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Digital signal processing of data from borehole creep closure

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ABSTRACT: Digital signal processing, a technique commonly used in the fields of electrical engineering and communication technology, has been successfully used to analyze creep closure data obtained from a 0.91 m diameter by 5.13 m deep borehole in bedded salt. By filtering the "noise" component of the closure data from a test borehole, important data trends were made more evident and average creep closure rates were able to be calculated. This process provided accurate estimates of closure rates that will be used in the design of lined boreholes in which heat-generating transuranic nuclear wastes will be emplaced at the Waste Isolation Pilot Plant.

1 INTRODUCTION

The Waste Pilot Plant (WIPP) is a research and development facility which is being developed by the U.S. Department of Energy to demonstrate the safe disposal of radioactive wastes from U.S. defense programs and activities. Located near Carlsbad, New Mexico, the facility is about 655m underground in a bedded salt formation.

Current plans call for emplacing "remote-handled" transuranic nuclear wastes in horizontal boreholes drilled in the walls of mined underground openings at WIPP. These wastes emit ionizing radiation and heat as a result of radioactive decay. At present, a borehole depth of about 5.2 m and diameters in the range of 0.78 to 0.96 m are being considered in the design. The conceptual design calls for lining these boreholes with steel sleeves to resist creep closure and to prevent sloughing of material into the borehole; thus, ensuring that the emplaced wastes can be retrieved from the storage locations.

Accurate data on the rate of borehole closure is essential to the design of the borehole and the steel liner. Because relatively small errors in closure rates are magnified when projected over the long times of interest, accurate estimation of rates is particularly important. The digital signal processing technique described here was selected because it could provide the required accuracy by filtering the "noise" component of the data.

2 FIELD MEASUREMENTS

After cores of clear halite were obtained for laboratory testing of the properties of salt, the resulting 0.91 m in diameter by 5.13 m deep horizontal borehole was instrumented to obtain closure data for use in the design of emplacement boreholes for remote-handled transuranic wastes. The borehole was drilled in three stages, as dictated by the coring program: drilled to 1.70 m on day one, advanced to 4.27 m on day nine, and advanced to total depth of 5.13 m on day ten. Instrumentation was installed and readings commenced on the tenth day. As a result, creep relaxation occurred for nine days in the initial 1.70 m and for one day in the zone between 1.70 and 4.27 m before any measurements were made.

Instrumentation consisted of micrometer readings between sets of stainless steel reference points. These reference points were installed at depths of 0.30, 1.52, 2.74, and 3.96 m at azimuths of 0 (vertically up as viewed looking into the borehole), and 60, 120, 180, 240, and 300 degrees clockwise from vertical. At each location, a stainless steel reference point was installed by gluing it into a small diameter hole in such a manner that it was flush with the inside surface of the borehole. An adjustable inside micrometer with a precision of 0.01 mm was used to measure the inside diameter of the borehole between these sets of reference points. In general, measurements were made each day that there was underground access. As a result, there are missing data on weekends and holidays.

Borehole displacements were calculated as the difference between the current reading and initial reading for the respective depth and azimuth combination. A typical example of data from each of the azimuth combinations at the 3.96 m depth is shown in Figure 1. These data display the uniformity between the 60 to 240 degree azimuth and the 120 to 300 degree azimuth and the difference between these two data sets and the 0 to 180 degree (vertical) azimuth. The available data suggest that this difference occurs because the bedded salt formation is somewhat orthotropic and includes an anhydrite and clay seam about 0.3 m above the borehole. In addition, short-term temporal variability and long-term trends are evident in these data sets.

3 DATA ANALYSES

Although the application of digital signal processing is a standard technique in electrical engineering and communication technology, its potential value for aiding in the processing of time-series signals from geotechnical instruments is largely untapped. The method used here is based on fundamental concepts of digital time-series processing (Chakrabarti, et al. 1986).

In this analysis, the borehole creep closure data were assumed to be a time-series consisting of two components: legitimate data that describe the time-dependent borehole closure (creep), and random errors in the measurements that are superimposed on the legitimate data. The legitimate data comprise the "signal" and the random errors, which arise primarily from nonsystematic operator error, minor temperature fluctuations, and inherent inaccuracies in the instrumentation, constitute the "noise" in the recorded measurements. The noise component must be eliminated to determine the true rate of creep closure.

