Determination of Deflection of Pavement Systems Using Velocity Transducers

SOHEIL NAZARIAN AND ALBERT J. BUSH III

The analytical models used to design and rehabilitate pavements are becoming more sophisticated. The most appropriate process for verifying the accuracy and usefulness of these new analytical models (as well as for calibrating the parameters involved in these models) is to observe the behavior of pavements in the field. Unfortunately, few devices or techniques are available for determining the displacement of a pavement section under actual loads. In addition, the available methods for monitoring the performance of pavements in terms of displacement are expensive and/or inaccurate. One economical alternative is the use of velocity transducers (geophones). Geophones are quite inexpensive and readily available. In addition, if used properly, geophones can provide quite accurate deflection-time histories. The methodology involved in determining deflection from geophones is complex. Proper mathematical manipulation of the geophone record, using signal analysis techniques and theory of vibration, should be carried out so that the deflection-time history can be accurately determined. Fortunately, the necessary mathematical manipulation can be programmed into a portable microcomputer so that the deflection-time history can be obtained rapidly in the field. This paper presents an overview of theoretical alternatives available for determining the deflection-time history of pavements using geophones. The limitations and advantages of each alternative are discussed. The practical problems that should be addressed in developing a proper algorithm for each alternative are also included. Through an illustrative example and a case study, the versatility of using geophones as a tool for determining the deflection-time history of pavements is demonstrated.

Monitoring long-term pavement performance has been greatly emphasized in the last few years. A good example is the level of effort and the amount of funds dedicated to collecting this type of data by the Strategic Highway Research Program (SHRP). An economical alternative for collecting the deflection-time history of pavements is to install and monitor geophones, which are quite inexpensive. In addition, the methodology required for determining deflection from the geophone output can be automated.

In this paper, different methods that may be used to determine the deflection-time history of a pavement section from a geophone (velocity transducer) record are reviewed. The theoretical background behind each method is discussed. Practical problems associated with the implementation of these theoretical methods are also addressed. An illustrative example provides better insight into each process discussed. Actual records obtained from a falling weight deflectometer (FWD) device were used in this example. Finally, a case study is included to demonstrate that, if used properly, geophones can provide accurate deflection-time history records of pavements under actual loads.

S. Nazarian, Department of Civil Engineering, The University of Texas at El Paso, El Paso, Tex. 79968. A. J. Bush III, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Miss. 39180.

GENERAL BACKGROUND

An undamaged geophone can be modeled accurately as a damped single-degree-of-freedom (SDOF) system. The fundamentals of the response of such a system to an arbitrary excitation are included in this section. (It should be mentioned that only subjects relevant to this report are discussed here. For further information, the reader can refer to any structural dynamics textbook.)

Idealized Model of a Geophone

Geophones are coil-magnet systems, as shown schematically in Figure 1. A mass is attached to a spring, and a coil is connected to the mass. The coil is located such that it crosses the magnetic field. On impact, the magnet moves but the mass remains more or less stationary, causing a relative motion between the coil and the magnet. This relative motion generates a voltage in the coil, which is proportional to the relative velocity between the coil and magnet.

The geophone system can be considered an SDOF system. This idealized system is shown in Figure 2. To describe a geophone properly, the natural frequency, transductivity, and damping properties should be addressed. The natural frequency is the undamped natural frequency of the system.

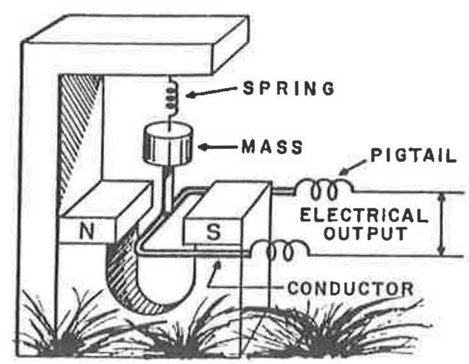


FIGURE 1 Elements of a geophone (2).

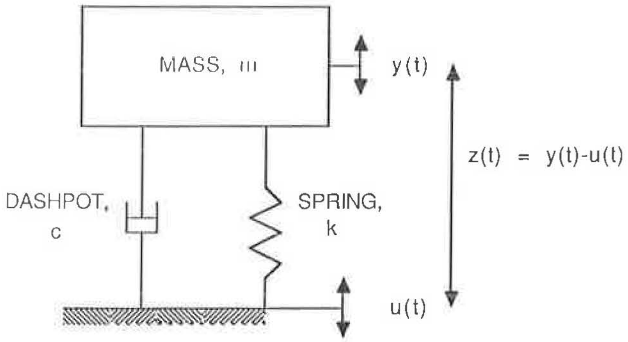


FIGURE 2 Idealized model of a geophone.

Transductivity is the factor of proportionality between the velocity and the output voltage and can be considered a calibration factor. Damping the system indicates the attenuation of the motion with time.

In an actual test, an impact is imparted to the system (say, a pavement section) which causes waves to propagate in the body as well as the surface of the pavement. If the geophone is securely attached to the pavement, the base of the geophone will follow closely the movement of the pavement. The movement of the geophone base generates a voltage output in the coil-magnet system. Finally, this voltage is monitored by an oscilloscope or a voltmeter. The voltage output of a geophone is not proportional to the actual movement of the pavement, but it is proportional to the movement of the coil-magnet system. Therefore, in order to obtain the actual movement of the pavement surface, the movement of the coil-magnet system should be translated to the actual movement of the base. To derive this relationship theoretically, the equivalent components of the model (Figure 2) and an actual geophone should be identified.

The mass, m, in the model is equivalent to the total mass of the spring, suspended mass, and the conductor (Figure 1) of the geophone. The dashpot, which provides viscous damping in the model, simply corresponds to the electrical resistance of the conductor, pigtail, and any external resistor added to the system. The movement of the base is shown as a vertical excitation, $u(t)$. The coil-magnet movement (or the voltage output) is equivalent to the relative movement of the mass, m, in the model. If the movement of the base, $u(t)$, is measured relative to a fixed-reference datum, and if the movement of the mass, $y(t)$, is measured relative to the same fixed datum, the coil-magnet movement is then equal to $z(t) = y(t) - u(t)$. The relationship between $z(t)$ and $u(t)$, which is equivalent to the relationship between the output voltage of the geophone and the ground movement, is described below.

Dynamic Response of an SDOF System

If the idealized system shown in Figure 2 is excited by a base movement, $u(t)$, the differential equation describing the response motion can be derived by specifying that the sum of all the forces in the system be equal to zero. The forces consist of spring force, damping force, inertial force, and finally the excitation force. The equation of motion can be written as

$$m \cdot y(t) + c \cdot z(t) + k \cdot z(t) = 0 \tag{1}$$

For simplicity, let $u(t)$ be a harmonic motion with a frequency of f, so that

$$u(t) = u_0 \exp(i\, 2\pi f t) \qquad (i = \sqrt{-1}) \tag{2}$$

Then the solution to Equation 1 can be written as

$$z(t) = z_0 \exp(i\, 2\pi f t) \tag{3}$$

where

$$z_0 = u_0 \cdot r^2 / [(1 - r^2) + (i\, 2Dr)] \tag{4}$$

$$r = f/f_n = f/[(k/m)^{0.5}/2] \tag{5}$$

$$D = c/c_c = c/(2km)^{0.5} \tag{6}$$

f_n and c_c represent the natural frequency and critical damping of the SDOF system, respectively. D is the damping ratio. In Equation 3, z_0 corresponds to the maximum relative deformation of the mass.

