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Nondestructive Testing Method to Assess and Detect Road Performance

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Abstract: At present, China is faced with major problems in infrastructure management, such as improper scheduling and belated implementation of maintenance work or huge maintenance budget outlays. Therefore, it is essential to implement rapid and effective management measures to ensure road safety, prevent catastrophic damages, and increase economic growth. In this paper, five nondestructive road-testing methods and their associated testing equipment are introduced in accordance with the American Society for Testing and Materials. These include the falling weight deflectometer, ground penetrating radar, macro texture depth, international roughness index, and spectral analysis of surface waves. The operating principles and applications of each testing method are elaborated to guide relevant personnel to make an informed choice according to their actual situation. The application of these testing methods will accelerate the assessment of projects without traffic closures, likely provide a new approach for establishing a high-efficiency intelligent road network monitoring system, and present a practical and feasible method for sustainable road development and efficient utilization of capital.
Keywords: road detection; road defects; nondestructive testing

1 Introduction

Infrastructure is not only the foundation of an urban society, but also a guarantee of universal life. The construction and maintenance of infrastructure require a huge investment. A report issued in 2008 by the United States Federal Highway Administration (FHWA) showed that approximately 6.4×10^6 km of roads in the United States required extensive repairs [1]. In 2014, a report issued by American Society of Civil Engineers rated American roads as level D (where the levels are divided into four, A, B, C, and D) [2]. In the United States, 42 % of the major urban roads are overcrowded due to damages. In 2014, the federal, state, and local governments invested 91 billion USD on road infrastructure. Although the situation will improve in the short term, these investments are not sufficient. Based on the FHWA's estimates, an additional 170 billion USD needs to be spent each year to significantly improve the condition and performance of the roads [2].

At present, the detection methods for roads in China are primarily aimed at damaged sections, using visual inspection to find diseases and damages. This method is not adequate for the increasing road facilities and pressure due to heavy traffic. Therefore, there is an urgent need for techniques that can economically and effectively monitor the status of the road network, and provide priority information for their accurate and timely maintenance, so that methods for the detection of faults on roads can be developed from regular local inspections to the continuous monitoring of the health of road networks.

2 Road diseases and defects

Pavement deterioration usually occurs below the road surface and cannot be detected by visual measurements (Fig. 1).

Common road diseases include horizontal cracks, longitudinal cracks, ruts, waves, pits, delamination, and leakages, etc.

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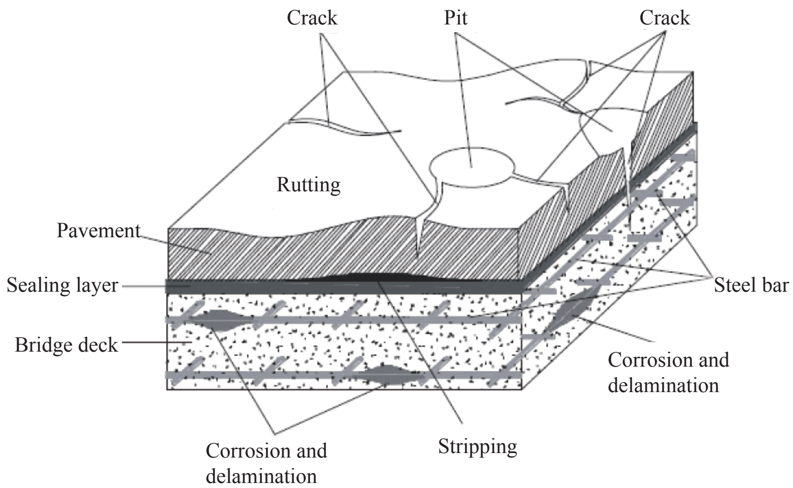


Fig.1. Pavement deterioration.

