Evaluation of In-Situ Resilient Modulus Testing Techniques

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Abstract

A series of field experiments has been conducted to evaluate various non-destructive testing techniques, which attempt to determine the resilient moduli (RM) of pavement layers. Nuclear density gauges have been used as a standard quality control device in pavement construction. However, in pavement design, RM of pavement layers are used instead of density. Apparently, a link between the design and construction of pavement structures is missing. The main reason for the missing link is the lack of appropriate tools to determine the in-situ resilient moduli.

Approximately 100 field stiffness tests on different subgrade and base materials over 6 Texas Districts (Fort Worth, Pharr, Atlanta, Abilene, Austin and El Paso) were conducted in this study. Several innovative tools, such as the Humboldt Stiffness Gauge (HSG), Dirt Seismic Pavement Analyzer (D-SPA), Falling Weight Deflectometer (FWD), and Olson Spectral Analysis of Surface Waves (SASW) were employed. The Nuclear Density Gauge was used to explore the opportunity to establish an empirical relationship between stiffness and density. It is found, based on the test results, that all of these testing techniques are able to differentiate the quality of pavement layers in terms of RM values. The HSG and D-SPA have a great potential to be used as inspection devices because of their simplicity, sensitivity, and ability to measure the mechanical behavior of base and/or subgrade soils. The HSG is the easiest device to use when measuring a single layer. The FWD and seismic techniques are more comprehensive, and are able to yield the stiffness profile of a pavement system. Some technical background is required to interpret the results obtained by both FWD and seismic techniques. A criterion to evaluate the quality of base materials using HSG, D-SPA, and FWD is proposed.

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Introduction

Traditionally, engineers have specified density (or a percentage of the lab density) and moisture content as the primary quality control guides for pavement structures [1]. However, in pavement design, the resilient modulus (RM) is used to determine the required layer thickness of a pavement structure. Density and moisture content are not usually in the pavement design equation. Density and strength are very different material characteristics, even though density is a good indicator of the strength of granular materials in the construction of pavement system.

Experience from daily operation of the Nuclear Density Gauge (NDG) indicates that it can be a slow and labor-intensive process, especially when the base materials contain large aggregates of size greater than one inch. There are many safety concerns and much paperwork associated with the operation of an NDG. The presence of certain mineral compounds in the soil can render density and moisture measurements inaccurately, especially if the NDG calibration is not performed prior to taking measurements at each construction project.

For the purposes of quality control and tying results into design practice, a device that can provide the stiffness of the pavement layer is a rational choice. Currently there is no field equipment designed to determine the resilient modulus of base materials or subgrade soils for construction quality control purposes. Falling Weight Deflectometers (FWDs) have been widely used in pavement engineering. However, the FWD device is designed to be applied after the surface concrete or asphalt concrete treatment is completed. If the stiffness of the base and/or subgrade do not meet design values, it is too late to take remedial action after the surface treatment is completed. Therefore, unless FWD testing and analysis procedures are modified, the FWD will not be suitable for routine quality control checks.

The objective of this study is to evaluate the existing technologies that may be used to measure the in-situ RM of base and subgrade materials. Several innovative tools, such as the Humboldt Stiffness Gauge (HSG), Dirt Seismic Pavement Analyzer (D-SPA), and Olson Spectral Analysis of Surface Waves (SASW) were employed. To provide a basis for comparison, the FWD and nuclear density gauge were applied at the same locations. Approximately 100 field stiffness tests on different subgrade and base materials over 6 Districts (Fort Worth, Pharr, Atlanta, Abilene, Austin and El Paso) were conducted. All testing for this study was conducted after the subgrade and/or base was prepared, and before the surface-course treatment was applied.

Humboldt Stiffness Gauge (HSG)

The Humboldt Mfg. Co. provided the stiffness gauge (HSG) used in this study. The gauge is about 280mm in diameter and 254mm tall, as shown in Figure 1A. It weighs about 0.11 kN. The principle of operation of the HSG is to generate a force P and to measure the corresponding displacement δ. The ratio $K = P/\delta$ is the stiffness of the soil. The HSG generates a very small dynamic force at frequencies of 100 to 200 Hz. This produces a very small deflection that is measured by a geophone within the body of the gauge. The HSG is powered by a set of D-cell batteries.

