Application of Spectral Analysis of Surface Waves (SASW) in the characterisation of railway platforms

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ABSTRACT: The functionality requirements for modern railway tracks lead to the use of performance based specifications regarding the quality control of substructure layers. Those specifications require the construction of the layers to be evaluated through specific tests to be performed under different state conditions, in order to estimate material properties, namely deformability modulus. The Surface Wave Method (SWM) has been used in a research work during the renewal of a Portuguese railway line platform (Northern Line), in which minimum values for deformability modulus at the top of capping and sub-ballast layers were specified. This paper presents some aspects related with the application of this method and some results obtained. The results are discussed and both the advantages and the disadvantages of the method are identified.

1 INTRODUCTION

The requirements of modern railway tracks, namely those related with the geometry and the type and volume of traffic, lead to the use of performance based specifications regarding the quality control of substructure layers. Indeed, both the performance of tracks and the operation and maintenance costs, depend strongly on the behaviour of those layers.

Those specifications in the quality control require that construction of the layers is evaluated through specific tests under different state conditions, in order to estimate material properties, namely the deformability modulus. As a consequence, there has been significant research on methods intended to characterise the substructure based on physical and mechanical parameters, namely geometric characteristics and the stiffness of layers and, indirectly, the deformability modulus of the materials.

Not surprisingly, current trend is to perform the quality control by assessing the final output, against performance based specifications. That procedure has been used as complement, or as alternative to the traditional control methods, as an imposition of construction procedures (specification of the method), and to the control by defining minimum characteristics to be achieved for the final product (specification by product).

Resorting to performance-related specifications, other than making it possible to obtain an indicator of quality in construction, makes also possible to obtain the validation, by designers, of the design assumptions and, should it be necessary, to reformulate those in time, namely as construction materials, thickness and construction methods of the layers are concerned.

From the Owner’s viewpoint, the adoption of performance related specifications transfers to the Contractor the full responsibility for the final characteristics and opens way to using non-traditional materials, even if they are not included in the specifications.

Furthermore, in the rehabilitation and renewal process of railway tracks, the role played by “in situ” physical and mechanical characterisation of the substructure in the choice of solutions has remarkably increased in the recent past. That choice presupposes the knowledge of the condition of the substructure before the intervention. In the case of very old railway tracks, the substructure is usually very heterogeneous, making the collection of representative samples difficult and rendering the representativeness of the characteristics determined in laboratory debatable.

Those facts, together with the amount of information necessary for the generalised renewal of a track platform along significant sections, may be decisive for making it more favourable, from a technical and economic point of view, to focus on the “in situ” characterisation methods, rather than on the laboratory characterisation even with sophisticated techniques.

The Surface Wave Method (SWM), which is based on the propagation of elastic surface waves along the ground, is a powerful method that has had a significant development in the last ten years (Stokoe *et al*. 2004). As a geophysical method, it relies on the propagation of seismic waves across the medium with very low strain values, typically below 10^{-5} rendering it possible to use Linear Elasticity Theory to interpret the results. It allows fast and non-invasive testing thus avoiding delays in the construction works and decreasing repairing costs in the tested places; the equipment is compact, lightweight and easy-to-use.

This method has been used in a research work during the renewal of a Portuguese railway line platform (Northern Line), in which minimum values of deformability modulus at the top of capping and sub-ballast layers were specified.

This paper presents the equipment, the experimental procedures and the test conditions, as well as the models and software used in the calculation of the modulus of the track substructure materials. The results are discussed and both the advantages and the disadvantages of the method are identified.

2 CHARACTERISATION OF THE RAILWAY PLATFORM WITH THE SURFACE WAVE METHOD

2.1 *Overview of the project and specific studies*

During the renewal project of the Northern Line, in Portugal, in order to increase of the maximum loads and to allow high-speed circulation it was necessary to improve the characteristics of the railway platform. In the cases where the existing platform was found inadequate, it was necessary to replace some superficial materials with reinforcement layers.

Regardless of the quality of the existing platform, a sub-ballast layer was placed and drainage systems were implemented. In some zones, a new replacement platform was built close to the old one.

