Impact of Digital Filtering on FWD Load Cell and Deflection Sensor Responses

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The deflection response of pavements under an applied load will be studied in the Strategic Highway Research Program's (SHRP's) Long-Term Pavement Performance (LTPP) study using a falling weight deflectometer (FWD). The SHRP computer software system for the collection of data also possesses the capability to filter the data by means of a digital low-pass filter. SHRP decided to assess the effects of digital filtering of FWD data before implementation of the software in the field. Comparative analyses of noise were performed using the results of an FWD pilot study conducted in Greensboro, North Carolina, as well as other test sections throughout the United States. The results show that filtering of FWD data introduces significant random errors, particularly for rigid pavements tested under heavy loads. These errors tend to compound each other when the filtered deflections are normalized by the filtered load data. Also, the use of filtered load and deflection data may yield normalized deflection responses that exceed current normalized deflection tolerance limits, particularly for heavy loads on rigid pavements. Accordingly, it has been recommended that all FWD data be collected by SHRP with the filter off. However, because some unknown level of noise is contained within FWD data, it is also recommended that additional load- and deflection-time histories be collected and stored. Thus, if advances occur in the filtering process, the data can be reanalyzed to obtain more accurate peak load and deflection values for use in the backcalculation of layer moduli.

The Strategic Highway Research Program's (SHRP's) Long-Term Pavement Performance (LTPP) study is based on the collection both of inventory and monitoring data for numerous pavement sections located throughout the United States. Within the monitoring data, one of the most significant items that will be collected is the deflection response of these pavement sections under an applied load. This response is an important indicator of structural capacity, material properties, and subsequent pavement performance.

In order to measure this response, SHRP is using a nondestructive testing device called the falling weight deflectometer (FWD). The four FWD units purchased by SHRP, one for each SHRP region, are manufactured by Dynatest and are capable of measuring deflections under an impulse load varying from approximately 2,500 to 27,000 lb (11 to 120 kN).

Because the accurate measurement of deflections is a key element in the success of the LTPP study, SHRP has established guidelines to provide for a uniform and standardized field testing procedure (*1*). This procedure relies on a computer software system for test set-up, data collection, data storage, and a limited amount of data checking.

Although the main purpose of the software is to automate the data collection process, it also possesses the capability of filtering data by means of a digital low-pass (60 or 120 Hz) filter. This filter is intended to screen out high-frequency noise from both the load and deflection signals. Figure 1a provides an example of negative noise, whereas Figure 1b provides an example of positive noise. The noise itself is a high-frequency signal separately imposed on the normal load and deflection signals. When this noise is removed, the expected shape (approximately half-sine) of the signal is present. The unfiltered data are recordings of load and deflection time histories, an inherent capability of these FWDs. The filtering is imposed on these time histories to yield filtered peaks.

At the onset of the FWD testing of the SHRP general pavement sections (GPSs), limited information on the effects of digital filtering on FWD load and deflection response was available. As a result, a study was undertaken by SHRP to assess the impact of data filtering on the SHRP FWD data before routine implementation in the field (*2*). In this study, a comparative investigation of noise, defined as the difference between filtered (X_f) and unfiltered (X_{uf}) data, was performed.

Whereas noise is generally compared to a baseline signal in order to determine its significance, knowledge may be gained from information regarding its absolute magnitude. Accordingly, two variables describing noise were introduced in this study to quantify and define its properties. They are

$$\text{Absolute Noise} = X_f - X_{uf} \qquad (1)$$

$$\text{Relative Noise} = \frac{X_f - X_{uf}}{X_{uf}} \times 100 \qquad (2)$$

A summary of the SHRP FWD digital filtering study, including results and conclusions, is presented in this paper. The next section provides a brief summary of the FWD data used in the study. The detailed analysis results and conclusions are presented in later sections, and the implications of the findings are discussed in the final section.

SOURCE OF DATA

Analyses and conclusions contained herein are based on the test results of an FWD pilot study conducted in Greensboro,

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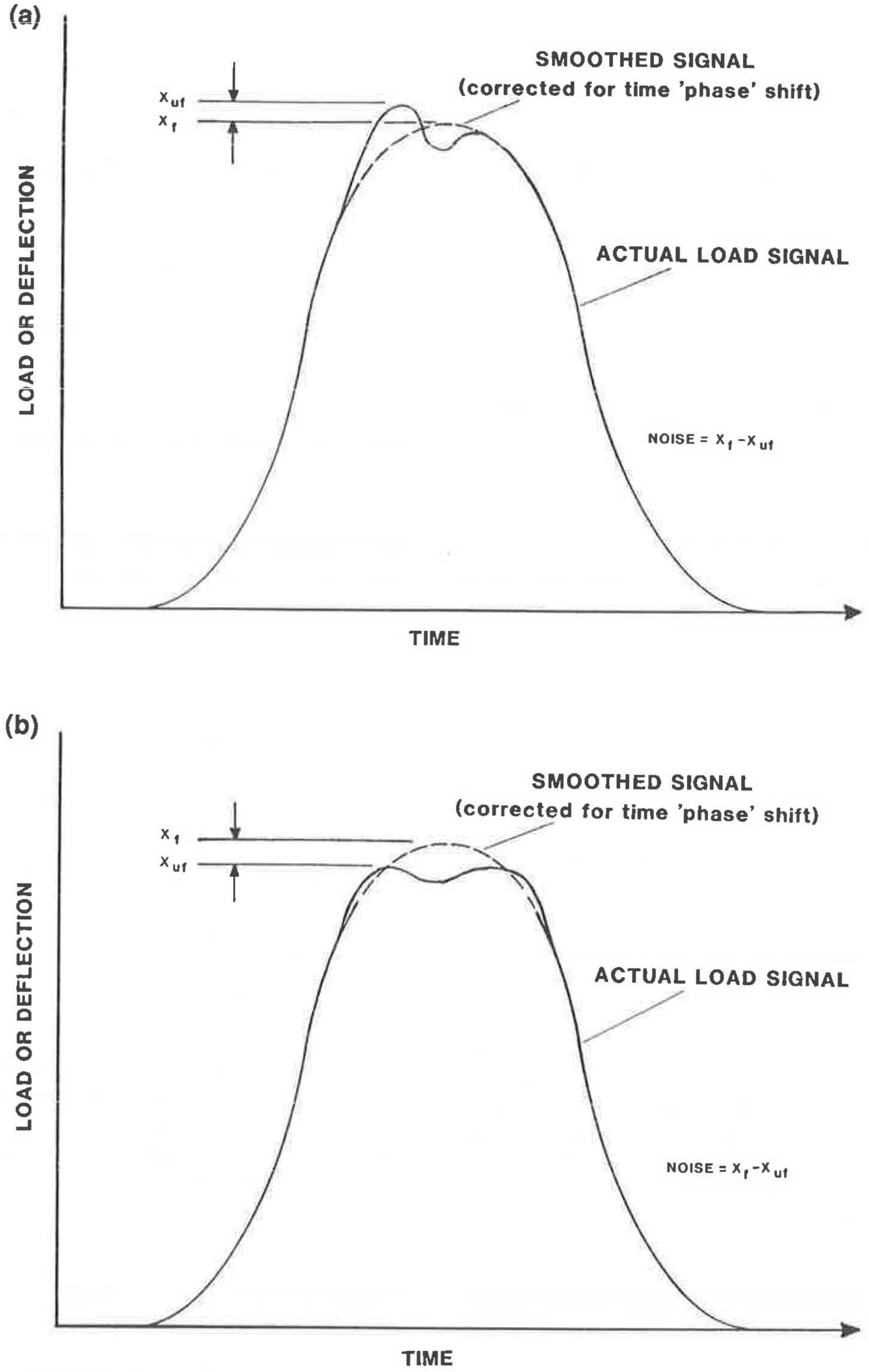


FIGURE 1 Load signal and noise.

North Carolina, in December 1988. Three pavement sections were tested in this pilot study: (a) a 4.5-in. asphalt concrete (AC) over 12-in. crushed-stone flexible pavement, (b) an 8-in. jointed plain concrete (JPCP) over 4-in. lean concrete subbase rigid pavement, and (c) an 8-in. continuously reinforced concrete (CRC) over 4-in. crushed-stone subbase pavement.

A total of 44 locations were tested on the flexible pavement: 23 locations along the midlane (SHRP Test Point Identifier F0–F1) and 21 outer-wheel path (F3) locations. Testing of the rigid pavement included 122 separate locations: 26 midlane, midpanel locations (J0–J1); 24 pavement edge, slab corner locations (J2); 24 pavement edge, midpanel locations (J3); 24 location pairs at joints along the outer-wheel path, on the approach side (J4) and leave side (J5). In the case of the CRC pavement, tests were conducted at 99 separate locations as follows: 23 midlane, midpanel locations (C0–C1); 19 pavement edge locations centered on the crack (C2); 19 pavement edge, midpanel locations (C3); 19 location pairs at cracks along the outer-wheel path, on the approach side (C4) and leave side (C5).

Although temperature effects were not being ignored during testing, they were also not specifically addressed. However, the order in which tests were performed may mitigate some concerns as to the source of the noise. Center-of-slab testing was performed early in the day and edge testing of slabs was generally performed in the afternoons to ensure that the slab areas at the test locations were in contact with the subbase.

Because four load levels were used for the flexible pavement and three load levels were used for the rigid and CRC pavements, the North Carolina FWD pilot study yielded a total of 839 load and 5,873 deflection measurements. (Each of the seven individual geophones on the FWD is considered a measurement.) More important, this pilot study provided an excellent data base for assessing the impact of FWD data filtering on a wide range of pavement types, load levels, and test locations.

ANALYSES AND RESULTS

On completion of the field data collection phase, an analysis of the data was undertaken to quantify the effects of the digital filtering. Both absolute and relative noise values were first computed from Equations 1 and 2, for all of the load and deflection measurements contained in the North Carolina FWD data files.

Various statistics were then calculated for each data set, including minimums, maximums, means, standard deviations, and coefficients of variation as well as other key distribution statistics associated with noise. Histograms and cumulative frequency distributions were also developed using the computed standard deviation and coefficient of variation values.

On the basis of this information, numerous observations were made and are summarized in the ensuing sections. The initial discussion describes the effect of data filtering on the load cell response output; the effect of filtering on deflection response is presented in the following section of the report.

Load Analysis

The analysis of load signal filtering was performed according to drop height, test location, and pavement type to assess the impact of each factor on the magnitude of both the absolute and relative noise. Statistical summaries of the analysis results are presented in Tables 1 through 3. Table 1 presents average absolute and relative noise values as well as other key distribution statistics for all test location and drop height combinations associated with the flexible pavement. Tables 2 and 3 present similar statistics for the rigid and CRC pavements, respectively. All statistical results generated for this study are contained in the North Carolina Pilot Study (*2*).

