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Monitoring the structural capacity of airfield pavement with built-in sensors and modulus back-calculation algorithm

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HIGHLIGHTS

- Theoretical relationship between in-pavement responses and modulus was derived.
- Modulus back-calculation algorithm was developed upon the theoretical results.
- The proposed modulus back-calculation algorithm is absolutely convergent.
- Modulus back-calculation process with built-in sensors does not affect traffic.

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ABSTRACT

The degree of deterioration in the structural capacity of a pavement is an important indicator of its performance. Conventional falling weight deflectometer, which assesses pavement capacity based on the deflection bowl data under impact loads and is the prevalent method in practice, only characterize the overall bearing capacity of pavement. It does not possess sufficient accuracy in measuring the modulus of pavement structural layer. In this paper, a smart pavement schema was proposed where built-in sensors are incorporated to monitor pavement stress and strain responses under aircraft loads. Theoretical relationship between pavement mechanical responses of a two-layered elastic system subjected to service load is established, which is used for back calculating the modulus of asphalt layer. To demonstrate the concept, sensors are deployed along a taxiway in Beijing Capital International Airport, Beijing, China. The measured mechanical responses by the sensors were incorporated to back-calculate the modulus of asphalt layer, which are then verified through dynamic modulus experiments. The results show that back-calculated modulus by incorporating sensor data is repeatable and can be applied for real-time evaluation of pavement performance without affecting the traffic. Extension of the model and analysis to multi-layered elastic system are discussed.

1. Introduction

The structural modulus of a pavement is a key mechanical parameter for pavement design and evaluation, such as for theoretical analysis of mechanical responses and for empirical estimation of pavement damages including fatigue and rutting [1]. The degree of deterioration in the structural capacity is directly related to the performance and service life of a pavement. Therefore, accurate evaluation of the modulus of in-service pavement is crucial for its condition assessment.

The falling weight deflectometer (FWD) is a common nondestructive testing device to evaluate pavement structural capacity. It involves dropping a large mass at a certain height to the pavement to generate a transient impulse dynamic load. The pavement responses are captured with a string of geophones whose data can be processed to obtain the profile of pavement structural deflection. The measured vertical deflection bowl data are used to evaluate the pavement structural capacity and back calculate the modulus of pavement structural layer [2–4].

The solution of surface displacements of pavement under transient impulse load has been developed based on analytical, spectral element, and finite element methods [5–9]. Back-calculation of the modulus of each layer is a typical problem of inverse parameter

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identification. Numerous algorithms have been developed to identify the layer moduli using the measured vertical surface displacements, such as artificial neural networks [10], ant colony optimization algorithm [11], probabilistic approach [12], and fuzzy algorithm [13]. In addition, the identification of complex and diverse parameters, such as viscoelasticity of asphalt layer [14], nonlinear properties of pavement materials [15–17], and thickness of pavement structural layers [18,19], were considered and discussed in previous studies.

However, modulus back-calculation based on FWD testing method has several limitations. Firstly, the load pattern of the FWD loading system is quite different from that of a moving vehicular load in terms of pulse durations and magnitudes of pavement responses [20]. No clear equivalent correspondence between the FWD and vehicle loads is known. Therefore, the results of back-calculated modulus could not reflect the pavement modulus under real vehicle load. Secondly, although various algorithms have been applied to the modulus back-calculation, most face the challenges of convergence of the back-calculated results for a multi-layered system. This is due to the fact that the measured pavement vertical surface displacements can only characterize the overall bearing capacity of the pavement, it lacks the resolution to identify the differences between the structural layers of pavement. Thirdly, FWD survey typically requires traffic control which affects the traffic operation. These all demand a new method to overcome limitations.

A smart road that monitors the pavement health is a viable approach to overcome these limitations. For the smart road, the pavement mechanical responses under actual moving vehicular load (e.g., stress, and strain) will be measured by the embedded sensors, which are analyzed in real time to elucidate the mechanical behavior of a pavement.

As demonstrated through practice on numerous test roads [21–25], pavement health monitoring could provide a large amount of data for pavement design, performance evaluation, maintenance decision making, etc. Pavement condition model, traffic monitoring [26,27], and road roughness evaluation [28] could be achieved by analyzing the monitoring data measured by embedded sensors under pavement.

