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Simple Power-Law Characterization of Transient Ground-Borne Vibrations

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ABSTRACT

Practical characterization of transient ground-borne vibrations in civil and geotechnical engineering problems is often a difficult and frustrating task. Some modern engineering seismographs now routinely permit the collection of histogram-type data where the peak vibration for a pre-set time interval can be measured and stored for significant time periods. Such data is amenable to analysis utilizing concepts of fractal geometry and self-ordered criticality. Resulting data trends tend to follow power-law relationships that plot as essentially straight lines in log-log space. This application is similar to the Gutenberg-Richter relationship for earthquakes where the relationship between magnitude and frequency is fractal. However, the largest vibrations appear to follow another power-law trend appropriate to characterizing extreme events. Four cases of monitoring apparently random transient ground-borne vibrations are examined using this power-law approach: traffic induced vibrations near the curb of an urban arterial street, an unidentified vibration interfering with a precision machining operation, vibrations induced by vacationing children using the front door of a residence, and vibrations induced by water transport in a pipeline. All cases could be characterized by this approach.

INTRODUCTION

Ground-borne vibrations generated by construction, industrial, or transportation activities can, under certain circumstances, be an annoyance to nearby persons or sensitive equipment or processes. Transient vibrations, those vibrations that are non-steady state or include infrequent large spikes in vibration levels, can be difficult and frustrating to monitor and quantify. Before the development of seismographs with considerable digital data storage capacity, vibration data was typically recorded in analog form on chart paper (light-sensitive paper was a common format). A consultant typically had to be present and ready and the equipment activated to measure when a significant transient vibration event occurred. Otherwise, essential measurements of the transient events could not be collected for analysis. Lacking a relatively large body of data to quantify trends in the largest or extreme events, analysis and presentation of results was often limited to describing the largest readings. Modern microcomputer-based engineering seismographs with electronic data storage have relatively long-term data collection capabilities. Peak vibrations within a pre-set time interval ranging from seconds to minutes can be measured and stored for significant time periods. Such histogram-type data can routinely be acquired for hundreds or thousands of time periods. The resulting data collections can be analyzed, and vibration behavior trends described, on standard spreadsheet software using power-law based techniques.

POWER-LAW ANALYSIS

Behaviors of many complex natural and physical systems processes have become measurable with the development of such concepts as fractal geometry (Mandelbrot, 1983; Barton and LaPointe, 1995) and self-ordered criticality (Bak, 1996; Turcotte, 1999). These behaviors tend to follow power-law relationships that plot as roughly straight line trends in log-log space. The Gutenberg-Richter relationship of earthquake frequency of occurrence to magnitude (energy) is such a power-law. Inherent in that power-law relationship is the predictability that earthquake events of various sizes occur at interrelated rates. Unfortunately, the relationship cannot predict when events of specific sizes will occur. Fortunately, the infrequent occurrence of very large earthquakes in the historic record has limited analysis and characterization of the largest, extreme events in this relationship. Discussions and assessments of maximum earthquakes and maximum credible earthquakes are common in the literature (for example, see Coppersmith, 1994).

Ground-borne transient vibrations are more readily sampled and monitored than earthquakes. With sufficient sampling, it is more likely that very large or extreme transient events can be included in the monitoring program. Power-law analysis can then provide a simple means to analyze frequency and magnitude of event occurrence.

Vibration Data Acquisition

Acquisition of histogram-type data is straightforward using engineering seismographs with that feature built-in. Monitoring time intervals are pre-selected prior to data acquisition. The instrument is set up appropriately for the monitoring task, and activated in the monitoring mode. The data presented in Fig. 1 was acquired by one of the authors as an example of transient vibrations in a residence. A seismometer was set up on a holiday on a low window ledge approximately 0.4 m from the front door of his residence. The structure wall was masonry and the floor was ceramic tile installed on concrete slab. Opening, closing and slamming of the front door by that author's three small boys and a neighbor boy generated most of the transient vibrations. Monitoring proceeded at one minute time intervals for ten hours beginning at about 11 am. PPV values ranged from the instrument's sensitivity limit of 0.05 mm/sec to over 7 mm/sec. Only 3 events exceeded 5 mm/sec.

