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ATTENUATION OF BLASTING VIBRATIONS IN SOUTH FLORIDA

by

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ABSTRACT

Several large quarrying projects recently occurred in Miramar, Florida. These were closely monitored by the Seismologist of Record and Broward County in accordance with County and City regulations. In addition to this monitoring, the City of Miramar employed The Pepper Engineering Group, Inc., to provide additional spot check monitoring and to review the records of the other two parties on a routine basis.

Broward County ordinances require that the location of each shot and the nearest protected structure be recorded along with seismograph measurement of each shot at the nearest protected structure. The positions of the blasts and nearest protected structures were determined using GPS. The blast vibrations were measured by seismograph. Over 600 shots, which are the subject of this study, were measured both by the County, the Seismologist and, on many occasions, The Pepper Engineering Group. As such, the vibration data was constantly cross-checked for consistency. The blasting contractor also provided blast designs for each shot.

In this paper, the measured vibrations are plotted in terms of Resultant Peak Particle Velocity (RPPV) versus Scaled Distance (SD) on logarithmic scales. The data curves are fitted with least squares and upper 95% and 99% prediction limits are provided. Equations are presented to predict the RPPV based on scaled distance and prediction level using power fits. Statistical information concerning the derivation of the various limits is presented.

The raw data used to develop this paper, along with other information concerning the shots, will be posted on the Internet for use by other researchers.

INTRODUCTION

Due to its unique topography and geology, South Florida could not have come to exist as it does today without the use of explosives. Explosives are used on an almost daily basis to excavate limestone used for concrete, concrete block and fill for residential development in the western portion of southeast Florida. The result is large planned communities where over a million people live in single family homes, town homes and apartments with schools, stores, parks and golf courses, all surrounding many lakes and bordering canals created with the use of explosives.

The major drawback of explosive use in quarrying and excavation operations is the by-product of vibrations resulting from the energy that is not used in the breaking or moving of rock. At high intensities, the vibration energy has the ability to damage structures and their components. An additional, but related problem, is the perception of the vibrations by the people in the vicinity and even for great distances away from the blast sites, and their concern for possible damage to their homes and other structures.

The regulatory limitations in Broward County limit the blasting vibrations and require that each shot be measured by seismograph. The regulations specify the maximum Resultant Peak Particle Velocity (RPPV) that is allowed to occur at the ground adjacent to the nearest protected structure. For this reason, our study concerns propagation in terms of RPPV instead of Peak Particle Velocity (PPV). It should be noted that for many studies, Peak Particle Velocity (PPV), rather than RPPV is used and this should be taken into account when making comparisons to other studies.

APPLICATION OF THE STUDY

This study has two applications:

1. The prediction, within a specified degree of certainty, of the RPPV at a site distant from the point of the detonation of the explosive charge based on the charge weight per delay of explosive and the distance to the point of interest.

2. The prediction, within a specified degree of certainty, of the RPPV at a site distant from the point of seismographic measurement to another location, based on the distance from the point of detonation to the measurement point and the distance from the point of detonation to the point of interest.

Both applications assume a geology similar to that of South Florida, measurement of the distance from the site of each shot to the seismographic monitoring location within a reasonable degree of accuracy, and a professionally designed and constructed shot.

PROJECTS STUDIED

Eight projects in the City of Miramar, Florida, were monitored by two of the co-authors serving as the City's Blasting Inspector.

For the majority of shots, 4½" diameter cardboard tubes were used for shots below the water table. These tubes were filled with explosives and stemmed with either drill cuttings or small diameter rock. Both decked and un-decked shots were used, the majority being un-decked.

Two smaller projects used 7" cardboard tubes for all or most of the shots. In order to minimize the number of variables concerning the explosive charge, only projects using 4½" diameter tubes are considered in this study.

Two projects were geographically contiguous, separated only by a road. For purposes of this study, they were combined together as one project. One project, which is ongoing, was excluded rather than determine an arbitrary cut off point.

For the purposes of this paper, the arbitrary designations of Project 1, Project 2, Project 3, and Project 4 were used for the remaining projects. Their individual plots can be seen in Figures 1, 2, 3 and 4. The four projects considered contained over 600 shots of varying sizes, from single holes to large patterns.