Lateral cracks are often more prone to longitudinal cracks that can develop from cracks that are less than 0.5-mm-wide and 2-cm-deep. Such cracks are difficult to detect on sunny days but can be seen after rains because of the residual water in the cracks after the local surface water evaporates. Small cracks need to be repaired promptly to prevent the development of larger cracks. Large cracks are usually more than 1-mm-wide and 5-cm-deep, and can be a few meters long. If large cracks do not seal, delamination and shrinkage will occur. If the cohesion between the pavement and the concrete slab decreases, the cover will debond from the concrete slab. The pits caused by cracks or leakage usually arise because of reduced adhesion. Local debonding may extend a few square centimeters, but the crack is difficult to find because the pavement seems to be in good condition. Large areas of delamination may develop into large cracks in the pavement and eventually lead to large pavement trenches and damage. Cracks and pits are often accompanied by seepage. Water enters the coating through the cracks. Asphalt and concrete slabs are highly susceptible to seepage water. The water inside the crack in the road surface will be retained or even continue to leak downwards. This is the largest damage for asphalt pavements.

In order to assess and determine the condition of freeway pavement and decks, several nondestructive testing methods were explored in this paper to detect diseases and defects in the subgrade and pavement, and to list some commercial products and testing procedures to facilitate early road maintenance. The advantage of non-destructive testing is that it evaluates the state of the structure accurately and efficiently without blocking traffic.

In China, pit and other road diseases plague the city's infrastructure. The pit shown in Fig. 2 exists on most roads. The patch shown in Fig. 2 is the common and economical method but its effectiveness varies significantly. It is easily compromised due to rapid repair needs and lack of adequate compaction of small patch areas. Therefore, maintenance methods should be improved, while monitoring and testing of road and road-related diseases should be stepped up to identify early pit and local damage to extend road life.

3 Pavement condition evaluation from American Society for Testing and Materials

The National Association of Highway Administrators (AASHO)

(a) Repeated repair of the pit (b) The restored pit has sunk

Fig. 2. Repair of damaged section of pit.

is one of the most comprehensive pavement rapid testing organizations that can detect road conditions and explain the causes of road deterioration. The accuracy of pavement services performance index has improved as AASHO computes the number of road diseases visible on US roads such as cracks, patches, and slope instability and rut depth. The profiled data are used to calculate the road surface roughness and compare it with the four grades used by experts for evaluating roads [3]. The road surface services performance index is calculated through the following formula:

$$PSI = 5.03 - 1.9\log(1 + SV_t) - 1.375RD_t2 - 0.01(C_t + P_t)0.5 \quad (1)$$

in formula (1), PSI is the road surface service performance index; SV_t is the slope change at time t; RD_t is the mean rut depth in inches (1 in≈2.54 cm); C_t is the crack length per 1000 ft^2 (1 ft^2 ≈ 929.0304 cm^2); P_t is the repair area per 1000 ft^2.

Before conducting a visual survey, roads in different areas are divided into sections according to their grades. Only a part of a given area, called a road surface sampling unit, is investigated during the survey. Typically, a pavement sampling unit has an area of 2500 ft^2. The ASTM D6433–2011 standard recommends that each region should investigate and assess road areas from 33% to 50%. The standard identifies 19 road surface diseases and further classifies the diseases according to their density and severity and calculates the corresponding scores based on the data contained in the tables provided by the standard. For example, the three curves in Fig. 3 represent the deducted scores for three different diseases: high, medium, and low, respectively. Based on the density of a particular sample unit's disease, the calculated score for the pavement condition index (PCI) can be used throughout the region.

MicroPaver is a software program that collects PCI findings as input and performs pavement condition calculations. In addition, it is equipped with a pavement management system, that is a pavement degradation model, cost budget analysis, and a cost-benefit analysis system.

While using the value of PCI in the ASTM D6433–2011 standard, check that the equipment does not transfer and inspect images automatically, as the non-contact sensor device is not very advanced. Until now, automation detection only takes high-quality images of the road, and then relies on artificial assessment of the relevant images to determine the road conditions. The PCI approach has numerous limitations such as: it is time-consuming, causes obstruction of traffic, involves high security risk for inspectors, and has a need for highly trained professionals with limited accuracy (e.g. each street has a single PCI value at an intersection), and the condition below the pavement is completely ignored. It is necessary to derive the structural characteristics below the road surface in combination with some measurement systems based on the physical, acoustic, or electromagnetic properties. Macrostructure and international flatness index are widely used to assess road roughness and driving comfort.

