Assessment of the double integration method using accelerometers data for conventional railway platforms

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Abstract

The main goal of this paper is to show a valid method to filter and double-integrate acceleration data from piezo-electric accelerometer installed in conventional railway platforms. The experimentation site involved is located in the region of Lille (north of France). Prospection tests were carried out at this site, including boreholes till 10 m depth and Panda tests (dynamic cone resistance) till 1.2 m depth. Accelerometers were installed in the interlayer of the platform. Acceleration data were recorded during the circulation of different types of train. Theses acceleration signals were then double-integrated in order to obtain the velocity and displacements within this layer. Different filters were applied to obtain relevant displacement results. Comparison was made regarding different axial weights corresponding to Intercity, Freight and TGV trains.

Keywords: conventional railway platform; interlayer; axial displacement; double-integration; acceleration data; axle weight influence.

1 Introduction

In order to improve the service of transportation and to optimize the use of the infrastructure, it is necessary to increase the load and the speed of trains. This can cause accelerated degradation of the ballasted track and platform, and thus more frequent maintenance operations are needed. In France, the conventional lines represent 94% of the whole network and the high-speed lines represent 6% only (Figure 1).

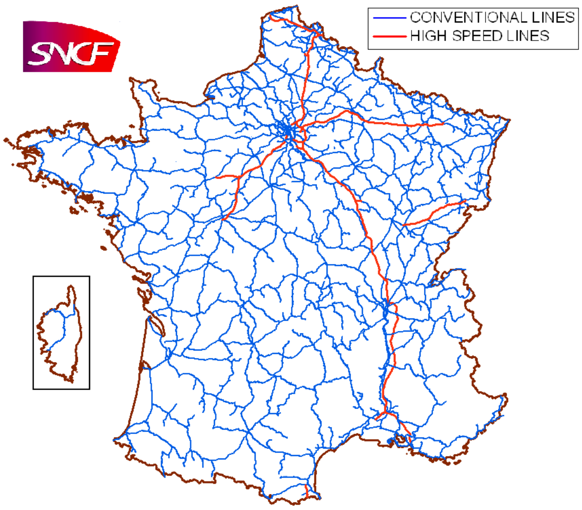

Figure 1: French railway network in 2012.

The main difference between a conventional line and a new line is the existence of a layer named Interlayer (ITL) naturally formed between the ballast and the subgrade by the attrition of the ballast over time and the pushing-up of the fines from the subgrade [1]. The sub-ballast layer in the new lines consists of a well graduated soil insensitive to water content changes, and plays the role of a load supporting layer between the ballast layer and the rest of track structure. The interlayer in the conventional lines corresponds also to a transition layer (Figure 2). Note that large variability of interlayer soils exists due to the natural formation of this layer, mainly by the interpenetration of ballast and natural sub-grade soils. Figure 3 shows the grain size distribution of the ITL from the site of Sénissiat [2] compared to the grain distribution limits of the sub-ballast used in new platforms of the French network [3].

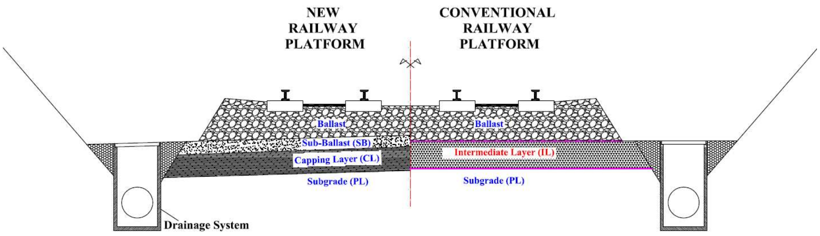

Figure 2: Comparison between new and conventional tracks structures.

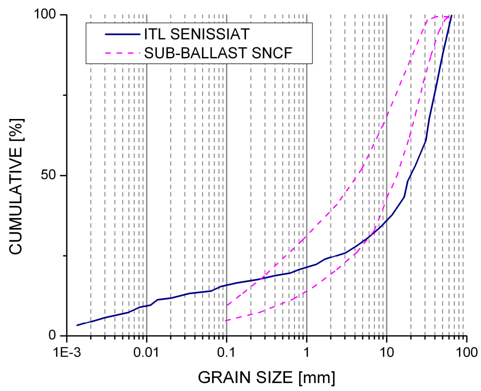

Figure 3: Comparison between the interlayer grain size and the size limits for the sub-ballast used by the SNCF [2].

Changes in train load could be the result of the increase of train speed or the increase of train weight. Some authors studied the displacement and deformation of the railway platform during the circulation of different types of trains [4, 5, 6]. Each type of train has a corresponding axle weight, thereby resulting a specific behaviour of track layers. And, the axles weight an important parameter when determining the amplitude of acceleration, the speed and the displacement of a particle induced by the train circulations. In order to optimize the infrastructure maintenance cycle, other authors [7] assessed the importance of the tracks quality in case of different traffic loads (Figure 4). Nonetheless, no studies have been conducted to identify the behaviour of the interlayer.

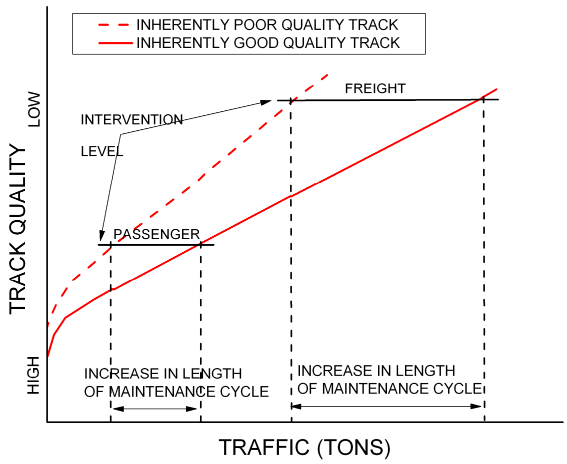

Figure 4: Optimization of the maintenance using the track quality versus traffic load. [7]

In this study, we present a method to determine the behaviour of the interlayer of a conventional railway platform due to its importance in conventional tracks regarding maintenance decisions for the renewal of the track. The mechanical response of a representative site of the French conventional line will be presented, analyzing different types of trains. To determine the response of the interlayer under the circulation of different trains, we use a simple method that is based on the acceleration measurements. Using a double-integration and the adequate signal processing filters for the acceleration signals, the speed and displacement of the interlayer can be calculated.

