RAILWAYS PLATFORMS MONITORING USING LAND SURFACE WAVE ANALYSIS – BOTH DCOS AND MASW PROCESSING. PART TWO: MEASUREMENTS, PRODUCTION AND RESULTS.

CONTROLE DES REMBLAIS DE PLATEFORME PAR L'ANALYSE DES ONDES DE SURFACE – TRAITEMENT DES DONNEES PAR METHODE DCOS ET MASW : MESURES, RENDEMENTS ET RESULTATS

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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). In the part one of this paper, the DCOS measurement and processing are presented. In this second part, two surveys on railway sites with MASW, DCOS analysis and geotechnical results are presented.

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. Dans la première partie de cet article, les mesures et l'analyse DCOS sont présentées. Dans cette seconde partie, deux études de cas avec des résultats de géophysiques (MASW, DCOS) et géotechniques sont présentés.

1. Introduction

In a first paper, it has been presented the DCOS analysis principles based on signal processing and statistical analysis to show the variations of the energy distribution of the Rayleigh wave before and after its interaction with a local inhomogeneity (SismOcean, 2005). This analysis does not use any assumptions about the ground geology, does not need any active seismic source and does not require any numerical model inversion.

After three operational trials, with different geological and urban environment, the DCOS analysis has been validated and requested by SNCF for a survey in an urban site. The depth investigation required, for the geological anomalies detection (DCOS), was 20 meters and the quantities of measurements were 8 km. In the most part of the area, the acquisition lines were parallels and permitted to build a 3D data block. These data have been used for the data interpretation, and to define the geotechnical borehole locations, doing vertical profiles 2D (X, Z) and horizontal slices at constant depth (X,Y) results.

A return of experiment on a site is also presented with a comparison between the results obtained by geo-radar, MASW, DCOS analysis (seismic results) and boreholes. A good correlation between the geophysical results and the geotechnical campaign is shown.

2. Measurements

2.1. Set-up MASW/DCOS

The seismic streamer is composed of 96 geophones of 4.5 Hz, equally spaced of 2, 2.5 or 3 meters. In function of the depth investigation, the quantity of measurement and the daily production rate, a streamer set-up is chosen.

For the two sites presented in this paper, the space between the receivers was 2 meters. The land streamer has been adapted in order to work in rough conditions: rail, railway switch, ballast, and metallic or glass wastes on the railways (figure 1). Like the measurements are performed on the ballast, the geophones are equipped of a tripod plate to ensure their stability, verticality and the soil coupling (figure 2).

Figure 1. Seismic streamer

Figure 2. geophone laid on the ballast

2.2. Acquisition and QA/QC

The seismic signal acquisition is natural or anthropic micro-tremor. On site, during the acquisition time and for every records, a QA/QC is done by the visualization of the signal acquired and its FK representation. On the figure 3, an example of QA/QC visualization is shown. During the acquisition, the signal representation permits to check that there is no problems with the receivers such as bad coupling, non-expecting punctual event (bird, animal, …), local noise due to some railways' equipment. The FK representation, with a color scale in dB, allows to the observer to check that the signal acquired is well defined in the frequency domain and for the both direction (positive and negative). The records selected will be the signal presenting a homogeneous repartition of the energy.

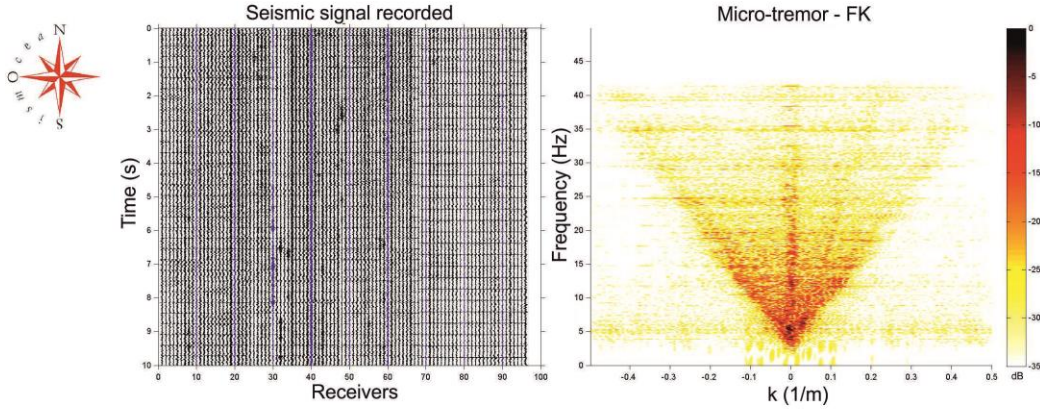

Figure 3. QA/QC on site during the acquisition.