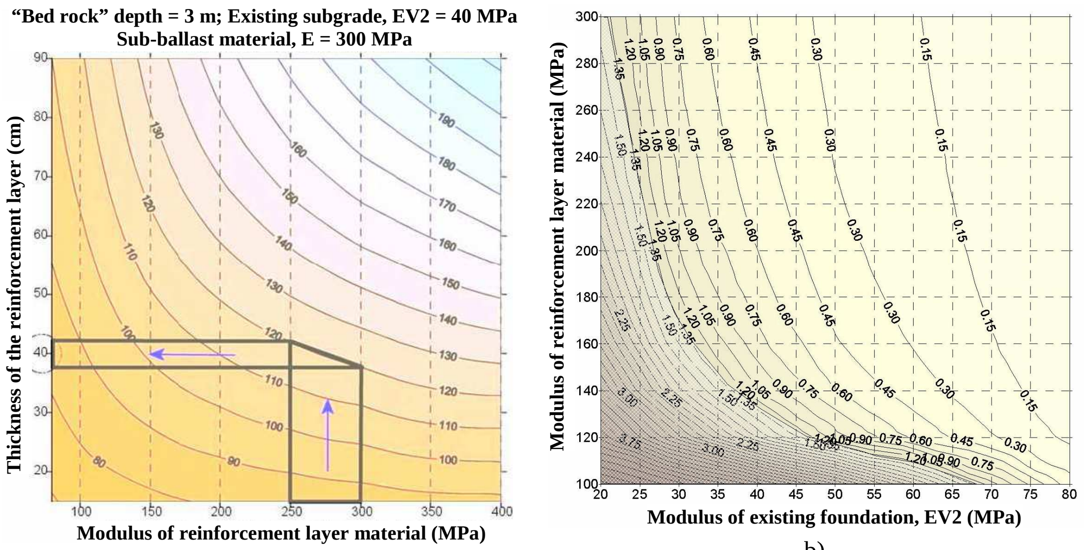
The thickness of the layers and the construction materials were defined so as to guarantee that the value of the equivalent deformability modulus (i.e. EV2 corresponding to the second cycle of the static plate load test) of the renewed railway platform (upper surface of the sub-ballast layer) was higher than 120 MPa (UIC 1994).

The design thickness of reinforcement layers was defined through parametric simulations of the plate load test on representative layered elastic profiles, by varying the deformability modulus of the materials and the thickness of layers.

As an output of those simulations several charts were obtained (Fortunato et al. 2001, Marcelino & Fortunato 2006).

A first type of charts, as illustrated in Figure 1a, allows one to define the thickness of the reinforcement layer given its deformability modulus and that of the sub-ballast, the “bed rock” depth, the measured EV2 value at the subgrade and the EV2 value established at the top of sub-ballast (e.g.: 120 MPa in Figure 1a).

A second type of charts, e.g. the one in Figure 1b makes it possible to determine the thickness of the reinforcement layer necessary to obtain a value of 120 MPa for the EV2 modulus at the top of sub-ballast, when the foundation soil is treated with lime in a depth of 35 cm. In the latter case, it was considered that the lime treatment doubled the value of the deformability modulus of the foundation material up to a maximum of 100 MPa.



a)

b)

Figure 1. Abacuses to determine the thickness of the reinforcement layer of the railway substructure.

2.2 *Equipment used in the characterisation*

In this work, two techniques were used, i.e. the Spectral Analysis of Surface Waves (SASW) and the Continuous Surface Waves (CSW) (Matthews *et al.* 1996). Generally, both the equipment and some of the calculation programmes used by the authors were developed by GDS Instruments (GDS 1999, 2001). From among the equipment used, reference is made to: i) an electro-mechanical vibrator (for the CSW method); ii) a controlling unit of the vibrator receiving the signal from the general control unit and generating an electrical signal that starts the vibrator (for the CSW method); iii) six 2 Hz geophones; iv) a general control unit of the test for definition of parameters, for acquisition and analysis of load and geophones signals, for data processing and data recording; v) hammers of different masses (for the SASW method); and vi) a power generator.