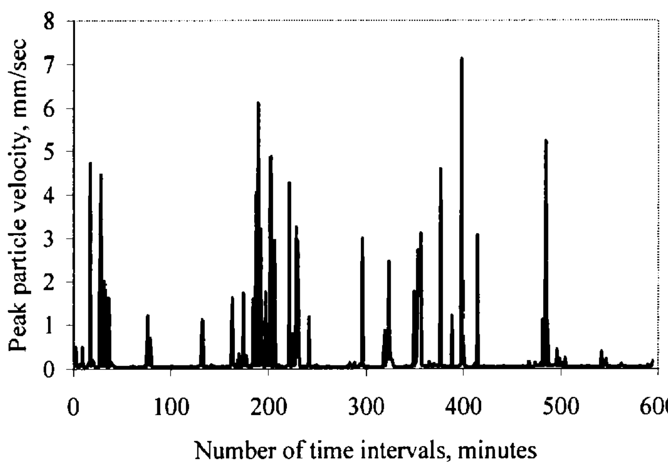

Fig. 1. Histogram presentation of PPV for 1 minute intervals near door of residence between 11 am and 9 pm New Year's Day.

After completion of monitoring, the data is downloaded to a computer, and file conversion is performed as necessary to format the data into a usable form. Files converted to ASCII format with spaces or tabs as delimiters can be imported into standard spreadsheet programs for manipulation and analysis. A suitable format will include the total number of time intervals monitored as a series of spreadsheet rows; the time and readings for each time interval are in a single spreadsheet row.

Power-Law Analysis of Histogram-Type Data

Once the acquired data resides in a spreadsheet, it is assumed that the desired peak particle velocity (PPV) data to be analyzed resides in a spreadsheet column encompassing the rows of data for the time intervals of interest. That column is copied onto a blank column to the right of the existing data, and the copied column of PPV data is sorted from largest to smallest values. Another column of numbers, the cumulative events or rank order, is prepared beside the sorted PPV data. The number at the top of this column is 1, which correlates with the largest PPV value. Numbers are increased by 1 at each row down the cumulative events column until each sorted PPV value has a cumulative events or rank order number assigned. The largest cumulative event number corresponds to the smallest PPV value in the data set. The relation between PPV magnitude and rank order or cumulative event is plotted on a log-log scale such as Fig. 2. Figure 2 presents the same data as Fig. 1, but presented in a cumulative events or rank order form.

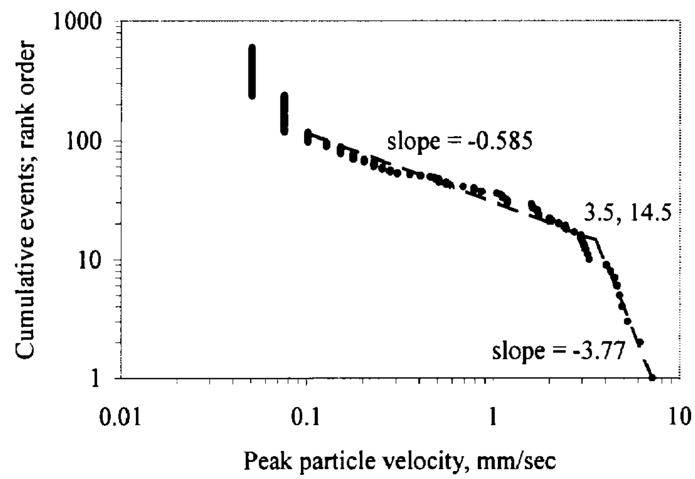

Fig. 2. Power-law frequency-magnitude presentation of PPV data from Fig. 1. Note the two distinct, nearly straight-line trends above and below PPV=3.5 mm/sec. The seismograph sensitivity is 0.05 mm/sec.