In all cases, both the Seismologist of Record and a representative of Broward County monitored the shots. Additionally, we monitored shots on a random basis and reviewed the documentation of the full time monitors on a routine basis. The result of this process was that at least two, and many times three, seismographs recorded the measurements of vibrations at the nearest structure to the shot. Additionally, the locations of the shot pattern and nearest structure were found using GPS.

PREDICTION RPPV BASED ON EXPLOSIVE CHARGE

The prediction of particle velocity requires that average and upper bound values be well known. For the bounds to be established, site-specific studies must be made.

The method we used to predict RPPV based on the charge weight per delay was standard. We plotted Scaled Distance (SD) on the X ordinate and RPPV on the Y ordinate. Scaled Distance is a function of the distance (D) from the nearest point of the shot to the seismograph and the Charge Weight per Delay (W) defined as follows:

$$SD=(D/W^{1/2})$$

Once this was done, the data was checked, with particular emphasis of the evaluation of outliers. Corrections were made to both distances and vibrations where errors were found, but outliers that were correct were left in the data, as they were part of a controlled blasting program and therefore must be accounted for in any predictive study. After plotting the data on a log log scale, the 50% line was fitted using a power function.

At this point, the analysis deviates slightly from the standard ones in that statistical techniques were applied to obtain the degrees of certainty that will be explained later in this paper. These techniques provide a statistically valid basis for the prediction limits given on the plots. Differences from translations of the 50% curve may be more noticeable for smaller data sets.

This is shown on the plot of Figure 5, which gives the 50% line and the estimated 95% and 99% upper bounds. Using either Figure 5 or the equations provided, the RPPV at a given distance from the nearest hole of the detonation may be estimated.

PREDICTION OF RPPV BASED ON SEISMOGRAPH MEASUREMENT

In order to predict an RPPV based on the reading of a seismograph at a known location in relation to the shot, the slope of the attenuation curve must be known. The slope of the attenuation curve must be statistically supported and mechanistically explained. Given a known blast, location of the seismograph and distance from the blast to the structure in question, the particle velocity may be predicted by the following formula:

$$V_h = V_s (D_h/D_s)^{-b}$$

V_h = particle velocity at the structure or house (ips)
Vs = particle velocity measured by the seismograph (ips)
D_h = distance from the blast to the structure (ft)
D_s= distance from the blast to the seismograph (ft)
$-_b$ = the slope of the attenuation curve

The second and complementary goal of this study was to determine the slope of the attenuation curve for blasting in South Florida so that the particle velocity at a desired location may be determined with reasonable accuracy.

In this study, the slope of the equations for the 50% line, 95% upper bound and 99% upper bound prediction curves are all about equal and the assumption that the slope of the 50% line represents the slope of the others is valid. The predictive equation, rounded to two decimal places is, as follows:

$$V_h = V_s (D_h/D_s)^{-0.80} \quad \text{or in a simplified form:} \quad V_h = V_s (D_s/D_h)^{0.80}$$

STATISTICAL ANALYSIS

Statistical analysis of blasting data used the results of 609 events (shots). Events that had identifiable difficulties, such as inaccurate distance measurements, were excluded from the analysis where corrections to the data could not be made. The scrubbed data included the resultant peak particle velocity (RPPV) and the scaled distance (SD). The classical relationship between these variables is given by:

$$\mathrm{RPPV} = a\,\mathrm{SD}^b,$$

where the parameters a and b are to be estimated from the data. We assume that the data is in the form (RPPV_i, SD_i) for $i = 1, 2, \ldots, n$ (the number of data points). In addition to finding least squares estimates of a and b using standard statistical fitting methods, we also provide in this section prediction limits. Hence, given a particular scaled distance, we offer a best guess as to the RPPV as well as upper 95% and 99% prediction limits below which we expect future blasts to occur.

The basic scheme for obtaining the best fit and prediction limits is given, as follows:

1. Log10 transformation.

   Let $z_i = \log10(\mathrm{RPPV}_i)$. Let $w_i = \log10(\mathrm{SD}_i)$.