The vibrator consists of an oscillator capable of generating loads up to 500 N, installed on a spring suspension system, allowing the vibrator body to be used as an inertial mass of about 64 kg. The recording system is a spectral analyser, which collects displacement time histories. The signals are amplified, digitised, recorded and transformed into the frequency domain using the fast Fourier transform algorithm (FFT).

From these spectral records, the phase of the signal generated by the source in each geophone position is determined and the phase difference between the signals in each geophone and the coherence between signals is calculated. In the particular case of CSW, the minimum square method is used to determine the phase angle for each vibration frequency.

From the dispersion curve, the system calculates, in a simplified way, the variation of the shear modulus, G, with depth, z, considering user supplied values of the unit weight and of the Poisson's ratio of the soils and a relation between depth (z) and the wave length (λ) of the type $z=\lambda/n$ (usually, n ranges from 2 to 4, and in this particular case, it is considered as equal to 3).

During the test, the system provides, in real time, significant information about the data being registered by displaying both in time and frequency domains. After completion of tests, the system displays the phase spectra corresponding to each geophone, as well as the coherency and the estimated profile of the shear modulus. This way, the user has the possibility of assessing the quality of results obtained in each site and changing the test parameters, whenever necessary.

Prior to the application of those methods on the substructure of the railway track, several "in situ" studies were developed, in zones with different geotechnical characteristics and on road pavements, either flexible or rigid. The main purpose of these studies, which detailed analysis is outside the scope of this work, was to analyse the repeatability of the methods and the influence of some variables on results obtained, namely: i) the intensity of the "environment noise"; ii) in the case of SASW, the energy source adequateness for the test scenario (light or heavy hammer or impact deflectometer); iii) for the CSW case the nominal values of vibration frequency between 5 and 600 Hz; and iv) the spacing between geophones.

The conclusions of these preliminary studies are as follows: i) the method should not be used near operating machines nor traffic due to the negative effect on the signal noise ratio (in some situations heavy equipment operating at about one hundred meters from the test site produced a significant “environment noise”); ii) the results obtained with CSW were similar to those obtained with SASW; iii) the data processing for obtaining the dispersion curve with only the simplified software provided by the manufacturer, did not produce satisfactory results; and iv) the simplified calculation of the shear modulus profile, G, with depth, z, considering the relation $z=\lambda/n$, did not produce satisfactory results.

The two first conclusions, when associated with the obviously greater difficulty in handling the vibrator (with a weight higher than 600 N and a volume that prevented it from being transported in an automobile), and the longer duration of the CSW tests makes the SASW technique the preferred choice in detriment of the CSW, as far as the characterisation of the substructure of the railway track is concerned.

2.3 *Methods used in the analysis of results*

Both the analysis and the processing of data regarding the SASW, as well as the inversion in the dispersion curve and the calculation of the variation of the shear modulus in depth, were performed with the software *WINSASW 2.0* (Joh 2002). In this programme a processing algorithm of the phase spectrum and another to calculate the simplified average dispersion curve based on the experimental dispersion curve are included.

The spectrum phase algorithm relies on filtering the cross-spectrum of each pair of receivers, leading to a regular phase spectrum, without interference of different wave groups and of environment noise. This algorithm is intended to determine the number of the jumps of the originally wrapped spectrum and making it possible to unwrap it. This technique is particularly important in stratified profiles with high stiffness contrasts, where propagation of waves associated with more than one group due to refraction and reflection in layer interfaces. Those waves travel at different speeds and interact mutually, by this way producing an intricate spectrum which causes incorrect velocity phases to be obtained after the unwrapping process. Therefore, it is necessary to identify the groups of waves, either through deconvolution of time signals of two receivers, or by inverse Fourier transform of the transfer function which contains information related with the amplitude ratio of the signals and with the phase difference. The detection of the wave groups can be done using Gabor’s spectrogram (Joh 1996), namely by separating the signals with low frequency content from those with high frequency content and to determine the travel time of each group between the two receivers. The separation of the wave groups can be done by imposing, to the signal, the extraction, both of the low frequency domain (lower mode) and of the high frequency domain (upper mode). For the extraction of each mode, the signal must be adequately filtered in the time domain.

