivers. Considering a far field seismic source and, in this case, no heterogeneity in the soil, the Rayleigh wave energy propagation will not be disturbed along its travel. The level of the energy can be expected to be more or less the same between the first and the last geophones (Mouton et al., 2006).

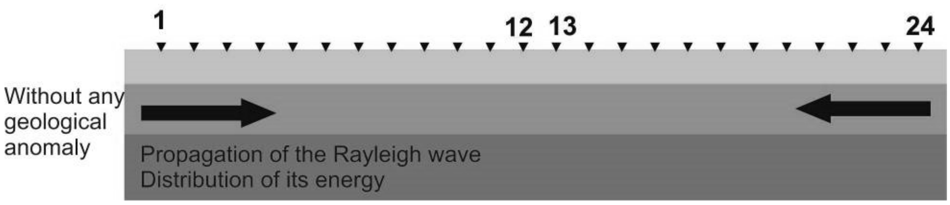


Figure 7. Rayleigh wave propagation without any geological anomalies.

While, in the case of the presence of a geological anomaly, the Raleigh wave energy distribution will be modified along its propagation (Figure 8).

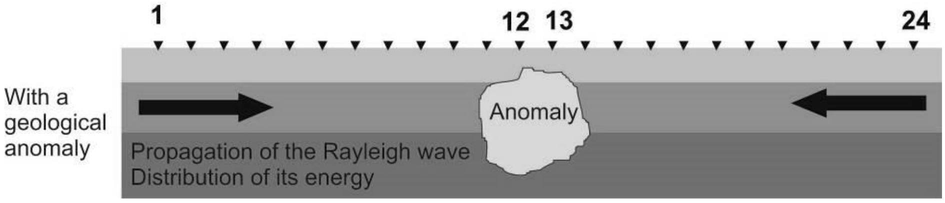


Figure 8. Rayleigh wave propagation with a geological anomaly (cavity).

The Rayleigh wave energy propagating from geophone 1 to geophone 24 will have interactions with the anomaly. The Rayleigh wave energy measured by the group of geophones 1-12 will be higher than the one measured by the geophones 13-24.

As a function of direction of the slant stack transform applied (from geophone 1 to 24 or from 24 to 1), it is possible to define two propagation directions related to the streamer:

- Direct or positive propagation for the one from the geophone 01 to 24.
- Reverse or negative propagation for the one from the geophone 24 to 01.

The slant stack transform will also be used to compare the energy distribution as a function of the wavelength λ defined by $\lambda = \frac{phase\ velocity}{frequency}$.

Thereby, the analysis of the anomalies detection called DCOS is based on a comparison of the Rayleigh wave energy distribution measured by half part of the streamer for the two directions of propagation (positive and negative). Separating the analysis of the two directions allows to be less influenced by strong variations of the energy level of the micro-tremor received from the both side of the streamer (positive and negative).

4.2. Energy distribution variation

The DCOS analysis is based on the influence of the geological anomaly on the energy distribution of the Rayleigh surface wave. In order to explain the analysis principles, an example based on the used of 24 receivers is explained in this chapter. In the case where there is no geological anomaly, the processing performed is detailed on figure 9. On this figure, the geophones are represented by triangles and separated in two groups: 1-12 and 13-24.

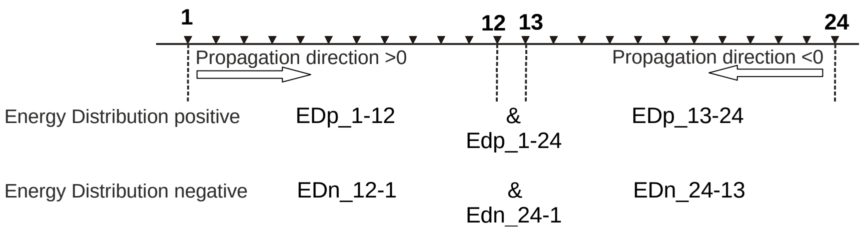


Figure 9. Rayleigh wave energy distribution without any geological anomalies.

Taking into account the direction of the Rayleigh wave propagation measured (positive and negative), the energy distribution of the Rayleigh wave (called ED on the figure 9) is computed for the following combinations:

Positive direction (EDp)

- EDp_1-24 is the slant stack transform of the acquisition for the receivers 1-24.
- EDp_1-12 is the slant stack transform of the acquisition for the receivers 1-12.
- EDp_13-24 is the slant stack transform of the acquisition for the receivers 13-24.

