Nondestructive Pavement Testing by Wave Propagation: Advanced Methods of Analysis and Parameter Management

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ABSTRACT

Wave propagation methods for the nondestructive testing of pavements use an impulsive input of force at a point on the surface of a pavement structure in order to generate surface waves. Surface waves are dispersive in layered systems such as pavements. Two accelerometers acquire the shape of the surface wave as it passes. The two wave shapes experience signal analysis to determine the details of the dispersion that has taken place. The results are used to plot the several elements of the dispersion field: the graph of wave speed versus wavelength for the pavement structure. The dispersion field is the principal product of the wave propagation test. Success in determining layer properties depends on the accuracy with which the several dispersion curves may be computed that combine to form the dispersion field for the structure. The results of analysis are found to be strongly dependent on test parameters, pavement geometry, and the signal analysis methods chosen. Current test methods and methods of analysis sometimes lead to ambiguity, phase problems with reflections, and near-field distortions. The purposes of this work were to examine, find the causes for, and seek to remedy inconsistencies displayed at intervals by the analysis. Several recommendations have resulted; one is that current broadband methods be replaced by the medium-band method; another is that a Bessel transform developed by the authors replace the Fourier transform for analysis of signals at long wavelengths. Other methods overcome the errors in phase caused by reflections.

Nondestructive pavement testing by wave propagation (NDPT/WP) has been under development in the United States for some years and several hardware systems exist. Although some awareness of the method exists, few engineers are familiar with its details. Its progress can be traced in technical reports of the U.S. Air Force and in the reports of other federal and state agencies that have contributed to the work (1-5); however, little has appeared in the literature until several recent papers by Nazarian and Stokoe (6,7). Their experimental methods have many useful features.

The NDPT/WP method is attractive in respects that have made it of particular interest to the U.S. Air Force. Although based on low levels of strain, which may cause relating the properties to performance under moving wheel loads to appear somewhat arbitrary, the method deals with fundamental parameters, the elastic constants. This means that the equipment and method may be used with structures for which there is no available history. The results, described by Douglas and Eller (8), are current in situ parameters.

Another advantage of the NDPT/WP method is that the results are from tests of a simple character, not calling for experienced operators. The data are then subjected to sophisticated signal analysis methods. NDPT/WP follows the pattern of simple test-sophisticated analysis. Also, the equipment is not expensive, and it can be transported easily by light aircraft, small vans, or even backpack.

As a result of one or more of those advantages, interest in the wave propagation method is increasing as engineers come into contact with it. Administrators at various levels of responsibility have begun to inquire how and when they might utilize the method.

However, it has taken some years to bring this method to its current state, and improvement of the method continues as expert systems built into the analysis are modified to treat new situations. This is because this application of wave propagation theory is more sophisticated than radar and the medium is not air; rather, the layered structure of a pavement is an inverted geologic structure that combines the often intractable stuff of soil mechanics with the mechanics and mathematics of both linear and nonlinear manmade materials.

This research has caused the authors to examine in detail the elements of the method of analysis. It may be useful for those not familiar with the method to follow the development of the analysis up to this time in order to see where anomalies have appeared and how the improvements mentioned will function.

INITIAL SIMPLICTY

The early form of this method is described by Jones in his work at the Road Research Laboratory in England during the 1950s and 1960s; three of his publications are particularly informative (9-11).

All of the NDPT/WP methods are based on the dispersion of surface waves in a layered medium. Surface waves remain attached to the free surface and move parallel to the surface as they expand outward from a source. They decay rapidly with depth below the

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surface. Waves with short wavelengths may be detected only in the uppermost layer, and increasingly longer wavelengths penetrate to deeper and deeper levels. The general scheme is that by using surface waves of different wavelengths, the wave speed associated with each layer could be determined; the wave speeds could then be used to find the elastic constants of each individual layer. The process is described in detail by Jones (11), Finn et al. (12), and Nielsen and Baird (1).

The analysis is built about the fundamental relationship among the wavelength (WL), wave speed (WS), and period (T), as

$$WL = WS \times T \qquad (1)$$

Instead of the period T, the time associated with the passage of a single wavelength, the relationship may be written in terms of the frequency F (the reciprocal of T) as

$$WL = WS \times (1/F) \qquad (2)$$

The first employment of an NDPT/WP system took advantage of Equation 2 in a direct manner. A vibrator generated a single frequency at a time so that F, and its inverse T, would be known quantities. In a test, an accelerometer would be moved by increments to successive locations away from the source until a series of minimum readings was obtained. These represented the nulls at the nodal points of the standing wave pattern set up by the vibrator. Thus, the wavelengths were measured, null to null to null.

The first wavelengths were associated with surface layer behavior. The next sets of wavelengths, each shorter than the one before, indicated lower speeds and were associated with the next layers down. After the structure had been explored adequately at one frequency, another frequency was selected and the process repeated. An improvement was to use an accelerometer array to trigger the array to capture the signals, then to use a Fourier transform to sort out the components of the wave, each of the same frequency and varying from the others only in wavelength (1,2).

The method was thoroughly tested and found to be successful but time consuming. The vibrator and power supply needed were large, expensive, and difficult to transport.

CURRENT METHOD

A major change took place in the mid-1970s (2): the vibrator was replaced by a broadband system based on single impulsive loading. A falling weight was used. It created many frequencies at one time, and a single thump (no other term for the impact process has stuck) would contain the entire range of frequencies needed.

In the current method, several accelerometers are arranged radially away from the source, to be triggered either by the thump or by arrival of the wave at the gauges if pretrigger capabilities exist in the recording diagnostics. Any two gauges form a gauge pair and the concept of a gaugelength (GL) between two gauges is now required.