2. Linear regression.

   Fit the data using least squares for the relation $z = c + d\,w$, where c is the intercept and d is the slope of the resultant fit. This is the best-fit curve in the log-log-transformed space.

3. Auxiliary calculations.

   Compute the following three auxiliary values necessary for later prediction limit determinations:

   $$MSE = \Sigma (z_i - c + d\, w_i)^2,$$

   $$Ave(w) = (\Sigma\, w_i) / n,$$

   $$WSS = \Sigma (w_i - Ave(w))^2,$$

   where the summations are each from 1 through the number of data points n.

4. Best fit curve.

   Transforming back to the original scale (which is to be plotted on log-log paper), the appropriate best-fit function is:

   $$RPPV = 10^c (SD)^d$$

5. Upper prediction limits.

   For a given SD value, let w = log10(SD) and compute the following quantity:

   $$SE = [MSE\ (1 + (1/n) + (w - Ave(w))^2 / WSS\ )\ ]^{1/2}$$

   The upper 95% prediction limit is:

   $$UL(95\%) = 10^{c + d\,w - 1.645\ SE}$$

   The upper 99% prediction limit is:

   $$UL = 10^{c + d\,w + 2.326\ SE}\ .$$

   These quantities are suitable for plotting on log-log paper.

The procedure given above describes the steps necessary to generate the RPPV to SD best-fit relationship along with 95% and 99% upper prediction limits.

Appendix 1 provides a more complete numerical example using the full data set of blast events. .

SUMMARY and CONCLUSION

A method has been presented that allows the estimation of vibrations due to quarrying operations in South Florida based on both charge weight per delay as well as seismographic measurements at other locations.

As shown in Figure 5, the results indicate that the slope of the attenuation equation is approximately -0.80. This is different from the -1.5 to -1.6 often used in areas when no other data is available.

The suggested equations, when SD is known, round off to the following:

$$RPPV(50\%) = 6.57\ SD^{-0.80}$$

$$RPPV(95\%) = 12.00\ SD^{-0.80}$$

$$RPPV(99\%) = 15.40\ SD^{-0.80}$$

The suggested equation when a seismographic reading is known is:

$$V_h = V_s\ (Ds/Dh)^{0.80}$$

The difference between the numbers commonly used and the ones derived in this paper are due to the unique geology and topography of South Florida, including its high water table.

REFERENCES

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3. Siskind, D.E., Stagg, M.S., Pierce, W.E., Crum, S.V., "Low-Frequency Blast Vibrations at a Florida Construction Site', August 1995, U.S. Department of the Interior, Bureau of Mines Twin Cities Research Center, Minneapolis, MN

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APPENDIX 1. NUMERICAL EXAMPLE

We illustrate the statistical calculations using the full data set consisting of 609 shot events. Table 1 presents standard summary output from an EXCEL regression analysis performed within the data analysis tool. Of particular interest are the following quantities, extracted and presented below:

R Square	0.547
Residual MS	0.02534
Intercept Coefficient	0.8177
log10(scdist)	-0.7959

The R Square quantity is a basic measure of the quality of the fit. In this case, a value of 0.547 indicates that 54.7% of the RPPV variability is explained by the linear regression. The Residual MS value corresponds to the MSE expression introduced earlier in the paper. The intercept coefficient is obtained from the linear regression in the log-log transformed space. Note that 10^0.8177 equals 6.5721 which is in agreement with Figure 5. Finally, the critical slope value of -0.7959 is easily extracted from the summary output.

