



HAL
open science

Evaluation of the use of geophones and accelerometers for monitoring pavement deflections, using accelerated pavement tests

Natasha Bahrani, Juliette Blanc, Pierre Hornych, Fabien Menant

► **To cite this version:**

Natasha Bahrani, Juliette Blanc, Pierre Hornych, Fabien Menant. Evaluation of the use of geophones and accelerometers for monitoring pavement deflections, using accelerated pavement tests. 6th International Conference on Accelerated Pavement Testing, Université Gustave Eiffel, Apr 2022, Nantes (Cité des Congrès), France. pp.526-535, 10.1007/978-3-030-55236-7_54 . hal-04372881

HAL Id: hal-04372881

<https://hal.science/hal-04372881v1>

Submitted on 4 Jan 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution - NonCommercial - NoDerivatives 4.0 International License

Evaluation of the use of geophones and accelerometers for monitoring pavement deflections, using accelerated pavement tests

Natasha Bahrani, Juliette Blanc, Pierre Hornych, Fabien Menant

MAST-LAMES, Université Gustave Eiffel, centre de Nantes, Route de Bouaye, 44341
Bouguenais CEDEX, France, natasha.bahrani@ifsttar.fr

Abstract In accelerated pavement tests performed at IFSTTAR, it is common to perform continuous deflection measurements under applied loading, using deflection sensors. These sensors, which consist of an LVDT attached to a rod anchored at a depth of about 4 meters, are difficult to install and relatively expensive. In this project, the possibility of using geophones or accelerometers, as an alternative method to measure pavement deflections has been investigated. Geophones and accelerometers measure respectively the vertical velocity and the vertical acceleration, and by integrating their signals, it is possible to calculate the deflection. Two types of geophones, and two types of accelerometers have been selected for the study. They have first been submitted to laboratory tests, on a vibrating table, simulating pavement deflections signals. Based on these tests, suitable signal treatment methodologies, to filter and integrate the signals, to obtain reliable deflection measurements, have been developed. The sensors have then been installed in an experimental pavement section, tested on the IFSTTAR APT facility. Deflections obtained with the geophones and accelerometers have been measured under different load conditions. The obtained values were in good agreement with those measured with a reference deflection sensor.

Keywords Pavement instrumentation, deflection measurements, Accelerometers, Geophones .

1 Introduction

Pavement deflection represents a very useful parameter to evaluate the overall performance of a pavement, its evolution with traffic, and its deterioration. The deflection basin can also be used to back-calculate pavement layer properties. In full scale accelerated tests performed at IFSTTAR, deflection measurements are made

using FWD tests, and also using sensors embedded in the pavement. Sensors offer the advantage of allowing continuous measurements, under applied loadings, and therefore give a better information about the evolution of pavement response. The sensors used for this type of measurements are generally single level (or possibly also multiple level) deflection sensors. These sensors consist of an LVDT, attached to a rod anchored at a depth of about 4 meters, which measures the displacement between the pavement surface, and the bottom end of the rod, which is supposed to be fixed. These sensors give accurate measurements, but they are expensive, and relatively difficult to install, because they must be placed in a bore-hole of sufficient depth (minimum 4 meters)

In this project, alternative solutions for measuring pavement deflections using geophones and accelerometers have been investigated. Geophones and accelerometers are robust and relatively small sensors, which can be easily embedded in a pavement layer. They measure respectively the vertical velocity, and the vertical acceleration, and it is possible to convert their response into displacements by an integration, or a double integration of the measurements. The possibility of measuring pavement deflections using accelerometers and deflectometers has already been investigated by Arrigada et al. (2009); The work done by Levenberg (2012) describes the use of accelerometers and the correction of their signals to get accurate deflection measurements. Duong et al (2018) used geophones and strain gauges to measure pavement deflections and strains, and to monitor evolution of pavement layer properties on a motorway section.

Based on these previous studies, two types of geophones and two types of accelerometers, with appropriate measurement ranges, were selected, and a research program was defined, to evaluate their suitability for the measurement of pavement deflections. For this purpose, a laboratory study was first conducted, to test the response of the sensors to controlled displacement signals. In a second phase, the sensors were also tested in real field conditions, under moving wheel loads, on the IFSTTAR accelerated pavement testing (APT) facility.