Figure 1 shows accelerometer records from a lightly damped broadband input. The change in shape between the two records is the trademark of dispersive propagation. A linear change of size is not the same at all because it can occur as the consequence of distance of travel or through altering the gain setting of the diagnostics and does not imply dispersion. The broadband response of each accelerometer of an array is stored; a dispersion analysis can then be conducted for any two gauges.

A Fourier transform of each of the sets of data is performed, usually by FFT (fast Fourier transform) software. Two new sets of information are obtained, describing magnitude versus frequency and phase angle versus frequency for each gauge. It is phase versus frequency that is used for the dispersion analysis.

AMBIGUITIES OF ANALYSIS

The meaning of phase angle lies in the answer to this question: at a particular gauge, at the time of recording, and for a particular frequency, what was the position in time of that frequency as recording started? Was it at the beginning of the cycle? The phase angle would be zero (or was that phase angle 360 degrees?). Was it halfway along the first lobe of a sine curve? The phase angle would be 90 degrees.

Computation of wavelength is based on phase difference (PD), the difference between the phases computed for two frequencies. The wavelength (WL) comes from the relationship

$$WL = GL/(PD/360) \qquad (3)$$

and wavespeed, from Equation 2 becomes

$$WS = WL \times F \qquad (4)$$

or, in terms of Equation 3,

$$WS = (GL \times F/(PD/360) \qquad (5)$$

In Equation 3, the term (PD/360) establishes the fraction of a wavelength corresponding to the gaugelength. If the two phases differed by 30 degrees, the gaugelength would be 30/360 of a wavelength. But was the phase difference 30 degrees, or 30 degrees plus 360 degrees, or 30 degrees plus 720 degrees?

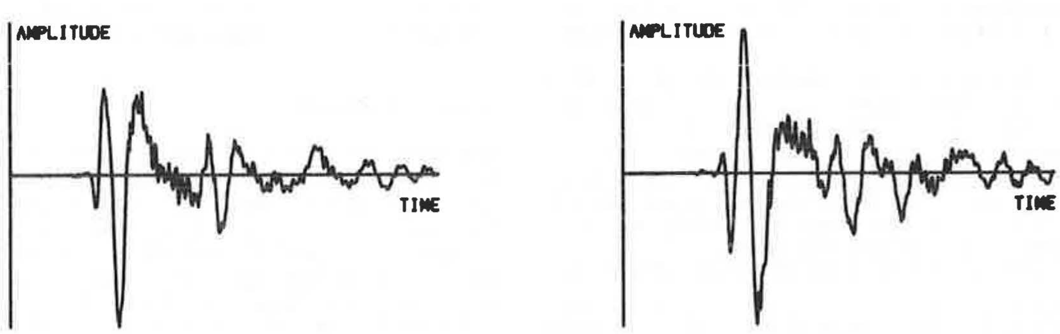


FIGURE 1 Lightly damped signals.

The individual values of phase do not disclose the phase difference uniquely. Attempts have been made to create an expert system to examine the data by using programmed rules to determine the correct value of each of the wavelengths in the broadband response, but they have been only partially successful.

Currently, this program for dispersion analysis computes the phase difference for several (selectable) of the different possible values of the phase difference, as well as the possibilities of lead and lag at each value; it also plots those possibilities. Figure 2 shows two signals captured at a gauge pair from an input with medium damping. Figure 3 shows the results obtained from an analysis of those two signals by using the authors' typical plotter output from which it is visually possible to identify the several dispersion curves that make up the dispersion field. The abscissa and ordinate are wavelength and wave speed, respectively. The lines that extend radially from the origin are lines of constant frequency. Figure 4 shows elements of the dispersion field identified by examination of Figure 3.

Figure 5 shows a choice that must be made continually. The start is at the lowest, rightmost point, moving left and up until, at the approximate coordinates (10,2500), a choice must be made: go left and up, or right and up, or left and down? In this case, go left and up. Soon it would be necessary to make another choice, then others. Figure 6 shows the high-frequency portion of a dispersion field from a different test, in which a number of choices exist.

A troublesome rule is that only one point may be chosen on a given frequency line. The signal comes to each accelerometer from different parts of the pavement structure, each segment arriving at a different time. The accelerometer reports the sum of the magnitudes of the signals it receives. The analysis and computation of phase by FFT averages the results for a given frequency. The result is some kind of average, which is sometimes erroneous.

The decisions involved in determining the family of curves in the dispersion field are based on knowledge of what is possible and what is probable, and on experience. Figure 7 shows the general geometry to be expected of the dispersion field from a structure with two layers over a half space. Jones (10,11), Vidale (13), and Watkins, Lysmer, and Monismith (14) describe the relationship of the dispersion field for simple layered structures. Figure 8 shows a line of constant frequency superimposed on the elements of the dispersion field. It shows that at each frequency, an individual accelerometer registers inputs from different elements of the dispersion field, yet the analysis can provide only a single composite value.

PROBLEM OF REFLECTIONS

Where cracks exist in a layer, or if the pavement is jointed, reflections occur and distort the dispersion field. On airfield pavements, often the entire test setup is on a single slab. Reflections from side joints and ends return quickly and after the phase values. Figures 9 and 10 show two sets of first and second gauge results from tests on a large slab, each set for the same thump and gauge pair arrangement,

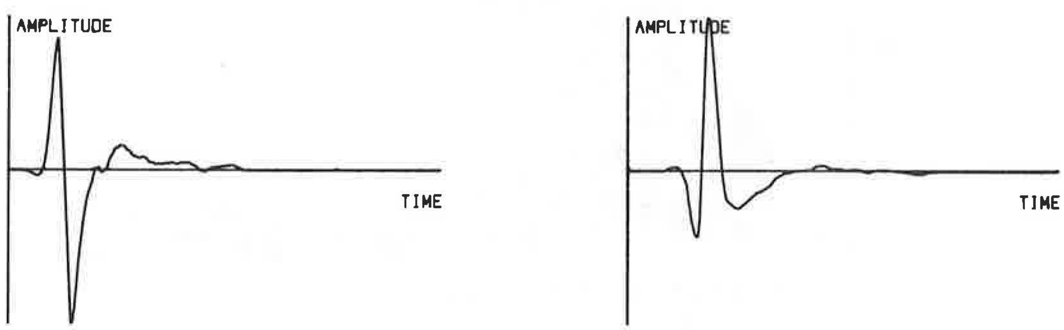


FIGURE 2 Medium damped signals.