Drop Height

Load-related noise for the flexible pavement appears to depend on the drop height (i.e., load level). As presented in Table 1, the magnitudes both of the absolute and relative noise

TABLE 1 STATISTICAL SUMMARY OF LOAD-ASSOCIATED NOISE—FLEXIBLE PAVEMENT

Test Location	Drop Height	Average Absolute Noise (kPa)	Relative Noise (%)		
			Average	Positive Noise (%)	Noise Greater than "±" 5%
F0,F1	1	-5.9	-1.4	12.5	0.0
	2	-5.7	-1.0	20.9	0.0
	3	2.0	0.2	58.3	0.0
	4	1.3	0.2	66.7	0.0
	All	-2.1	-0.5	39.6	0.0
F3	1	-9.6	-2.5	0.0	0.0
	2	-14.5	-2.7	0.0	0.0
	3	-8.5	-1.2	19.1	0.0
	4	-1.0	-0.1	61.9	0.0
	All	-8.4	-1.6	20.3	0.0
ALL	1	-7.7	-2.0	6.8	0.0
	2	-9.9	-1.8	11.4	0.0
	3	-3.0	-0.4	40.9	0.0
	4	0.2	0.0	65.9	0.0
	All	-5.1	-1.0	31.2	0.0

Note: Nominal load levels are as follows:
Ht 1, 6000 lbs.
Ht 2, 9000 lbs.
Ht 3, 12000 lbs.
Ht 4, 16000 lbs.

TABLE 2 STATISTICAL SUMMARY OF LOAD-ASSOCIATED NOISE—RIGID PAVEMENT

			Relative Noise (%)		
Test Location	Drop Height	Average Absolute Noise (kPa)	Average	Positive Noise (%)	Noise Greater than "±" 5%
J0,J1	1	-16.0	-4.4	100.0	11.4
	2	-22.2	-4.2	100.0	3.8
	3	-28.7	-2.7	100.0	0.0
	All	-22.3	-3.7	100.0	5.1
J2	1	-24.2	-4.2	100.0	16.8
	2	-20.6	-3.6	100.0	8.4
	3	-18.7	-3.4	100.0	8.4
	All	-21.1	-3.8	100.0	11.2
J3	1	-19.5	-5.5	100.0	37.6
	2	-25.8	-5.1	100.0	22.0
	3	-32.5	-3.1	100.0	12.6
	All	-25.9	-4.6	100.0	24.1
J4	1	-14.5	-4.1	100.0	8.3
	2	-21.1	-4.1	100.0	0.0
	3	-30.8	-2.9	100.0	0.0
	All	-22.1	-3.7	100.0	2.8
J5	1	-14.2	-4.0	100.0	0.0
	2	-20.3	-4.0	100.0	0.0
	3	-28.1	-2.7	100.0	0.0
	All	-20.9	-3.6	100.0	0.0
ALL	1	-15.8	-4.5	100.0	14.8
	2	-22.2	-4.3	100.0	6.8
	3	-29.4	-2.8	100.0	4.2
	All	-22.5	-3.9	100.0	8.5

generally decrease as the drop height increases. Whereas this trend was anticipated for the relative noise because of the increase in load magnitude, it was somewhat unexpected for the absolute noise. However, a closer look at the data reveals that as the load level increases, there is a significant shift in the overall distribution of noise values from negative to positive, causing the average absolute value to decrease. For the first drop height, 12.5 percent of the noise at location F0–F1 and 0.0 percent at location F3 is positive and increases to more than 60 percent for the fourth drop height.

As for flexible pavement, rigid-pavement load-related noise also appears to depend on drop height. As presented in Table 2, absolute noise levels increase and relative noise levels decrease as the drop height increases. Unlike the flexible pavement, there is no shift in the noise distribution from negative to positive with increasing drop height and there are no positive noise values. There is, however, a definite trend regarding the distribution of large noise values. In all cases, the distribution of relative noise values exceeding 5 percent (the so-called "large noise") decreases as the load level increases.

Unlike the previous pavement types, the results presented in Table 3 show no clear trends between noise level and drop height for the CRC pavement. At some locations, noise levels decrease as the load increases, whereas at other locations maximum noise levels occur at the second drop height. A possible explanation for this lack of trend is the shift in the noise distribution from negative to positive with increasing drop height. Also, the percentage of large noise decreases as the drop height increases.

Test Location

Although only two locations were tested, noise levels associated with the flexible pavement appear to depend on the test location also. As presented in Table 1, average absolute and relative noise values in the wheel path (F3) are much larger than those at midlane (F0–F1). However, much of this difference may be due to the distribution of positive and negative values at each location.

Unlike the flexible pavement, load-related noise for the rigid pavement does not appear to depend on the test location. Although noise levels vary from one location to another, the values presented in Table 2 show that these differences are small. The largest difference in average absolute noise occurs between locations J5 and J3 and is equal to 5.0 kPa (0.7 psi). The maximum average relative noise difference also occurs

TABLE 3 STATISTICAL SUMMARY OF LOAD-ASSOCIATED NOISE—CRC PAVEMENT

Test Location	Drop Height	Average Absolute Noise (kPa)	Relative Noise (%) Average	Relative Noise (%) Positive Noise (%)	Relative Noise (%) Noise Greater than "±" 5%
C0,C1	1	-5.1	-1.3	25.9	0.0
	2	-2.1	-0.4	39.0	0.0
	3	-1.7	-0.1	47.8	0.0
	All	-3.0	-0.6	37.6	0.0
C2	1	-12.6	-3.0	0.0	15.9
	2	-11.8	-2.0	26.3	10.5
	3	-6.3	-0.6	26.4	0.0
	All	-10.2	-1.9	17.6	8.8
C3	1	-13.9	-3.4	0.0	0.0
	2	-15.3	-2.7	0.0	0.0
	3	-7.3	-0.8	15.8	0.0
	All	-12.2	-2.3	5.3	0.0
C4	1	-11.7	-3.0	0.0	5.3
	2	-21.6	-3.9	0.0	0.0
	3	-9.6	-1.0	0.0	0.0
	All	-14.3	-2.6	0.0	1.8
C5	1	-11.8	-3.0	0.0	10.6
	2	-20.8	-3.8	0.0	0.0
	3	-7.9	-0.8	5.3	0.0
	All	-13.5	-2.5	1.8	3.5
ALL	1	-10.8	-2.7	5.2	6.4
	2	-13.8	-2.5	13.1	2.1
	3	-6.4	-0.6	19.0	0.0
	All	-10.3	-1.9	12.5	2.8

between locations J5 and J3 and is equal to −1 percent. There are, however, significant differences in the amount of large noise between test locations.

Load-related noise levels on CRC pavements also do not appear to depend on test location. With the exception of location C0–C1, both absolute and relative noise values vary little from one location to another. Aside from location C0–C1, the largest average absolute and relative noise differences occur between locations C2 and C4. However, there are significant differences in the amount of positive noise as well as large noise between test locations.

Pavement Type

In order to assess the effects of pavement type on load-related noise, the analysis results generated in previous sections were combined to develop Figure 2, which shows noise as a function of pavement type and drop height. Note that average values for all test locations were combined to produce those values.

On the basis of the information provided in this figure, there is a definite increase in the average relative noise level as the rigidity of the pavement increases (i.e., from flexible to CRC to rigid). The overall average noise values for each pavement type are −1.0, −1.9, and −3.9 percent, respectively. No trends of relative noise variability (standard deviation) due to pavement type are apparent. The CRC pavement has the highest standard deviation; however, all are within 0.4 percent of each other.

There are also a definite increase in the amount of positive noise and a decrease in the amount of large noise as pavement flexibility increases. Overall, 0.0 percent of the rigid pavement noise data has positive values, compared with 12.5 percent of CRC pavement and 31.2 percent of flexible pavement. In addition, 0.0 percent of flexible pavement noise data is large noise, compared with 2.8 percent of CRC pavement and 8.5 percent of rigid pavement.

Overall Discussion

The major objective of the load signal analysis was to assess the impact of data filtering on the load cell response output. Thus, FWD test results were analyzed to determine the influence of drop height, test location, and pavement type on the load signal. Figures 3 and 4 show the effects of pavement type

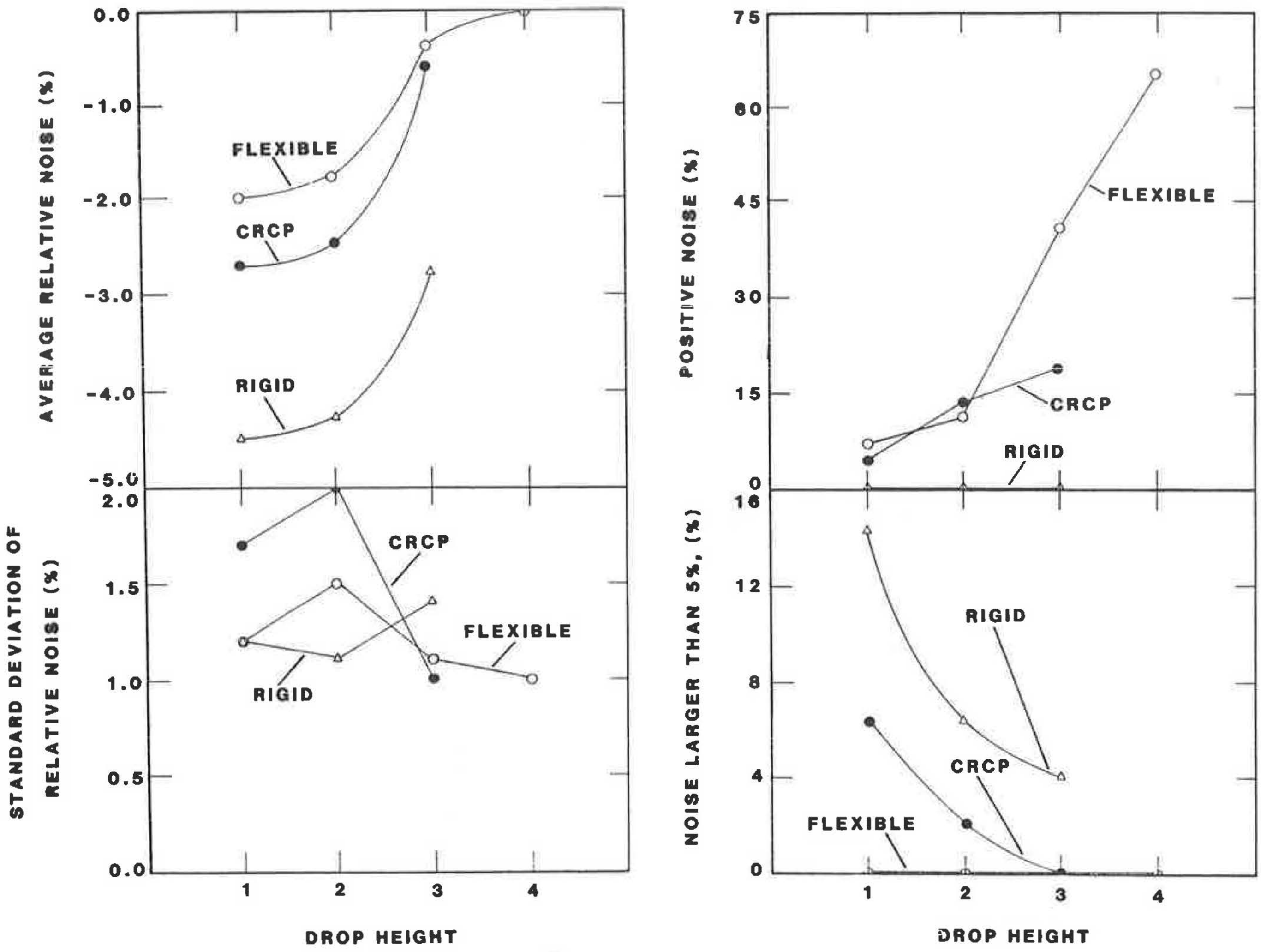


FIGURE 2 **Effect of drop height and pavement type.**

and FWD drop height on the absolute and relative noise magnitudes, respectively. From this study, the following major conclusions for load signal filtering were developed:

1. Both the absolute and relative noise values appear to be functions of pavement type and load magnitude. Test location does not appear to be as significant an influence on the magnitude of noise.
2. Both absolute and relative average noise values increase with increasing pavement rigidity (i.e., from a flexible to a CRC to a rigid pavement system).
3. Average noise levels were found to be negative for all pavement type and drop height combinations studied, implying that the noise magnitude is not purely random and that filtered load response data are, on average, always less than the unfiltered response.
4. The magnitude of the absolute noise is surprisingly large, especially when viewed through the statistical distribution results. The most severe case is associated with heavy loads on rigid pavements. For this condition, an average noise of −425 lb, with $\bar{X} \pm 2SD$ (average ±2 standard deviations) limits of 0 to −850 lb were computed.
5. The random component of the load filtering process had a coefficient of variation in the 1.3 to 1.5 percent range (*3*). In contrast, load repeatability errors on unfiltered load data, because of replicate drops at a given point and drop height, were approximately CV = 0.4 percent. It could therefore be concluded that the introduction of a load filter procedure introduced an additional variability to load response that was approximately 3 to 4 times as large as the replicate error on unfiltered load response.