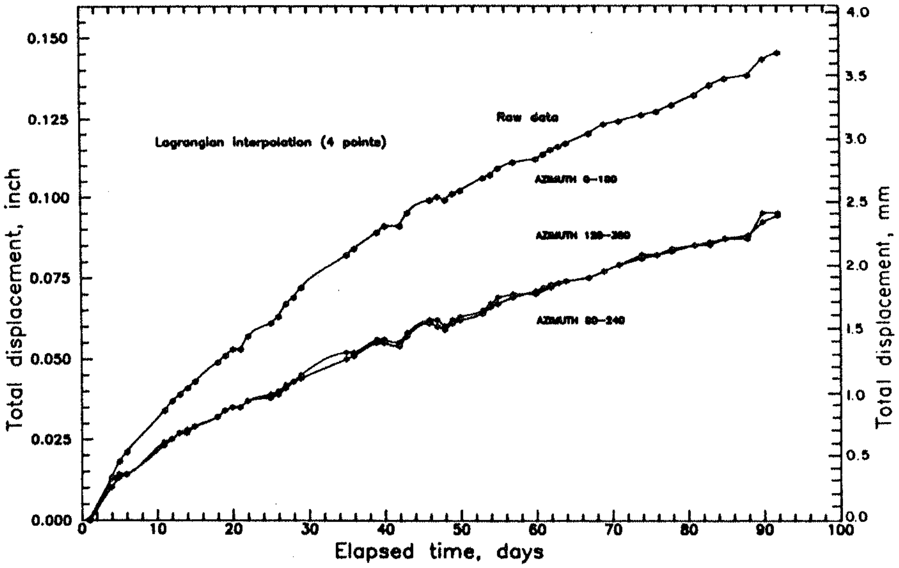

Figure 1. Displacement time history at 13-foot (3.96 m) depth.

Filtering of the noise component was accomplished using the five-step approach discussed below.

3.1 Spectral analysis

Separation of the signal from the noise component of the measurement requires knowledge of the power or energy spectrum. One of the methods by which the energy spectrum may be calculated is using a "Fast Fourier Transform" (FFT) routine whereby the time-domain record, x_i, is transformed into the frequency domain function, $X(f)$, where f is frequency. The minimum frequency component in $X(f)$ is given by $(1/T_r) = (1/Nh)$, where T_r is the length or duration of the record, N is the number of data points, and h is the time interval. The energy spectrum is then calculated as:

$$H(f) = 2[X(f)^* \cdot X(f)] \qquad (1)$$

where $X(f)^*$ = complex conjugate of $X(f)$ (Bendat and Piersol, 1971).

Energy spectral evaluation was performed on measured (both raw and interpolated) data, differentiated raw data, and filtered raw data. Key features of the spectral analysis used here include: truncation of the data sets to 71 points to allow application of the selected FFT techniques, application of a cosine taper over 1/10 of the record length at each end of the data sets, determination of $X(f)$ using an FFT routine, calculation of $H(f)$ using Eq.1, and adjusting the values of $H(f)$ to compensate for the cosine taper scale factor (Bendat and Piersol, 1971).

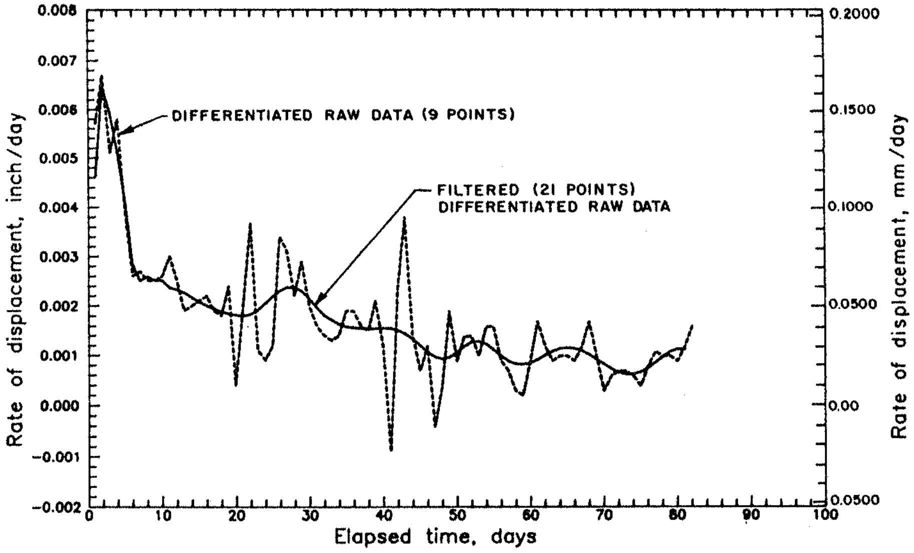

Figure 2. Rate of displacement time history at 13-foot (3.96 m) depth.