2 Laboratory evaluation of the sensors

The Two types of geophones and accelerometers selected for the study are presented on figure 1. To evaluate their response, laboratory tests were performed using a hydraulic, servo controlled, vibrating table. The tests consisted in submitting the sensors to displacement signals, simulating deflection signals produced by 5-axle heavy vehicles on real roads, and comparing their response with that of laser displacement sensor (Keyence sensor LC2100), which was used as a reference to measure the displacements of the vibrating table.



Fig. 1 geophones and accelerometers selected for the laboratory tests

To define the reference deflection signals, calculations have been performed with the multi-layer linear elastic pavement design soft ALIZE (Remaud, 2017), for a reference bituminous pavement, with characteristics defined in table 1, under the loading of a 5 axle semi-trailer truck loaded at 40 tons. An example of calculated deflection signal is presented on figure 2.

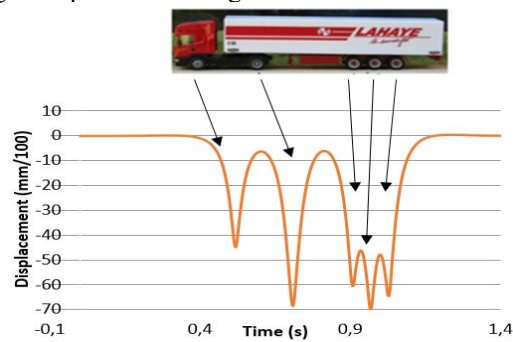
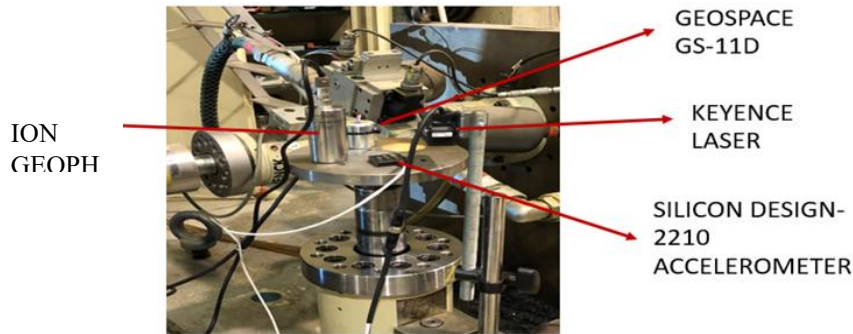


Fig. 2 Example of deflection signal under a five axle semi-trailer truck calculated with ALIZE

Table 1: Pavement model characteristics for Alize modelling

	Material	Thickness (cm)	Modulus (MPa)
Bituminous layer	BBSG 0/10	11	9191
Granular base	0/20 mm crushed rock	30	169
Subgrade	Clay sand	260	113

The setup used for the tests on the vibrating table is shown on figure 3. In each test, 3 sensors were placed on the vibrating table, and submitted to a series of deflection signals similar to that of figure 2. For each sensor, measurements have been made under truck signals with 3 different amplitudes (0.1, 0.5 and 1 mm), and 2 frequencies, corresponding to vehicle speeds of 35 and 70 km/h. The signals of each sensor have been recorded and treated, and compared with the reference displacements measured by the reference Keyence Laser sensor. In a first step, the signals of the geophones have been simply integrated, to obtain displacements. An example of signal obtained after this integration, is shown on figure 4a. It can be seen that the integrated geophone signal is quite different from the reference signal of the Keyence laser sensor. The signal presents in particular positive peaks, which correspond to an upward displacement, which do not seem realistic.



3 Sensor signal treatment

Following these results, different methods were tested, to correct the geophone response. More details about this work can be found in Bahrani et al. (2018). Finally, the following signal treatment procedure, which includes 4 steps, was defined to process the geophone measurements :

- Noise filtering, using a IIR chebyshev filter, with a cut-off frequency depending on the vehicle speed.
- Integration to convert the velocity to vertical displacement.
- Amplification of the signal, as the signal amplitude is reduced after the filtering process.
- Finally, application of a Hilbert Transform, to eliminate the oscillations in the signal. This final treatment eliminates the positive peaks, and leads to a response close to the theoretical truck deflection.