When the number of the acquisitions, having a “positive” appreciation by the observer, is reached, the seismic streamer is moved, firstly on the parallel tracks and then, in the continuity of the previous streamer positions.

2.3. MASW processing: sliding windows, investigation,

In the part one of this article the geophone extraction using a sliding windows is presented for the DCOS processing. For the MASW (Park, C.B., 1999), the extraction processing is similar but this time all the geophone extracted are used to compute the energy distribution associated to the Rayleigh wave. Every group of geophones selected gives access to a vertical shear wave velocity profile.

The figure 4 shows the part of the streamer giving the “Vs Log” results in the case of an extraction of 48 geophones (deep investigation) equally spaced of 2 meters. The vertical Vs profile obtain with the first 48 receivers is located at the middle of the geophone extracted that is to say between the geophones #24 and #25.

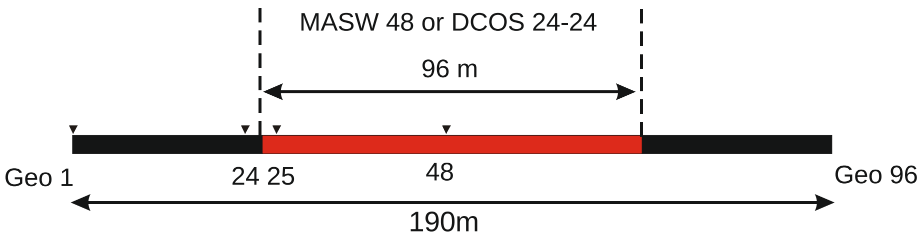

Figure 4. Active part (in grey) of the streamer for an extraction of 48 receivers.

The table 1 presented here below summarizes the number of MASW analyses (vertical Vs profile) for one spread (one acquisition) in function of the number of geophones used.

Table 1. MASW, Number of Vs velocity profiles per spread

	Number of Vs velocity profiles per spread	
Streamer geophones’ number	24 geophones extracted	48 geophones extracted
72	49	25
96	73	49

The maximal depth investigation using MASW can be estimated dividing by 2 or 3 the length of the part of the streamer used (active geophones). The table 2 indicates the depth investigation in function of the space between the receivers and the number of geophones used to compute the energy distribution of the Rayleigh wave.

Table 2. MASW, estimated depth investigation

	Estimated depth investigation	
Geophones’ spacing	24 geophones extracted	48 geophones extracted
1 m	8 - 15 m	15 – 23 m
2 m	15 – 23 m	31 – 47 m
3 m	24 – 36 m	> 47 m

Obviously, these depth investigations are strongly dependant of the soil parameters and of the frequency contents in the energy distribution measured. The use of streamers of 96 geophones, instead of 72, allows to double the length of the interpreted part per seismic spread for the deep investigation (48 geophones in the table 3).

Table 3. MASW, Interpreted length per seismic spread

	Interpreted length per spread			
	Streamer of 72 geophones		Streamer of 96 geophones	
Geophones' spacing	24 geophones extracted	48 geophones extracted	24 geophones extracted	48 geophones extracted
1 m	48 m	24 m	72 m	48 m
2 m	96 m	48 m	144 m	96 m
3 m	144 m	72 m	216 m	144 m

2.4. DCOS – sliding windows, investigation

The number of DCOS analyses per seismic spread and the interpreted length are the same than the MASW analyses using the sliding windows processing. On the other hand, the depth investigation estimated for the DCOS analysis is different and, like for the MASW, is function of the number of geophones used (table 4)

Table 4. DCOS, estimated depth investigation

	Estimate depth investigation	
Geophones' spacing	24 geophones extracted	48 geophones extracted
1 m	4 – 7.5 m	7.5 – 11.5 m
2 m	7.5 – 11.5 m	15.5 – 23.5 m
3 m	12 - 18 m	> 23.5 m

2.5. Production rates

In the table 5 the production per day is based for seismic spread composed of 96 geophones equally spaced of 2 meters. This production is also dependant of the site conditions (large surface, long linear …). For both MASW and DCOS, the shallow investigation (respectively deep investigation) is obtain with 24 receivers (respectively 48 receivers).