Deflection Analysis

The analysis of deflection signal filtering was performed according to geophone number (radial offset), drop height, test location, and pavement type to assess the impact of these factors on noise level. Unlike the load signal, however, no analysis of positive noise or large noise distributions was conducted; only 0.5 percent of all 5,873 deflection values collected were found to have positive noise characteristics, whereas only 1.4 percent of the values exhibited large noise.

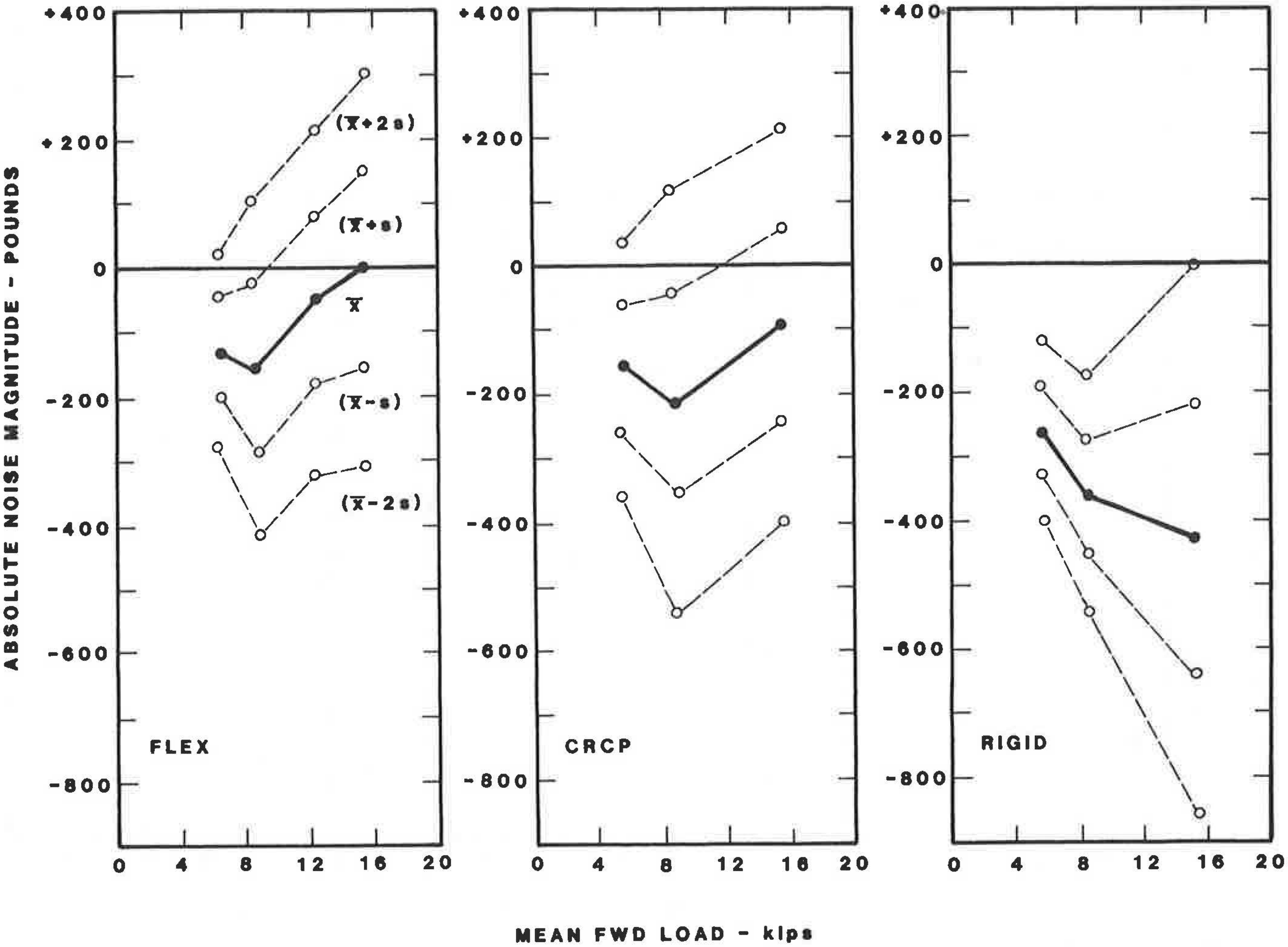


FIGURE 3 Absolute noise magnitude as a function of pavement type and FWD drop height (load).

Results of this analysis are presented in Tables 4 through 6. Table 4 presents average absolute and relative deflection noise for all combinations of test location, drop height, and geophone number on flexible pavement. Similar statistics for rigid and CRC pavements are presented in Tables 5 and 6, respectively.

Geophone Number

The deflection noise associated with the flexible pavement appears to heavily depend on the geophone number. With few exceptions, absolute noise levels decrease whereas relative noise levels increase as the radial distance increases. As presented in Table 4, the overall average absolute value decreases from −1.1 μm (0.043 mils) at Geophone 1 to −0.3 μm (0.012 mils) at Geophone 7, whereas the average relative value increases from −0.2 percent at Geophone 1 to −0.9 percent at Geophone 7.

Like the flexible pavement, rigid pavement deflection noise also appears to depend on the geophone number. In general, absolute noise levels decrease, whereas relative noise levels decrease as the radial distance increases. As presented in Table 5, the overall average absolute noise value decreases from −1.1 μm (0.043 mils) at Geophone 1 to −0.5 μm (0.020 mils) at Geophone 7, and the average relative value increases from −0.8 percent at Geophone 1 to −1.6 percent at Geophone 7.

CRC pavement deflection noise also appears to depend on the geophone number, particularly when compared to that of drop height and test location. Although no clear trend between absolute noise and radial distance is apparent, there is a definite increase in the relative noise levels with radial distance, particularly for the outer geophones. As presented in Table 6, the overall average relative noise varies from −0.2 percent at Geophone 1 to −0.9 percent at Geophone 7.

Drop Height

Deflection noise levels associated with flexible pavement also appear to depend on drop height, but to a lesser degree when compared to geophone location. Although no clear trends in the absolute noise values can be observed, relative noise

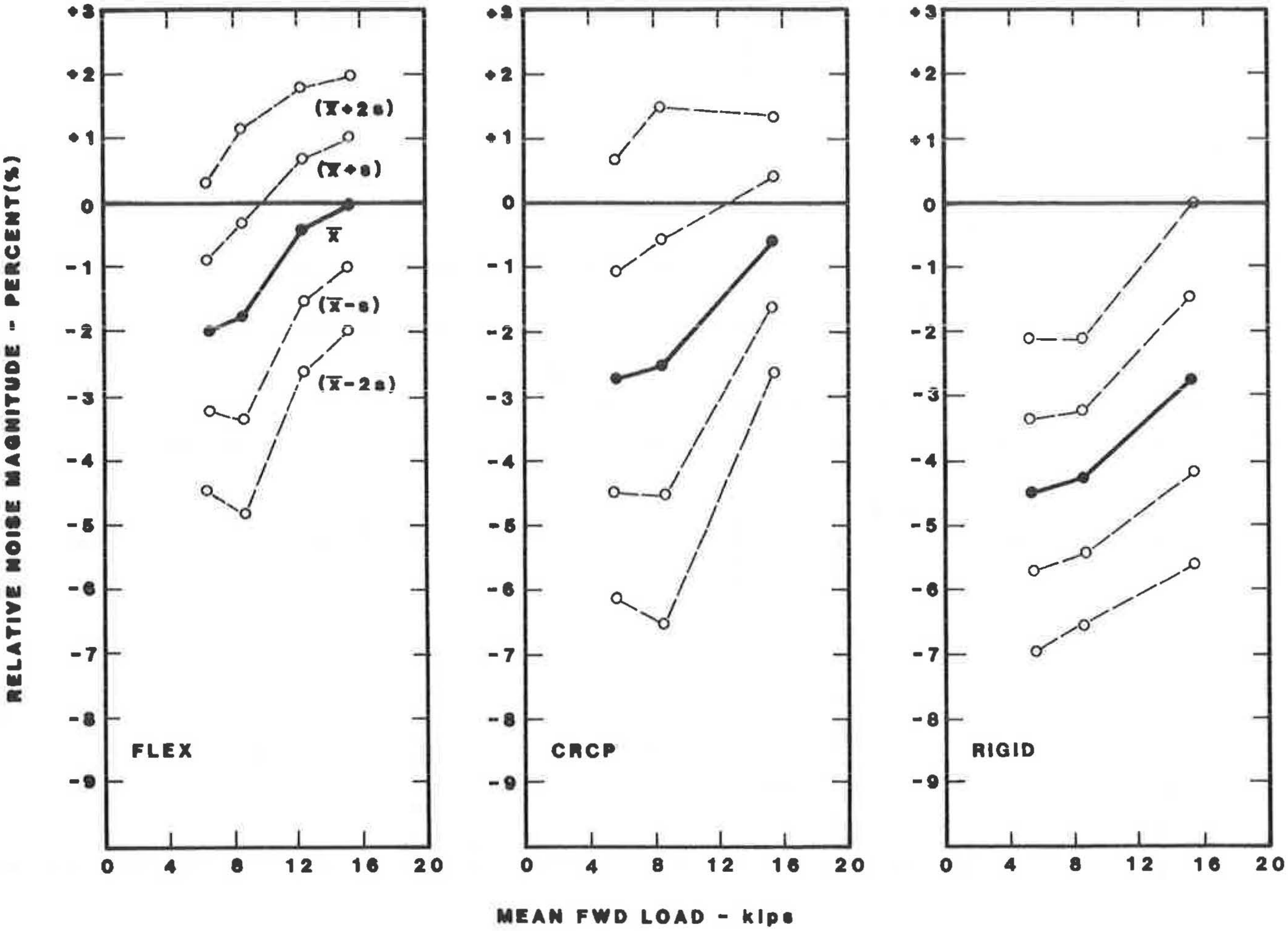


FIGURE 4 **Relative noise magnitude as a function of pavement type and FWD drop height (load).**

definitely decreases as the drop height increases. As presented in Table 4, the overall average relative noise value for Geophone 1 decreases from −0.4 percent at the first drop height to −0.1 percent at the fourth drop height and from −1.2 to −0.7 percent at Geophone 7.