The deflection produced from equipment operating nearby will not affect the HSG measurement, because the HSG operation frequency is from 100-200Hz. Any signals generated below those frequencies can be easily filtered out. Note that the frequency generated by traffic (at highway speed) is approximately 30Hz, and the operating-equipment frequency is well below 30Hz. The stiffness gauge is calibrated on a theoretical basis by shaking a known mass body attached to the bottom of its contact ring. By measuring the deflection of this mass under the known vibrating force, the HSG compares the measured stiffness to the expected value, and a correction is made in the computation (embedded software).

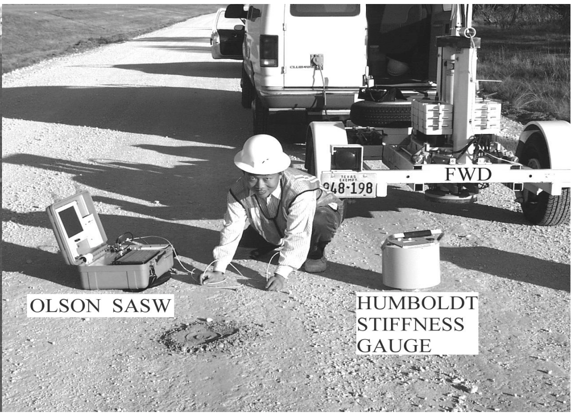
Operation of the stiffness gauge is simple, usually requiring only the push of one button per test. The most important aspect in using HSG is to have a flat and smooth contact with the ground. Occasionally a sprinkling of sand onto coarse materials is required to get smooth contact. The measurement takes about 2 minutes per point. This inspection rate and its non-destructiveness make it possible to conduct a much more thorough quality-assurance test during the construction of a pavement structure than the current process of using a nuclear density gauge.

D-SPA and Olson SASW

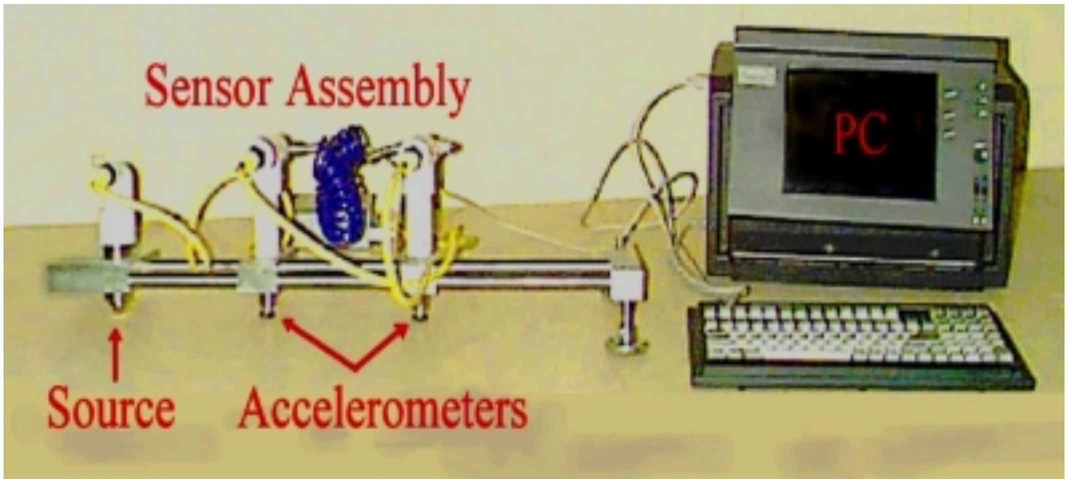
The Seismic Pavement Analyzer (SPA) was designed for a comprehensive diagnosis or evaluation of a pavement structure [2]. It was designed and developed by Dr. Soheil Nazarian of the University of Texas at El Paso. For quality control purposes or for routine operation, the portable version of the SPA, or PSPA, is more practical. The original PSPA was designed to operate on paved roads [3]. A revision of the P-SPA called D-SPA, or “Dirt” SPA, is now available for operation on rough bases or subgrade, as shown in Figure 1C. The D-SPA was the device used in this study.