If both sides of Equation 4 are divided by u_0, the maximum movement of the base, the outcome is the frequency response of the system and is denoted as H. Therefore

$$H = r^2 / [(1 - r^2) + (i\, 2Dr)] \tag{7}$$

The frequency response of a geophone is better known as the calibration curve. At each frequency, the calibration curve is a complex quantity. A complex quantity can be represented by its real and imaginary components, or alternatively by its magnitude and phase. The modulus of frequency response, M, is called the magnification factor and is calculated from

$$M = r^2 / [(1 - r^2)^2 + (2Dr)^2]^{0.5} \tag{8}$$

The arctangent of the ratio of the imaginary and real components of Equation 7 yields the phase difference between the input and the output. This relationship can be written as

$$\phi = \arctan [2Dr/(1 - r^2)] \tag{9}$$

where ϕ is the phase difference.

The significance of this formulation is that the response of an SDOF system excited by any harmonic excitation can be easily determined, if the natural frequency and the damping ratio of the system are known. It should be emphasized that a complete calibration curve consists of the magnitude and the phase information (or alternatively, the real and imaginary components). It is customary to demonstrate the calibration curve in terms of magnitude only. The magnitude by itself is of little value for determining deflections.

Response of a Geophone to an Arbitrary Excitation

A closed-form solution is available for only a limited number of well-defined excitation forces. However, three alternative numerical approaches are widely used to obtain analytical expressions for the response of a system to a general dynamic loading. These three approaches are the time-domain solution (also known as the Duhamel integral method), the Laplace transform method, and the frequency-domain solution (the Fourier transform method). In this paper, only the time and frequency-domain methods are included; however, the Laplace transform method is most appropriate for hand calculation (as opposed to using a computer).

Time-Domain Solution

If an arbitrary excitation, $u(t)$, with a duration of t_0 is applied to a system, the response motion, $z(t)$, can be written as

$$z(t) = \int_0^t u(\tau) \cdot I(t - \tau)d\tau - u(t) \qquad (10)$$

where

$$I(t) = -\omega_n \cdot \exp(-D\omega_n t) \cdot [2D\cos(\omega_d t) - A\sin(\omega_d t)] \qquad (11)$$

$\omega_n = 2\pi f_n$ = natural circular frequency,
$\omega_d = \omega_n (1 - D^2)^{0.5}$ = damped natural circular frequency, and
$A = (2D^2 - 1)/(1 - D^2)$.

In Equation 11, $I(t)$ is called the unit impulse function. Unit impulse function is the motion response of an SDOF system to an impulse of short duration. The integral in Equation 10 is the convolution integral. In other words, the response of an SDOF system to an arbitrary excitation is simply the convolution of the excitation with the unit impulse function. This solution is convenient, because it can be easily programmed in a computer.

Frequency-Domain Solution

Any function in the time domain can easily be expressed in terms of a limited number of harmonic functions, if Fourier transform is used. If an SDOF system is linear, the response motion of the system can be obtained by (a) transforming the input motion to the frequency domain, (b) multiplying the transformed input by the frequency response curve of the system (as derived Equation 7), to obtain the response in the frequency domain, and (c) inverse-transforming the resultant of Step 2 into the time domain.

To clarify this matter further, say $u(t)$ is the motion at the base of a geophone (i.e. the input). If $U(f)$ is the Fourier transform of $u(t)$, and $H(f)$ is the frequency response of the geophone (see Figure 2), then the output voltage of the geophone (i.e., the response motion) in the frequency domain, $Z(f)$, can be written as

$$Z(f) = H(f) \cdot U(f) \qquad (12)$$

The output of the geophone in the time domain, $z(t)$, is simply equal to the inverse-transform of $Z(f)$. It can be shown that $I(t)$, the unit impulse response function is the inverse-Fourier transform of $H(f)$, the frequency response function. Also it can be proven that convolution in the time domain is equivalent to multiplication in the frequency domain. Therefore, if the response of a known SDOF system subjected to an arbitrary input function, $u(t)$, is to be determined, any of the two approaches described above can be used interchangeably to obtain identical results. At first glance, it may seem that the second method is not as straightforward as the first. However, for complicated input functions, the second method is computationally more efficient.

Illustrative Example

Let us assume that a geophone has a natural frequency of 4.7 Hz, and a damping ratio of 0.64, and let the base of this geophone be subjected to a half-sine velocity impulse with a duration of 25 msec as shown in Figure 3. The unit impulse function corresponding to Equation 11 is shown in Figure 4.

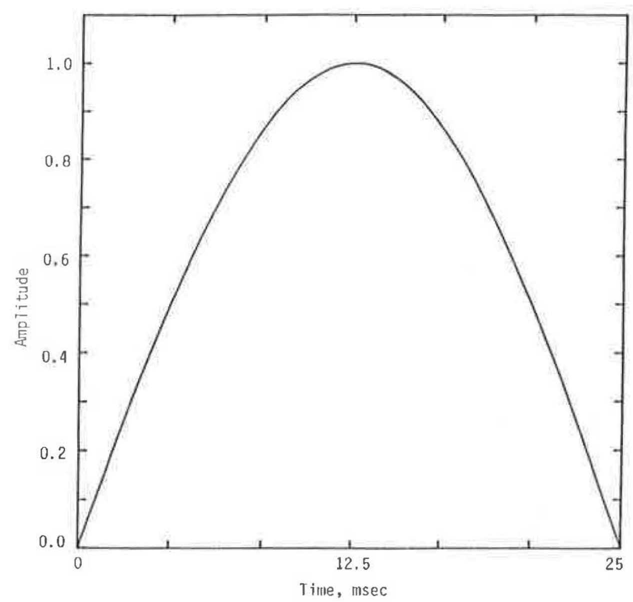


FIGURE 3 Half-sine velocity impulse.

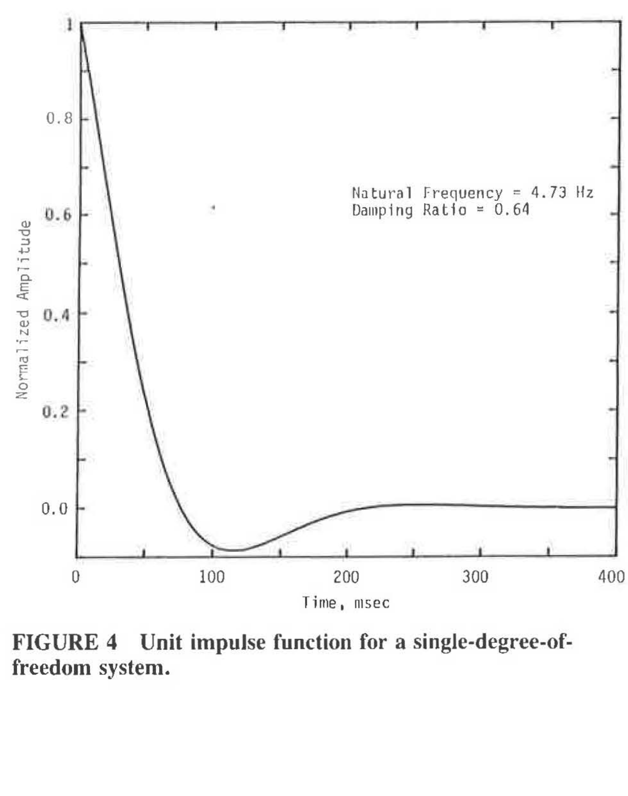


FIGURE 4 Unit impulse function for a single-degree-of-freedom system.