Two approximate straight-line trends characterize the data plot in Fig. 2. Minimum PPV values of 0.05 to 0.1 mm/sec represent the limits of instrument sensitivity and, perhaps, those moments when the children are not in the vicinity of the front door. A region characterized by a relatively shallow slope trend begins at a PPV of about 0.1 mm/sec and extends to about 3 mm/sec. Transient vibration occurrences within this region might be considered to be 'normal' events. The region above 3.5 mm/sec is characterized by a steep slope trend. Transient vibration events within this region might be considered to be 'extreme' events. Adults in the residence considered the largest events to be at least an annoyance.

The data trends presented in Fig. 2 can be compared with earthquake frequency-magnitude trends. Both earthquake data and this transient vibration data plot as straight-line trends in log-log plots. However, 'extreme' events may be more easily characterized as a separate power-law trend when dealing with transient vibrations, since so few 'extreme' events are present in the historic earthquake records.

Prediction Utilizing Power-Law Trend

Frequency-magnitude relationships characterized as power-law trends may be useful as a predictive tool. Due to the nature of sampling and usual cost constraints, practical ground-borne vibration monitoring normally cannot be expected to include the largest extreme events. Of course, sampling must take place while relevant transient vibrations are occurring. Experience, common sense and engineering judgment must be utilized in a prediction exercise. A very different series of transient events would be anticipated in the Fig. 1 vibration scenario while the children are sleeping or during school time.

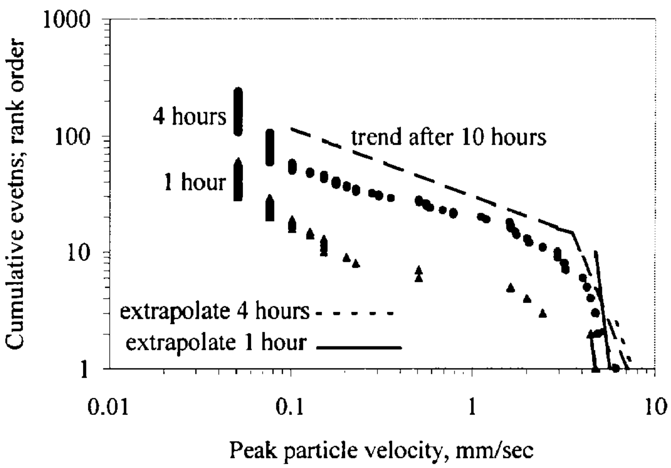

Fig. 3 Extrapolation of power-law trends from partial data sets from Figs. 1 and 2 of 1 hour (triangles) and 4 hours (circles) duration to predict maximum PPV value over 10 hours duration.

An example of limits and effectiveness of simple power-law prediction is presented in Fig. 3. Plots of the first hour and first four hours of the data from Figs. 1 and 2, and the power-law trend for the entire ten hours of data is shown in Fig. 3. The actual maximum sampled PPV over the entire ten hours is 7.1 mm/sec. In the first hour of data, the maximum sampled PPV is 4.7 mm/sec. Only the two largest data points even indicate the possibility of an extreme event trend. If the slope of this two-point trend is extended by a factor of ten to represent ten hours of data, a maximum PPV of 5.7 mm/sec is predicted. It is apparent that insufficient data was collected in the first hour to characterize the largest events for the subsequent nine hours. A period of relative quiet ensues for the second and third hours of sampling, and no large events occur during this time.

In the first four hours of data, the maximum sampled PPV is 6.1 mm/sec. Six data points establish a clear power-law trend for the largest events. If this trend is extended by a factor of 2.5 to predict ten hours of sampling, a maximum PPV of 7.6 mm/sec is predicted.

More complete prediction analyses may be possible using fractal analysis to characterize time duration between large events as well as large event magnitudes and frequency. Such analysis is beyond the scope of this paper.

EXAMPLES OF POWER-LAW ANALYSIS

Three cases of power-law analysis of actual transient vibration monitoring data will be presented. These cases include traffic-induced vibration, an unidentified vibration at a precision machine, and vibration induced by a large waterline.