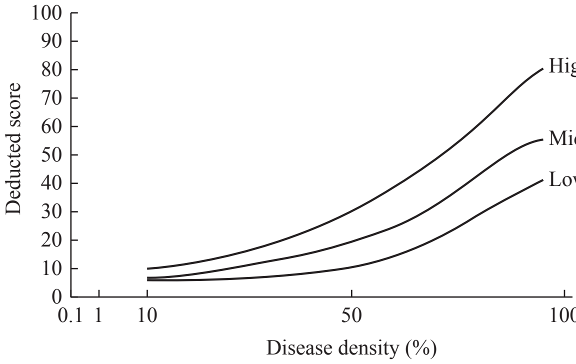


Fig. 3. Deducted scores for different disease densities.

4 Non-destructive testing technologies for road surfaces

Due to advancements in technology, data collection and analysis of pavement management systems has improved from manual methods to automated methods. Automated data acquisition and analysis started in the United States. Although automation technologies are costly, errors caused by manual methods can effectively be avoided, and data acquisition can be done without disrupting traffic. These advantages make automation technologies very popular. The main equipment for data collection is an optical camera mounted on the back and side of a vehicle that allows continuous capturing and saving of images so that technicians could analyze images offsite and use the data to estimate road diseases [4]. However, there are many unfavorable factors, such as shading, lighting, sharpness, etc., which can affect the quality of the images captured. With the widespread use of automatic data acquisition technologies, the ASTM D6433–2011 standard has been upgraded to the ASTM D5340–2012. To date, many agencies use automatic acquisition of digital street images through optical cameras that can be manually evaluated once the data has been collected. Related agencies use MicroPaver and other software, such as StreetSaver or Cartegraph to calculate PCI values to meet the needs of further pavement analysis.

4.1 Falling weight deflectometer (FWD)

FWD was developed in Europe, and has been used in the United States since the 1980s. The FWD is an instrument used to measure the physical properties of pavements. It is composed of a power supply, control system, susceptor, deflection sensor, data storage, and processing system. The FWD test is a non-destructive testing procedure that not only detects diseases quickly but also does not require the removal of the pavement material, as shown in Fig. 4 [5], so it is more popular than other destructive methods. The ASTM C131–2014 standard [6] stipulates that in the measurement of road deflection values, the test vehicle should stop, and that the carrier plate should be above the test position. Therefore, the FWD is an intermittent driving measurement that involves normal travel from one measuring point to another measuring point, with the vehicle stopping upon reaching a measuring point. The FWD method uses a dynamic load on the road surface to simulate a single wheel load. The deflection unit in each measurement position is in the micron range, as shown in Fig. 5. The method can measure the road vertical deflection response when an impact load acts on the road surface. When using FWD for testing, the main factors that affect the deflection are the thickness of the pavement, the type of material in each layer, the quality of the material, the support of the subgrade, environmental factors, the discontinuity of the pavement, and the type of pavement structure. The FWD testing equipment requires regular maintenance that will improve equipment performance and service life, making the measured data more reliable.

Based on the operational principles of the FWD, the Dynatest Company in Denmark proposed an improved device in the late 1990s: the rolling-type deflectometer (RWD). The purpose of the RWD is to test the road at normal speeds without blocking traffic. The latest RWD was introduced in 2003, as shown in Fig. 6 (a). It consists of a 16.2 m long trailer with a standard two-wheeled assembly that applies an 80 kN standard load to the pavement structure on the rear single axles. The RWD adopts a method of overlapping wheel tracks to test the deflection in the direction of tires on the road surface. The procedure involves first recording the deformation of the road surface without tire deflection, and then taking the laser readings of each test point. On the root aluminum beam, measure the road surface every 2.6 m. The system has a measuring range of 100 mm and an accuracy of ± 0.0245 mm. At run time, the data of deformation and non-deformation state are collected by means of coincidence of space. Through the 3D finite element analysis method, the parameters of springback modulus can be obtained well, which can reflect the bearing capacity and life cycle of pavements (Fig. 6(b)).