The SPA is based on the velocity of a Rayleigh wave through a material, which is proportional to it's Young's modulus and density. By measuring the wave velocity, which is done by recording the wave arrival time at two different locations, (a known distance apart) the modulus is determined. One of the difficulties in doing so is in separating the arrival time of Compressive (P), Shear (S), and Rayleigh (R) waves. Also, the modulus obtained from this calculation is a composite value. Spectral analysis of a surface wave will distinguish a wave by Fast Fourier Transformation (FFT). FFT decomposes a wave into sub-waves or wavelets having different wavelengths. Through the FFT process, moduli can be computed at different depths within the pavement structure. Sharp changes in modulus with depth can help to determine layer thickness or the presence of defects. Generally, FFT provides more technical information than does the direct computation of arrival time. It allows the computation of a dispersion curve, or plot of wave velocity vs. wavelength. A velocity-to-modulus conversion, applied to a dispersion curve, provides a profile of modulus along the depth of a pavement structure. A typical dispersion curve is presented in Figure 2 for the US380 project (Abilene District) on top of the subgrade. Figure 2 shows the repetitive test results at the same location measured by the Olson SASW.

(A) HSG



(B) Olson SASW, HSG, and FWD



(C) D-SPA

Figure 1. Field Testing Equipment for I-20 Project on Top of Base: (A) Humboldt Stiffness Gauge (HSG); (B) Olson Spectral Analysis of Surface Waves (SASW), HSG, and Falling Weight Deflectometer (FWD); (C) Dirt-Seismic Pavement Analyzer (D-SPA)

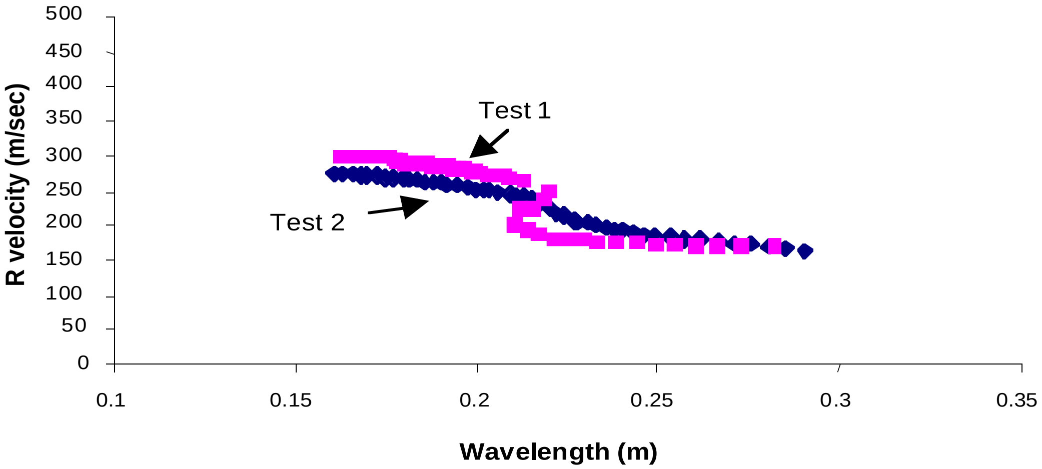


Figure 2. Dispersion Curve for US380 Project (Subgrade)

FWD and Nuclear Density Gauge

The Falling Weight Deflectometer and Nuclear Density Gauge are two other devices used in this study. Both devices are commonly used, and their working mechanisms are not repeated here [4].

Test Results

At each construction site, the HSG and Olson SASW measurements were taken at 3 to 5 locations. At each location, a minimum of three measurements were performed to determine the repeatability of each test. At the same locations, resilient moduli were also measured by the FWD. The physical state of the soils was determined by a nuclear density/moisture gauge. Not all sites have been tested with all four devices listed above, because of the difficulty of testing on overly loose or soft soil, and the availability of the equipment. The following is a summary of the test results.

Correlation between Stiffness and Resilient Modulus by FWD

FWD is the most common device among all of the non-destructive testing devices used in this study. Back-calculated moduli from FWD data have been used extensively in pavement design and other management activities. Thus, FWD moduli provides a basis for comparison with moduli from the HSG. Although using the FWD directly on top of base or subgrade might induce nonlinear displacement, a linear-elastic program was used to compute the layer moduli. The intent of this study is not to change the FWD back-calculation procedures, but to find whether or not the HSG and D-SPA technologies can be used for quality control purposes. To develop a more theoretically sound equation, a comprehensive nonlinear program needs to be used to back-calculate the layer moduli.

