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Accurate measurement of pavement deflection velocity under dynamic loads

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ABSTRACT

Bearing capacity is one of the most important indices that reflects the condition of road pavements. For high-speed and non-destructive measurement of bearing-capacity values, advanced dynamic deflectometers have been developed in the past decade. The deflection range is typically computed based on the Euler-Bernoulli elastic equation with a number of deflection velocity values. The deflection velocity refers to the vertical velocity of pavement deflection under a force action; it can be captured by a number of positions in the deflection basin by laser Doppler sensors. Thus, the accurate measurement of deflection velocity is of vital importance to the performance of a deflectometer system. In this paper, we consider the problem of accurately measuring the deflection velocity based on dynamic posture and calibration. Both methods build the relationship between the measured values and the relative postures of the sensors and targets. We first validate the effectiveness of the static calibration that determines the relative postures of the sensors with indoor settings. Second, with respect to self-correlation of the velocity values, the dynamic-posture-based method and the calibration-based method are compared. Third, the impact of traffic speed on the measuring results is investigated. Last, we further validate the accuracy of the measured velocity by computing deflection ranges and comparing them to ground-truth values. Experiments in real measuring tasks demonstrated that both the calibration-based method and the dynamic-posture-based method can produce accurate and effective results.

1. Introduction

For road construction and maintenance, bearing capacity, which is influenced by compacted material density [1] and material stiffness [2], is an important index for road condition assessment and should be measured regularly to check the road conditions. In the measuring task, a deflectometer can be used to assess bearing capacity by measuring the pavement vertical deformation values. With the rapid increase of highway construction, *e.g.*, more than 2000 miles of road were constructed annually in China in the last decades. However, traditional deflectometers, *e.g.*, the Benkelman beam or the falling weight deflectometer (FWD) [3–6], would be either labor-intensive or time-consuming. Hence, it is urgent and necessary to develop automatic and efficient methods and equipments for the modern pavement deflection measurement task.

Pavement deflection refers to the total vertical deformation value or vertical rebound deformation value of the subgrade or the pavement surface at wheel gap position under a standard vehicle load. It is a distance dimension used to reflect the bearing capacity of pavement structure. Many efforts have been made to achieve a high-speed and non-destructive deflection measurement [7–11]. Considering that the pavement deflection is naturally a distance dimension, many high-speed measurements were developed based on the classical force-displacement method. Typical high-speed measuring products include the rolling wheel deflectometer (RWD) [12,13], the Swedish road deflection tester (RDT) [14], and the rolling dynamic deflectometer (RDD) [8,15-17]. Though some of these methods have been made progress in laboratory experiments, few have been applied in practical engineering applications. In the 1990s, collaborating with the UK's Transport Research Laboratory (TRL) and the Danish Road Institute, Greenwood Engineering (GE, Denmark) developed an advanced deflectometer — a traffic-speed deflectometer (TSD) [9,18]. The idea depends on the deflection range value of road pavement being able to compute based on the deflection velocity captured by laser Doppler sensors, thus avoiding the difficulty of directly measuring the displacement of pavement deformation. In 2000, the first prototype equipment was developed, equipped with two Doppler vibrometers. One vibrometer measured the deflection velocity at the loading wheel under a load of 50 kN, and the other measured the deflection velocity at a position 3.6 m away from the loading wheel. The pavement deflection

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observed by the second laser Doppler is supposed to be zero, which is taken as a reference. This equipment can measure road deflection under a speed of 20 to 90 km/h. In 2005, an upgraded TSD consisting with four Doppler sensors was developed, and it was reported to have been applied in a real pavement network reconnaissance survey. Following the idea of inferring deflection range from deflection velocity, a prototype system, a laser dynamic deflectometer (LDD), was developed by the Transportation Research Center (TRC) of Wuhan University [19]. The LDD has four laser Doppler sensors and a rigid beam, and calibrates a relative-motion-based method efficiently.

For the aforementioned methods and systems, laser Doppler sensors have greatly reduced the cost and risk of the traditional Benkelman beams or FWDs, which directly measure the deformation displacement. Once the deflection velocities are accurately measured, an accurate deflection displacement can be calculated by using the Euler-Bernoulli elastic equation. As a consequence, the performance of the whole system relies heavily on the measurement of the deflection velocity. It is desired to get the deflection velocity perpendicular to the pavement. However, the velocity measured by the laser Doppler sensor consists of several velocity components, *e.g.* — pavement deflection, vehicle, and movement velocities of the beam. Inferring the pavement deflection velocity perpendicular to the pavement from the velocity components is a key step in constructing a practical system.