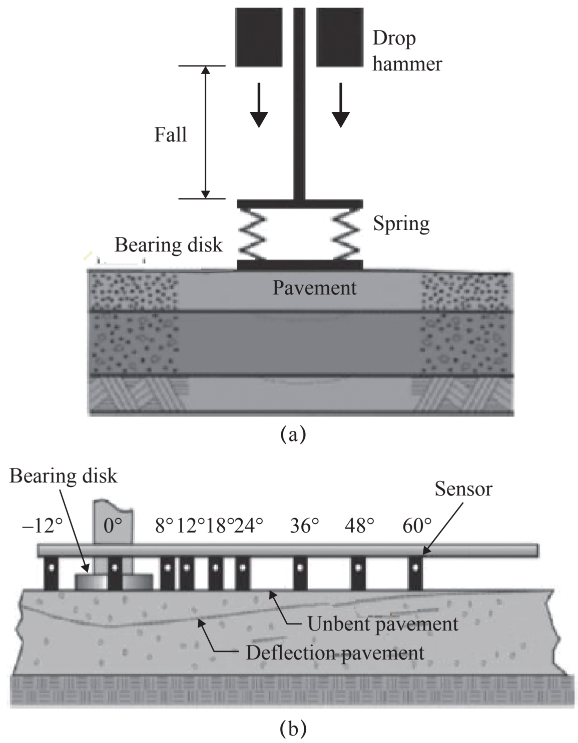


Fig. 4. FWD device composition diagram.

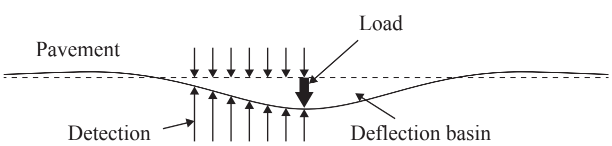


Fig. 5. FWD load and deflection measurements.

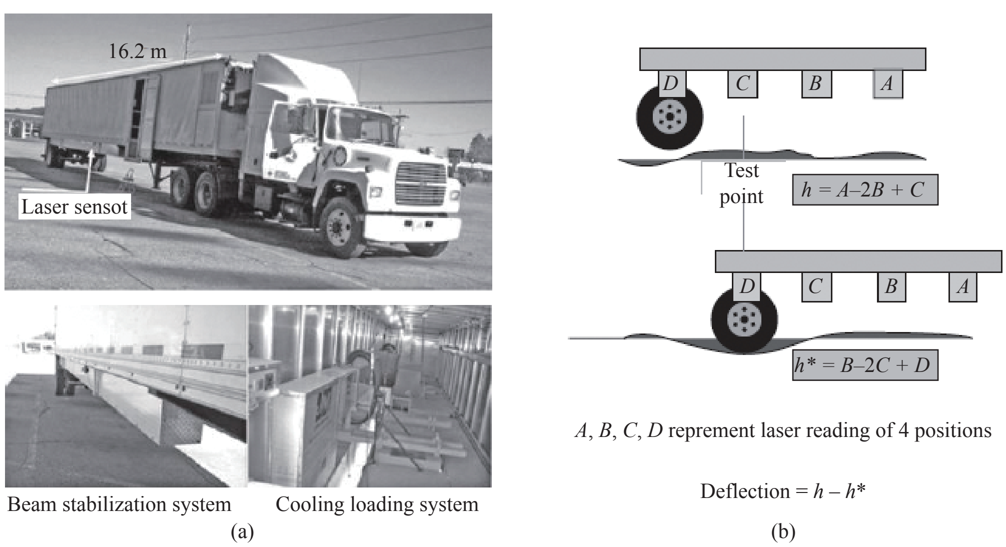


Fig. 6. RWD test principle and equipment.

4.2 Ground-penetrating radar (GPR)

GPR is an electromagnetic wave method that employs a high-frequency pulsed electromagnetic wave for the detection of the geological structures of a target internal structure. It can provide high-resolution two-dimensional and three-dimensional underground images. The electromagnetic waves emitted by the antenna propagate in the material, where the speed of propagation is determined by the dielectric properties of the material. If an electromagnetic wave encounters a buried object or reaches the boundary of two materials with different dielectric properties, part of the energy of the electromagnetic wave is reflected back to the surface and the remaining part continues to propagate downwards. The antenna receives the reflected wave and records the data in a digital storage device for analysis.