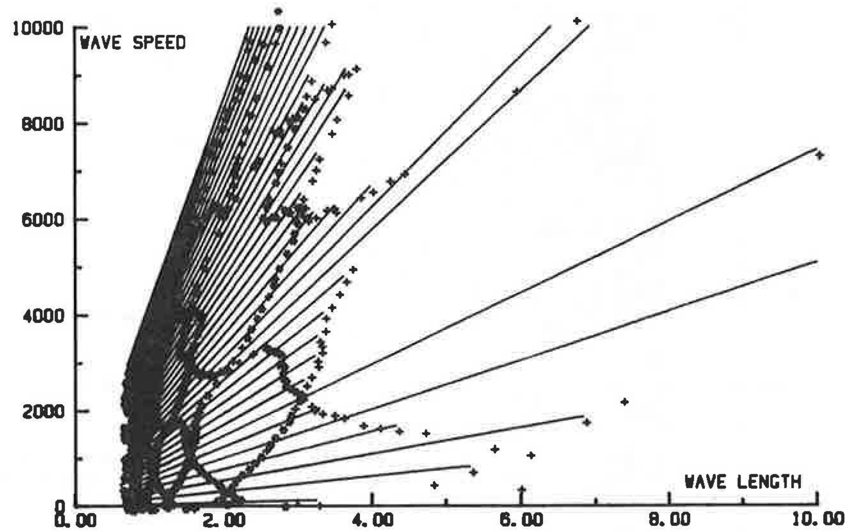


FIGURE 3 Dispersion field before identification.

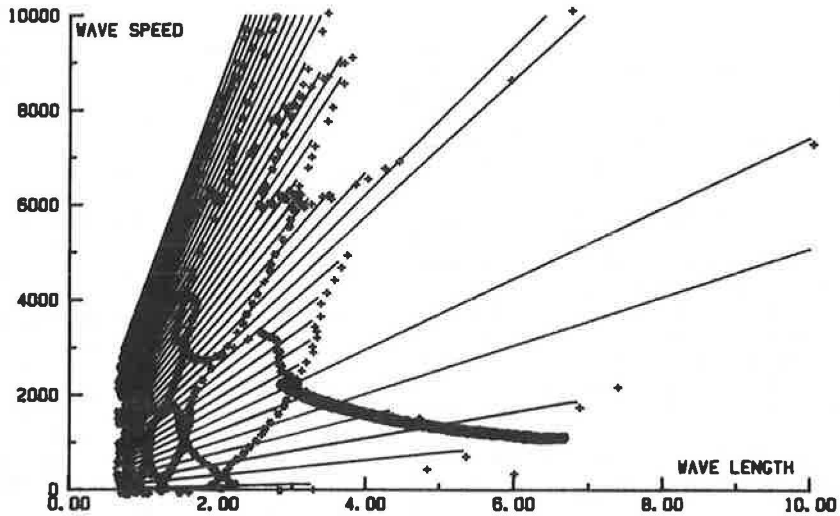


FIGURE 4 Dispersion field after identification.

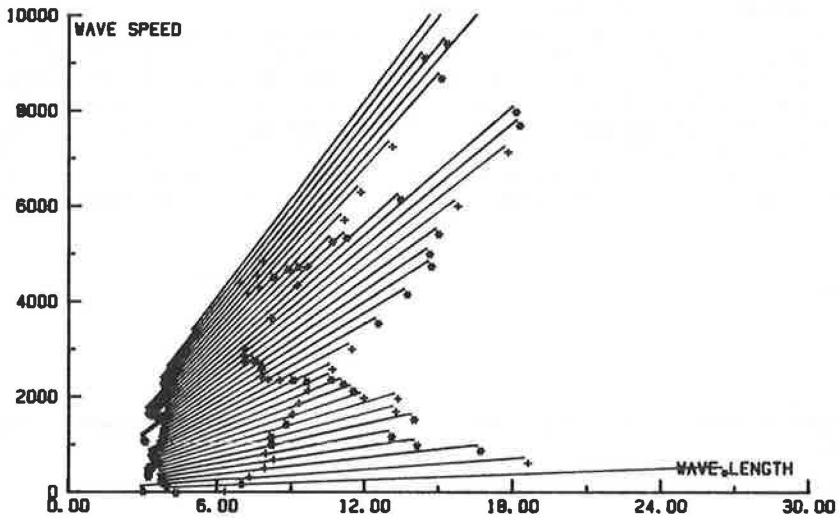


FIGURE 5 Alternate paths in a dispersion field.