Figure 4 shows the displacement signals obtained before and after applying the signal processing, for geophone GS-11D. It can be seen that the proposed pro-

cessing leads to a realistic signal, both in shape and maximum displacement amplitude.

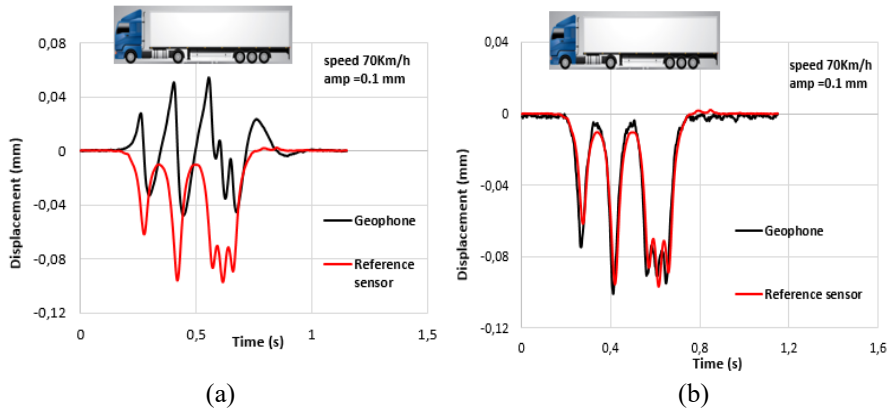


Fig. 4 Displacement signals obtained for geophone GS-11D, before signal treatment (a) and after signal treatment (b)

This same procedure was applied to the measurements of geophone ION. For the accelerometers, the only difference in the signal treatment is that a double integration was applied in the second step, to convert the acceleration to vertical displacement. Figure 5 shows examples of deflection signals obtained with the 4 different sensors, for a deflection amplitude of 1 mm, and a speed of 70 km/h. The proposed signal treatment procedure gives similar results for all the transducers.

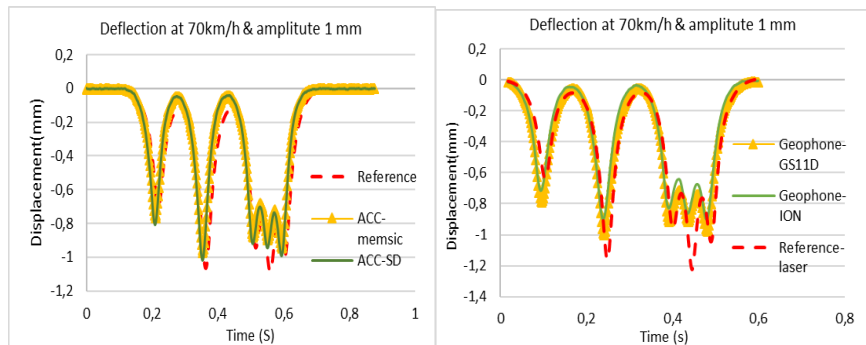


Fig. 5 Comparison of deflection values obtained with geophones and accelerometers, and reference values obtained with the laser displacement sensor

4 Full scale APT experiment

4.1 The IFSTTAR APT facility and the experimental pavement

Following the satisfactory results obtained for all the sensors in the laboratory, it was decided to test them in realistic field conditions, on the IFSTTAR APT facility. This outdoor facility consists of a circular test track, with a diameter of 40 meters and a central motor unit, with four loading arms, which can each carry loads up to thirteen tons, at a maximum loading speed of 100 km/h (figure 6). The maximum loading capacity is approximately 500 000 loads per month. A lateral wandering of the loads can be applied to simulate the lateral distribution of loads due to real traffic (Nguyen et al., 2013, Nguyen et al., 2017)

The sensors were installed in a pavement structure consisting of two layers of asphalt material, and a granular subbase (figure 6). They were placed in the middle of the wheel path, just below the pavement surface and close to an anchored deflection sensor, used as reference for the deflection measurements (figure 7).