2 Experimental site

2.1 Description

The experimental site is located at Somain, in the French region of Nord - Pas de Calais, in the middle of the 'Douai – Valenciennes' line. This site was instrumented at kilometer 230+400 of the line number 262000 of the French railway network. Different trains run on the tracks of this site: TGV, Intercity (TER) and Freight. The speed in the site is limited to 110 km/h, we can consider that no dynamic amplifications would be considered for loads at this speed [8, 9].

This site was used to study the hydro-mechanical behaviour of the interlayer soil [2]. It is located in a cutting zone with embankments of about 2 m height. The line was constructed in the late XIXth century. Different boreholes were conducted in the zone from kilometer 230+000 to kilometer 231+000 in order to identify the different materials in the platform, in particular the depth of the interlayer (Figure 5). It was found that the thickness of the ballast layer was about 50 cm along the analyzed length, with about 30 cm fresh ballast and 20 cm fouled ballast. The interlayer thickness varied from 38 cm to 57 cm. The subgrade consists on either sandy or clayey silt, with the presence of chalk and clay mixed with sand and rock in some locations. This track allows running a train with a maximum axle weight of 22.5 Mg.

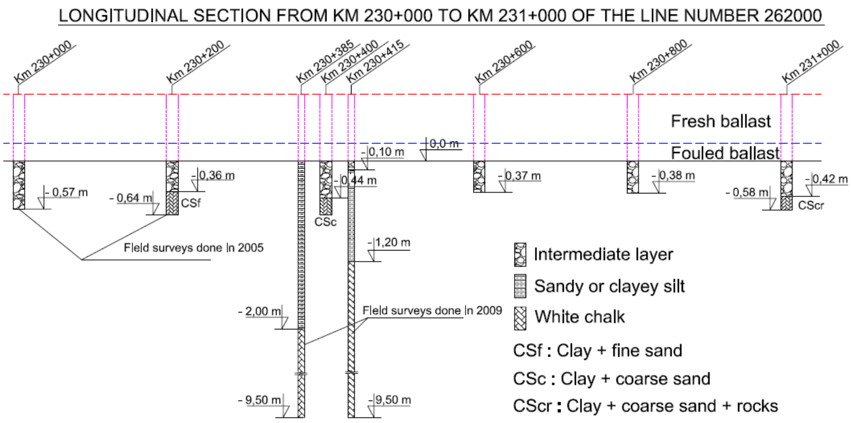

Figure 5: Longitudinal section of kilometre 230 of the Douai-Valenciennes line (adapted from [2]).

2.2 Instrumentation & auscultation of the site

The field instrumentation was done at kilometre 230+400 of the line. In the instrumentation zone, there were two field surveys of 9.5 m depth at 230+385 and 230+415 with six PANDA tests performed, and four piezo-electric accelerometers ICP/PCB-601A12 with a measurement range of ±10 g, a frequency ranging from 0.47 Hz to 4000 Hz and a resonant frequency of 16000 Hz. Two accelerometers were implemented in a first zone near the field survey at 230+385 km, and the two others were implemented at the second at 230+415. The two zones were distant of 18.5 m. In each zone the two accelerometers were installed between two sleepers, at different depths: the first one at 0.40 m and the second one at 0.10 m from the bottom of the ballast, in the interlayer (Figure 6).

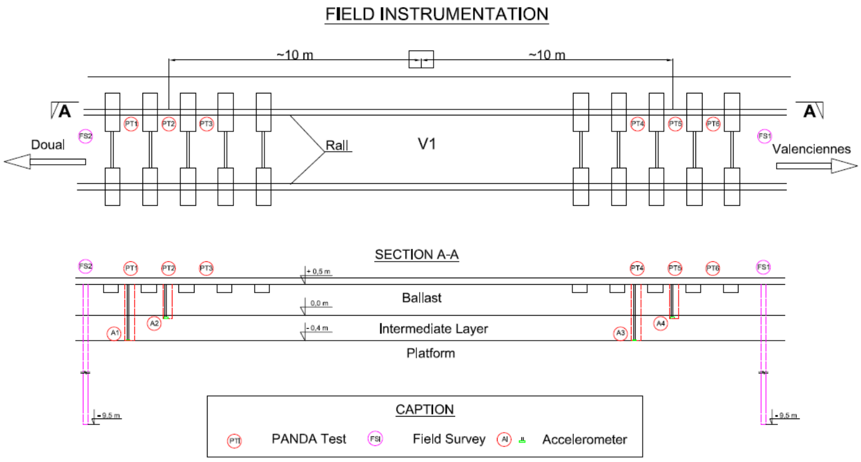

Figure 6: Field instrumentation at the site of Somain (PK 230+400)

The PANDA test is a dynamic cone penetrometer test [10]. The result that can be obtained from this test is the cone resistance over depth. Figure 7 presents the obtained cone resistance at the different locations. The auscultation depth was between 1.2 m and 1.3 m for each test (Figure 7). The results shown in Figure 7 are normalized, being 1 the maximum cone resistance value found for each PANDA test. It is important to note that the beginning and the end of the interlayer layer shown in Figure 7 were determined based on the results of field surveys and also of endoscope surveys. It can be observed that the thickness of the interlayer was constant in the experimental site, around 40 cm. A ballast layer composed of 30 cm fresh ballast and 20 cm fouled ballast overlies the interlayer. The subgrade consists of a clayey silt layer of about 1.5 m overlying a thicker chalk layer.