The relationship between back-calculated resilient moduli from FWD test results and direct readings from the HSG is presented in Figure 3A. Measurements were taken at 3 to 5 locations per test site, and the median or most reasonable single resilient modulus was selected. Though the data is limited, a general relationship between the stiffness and resilient modulus (by FWD) was found. For an HSG reading of 10 MN/m, the FWD back-calculated modulus is approximately 140 MPa (20 ksi). Quality of base layers can be categorized by FWD or HSG results as shown in Table 1. The corresponding shear wave velocities (V_s) for different quality bases are also shown.

Table 1. Base Quality Using Different Testing Techniques

Base Quality	HSG (MN/m)	HSG (MPa)	V_S (m/sec)	FWD (MPa)
Weak	<10	<87	<250	<140
Good	18-24	156-208	300-350	310-450
Excellent	>30	>260	>400	>700

A subgrade with an HSG reading of 10 MN/m can be classified as “good,” while a reading of 20 MN/m indicates an excellent subgrade.

Almost all project engineers and inspectors want to know how well the pavement structure was built, as compared to the design. Since there currently is no stiffness-measuring device for routine field application, the HSG would help to evaluate the quality of constructed base and subgrade in order to better make a decision on project acceptance. A project engineer or inspector can check the quality of each pavement layer as it is constructed. Note that the HSG manufacturer (Humboldt) recommends that this equipment be used only up to 23 MN/m.

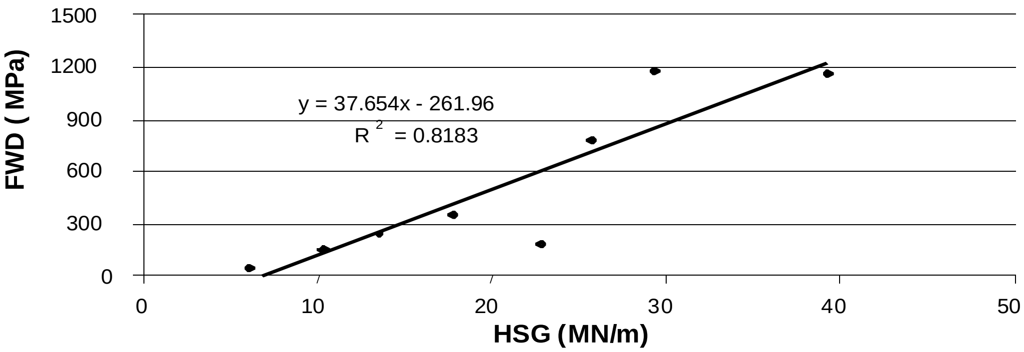
CNA Consulting Engineers (of Minneapolis, MN) proposed the following equation to convert stiffness to modulus:

$$E_h = H_{rg}*K*(1-\nu^2)/(1.77*R) \tag{1}$$

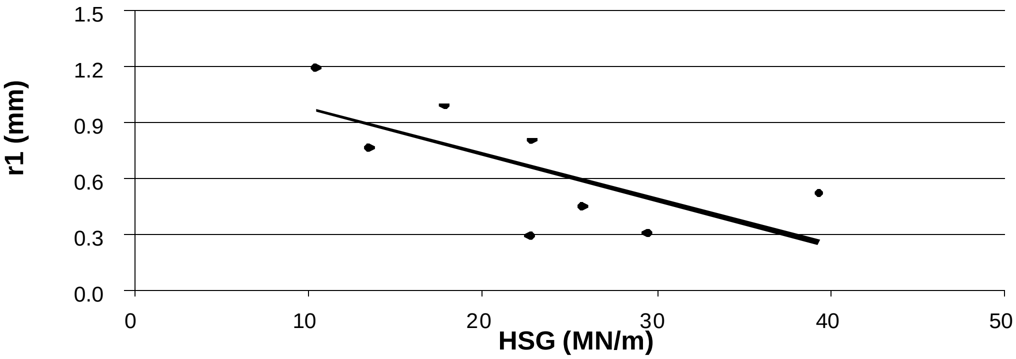
Where E_h is the modulus in psi, H_{rg} is the reading from the HSG, in MN/M, K is a constant (5709 in this case), ν is the Poisson's ratio, and R is the radius of the HSG's foot (2.25 inches)