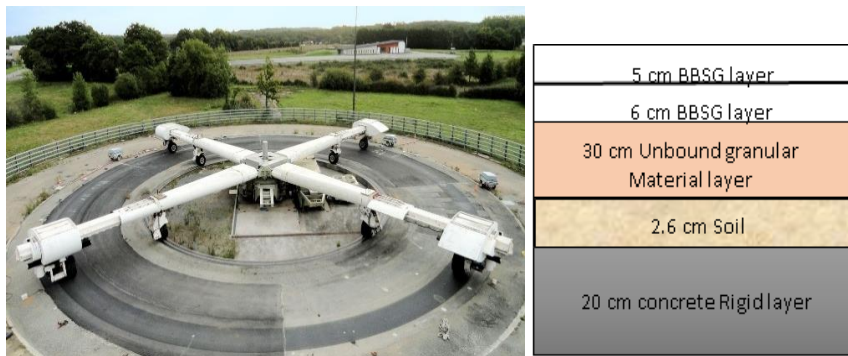


Fig. 6 The IFSTTAR APT facility and the experimental pavement section

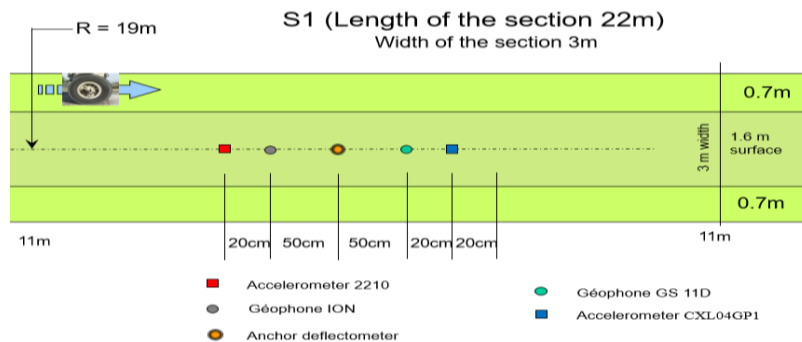


Fig. 7 position of the sensors on the experimental pavement section

4.2 Test program

The sensor measurements were made under dual wheel loads, and for different loading conditions: 5 different load levels, varying between 45 and 65 kN, 7 different speeds, varying between 7 and 86 km/h, and 11 different lateral positions of the wheels and temperatures between 18 to 23°C. For each measurement sequence, the responses of all the sensors were recorded during 24000 successive load applications. Then, the measurements of the geophones and accelerometers were treated using the same procedure as for the laboratory measurements, to determine deflection values and to compare them with the reference measurements of the deflection sensor.

5 Comparison of the accelerometer and geophone measurements with the reference deflection values

In this section, we present deflection values obtained with the different sensors for measurements made with a dual wheel load of 65 KN, and a temperature of 18.5 °C. Two series of measurements are presented:

- Measurements for 3 speeds (6, 12 and 20 m/s), with a constant wheel lateral position.
- Measurements for 2 different lateral wheel positions, and for a constant speed of 16 m/s.

Figure 8 presents the results obtained for different speeds, and for load position 6, for which the center of the dual wheel axle is above the transducers. The two accelerometers and the two geophones all give deflection values that are very close to the reference. However, the deflection signals present a more regular shape, with less noise, at higher speeds (12 and 20 m/s). For each sensor, an error parameter R is calculated. This parameter R, defined by Eq.1, indicates the difference in percentage between the reference signal (anchored deflectometer) and the signal of the other sensor.

$$R = \frac{1}{N} \sum \frac{\text{Reference value} - \text{Calculated value}}{\text{Max(Reference value)}} \times 100 \quad (1)$$