For the rigid pavement, deflection-related noise also depends on drop height, particularly when compared to the flexible pavement. Although no clear trends in the absolute noise are apparent (see Table 5), the magnitude of the relative noise definitely decreases as the drop height increases. As presented in Table 5, the overall average relative value at Geophone 1 decreases from −1.2 percent at the first drop height to −0.7 percent at the fourth drop height, whereas that at Geophone 7 decreases from −2.5 to −1.6 percent.

Deflection noise in CRC pavement does not appear to be as sensitive to drop height as that for rigid and flexible pavements, specially when compared to geophone location. No general trend between absolute noise and drop height is apparent. Also, no definitive trend is apparent for the relative noise, particularly for the first four geophones. For the last three geophones, as presented in Table 6, the relative noise clearly decreases with increasing load level.

Test Location

From a practical viewpoint, flexible pavement deflection noise does not appear to depend on test location. Although significant differences in the average absolute values are apparent between locations F0–F1 and F3 at the first two geophones, the overall average absolute and relative noise values are similar at both locations (see Table 4). This similarity is particularly true for the relative noise at Geophone 7, where the largest difference, 0.3 percent, occurs.

Unlike the flexible pavement, deflection noise for the rigid pavement does appear to depend on the geophone location but to a lesser degree when compared to the test location. In general, absolute noise differences between test locations appear to decrease, whereas relative noise differences increase as the radial distance increases. Overall, average values are similar, specially when isolated data points are eliminated from the comparison (see Table 5).

Like the flexible pavement, the effects of test location on CRC pavement deflection noise are not significant. Absolute noise differences between test locations decrease as radial distance increases. As presented in Table 6, the maximum

TABLE 4 AVERAGE ABSOLUTE AND RELATIVE DEFLECTION NOISE VALUES—FLEXIBLE PAVEMENT

		Average Absolute Noise (Microns)							Average Relative Noise (%)						
		Geophone Number							Geophone Number						
Test Location	Drop Height	1	2	3	4	5	6	7	1	2	3	4	5	6	7
F1	1	-0.8	-0.7	-0.7	-0.5	-0.6	-0.4	-0.4	-0.4	-0.4	-0.4	-0.4	-0.6	-0.9	-1.8
	2	-1.1	-1.0	-0.9	-0.9	-0.7	-0.6	-0.3	-0.4	-0.4	-0.4	-0.4	-0.5	-1.0	-0.8
	3	-1.0	-0.8	-0.8	-0.5	-0.7	-0.7	-0.5	-0.2	-0.2	-0.2	-0.2	-0.3	-0.7	-1.1
	4	-0.7	-0.5	-0.4	-0.4	-0.2	-0.4	-0.3	-0.1	-0.1	-0.1	-0.1	-0.1	-0.3	-0.5
	All	-0.9	-0.7	-0.7	-0.6	-0.5	-0.5	-0.4	-0.3	-0.3	-0.3	-0.3	-0.4	-0.8	-1.1
F3	1	-1.0	-1.1	-0.6	-0.9	-0.8	-0.3	-0.1	-0.3	-0.4	-0.3	-0.5	-0.7	-0.9	-0.7
	2	-1.1	-1.3	-1.1	-0.7	-0.8	-0.5	-0.3	-0.2	-0.3	-0.3	-0.3	-0.4	-0.8	-1.1
	3	-1.5	-1.5	-1.2	-0.8	-0.7	-0.4	-0.3	-0.2	-0.2	-0.2	-0.2	-0.2	-0.4	-0.7
	4	-1.5	-1.0	-0.8	-0.8	-0.4	-0.3	-0.5	-0.1	-0.1	-0.1	-0.1	-0.1	-0.2	-0.8
	All	-1.3	-1.3	-0.9	-0.8	-0.7	-0.4	-0.3	-0.2	-0.3	-0.2	-0.3	-0.3	-0.6	-0.8
ALL	1	-0.9	-0.9	-0.6	-0.7	-0.7	-0.4	-0.3	-0.4	-0.4	-0.3	-0.5	-0.6	-0.9	-1.2
	2	-1.1	-1.1	-1.0	-0.8	-0.8	-0.5	-0.3	-0.3	-0.3	-0.4	-0.4	-0.4	-0.9	-1.0
	3	-1.3	-1.1	-1.0	-0.6	-0.7	-0.5	-0.4	-0.2	-0.2	-0.2	-0.2	-0.3	-0.6	-0.9
	4	-1.1	-0.8	-0.6	-0.6	-0.3	-0.4	-0.4	-0.1	-0.1	-0.1	-0.1	-0.1	-0.3	-0.7
	All	-1.1	-1.0	-0.8	-0.7	-0.6	-0.5	-0.3	-0.2	-0.3	-0.3	-0.3	-0.3	-0.7	-0.9

TABLE 5 AVERAGE ABSOLUTE AND RELATIVE DEFLECTION NOISE VALUES—RIGID PAVEMENT

		Average Absolute Noise (Microns)							Average Relative Noise (%)						
		Geophone Number							Geophone Number						
Test Location	Drop Height	1	2	3	4	5	6	7	1	2	3	4	5	6	7
J0,J1	1	-0.4	-0.5	-0.6	-0.6	-0.6	-0.5	-0.4	-1.1	-1.3	-1.7	-1.7	-1.8	-2.0	-2.6
	2	-0.6	-0.5	-0.4	-0.4	-0.5	-0.5	-0.6	-1.0	-0.9	-0.7	-0.7	-1.0	-1.3	-2.5
	3	-1.4	-1.0	-1.2	-1.0	-0.7	-0.5	-0.5	-1.0	-0.7	-0.9	-0.8	-0.6	-0.6	-0.9
	All	-0.8	-0.7	-0.7	-0.7	-0.6	-0.5	-0.5	-1.0	-1.0	-1.1	-1.1	-1.2	-1.3	-2.0
J2	1	-1.5	-1.5	-1.1	-1.0	-0.9	-0.5	-0.5	-0.8	-0.9	-0.8	-0.7	-0.8	-0.9	-1.3
	2	-2.2	-1.2	-1.0	-0.7	-1.0	-0.6	-0.3	-1.0	-0.8	-0.6	-0.5	-1.0	-1.1	-0.8
	3	-2.1	-1.4	-1.2	-0.9	-1.0	-0.8	-0.6	-0.9	-0.7	-0.8	-0.7	-0.6	-1.3	-1.6
	All	-1.9	-1.3	-1.1	-0.8	-1.0	-0.6	-0.5	-0.9	-0.8	-0.7	-0.6	-0.8	-1.1	-1.2
J3	1	-0.6	-0.7	-0.6	-0.4	-0.6	-0.3	-0.3	-1.1	-1.2	-1.1	-0.9	-1.4	-1.1	-1.6
	2	-0.4	-0.5	-0.5	-0.6	-0.4	-0.4	-0.5	-0.5	-0.5	-0.6	-0.8	-0.5	-0.8	-1.7
	3	-1.8	-1.4	-1.1	-1.0	-0.8	-0.5	-0.6	-0.9	-0.7	-0.6	-0.6	-0.5	-0.4	-0.8
	All	-0.9	-0.9	-0.7	-0.7	-0.6	-0.4	-0.5	-0.8	-0.8	-0.7	-0.7	-0.8	-0.8	-1.4
J4	1	-1.2	-0.3	-0.5	-0.8	-0.5	-0.8	-0.4	-1.3	-0.8	-1.5	-1.1	-1.6	-3.6	-2.8
	2	-0.7	-0.5	-0.4	-0.4	-0.4	-0.3	-0.5	-0.4	-1.0	-0.9	-0.4	-1.0	-0.9	-2.2
	3	-1.5	-0.5	-0.4	-1.3	-0.5	-0.5	-0.3	-0.5	-0.3	-0.3	-0.5	-0.6	-0.6	-0.5
	All	-1.1	-0.4	-0.4	-0.8	-0.5	-0.5	-0.4	-0.7	-0.7	-0.9	-0.6	-1.0	-1.7	-1.8
J5	1	-0.8	-0.5	-0.5	-0.5	-0.3	-0.5	-0.6	-1.0	-0.7	-0.9	-1.5	-0.6	-1.6	-3.4
	2	-0.4	-0.2	-0.3	-0.5	-0.3	-0.5	-0.5	-0.4	-0.2	-0.3	-0.9	-0.4	-1.1	-1.8
	3	-1.6	-1.0	-1.0	-0.4	-0.6	-0.5	-0.2	-0.6	-0.5	-0.5	-0.3	-0.4	-0.4	-0.3
	All	-0.9	-0.6	-0.6	-0.4	-0.4	-0.5	-0.4	-0.7	-0.5	-0.6	-0.9	-0.5	-1.1	-1.8
ALL	1	-0.9	-0.7	-0.7	-0.6	-0.5	-0.5	-0.5	-1.2	-1.1	-1.3	-1.2	-1.3	-2.0	-2.5
	2	-0.7	-0.6	-0.5	-0.5	-0.5	-0.5	-0.5	-0.8	-0.8	-0.8	-0.8	-0.9	-1.2	-1.6
	3	-1.7	-1.1	-1.0	-0.9	-0.8	-0.5	-0.4	-0.6	-0.7	-0.6	-0.7	-0.8	-1.1	-1.8
	All	-1.1	-0.8	-0.7	-0.7	-0.6	-0.5	-0.5	-0.7	-0.5	-0.5	-0.5	-0.5	-0.5	-0.6