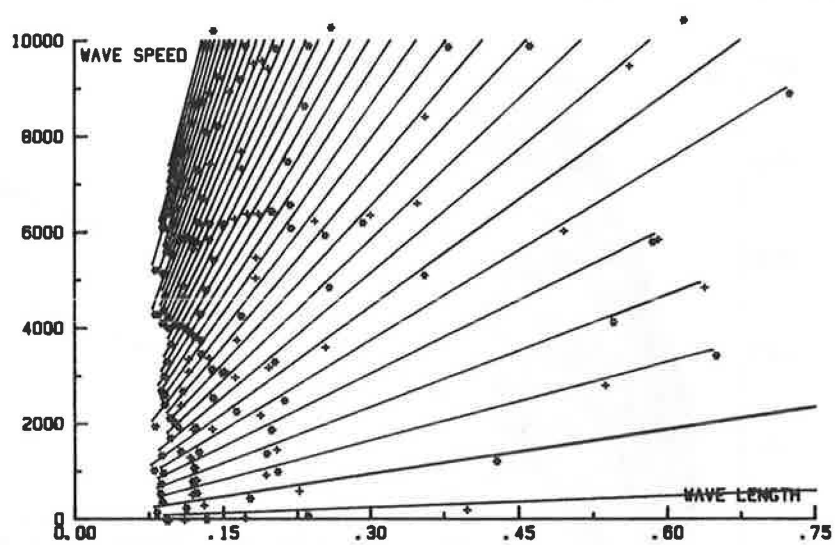


FIGURE 6 Multiple solutions.

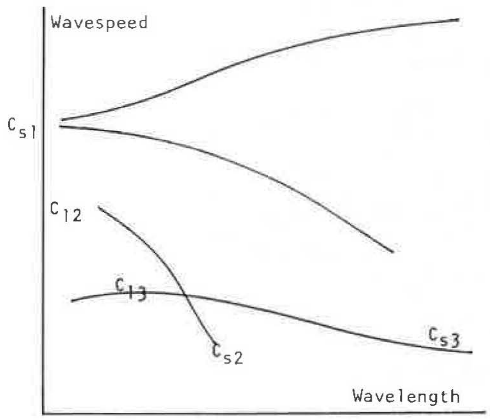


FIGURE 7 Elements in a dispersion field.

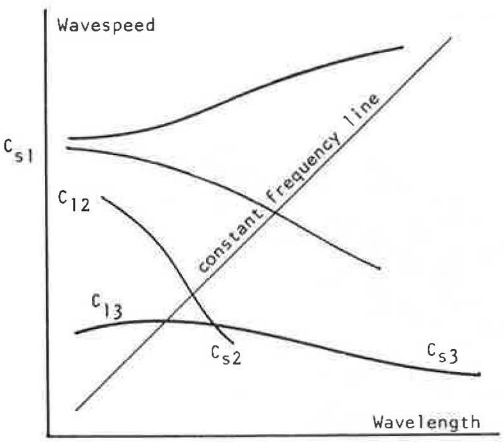


FIGURE 8 Constant frequency line.

but at different orientations with respect to the boundaries of the slab. The pavement structure was the same in each case, as were the gauge length and the thump.

Figure 9 shows records with the thump and gauges so far from the boundaries of the large portland cement concrete slab (60 ft on a side) that reflections did not return during the test period. Figure 10 shows the signals when the line formed by thump and gauges is moved close and parallel to a lateral boundary. The signals are visibly different than those in Figure 9.

Figures 11 and 12 show two dispersion fields that were computed from the two pairs of signals of Figures 9 and 10. The differences are obvious, yet the results are from the same pavement structure and should be the same. Figure 13 shows three dispersion fields from a similar test superimposed (low-frequency portions only), and demonstrates vividly the magnitudes of the errors that can result from reflections. The problem of reflections is an acute one because interpretation of the dispersion field in order to determine accurate values for the material constants depends on a dispersion field without distortion. Changes in procedure and analysis to minimize these effects are described later.

NEAR-FIELD PROBLEM

In the analysis itself, a problem is buried that can distort the dispersion field significantly in the region of longer wavelengths that is associated with deeper layers. The user of the Fourier transform unwittingly adopts a number of assumptions that may not be appropriate to the particular signal processing problem that is involved. Above all, the Fourier transform of data should be used only for problems whose solutions are suitably described by sinusoids.

The situation here involves the responses of the buried layers for which the wavelengths are longer

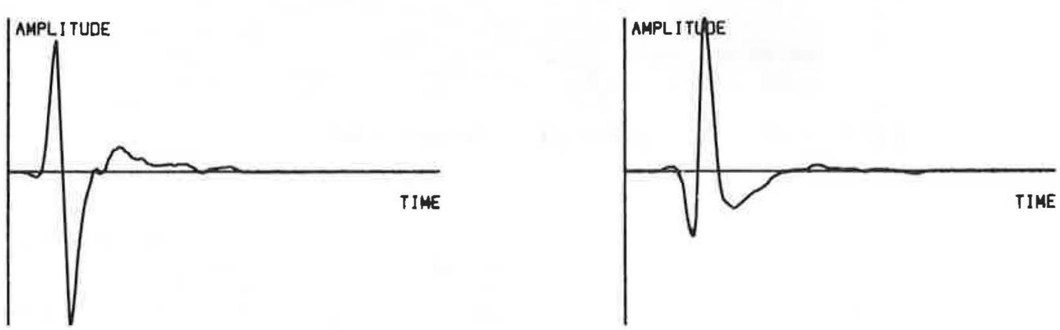


FIGURE 9 Signals from first and second gauges: no reflections.

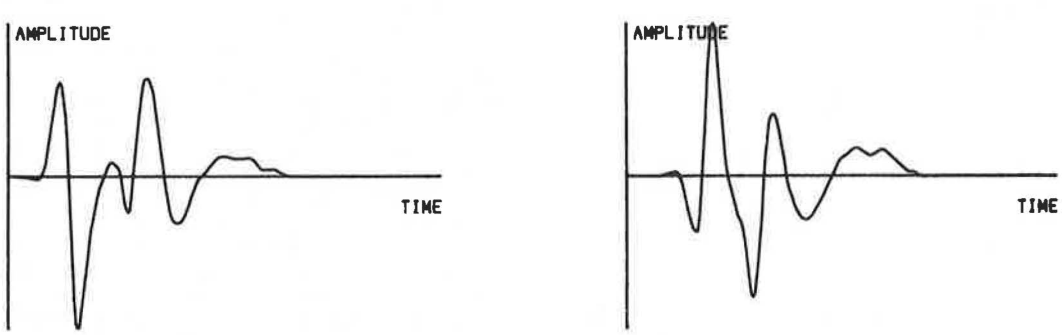


FIGURE 10 Signals from first and second gauges: reflection from side.

