Accelerating Creep Of The Slopes Of A Coal Mine

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ABSTRACT

A 249 day long record of the accelerating creep of a slope of an open-pit coal mine is analyzed, using linear regression, to test four creep laws. The Saito and Zavodni and Broadbent laws did not lead to a satisfactory estimation of the time of failure as a range of times of failure satisfied the goodness of fit criteria. Using the generalized Saito law, the upper limit for the time of failure was 168 days after the actual failure. Our prediction of a critical slide velocity for the evacuation of pit personnel and equipment, as an indication of impending failure, used two new methods employing the power and exponential laws. Three accelerating creep stages were identified, threshold velocities of 0.02 mm/min and 0.1 mm/min marked the initiation of the second and third stages, respectively.

LIST OF SYMBOLS

t = Relative time

T = Absolute time

X = Time constant

T_f = Absolute time of failure

t_f = Relative time of failure

ϵ = strain or displacement

ϵ_o = displacement at time zero, a constant

$\acute{\epsilon}$ = displacement rate

$\acute{\epsilon}_1$ = $\acute{\epsilon}$ at 1 minute

$\acute{\epsilon}_m$ = $\acute{\epsilon}$ at the mid-point in the second acceleration stage

$\acute{\epsilon}_o = \acute{\epsilon}$ at the onset of failure

$\acute{\epsilon}_f = \acute{\epsilon}$ at the failure

C, K, a, b, k, n : Constants

I = number of measurements

INTRODUCTION

Recent developments in electronic distance measurement have made possible reliable remote monitoring of rock slope movements. If observations of slope movements in surface mines can be reliably extrapolated to predict slope failure, the slope movements can be treated as "another mining problem". We have applied the two widely known extrapolation techniques to a particular history of movement for a retrospective assessment of these techniques.

We have studied the movement of the north wall of 51-B-2 pit of the Luscar coal mine in the Rocky Mountains of Alberta, Canada during 1979. The displaced mass was 245 metres in length, 106 metres high and 1.07 million cubic metres in volume. Though sixteen displacement prisms provided data, we concentrated on the observations from the longest record, the 26-B prism.

First the mine geology and monitoring program is briefly described. Then four relations for assesment of displacement-time data are presented and evaluated. Linear regression methods were incorporated into computer programs to allow statistical analysis of the data. Two criteria were set to be satisfied; i.e. the test of slope significance and the Durbin Watson statistic. Two new methods for prediction of failure are presented.

MINE GEOLOGY AND MONITORING PROGRAM

The stratigraphy of the Lower Cretaceous coal-bearing rocks of the Luscar mine was described by McLean [1] and Hill [2]. The north wall of the 51-B-2 pit consisted of interbedded sandstones and siltstones which dipped into the pit with dip and dip direction of 38/204. MacRae [3] reported ground water elevations of about 50 metres below the crest of the slope.

The instability in the north wall had resulted from a weak zone sub-parallel to the wall intersecting overturned beds at the toe of the wall. Moderate to steeply dipping sandstone strata, jointed by four sets, and overlying siltstone and shale strata formed five moving blocks. Two major directions of movement were identified; nearly parallel to the strike of the bedding and down the dip direction of the bedding. The latter movement was much larger than the former. A common plane of movement dipped 28° to the west [4].

Slope deformation measurements used an electronic distance meter to measure slope distances, and a theodolite to measure horizontal and vertical angles to permanently placed retroreflector prisms [5 and 6]. Munn [7] explained a philosophy behind the monitoring program and the subsequent remedial measures. The displacement record analyzed in the paper, consisting of 45 measurements extending over 249 days, from 6

March till the pit wall failed on 10 November, 1979, was listed by Johnson [6].

REVIEW OF ACCELERATING CREEP LAWS

General

Displacement-time relationships during accelerating creep have been divided into the following four laws [8 and 9]:

Saito laws

exponential laws

power laws

Zavodni and Broadbent laws

Various formulations of these laws are presented below. The application of these laws to the 26-B prism displacement data will be discussed in the next section.