Traffic-Induced Vibrations

Figures 4 and 5 present histogram PPV data or measurements taken during lunch time 2 meters from the curb of an urban arterial street in Phoenix, Arizona. The street is 3 lanes wide in each direction and serves an industrial area. There is a mix of private and commercial traffic, including occasional heavy trucks. Traffic was moving in all of the lanes, so that vehicles in the lanes on the other side of the street generated smaller vibrations at the measuring point than vehicles traveling in the adjacent curb lane. Seismograph time sample intervals of 5 seconds were used, and monitoring proceeded for about 11 minutes. A total of 140 readings were taken.

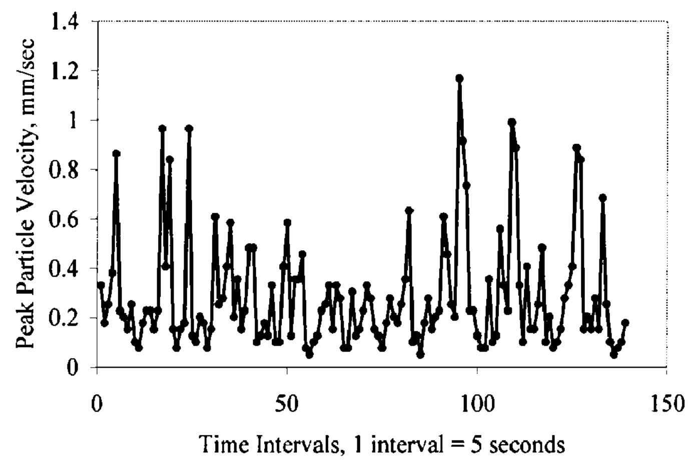

Fig. 4. Plot of histogram-type traffic-induced vibration PPV data at 2 meters from curb of major urban arterial street. Each time interval is 5 seconds.

Figure 4 presents the data in a histogram-type format. The maximum PPV is 1.2 mm/sec, and the minimum PPV is the instrument sensitivity of 0.05 mm/sec.

Figure 5 presents the Fig. 4 data in frequency-magnitude form. Similar to the Fig. 2 data, there are two relatively straight-line power-law trends, this time above and below about 0.8 mm/sec PPV. Ambient vibrations are typically greater than the seismograph sensitivity, so that the slope of the power law trend becomes flatter at PPV levels below about 0.15 mm/sec. The power-law trends appear to be well developed with 140 data points.

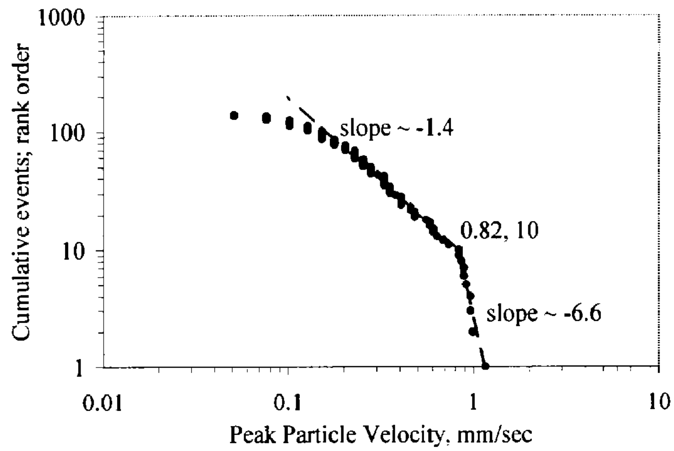

Fig. 5. Power-law frequency-magnitude presentation of PPV data from Fig. 4. Note the two distinct, nearly straight-line trends above and below PPV=0.82 mm/sec, and a flattening of the slope below about 0.15 mm/sec. The seismograph sensitivity is 0.05 mm/sec.

Ten data points define the power-law trend for the largest events. Predictions of anticipated maximum PPV values for longer time periods is straightforward based on this trend. However, actual traffic patterns may be different at other times of day. Further investigation and verification would be needed to assure that this is a reasonable characterization.

Unidentified Vibration at a Precision Machine

Histogram PPV data was obtained on a precision machine measurements platform where unidentified random vibrations were interfering with measurements requiring 0.0003 mm precision.