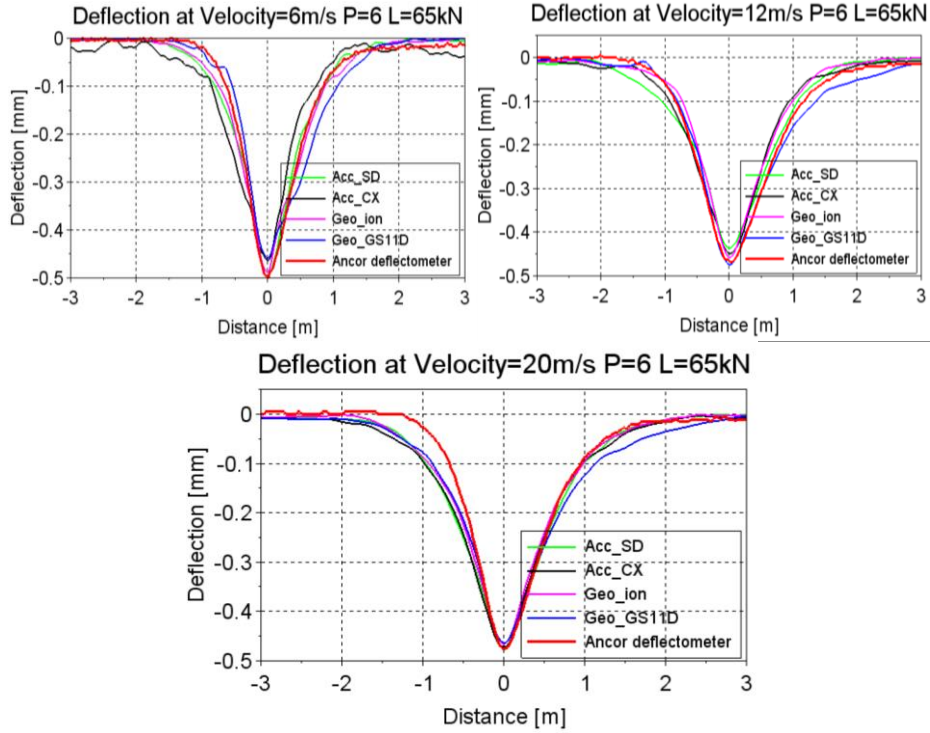


Fig. 8 Comparison of the accelerometer and geophone measurements with the reference deflection values, for a dual wheel axle loaded at 65 kN and for 3 different speeds (6, 12 and 20 m/s).

Figure 9 presents the results obtained for a constant speed of 16 m/s, and for two wheel positions: position 6 (center of the axle above the transducers) and position 4 (centre of one wheel above the transducers). For both positions, realistic deflection basins are obtained.

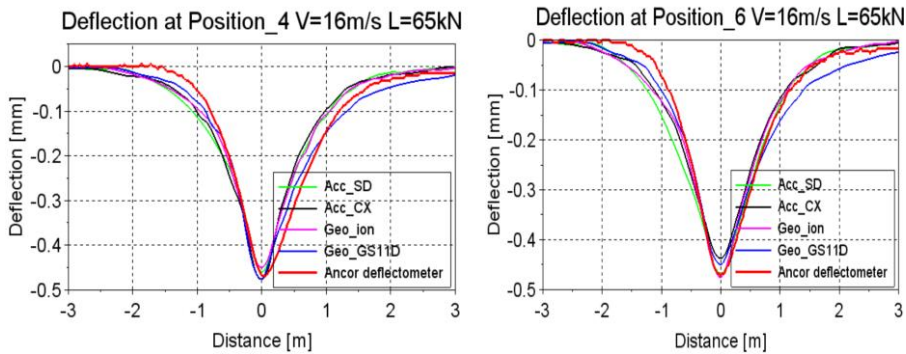


Fig. 9 Comparison of the accelerometer and geophone measurements with the reference deflection values, for a dual wheel axle loaded at 65 kN and for wheel positions 4 and 6 (speed 16 m/s)

To compare the results obtained for the different sensors, table 2 summarizes the error values (parameter R) obtained for the different test conditions (different speeds and different wheel positions), for each sensor. A mean error value, corresponding to the mean of all the individual errors, is also calculated for each sensor. The results indicate low error values (between 2.2 and 6.3 %), with no significant difference between the different test conditions. Concerning the sensors, slightly lower mean error values are obtained for the geophones (3.7 % and 3.8 %), compared with the accelerometers (4.8 % and 4.3 %). This might be due to the double integration performed for the accelerometers, which might introduce a larger error than the simple integration used for the geophones.