SUMMARY
OUTPUT

Regression Statistics	
Multiple R	0.740013536
R Square	0.547620033
Adjusted R Square	0.546874761
Standard Error	0.159176263
Observations	609

ANOVA

	df	SS	MS	F	Significance F
Regression	1	18.61749577	18.617496	734.792396	1.2179E-106
Residual	607	15.37960925	0.0253371		
Total	608	33.99710502			

	Coefficients	Standard Error	t Stat	P-value
Intercept	0.817705776	0.064618694	12.654322	9.7144E-33
log10(scdist)	-0.795878647	0.029360573	-27.107054	1.218E-106

Table 1

PROJECT 1

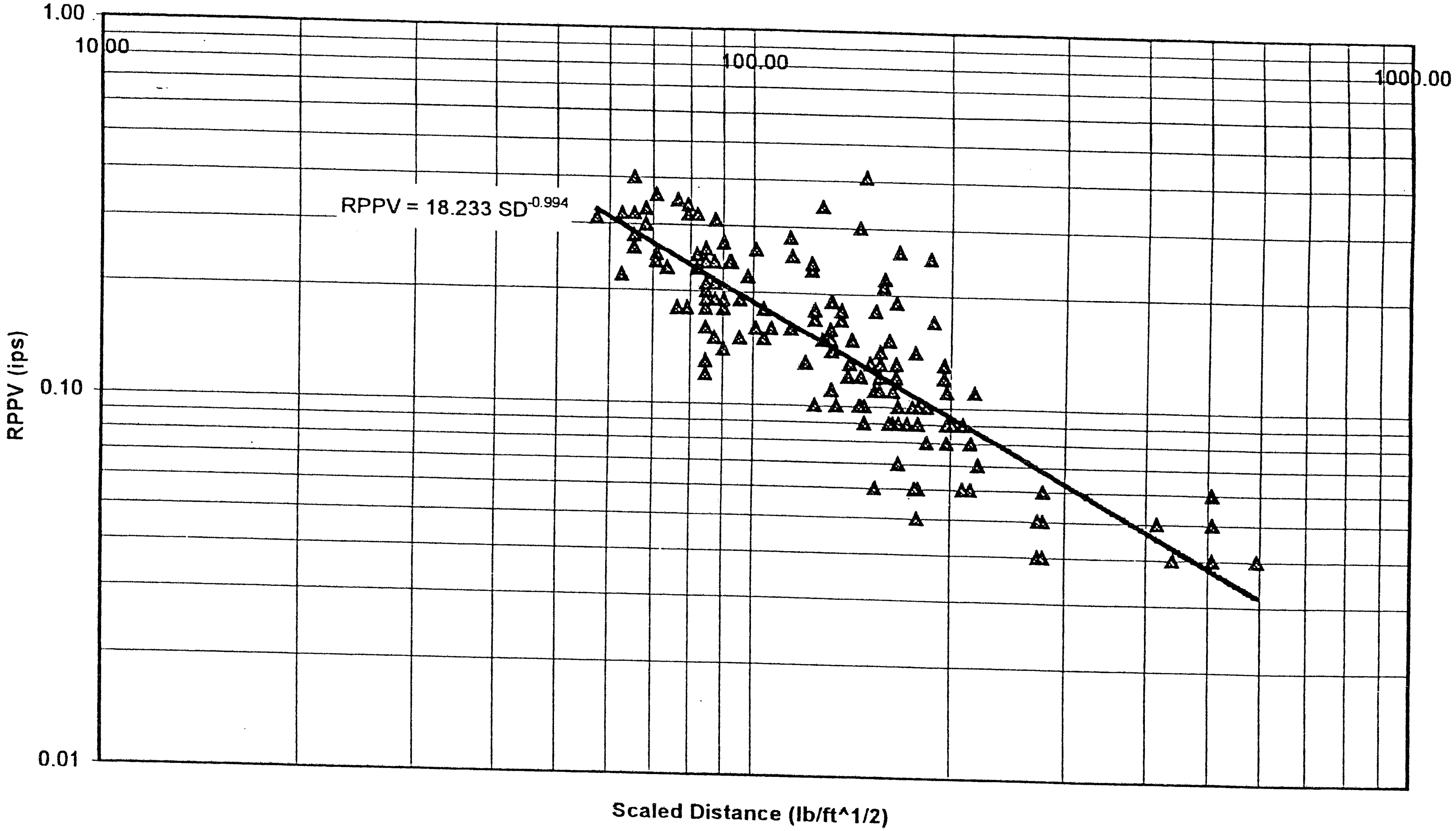


Figure 1

PROJECT 2

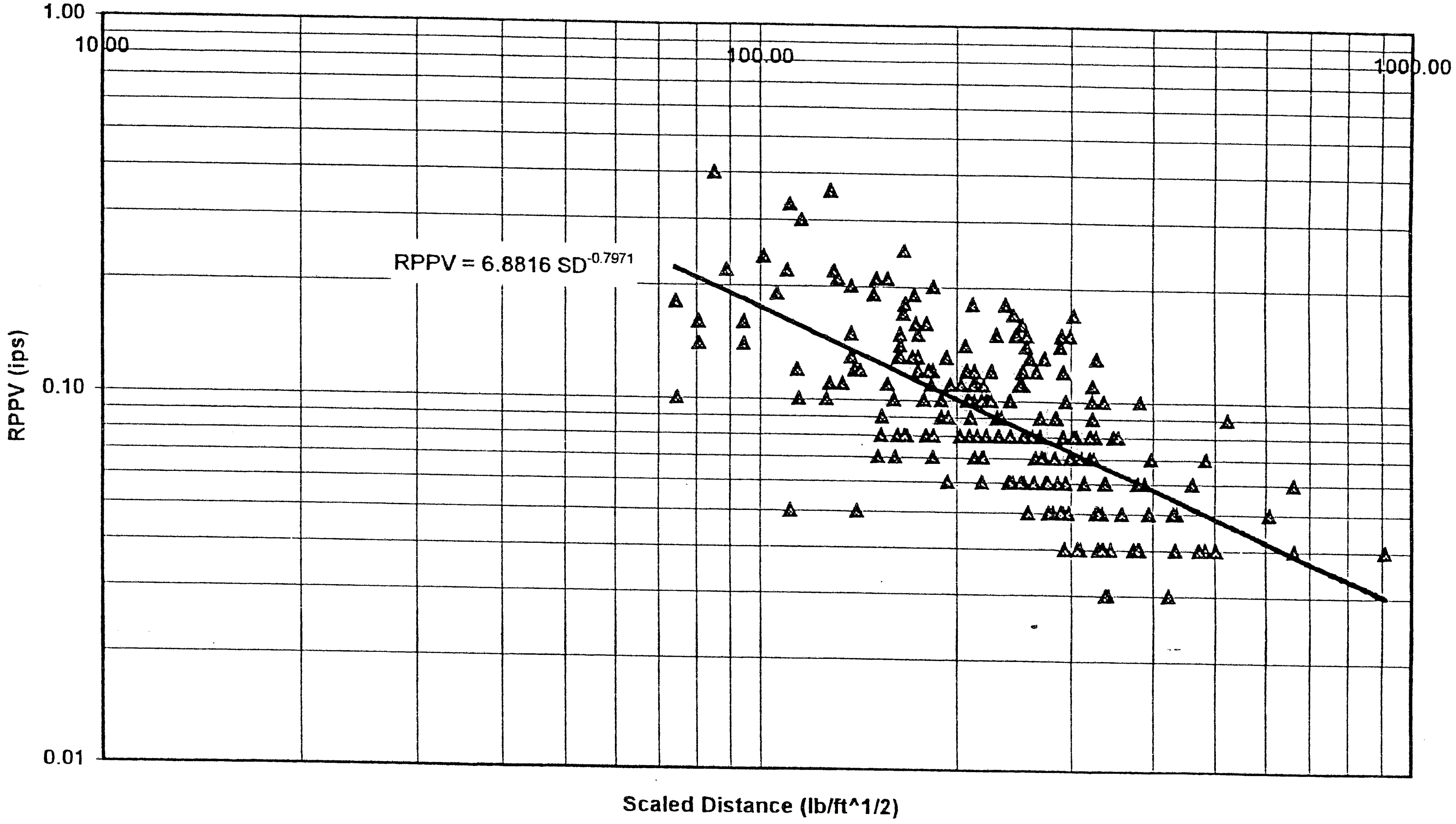
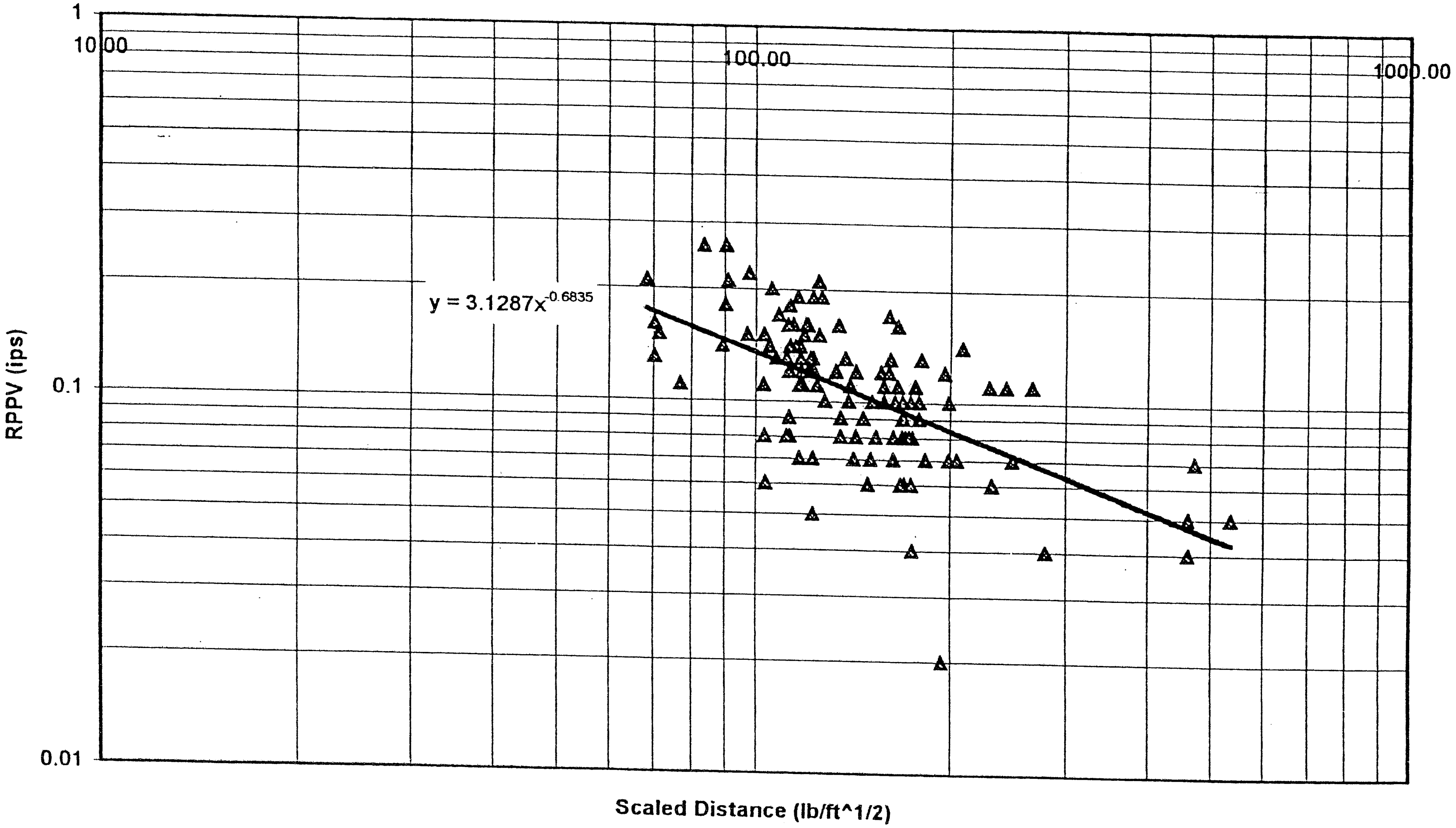