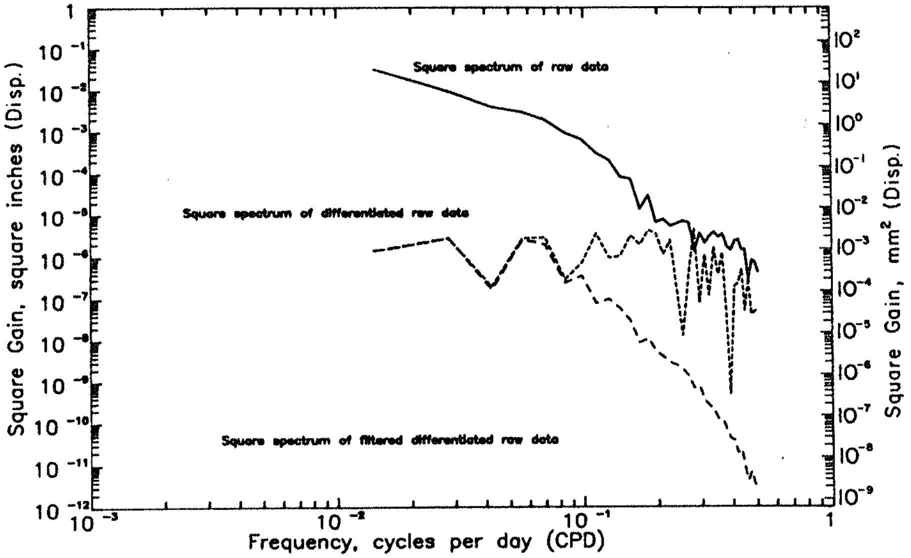

Figure 3. Energy spectrums for 1-foot (.305 m) depth, Azimuth 0-180.

3.2 Data interpolation

In order to use the FFT technique, the data points must be equally spaced. A Lagrangian polynomial interpolation scheme was chosen because a linear technique would have resulted in a constant when differentiated (creep rate) data were analyzed. The Lagrangian polynomial was of the form (Atkinson, 1984):

$$P_n(x) = f_o l_o(x) + f_n l_n(x) \tag{2}$$

where each function $l_i(x)$ for i = 0, 1, ..., n is itself a polynomial of degree n where x_i are the data points. Each of the polynomials $l_i(x)$ has the form:

$$l_i(x) = \frac{(x-x_o)(x-x_1)\cdots(x-x_{i-1})(x-x_{i+1})\cdots(x-x_n)}{(x_i-x_o)(x_i-x_1)\cdots(x_i-x_{i-1})(x_i-x_{i+1})\cdots(x_i-x_n)} \tag{3}$$

In this study, the fourth degree polynomial was used. As evidenced in Figure 1 by the solid curve through the data points, the results of interpolation performed in this way proved to be an acceptable solution.

3.3 Differentiation of closure data

In order to obtain the creep rate from borehole closure measurements, the data had to be differentiated. In general, differentiation exaggerates any rounding errors or other irregularities, may act as a filter on the data (Hamming, 1971), and amplifies high frequencies (typically noise) much more than low frequencies.

A nine-point differentiation formula was applied to the data (Nielsen, 1964):

$$x'_{i=n-4} = \frac{1}{840h}(105x_{n-8} - 960x_{n-7} + 3,920x_{n-6} - 9,804x_{n-5} + 14,700x_{n-4} - 15,680x_{n-3} + 11,760x_{n-2} - 6,720x_{n-1} + 2,283x_n) \tag{4}$$

for $N-4 \geq i \geq 4$. Note that the formula for the first four points and the last four points are different. A typical example of differentiated raw data is shown in Figure 2.

3.4 Frequency transformation

Spectra of raw data (borehole closure), differentiated raw data (borehole closure rate), and filtered differentiated raw data were examined for each borehole depth and azimuth; a total of 12 spectra for each data type. For all spectra plotted, the components of the signals that were judged to be predominately noise were observed at frequencies greater than 0.1 cycle per day (cpd) (Figure 3). Therefore, the data were processed with a cutoff frequency of 0.1 cpd.

3.5 Digital filtering

To eliminate the random fluctuations in accordance with the frequency cutoff criterion discussed above, a 21-point Spencer's smoothing formula (Hamming, 1977) was used. This filter was selected after evaluating a five-point least-square quadratic and Spencer's 15-point smoothing formula.