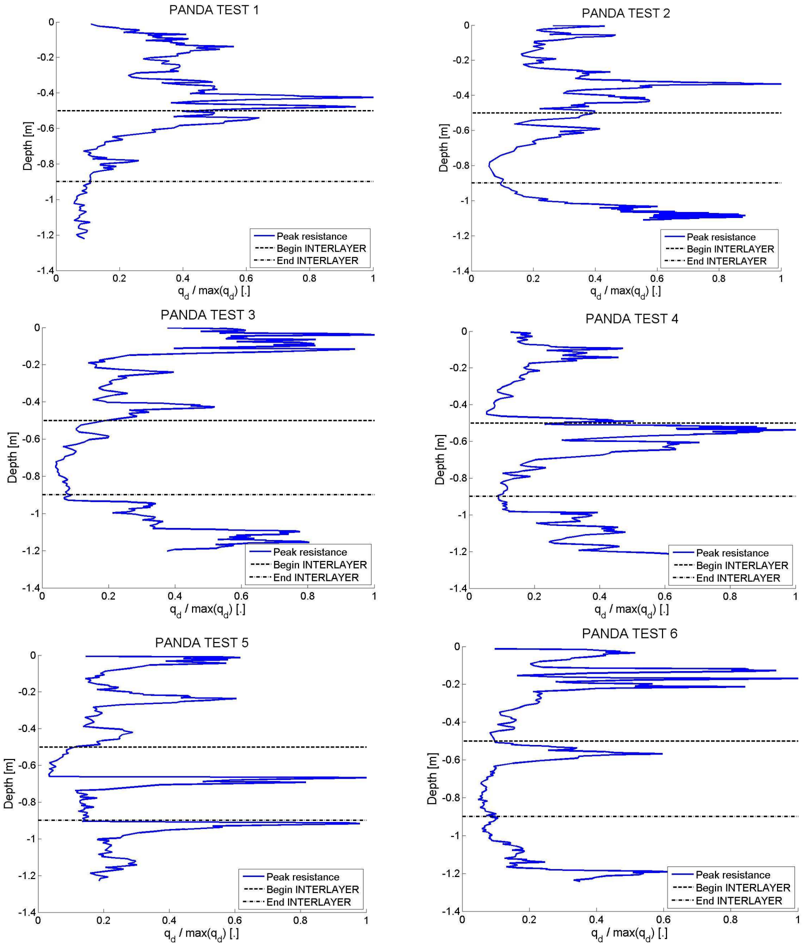

Figure 7: Normalized tip resistance from the six PANDA tests.

The cone resistance of the intermediate layer is lower than those of ballast and subgrade. Some authors proposed an analytical equation to calculate the elastic modulus from the value of cone resistance, obtained from a PANDA test for example, for each type of materials [11, 12].

3 Description of the different analyzed trains

Four types of train are analysed in this study: the TGV/TMST-NOL (EUROSTAR), the TGV/Réseau, the intercity (TER) Z24500 and various freight trains. A total of ten Eurostar trains, four TER Z24500, one TGV Réseau and three Freight trains were analyzed. All the analyzed trains were running at 80 km/h. At this speed there is no dynamic amplification of train load [13]. This is an important point in order to make a comparison with the response of tracks loaded by different axle weights.

- EUROSTAR (TGV/TMST-NOL)

The EUROSTAR is a version of the French TGV capable of running on tracks with different voltages in the French, British and Belgian networks. Four of the Eurostar trains are assigned to ensure the domestic service on the ‘Paris Nord – Arras – Douai – Valenciennes’ line. Each train consists of two locomotives at the head and at the rear of the train with 3 double-axled bogies. The weight on each axle is about 17 Mg. The NOL (North of London) model consists of 2 groups of 7 coaches between the two locomotives, with only one bogie every two coaches and a weight of about 16 Mg per axle. In total, there are 40 axles by train (Figure 8). The two axles in each bogie are distant of 3 m, and the length of each coach is about 18.6 m.

Figure 8: Disposition of bogies in the EUROSTAR (TGV/TMST-NOL)

- TGV/Réseau

The TGV/Réseau was commissioned in 1992. There are 69 trains in total, among them 60 owned by SNCF and 9 by THALYS. The trains of SNCF serve the French provinces from the South-East to the North; they also connect Paris to the North of France and Belgium. This kind of trains is composed of two locomotives, one at the head and one at the rear with two bogies for each. There are eight coaches with one bogie between two coaches. Each bogie is composed of two axles. The bogie for locomotive weights 17 Mg, while the one for coach weights 16 Mg [14]. The space between axles of a bogie is 3 m. The coaches are 18.7 m long each while each engine is 22 m long (Figure 9). This train is able to run in a simple unit or multiple unit (2 TGV together).

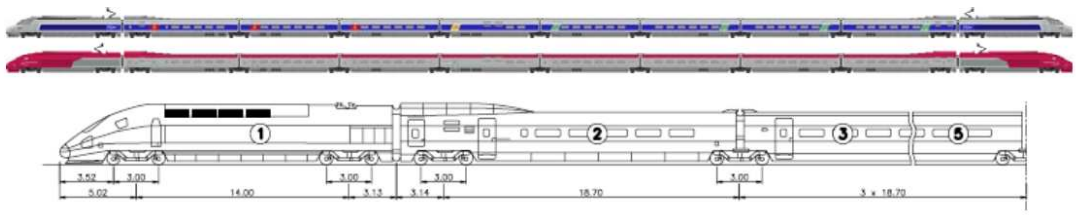

Figure 9: Disposition of bogies of the TGV/ Réseau and THALYS [15].

- TER Z24500

The intercity train TER Z24500 is a two level train, commonly used in different regions of the French railway network. The SNCF has 211 units of this model. It is able to run in double or triple coach configuration (Figure 10). Each coach has two bogies. A bogie is composed of 2 axles of 15.8 Mg each. The distance between the two axles is 2.06 m.

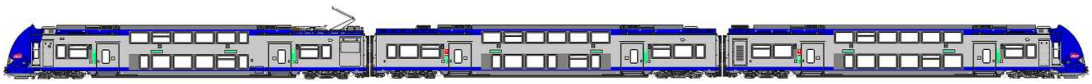

Figure 10: Scheme and disposition of bogies in a triple coach configuration Z24500

- Freight trains

The freight trains are the heaviest ones. They can reach 22.5 Mg per axle in the French network. The types and models of locomotives and wagons are quite heterogeneous. The distance between two axles of a bogie is 3 m.

4 Signal processing

A train at a given speed can excite different frequencies due to the different wavelengths present in the railway system (Figure 11). Thus, an acceleration signal at the interlayer contains various peak amplitudes related to different wavelengths of the global train and track system. Figure 12 presents the Power Spectrum Density (PSD) of the acceleration measured in the interlayer when a TGV/Réseau circulates at 80 km/h. It can be underlined that the energy content of the lower frequencies (0-10 Hz), corresponding to wagon, bogie and axle wavelengths, is much higher than that for higher frequencies (>10 Hz) (Figure 12). We can differentiate, in the range of lower frequencies, the inter-bogie frequency (about 6 Hz for a train at 80 km/h) from the inter-axle frequency (about 8 Hz for a train at 80 km/h). The peak of energy induced to the system at about 40 Hz corresponds to the sleepers spacing as we can see in Figure 11.