Saito Laws

Saito [10] suggested that equation (1) described accelerating creep:

$$\acute{\epsilon} = C/(t_f - t)^n \quad (1)$$

where $\acute{\epsilon}$ is the strain or displacement rate at time, t; t_f, the time of failure, C and n are constants to be estimated. Equation (1) indicates that the strain rate approaches infinity as t approaches t_f. Varnes [8] named equation (1) "pure Saito", when n was near to or equal to 1, and "generalized Saito" when $n \neq 1$.

Saito [11] stated that a plot of the displacement, ϵ, against the logarithm of time to failure, $(t_f - t)$, would be linear if t_f was chosen correctly. The "pure Saito" law thus provided a simple estimate of the time to failure during accelerating creep.

Exponential Laws

may be expressed as:

$$\epsilon = k[\exp(T/a) - 1] \quad (2)$$

$$\ln\acute{\epsilon} = \ln(k/a) + T/a \quad (3)$$

$$\acute{\epsilon} = k/a + \epsilon/a \quad (4)$$

where T is the time from the beginning of accelerating creep, ϵ is strain or displacement and a and K are constants to be estimated.

Fit to equation (3) is tested by the linearity of a plot of the logarithm of strain rate versus time, equation (3), or of strain rate versus strain, equation (4). Prediction of the time of failure, t_f, by this law requires knowledge of the strain rate, $\acute{\epsilon}_f$, or strain, ϵ_f, at failure.

Power Laws

may be expressed as:

$$\epsilon - \epsilon_o = \acute{\epsilon}_1 T^{b+1}/(b+1) \quad (5)$$

$$\acute{\epsilon} = \acute{\epsilon}_1 T^b \quad (6)$$

$$\log\acute{\epsilon} = \log \acute{\epsilon}_1 + b \log T \quad (7)$$

where $\acute{\epsilon}_1$ and b are constants to be estimated.

This form is tested by the linearity of a plot of log strain rate versus log time, equation (7). Again prediction of t_f requires knowledge of $\acute{\epsilon}_f$ or ϵ_f.

Zavodni and Broadbent Laws

Zavodni and Broadbent [9] recognized two stages in the typical slope movement which led to failure:

1. A regressive stage during which the moving mass would stabilize if some disturbance external to the rock and structure was removed; the average velocity in this stage could slightly accelerate, remain constant, or decelerate.

2. A progressive stage during which the rock mass would displace at an accelerating rate to failure unless active control measures were taken. The majority of the total displacement of the rock mass took place in this stage rather than in the regressive stage.

Displacements in both stages were exponential with a break occurring at the "onset of failure". Bi-linear plots of the log of the displacement rate versus time to failure, representing the two creep stages, were demonstrated for slides that proceeded to failure.

Zavodni and Broadbent [9] found that once the pattern of the second stage of movement was established, they were able to estimate the number of days until failure from a semi-log plot by assuming that:

$$\acute{\epsilon}_m/\acute{\epsilon}_0 \cong K \qquad (8)$$

where,

$\acute{\epsilon}_m$ is the velocity of the rock mass at the mid-point of the second stage, $\acute{\epsilon}_0$ is the velocity at the "onset of failure" and K is a constant.

Assuming that:

$$\acute{\epsilon} = c \exp(st) \qquad (9)$$

where c and s are constants. With t=0 at the onset of failure, equation (9) becomes for the second stage ;

$$\acute{\epsilon} = \acute{\epsilon}_0 \exp(st) \qquad (10)$$

From equations (10) and (8), Zavodni and Broadbent [9] determined the velocity at failure, $\acute{\epsilon}_f$,

$$\acute{\epsilon}_f = K^2 \acute{\epsilon}_0 \qquad (11)$$

EVALUATION OF METHODS OF PREDICTING THE TIME OF FAILURE

Introduction

Data for predicting the time to failure, t_f, can be divided into two groups. In the first group the origin of the time axis, T_0, is known (Figure 1). T_0 in a creep test is the moment that load ceases to be added to the test specimen. This group is discussed by Cruden, Leung and Masoumzadeh [14].

In the second group, the origin of the time axis, T_0, is not known. In a natural slope, shear movements along discontinuities may have begun millions of years ago. A displacement measurement shows the position of a point at time, t_1, after t_o, where t_o is the time when the first measurements were recorded. So, the interval, X, since movement began (Figure 1) is unknown. The origins of time, T_o, for all field data obtained from north wall of 51-B-2 pit are unknown.