The transfer functions of the filtered signal are calculated for the two wave groups, in order to obtain the spectra of regular phases for each group. The modified spectra referring to the lower mode and to the upper mode are then unwrapped and both are concatenated to produce the final unwrapped regular phase spectrum. Lastly, the phase spectrum of the original transfer function is unwrapped based on the number of cycles of the regular spectrum.

After performing these operations for all geophone pairs, the composite experimental dispersion curve is calculated. In order to reduce the calculation time referring to the inversion of the dispersion curve, a technique was used to simplify the curve and to create an average curve, without impairing the quality of the results. The algorithm used to determining the average dispersion curve, based on the composite experimental dispersion curve, makes it possible to determine a representative dispersion curve with a limited number of points, facilitating the inversion. The algorithm makes use of a moving average filter.

After defining the dispersion curve, a determination is done regarding either the profile of the shear wave velocity, which produces the experimental dispersion curve, or the profile that maximises the probability of obtaining that curve. For the purpose, the *maximum likelihood approach* has been used in the formulation of the inverse problem. Accordingly, the optimal shear wave profile is the one that maximizes the likelihood of a given experimental dispersion curve. The follow-up of the iterative procedure, through the evaluation of the relative error between a theoretical dispersion curve and the experimental one, was done by the approach of (Joh 1966) which involves a sensitivity matrix to analyze by a RMS (root-mean-squared) distance the model parameter resolution matrix. The theoretical dispersion curve is obtained with a three-dimensional model of wave propagation, taking due account of the locations of the energy source and of the receivers.

2.4 *Tests performed on a zone of renewal of platform*

During the renewal of the North Line platform, the surface wave method was used in several places, along with plate load tests (PLT) and portable falling weight deflectometer tests (PFWD) (Fortunato 2005).

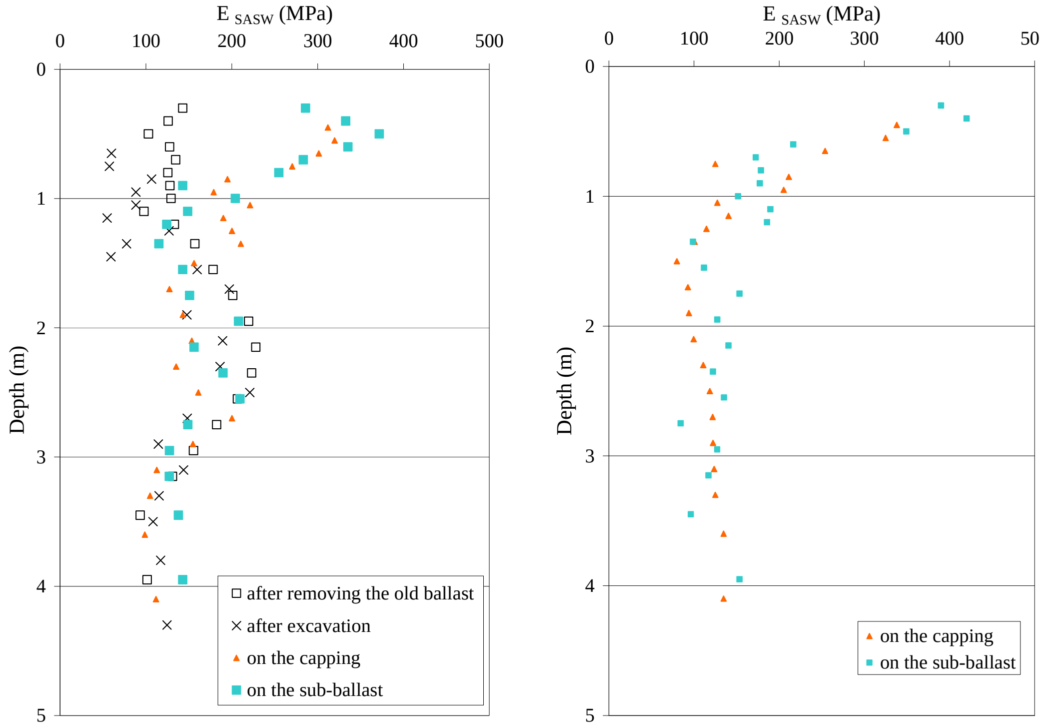
In one of the sites (km 289.350), the old platform with two tracks (Upward Track and Downward Track) had been constructed approximately at the level of the natural soil. On the Downward Track (DT), tests were performed in various stages of the process of renewal of the platform, namely: i) after removing the old ballast; ii) after excavating around 35 cm deep of the existing soils in order to allow placing the capping and sub-ballast layers; iii) after placing the capping layer; and iv) after placing the sub-ballast layer. On the Upward Track (UT), due to the progress of the works, it was only possible to perform tests during the two later phases mentioned. Figure 2 illustrates some aspects of the tests performed.