Figure 2



PROJECT 3

Figure 3

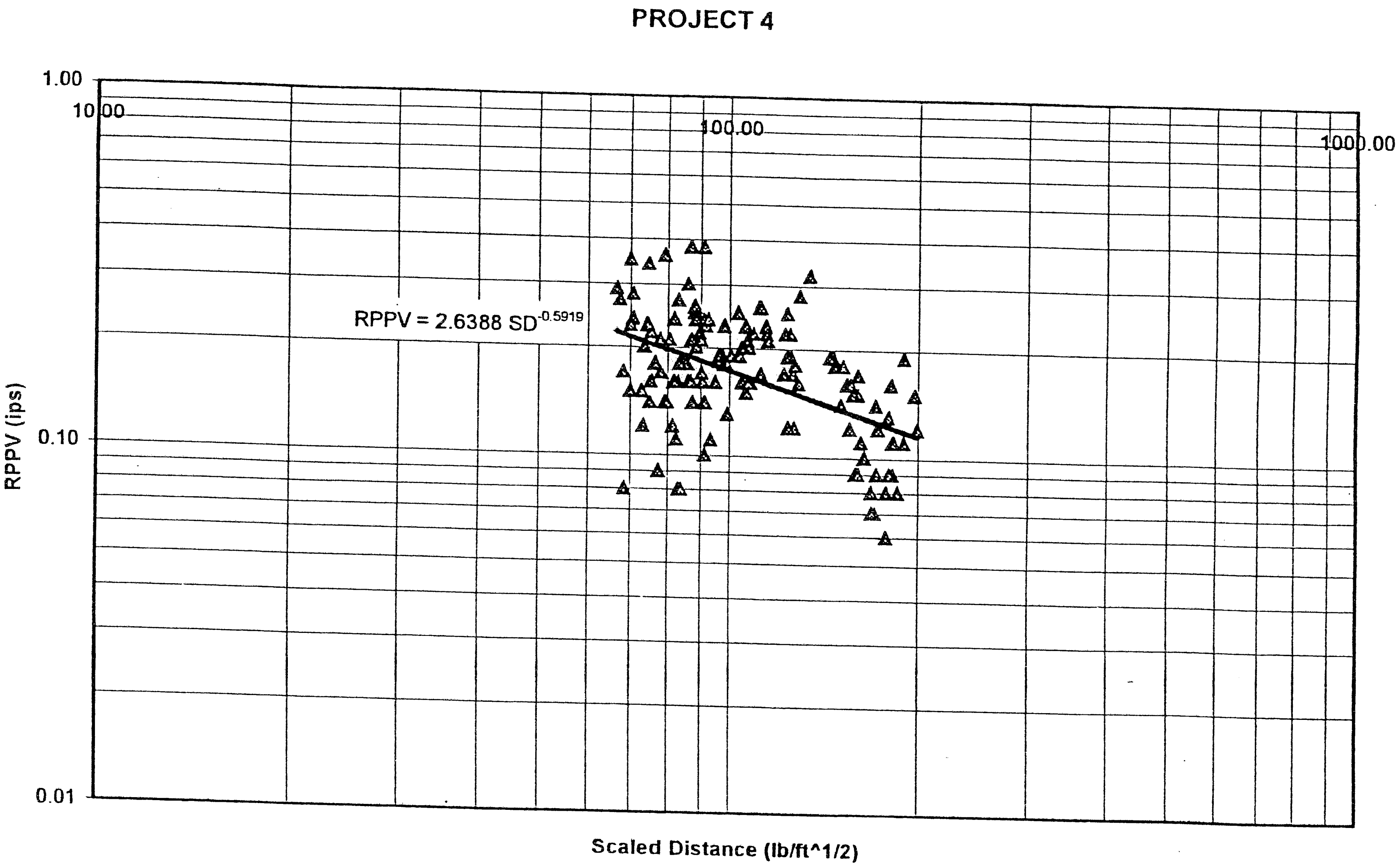

PROJECT 4
1.00
10.00
100.00
1000.00
RPPV = 2.6388 SD$^{-0.5919}$
RPPV (ips)
0.10
0.01
Scaled Distance (lb/ft^1/2)