Finally, all the results can be considered as very satisfactory, and show that, with the signal treatment procedure which has been developed, geophones and accelerometers can be used for the continuous measurement of pavement deflections under traffic, and represent an interesting alternative to classical displacement sensors. When comparing the performance of the 4 evaluated sensors, it can be concluded that all present a good accuracy, and could be used for field measurements. Selection of the best sensor for a given application will also depend on other criteria like size, durability and cost.

Table 2 Error values (parameter R) obtained for the deflection signals predicted from the accelerometer and geophone measurements, for different loading conditions in the APT tests

Load condition	Geophones		Accelerometers	
	Geospace GS-11D	Ion LF24	Silicon design	Memsic
Speed 6 m/s, position 6	3.8 %	2.7 %	6.3 %	2.7 %
Speed 8 m/s, position 6	2.8 %	2.2 %	3.6 %	3.2 %
Speed 12 m/s, position 6	2.7 %	4.7 %	4.3 %	4.9 %
Speed 20 m/s, position 6	4.7 %	3.5 %	4.5 %	4.1 %
Speed 16 m/s position 2	4.7 %	4.3 %	4.0 %	5.2 %
Speed 16 m/s position 4	3.5 %	5.1 %	6.1 %	5.8 %
Speed 16 m/s position 6	4.0 %	3.8 %	4.5 %	4.4 %
Mean error R	3.7 %	3.8 %	4.8 %	4.3 %

6 Conclusions

This article presents a study performed to evaluate the feasibility of using geophones and accelerometers to monitor pavement deflections. After selecting 4 appropriate sensors, laboratory test were performed to evaluate their response to realistic deflection signals produced by heavy vehicles. A specific signal treatment procedure was developed to integrate and correct the sensor signals, in order to obtain accurate deflection values. Then the sensors were installed in an experimental pavement section, tested on the IFSTTAR accelerated pavement testing fa-

cility. 2 geophones and 2 accelerometers were installed in the pavement, close to an anchored deflection sensor, serving as reference. Test under dual wheel loads, with different load conditions, (load levels, speeds, load positions), have shown that the deflections estimated with the geophones and accelerometers were very close to the reference measurements, for all loading conditions, with differences between the predicted deflections and reference values ranging approximately between 2 and 6 %. The results obtained with the geophones were found to be slightly more accurate than those of the accelerometers.

After this study, it is planned to instrument a real pavement section with some of the sensors which have been tests, and to perform monitoring under real traffic. The objective will be to monitor the evolution of the deflections with time, but also to determine vehicle types and speeds, using the deflection signals (as already tested by Duong, 2018). Another perspective will be to test the possibility of using the deflection signals to back-calculate pavement layer properties, similarly to what is done for FWD tests.

References

- Arraigada M., Partl M.N., Angelone S.M., Martinez F. (2009) Evaluation of accelerometers to determine pavement deflection under traffic loads, *Journal of Materials and Structures* 42 .779-790
- Duong N.S., Blanc J., Hornych P., Bouveret B., Carroget J., Lefevvre Y. (2018) Continuous strain monitoring of an instrumented pavement section, *International Journal of Pavement Engineering*. 20:1435-1450.
- Duong N.S., Blanc J., Hornych P., Menant F., Lefevvre Y., Bouveret B. (2018) Monitoring of pavements using geophones, *International journal of pavements Engineering*. DOI 10.1080/10298436.2018.1432859
- Levenberg E. (2012) Inferring Pavement Properties using an Embedded Accelerometer, *International Journal of Transportation and Technology* 1.3: 229-246
- Nguyen M.L., Blanc J., Kerzrého J.P., Hornych P. (2013), « Review of glass fiber grid use for pavement reinforcement and APT experiments at IFSTTAR», EATA Conference, *International journal of road materials and pavement design (Special edition)*, 14: 287-308
- Nguyen M.L., Balay J.M., Di Benedetto H., Sauzéat C., Bilodeau K., Olard F., Héritier B., Dumont H., Bonneau D. (2017) Evaluation of pavement materials containing RAP aggregates and hydraulic binder for heavy traffic pavement, *Road Materials and Pavement Design*, 18:2, 264-280
- Remaud D et al, Alize-LCPC software Analysis and structural design of pavement structures, RGRA hors série report, December 2017.