A program that convolves the input and impulse function was used to determine Equation 10 (*1*). The input (half-sine velocity impulse) and the response (relative velocity of the coil-magnet) are compared in Figure 5. The maximum value of response is about 75 percent of the input, and the maximum response occurs at about 20 msec, which is about 2.5 msec before the maximum of the input takes place.

The same example is solved using frequency-domain approach. The Fourier transform of the half-sine impulse is shown in Figure 6 in terms of magnitude and phase. The frequency response function derived in Equation 7 is shown in Figure 7 in terms of magnitude and phase also. The product of these two curves, which is the velocity of the coil-magnet system, is shown in Figure 8. The last step is to inverse-transform this response to the time domain to obtain directly the coil-magnet velocity response time history. The result is almost identical to that of the time-domain solution shown in Figure 5. This process is coded in a FORTRAN algorithm as well (*1*).

DETERMINATION OF DEFLECTIONS FROM AN ARBITRARY IMPACT

In the last section, the discussion focused on the response of a geophone given the base motion. However, in this section, the response of the system (the recorded signal) is known and the motion of the base is of interest. In other words, our main interest is to remove the distortion in the signal caused by the geophone system so that the actual movement of the pavement surface can be determined. Several procedures are available for determining displacement from geophone output. These procedures are discussed in the next few sections. The impact due to an FWD device will be used as an example throughout this section.

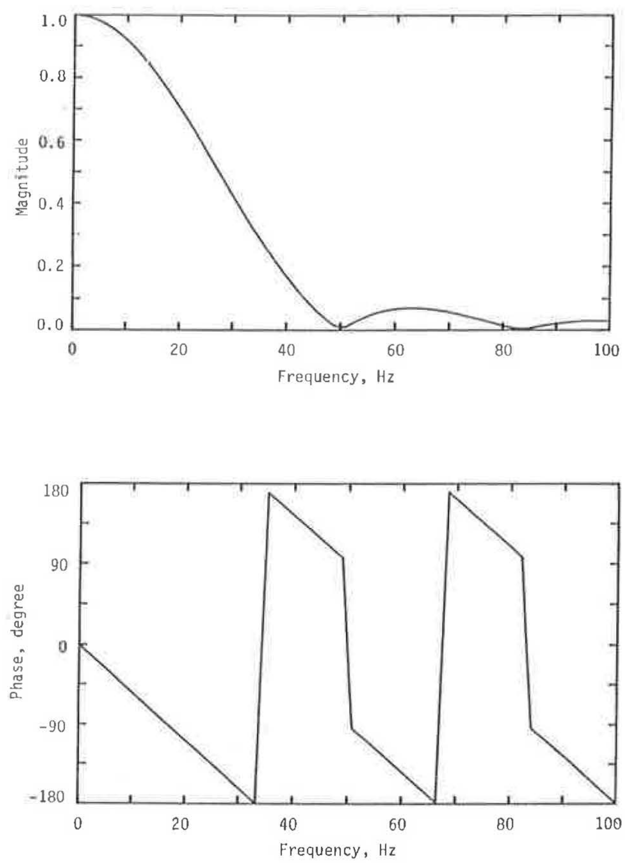


FIGURE 6 Fourier transform of a half-sine pulse with a duration of 25 msec.

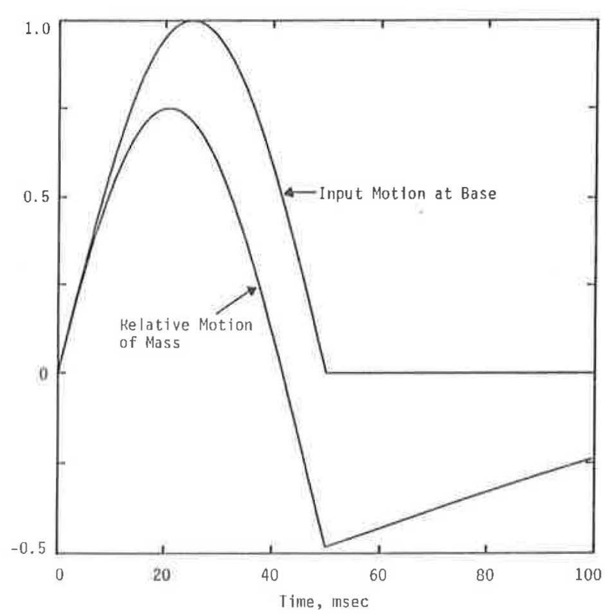


FIGURE 5 Comparison of input motion at base with relative motion of mass in an SDOF system.

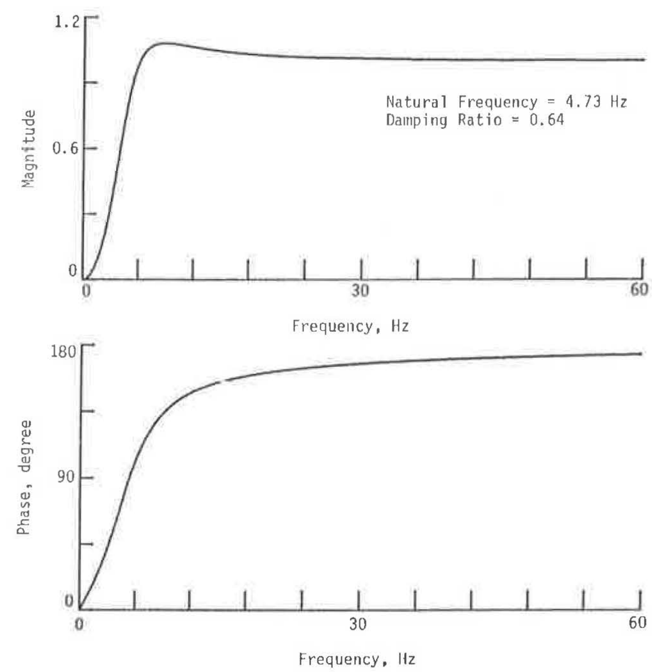
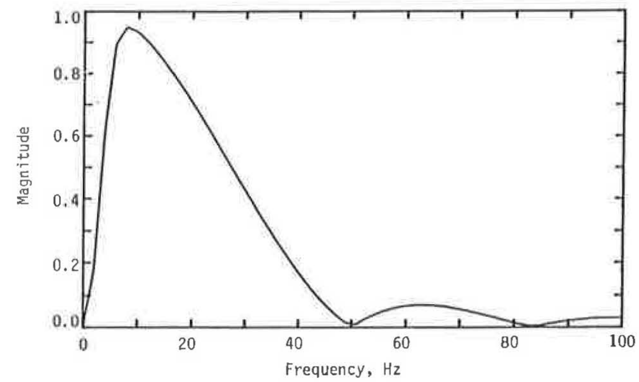


FIGURE 7 Frequency response function (calibration curve) of geophone.