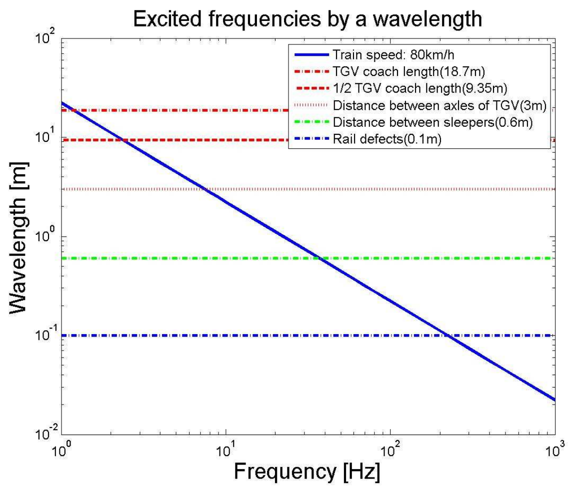

Figure 11: Excited frequencies by a TGV at 80 km/h (adapted from [15])

The piezo-electric accelerometers used in this study are not able to measure the frequencies in the range 0 - 0.47 Hz. It is then important to apply a high-pass filter to the registered acceleration data if we want to integer the data without significant error in the integration result. We have to eliminate the part of the signal caused by high frequencies (frequencies higher than 200 Hz). These frequencies are due to defects on the roundness of the wheel (from 1 to 5 cm), defects on the rail (smaller than 10 cm) and other short wavelength defects. They should be filtrated using a low-pass filter to obtain the acceleration response regardless of specific defects of a given train.

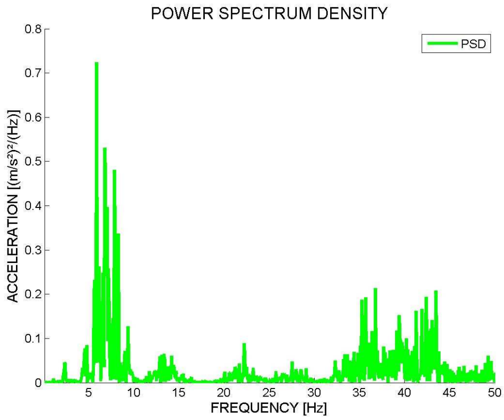

Figure 12: 0-50 Hz range of the Power Spectrum Density (PSD) of a TGV/Réseau train at 80 km/h

4.1 Used filters

Two different filters are used, a Butterworth filter and an elliptic filter. These filters were used to eliminate the low frequencies (0 – 0.47 Hz) which are not measured by the used accelerometer, and the high frequencies (f > 200 Hz) induced by track defects of wavelengths smaller than 10 cm which do not influence displacements calculation. The effects of both filters were investigated separately. The cut-off frequency for the low-pass filters, used to eliminate the high frequencies, was 200 Hz (Figure 13), while the cut-off frequency for the high-pass filters, used to eliminate the very low frequencies was 0.75 Hz (figure 14) to ensure that frequencies lowers than 0.47 Hz does not influence the integrations. The used accelerometer is not able to measure these low frequencies and they can result in a baseline error after the integration if they remain in the processed signal. The high-pass elliptic and Butterworth filters at 0.75 Hz do not take into account the excited frequencies lower than 0.47 Hz. For both, high and low pass elliptic filters, the pass-band ripple was taken equal to 0.1 dB and the stop-band attenuation equal to 60 dB. Figures 13 and 14 present the filtering magnitude factor applied to the signals according to the excited frequency for each used filter type (Butterworth and elliptic). This magnitude factor is the factor which multiplies the value of the signal at each frequency.

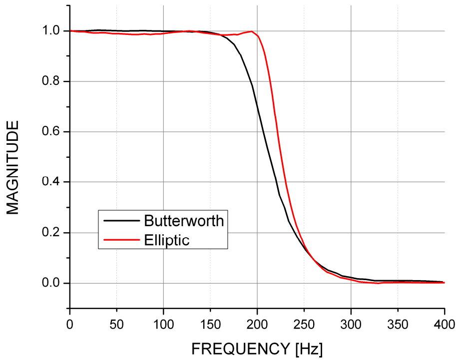

Figure 13: Butterworth and elliptic low-pass filters used to eliminate the high frequencies of the acceleration signal before doing the first integration. Cut-off frequency 200 Hz.

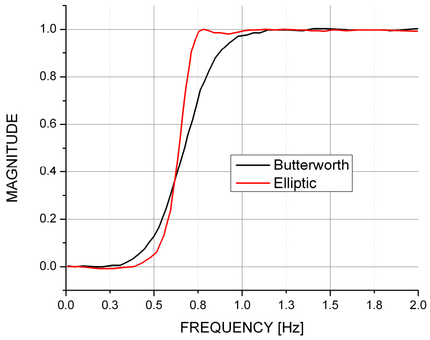

Figure 14: Butterworth and elliptic high-pass filters used to eliminate the low frequencies that were not measured by the used accelerometer. This filter was applied to the acceleration signal before the first integration and before the second integration. Cut-off frequency 0.75 Hz.

These applied filters are the best choice to keep the low frequencies (0.5 Hz – 10 Hz) and the mid-high frequencies (40 Hz – 200 Hz) into the signal. The piezo-electric accelerometers are able to measure the low frequencies under about 10 Hz but not in a good way (there are errors due to the inertia of the sensor). But we cannot ignore the frequencies lower than 10 Hz because they are the origin of the displacements at the analyzed trains speed (80 km/h). Then we have to keep them in the treated signal. The displacements are caused by the excited frequencies of bogies and axle distances (6 Hz and 8 Hz respectively for a TGV at 80/h). The mid-high frequencies under 200 Hz of a train at 80 km/h seem reasonable to study the influence of the increased acceleration level caused by different types of train. After filtering at a cut-off frequency of 200 Hz we receive a signal which takes into account wavelength defects even as short as 0.1 m at 80 km/h.