Negative direction (EDn)

- EDn_24-1 is the slant stack transform of the acquisition for the receivers 24-1.
- EDn_12-1 is the slant stack transform of the acquisition for the receivers 12-1.
- EDn_24-13 is the slant stack transform of the acquisition for the receivers 24-13.

Considering an homogeneous soil and without any geological anomalies, the energy distribution should be the same all along the propagation. EDp_1-12 (respectively EDn_12-1) should be equal to EDp_13-24 (respectively EDn_24-13).

The figure 10 shows the case of the presence of a geological anomaly.

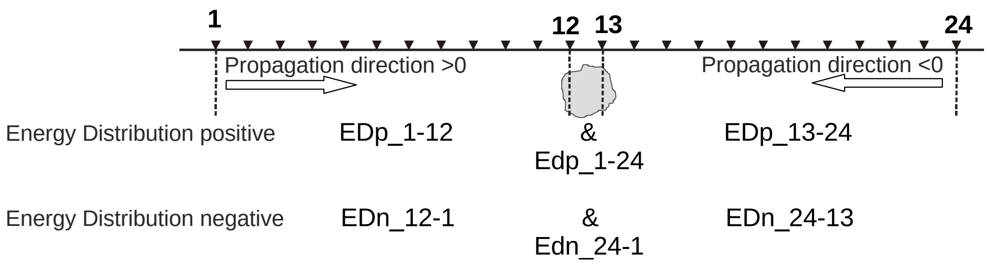
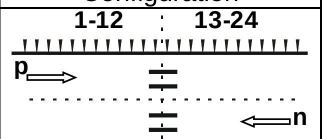
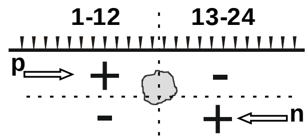
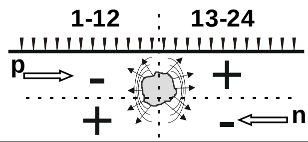
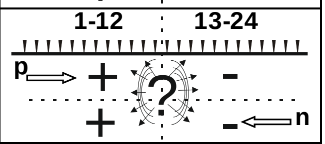


Figure 10. Rayleigh wave energy distribution with a geological anomalies.

In this case, a unique possibility of the energy distribution can be found: EDp_1-12 > EDp_13-24 and EDn_12-1< EDn_24-13.

Table 1 below synthetizes the different possibilities which can be found for the sign of comparison of the energy distribution.

Table 1. Energy distribution configuration

Case #	Description	EDp_1-12 – EDp_13-14	EDn_13-24 – EDn_12-1	Configuration
1	Homogeneous soil	0	0	
2	Geological anomaly (void, karst unconsolidated area…)	EDp_1-12 > EDp_13-14 or +	EDn_13-24 > EDn_12-1 or +	
3	Local seismic source along the streamer	EDp_1-12 < EDp_13-14 or -	EDn_13-24 < EDn_12-1 or -	
4	Physically impossible	+	-	
5	Physically impossible	-	+	∅

The case #3, which is described as local seismic source is a punctual seismic vibration measured by the receivers: water circulation in a karst, pylon vibration due to the wind …

The cases #4 and #5 are physically impossible because they correspond to the case of a cavity coupling to a local source emitting seismic wave but only in one direction.

4.3. DCOS measurement and processing

The measurements are performed with streamers composed with string of receivers equally spaced. The natural or anthropic micro-tremor is the most commonly used as seismic signal because it avoids the coupling problems of seismic source and near field effects encountered with conventional seismic shots. This technic offers the possibility (with the seismic streamer used), to carry out an analysis with a sliding window by the extraction of the number of traces required from the global seismic recorded. Figure 11 illustrates this step in the DCOS processing.

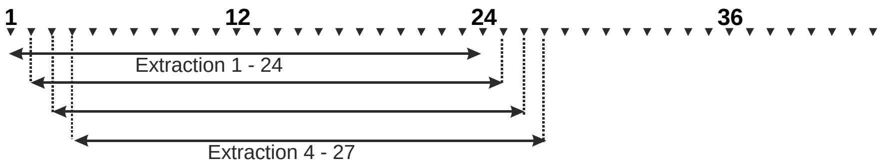


Figure 11. Seismic traces selection using a sliding windows.