For a Poisson's ratio of 0.35, a factor of approximately 8.67 can be used to convert the HSG stiffness (in MN/m) to a resilient modulus (in MPa). Still, the moduli converted from HSG readings tend to be lower than those from the FWD. A previous study by Chen et al. (1999) [5] also found that base moduli from the FWD are higher than those from the HSG. The authors believe that further research work is required to provide a solid relationship between resilient moduli back-calculated from FWD data and the HSG stiffness values. The primary reasons for this are the inaccuracies associated with FWD moduli back-calculation and the fact that the HSG may lose accuracy when measuring stiffness greater than 23 MN/m.

An effort was made to compare the FWD measurements with those from the HSG. The r1 deflections (deflections at the center of the load) taken at the FWD's second drop height were normalized to a load of 40 kN. A fair correlation between the r1 deflections and the HSG readings was observed, as shown in Figure 3B. As expected, higher stiffness values correspond to lower deflection measurementsThis shows that the HSG technology could be applied to measure the stiffness of the base and subgrade.



(A) HSG Stiffness vs FWD-Determined Modulus



(B) HSG Stiffness vs Maximum (r1) FWD Surface Deflection [Normalized to 40 kN]

Figure 3. Field Test Results from Six Districts: (A) HSG Stiffness vs FWD Modulus; (B) HSG Stiffness vs Maximum (r1) Surface Deflection [Normalized to 40 kN]

Correlation between Stiffness and Resilient Modulus by Seismic Technologies

Results from the D-SPA and Olson SASW were compared with the results from the HSG. Since the principles used by these two machines are the same, the moduli obtained by the D-SPA and Olson SASW are not distinguished in this paper. The comparison study between D-SPA and Olson SASW shows that the results from these two devices are similar.

The computation of seismic modulus from velocity is as follows:

$$E_s = V_s^2 * \rho * 2 * (1 + \nu) \qquad (2)$$

and

$$V_s = (1.06\sim1.1)\ V_R \qquad (3)$$

Where E_s is the seismic modulus, ρ is the mass density, V_s is the shear velocity, V_R is the Rayleigh wave phase velocity, and ν is the Poisson's ratio [6].

A Poisson's ratio of 0.35 is typical of base materials, and was used throughout the study. Figure 4 illustrates the relationship between the HSG-determined stiffness and the resilient modulus by seismic technologies (D-SPA and Olson SASW). The tests cover a wide range of materials from soft to medium-stiff subgrade to very stiff base. Linear trendlines were added to Figure 4 to provide a relation between the stiffness and the seismically-determined resilient modulus. Shear velocities less than 250 m/s indicate a very soft or weak base, and velocities greater than 400 m/s denote an excellent base, as shown in Table 1.

Overall, the relationship between the seismic resilient modulus and the stiffness value is obvious and convincing. Operation of an HSG is very simple and feasible for the purpose of quality control. However, seismic techniques provide more (stiffness with respect to depth) information.

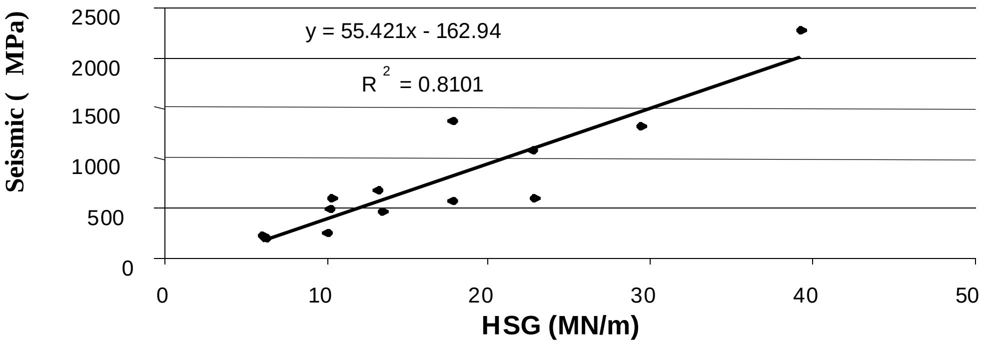


Figure 4. Relationship Between HSG Stiffness and Seismic Modulus (Field Test Results from SixTexas Districts)

Correlation between Stiffness and Dry Density

Figure 5 illustrates these relations. It can be seen that in general, the stiffness increases with the dry density. However, stiffness can be low even when the dry density is high, because of the differences in densities of the minerals which compose the base or subgrade soil. It is very interesting to note that the range of density (~50%) and stiffness (~500%) on the project sites tested are very different. A HSG is much more (~10 times) sensitive to the quality of base and subgrade soils than a nuclear density gauge.