4.2 Double-integration scheme

To obtain the speed and the displacement from acceleration signal, a simple and double integration are needed, respectively. The integration of a discretized signal, like the accelerometer one, can be addressed by considering the trapezoidal rule [16].

$$v(n) = v(n-1) + \frac{\Delta t}{2}[a(n) + a(n-1)] \tag{1}$$

$$d(n) = d(n-1) + \frac{\Delta t}{2}[v(n) + v(n-1)] \tag{2}$$

where v(n) and d(n) are respectively the first integration (speed) and second integration (displacement) of the discrete acceleration signal a(n). The scheme used in the double integration of this analysis is presented below (Figure 15):

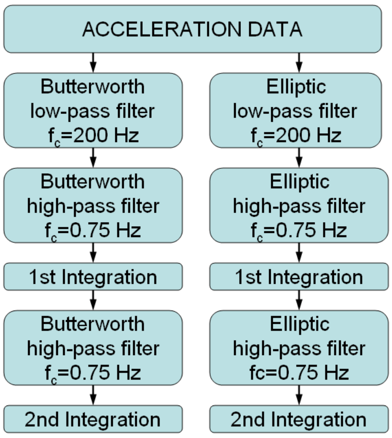

Figure 15: Integration scheme

5 Results of the integrations

In this section, the results of data processing for different types of train are presented, including the results of particle acceleration, speed and displacement in the interlayer of three types of trains: TGV/TMST (Eurostar), Z24500 and Freight. The TGV/Réseau was not analysed because it has similar axle weight and composition of loads as the TGV/TMST train.

5.1 Results of the analysis

To differentiate the train types and determine their axle weight and number of axles, the rail strain results during the train passages can be used. This rail strain was measured with a strain gauge attached to the rail, and can be directly related to the axle weight. We can then differentiate the types of train by their ‘signatures’ of their passages (Figure 16). In Figure 16.a we can see a 18-coach TGV/TMST train (300 m long), in Figure 16.b a 3-coach TER train (50 m long) and in Figure 16.c a 23-wagon freight train (430 m long). We can determine the axle weight, allowing identifying whether a freight wagon was empty or not. In Figure 16.c, for instance, we can identify five empty wagons at the head of the freight behind the locomotive. We can appreciate the different axle loads of the analyzed train. The axle weight can help us to analyse the obtained maximum values of acceleration, speed and displacement by each axle.

In order to start the analysis, the measured acceleration in two instrumented levels of the interlayer, with the accelerometers placed at -0.10 m and -0.40 m under the ballast, filtered with an elliptic low-pass filter at 200 Hz is showed in Figure 17.

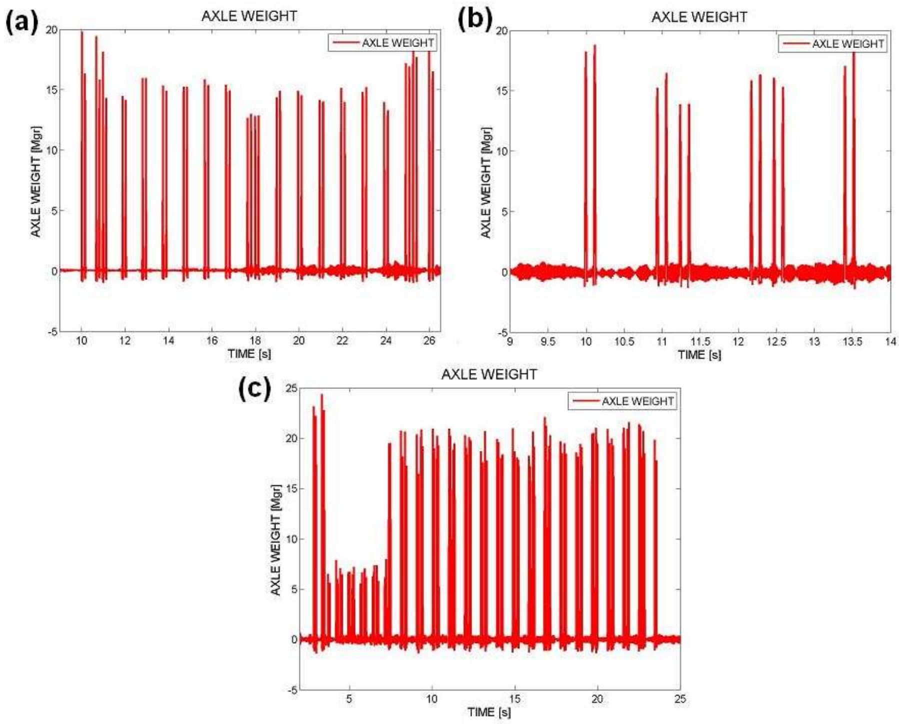

Figure 16: Axle weight of the different axles of a complete train.
(a) TGV/TMST (b) TER Z24500 (c) Freight

We can see that the accelerations obtained for the three models of train are greater at -0.10 m than at -0.40 m. As expected we can appreciate a decreased amplitude of the registered acceleration at -0.40 m depth than at -0.10 m depth due to the damping of the interlayer. We can see a decrease of the mean maximal acceleration measured between the two different depths, of about 0.25 m/s² at 80 km/h speed. This is a result of the damping of the ITL at the level of strain imposed by these trains.

The acceleration amplitudes can fluctuate depending on the used filter. If we do not filter the signal we would obtain a signal with higher amplitudes. These amplitudes could correspond to different geometric defects existing on the railway system such as rail defects of medium and short wavelengths (from 10 cm to 1 cm) or the wheel's defects of roundness of short wavelength (from 1 to 5 cm).

After a first integration of the acceleration, we obtain the speed induced for each analyzed train type. The results at -0.10 m for both elliptic and Butterworth filters are shown in Figure 18.