Thus, for a spread composed of 96 geophones and with a selection of 24 receivers, the DCOS analysis applied on the selected traces will permit to obtain 73 results equally spaced (and equal to the distance separating two receivers). In the same way, a DCOS analysis using 48 receivers (deeper investigation) will give 49 results for the same seismic acquisition.

The processing methodology is as follow:

- Micro-tremor acquisition using the whole land streamer
- Geophones extraction using a sliding window
- DCOS analysis for each group of receivers selected
- Production of a profile (distance vs depth) with all the DCOS results equally spaced of the distance between two receivers

4.4. Energy comparison

Figures 12 and 13 show the Rayleigh wave energy distribution obtained on Chaulnes site for the different configurations (EDp_1-12, EDp_13-24, EDn_12-1, EDn_13-24). The cavity B was located between the geophones 12 and 13 of the seismic spread.

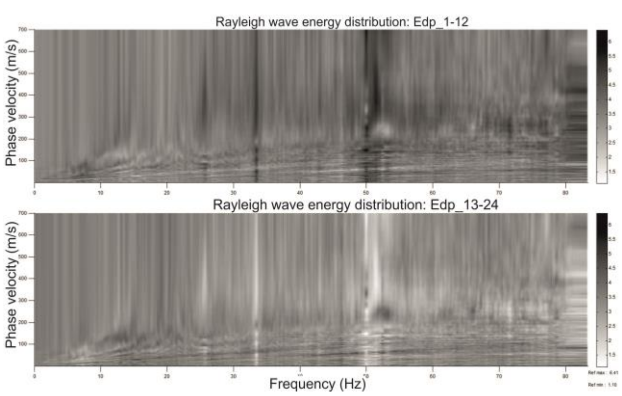


Figure 12. Chaulnes site, energy distribution EDp_1-12 and EDp_13-24

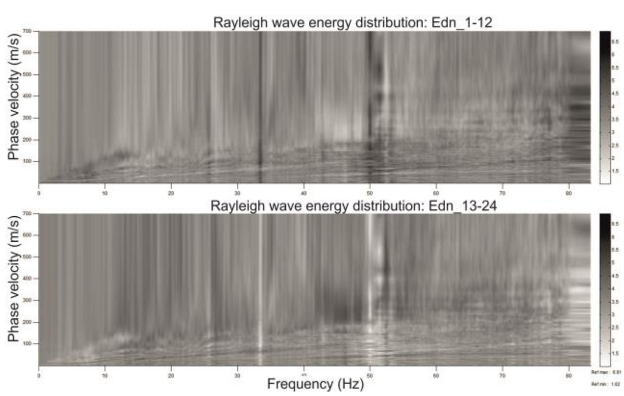


Figure 13. Chaulnes site, energy distribution EDp_1-12 and EDp_13-24

In order to compare these four images, a scan of the energy distribution is applied in the wavelength domain. As the wavelength is a geometrical parameter as a function of depth investigation, this scan permits to compare the energy variation for different depth. For each value of the wavelength, the energy distributions values are extracted and compared. Figures 14 and 15 present an example of the wavelength scan of the energy distribution and the corresponding level of energy extracted. For each wavelength and each group of receivers, the cumulative distribution (figure 15) is used to compare the energy distributions EDp and EDn. The energy level variation, for the different groups of EDp and EDn, is computed. Then as a function of its sign configurations presented in table 1, an interpretation is carried out.

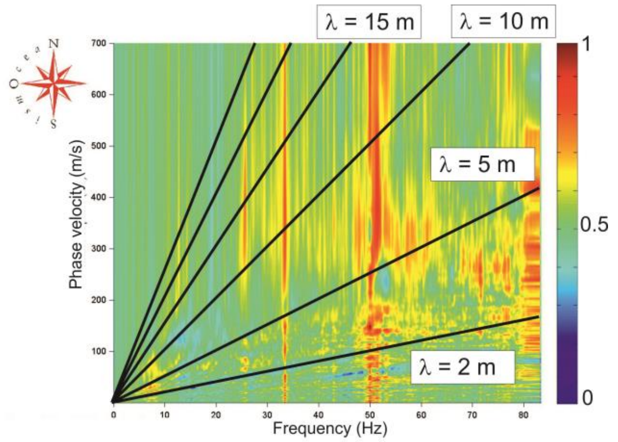


Figure 14. Scan of the energy distribution in the wavelength domain

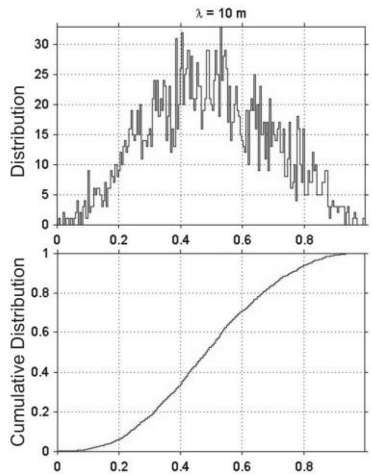


Figure 15. Energy value distribution and cumulative distribution, λ= 10 m.

