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MEASURING PAVEMENT DEFLECTIONS WITH SENSORS: A REVIEW

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Abstract

Road pavement is a valuable asset for the development of modern society, the quality of which plays a fundamental role in the safety, economy, and sustainability of the free movement of people and goods. The assessment of road pavement condition and their evolution with time is a crucial component for planning and implementing appropriate maintenance and rehabilitation activities to maintain pavement specified minimum quality requirements. Pavement deflections measurements can be used as a quick and easy method for non-destructive determination of the structural capacity of existing pavement and evaluation of its ability to withstand future traffic loads. Pavement deflections are usually measured with Benkelman Beams, Le Croix-type deflectographs or Falling Weight Deflectometer. In the last decades, an alternative deflection measuring solution, via deflection, velocity and acceleration measuring sensors embedded in the pavement has attracted more and more attention. Integration of sensors in the road pavement allows the assessment of the complete history of pavement response under real traffic, starting from sensor installation. This paper will provide an overview of the sensors most commonly used for measuring deflections, linear variable differential transformers, geophones and accelerometers.

Keywords: pavement deflections, linear variable differential transformers, geophones, accelerometers

1 Introduction

Road pavement is a valuable asset for the development of a modern society, the quality of which plays a fundamental role in the safety, economy, and sustainability of the free movement of people and goods. The gradual degradation of pavement quality over time should be assessed so that maintenance and rehabilitation measures can be properly planned and implemented on time to maintain its specified minimum quality requirements [1]. When evaluating pavement condition, deflection measurements can be used as a quick and easy method for non-destructive pavement assessment. Pavement deflections are basic input parameter in structural analysis of in-service pavements, the identification of sections with structural capacity deficiencies, and design of pavement reconstruction or rehabilitation treatments [2]. The main purpose of deflection measurement is to determine the structural capacity of an existing pavement and evaluate its ability to withstand future traffic loads. Hveem [3] found that there is a strong correlation between pavement deflection and the ability of the pavement to carry traffic loads at a prescribed minimum service level. An attempt was made to determine maximum deflection limits based on experience and observations of the performance of similar pavements. It is assumed that the pavement will perform well below these limits. This concept has been applied to the overlay design, where the required overlay thickness is determined by keeping the deflection of the pavement below the maximum limits [2].

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Pavement deflection can be used to characterise the existing pavement condition. For example, deflection plots along a pavement can help to identify non-uniform sections, on which further investigation by destructive testing is required. Daily and seasonal deflection data can provide insight into a pavement's response to environmental factors, such as thermal curling, frozen support conditions, and asphalt stiffening [2]. Deflections could be used to establish seasonal loading restrictions for low-volume roads. Deflection measurements at the network level can provide a general indication of the pavement structural capacity [2].

Over the years, various testing devices have been used for pavement deflection measurements, from simple beam-like devices with mechanical dial gauges to sophisticated devices with laser technology [2]. Pavement deflection testing has historically been carried out using Benkelman Beams [4], Le Croix-type deflectographs [5, 6] or, particularly in the recent Falling Weight Deflectometer – FWD, [7, 8, 9]. All three of these technologies collect data at low travelling speeds. Therefore, they are poorly suited to the collection of continuous data along with large lengths of a road or entire road networks. The Traffic Speed Deflectometer – TSD, system developed by Greenwood Engineering in Denmark represents the first commercially available system that collects near continuous pavement deflection data at highway traffic speeds [10]. There are two additional devices that can collect deflection data at highway speeds – ARA Rolling Wheel Deflectometer – RWD [11], Dynatest's RAPTOR™ Rolling Weight Deflectometer – RWD [12], but neither of these are available for commercial purchase.

These ex-situ monitoring solutions provide consistent observation of the overall condition of the road network, but they are time-consuming and tend to detect damage only after it has occurred. They require disruption of traffic flow, are costly, and provide only punctual—at best, periodic information on deflection [13].

In pavement engineering, instrumentation of the pavements with a sensor is one of the most successful and effective methods for monitoring pavement deflections [14]. The need to collect deflection data without interrupting traffic flow and to continuously measure the response under regular traffic has led to the development of pavement instrumentation with various sensors [15]. The primary main types of such sensors are deflection, velocity and acceleration measuring sensors. They can be connected to a wireless data acquisition system, allowing continuous and remote monitoring. Therefore, they provide better information on the evolution of pavement response at different layers of the pavement structure [14]. Monitoring of the pavement deflection over time can be useful to follow the evolution of pavement layer moduli, and thus to detect the change in the layer properties that indicate material damage.