Failure Definition

Definitions of failure in the literature are not precise. The Saito laws, equation (1), suggested an infinite rate of displacement at failure which is physically impossible. The exponential and power of time laws [9] show that the velocity increases with time, but the time of failure requires a separate prediction criterion.

Zavodni and Broadbent [9] reported displacement rates ranging from 0.04 to 1.04 mm/min at the time of failure. MacRae [5] and Wyllie and Munn [15] suggested a slide velocity of 0.5 mm/min, the critical slide velocity, should trigger evacuation of pit personnel and equipment under the moving mass a few hours before failure. Munn [7] defined failure as excessive wall movement which may cause rock to fall into the active mine area, "failure" was not a cataclysmic event but just another mining problem. We consider that requirements for the proper protection of men and equipment can greatly influence the definition of failure and critical slide velocity. The critical velocity of slope movements can best be determined by personnel with experience in coping with the movements. The procedures we propose here will support their judgement.

General Procedure For Analysis of Displacement-Time Data

Transformation of creep laws into linear relations allows linear regression methods to be used, t_f predictions to be more convincing, and slopes and intercepts of lines to be more easily determined. In a numerical analysis with the help of a computer, the actual values of displacement and time obtained from field measurements can be used directly.

If logarithmic axes such as $\log\epsilon$ and $\log t$ are used, zero quantities cannot be plotted, but the use of displacement rate instead of displacement provides plots which are independent of the zero point of displacement measurements. Although displacement rate analysis avoids the zero point of displacement, the estimation of the rate itself may be only approximate. Linear interpolation was used to compute velocity and long time intervals may reduce the accuracy of estimates of the displacement rates.

Analysis Of The Data

Computer Programs

A program described by Cruden [12] was used to fit the power and exponential laws. This program was modified so that strain observations were replaced by displacements in the input file. One or two components of the displacement vectors can be entered. The displacement records are smoothed by recursion formulae described in [14].

Two programs were coded to examine the Pure and Generalized Saito relations. For a value of t_f within a given range of t_f, these programs calculate fit parameters. Iteration continues till the Durbin Watson statistic described below reaches a preset value, then a graph of $\log(t_f - t)$ versus $\log \dot{\epsilon}$ or $\dot{\epsilon}$ is produced.

Listings of the four programs together with the definition of input parameters, examples of input and output were presented by Masoumzadeh [4].

Criteria For Goodness of Fit of The Laws To The Displacements

As a test for serial correlation the Durbin Watson statistic, dw, was used. If the residuals are positively serially correlated, dw will tend to be small. If the residuals are negatively serially correlated, dw will tend to be large. Durbin and Watson [13] tabulated two groups of critical values for dw against I, the number of observations; an upper value of dw, which, if not exceeded, suggested that positive serial correlation of the residuals might exist in the observations, and a lower value of dw, which, if not exceeded, suggested that positive serial correlation existed in the data [12].

The test of slope significance examines the hypothesis that the fitted line does not have a slope significantly different from zero, a hypothesis equivalent to suggesting that the data might be as well represented by their mean, and that the fitted line has not picked out any significant variation [12]. The test of slope significance statistic, can be referred to F-tables with one and (I-2) degrees of freedom.

26-B Prism Displacement Analysis

The displacement of the 26-B prism was chosen for analysis, since it had the longest duration and moved more than the other prisms. The total displacement and duration were 1557.7 millimetres and 358380 minutes, respectively. A displacement vector was calculated from its vertical and horizontal components as measured by the EDM and the theodolite [6]. The resultants of the displacement vector were chosen as proper representations of movements. It was assumed that all displacement vectors had identical orientations.

As the acceleration of the slide increases, linear interpolation methods of estimating velocity become less precise. Therefore, the data was divided into two parts. Part two contained measurements taken after 29th October 1979, when MacRae's [5] observations confirmed drastic acceleration in displacements. A visual examination of the log $\dot{\epsilon}$ versus log t and t plots (Figures 2 and 3) showed 2 distinct clusters of data.

Complete Data Set

The whole data set was not adequately described by the power, exponential and pure Saito laws. However, it was satisfied by the generalized Saito law.