a) b)

Figure 2. Some aspects of the tests a) SASW on the old platform; b) CSW on the renewed platform.

Figure 3 presents the profiles of the deformability modulus obtained with the SASW, E_{SASW}, during the phases of renewal of the railway platform at km 289.350. The depths presented concern the basis of sleepers, prior to old ballast removal. The following comments may be issued: i) the variation in the deformability modulus is significative, both in depth and between tests; ii) after removing the old ballast, modulus values of approximately 140 MPa were measured from the surface, which are likely to correspond to a zone of higher compactness, due to the trains circulation over the years; below and until about 1.0 to 1.2 m depth, the average modulus ranged from 100 to 130 MPa; between that depth and around 2 m deep, E_{SASW} ranged between 200 and 230 MPa, reaching a value of 100 MPa between this depth and above 3.5 m deep; iii) the results obtained after a thickness of 35 cm was excavated seem to indicate that the consequent vertical stress reduction caused a decrease of the modulus, when compared with the values at the same depth previously to excavation, particularly up to about 1.5 m deep; iv) after placing the 20 cm thick capping layer of a well graded crushed limestone material of continuous particle-size distribution, the modulus value raised to approximately 300 MPa at that layer; and v) the values of the modulus in the sub-ballast layer were about 300 to 350 MPa; since the placement of that layer on the capping layer seems to have increased the value of the modulus of the latter to almost 400 MPa.

The results presented in Figure 3b, referring to the tests performed on the UT, first after placing the capping layer and then on the sub-ballast layer, show a general trend similar to the results previously mentioned. On the surface zone, corresponding to the support layers, the values of the deformability modulus range from 300 to 400 MPa. In depth, the values remained fairly close to 100 MPa.



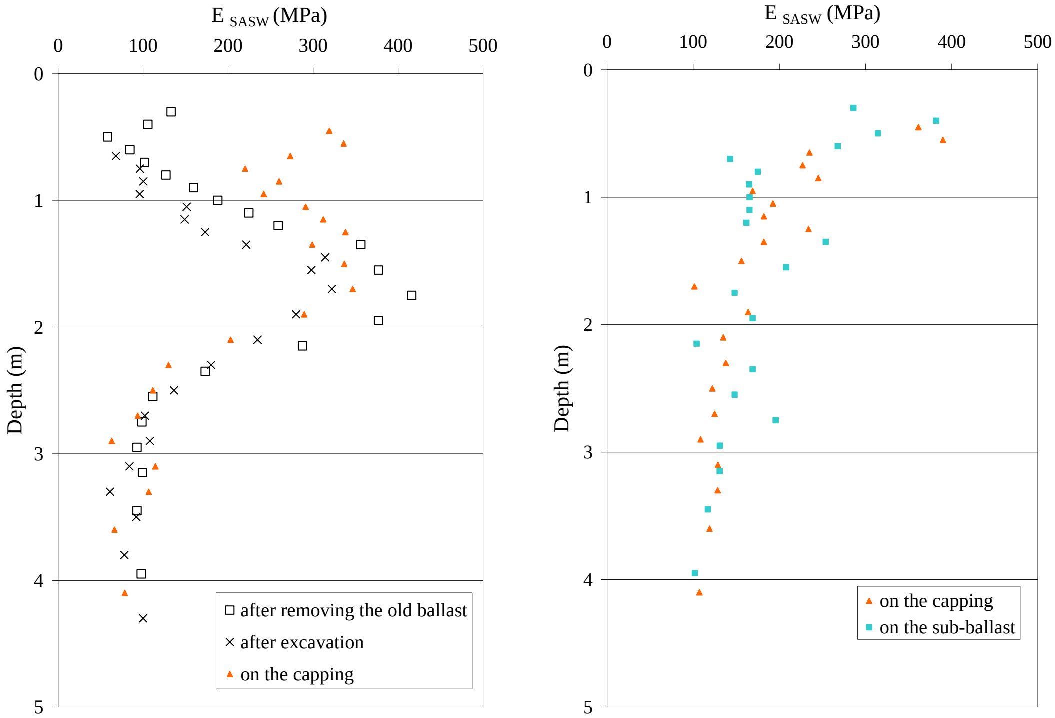
a) b)