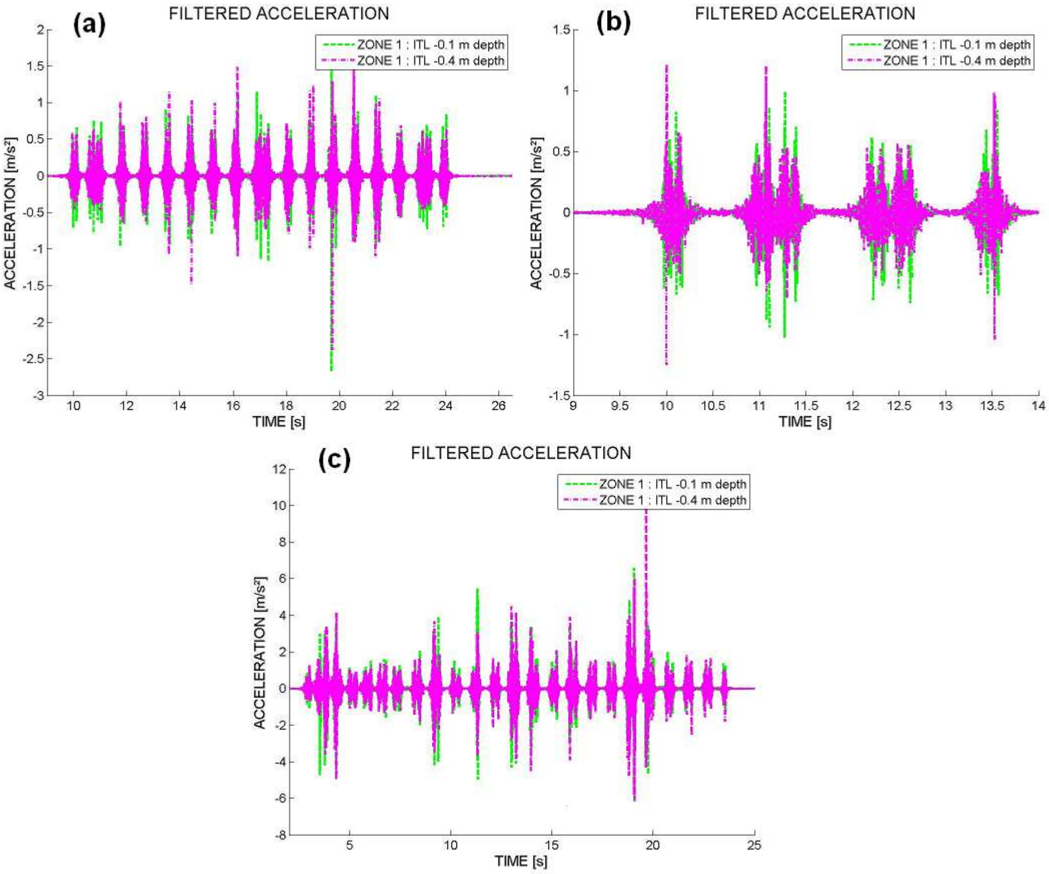

Figure 17: Acceleration at different levels of the interlayer induced by a train running at 80 km/h:
(a) TGV/TMST (b) TER Z24500 (c) Freight

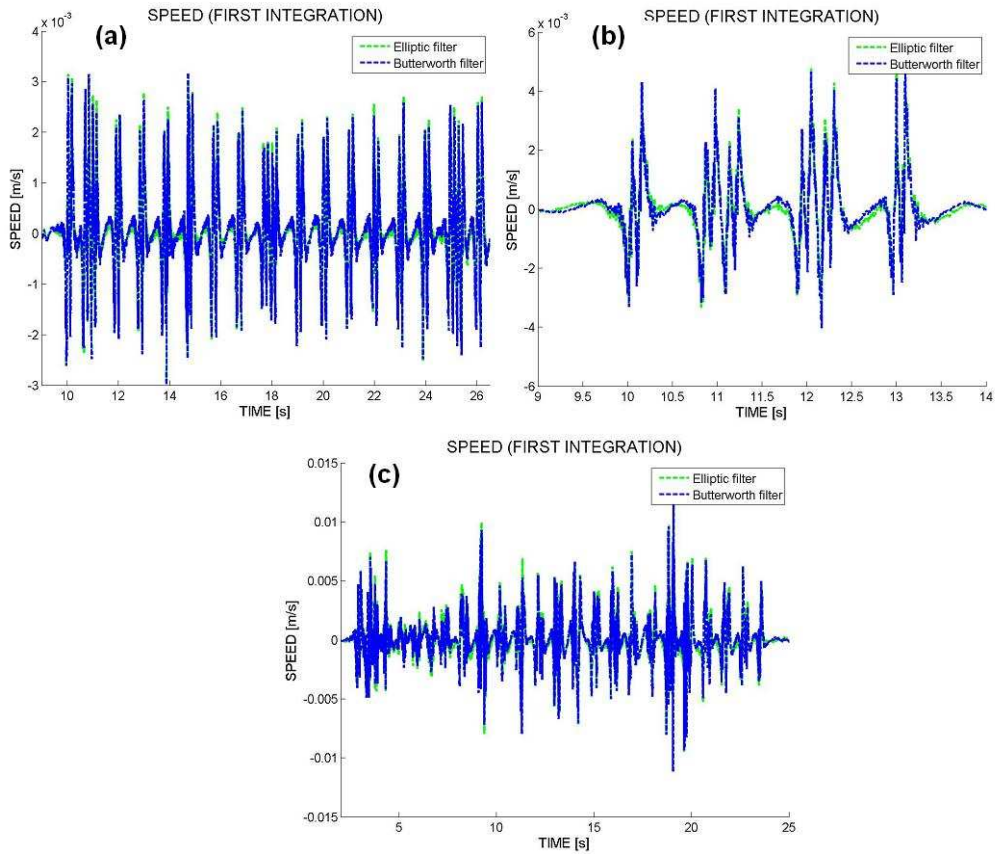

Figure 18: Speed at -0.10 m of the interlayer induced by a train at 80 km/h by integration of filtered acceleration data (elliptic and Butterworth filters)
(a) TGV/TMST, (b) TER Z24500, (c) Freight

We can see that the amplitudes of the signal filtered with an elliptic filter are slightly greater for the signal filtered with a Butterworth filter (Figure 18). This can be explained by the filter form as shown in Figures 13 and 14. It is observed that the heaviest axles caused greater amplitudes of particle speed in the interlayer soil.