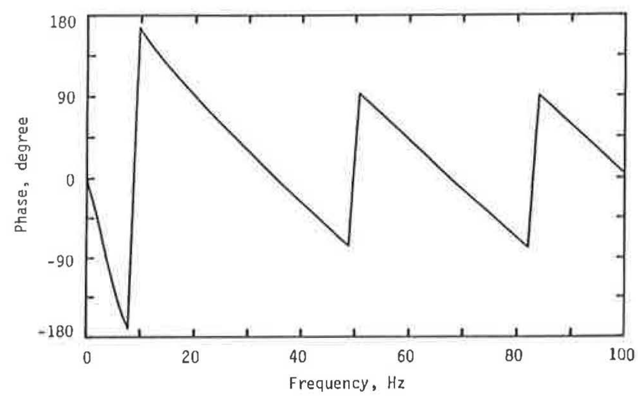


FIGURE 8 Coil-magnet system response spectrum of sensor due to a 25-msec impulse.

Impulse Method

The impulse method is adapted from the shock engineering discipline. In this approach, one is only concerned with the maximum response rather than the complete time history or the frequency content of the response. To implement this method, one simply assumes an impulse shape (in our case, a half-sine) and solves the equation of motion to obtain the value of maximum response of the system. By varying the natural frequency of the system and repeating this process, the so-called shock response spectrum (SRS) is determined (*3*).

An SRS is the relationship between the ratio of the maximum response and the maximum input, versus the natural frequency of the system for a given damping ratio. A major outcome of this process is that if the natural period of the system is much greater than the duration of impulse, the shock response value is more or less independent of the shape of the pulse. The significance of this statement is that as long as the duration of the pulse is small, if the shape of the input impulse deviates from the assumed one, the shock response value would not change significantly.

One major question is then, given the natural period of the system, at what impulse duration is the shape of the impulse immaterial to the response of the system? The answer to this question will be explored in the next section. However, the answer obviously depends on the desired accuracy with which the response should be determined.

Implementing this method requires three steps:

1. Calibrate the receiver and calculate response characteristics of the receiver,
2. Determine the theoretical response of the receiver to a half-sine pulse, and
3. Combine the outcomes of Steps 1 and 2 with the receiver output to determine the deflection.

Each of these steps is discussed next.

Calibration of Geophone

The fastest method of calibration is to use a shake table. In this method of calibration, a reference accelerometer is rigidly connected to the shake table and the geophone, in turn, is rigidly connected to either the accelerometer or the shake table. The shake table is vibrated with a sweep-sine steady-state source, a random-noise source, or an impulse. The calibration curve of the geophone relative to the reference accelerometer is independent of the type of excitation (*4*). The output voltages of the reference accelerometer and the geophone are then monitored simultaneously. The response of the accelerometer is integrated to obtain its response in terms of velocity. The ratio of the geophone output voltage and the integrated accelerometer record at each frequency is the calibration curve of the geophone.

As an example, the normalized calibration curve of a typical sensor of an FWD device is shown in Figure 9. To normalize the curve, the calibration value was divided by the transductivity of this geophone (denoted as T_g), which is equal to 0.57 volt/in./sec. This value corresponds to the actual magnitude of the calibration curve at high frequencies (above 15 Hz). The natural frequency and the damping ratio of this system were determined by a built-in feature of the spectrum analyzer used as the recording device. This geophone has a natural frequency of 4.7 Hz (actually, 4.73 Hz) and the damping ratio of 0.64.

Theoretical Response of Geophone to Impulse

On the basis of the characteristics of the geophone, the response of the coil-magnet system to a 25-msec half-sine impulse at the base of the geophone is obtained. To obtain the coil-magnet response of the geophone to the impulse, either of the two methods described previously may be used.

To continue our example, the properties of the geophone just demonstrated are used. The coil-magnet response time history is shown in Figure 5. Also shown in Figure 5 is the actual input to the base of the geophone. From the figure, it can be seen that if the input has a maximum velocity of unity, the coil-magnet response will register a maximum of 0.75. Therefore, the voltage output from this geophone should be divided by 0.75 to compensate for the distortion of the output caused by the geophone (provided that the input impulse resembles reasonably a half-sine wave with a duration of 25 msec). This adjustment factor will be referred to as C_g hereafter.

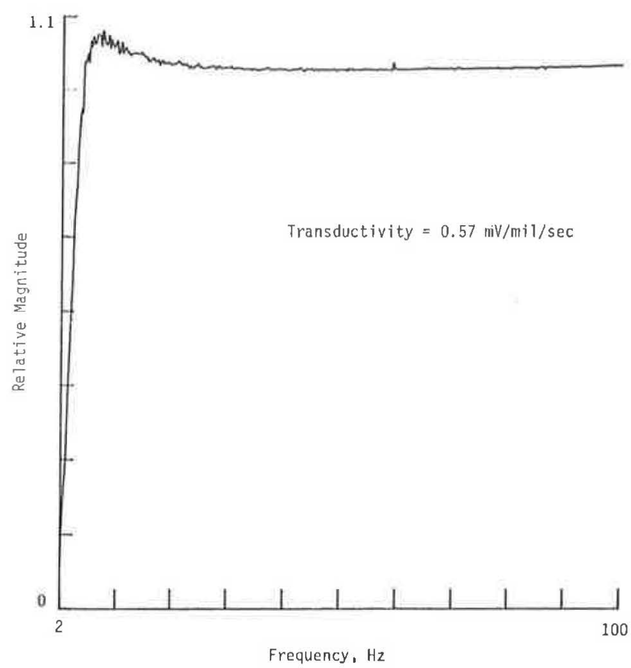


FIGURE 9 Calibration curve for a typical FWD sensor.

Determination of Deflection

To obtain the deflection from the voltage representing the output of the geophone, first, the record is divided by the transductivity of the geophone to convert voltage to velocity. Second, the converted velocity time record is divided by the adjustment factor, C_g, to compensate for the effect of the geophone on the signal. Then, the signal is integrated with respect to time to obtain the maximum deflection. This discussion can be summarized in the following formula:

$$\text{DEFLECTION} = \text{FACTOR} \cdot \text{INTVOLT} \tag{13}$$

where

DEFLECTION = deflection of pavement at geophone base,
FACTOR = $1/(T_g \cdot C_g)$, correction factor for shape and duration of impulse and transductivity of geophone, and
INTVOLT = maximum output voltage after integration of raw geophone signal saved in recording device.

To continue with our example, a typical voltage time history of an FWD sensor is shown in Figure 10. This signal was captured using a Hewlett-Packard Model 3562A spectrum analyzer. A high-frequency vibration with a low amplitude is evident in the signal. This additional vibration is due to the excitation of the raise/lower bar of the FWD trailer during impact. In Figure 10, the portion of the record to the left of Point A depicts the time history before the actual arrival of the signal. The voltage output in this region is constant and is approximately equal to 20 mv. The reasons for this deviation from zero are not known at this time and should be investigated. The second portion of the signal enclosed between Points A and B is the response of the coil-magnet system to the impact. The record to the right of Point B with a constant output is the at-rest area of the signal. This portion has a constant magnitude of approximately 46 mv.