Figure 3. Values of the deformability modulus measured with the SASW during the renewal of the track at km 289.350: a) *DT* b) *UT*.

Figure 4 presents the values obtained with the same tests at a location identified as km 288.725, on both tracks. Again, the existing track had been constructed at the level of the natural soil. Also, in the case of the DT, there was no opportunity to perform tests by the seismic wave methods on the sub-ballast layers.

In this site, high stiffness layers at small depths had been previously identified from dynamic cone penetrometer (DCP) forcing the test interruption due to very high penetration resistance. This way, it is not a surprise that in Figure 4a a different profile pattern from that in Figure 4b is presented. The deformability modulus increases continuously, from the bottom of the excavation, until about 2 m deep, and then it decreases significantly, until values of approximately 100 MPa are reached, at about 3 m deep. These values are similar to those observed in other places at the same depth.

As a conclusion, despite the fairly important difference of the modulus values with depth and the differences obtained, for each depth, among various tests, it is possible to identify general trends, should the stiffness contrast happen to be significative. The differences obtained in the successive tests may arise from the operations of removal and placement of soils and of layers compaction, but also from the incomplete repeatability of the method. For fairly low depths, the joint analysis of results obtained with the DCP and of those obtained by the Surface Wave Method can lead to highly relevant information to the platform renewal process. In some cases, when the platform is in poor condition and shows a low deformability modulus, the detection, during the survey stage or even during the works, of the modulus improvement threshold depth, makes it possible to establish criteria for the treatment of the upper part of the existing foundation and (or) for remove the inadequate soils.



a) b)

Figure 4. Values of the deformability modulus measured with the SASW during the renewal of the track at km 288.725: a) *DT*; b) *UT*.

During the renewal works, tests with the PFWD using a 300 mm diameter plate and a vertical imposed stress of 200 kPa were also performed on the DT. At the km 289.350 site, values of the deformability modulus of 32 and 95 MPa, respectively, were obtained, after removing the old ballast and on the new capping layer, respectively. At the km 288.725 site, the corresponding values of 62 and 112 MPa, respectively, were obtained.

Load tests with a 600 mm diameter plate were performed on the sub-ballast layer, on both sites. The EV_2 values of 131 and 163 MPa were, respectively, obtained.

The difference between the values of the deformability modulus obtained at each site is likely to be related with the difference in the values of the modulus of existing layers between the base of the capping layer and approximately 2.5 m below. Indeed, the comparison of Figure 3a with Figure 4a, suggests that at those depths, the average value of the modulus of the layers is about 150 and 300 MPa, respectively.

On a third location, close to km 266, in a zone where the old platform had been built after a slight excavation of the natural soil, and was in a poor condition, the soils were replaced by a rockfill about 60 cm thick. A 50 cm thick layer of well graded crushed limestone aggregate was placed over that layer; followed by a 15 cm thick granite aggregate. On that site, a deformability modulus equal to 130 MPa was obtained on the sub-ballast layer through PFWD test. The SASW tests led to the results presented in Figure 5.

The deformability modulus on the sub-ballast and capping layers ranged from approximately 370 to 470 MPa. On the upper zone of the rockfill layer, the values ranged from 180 to 320 MPa, while the values of the deeper part of the layer, until about 2.5 m depth, ranged approximately from 120 to 140 MPa. From that depth below, the modulus increases, reaching about 660 MPa, close to a depth of 7 m.