TABLE 6 AVERAGE ABSOLUTE AND RELATIVE DEFLECTION NOISE VALUES—CRC PAVEMENT

		Average Absolute Noise (Microns)							Average Relative Noise (%)						
		Geophone Number							Geophone Number						
Test Location	Drop Height	1	2	3	4	5	6	7	1	2	3	4	5	6	7
C0,C1	1	-0.4	-0.5	-0.7	-0.4	-0.5	-0.6	-0.6	-0.4	-0.4	-0.7	-0.4	-0.6	-1.2	-2.0
	2	-0.6	-0.2	-0.4	-0.5	-0.5	-0.4	-0.5	-0.3	-0.1	-0.3	-0.4	-0.4	-0.5	-1.0
	3	-0.8	-0.4	-0.5	-0.5	-0.3	-0.3	-0.4	-0.3	-0.2	-0.2	-0.2	-0.2	-0.3	-0.5
	All	-0.6	-0.4	-0.5	-0.5	-0.4	-0.5	-0.5	-0.3	-0.2	-0.4	-0.3	-0.4	-0.6	-1.2
C2	1	-0.8	-0.9	-0.6	-0.6	-0.7	-0.8	-0.7	-0.3	-0.4	-0.3	-0.3	-0.4	-0.8	-1.4
	2	-1.0	-0.9	-0.7	-0.8	-0.7	-0.5	-0.4	-0.3	-0.3	-0.2	-0.3	-0.3	-0.3	-0.5
	3	-1.4	-1.2	-1.1	-0.9	-0.9	-0.8	-0.3	-0.3	-0.2	-0.2	-0.2	-0.2	-0.4	-0.2
	All	-1.1	-1.0	-0.8	-0.8	-0.8	-0.7	-0.5	-0.3	-0.3	-0.3	-0.3	-0.3	-0.5	-0.7
C3	1	-0.6	-0.8	-0.7	-0.7	-0.6	-0.5	-0.5	-0.3	-0.5	-0.4	-0.4	-0.4	-0.5	-0.9
	2	-0.7	-0.8	-0.8	-0.8	-0.6	-0.2	-0.5	-0.2	-0.3	-0.3	-0.3	-0.3	-0.2	-0.6
	3	-1.1	-1.1	-1.0	-1.2	-1.0	-0.9	-0.6	-0.2	-0.3	-0.2	-0.3	-0.3	-0.4	-0.5
	All	-0.8	-0.9	-0.8	-0.9	-0.7	-0.6	-0.5	-0.3	-0.3	-0.3	-0.3	-0.3	-0.4	-0.7
C4	1	-0.3	-0.1	-0.2	-0.5	-0.5	-0.7	-0.4	-0.2	-0.1	-0.1	-0.5	-0.6	-1.2	-1.0
	2	-0.2	0.0	-0.1	-0.2	-0.5	-0.5	-0.6	-0.1	0.0	-0.1	-0.1	-0.3	-0.5	-1.1
	3	-0.6	-0.4	-0.6	-0.5	-0.4	-0.4	-0.5	-0.2	-0.1	-0.2	-0.2	-0.1	-0.2	-0.4
	All	-0.4	-0.1	-0.3	-0.4	-0.5	-0.5	-0.5	-0.2	-0.1	-0.1	-0.2	-0.3	-0.6	-0.8
C5	1	-0.2	-0.3	-0.3	-0.4	-0.4	-0.6	-0.5	-0.1	-0.3	-0.2	-0.3	-0.4	-1.0	-1.2
	2	-0.1	0.0	-0.2	-0.2	-0.4	-0.7	-0.4	-0.0	0.0	-0.1	-0.1	-0.3	-0.7	-0.8
	3	-0.5	-0.3	-0.2	-0.4	-0.5	-0.4	-0.5	-0.1	-0.1	-0.1	-0.1	-0.2	-0.2	-0.5
	All	-0.2	-0.2	-0.2	-0.3	-0.4	-0.6	-0.5	-0.1	-0.1	-0.1	-0.2	-0.3	-0.6	-0.8
ALL	1	-0.5	-0.5	-0.5	-0.5	-0.5	-0.6	-0.5	-0.3	-0.3	-0.4	-0.4	-0.5	-0.9	-1.3
	2	-0.5	-0.4	-0.5	-0.5	-0.5	-0.5	-0.5	-0.2	-0.1	-0.2	-0.2	-0.3	-0.4	-0.8
	3	-0.9	-0.7	-0.7	-0.7	-0.6	-0.6	-0.5	-0.2	-0.2	-0.2	-0.2	-0.2	-0.3	-0.4
	All	-0.6	-0.5	-0.5	-0.6	-0.6	-0.6	-0.5	-0.2	-0.2	-0.3	-0.3	-0.3	-0.6	-0.9

absolute average noise difference between locations at Geophone 1 is 0.9 μm and decreases to 0.0 μm at Geophone 7. Unlike the absolute noise, relative noise values appear to be independent of the test location.

Pavement Type

In order to assess the effects of pavement type on deflection-related noise, the analysis results contained in Tables 4 through 6 were used to develop a series of figures that summarize noise as a function of pavement type and other key variables.

Figure 5 shows the cumulative frequency diagrams for absolute deflection noise as a function of the three pavement type categories investigated. As can be observed, although there are small differences between pavement types, their difference from a practical viewpoint is quite insignificant. In addition, unlike the load analysis, there appears to be no significant and observable trend in the absolute noise magnitude relative to the overall flexibility of the pavement structure. In general, average absolute noise levels are quite similar for both flexible and rigid pavements, whereas CRC pavement had the lowest absolute noise level, particularly at geophones near the load plate. Because of this, average relative noise levels are generally the same for flexible and CRC pavements, whereas the rigid pavement average relative noise levels are about 2 to 4 times as great. Therefore, although minor differences between pavement types are noticeable, they are quite insignificant from a practical viewpoint, and it is concluded that the absolute noise distribution is generally independent of pavement type.

Figure 6 shows the effects of drop height on the average deflection noise levels for the three pavement types studied. There is no clear trend for absolute noise level between pavement types and drop heights, with average values ranging between −0.6 and −0.7 μm. In contrast, the average relative noise shows a decreasing trend in noise level with increasing load. However, it can also be observed that there is no unique trend in noise for all pavement types. This indirectly justifies the statement that the best parameter to describe deflection noise is the absolute noise, which appears to be independent of deflection magnitude. Figure 7 shows the absolute noise frequency distribution patterns by drop height and pavement type. It can be observed for all cases that the largest percentage of noise is within the 0 to −2 μm range.

As noted earlier, the one variable that appears to have the most significant impact on deflection noise was geophone location. Figure 8 shows the effects of this variable on the deflection noise values. As shown, there is a general decrease in the average absolute noise level as distance from the load plate increases. From a relative noise viewpoint, the noise is nearly constant for a particular pavement type, specially for

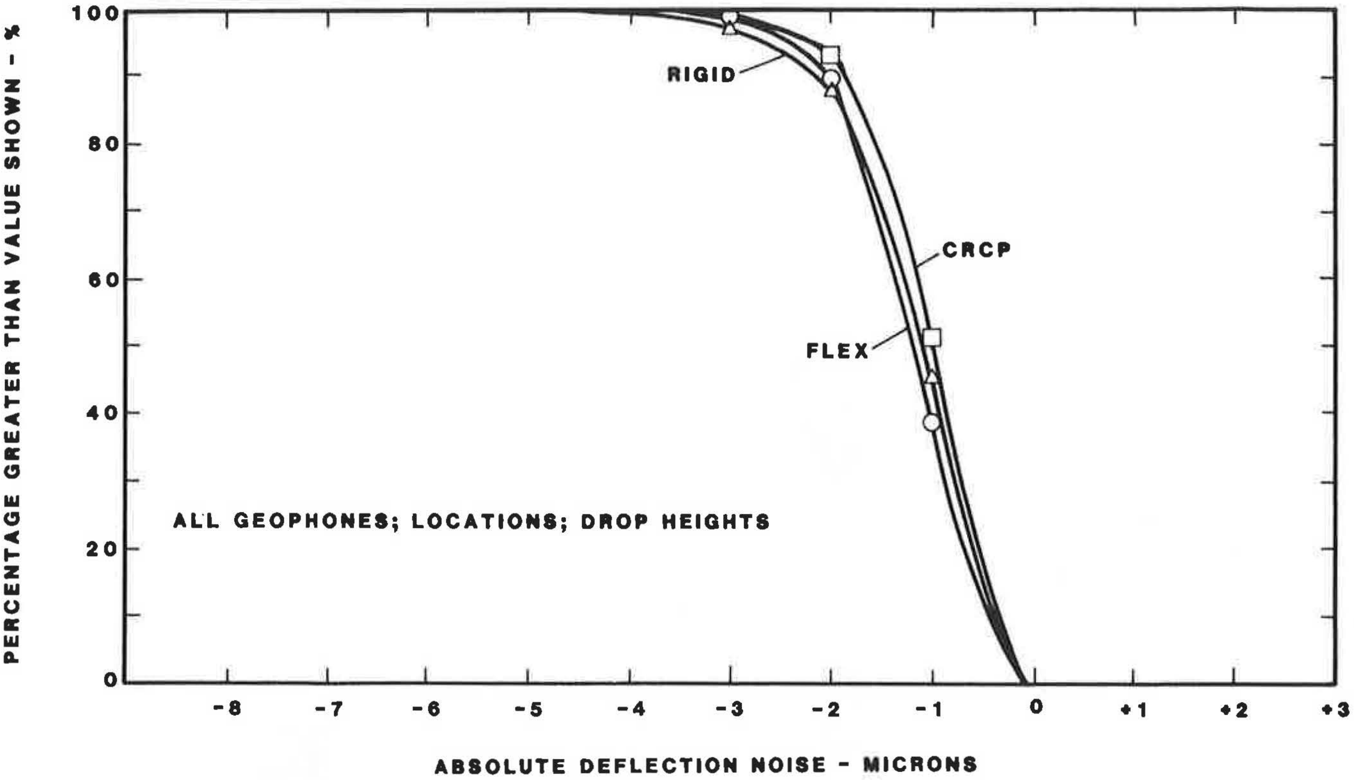


FIGURE 5 Cumulative frequency plot of absolute deflection noise by pavement type.

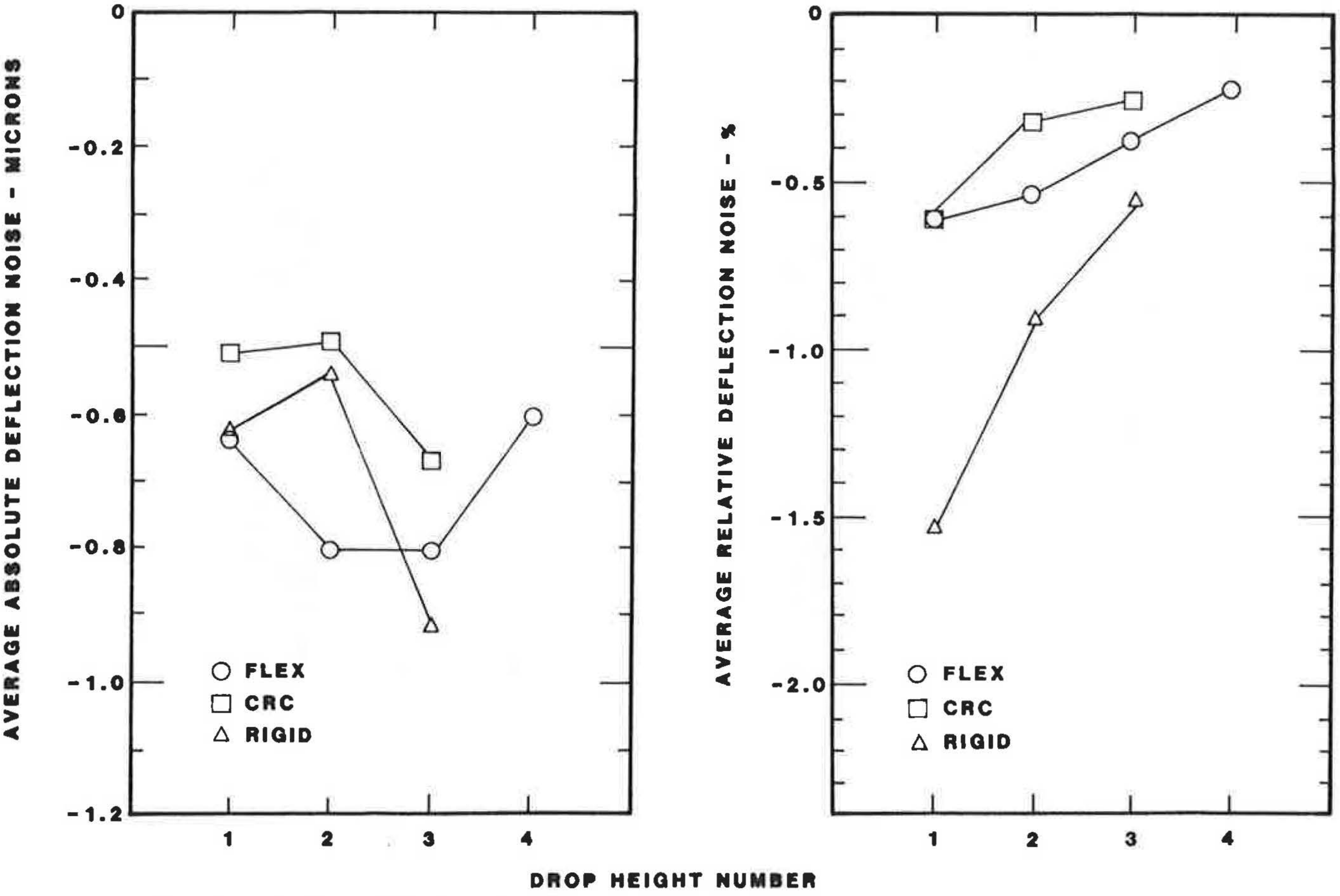


FIGURE 6 Effect of drop height on deflection noise as a function of pavement type.