Table 5. MASW and DCOS, production per day

	Active acquisition	Passive acquisition (natural or anthropic noise)
Refraction	2 – 4 seismic spreads 380 m – 760 m	Not performed
MASW	2 – 4 seismic spreads 380 m – 760 m	10 – 15 seismic spreads Shallow investigation: 1500 m – 2250 m Deep investigation: 1000 m – 1500 m
DCOS	Not performed	10 – 15 seismic spreads Shallow investigation: 1500 m – 2250 m Deep investigation: 1000 m – 1500 m

In the case of the railway environment, the working conditions are more difficult and thus the production presented in the table 6, is lower. This is due to:

- The short time for the railway track access (between 3 and 5 hours),
- The work during the night,
- Many manually manipulations for the streamer displacement.

Table 6. MASW and DCOS production per night (railway environment)

	Active acquisition	Passive acquisition (natural or anthropic noise)
Refraction	Not performed	Not performed
MASW	Not performed	3 – 4 seismic spreads Shallow investigation: 436 m – 582 m Deep investigation: 292 m – 390 m
DCOS	Not performed	3 – 4 seismic spreads Shallow investigation: 436 m – 582 m Deep investigation: 292 m – 390 m

3. Site 1 – Gare de l'Est – Paris, France

3.1. Geology and objectives

The train station "Gare de l'Est" is located within the perimeter of risks due to the phenomena of dissolution of Pre-Ludian gypsum. The latter geological event was open-pit (quarries) which have been backfilled. The formations encountered, with varying dominances, are embankments, then the sands of Monceau (low dominance below the train station), marl limestones of Saint-Ouen, sands of Beauchamp, marls and "Caillasses" and finally limestone coarse (Talfumiere V. et al. 2008).

The groundwater is about 20 m below the surface (in the sand layer). It is alimented by both natural (rainwater infiltration in permeable soils) and artificial origins (leaks of the water network such as the Ourcq canal). The water level fluctuations are due to climatic variations but also to the pumping of the groundwater. Adding the existence of upper groundwater in the sands of Beauchamp and in the limestones, the conditions favouring the dissolution of gypsum are met.

From previous geophysical surveys, two kind of anomalies have been defined:

- Type 1: anomalies at the depth between 11 and 14 meters in the marl limestones of Saint-Ouen
- Type 2: anomalies at the depth between 29 and 41 meters in marls and "Caillasses"

The priority was to localize the first type of anomalies related to voids and to the geological units highly under consolidated. This kind of anomaly is in relation with the gypsum dissolution phenomena and presents a strong probability of going up at the surface.

The objectives was to implement a geophysical method allowing to adapt to the context, of the railway station activities (numerous tracks, significant traffic of both trains and passengers, presence of other works), of the anomalies depth sought (up to about 15-20 m) and the presence of ballast (the passenger platforms are present only for the first 400 meters). The method had also to permit a fairly high daily production rate to be sufficiently large (about 100 m/h) allowing the intervention of the other projects.

3.2. MASW results using micro-tremor

Working on the railway tracks gives the possibility to perform acquisition with parallel seismic spreads and to obtain vertical profiles (distance versus depth) of the shear wave velocity variations. The figure 5 is the result obtained for one seismic spread acquisition and with one vertical Vs profile every 2 meters.