The results show that besides having obtained an adequate value of the deformability modulus on the railway platform, the layers placed on the rockfill were adequately compacted, since the values of the final modulus of these materials are fairly high. The variation in the modulus along the 60 cm thick rockfill layer is likely to be related with the fact that this layer has been built in two stages: in a first stage, the material was spread over a thickness of 30 cm without compaction; in a second stage, the placed material was compacted with a vibratory compactor. That compaction is the likely cause of a higher value of the deformability modulus detected in the SASW test.

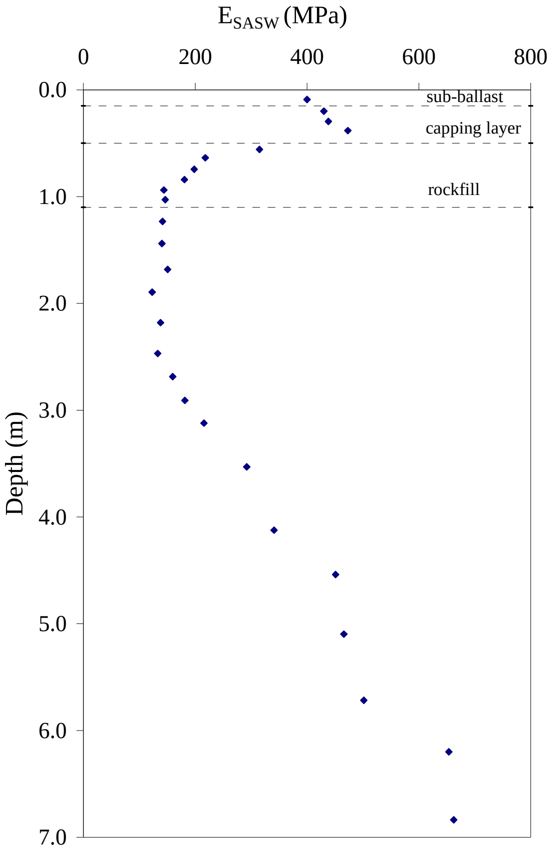


Figure 5. SASW test done on a zone where the soils had been replaced.

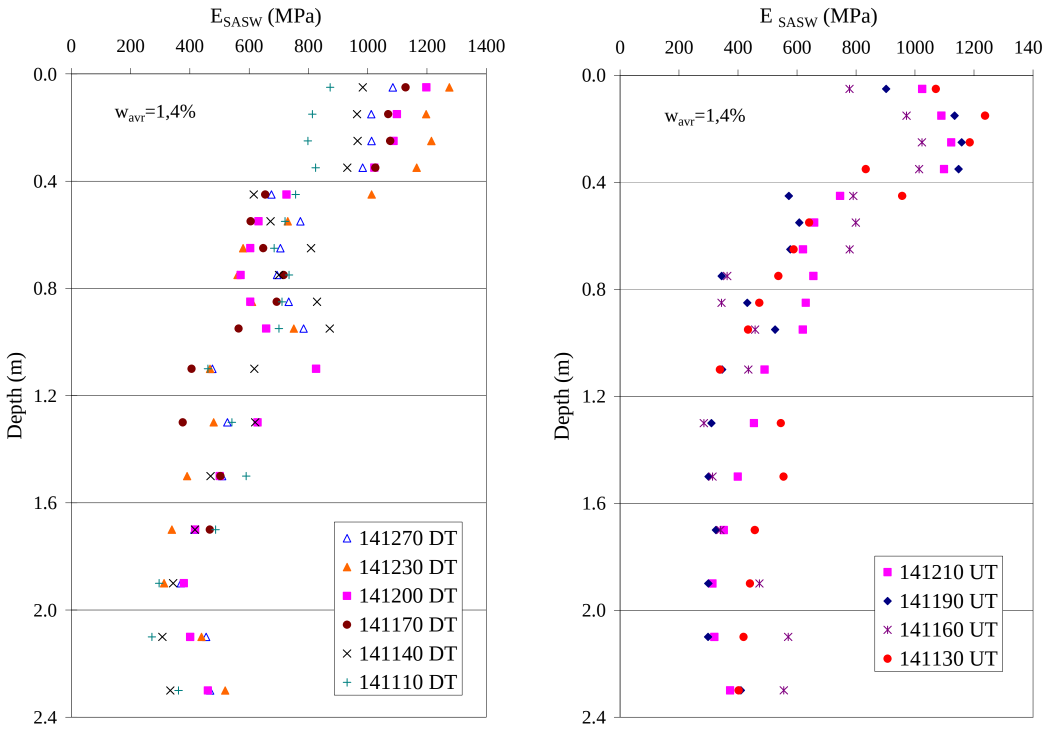
The analysis of results obtained on the various sites points out to the conclusion that the deformability modulus of the materials of the sub-ballast and capping layers, in general, increases with depth, which is probably related with the increase in the effective stress and with some disturbance induced at the surface by the compaction equipment.