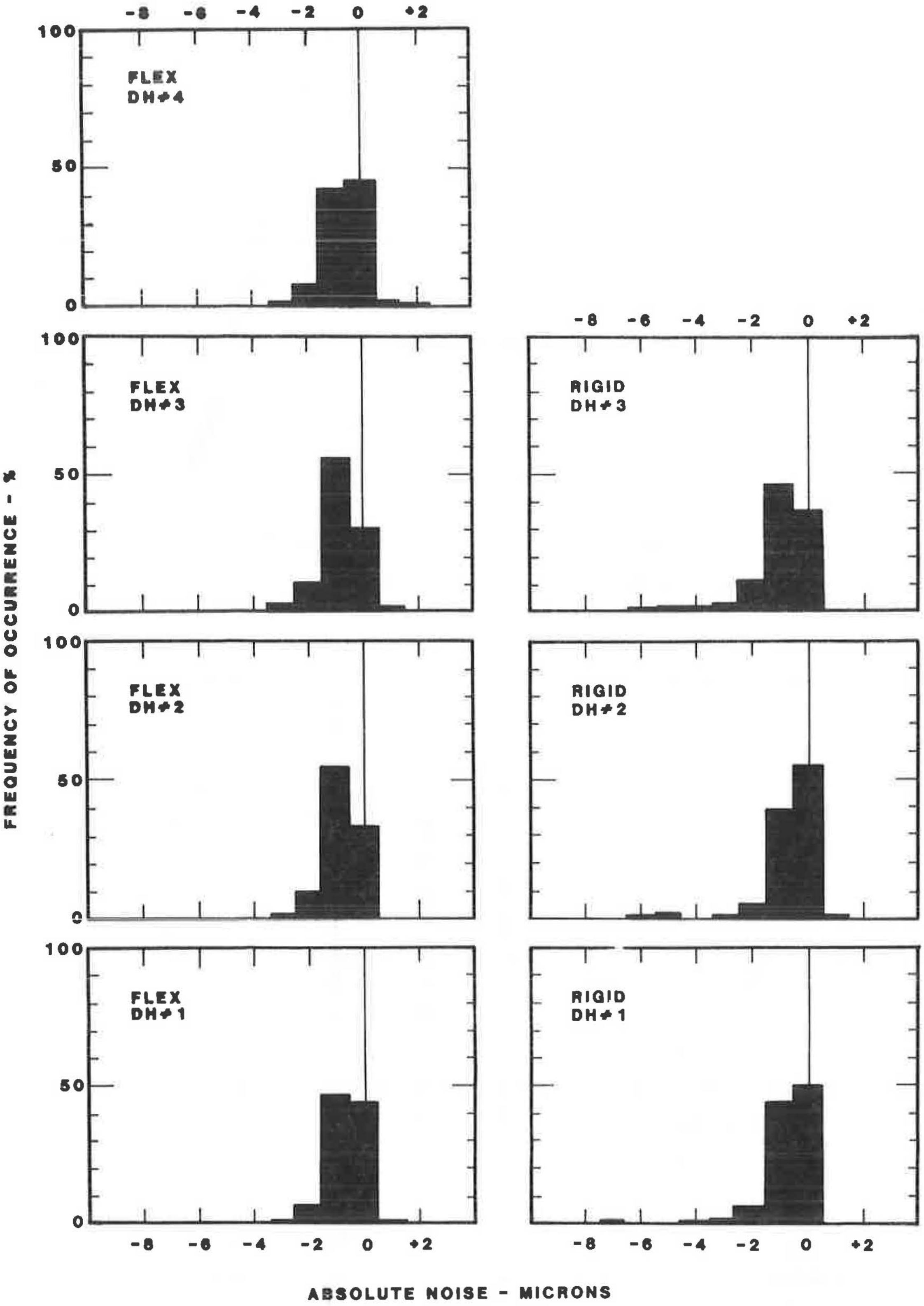


FIGURE 7 Absolute deflection noise frequency distributions as a function of pavement type and drop height.

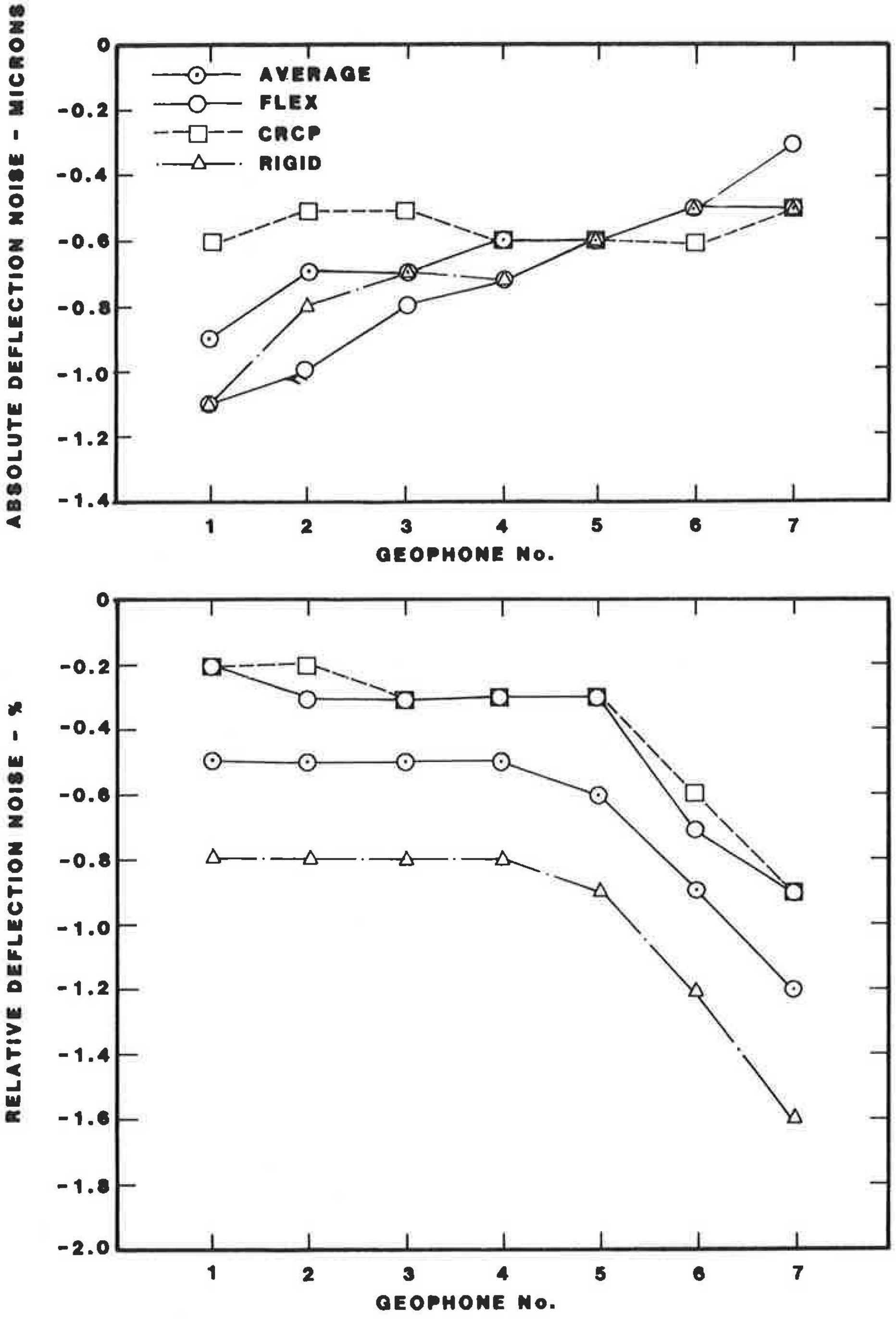


FIGURE 8 Effect of geophone location on deflection noise as a function of pavement type.

the first five geophone locations. Beyond the fifth geophone, the relative noise percentage rapidly increases. Figure 9 similarly supports this conclusion by showing the continuous shift in the cumulative frequency distributions of the absolute noise with increasing geophone number. Although this difference is noticeable by geophone, the overall difference between geophones is quite small.

Overall Discussion

The major objective of the deflection signal analysis was to assess the impact of filtering on the deflection data. Using 5,873 individual test results, the effects of pavement type, test location, drop height, and geophone number were investigated. From this analysis, the following major conclusions were developed:

1. In general, the deflection noise is almost exclusively negative in nature; i.e., filtered deflections are smaller than unfiltered deflections, consistent with expectations.
2. In comparing absolute noise to relative noise parameters, absolute noise is a better descriptor. Using this variable, it appears that pavement type, drop height, and test location do not affect the distribution of absolute deflection noise. The

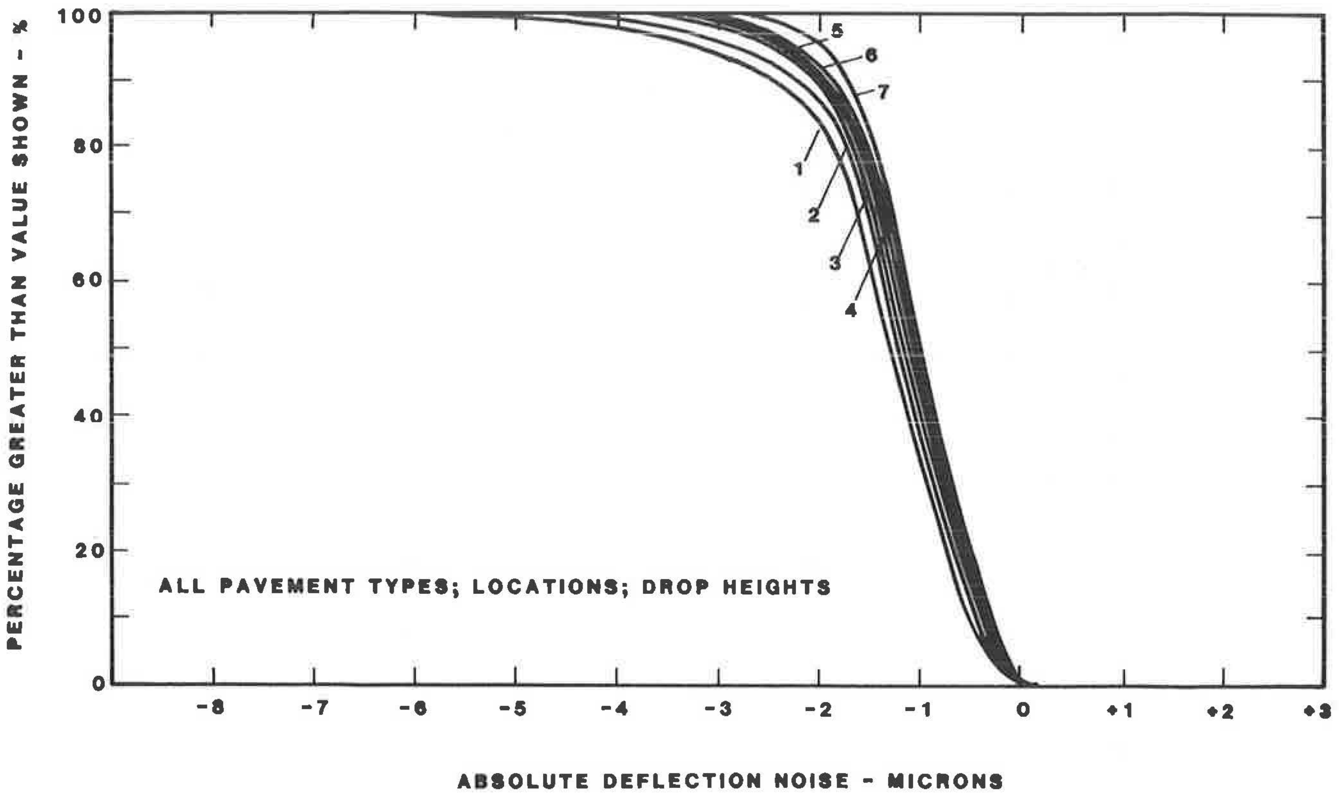


FIGURE 9 Cumulative frequency plot of absolute deflection noise by geophone.

only variable slightly influencing noise was found to be geophone location.