Single-frequency GPR pavement detection is one of the earliest technologies applied to livelihood projects. The single-frequency GPR accurately draws the layers of the road without blocking traffic. Loizos et al. [7] showed that a GPR system with different frequencies was used to test the pavement layer, with the reliability of the system deeply studied by comparing the test results with the actual situation of the pavement. The dielectric constant of pavement materials can be calculated through the wave velocity in each layer of pavement or the reflection coefficient of the pavement. Reflected waves may interfere with each other if there are too many layers of pavement, requiring special data processing methods to extract the layer information.

4.3 Macrostructure depth (MTD)

The MTD of a pavement is the average depth of the open voids in the uneven contact surfaces between the tire and the pavement. It is the level of anti-slip of the pavement (Fig. 7). The value of the MTD can be used to measure the friction characteristics of pavements (skid resistance) and to detect the bleeding, separation, or non-uniformity of asphalt concrete during pavement construction. Low MTD means that the surface is smooth, while high MTD means that the surface is rough.

“Sanding method” or “volume repair method” is the traditional method for measuring the MTD value in the ASTM E965–2001 standard [8]. This method uses the MTD value to characterize the macroscopic structure of the surface. It was originally designed by the British Institute of Transport and Roads and is greatly influenced by man-made operations and should not be used in wet weather. Nowadays, the more commonly used method is the laser profilometry method that is a more advanced, safe, and economical method. ASTM E2157–2009 [9] proposed a method using a circular orbit to measure and evaluate the macroscopic structural characteristics of the actual pavement in the laboratory and on the road.

The MTD is generally measured by laser profilometry, scanned by a motor-driven sensor, while the horizontal and vertical components are collected to obtain the profile data for the measured road surface.

Northeastern University (NEU) has developed a more convenient method: the use of noise from moving vehicles to estimate MTD values; the greater the noise, the greater the MTD value. For example, if the MTD value of the road surface measured by a laser profilometry is 0.5 mm and the noise of the tire and the road surface is 3.2 dB, and the MTD value of a different road surface is 2.5 mm and the noise is 9.6 dB, then the median interpolation method can be used to estimate the MTD value when the noise is between 3.2 and 9.6 dB. Fig. 8 shows a photograph of the test road. In order to verify the accuracy of the method, the MTD value of each road surface was measured by laser profilometry, and then compared with the estimated MTD value from NEU. As shown in Table 1, the MTD values from the two methods are very close, which proves that the method is feasible.

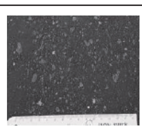
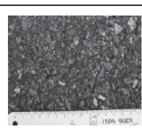
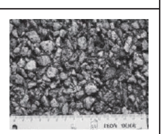
MTD (mm)	0–0.4	0.4–1.2	>1.2
Physical meaning	Poor	General	Good
Specimen surface			

Fig. 7. Physical meaning of the macroscopic structure of roads (measuring ruler length = 15 cm).

4.4 International roughness index (IRI)

The IRI was proposed by the World Bank in 1986 and is now widely used. The index shows how comfortable drivers and passengers are in a moving car. The IRI value is usually measured by a quadrant vehicle (also called a golden car), as shown in Fig. 9, where the measured distance is longer than 160 m (about 0.1 mi). The vehicle travels on the road at a specified speed to analyze the cumulative vertical displacement of the dynamic reaction suspension within the travelled distance.