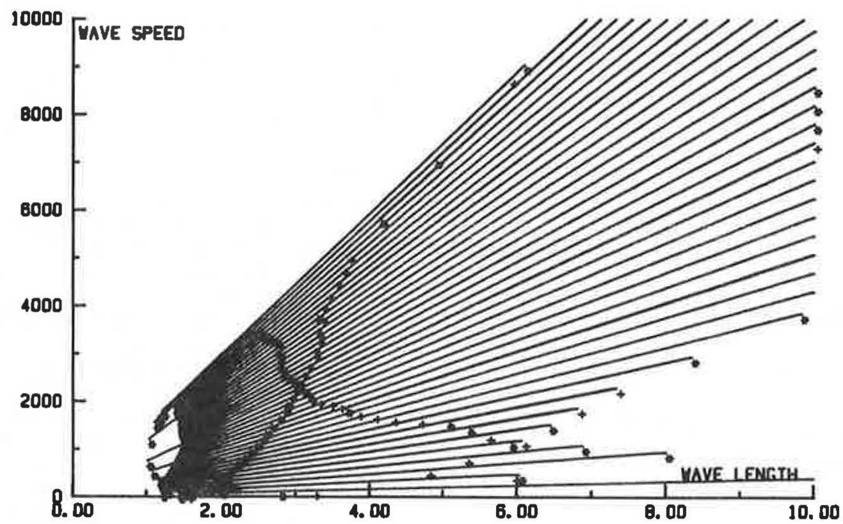


FIGURE 11 Reflections in dispersion field: no reflection.

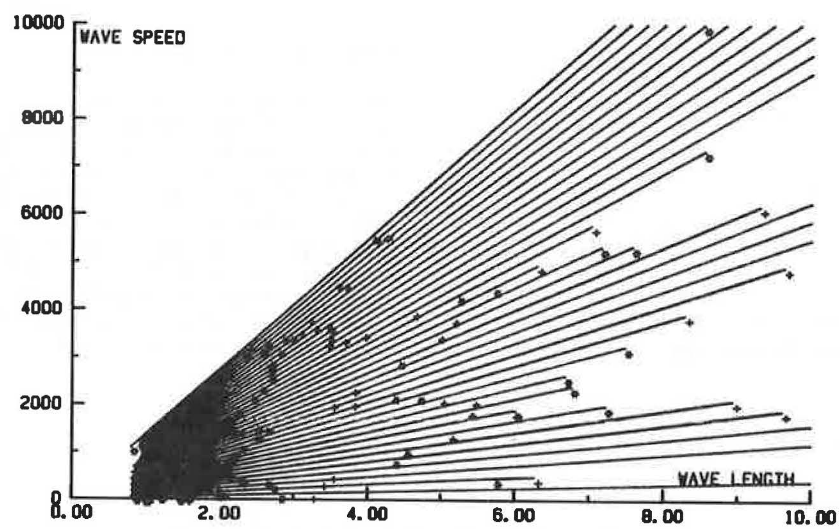


FIGURE 12 Reflections in dispersion field: reflection from side.

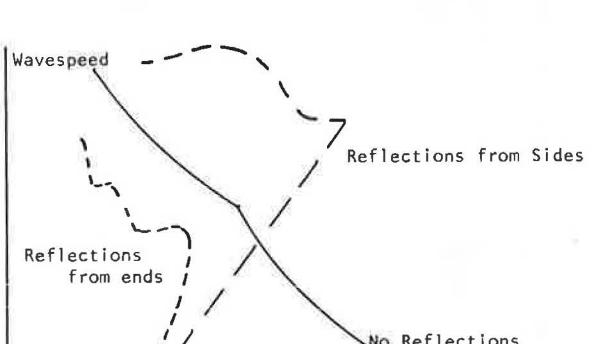
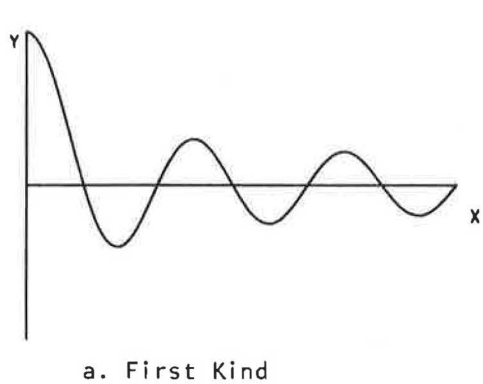


FIGURE 13 Effect of reflection conditions.

and the wave speeds lower than for the surface layer. The duration of the captured signal is involved. It tends to be shortened rather than lengthened to minimize reflections and avoid plate vibration modes.

The traveling waves that are created by a thump on the surface are described by Bessel functions [see Schroedinger (15), Weinstock (16), and Tasi (17)]. Figure 14 shows the irregular nature of the Bessel functions J_0 and Y_0 for early values of the arguments. Figure 15 shows how the disturbance from the source travels outward in the form of several Bessel functions, looking similar to a snake with its head raised, and with the largest values in the first few cycles. The first few zeros of the function are irregular, but then the functions become sinusoidal. When many zeros are involved, the Bessel functions approximate sinusoids and could serve as the sine and cosine terms of a Fourier transform.