3. Although the geophone location affects the absolute noise level, the practical implication of its effect is considered quite small. Figure 10 shows the statistical distribution effects of both absolute and relative noise as a function of geophone number. For all data analyzed, the average absolute noise is approximately −0.9 μm, with $x \pm 2s$ range of +1.1 to −2.9 μm for the geophone directly under the load plate. Similar values for Geophone 7 are −0.5 μm and +0.7 to −1.4 μm, respectively.

4. Based on all observations, the overall average absolute deflection noise was −0.65 μm with a standard deviation (s) of 0.73 μm (*2*). This value of s is of the same order of magnitude found for the raw deflection repeatability error (s = 0.6 μm) for repeat drops (*3*). Thus, for filtered raw deflection responses, the random error is approximately twice as large as that for unfiltered data.

SUPPLEMENTAL STUDY

Because of the surprisingly large noise magnitudes found in the original study, specially for the rigid pavement, an additional filtering study was conducted to substantiate these results. In this study, five additional rigid pavements were evaluated: one in Nevada, one in North Carolina, and three in Georgia. Overall, an additional 1,482 load and 10,374 deflection measurements were evaluated.

Like the original study, a comparative statistical analysis of the data was conducted to quantify the effects of the digital filtering process. A complete summary of the analysis results is contained in the North Carolina study (*4*). Figure 11 shows the average absolute and relative load noise as a function of drop height for all pavements investigated. Similar to the North Carolina study, the average absolute noise increases with drop height, whereas no unique trend is apparent for the average relative noise. Also, almost 100 percent of the results are negative, indicating that filtering reduces the peak load. More important, the load signal analysis results confirm the original report results in that the noise level is of significant magnitude. In fact, the average noise of the additional sections is larger than that reported for the North Carolina pilot section. At the maximum drop height, absolute noise levels for the original section varied from 0 to −850 lb (−7.8 psi plate pressure) and from 0 to −1,100 lb (−10.0 psi) for the additional sections.

Average absolute and relative deflection noise levels as a function of drop height and geophone number are shown in Figures 12 and 13. As in the original study, absolute deflection noise appears to be independent of drop height but is related to the geophone location. Also, the relative noise level decreases with increasing drop height, but is essentially independent of geophone location, specially for the first five or six geophones. In summary, the results of the additional study support the conclusions regarding deflection noise found in the original study. From an absolute deflection viewpoint, the additional sections have noise levels generally greater than that found

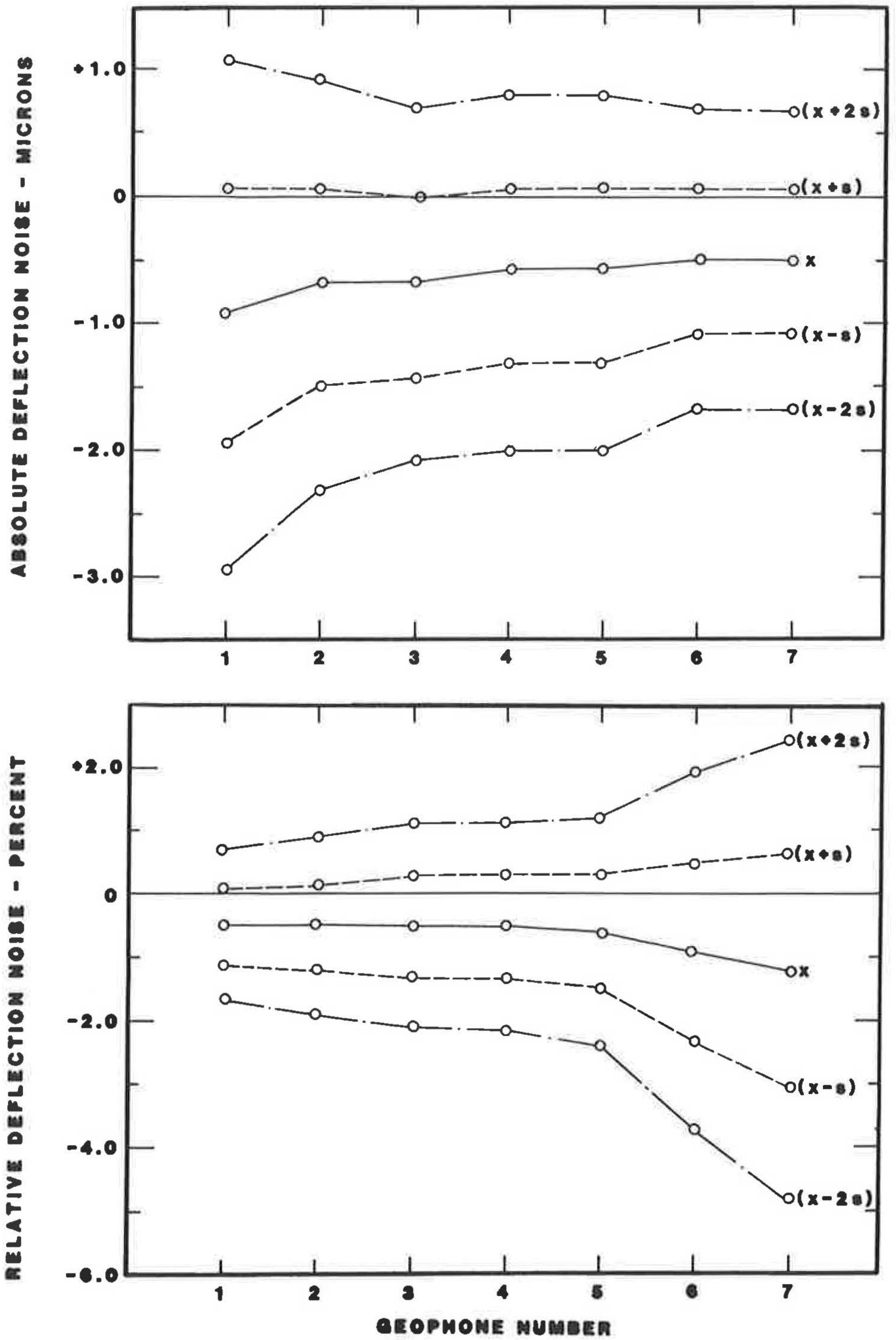


FIGURE 10 Absolute and relative deflection noise limits by geophone location.

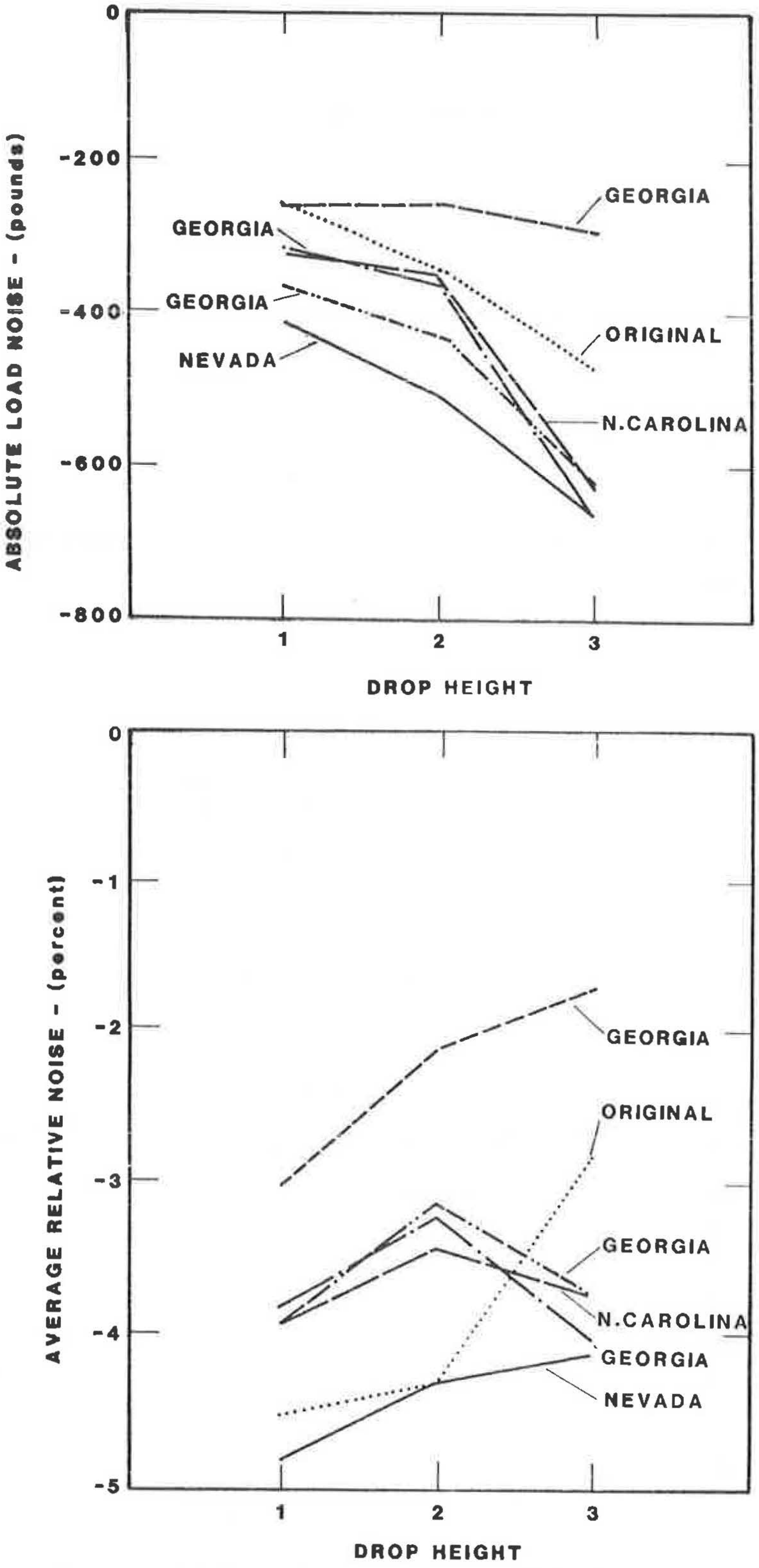


FIGURE 11 Effect of drop height and pavement section on load noise—supplemental study.