2 Sensors for pavement deflection measuring

The three most popular sensors used for measuring pavement deflections are linear variable differential transformers, geophones and accelerometers [13]. Their advantages and disadvantages are shown in Table 1. Basic operational principle in measuring pavement deflections for each sensor specified in Table 1 is discussed below.

Table 1 Advantages and disadvantages of sensors for pavement deflection measuring [16]

Sensor	Advantages	Disadvantages
Linear variable differential transformers	Measures displacement time history directly. Works with both static and dynamic loads.	Requires a reference point deep into pavement foundation. Installation is difficult and tedious.
Geophones	Measures velocity time history. Can be easily ruggedized. Installation is easy since it does not need a reference point. Least expensive option.	Does not respond to static loads. Should be thoroughly calibrated. Integration of velocity to calculate displacement should be done carefully.
Accelerometers	Installation is easy since it does not need a reference point. Calibration is linear.	Most models do not respond to static loads. Double integration of acceleration to calculate displacement should be done carefully. Most expensive option for sensors appropriates for this study.

2.1 Linear variable differential transformers

Pavement deflections under load can be measured with Linear Variable Differential Transformers – LVDT. LVDT is an electromechanical sensor for measuring linear displacement, the movement of an object in one direction along a single axis. The LVDT consists of a hollow metal cylinder with a shaft or push rod that moves freely back and forth within the cylinder [17]. The push rod is connected to a magnetically conductive core. A primary core is wrapped around the centre of the cylinder and is excited by a constant amplitude source AC known as the primary excitation. Two secondary cores with the same number of turns are wind around each side of the cylinder at an equal distance from the primary coil. Two secondary coils are connected in series to produce the output voltage AC. When the core is in the centre, no voltage appears at the secondary output, but as soon as the core moves even the smallest amount, a differential voltage is induced at the secondary output. The phase of the voltage is determined by the direction of the core displacement, while the amplitude is determined linearly by the amount of movement of the core from the centre. Voltage change is then multiplied by a calibration factor determined using a digital micrometer and data acquisition system software that correlates the output voltage to the measured displacement of the core of the LVDT. In an LVDT, any movement of the core results in a proportional change in the output signal, allowing infinite resolution, limited by the external output electronics [18]. LVDT sensors can measure movements from a few microns of an up to several centimetres.
In order to measure pavement deflections LVDT must be anchored below the deflecting pavement to remain undisturbed during the measurement to the extent required by the specified accuracy [19, 20]. So, the major disadvantage of LVDT sensors is their complicated and intrusive installation [19, 20]. LVDTs provide a very clean response signal, they can be used for deflection measurement of single or multiple pavement layers, and they are known to be accurate [19, 20]. They can be also useful for odelling responses and rutting profile of a flexible pavement [17, 18, 21] and evaluation of accelerometers and geophones to determine pavement deflections under traffic loads [22, 23].

2.2 Geophones

The vertical displacement of a point on the pavement under a given dynamic load can be determined by integrating the velocity signal at that point [19]. The vertical displacement velocity of a pavement can be measured using geophones [23]. Geophones are relatively simple, robust, and relatively small sensors that are easily installed in the pavement [23, 24]. They operate on the principle of a spring-mounted magnetic mass moving within a wire coil [23]. The geophone consists of a magnet and a mass attached to a spring, and a coil is connected to the mass [25, 26]. Under impact, the magnet moves but the mass remains relatively stationary, causing a relative movement between the coil and the magnet, that generates a voltage in the coil [26]. Delivered electrical signal is proportional to the vertical displacement velocity [23]. Pavement deflection is determinate by integrating measured velocity. Although geophones are not commonly used to measure pavement deflection, several studies address this issue. Geophones were used on the Minnesota Department of Transportation's test-track facility to evaluate the accuracy and precision of Traffic Speed Deflection Devices [16]. Sixteen geophones were embedded in the right wheel path of the surface layer at three flexible and one rigid pavement sections, four for each section. The accuracy of the geophone measurements was evaluated by FWD. The deflections of the FWD and installed geophones were within approximately 0.010 mm of each another. This study demonstrated that traffic-induced pavement deflections could be measured with geophones.