4. Result

Figure 16 shows the results obtain with DCOS analysis for the test station of Chaulnes. On this figure, the left vertical axis is the depth in wavelength (m), the right one is the corresponding depth (using the approximation z = λ/2 and z = λ/3) and the horizontal one is the distance. Usually the results are presented with a geographic color scale where the warm colors corresponds to the positive variations of the DCOS analysis (case 2 of table 1) and the cold color to the negative variations (case 3 of the table 1). On this figure the positive variations are shown by continuous lines and the negative variations with dashed lines. The color scale is used to show the “intensity” of the variations.

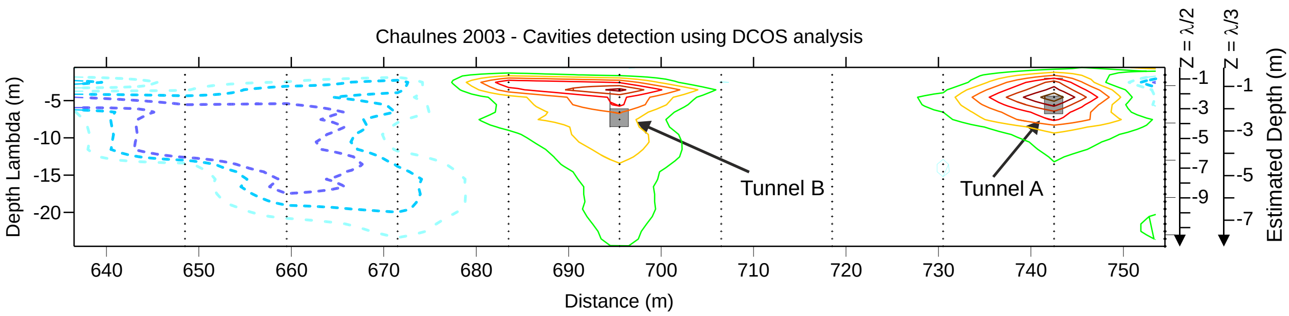


Figure 16. Chaulnes DCOS analysis results.

In 2003, the acquisition has been performed with a streamer composed of 24 geophones, 1 meter spaced. As soon as the acquisition was performed for one location, the seismic spread was moved from a distance corresponding to the half of the streamer length (12 m). Eleven seismic spreads have been performed to cover all the area including the zone without any geological anomalies. For every location, one DCOS analysis using the geophone groups 1-12 and 13-24 has been performed and that's mean that the DCOS analysis results are equally spaced of 12 meters. The consequence of this small density of results is the spreading of the anomalies detected. To increase the density of DCOS results it could be possible to reduce the number or receivers used during the sliding window processing (1-6 and 7-12 for example) But the consequence of the number receivers reduction, is to increase the "noise" on the energy distribution computed because a minimum of receivers are necessary to obtain a good dispersive pattern of the Rayleigh wave.

The two half fulfilled cavities A (distance m) and B (distance m) have been positioned in distance and well defined in depth as a function of the estimated depth approximation chosen. The DCOS negative values (case 3 in the Table 1) between the distances 650 and 660 m, correspond to a railway equipment generating a seismic noise. Its influence on the data was relatively important and could mask a geological anomalies.

5. Conclusions

The use of the micro-tremor seismic signal with the Rayleigh wave properties propagation allows to work in areas where it could be difficult to carry out a survey with classical active seismic sources. The DCOS analysis is based on signal processing and statistical analysis of the Rayleigh wave energy distribution that is to say without any numerical model, thus without any knowledge of the local geology.

The acquired data can be also used for a classical processing giving information on the shear wave velocity variation as a function of the depth (MASW processing). Thus the combination of both DCOS and MASW processing coming from the same seismic acquisition allows to identify possible geological anomalies and also to do a better description of the soil.

6. References

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