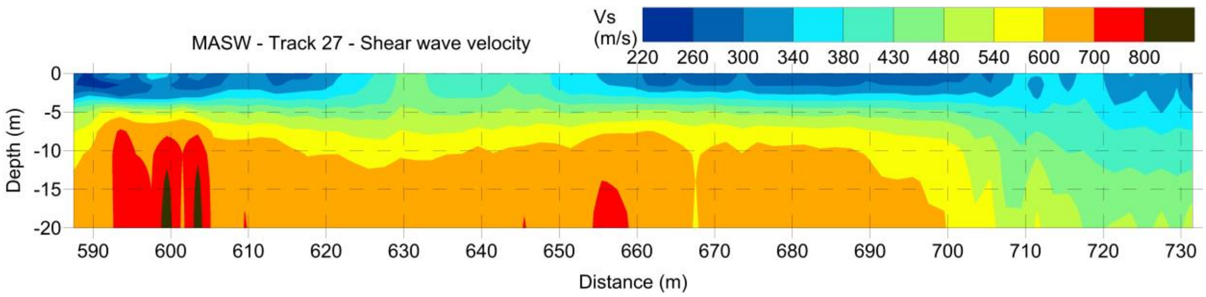

Figure 5. Shear wave velocity profile obtained using 24 geophones

The shear wave velocity variations are represented with a linear gray scale. The use of the parallel profile with the geo-referenced receivers allows to produce a 3D block (X, Y, Z) of data with the shear wave velocities variations obtained. From this 3D data, slices can be extracted at constant depth as showed in the figure 6. For every dots on the results a Vs vertical profile has been computed.

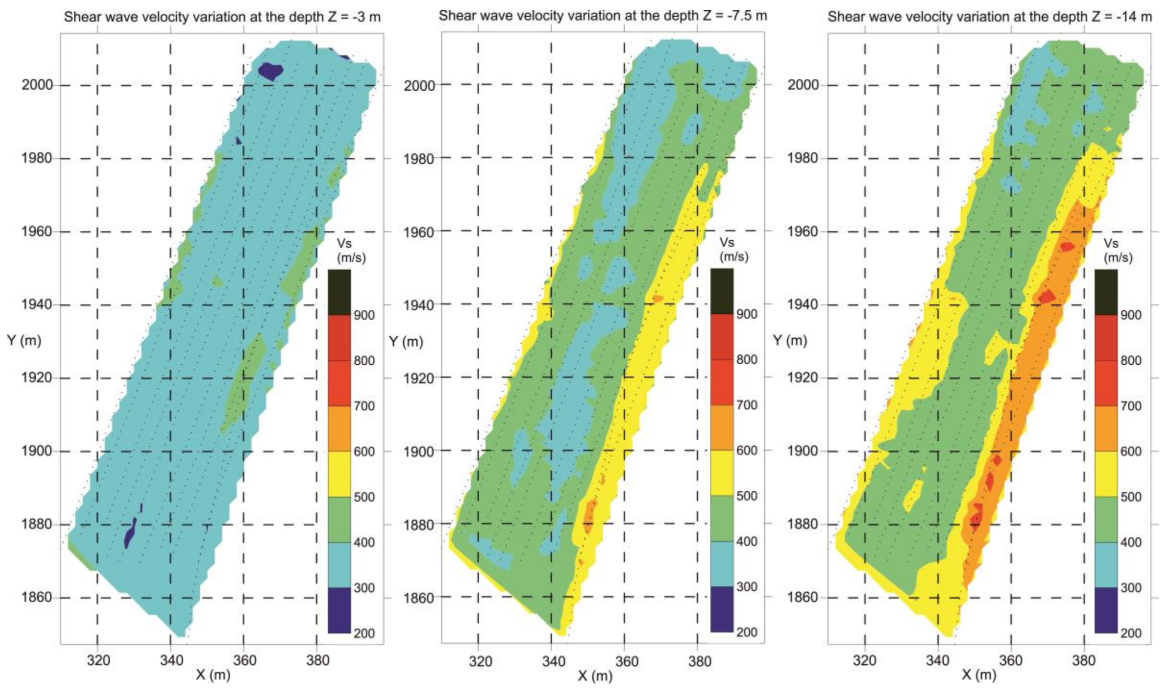

Figure 6. Shear wave velocity variations at constant depth (24 geophones).