If one assumes that the geophone was at rest up to the arrival of the impulse (i.e., Point A), the constant value of approximately 20 mv corresponding to the output voltage of this region should be subtracted from the signal at all times. Now, this record is integrated to convert velocity into displacement. The integrated signal is shown in Figure 11. The

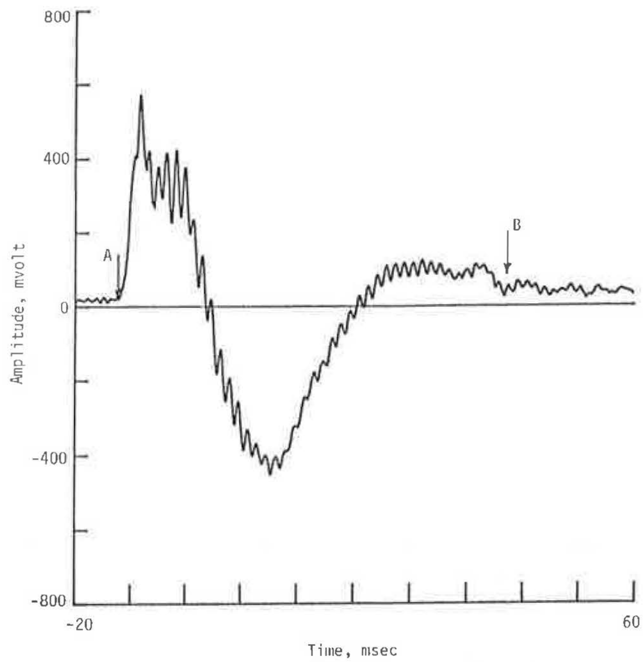


FIGURE 10 Typical velocity time history of FWD sensor.

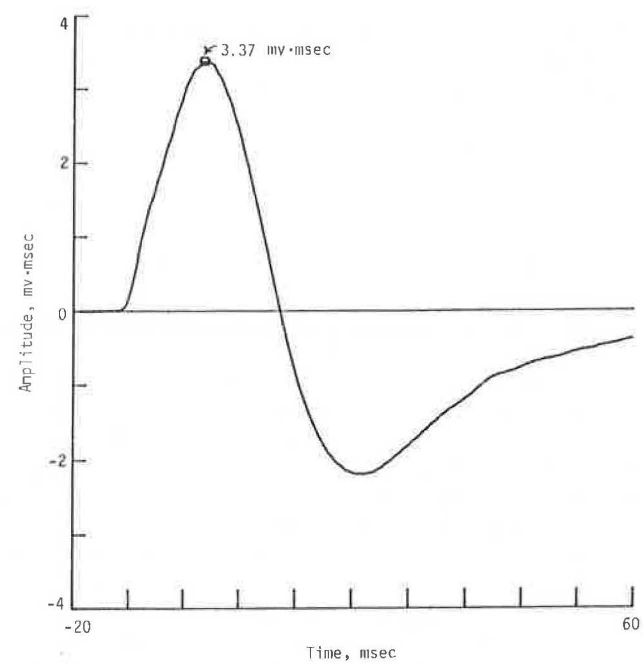


FIGURE 11 Time history of FWD sensor after integration.

open circle in Figure 11 corresponds to the maximum output. The magnitude of this point is equal to INTVOLT in Equation 16 and is equal to 3.37 mv.msec.

In the two previous sections, the values of transductivity, T_g, and adjustment factor, C_g, were reported as 0.57 mv/in./sec and 0.75, respectively. As such, parameter FACTOR is equal to 2.33 [1/(0.57 × 0.75)]. Knowing the values of parameters INTVOLT and FACTOR, the maximum deflection for this example is equal to 7.9 mil. The value of the maximum from actual FWD tests at this location is 7.7 mil. The difference between the two values is less than 3 percent.

It should be emphasized that the process mentioned above only yields a correct maximum deflection for an impact resembling a half-sine impulse with a duration of 25 msec, but the time history obtained after integration is not correct and still contains the errors caused by the geophone assembly.

Parametric Study of Factors Affecting Impulse Method

In the method described above, it was assumed that the duration of impulse is 25 msec. It would be helpful to study the effect of varying the duration of the impulse (from say 20 to 30 msec) on the adjustment factor, C_g, and in turn on parameter FACTOR in Equation 13. Also, the adjustment factor is obtained based on the assumption that the impulse is a perfect half-sine wave. Another interesting parametric study is to determine the change in C_g, if the impulse is not actually a half-sine wave but a function that resembles one.

Variation in parameter C_g with duration of impulse is shown in Table 1. The adjustment factor, C_g, decreases as duration of impulse increases. If the value of C_g at 25 msec is assumed as the reference value, the absolute maximum variation in the value of C_g is about 5 percent. This method of comparison is known as *equal maximum height* method. In this method of comparison, all impulses have a maximum magnitude of 1.

Another way of comparing the effect of different impulses on C_g is by using the so-called *equal impulse area* method. If the duration of the impulse is small relative to the natural period of the geophone, this method may result in a more consistent comparison. Using the area of a 25-msec-long half-sine impulse as the basis for comparison, and requiring that the area of the impulses be equal to it, one can determine an equivalent maximum magnitude of each impulse. The area under each impulse is included in Table 1. The values of C_g after correction for area are added, too. This method did not result in a more consistent comparison, as seen in the table. Therefore, its use was abandoned.

In the second series of tests, the duration of impulse was maintained at 25 msec, but, the shape of the impulse was changed. The impulse shapes used are summarized in Table 2. All functions used in this study are demonstrated graphically in Figure 12. The shape of all these functions resembles a half-sine wave. In actual tests, contrary to the five impulse functions included in Table 2, the time history of the load cell is not symmetrical. Therefore, a sixth case with an input time history as shown in Figure 13 was studied also. Variation in C_g with shape of the impulse is included in Table 2 also. From the table, the value of C_g may vary as much as 15 percent.

These two brief parametric studies give an indication of the accuracy of deflections obtained from the impulse method. In summary, the effect of duration of impulse is less significant, but the effect of shape on the impulse may be quite significant.

Frequency Response Method

The frequency response method takes advantage of the Fourier transform algorithm. The advantage of this method over the previous method is that the entire displacement time history can be determined, whereas with the impulse method only the maximum deflection could be found. In the frequency response method, no simplifying assumption about the nature of the load is made. As such, the results are more accurate than those from the impulse method. There is a trade-off, however. Computationally, the frequency response method is more time consuming.

The procedure involved in determining deflections from the geophone response consists of (a) the geophone is calibrated using the same procedure outlined before, (b) the time signal obtained from the geophone is Fourier transformed, (c) the Fourier transformed signal is divided by the calibration curve determined in Step a, and (d) the result from Step c is inverse-Fourier transformed to obtain deflection time history and the maximum deflection.