Prior to processing the second integration, it is necessary to apply a second filtration of the data using a cut-off frequency to eliminate the baseline error. Figure 19 shows the obtained particle displacement for each train, at the -0.10 m level of the interlayer with both types of filters (elliptic and Butterworth). As the speed of a particle is mainly related to the low-mid frequencies of a train signal, the displacement of a particle is mainly caused by the low frequencies of the train signal (bogie and axle), these frequencies being better filtered with an elliptic filter. The difference between maximal values calculated by the Butterworth and elliptic filters in displacements in Figure 19 are bigger than the difference between maximal values of speed obtained in Figure 18. That is because the low frequencies have a great influence of the cut-off frequency used in the filter to calculate displacement amplitudes. The elliptic filter is more accurate in eliminating the non-measured frequencies by the accelerometer. The positive displacement in the beginning for each axle is caused by the mass inertia of the piezo-electric accelerometer.

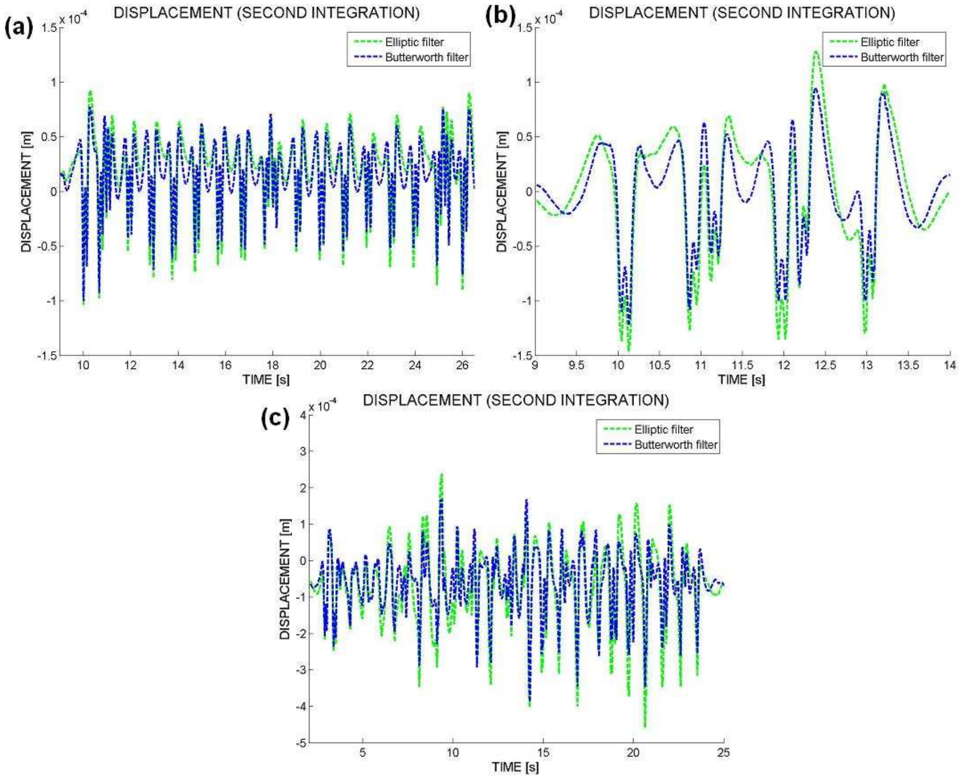

Figure 19: Displacement at -0.10 m of the interlayer induced by a train at 80 km/h by integration of filtered speed data (elliptic and Butterworth filters)
(a) TGV/TMST (b) TER Z24500 (c) Freight

If we focus on one bogie of each train we can compare the results of acceleration, speed and displacement more easily for the interlayer response under the effects of different trains. Thereby, a TGV/TMST engine bogie (mean axle weight: 17 Mg), a TGV/TMST coach bogie (mean axle weight: 16 Mg), a TER Z24500 bogie (mean axle weight: 15.8 Mg) and a full wagon of a freight train (axle weight: 22.5 Mg) are compared (Figure 20). The mean value axle weight of a TGV coach is very similar to that of the analysed TER train. For most of the full load freight wagons, with an axle weight of 22.5 Mg, the ITL reaches acceleration values between 1 m/s² and 1.5 m/s². The acceleration for a 16 Mg per axle bogie (TGV coach) is between 0.5 m/s² and 1 m/s². After the first integration, we can consider a mean value of 4 mm/s as speed at the ITL obtained for a full load freight wagon and 2 mm/s or 3 mm/s for a TGV coach bogie of 16 Mg. In the second integration, we can appreciate that the displacements induced by heavier weights are larger than those induced by the lightweight ones, as in Figure 20.c. The axial displacements are between 0.15 mm and 0.25 mm for most of the bogies from full load freight wagons. The mean values are about 0.075 for the ITL and 0.15 mm for a TGV coach bogie.

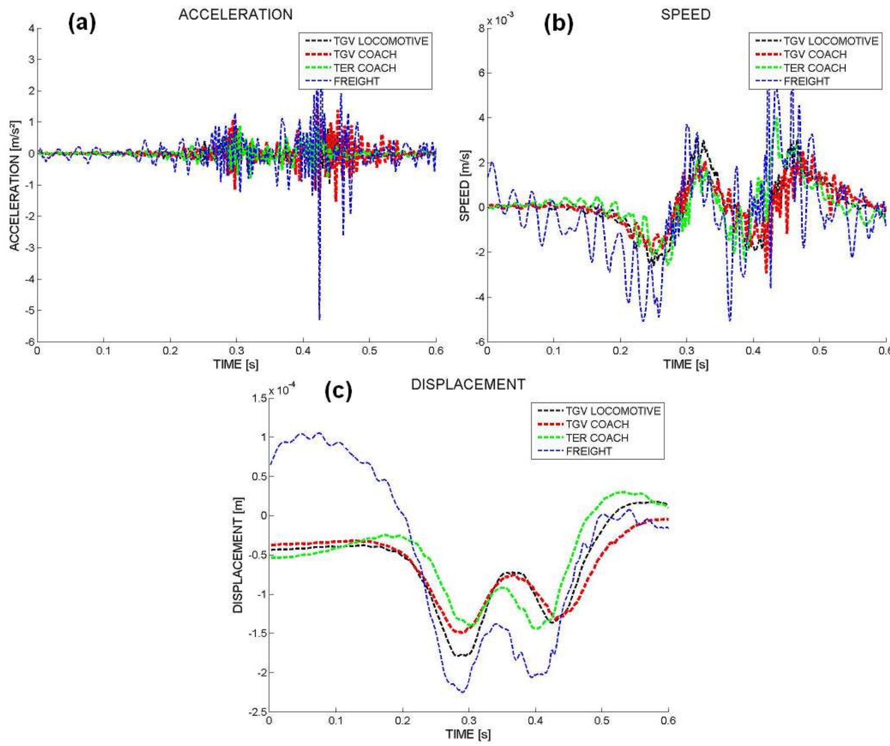

Figure 20: Acceleration (a), speed (b), and displacement (c) at -0.10 m depth of the interlayer induced by different types of bogies running at 80 km/h