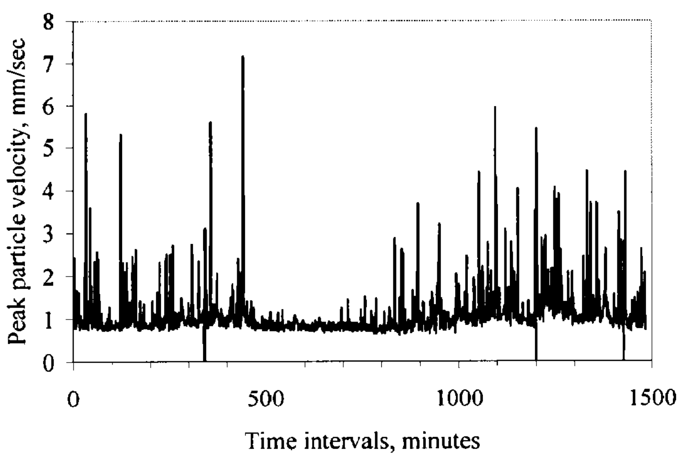

Fig. 6. Plot of histogram-type PPV data for 1 minute intervals on precision machine platform. Note lack of large events during nighttime (about 450 to 800 minutes).

Figure 6 presents the data in a histogram-type format. The maximum PPV is 7.2 mm/sec, and the minimum PPV is 0.6 mm/sec. This data set extends for more one day in one minute intervals. Consistent low PPV values are present between about 450 and 800 minutes, which was late night and early morning at the facility.

Figure 7 presents the Fig. 6 data in frequency-magnitude form. Similar to the Fig. 2 data, there are two relatively straight-line power-law trends above and below 5.3 mm/sec. Ambient vibrations are greater than the instrument sensitivity, so that the slope of the power-law trend becomes flatter at PPV levels below about 0.8 mm/sec.

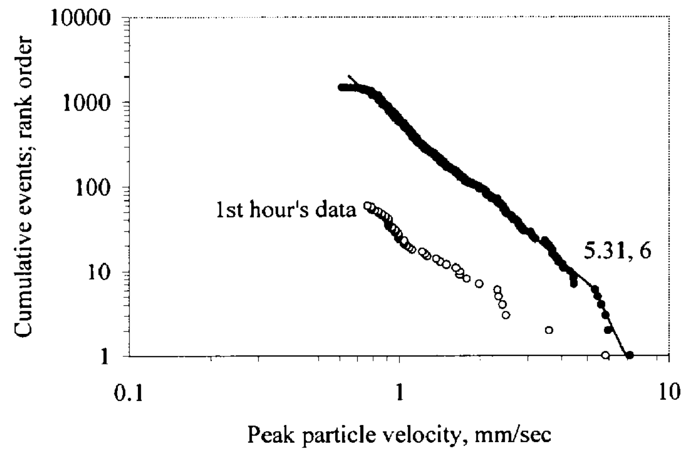

Fig. 7. Power-law frequency-magnitude presentation of PPV data from Fig. 6. The slope at PPV less than 5.3 mm/sec is about –2.8, and the slope at PPV greater than 5.3 mm/sec is about –6.8. The first hour's data is shown in open circles.

Six data points define the power-law trend for the largest events. Predictions of anticipated maximum PPV values for longer periods, perhaps days, is straightforward based on this trend. However, no 'large event' trend is apparent in the first hour's data. The largest PPV in the first hour is nearly 6 mm/sec, and a single power-law trend could easily be fit onto the first hour's data. On examination of the Fig. 6 histogram record, it is apparent that activity is minimal at night. Thus, establishment of a reasonable trend for the largest events may require a full day's monitoring.