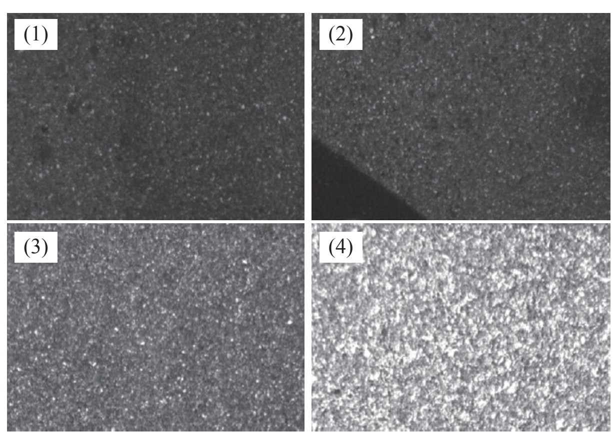


Fig. 8. Photo of the test road.

Table 1. Comparison of the laser profilometry and forecasting methods for computing MTD values.

Test method	Pavement (1)	Pavement (2)	Pavement (3)	Pavement (4)
Laser profilometry method for measuring the MTD value (mm)	0.5	0.9	1.2	2.5
Predicted MTD value (mm)	0.38	0.96	1.08	2.63

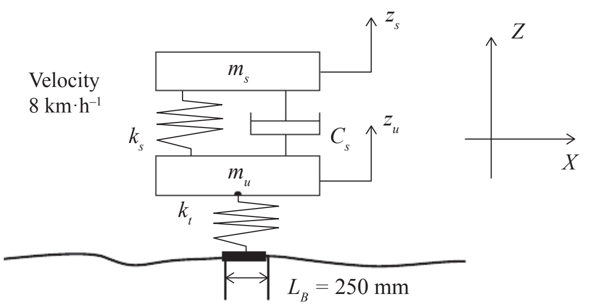


Fig. 9. Quadrant vehicle model.

In Fig. 9, k_s is the stiffness coefficient of the suspension spring; C_s is the suspension damping rate; k_t is the fatigue spring stiffness coefficient; m_u is the spring load (part of the body mass of the wheel support); m_s is the mass beside load (wheel, tire, half axle/suspension); L_B is the contact length of the tire with the road surface. The road has a given geometry as the quadrant vehicle moves on it. The geometry of the road surface is used as an input value to move the spring of the model car up. The spring movement gives the measuring system two degrees of freedom. The value of IRI can be calculated as:

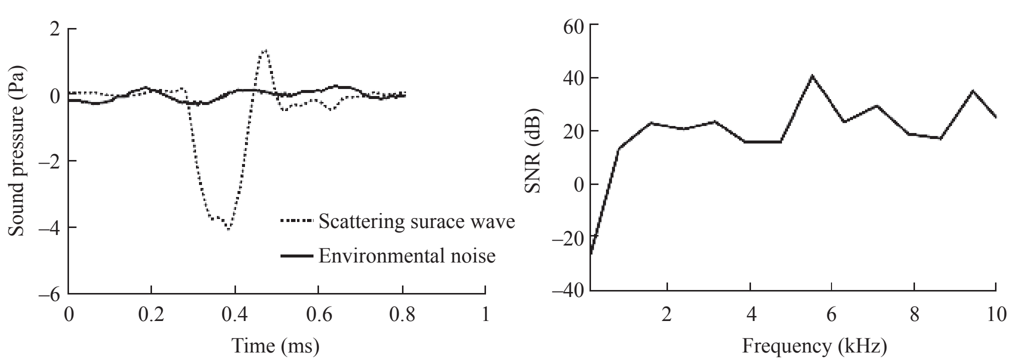
$$IRI = 1L\int_0^{L/V}|\dot{Z}_s - \dot{Z}_u|\mathrm{d}t \tag{2}$$

in formula (2), $\dot{Z}_s$ is the differential of the spring load center of gravity (vertical coordinate), $\dot{Z}_u$ is the differential of the mass beside the load center of gravity (vertical coordinate). When calculating the *IRI*, the relative movement is determined by the forward distance moved. There are two main ways to obtain the *IRI* value while measuring the outline of the road: manual measurement and traverse measurement. Manual measurement requires a person to push a stroller to measure the *IRI* while traverse measurement uses profiler and accelerometer measuring vehicles, whereby the speed is the drive speed. The road profile is calculated from the double integral of the measured acceleration.