For the back-calculation of pavement modulus, the mechanical responses of pavement structure are directly related to the modulus of each structural layer according to the theory of multi-layered elastic system. In addition, the pavement mechanical responses can indicate the mechanical properties of each layer which is not directly demonstrated by the pavement surface deflections. Therefore, this paper describes a smart road concept which is capable of back-calculating the asphalt layer modulus based on the stress and strain responses monitoring of pavement structure with built-in sensors. The modulus back-calculation process may not be suitable for the capacity evaluation for existing pavements without built-in sensors.

2. Sensor layout of the smart road

Embedding strain and stress sensors into pavement structure allows to capture the pavement mechanical responses. However, it is worthwhile to point out that the sensor responses can be complex and contaminated with random loads (such as stochastic tire pressure, vehicle operational speed and wandering along the lane, etc.). Thus, proper sensor layout is required to not only acquire the mechanical responses but also to identify the characteristics of load information.

With these in mind, a smart road was instrumented with the sensor deployed under the taxiway in Beijing Capital International Airport (i.e., Fig. 1) by use of fiber Bragg grating sensors. All these fiber Bragg grating sensors were embedded at the bottom of the second asphalt layer. The sensor layout consisted of three parts.

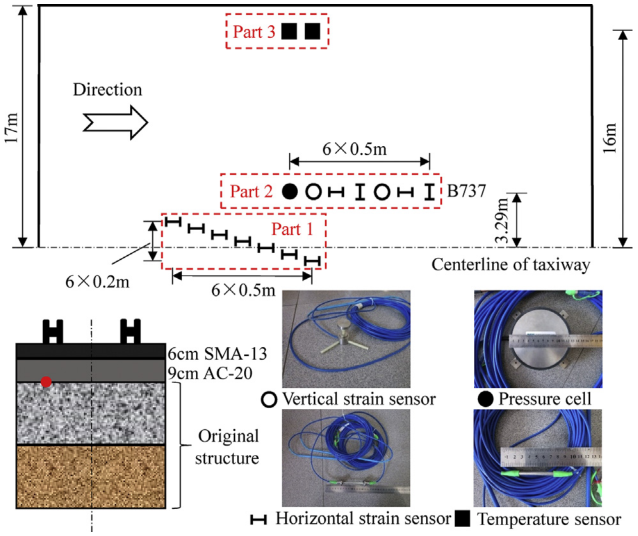

Fig. 1. Layout of sensor deployments along the smart road.

Fig. 2 illustrates the functions of these three different sensing components, which are annotated as Parts 1 to 3 respectively in the figure. Part 1 includes seven strain sensors aligned parallel to the driving direction and embedded near the centerline, which aim to identify the nose wheel wandering by each aircraft. The location of the sensor with maximum tensile strain response is used to determine the load position by the passing nose wheel. Part 2 includes the vertical strain sensors, horizontal strain sensors, and pressure cell and are embedded on the left side of the pavement because of the symmetry of wheel loads. In order to measure the mechanical responses under the main landing gear wheel loads of Boeing 737, the distance between the centerline and sensors is set to be equal to half of the sum of the main landing gear spacing and main wheel spacing (i.e., the left tire of the left main landing gear wheel is exactly located at the top the sensors when the aircrafts taxi along the centerline of the pavement without wandering). Another function of sensors in Part 2 is to measure the speed of the passing aircraft by analyzing the time lag in the sensor

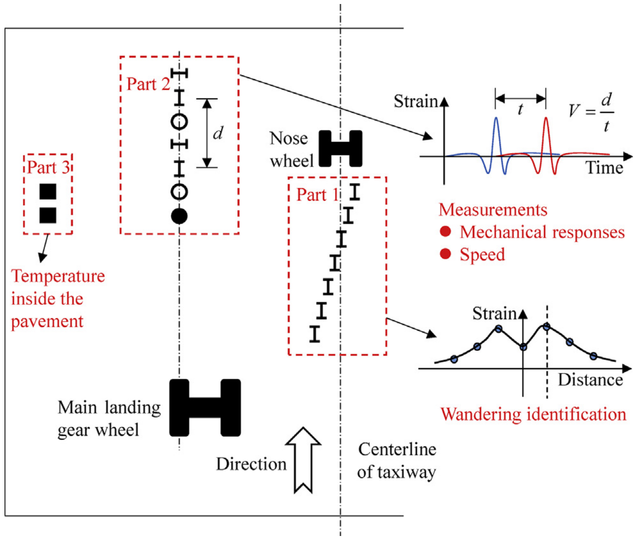

Fig. 2. Functions of the sensor layout.