In a study by Blanc et al. [27], two geophones were installed on top of cement-treated subbase layer. The geophone measurements, made under actual traffic, were recorded over a two-year period. The difference between the geophone signals is small (about 0.5 mm/100) with similar evolution of the two measurements, which confirms the good accuracy of the measurements. The pavement deflection measurement obtained using the curviameter was the same order of magnitude as that of the displacement amplitude of the geophones. These results show that it may be relevant to use the average vertical displacement amplitude measured by the geophones as an indicator of the overall pavement behaviour.

Liu et al. [26] investigated the possibility of measuring and evaluating asphalt pavement deterioration using data measured by geophones. Pavement surface deflections were measured using geophones distributed equidistantly on a longitudinal axis parallel to the traffic direction. The deflections derived from the measurement of each geophone show high agreement with each other. The deflections measured with geophones can be used to analyse the evolution of the pavement elastic moduli to evaluate its structural capacity.

In a study by Doung et al. [22], different applications of geophone measurements were tested for instrumentation of a motorway section with continuous monitoring of the measurement under normal traffic. The geophones have been installed in the bituminous base layer of the pavement, at several lateral and longitudinal positions under the wheel path of passing vehicles. The results show that the geophones are very sensitive to the small displacement levels produced by the traffic on the motorway. Simple integration of the geophone signals is not sufficient to obtain accurate deflections values. The accuracy of the measured pavement deflection data can be improved by applying the proposed correction procedure.

Bahrani et al. [28] evaluated the possibility to use geophones for pavement instrumentation, to monitor pavement deflections under vehicle traffic. The geophones were evaluated in the laboratory using a vibrating table. The displacements applied by the vibrating table were measured with a non-contact laser displacement sensor, which was used as a reference sensor. To obtain realistic deflection values displacement velocity signal measured by geophones was corrected using different processing and transformation procedures. The corrected signal was compared with the reference displacement measurements. The obtained results confirm the possibility of using geophones for the pavement deflection measurement. As a continuation of this laboratory research, geophones were also installed

in an experimental pavement section on the accelerated pavement tests facility [24]. Two geophones were placed in the middle of the wheel path, just below the pavement surface and near the linear variable differential transformer, which served as the reference sensor for the deflection measurements. The measurements were performed under different test conditions (three speeds and two different lateral wheel positions) with 65 kN dual wheel load. Results have shown that the deflections estimated with the geophones were very close to the reference measurements with error values between 2.2 % and 5.1 %, without any significant difference between the different test conditions.
The results of the presented studies confirm the possibility of using embedded geophones for measuring pavement deflections. Geophones present interesting characteristics for this type of measurements due to their high sensitivity, good robustness, and relatively low cost [28]. The installation of geophones in the pavement structure allows continuous measurements of daily and seasonal variations of the deflection [23]. Further work needs to be done to correct and validate the measured displacements by considering the actual frequency response function of the geophones to obtain a more realistic shape of the deflection signals.

2.3 Accelerometers

The accelerometer is an inertial sensor that allows the measurement of linear and angular acceleration. They can be incorporated into any layer of the pavement or installed on the surface because they do not require a reference point, since acceleration is an absolute value related to the resting state [13]. Accelerometers can only measure dynamic instantaneous displacements, since the measurement point should experience some excitation [19]. In the last decade, accelerometer technology has improved in terms of sensitivity, frequency response, power consumption, and size, and has become cheaper. Accelerometers used to measure deformations should be selected to minimize the possibility of propagation and amplification of the acceleration error [29]. This is especially important for very small deformations such as those that occur under normal traffic, pavement, and environmental conditions.
In the research [22], conducted on a highway section with two types of trucks, nine accelerometers were installed 40 mm below the pavement surface. In addition, the response of the structure under load was measured with a set of three magnetostrictive deflectometers installed in a line perpendicular to the direction of vehicle motion and coinciding with the positions of the accelerometers. By comparing the relative deflections measured by the magnetostrictive deflectometers with the deflections calculated from the accelerometer measurements, the authors concluded that the calculated deflection is always greater than the measured deflection. A similar effect is caused by the speed of the vehicle. The faster the vehicle, the smaller the deflection measured by the deflectometer. In addition, the results of the deflectometer between the two peaks generated by the front and rear axles show that the pavement suffers tensile deformation in the vertical direction. This effect is not registered by the accelerometers.
In the study [14], two accelerometers and an anchored deflectometer were embedded in a pavement structure. The anchored deflectometer measures displacements with high accuracy, so it was used to determine the reference value for deflection. The sensors were tested on the accelerated pavement test rig under real wheel loads. The test was conducted under various conditions such as wheel load, position and speed. The test results showed that the deflections determined with the accelerometers were very close to the reference value with mean error values between 3.94 % and 4.77 %.
Bahrani et al. [30] conducted a study on inverse analysis of pavement layer modules based on data collected from two types of embedded accelerometers was conducted on the accelerated pavement test rig under real wheel loads. It was found that the acceleration signals are slightly asymmetric. In addition, the signal is initially positive as the wheels approach,