This kind of representation is useful to see the lateral influences, and to correlate the shear wave velocities variations between the acquisition lines (dot lines).

3.3. DCOS results

Before to perform the complete survey, a feasibility phase has been requested by SNCF on a portion of railway. The figure 7 shows the result obtained for the acquisition composed of two seismic spreads and with a DCOS analysis (48 geophones) every 2 meters. On this figure, the left vertical axis is the depth in wavelength (m), the right one is the corresponding depth using the approximation $z = \lambda/2$ and $z = \lambda/3$ and the horizontal one is the distance. The positive variations of DCOS analysis are shown by continuous lines and the negative variations with dashed lines. The linear color scale is used to show the “intensity” of the variations from -0.8 to 1.6 (without unit dimensions).

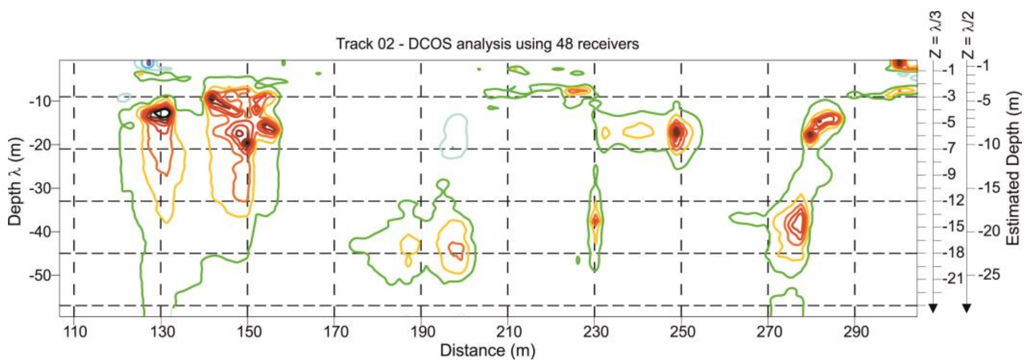

Figure 6. DCOS analysis results (48 geophones).

In the same way than for the MASW processing, the use of parallel profiles permits to compute a 3D block (X, Y, Z) and then to produce DCOS results at constant depth (figure 7). The linear color scale is the same as the gray scale used for the figure 6.

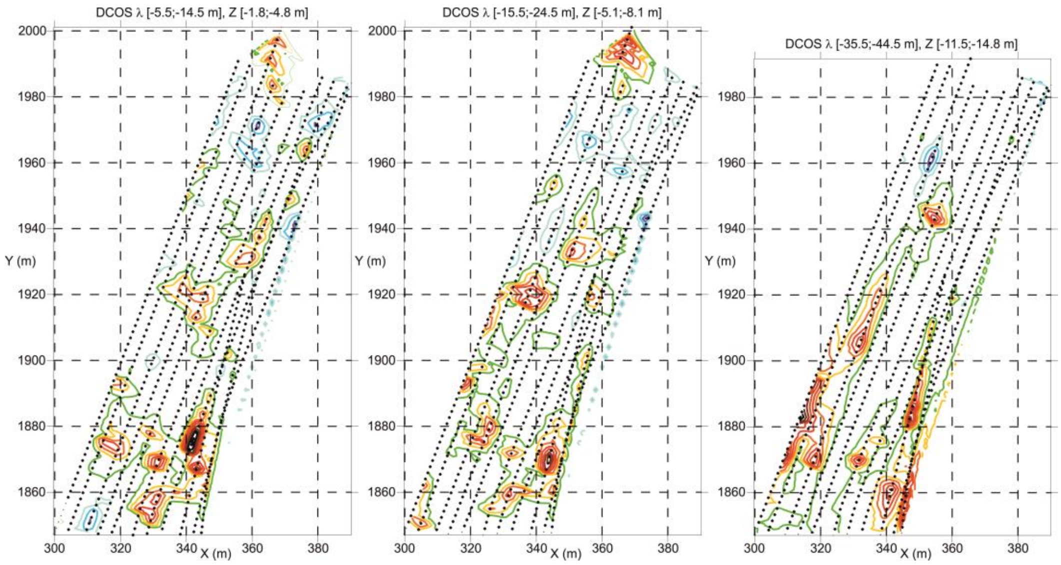

Figure 7. DCOS analysis results (48 geophones).