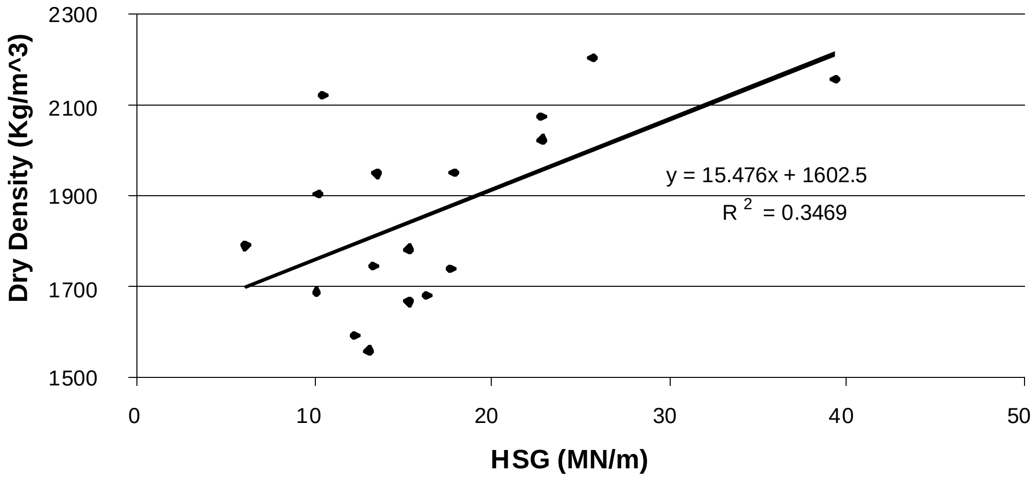


Figure 5. Comparison of Dry Density from the Nuclear Density Gauge and Stiffness from the HSG

Conclusions and Recommendations

The HSG, D-SPA, and Olson SASW were employed to measure in-situ resilient moduli of base and subgrade materials. To provide a basis for comparison, FWD and nuclear density gauge were applied at the same test site. Approximately 100 field stiffness tests on different subgrade and base materials over 6 Texas Districts were conducted. All testing in this study was conducted after subgrade and/or base layers were prepared and before the surface-course treatment was applied. Based on the analyses of test results, the following conclusions can be drawn:

- Quality control (using density and moisture content in pavement construction) is not consistent with pavement design. The test results show that density is not sensitive to a change in modulus, and the correlation with stiffness is very poor.

- Both the HSG and D-SPA posses potential to be used as quality control devices. Moduli from the HSG and seismic techniques (D-SPA or Olson SASW) were consistent with those from the FWD. The working stiffness range of the HSG needs to be modified to cover stiffer materials (>23 MN/m). Modification of the D-SPA is underway to achieve simple, fast and repeatable operation.

- Operation of the HSG is simple and fast, but only yields a stiffness value for the top layer of material. The depth of HSG measurement is typically 150mm, but varies with stiffness. Seismic techniques (D-SPA or Olson SASW) can generate a depth/modulus profile, but require (in current form) 2 days of operator training.

- HSG readings (in MN/m) of less than 10, between 18 and 24, or greater than 30 indicate that a base is weak, good and excellent, respectively. The weak, good, and excellent FWD-determined moduli are <140 MPa, between 310 and 450 MPa, and >700 MPa. Similarly, shear-wave velocities of less than 250 m/sec, between 300 and 350 m/sec, or greater than 400 m/sec indicate the same increasing quality of base layers.

- A preliminary correlation has been established between the stiffness and resilient modulus determined by seismic technology and the FWD, respectively. Additional research is required to determine a more confident relationship among these techniques.

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Keywords

Resilient Modulus, Falling Weight Deflectometer, Nuclear Density Gauge, Spectral Analysis of Surface Waves, Seismic Pavement Analyzer