If the signal must be truncated, then for short records, long wavelengths, and low wave speeds, possibly only one or two zeros of a Bessel function of any one argument may appear on the time signal. To



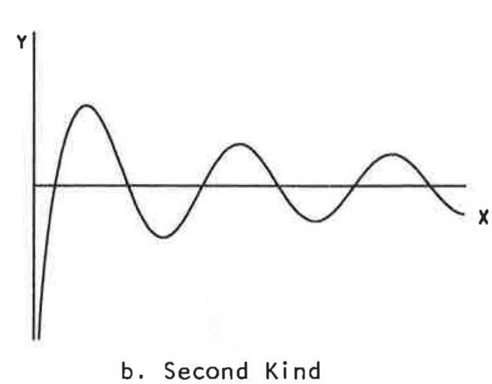


FIGURE 14 Bessel functions.

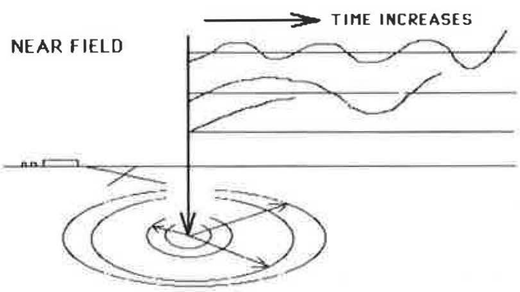


FIGURE 15 Emerging Bessel functions.

interpret that irregular signal by a Fourier transform would result in whimsical answers.

The obvious recourse is to utilize a transform based on Bessel functions of suitable arguments, and, instead of phase and phase difference, to return to the more intuitively acceptable concept: at what time did the function pass the first gauge, and at what later time did it pass the second gauge? The time interval and gaugelength will immediately give wave speed.

To demonstrate this behavior by the Fourier transform, Figure 16 shows the spurious dispersion field that results when the Fourier transform and its appropriate dispersion computations are applied to synthetic time signals for first and second gauges. The two artificial signals are created from Bessel functions of only three different arguments, each assigned a particular wavespeed. The true solution is only three single points in the dispersion field. The solution via the Fourier transform indicates a complete dispersion field, not dissimilar from those of customary tests. Figure 17 shows the same dispersion field, replotted to enlarge the high-frequency, short-wavelength portion, which does not exist.

Modified Transform Method for Fourier Portion of Analysis

The protocols of the FFT assume that the signal being transformed repeats in time; that is, wraparound is an inherent assumption of the correlation being made, with all frequency elements assumed to have been in the signal from the beginning. In NDPT/WP tests, the contributions from different channels enter the combined signal at different times; thus the information associated with each different frequency changes during the signal in response to each new input.

Repeating an earlier statement, the Fourier transform recognizes only two pieces of information for each frequency: a magnitude and a phase angle, each as an average involving the entire signal. The Fourier transform may be altered so that sine and cosine parts are evaluated in parallel, and so that phase is determined as a running sum during the computations rather than at the end. By this means it would be possible to determine the time of entry of information from new sources. If time of entry of information can be determined, the time difference between the entries of information at first and sec-

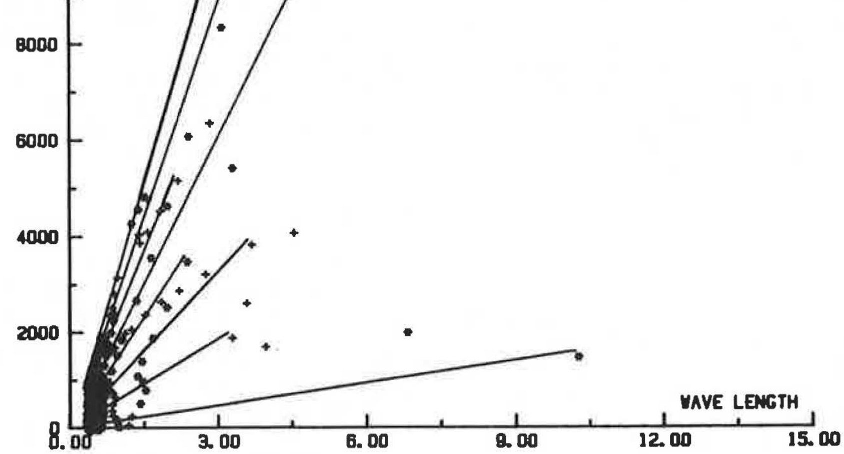


FIGURE 16 Fourier interpretation of three Bessel points.

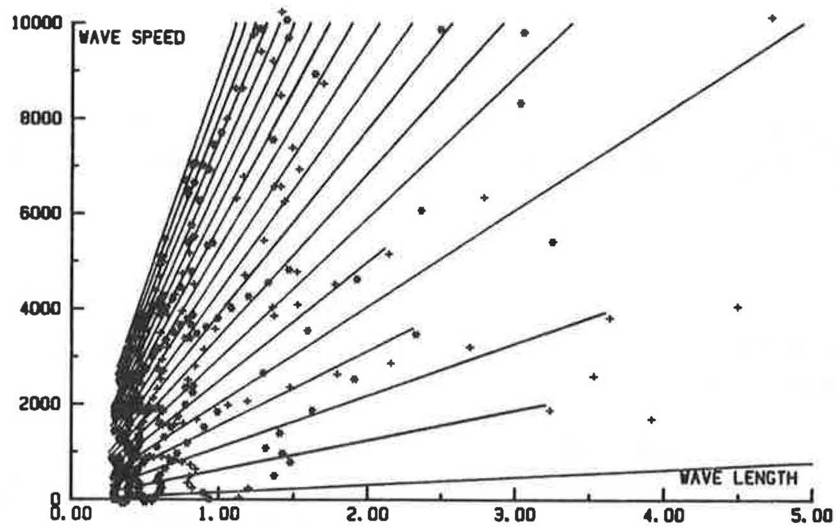


FIGURE 17 High-frequency part of Fourier interpretation.

ond gauges would be a quantity computed directly rather than being deduced on a basis of multiple phase differences with leads or lags. The computation of wave speed would be reduced to the simplicity of Equation 2, and velocity would be found by dividing gaugelength by transit time.