This kind of representation is useful to see the lateral extension of the anomalies detected and also to define the borehole locations for controlling their nature.

3.4. DCOS and geotechnical results

Using the results obtained during the feasibility phase, SNCF has performed geotechnical boreholes on the main anomalies detected by the DCOS analysis (figure 6). The figure 8 presents a synthetized view of the results (MASW and DCOS) compared with the geotechnical boreholes.

On the geotechnical borehole logs, the grey squares indicate the position of the under consolidated soil (destructive boreholes performed recording the parameters). Except for some cases, the correlation between the results from the DCOS analysis and the boreholes is good (Talfumiere and al., 2008).

It must be noted that, on the shear wave velocity result (upper part of the figure 8), nothing is clearly correlated with the DCOS analysis or with the geotechnical results. This can be explained by the fact that the MASW processing does not take into account the level of the energy distribution of the Rayleigh wave but only its position in the frequency-phase velocity domain (dispersive curve).

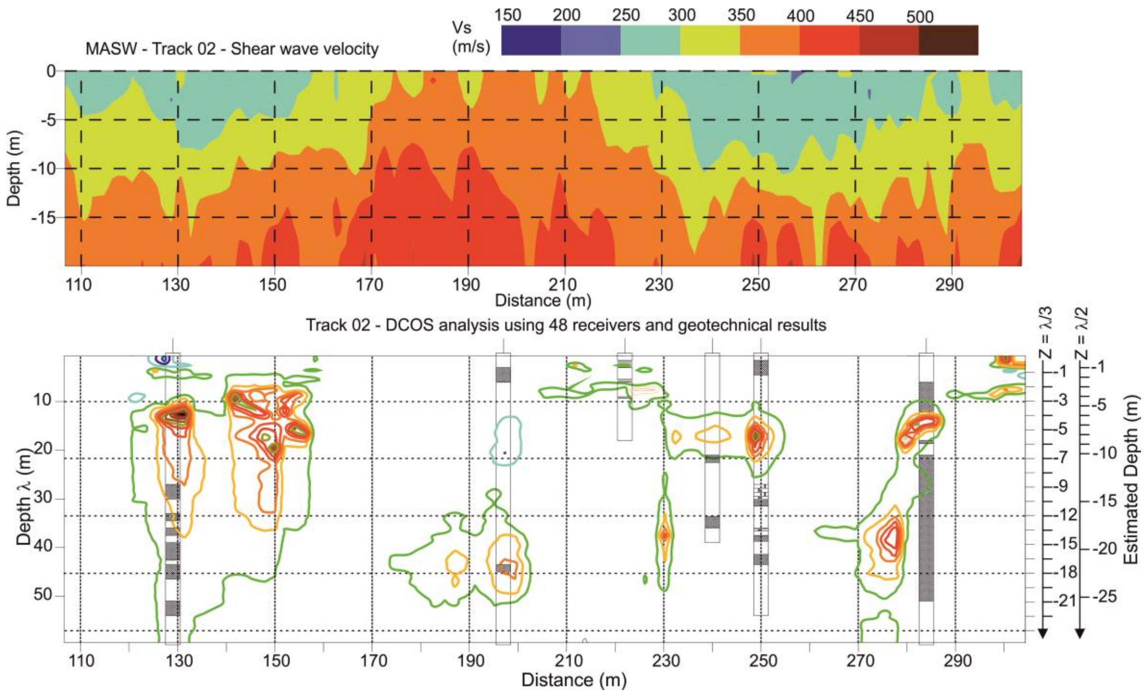

Figure 8. MASW, DCOS analysis and geotechnical results.

The classical direct use of the MASW processing does not allow easily, and with a good success ratio to localize karstic features, voids. Some changes in the shear wave velocities 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.