The same time signal depicted in Figure 9 is used in this example. The magnitude and phase relationship of the transformed time signal are shown in Figure 14. This transformed

TABLE 1 VARIATION IN ADJUSTMENT FACTOR WITH DURATION OF A HALF-SINE IMPULSE

Duration of Impulse, msec	Area Under Impulse, velocity-msec	Adjustment Factor	
		Equal Maximum Amplitude	Equal Area
20.0	12.73	0.79	0.64
22.5	14.32	0.77	0.70
25.0	15.91	0.75	0.75
27.5	17.51	0.73	0.81
30.0	19.10	0.72	0.86

TABLE 2 VARIATION IN ADJUSTMENT FACTOR WITH SHAPE OF IMPULSE

Impulse Shape Function	Adjustment Factor
$\mathrm{Sec}^2(\frac{2t}{\tau} - 1)\pi^*$	0.86
$e^{-(2t/\tau - 1)^2\pi}$	0.79
$[\sin(\frac{2t}{\tau} - 1)\pi][(\frac{2t}{\tau} - 1)\pi]$	0.81
$\frac{2}{\pi}\,\mathrm{Arc\ tan}\,[\frac{1}{2\pi^2(2t/\tau - 1)^2}]$	0.87
$\sin\,(\frac{t}{2\tau})\pi$	0.75
$543.66\ t\ e^{-t/0.05}$	0.88

* τ Corresponds to Duration of Impulse (25 msec for all cases)

signal was then divided by the frequency response function (presented in Equation 7 and Figure 7) to remove the effects of the geophone on the signal. The result, which is the excitation velocity at the base in the frequency domain, is presented in Figure 15. This operation accounts for both the phase shift and variation in the magnitude. If this function is inverse-Fourier transformed, the result is the velocity time history of the base of the geophone.

The voltage output of the geophone shown in Figure 10 is compared with the velocity of the base of the geophone in Figure 16. It can be seen that the two time histories follow each other in shape. However, the magnitude of the base velocity at a given time is less, and there seems to be a phase shift between the two curves.

Continuing with the example, the frequency domain velocity record shown in Figure 15 should be integrated to obtain displacement. Integration in the frequency domain is basically a simple division of the magnitude of the signal at each frequency by the corresponding angular frequency. The result of this operation yields the displacement spectrum that is shown in Figure 17.

The last operation is to inverse-Fourier transform the displacement spectrum to obtain displacement time history. Two more details must be taken care of before obtaining the actual displacement. First, the zero displacement point should be defined. Second, the maximum displacement should be divided by the transductivity of the geophone (0.57 volt/in./sec) to obtain the actual deflection. The open circle in Figure 18 corresponds to the maximum deflection. The maximum deflection from this method is equal to 7.8 mils [(4.46 mv)/(0.57 mv/mil/sec)]. As mentioned before, the deflection obtained from the FWD device at this point was 7.7 mils.

Another outcome of this example is the value of adjustment factor, C_g, that corresponds to the actual impulse imparted to the pavement (as opposed to the assumed half-sine wave impulse). In Figure 19, the ground deflection time history (solid line) is compared with the integral of the voltage output (dashed lines). From the figure, a phase shift between the two curves is obvious. Also notice the overshoot of the magnitude of the second half-cycle for the coil-magnet response. To obtain the actual adjustment factor, the maximum deflection from the ground deflection time history is divided by the maximum of the coil-magnet response. The adjustment factor for the type of impulses generated at the site is then equal to 0.79 (as opposed to 0.75 determined theoretically from a half-sine wave impulse).

CASE STUDY

A series of tests was performed on a rigid pavement section using the FWD device at the Corps of Engineers Waterways Experiment Station in Vicksburg, Mississippi. Two geophones independent from those of the FWD device were used in this study. Each geophone had a nominal natural frequency of 4.5 Hz and a damping ratio of 70 percent. These two geophones will be termed *well-calibrated* geophones, hereafter. The well-calibrated geophones were securely placed as closely as pos-

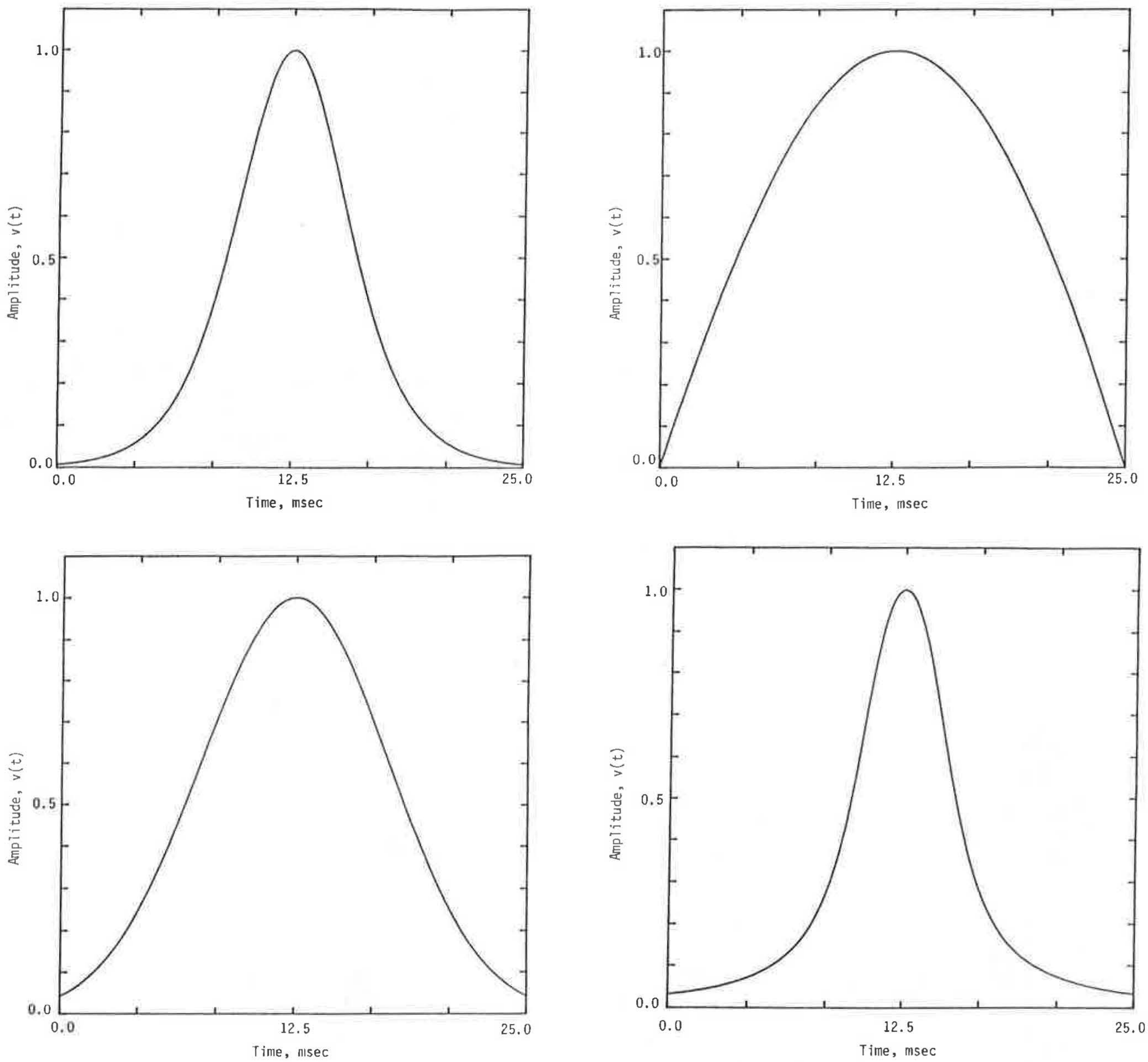


FIGURE 12 Graphical illustration of symmetrical functions resembling a half-sine function.

sible to the FWD device sensors. The signals from these geophones were captured on a recording device while the FWD device determined the deflections from the same impact simultaneously. The recording device used was a Hewlett-Packard Model 3562A spectrum analyzer. As this analyzer is a two-channel recorder, the process mentioned above was carried out several different times (each time at a different sensor location). For each process, one geophone (called the *reference* geophone) was maintained next to the FWD second sensor and served as the reference to ensure uniformity among individual impacts. A second geophone was moved each time to a new sensor location. Four drop heights were used for each geophone location. For the sake of brevity, only the results from the largest drop height are included here. However, the results from other drop heights were similar, and all discussions of this drop height can be extrapolated to all heights.