Figure 4

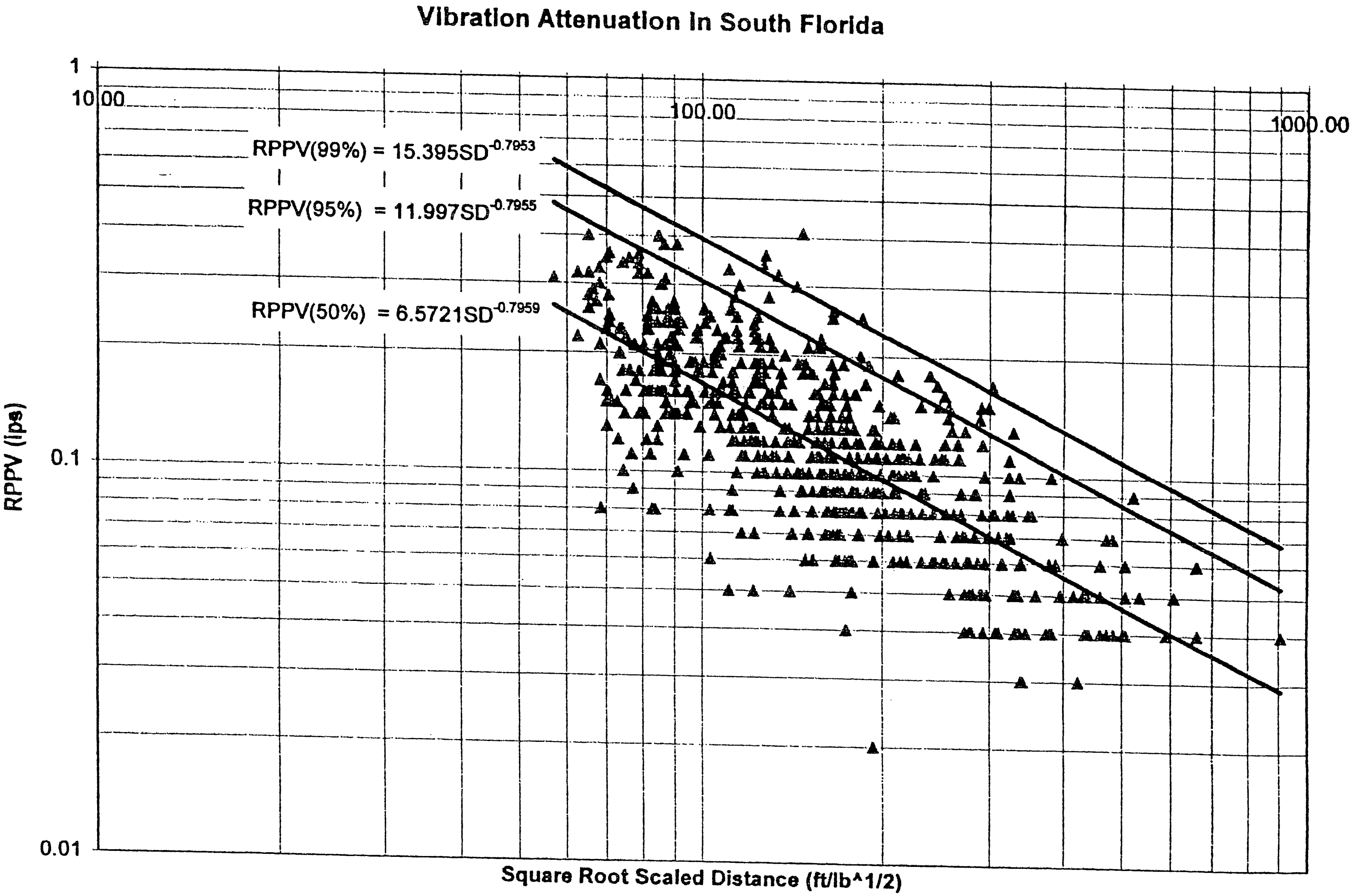

Vibration Attenuation in South Florida
RPPV(99%) = 15.395SD^-0.7953
RPPV(95%) = 11.997SD^-0.7955
RPPV(50%) = 6.5721SD^-0.7959
1
0.1
0.01
10.00
100.00
1000.00
RPPV (ips)
Square Root Scaled Distance (ft/lb^1/2)

Figure 5