Vibration at Water Pipeline

Histogram-type PPV data was obtained for ten hours on the ground near a structure servicing a water pipeline, where water flow through the pipeline generated the vibrations. Figure 8 presents this data in histogram-type form. The maximum PPV is 5 mm/sec, and the minimum PPV is 0.3 mm/sec. Variations are apparent in both the individual time interval measurements and in the overall baseline trend. Baseline trend peak periods are at about 7 and 10:30 am. Based on this data, it is not known if the baseline trend is based on transient PPV values occurring in each one minute interval, or if there is a true steady state vibration component in the data. Sample time histories of the vibrations for time periods of a few seconds to perhaps a minute would be needed to assess the presence of a steady state vibration component in the data.

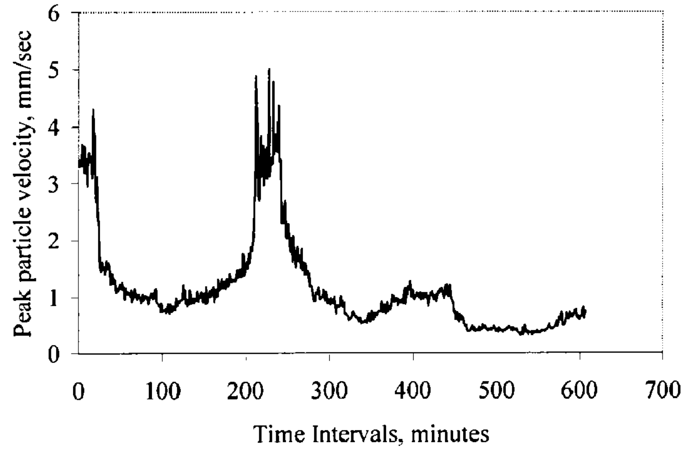

Fig. 8. Plot of histogram-type PPV data for 1 minute intervals at 1 meter from water pipeline terminal structure. Note variations in the baseline vibration levels over time.

Figure 9 presents the Fig. 8 data in frequency-magnitude form. Similar to the Fig. 2 data, there are two relatively straight-line power-law trends above and below 3.2 mm/sec. However, the straightness of the trend below 3.2 mm/sec is effected by the varying baseline PPV levels present in the data. The power-law trend above 3.2 mm/sec is determined from about 40 data points, the largest of which is 5.0 mm/sec.

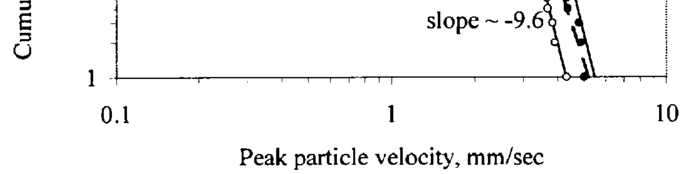

Fig. 9. Power-law frequency-magnitude presentation of PPV data from Fig. 8. Ten hours of data is shown in solid circles and the first hour of data is shown in open circles. An extrapolation of the first hours' large event trend to 10 hours is shown by the solid line.

A plot of the first hour of the data from Fig. 8 is also shown in Fig. 9. In the first hour of data, the maximum sampled PPV is 4.3 mm/sec. If the slope of the first hours' large event trend is extended by a factor of ten to represent ten hours of data, a maximum PPV of 5.5 mm/sec is predicted. This compares favorably with the actual maximum PPV of 5.0 mm/sec over the ten hour period.

CONCLUSIONS

Simple power-law based frequency-magnitude relationship characterization of peak particle velocity monitoring data for four very different transient vibration cases has been presented. Analyses were simple, and were successfully performed using standard electronic spreadsheet programs. Where sufficient data had been obtained, predictions of maximum anticipated vibrations for time periods longer than the duration of monitoring were made using frequency-magnitude trends of the largest vibration events. Predictions were made using initial parts of data sets, and were then compared to the entire data sets. Data sets containing insufficient data for effective predictions could be identified by simple visual examination.

Although applications of specific power-law relationships in engineering have been recognized and used for decades, generalized application of fractals, self-ordered criticality and other aspects of recently conceptualized nonlinear physics into practical geotechnical engineering is in its infancy. This paper has presented a practical use of these powerful physics concepts. It is hoped that further exploration into and application of nonlinear physics will enhance our insights into practical problems and improve our analytical skills in characterizing and solving those problems.

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