2.5 *Tests performed on a newly built zone*

In a stretch where the railway platform was built on a new embankment, tests were also performed with the Surface Wave Method and with the PFWD. Both the capping and the sub-ballast layers were constructed with well graded crushed limestone aggregate with a total thickness of 35 cm. This is a non-plastic material, with a sand equivalent value equal to 58% and a Los Angeles coefficient equal to 26%. The percentage of particles (in weight) smaller than 0.074 mm was 5.4% and the maximum size of the particles was 37.5 mm.

Figure 6 presents the values of the deformability modulus obtained with the SASW on the railway platform. The tests were performed when the average water content, measured at a depth of 15 cm on the limestone aggregate layer was 1.4%.

The analysis of results presented makes it possible to conclude that: i) on the surface zone, corresponding to the sub-ballast and capping layer, the values of the deformability modulus ranged from 800 to 1200 MPa; ii) at the zone corresponding to the upper part of the embankment, down to about 30 cm below the aggregate layers, the obtained modulus were between 600 and 800 MPa; iii) on the deeper layers, the values ranged from approximately 300 to 500 MPa. These results indicate that the embankment built with those sandy soils is likely to present a good performance in the future.



a) b)

Figure 6. Values of the deformability modulus measured with the SASW: a) *DT* b) *UT*.

The measured values of the deformability modulus, on the same date, on the railway platform, with PFWD ranged from 510 to 930 MPa. The comparison between these values and the values of the deformability modulus of the aggregate obtained with the SASW, at a depth of 15 cm, at nearby sites, makes it possible to conclude a likely relation between both sets of values. The first are usually about 60% of the latter. By taking into account the likely difference between the value of the PFWD deformability modulus determined in these circumstances (200 mm diameter plate on a layered sub-structure, with varying characteristics with depth), and the value of the modulus of a homogeneous limestone aggregate medium, it seems that it can be concluded that the value of the modulus determined in such load tests is closely related with the value of the modulus of deformability of the materials determined by the SASW.

The comparative analysis between the values of the modulus of deformability obtained on the aggregates of capping and sub-ballast layers of renewed platforms, as presented in 2.4, and the values now presented, which were obtained on the limestone aggregate that integrates the capping and sub-ballast layers of a platform built on a new embankment, makes it possible to conclude that the first ranged from 300 to 500 MPa and the second ranged approximately from 800 to 1200 MPa.

The significant difference observed in the values of the modulus of deformability is most likely related with the difference between the values of the water content of materials: in the first case, the tests occurred after construction, during a rainy season, with a fairly high saturation level of the aggregates (about 70 to 85%). In the second case, the saturation level of the materials was about 20%.

3 CONCLUSIONS

The Surface Wave Method was shown to be a useful tool to determine the values of the modulus of deformability in the substructure of the railway track, either with existing platforms or with the quality control of newly built layers.

This method makes it possible to obtain values of the modulus of deformability at fairly deep positions, comparatively with other methods.

The tests performed with the CSW are more time-consuming and the dimensions and the vibrator weight may become an obstacle. In the analysis of the upper layers of the railway track layer, no advantage was obtained comparatively with the SASW alternative.

The analysis of the results has made it possible to relate the modulus of deformability measured by the PFWD with the one measured by the SASW method, at a 15 cm depth.

The main disadvantages are the facts that dedicate expertise is required for carrying out and interpreting the tests and that accurate determination of the modulus of deformability requires complex data processing, particularly when the variation of the characteristics of layers in depth is rather significant.

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