4.5 Spectral analysis of surface waves (SASW)

Since the 1980s, China has been studying the SASW method [10] that has been developed and applied to many projects [11]. The SASW method is widely used in underground exploration and geological experiments instead of the traditional surface wave method. The traditional surface wave method is time-consuming and blocks traffic, and the sensor must be in contact with the road surface and needs to be repositioned for each measurement. The working principle of the SASW method is as follows: the impact load is applied, the dispersion characteristic of the surface wave propagating in the soil is measured using the phase difference between the two sensing channels, the dispersion curve is obtained through data transmission, and the shape of the soil is estimated through the inversion procedure and shear velocity. Based on this principle, Northeastern University developed a non-contact sensor for fast air-coupled surface wave analysis that can detect underground conditions at normal walking speed, and that greatly improves the detection accuracy. Currently, the prototype system is mounted on a three-wheeled cart, with an array of microphones mounted beneath the cart, where each microphone isolates ambient noise using acoustic foam. The hammer used in this system provides an adjustable and traceable source of impact. Typical sound signals from the surface waves and the signal-to-noise ratio (SNR) from the system are shown in Fig. 10.

The prototype was tested at a construction site in Rowley MA, Boston, USA, with an asphalt pavement for example drilled through the site as shown in Fig. 11(a), with the result shown

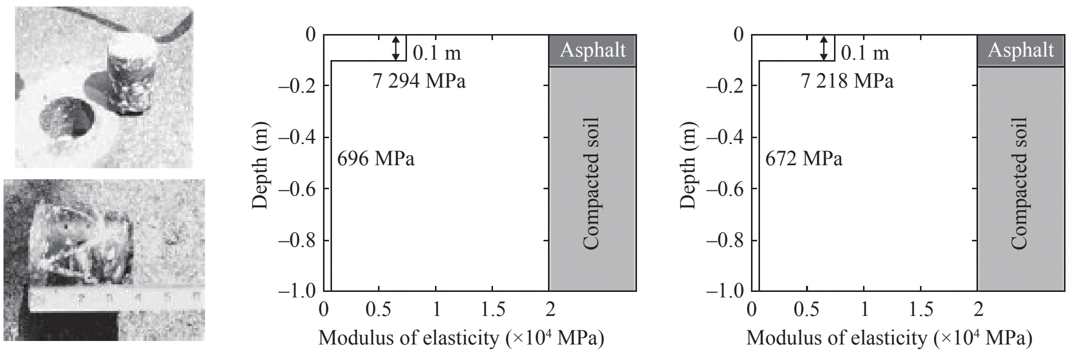


(a) Acoustic time domain signals and ambient noise (b) SNR of the system

Fig. 10. Typical SNRs on-site.

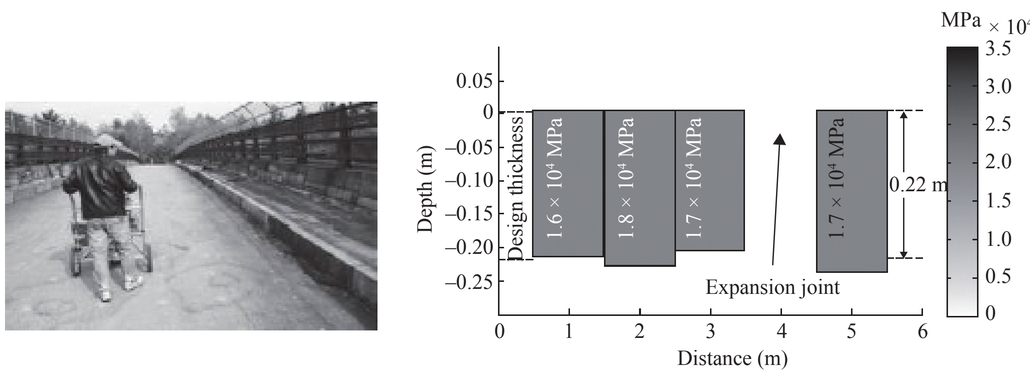
in Fig. 11(b). The results of trolley measurements are shown in Fig.11(c). Another on-site test was the bridge deck test at the Pingree Bridge in Rowley MA, with a deck 5 m in width. The test vehicle was run at walking speed, with continuous scanning method and measuring widths of 1 m each, as shown in Fig. 12(a), and a measured depth of 0.22 m. The test results are as shown in Fig. 12 (b). The measured results showed good agreement with the bridge design literature, while the scene test results proved that the new trolley SASW method has the capability for underground inspection.