3.4. Conclusion

Boreholes have been carried out to check the geophysical anomalies obtained by DCOS analysis and to reveal areas with significant under-consolidated layers. However in the first part of the Gare de l'Est, the geophysical correlation with the geotechnical results is good, in the second part of the site (figure 7) the geophysical anomalies are not related to specific heterogeneities in the soil. It may be that geophysics have been influenced by the presence of the cavities (caves) present under the buildings adjoining the railway tracks at this location. These possible lateral influences can also be seen on the shear wave velocities on the figure 6 where the soil seem to be stiffer for the tracks close the buildings (on the both sides of the limit of the survey).

4. Site 2 - France

5.1. Geology and objectives

On this site, the railways tracks cut clay, sandy and loamy materials over a high of 6 meter. The lateral ditches are made in concrete since the construction of the line. During the construction, a cavity was discovered and filled with silty material from the site. Many subsidence have been detected since 2006 and SNCF requested to perform a seismic survey in this area in order to detect geological anomalies until 20 meter of depth.

Passive measurement with MASW and DCOS analyses have been performed on the railway tracks (ballast), the lateral maintenance tracks (lateral embankment) and also on a bank (top and middle).

5.2. DCOS and MASW results

In the figure 9, MASW and DCOS analysis results are presented with a 2D representation slice at constant depth -6 m. The linear color scale used for the DCOS results shows the “intensity” of the variations from -0.6 to 0.7 (without unit dimensions). The combination of both analyses allows to do the correlation between the main anomaly found with the DCOS analysis at (X = 7 400, Y= 800) and the relative slow shear wave velocity at the same location. The other anomalies find with the DCOS analysis, do not find the any correlation with the shear wave velocity variations. These anomalies could be associated to voids or under consolidated layers but with too small dimensions to be localized only by the use of a classical MASW processing.

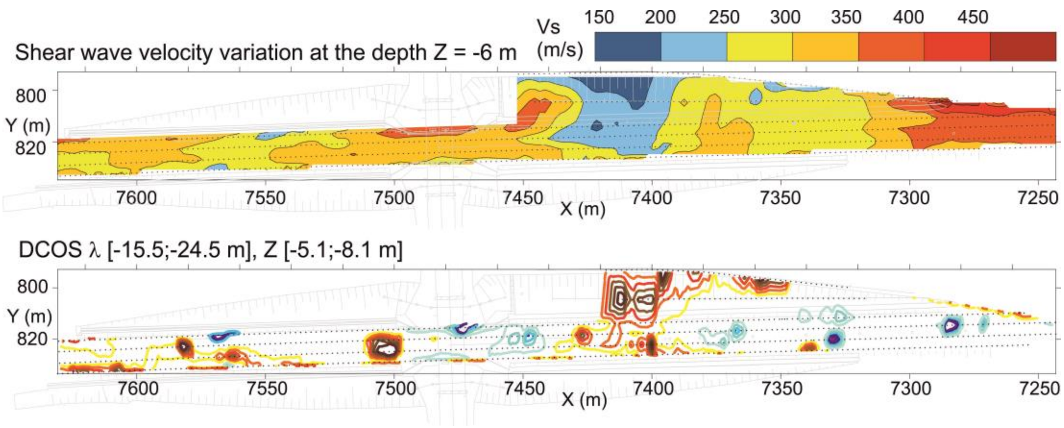

Figure 9. Comparison of the results from MASW and DCOS analyses.

5.3. Results integration, DCOS, MASW, radar and geotechnics

Following the geophysical survey investigations using seismic analysis (MASW, DCOS) and radar measurements, a geotechnical campaign has been performed. The results of this campaign are presented in the figure 10. The DCOS anomalies have been represented by color forms, the radar results by rectangles with different colors. The borehole are also indicated and the degree of soil under consolidated is shown by different color levels (see the legend of the figure 10).

It can be noted that many seismic anomalies have been correlated by borehole description as voids, or very under consolidated soil.

The lateral influence on the DCOS seismic analysis can be important for some anomalies (An.1 and An.4 for example). On the An.1, the borehole on the maintenance track has shown indices corresponding to voids, and in contrary, on the track #2, at 6 m of distance the borehole did not show any soil anomalies. On the anomaly An.4 we have the same phenomena between the borehole results spaced of 5 meters and obtained on the tracks #1 and #2.