Deflections determined from the well-calibrated geophones using the impulse and frequency response methods are demonstrated in Table 3, along with their corresponding values obtained directly from FWD tests. At each sensor location, the three methods yielded deflections that were within 4 percent of one another. Bentsen et al. (*5*) and Briggs (personal communication, 1988) in two recent studies have shown that, in general, the precision of measurement of deflections with an FWD is within 5 percent. Therefore, this example clearly demonstrates the precision and accuracy of the methods described herein.

SUMMARY AND CONCLUSIONS

The use of geophones in determining the deflection of pavement systems was discussed. Different methods of obtaining

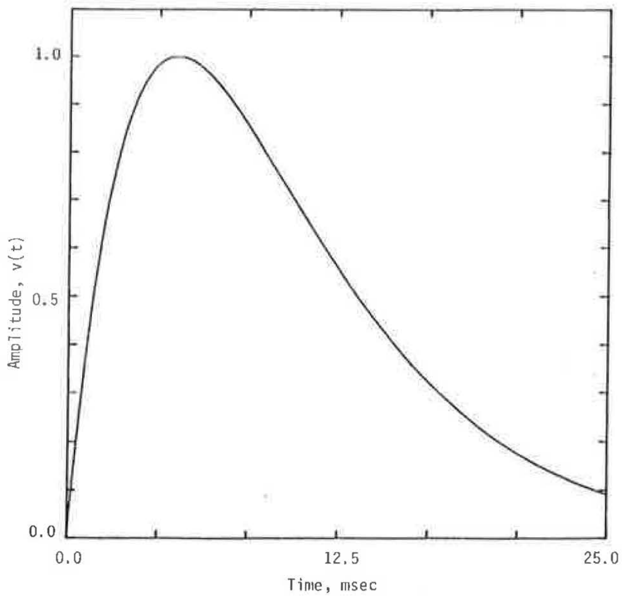


FIGURE 13 Velocity time history of an asymmetrical impulse.

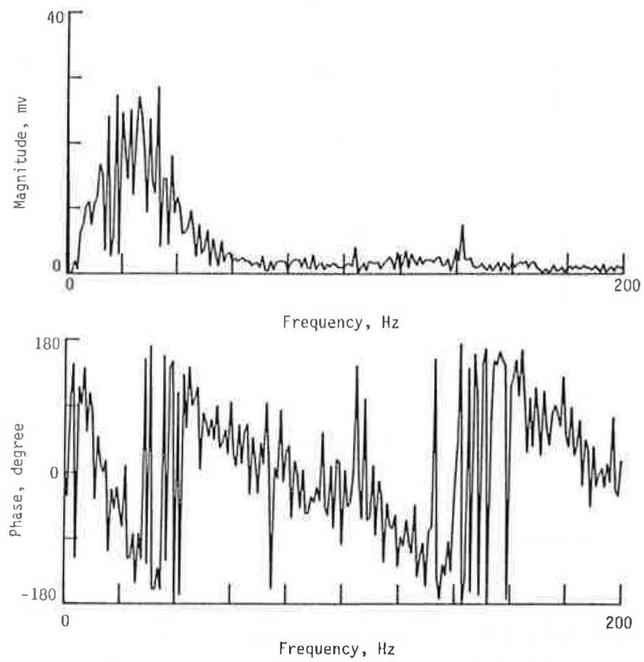


FIGURE 14 Fast Fourier transform of the typical signal from FWD sensor.

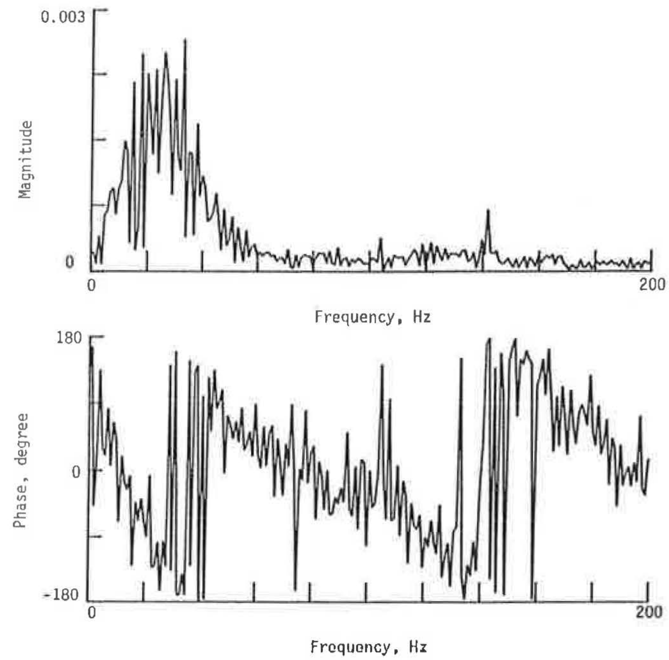


FIGURE 15 Velocity response spectrum of the base of FWD sensor.

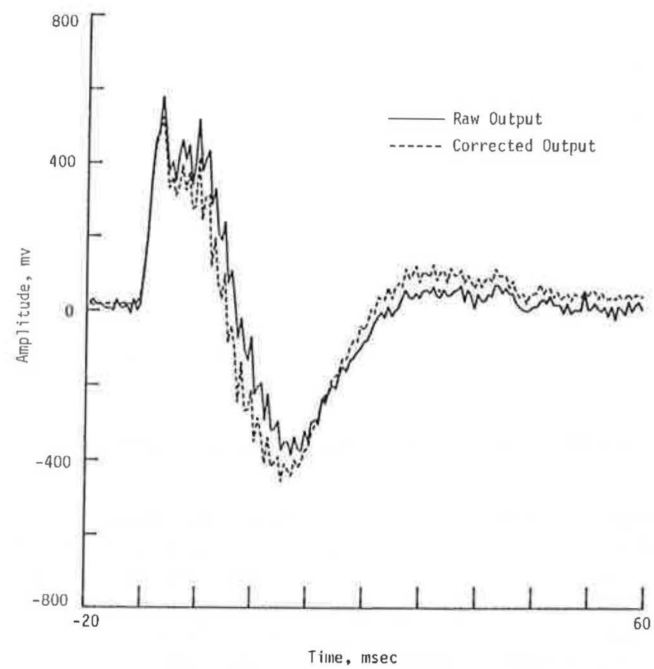


FIGURE 16 Comparison of raw voltage output with voltage corrected for geophone effects.

deflections from geophones were described. The limitations and advantages of each method were also described.