Spencer's 21-point smoothing function is given by:

$$x_n = \frac{1}{350}[-x_{n-10} - 3x_{n-9} - 5x_{n-8} - 5x_{n-7} - 2x_{n-6} + 6x_{n-5} + 18x_{n-4} + 33x_{n-3} + 47x_{n-2} + 57x_{n-1} + 60x_n + 57x_{n+1} + 47x_{n+2} + 33x_{n+3} + 18x_{n+4} + 6x_{n+5} - 2x_{n+6} - 5x_{n+7} - 5x_{n+8} - 3x_{n+9} - x_{n+10}] \tag{5}$$

The low-pass characteristics of this filter are good in that its transfer function correlates to a selective degree with the cutoff frequency of 0.1 cpd. However, this formula does not allow smoothing of the first and last 10 data points of the time-series. In future studies, the authors recommend use of a better, more efficient filter designed using currently available software such as SIG (Lager and Azevedo, 1985).

The powerful smoothing effect of this filter is evident in Figure 2. Variations in the differentiated data, which are sometimes quite extreme, have been effectively smoothed. As a result, the primary temporal trend in the closure rate is more evident than in the unfiltered data. The minor periodicity that remains may be an artifact of the processing technique or may be inherent in the data.

4 RESULTS

Analysis of the filtered creep rate data indicated that primary creep was nearly complete about 20 days following drilling of the borehole (Figure 2). Therefore, data from the 20th day to the last observation were analyzed to determine the creep-rate statistics.

For each day, the processed data from each of the four measurement depths were used to calculate a mean and standard deviation of the creep rate. Because the data trends obtained from the 60 to 240 and 120 to 300 degree azimuths were the same, these data sets were combined, giving statistics based on eight points each day. Four data points were used for the 0 to 180 degree azimuth.

An example plot of the mean, the plus and minus one-standard-deviation curves, and the upper and lower bound envelope curves is shown in Figure 4. The somewhat greater standard deviation at early times is attributed to these data coming from the period of transition between primary and secondary creep.

The creep rate was judged to be nearly constant after about day 50 so the data were merged and composite statistics were calculated for times between days 50 and 82. These statistics and upper and lower bound values are provided in Table 1.

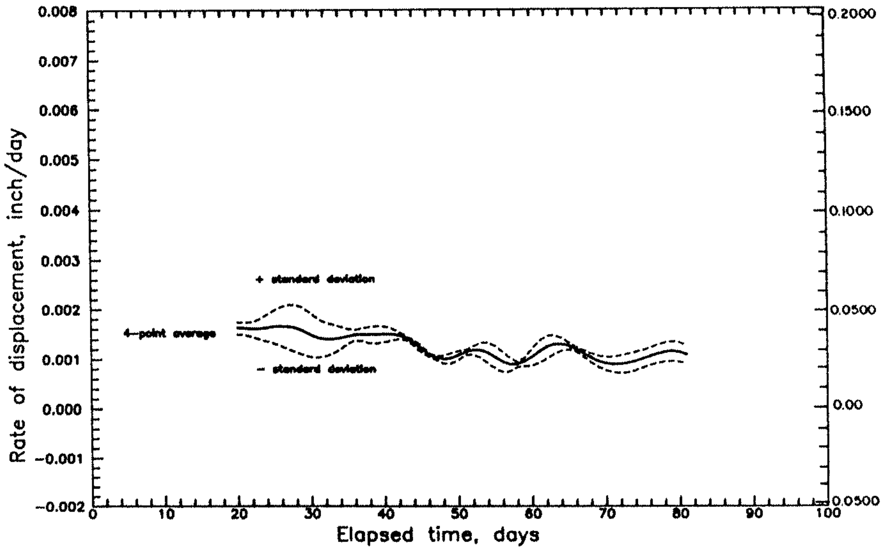

Figure 4. Rate of displacement bounds, Azimuth 0-180.

Table 1. Summary creep rate statistics.

Azimuth	Mean mm/day	Std.Dev. mm/day	Upper bound mm/day	Lower bound mm/day
0 to 180	0.0267	0.003	0.0348	0.0194
60 to 240 and 120 to 300	0.0170	0.002	0.0232	0.0109

5 CONCLUSION

This relatively elementary application of digital signal processing techniques clearly shows the value of applying this approach to geotechnical data. Although not optimal, the digital filter produced a data set which was essentially noise-free and depicted a smooth trend that was not otherwise observable. A relatively minor periodicity remained after filtering which may be inherent in the data or may be an artifact of processing. The authors hope to see application of such techniques in future analyses of geotechnical data.

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