5.2 Summary of results

The calculated maximums values of acceleration, speed and displacement per axle are presented in this section for all the analyzed trains. Thereby, we could analyse the trend of acceleration, speed and displacement as a function of axle weight. To this end, the results of an accelerometer installed at -0.10 m are presented. The applied filter for these results was an elliptic filter, following the integration scheme shown in Figure 15. Three freight trains, ten TGV type trains and five TER trains were analyzed. Note that different axles of a same train could have different weights.

One of the most important parameters which influences the maximum amplitude of acceleration measured is the low-pass frequency level applied to the data. As explained before, the filter used is a low-pass filter at a cut-off frequency of 200 Hz. The short wavelength defects of the track and the defects of wheels roundness provoke high frequencies excitation. These high frequencies could introduce greater acceleration amplitudes than the measured ones for a track with no defects. Figure 21 shows the maximum acceleration measured, obtained after being filtered, for each axle. The data was classified by train type.

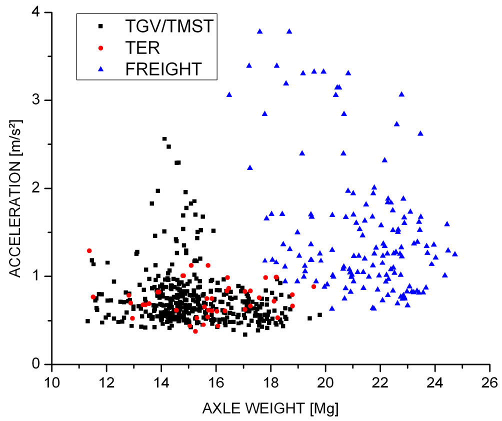

Figure 21: Measured acceleration at the ITL induced by different trains running at 80 km/h after applying a 200 Hz cut-off low-pass elliptic filter.

Figure 22 shows the maximal amplitudes per axle of the speed at the ITL (first integration of the acceleration data) after a high-pass filter with a 0.75 Hz cut-off frequency. These amplitudes of speed of the ITL are caused by the mid-frequencies in the frequency range analyzed (0.75 – 200 Hz). The increasing trend obtained is linear with the axle weight.

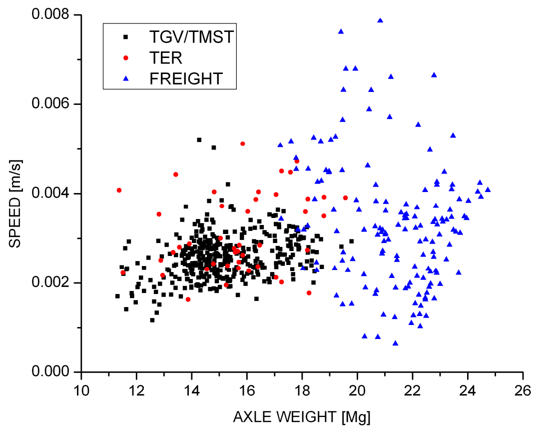

Figure 22: Maximum values of speed per axle at the ITL induced by different trains running at 80 km/h.

Figure 23 presents the maximal amplitudes of displacements per axle (second integration of acceleration data). These amplitudes are affected by the cut-off frequency used in the high-pass filter. We have to keep all the measured low frequencies into the filtered signal to obtain valid displacements amplitudes. With a 0.75 Hz cut-off the displacement amplitudes take into account the excited frequencies by the bogie and axle distances which provoke most of the displacement of the ITL.

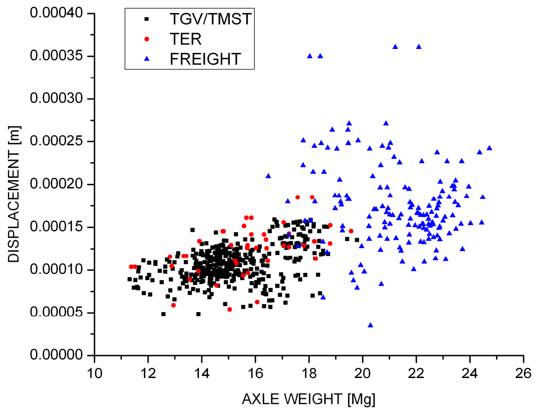

Figure 23: Maximum displacement per axle at the ITL induced by three type trains running at 80 km/h.

6 Conclusions

The main purpose of this study is to assess the method double integrating the acceleration data to obtain the acceleration, speed and displacement for the conventional railway platforms. The material studied was the interlayer (ITL) from a conventional railway platform. A conventional railway platform in the north of France was instrumented with piezo-electric accelerometers allowing studying the behaviour of the ITL under different loads (different train models). A total of 26 trains of four different types were analyzed: TGV/TMST, TER Z24500 and Freight trains, in terms of amplitude of acceleration, first integration (speed) and second integration (displacement) of the ITL. We note the importance of the accelerometer choice in determining the displacements by double-integration. Two types of filters were compared, elliptic and Butterworth. The influence of the filter type and the considered frequency range were evidenced. In this study the frequency range was taken as 0.75 Hz – 200 Hz. To analyze trains at low speeds we have to take into account the low frequencies caused by the bogie and axle distances which provoke most of the displacements of the ITL soil. We have obtained an increasing linear trend with the axle weight for the acceleration, speed and displacement. The acceleration obtained increases in a linear way from about 0.5 m/s² for a 12 Mg axle weight to about 2 m/s² for a 23 Mg axle weight. The displacements increase also linearly from 0.05 mm to 0.25 mm in the range of axle weights from 10 Mg to 23 Mg.

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