In this paper, we present two accurate measurement methods of the deflection velocity, namely the dynamic-posture-based method and the calibration-based method. To build the relationship between the measured values and the relative postures of the sensors and targets, the former uses a dynamic computing strategy that calculates the parameters in the measuring process. The latter uses a calibration strategy to calculate the parameters of the system model. Specifically, some airport runways data have been selected to test and calculate the system parameters, since the runway pavements are supposed to be rigid and hard enough to produce negligible deflection under wheel loadings. The proposed methods are conducted according to the following steps. First, we validate the effectiveness of the static calibration that determines the relative postures of the sensors with indoor settings. Second, we compare the dynamic-posture-based method with the calibration-based method with respect to the self-correlation of the velocity values. Third, we investigate the impact of traffic speed on the measuring results that were implemented. Last, we further validate the accuracy of the measured velocity by computing deflection ranges and comparing them to ground-truth values.

The rest of this paper is organized as follows. Section 2 introduces the related work. Section 3 gives the background knowledge for dynamic deflection measurement. Sections 4 and 5 describe the method and design to measure the pavement deflection velocity accurately. Section 6 reports our experiment results on laboratory settings and practical engineering tasks, and Section 7 concludes the paper.

2. Related work

The traditional deflection measurement methods are based on direct displacement measurement, which directly measures the displacement of pavement under the action of force. A straightforward way to measure the displacement is through the Benkelman beam, a labor-intensive and time-consuming way to perform the measurement. As an improvement, the FWD has been regarded as standard for deflection measurement in most countries. However, the FWD still suffers a stop-and-go weakness. With the development of advanced laser sensors, the deflection can be calculated by using deflection velocities in the deflection basin. By measuring the deflection velocities of several positions in the deflection basin, the deflection value can be calculated at a traffic speed. The deflection velocity and deflection under the action of load are illustrated in Fig. 1. In this section, we overview both the displacement-based and the velocity-based methods in deflection measurement.

2.1. Displacement-based deflection measurement

This method directly measures the deflection displacement of pavement under the action of force. Four main types of devices – the FWD, the lightweight deflectometer (LWD), the RDD, and the RWD – produce the deflection value by directly measuring the displacement. The FWD is a widely used testing device and is commonly considered a standard tool in measuring the bearing capacity of road pavement. In practice, the FWD is often used to check the structural condition index (SCI) at a network-level evaluation [3,6]. However, the FWD performs a discrete test with a stop-and-go strategy, greatly increasing the testing time and operational cost, and suffering from a dangerous working environment. The LWD is preferred in quality control/quality assurance since it quickly determines the equivalent surface elastic modulus. The LWD includes the light falling weight deflectometer (LFWD) [20] and the portable falling weight deflectometer (PFWD) [21,22]. Since the LWD produces a limited load on the ground, it is mostly used to evaluate pavement modulus for geological research [23,24]. To produce deflection of the pavement profiles continuously, the RDD has been developed [7,8,15-17,25-28]. The RDD [15] system was equipped on a Vibroseis truck, tested at a speed of 2.4 km/h. Then, on this basis, the second-generation RDD [17] was developed by applying advanced sensors, filtering rolling noise, and improving data-analysis methods, with an improved testing speed of 4.8 km/h. For the method described in Ref. [8], the RDD system was successfully applied to pavement rehabilitation projects. To evaluate concrete pavements, the RDD was tested on four structural conditions in Ref. [28]. The RDD is useful in continuously measuring pavement deflection; however, it is still too slow to perform evaluations at highway speeds. Another dynamic deflectometer is the RWD [12,13,29-31]. In Ref. [13], the RWD was used for network-level pavement deflection measurements in Kansas, and the testing speed was about 88 km/h. Nevertheless, the results of the RWD were reported to be unstable [30]. The road deflection tester (RDT) reported in Ref. [14] held the advantage of providing an entire transverse deflection profile instead of a single deflection value provided by some of the other devices. The RDT was assumed to move faster than the speed at which the deflection wave travels along the pavement. However, the validity of this assumption needs to be investigated, and some system errors still need to be rectified [32].

2.2. Velocity-based deflection measurement

By measuring the deflection velocity of several pre-defined positions in the deflection basin, the deflection value can be calculated by the deflection curve equation at a traffic speed. On this basis, a number of devices have been developed in the past decades, *e.g.*, the TSD [9-11,18,33-36], high-speed deflectograph (HSD) [37,38], and the LDD [19]. Initial research on HSD was reported in Ref. [37] by the Danish Road Institute, where the use of laser Doppler sensors to provide the deflection velocity of the pavement surface was proposed. Then in 2002, a prototype HSD was put into operation and performed a measurement at driving speeds of up to 80 km/h [38], with repeatable results competing to that of the FWD. In Ref. [18], the performance of the TSD was validated by a comparison study based on a two-year network-level evaluation. In Refs. [10,11,33], the prototype TSD was improved at the Transport Research Laboratory of the UK to enable network structural surveys at 80 km/h [35]. Further, in Ref. [34], the TSD was applied to measure the bearing capacity of an 18,000-km road network in Australia, and the results showed good repeatability and no speed dependency. In 2013, the prototype LDD was developed at the transportation center of Wuhan University [19], where an efficient calibration method was proposed. The TSD and LDD can generally provide continuous non-destructive measurements of the structural conditions of road pavement and are regarded as the state-of-the-art among all relative devices.

Generally, the displacement-based method has two work modes —

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