A Bessel Transform for Deeper Buried Layers

The authors' current work on a special-purpose Bessel transform to evaluate long wavelength portions of experimental data has been encouraging. Because of the layered nature of a pavement system, the authors use a few selected arguments rather than the regularly spaced frequencies of the Fourier transform. Cross correlations between J_o arguments and the first and second signals produce good results for the elapsed times, but it was necessary to discard the concept of wraparound. Instead, parity of comparisons is accomplished by using a truncated Bessel argument for both first and second gauge comparisons and limiting the range of cross correlation so that the function never moves past the end of the data.

The shortcoming of this Bessel transform is principally that of excessive computation time. The first exploration into such a transform was by use of a spreadsheet. The results were successful in showing the entry points of several signal components at each of the arguments used; however, the run time was several hours on a microcomputer because of continual reference to disc. The second version was programmed. The speed, although increased, could still be further improved. However, this shortcoming is not considered to be significant; it can be overcome in part by more effective programming, and completely with greater memory. Microcomputers will be completely adequate for this work now that the memory available to them is at the megabyte level.

Field Techniques

The entire method is being improved as the influence of individual parameters is determined. The relationship of the thump distance to the gauge length (Figure 18) is an example of this. Larger bases for accelerometers minimize errors from the lack of homogeneity of material immediately beneath as well as errors from any localized bond failures.

The authors have found a change in technique that

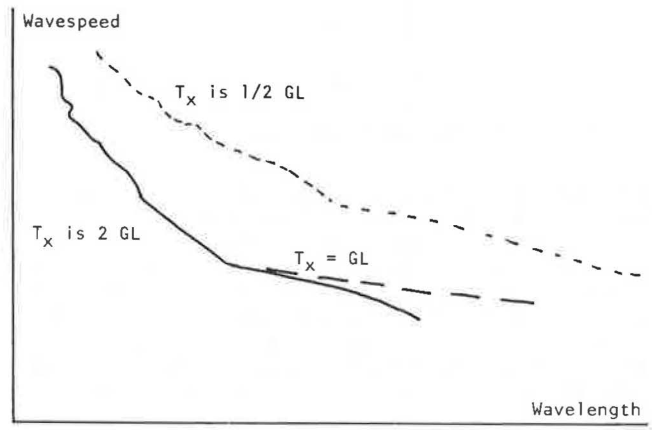


FIGURE 18 Effect of gauge length on thump distance.

substantially diminishes the consequences of reflections. The accelerometers are essentially unidirectional, with transverse sensitivity only 5 percent of the axial sensitivity. By mounting an accelerometer horizontally rather than vertically, and with the axis parallel to the lateral boundary, the reflections from that boundary become negligible. Figures 19 and 20 show the results from a test in which gauge pairs were placed side by side, one set with axes vertical in the customary position and the other set with the axes horizontal and parallel to the side boundary. Signals were recorded for both pairs simultaneously, from the same thump. Figure 19 shows the dispersion field with customary vertical gauge axes; Figure 20 shows the Rayleigh wave speed and also the longitudinal wave speed for the layer.

FUTURE RESEARCH

Several problems of a different type have yet to receive sufficient attention. Accuracy of results must be determined and documented. A method based on wave propagation is expected to produce results that are measures of fundamental quantities, in contrast with comparative studies; yet it has been learned that many parameters of test and analysis become involved in the results, and how to overcome their effects is being learned. To establish the accuracy of the method and the success of the corrective measures

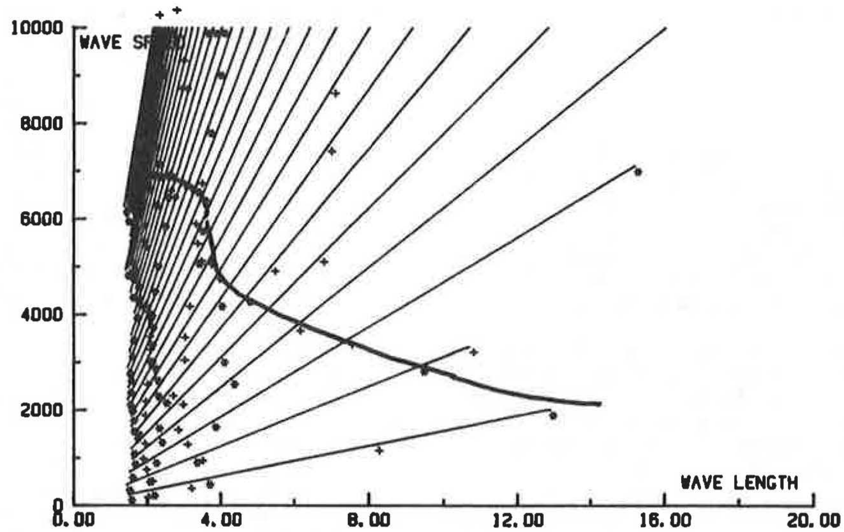


FIGURE 19 Effect of gauge axis orientation: axes vertical.