Table 2 provides a summary of commercial sensing technologies for pavement condition evaluation, while Table 3 shows



(a) Site drilling (b) Test results (Left: site drilling; Right: prototype vehicle)

Fig. 11. On-site testing of the prototype vehicle on asphalt roads.



(a) Prototype vehicle field (b) Test results

Fig. 12. On-site testing of the prototype car on the bridge panel.

Table 2. Commercial sensor technologies for the evaluation of road conditions.

Position	Commercial sensing technology	Measurement standard
Pavement surface	Sonic and ultrasonic technology	Longitudinal roughness Rutting depth
	Laser profiler	Longitudinal/transverse cracks, longitudinal rupture of joints, surface texture
	Video imaging technology	Surface cracks Quantification of disease data
	Computer storage system (database)	Pavement condition index forecast Pavement disease condition storage
	Lock wheel method (such as dynamic friction tester)	IFI Skid resistance
	Multifunctional pavement evaluation car (such as ROSAN system)	MTD, IRI Pavement shape, surface texture
	FWD	Single layer elastic modulus for multilayer systems
Below the surface	SASW method	Pavement modulus and layer thickness
	GPR technology	Layer thickness, dielectric constant, positioning reinforcement
	Thermal Infrared Imaging Technology	Void detection, stratification
	IE technology	Cracks, delamination, stripping, voids

Table 3. Commercially available products/companies for non-destructive testing: features, advantages, and disadvantages of evaluation methods.

Company name	Non-destructive testing method	Main function	Advantage(s)	Disadvantage(s)
Victoria as digital image technology (Shenzhen) Co., Ltd.	Optical camera	Pavement damage detection	Acquisition speed	Manual assessment, post-processing workload
American SSI company	CS8800 hand-push section instrument	Pavement roughness testing	For road, airport, ground and other special applications	Low efficiency, the maximum rate is the walking speed of the operator
American ICC company	Inertial Laser Profiler	Pavement roughness testing	Non-contact measurement	Low accuracy
American ICC company	APRES-K vehicle-mounted rut automatic detector	Road rut detection	High-speed, continuous testing, high reliability, safe operation, does not affect the normal passage of vehicles	Expensive, high cost of testing
American K.J.Law	Falling weight deflectometer	Road capacity test	Dynamic detection, high efficiency	Poor stability, susceptible to external
Canada Sensors & Software	GPR	Use radio waves to determine the subterranean media	Rapid detection of pavement thickness, non-destructive, efficient	Lack of supporting technology
Northeastern University	SASW	Estimate the thickness and elasticity of the basement	Do not block traffic, do not damage the road, high precision, high efficiency	The number of computation iterations, the test rate is low

the features, advantages, and disadvantages of commercially available non-destructive testing products. With its vast territory, China needs to develop non-destructive testing techniques to measure the vast network of road networks in order to deal with future maintenance issues.

5 Conclusions

Existing road surface automatic detection systems essentially adopt on-site inspection and off-line analysis. Undoubtedly, this method needs to be optimized and improved. The realization of a complete, rapid, and automatic identification of road damage images detection and ensuring of a fairly high accuracy are components of a technical problem that the relevant scholars need to solve urgently. This article outlines several non-destructive testing techniques that are in use in foreign countries as well as those that have been developed in China. In addition, it introduces the representative testing techniques in detail, points out their shortcomings, and lists the commercially available domestic and foreign non-destructive testing products. It equally enumerates the advantages and disadvantages of each company's products to guide the relevant personnel concerned with the actual project in making a reasonable selection. China should continue to expand the road network monitoring system and implement real-time monitoring on the basis of non-destructive testing technologies. Finally, the continuous improvement of the technologies for the non-destructive testing of roads, bridges, and the detection of other infrastructure diseases will significantly improve the life expectancy of these infrastructures.

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