The biggest seismic anomaly (An.12, An.13 and An.14) can be associated with voids indices noticed with some boreholes but mainly to the shear wave velocity variation obtained in the area (upper part of the figure 9)

The anomalies An.20 and An.21 are related to void indices in the description of the borehole performed at their location.

The anomalies found by the radar are not at the same locations than the seismic ones. These two approaches do not investigate the same depth penetration and the same kind of soil anomalies. Thus, they can be used as complementary tools for geological anomalies detection under railway tracks (Nebieridze S., 2009 and 2011).

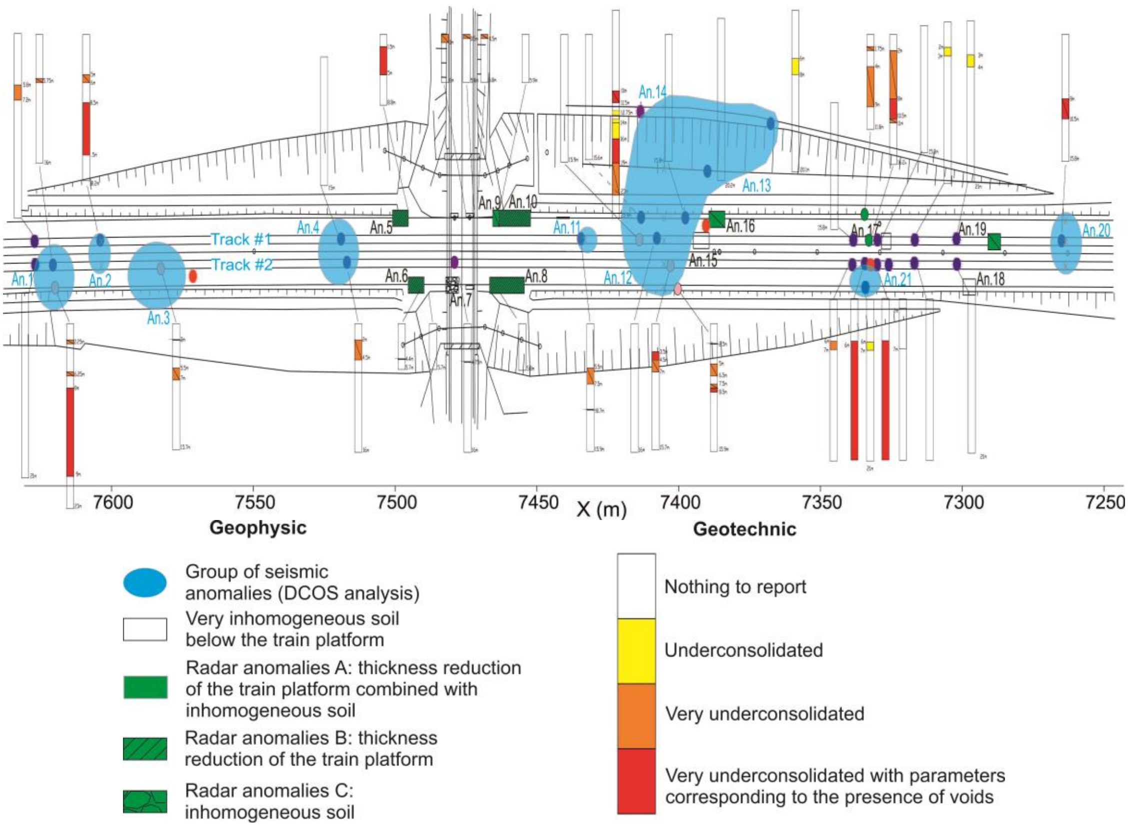

Figure 10. DCOS anomalies, radar and boreholes results.

6. 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 make a survey with the classical active seismic sources. A return experiment presented in this paper showed that the combination of both seismic (DCOS and MASW) and geo- radar measurements leads to a better description of the soil properties, in and bellow, the platform of the railway track. The correlation with the geotechnical borehole is good enough to plan a soil consolidation program by concrete injection.

Using these kind of seismic measurements and analyses, a monitoring of the soil below the railway track platform, before and post of the concrete injection is also possible.

7. References

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