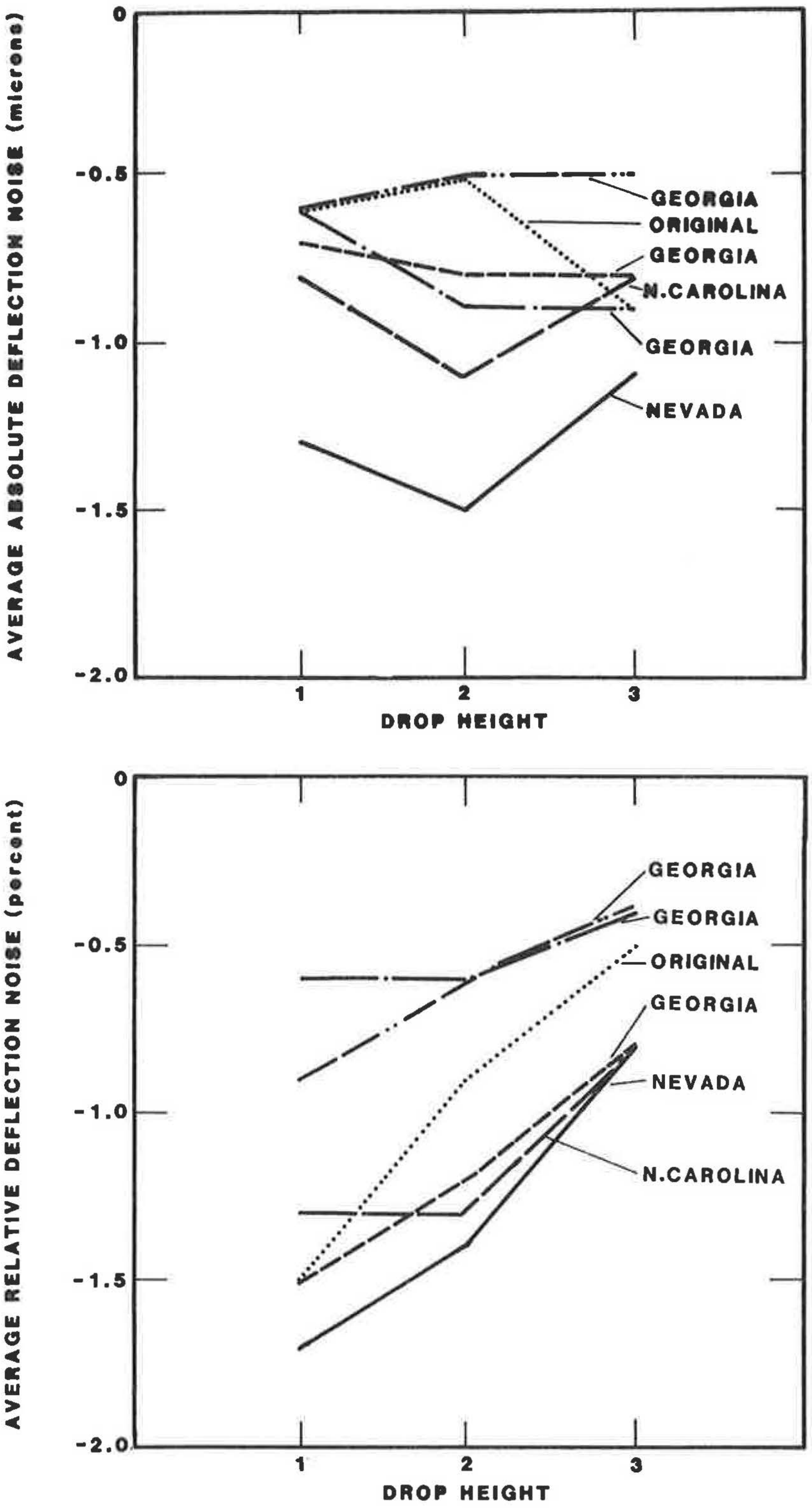
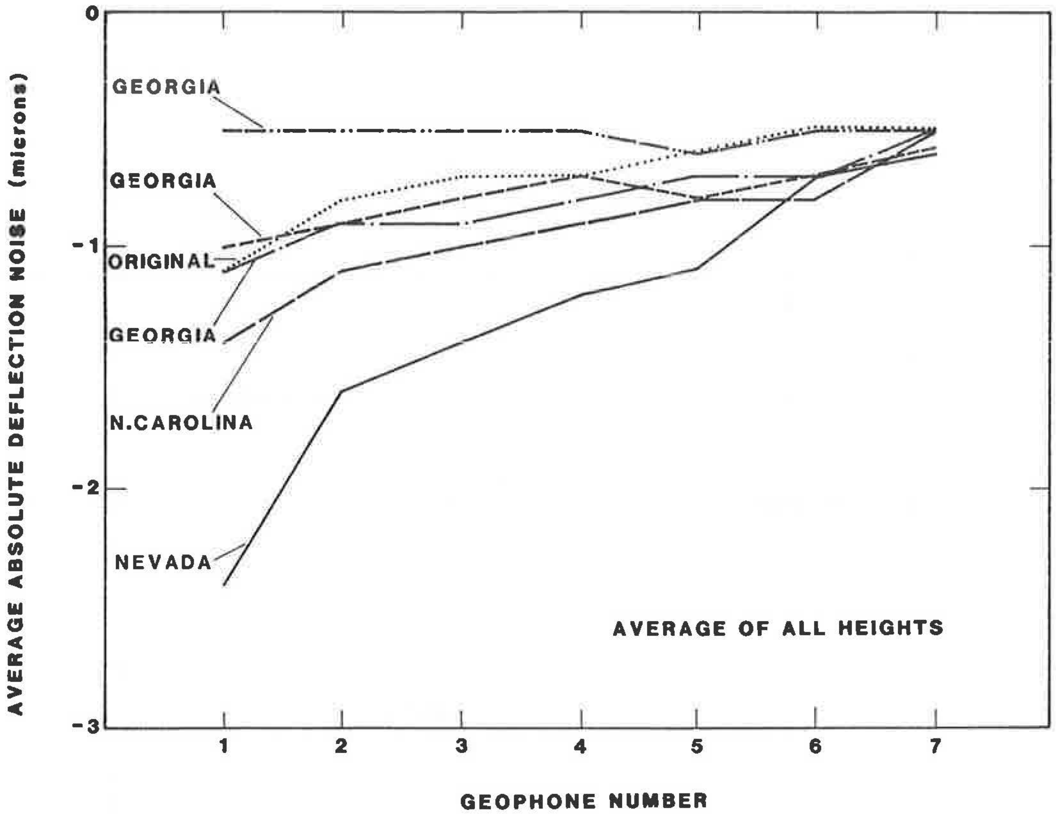


FIGURE 12 Effect of drop height and pavement section on deflection noise—supplemental study.



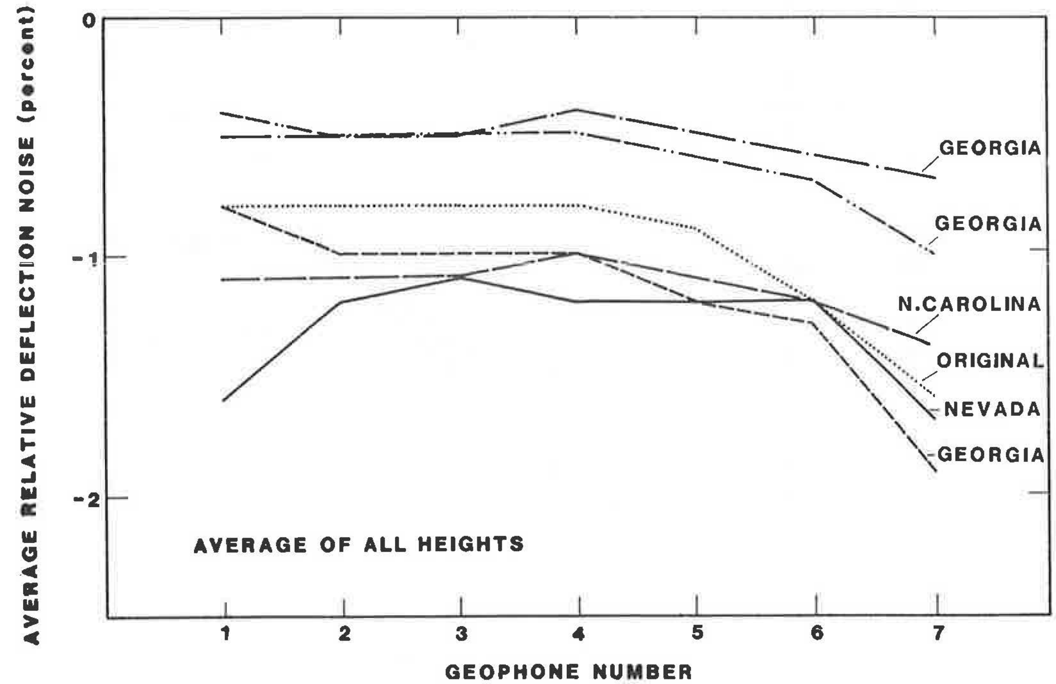


FIGURE 13 Effect of geophone number and pavement section on deflection noise—supplemental study.

in North Carolina. Typical values from −0.5 μm to as large as −1.5 μm were observed.

IMPLICATIONS OF FINDINGS

The findings of both the original and supplemental data filtering studies impact in a small, but significant, manner on SHRP FWD operational field guide procedures. It has been shown that filtering of load data increases the drop-to-drop variability in the peak values, particularly for rigid pavements tested under heavy loads. In addition, the filtering process on deflection data similarly causes an increase in random deflection measurement error (variability) between replicate drops.

Although these two filtering effects are significant in themselves, they tend to compound each other, when the filtered raw deflections are normalized by the filtered load data. It is therefore hypothesized that the use of filtered data yields normalized deflection responses that more than likely exceed current normalized deflection tolerance limits, particularly for rigid pavement and heavy FWD load conditions. Also, although not yet investigated, it can be confidently hypothesized that the use of filtered data will lead to significantly different backcalculated layer moduli than would unfiltered FWD data.

Although large noise magnitudes have been found, the best load-deflection value between filtered and unfiltered data is unknown. Because of the complexity of the problem, the final resolution of this question can only be accomplished through further research and time. It has been recommended that all current and near-future FWD data collected by SHRP be accomplished with the filter off; unfiltered peaks should be used in the data collection process until conclusive research regarding digital filtering is developed.

Because some unknown level of noise is contained within SHRP FWDs, it has also been recommended that additional load- and deflection-time histories be collected and stored. Thus, if future research advances do occur with regard to the filtering process, all unfiltered data can be reanalyzed to obtain the most accurate estimates of peak load-deflection values for use in the backcalculation of layer moduli.

ACKNOWLEDGMENT

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REFERENCES

1. SHRP P-001 Technical Advisory Staff. *SHRP-LTPP Manual for FWD Testing and Operational Field Guidelines*. Technical Manual, Strategic Highway Research Program, National Research Council, Washington, D.C., Jan. 1989.
2. SHRP P-001 Technical Advisory Staff. *Analysis of Data Filtering Results from the North Carolina Pilot Study*. Technical Report, Strategic Highway Research Program, National Research Council, Washington, D.C., March 1989.
3. SHRP P-001 Technical Advisory Staff. *Analysis of Within Drop (Replicate) Error of Load Cell and Sensor Responses of the FWD*. Technical Report, Strategic Highway Research Program, National Research Council, Washington, D.C., Jan. 1989.
4. SHRP P-001 Technical Advisory Staff. *Addendum To Analysis of Data Filtering Results from the North Carolina Pilot Study*. Technical Report, Strategic Highway Research Program, National Research Council, Washington, D.C., April 1989.

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