then negative under the wheels, and then positive again as the wheels move away. The measured responses were compared with calculations performed with a layer elastic model, and a method for back-calculating the pavement layer moduli was proposed. The initial results show good agreement between the modelled and measured responses and realistic back-calculated moduli. The results obtained with the two accelerometers differ slightly, with maximum relative differences between the responses of 2.78 % and 3.10 %.

The study [24] was conducted to evaluate the possibility of using different types of accelerometers to monitor pavement deflections using an accelerated pavement test. The test results showed that the deflections estimated with the two types of accelerometers were very close to the reference measurements obtained with the anchored deflectometer, with a relative error between 3.2 % and 6.3 %.

The field test [31] was performed with a truck of known weight and dimensions driven on different paths and at different speeds over the array of accelerometers. The measured accelerations were double integrated to determine deflections. It was found that computational corrections were required to compensate for the artificial data drift. Nevertheless, the discrepancy between the deflections calculated from the accelerations and the displacement transducer measurements was noted. The findings of the studies [19, 22, 29, 30, 31] showed also that simple integration of the results did not provide real deflection values. Use of accelerometers for monitoring pavement deflections was evaluated in [14]. In the first phase pavement deflection signals were simulated on a vibrating table. Based on the results of the laboratory tests, a new approach to signal processing was developed to increase the accuracy of determining deflection using accelerometers. New approach included implementation of additional processing measures such as: filtering, amplification and integration of the signal and application of the Hilbert transform [14].

Based on the previous findings, it can be concluded that the data collected with accelerometers, if interpreted appropriately, can be reliably used to determine pavement deflection with relatively low effort and costs. According to [22] accelerometers are not suitable for determining deflection in all circumstances. Slow-moving, lightly loaded vehicles that are far from the accelerometer's position present unfavourable conditions for accelerometers application. However, in study [32] author offered a practicable approach for using single-axis piezoelectric accelerometer sensors even when the traffic is slow-moving and lightweight. A distinctive component of the scheme is that readings are kept within the acceleration domain, and not double-integrated to arrive at displacements. So doing evades the amplification of errors caused by the integration process.

3 Conclusions

The structural capacity of a pavement is one of the most important parameters for maintenance planning and predicting remaining life of a pavement. The structural capacity at network and project level is usually evaluated based on pavement deflection data. Over the last decades, pavement deflection has been measured with various testing devices that provide information of the overall pavement condition, but are time-consuming, expensive, and provide periodic information on measured deflections. For this reasons, the possibility of measuring deflections using sensors embedded in the pavement has been increasingly explored. This paper gives a review on the sensors used for pavement deflection measuring.

Three most popular types of sensors for pavement deflection measuring are considered: linear variable differential transformers, geophones, and accelerometers. For each sensor, a basic operational principle is given and advantages and disadvantages of each sensor are addressed. Linear variable differential transformers measure deflections accurately, but are hard to install so their use is limited. The accuracy of geophones and accelerometers depends on integration process applied to measured signal. Therefore, further research should be paid to signal processing and integration techniques. Based on the given literature review it can be concluded that instrumentation of pavement with sensors to measure deflections could be a valuable alternative. Continuous measurements with sensors embedded in the pavement would provide a valuable insight into daily and seasonal variations of the deflection and thus enabled continuous monitoring of the pavement structural capacity.

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