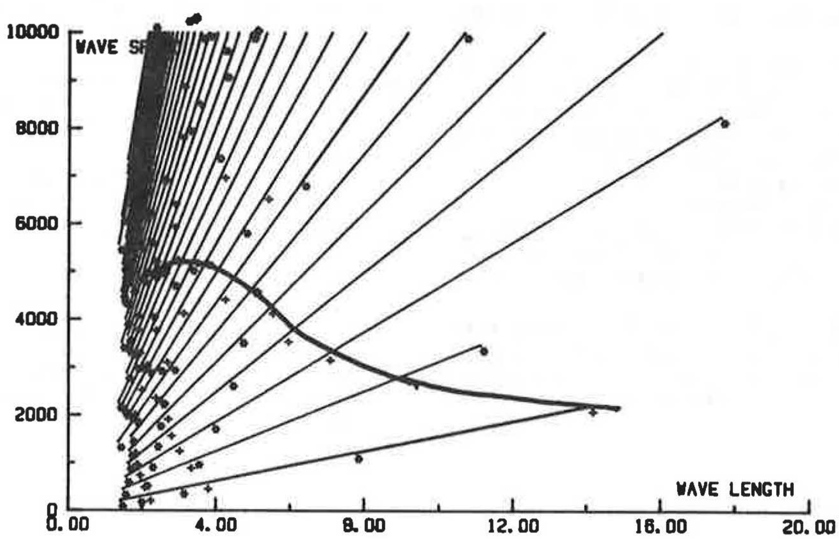


FIGURE 20 Effect of gauge axis orientation: axes horizontal.

that are being instituted, a separate method is needed. Cross-hole measurements are an obvious choice, but the tests needs to be modified substantially to deal with the thin layers of a pavement structure.

Linearity is another problem. To what extent are the results dependent on linear behavior by the individual layers of a pavement structure? Do the results vary if the energy and momentum levels associated with the thump are changed? Within what ranges of gauge location and energy and momentum level are results constant?

A continuing problem will be determining the nature of response from pavement structures that are less than ideal. The structures reasonably well understood at the current time involve few layers, and they display monotonic variation or properties with depth. What happens when there are flexible overlays to jointed rigid pavements? What happens when there are many layers present? What is the sensitivity of the method? What is the least value of the variation in properties that would permit two different layers to be identified?

CONCLUSIONS

As the problems described in this paper are overcome, nondestructive pavement testing by wave propagation nears the end of its development phase; however, answers must be found to the questions posed in the preceding section before it is fully ready to be adopted into practice. Fortunately the several systems currently in the field are providing shakedown results, and experience gained from them has helped to identify the problems the authors have discussed. Those same systems in the field will be useful testbeds for debugging these latest modifications to the analysis.

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REFERENCES

1. J.P. Nielsen and G.T. Baird. Pavement Evaluation System. Final Report. University of New Mexico, Albuquerque, Aug. 1976.
2. J.P. Nielsen and G.T. Baird. Evaluation of an Impulse Testing Technique for Nondestructive Testing of Pavements and Recommended Follow-On Research. University of New Mexico, Albuquerque, July 1977.
3. M.C. Wang. An Evaluation of the Air Force Pavement Nondestructive Testing Method. Final Report. U.S. Air Force Summer Faculty Research Program, Tyndall Air Force Base, Florida, 1981.
4. R.A. Douglas. Evaluation of the Nondestructive Testing of Airfield Pavements: Wave Propagation Aspects. Final Report. U.S. Air Force Summer Faculty Research Program, Tyndall Air Force Base, Florida, 1982.
5. H.R. Marien and G.T. Baird. U.S. Air Force Nondestructive Airfield Pavement Evaluation Method. Presented at meeting of TRB Task Force on Nondestructive Evaluation of Airfield Pavements, June 1981.
6. S. Nazarian, K.H. Stokoe II, and W.R. Hudson. Use of Spectral Analysis of Surface Waves Method for Determination of Moduli and Thicknesses of Pavement Systems. In Transportation Research Record 930, TRB, National Research Council, Washington, D.C., 1983, pp. 38-45.
7. S. Nazarian and K.H. Stokoe II. Nondestructive Testing of Pavements Using Surface Waves. In Transportation Research Record 993, TRB, National Research Council, Washington, D.C., 1984, pp. 67-79.
8. R.A. Douglas and G.L. Eller. Soil Properties at Depth from Surface Measurements. Proc., Symposium on Interaction of Non-Nuclear Munitions with Structures, Panama City Beach, Fla., April 1985.
9. R. Jones. A Vibration Method for Measuring the Thickness of Concrete Road Slabs In Situ. Concrete Research, Vol. 7, No. 97, July 1955.
10. R. Jones. In Situ Measurement of the Dynamic Properties of Soil by Vibration Methods. Geotechnique, Vol. 6, No. 1, 1958.
11. R. Jones. Surface Wave Technique for Measuring the Elastic Properties and Thickness of Roads: Theoretical Development. British Journal of Applied Physics, Vol. 13, No. 21, 1962.
12. F.N. Finn, B.F. McCullough, K. Nair, and R.G. Hicks. Plan for Development of a Nondestructive Method for Determination of Load-Carrying Capacity of Airfield Pavements. Final Report 1062-2(F). U.S. Naval Civil Engineering Laboratory, Port Hueneme, Calif.; Materials Research and Development Co., Oakland, Calif., Nov. 1966.
13. R.F. Vidale. The Dispersion of Stress Waves in Layered Media Overlying a Half-Space of Lesser Acoustic Rigidity. Ph.D. dissertation. University of Michigan, Ann Arbor, 1964.
14. D.J. Watkins, J. Lysmer, and C.L. Monismith. Nondestructive Pavement Evaluation by the Wave Propagation Method. Report TE-74-2. University of California at Berkeley; California Department of Transportation, Sacramento, July 1974.
15. E. Schroedinger. Zur Dynamik Elastisch Gekoppelter Punktsysteme. Annalen der Physik, 4, 44, 916, 1914.
16. R. Weinstock. Propagation of a Longitudinal Disturbance on a One-Dimensional Lattice. American Journal of Physics, Vol. 38, No. 1289, 1970.
17. J. Tasi. Far-Field Analysis of Nonlinear Shock Waves in a Lattice. Journal of Applied Physics, Vol. 44, No. 4569, 1973.

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