The impulse method yields a satisfactory value for the maximum deflection only, and does not yield a meaningful deflection-time history. In addition, as applied to pavement monitoring, the method is only applicable to short-duration loadings. The shape and duration of the impulse may cause error in the value of maximum deflection as well. In general, this method should be used with caution.

The time- and frequency-domain solutions work equally well, as long as the geophone used is well calibrated. Practically speaking, the frequency-domain solution is easier to implement. The frequency-domain solution has two additional advantages over the impulse method. First, the deflection-time history and the maximum deflection are obtained.

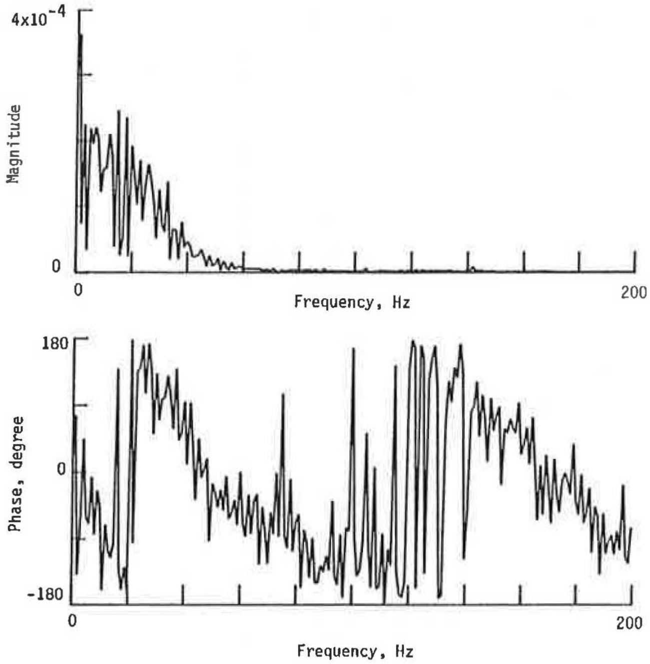


FIGURE 17 Integrated velocity response spectrum at the base of FWD sensor.

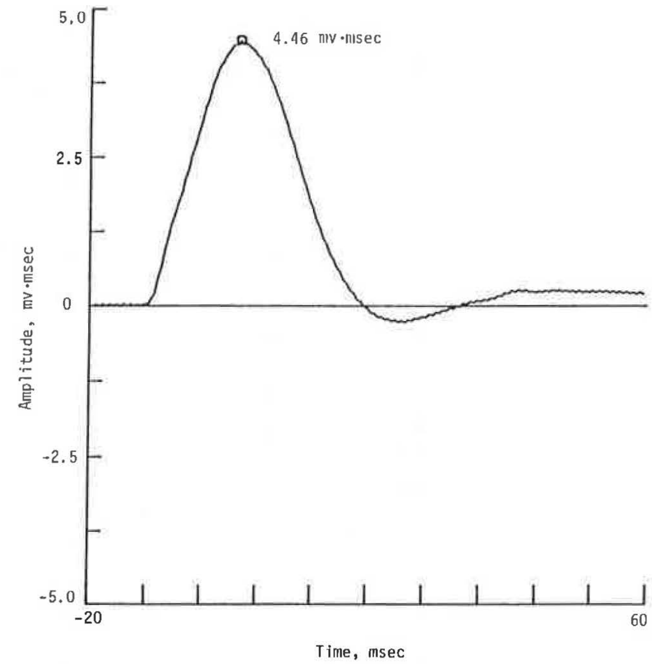


FIGURE 18 Integrated velocity time history at the base of FWD sensor corrected for zero deflection.

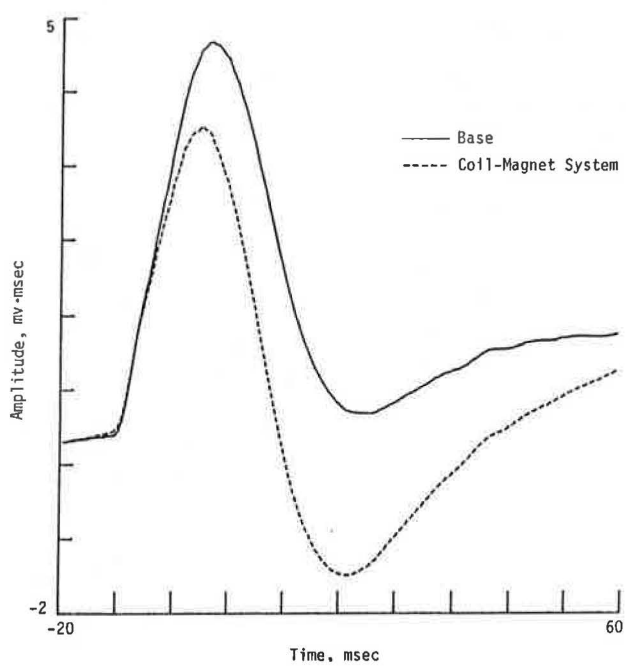


FIGURE 19 Comparison of integrated velocity time histories of the coil-magnet system and base of FWD sensor.

TABLE 3 COMPARISON OF DEFLECTIONS OBTAINED FROM IMPULSE METHOD, FREQUENCY RESPONSE, AND FWD TESTS USING TWO WELL-CALIBRATED GEOPHONES

Sensor	Deflection, mil		
Number	Impulse Method	Frequency Response Method	FWD Device
2(R)*	7.3 ++	7.4	6.9
3	6.6	6.8	6.6
2(R)	7.2	7.4	7.3
4	5.9	6.0	5.9
2(R)	7.2	7.3	7.2
5	5.3	4.7	5.3
2(R)	7.2	7.3	7.3
6	4.6	4.7	4.6
2(R)	7.1	7.3	7.4
7	4.0	4.1	4.1
Average Reference	7.20 (+0.07)+	7.34 (0.05)	7.22 (0.19)

* (R) denotes Reference Sensor

\+ Numbers in parentheses correspond to standard deviation

++ The value of adjustment factor of 0.79, which has obtained with a theoretically proper method, was used to determine the deflections from Impulse Method

Second, the results are independent of the duration and shape of impulse.

Through a case study, the use and precision of the methods described in the paper were demonstrated. Based on this study, geophones can be used effectively to monitor the behavior of pavements in terms of deflections. The methods described herein can be used to obtain maximum deflection values that compare closely with those reported by the FWD device.

REFERENCES

1. S. Nazarian. *A Calibration Process for Determination of Surface Deflections of Pavements Using Velocity Transducers.* Research Report GR87-2, Geotechnical Engineering Center, The University of Texas at Austin, 1987.
2. Mark Product, Inc. *Mark Products Product Catalog.* Houston, Tex., 1985.
3. R. B. Bouche. *Calibration of Shock and Vibration Measuring Transducers,* Naval Research Laboratory, Washington, D.C., 1979.
4. Hewlett Packard, Inc. *Operator's Introduction to the HP3562A Dynamic Signal Analyzer.* Product No. 3562A-1, 1984.
5. R. A. Bentsen, S. Nazarian, and J. A. Harrison. Reliability Testing of Seven Nondestructive Pavement Testing Devices. In *Proc., First International Symposium on Nondestructive Testing and Backcalculation of Moduli*, ASTM, Baltimore, Md., 1988.

Publication of this paper sponsored by Committee on Strength and Deformation Characteristics of Pavement Sections.