Saito laws

The Durbin Watson statistics showed serial correlation in the residuals indicating some variation was still unexplained by the pure Saito law when t_f varied from 358390 to 359000 minutes. The actual t_f was 358605 minutes. As t_f was increased, we saw what Saito [11] reported, on a $\log(t_f - t)$ versus ϵ plot the curvature of the fitted line close to the time of failure changed from downward to upward.

For the generalized Saito law, the optimum Durbin Watson statistic of 2.069 was at t_f=365,560 minutes, about 5 days after the actual time of failure. The statistic reduced to 1.403, at t_f=700,000 minutes, below the upper bound of the critical value at 5% confidence, indicating significant positive serial correlation. Figure 4 shows the variations of the generalized Saito fit statistics with the time of failure, the variation of the test of slope significance paralleled the Durbin Watson statistic. A wide range of t_f values was acceptable from 241395 minutes after the actual time of failure to a few minutes after the last measurements. In contrast with what Varnes [8] and Saito [10 and 11] stated, the exact prediction, "fine tuning", of the time of failure was not possible.

Velocities at times beyond the last measurements are a function of t_f for the generalized Saito fit. At t=358440 minutes, 165 minutes before failure, velocities of 2.09 and 0.02 mm/min were obtained when t_f was 358605 (Figure 5) and 600,000 minutes, respectively. Hence, the choice of t_f would have greatly influenced the prediction of velocities before failure.

Power and exponential laws

Figures 2 and 3 show the power and exponential laws fit to the resultants of the displacement vectors. Although the tests of slope significance were passed at the 5% confidence level (Table 1), the Durbin Watson statistic indicated positive serial correlation in the fit residuals.

Partial Data Sets

The power, Saito, exponential and Zavodni and Broadbent laws were all satisfactory fits. The first stage of the displacement record, before 29th October 1979, showed less than 40 centimetres movement.

Power and Exponential Laws

Power and exponential laws were reasonable descriptions of the data. Tables 2 and 3 show the analyses of the displacement vectors for parts one and two of the data. The

Durbin Watson statistics are more than the upper bounds for both parts. The test of slope significance exceeds the 5% confidence level for part two and is less than the limit for part one.

Zavodni And Broadbent Laws

Taking t_f=358605 minutes, equations for exponential law may be written as:

For part 1, i.e., first stage;

$$\acute{\epsilon} = 0.00276 \exp[-0.000007(t_f-t)] \quad (12)$$

For part 2, i.e., second stage;

$$\acute{\epsilon} = 0.093 \exp[-0.000084(t_f-t)] \quad (13)$$

Zavodni and Broadbent [9] after examination of 13 slope failures in open-pit porphyry copper mines concluded that a displacement rate above 0.035 mm/min indicated that a movement was probably in the second stage and that failure would occur within 48 days. Using equation (13) for the second stage, the displacement rate of 0.035 mm/min occurred 8 days before failure.

Third Accelerating Creep Stage

The accelerating creep laws predicted from stage 2 data for the 165 minutes prior to failure are compared in Figure 6. This shows that the power, exponential and Zavodni and Broadbent's 2-line laws greatly underestimate velocities close to the time of failure. These laws estimated velocities less than 0.13 mm/min, in contrast with the last measured velocity, 0.33 mm/min, 12 hours before failure and the critical slide velocity of 0.5 mm/min suggested by MacRae [5] and Wyllie and Munn [15]. We demonstrate that these higher velocities can be estimated by taking into account a third accelerating creep stage.

The generalized Saito law estimated velocities in excess of the suggested critical value, with the time of failure chosen as 358605 minutes (the actual time of failure). This law also suggested that the critical slide velocity of 0.5 mm/min occurred at 09:05, on November 10th 1979, 3 hours and 40 minutes before the time of failure. A close examination of the Saito relation is not possible, since the last measured velocity is 0.33 mm/min, 12 hours before the time of failure.

The velocity at t_f estimated from the second stage of the Zavodni and Broadbent law, equation (13), is 0.09 mm/min, a dangerous underestimate. Figure 3 shows that on the morning of November 10, there was a large increase in displacement rate which can be regarded, despite Zavodni and Broadbent's 2-line theory, as a third line with steeper slope after t_0=357150 minutes and $\acute{\epsilon}_0$=0.074 mm/min. Taking a typical k=7 value , a collapse velocity of $(7^2)(0.074)$=3.6 mm/min is obtained (Figure 6). This velocity is more than seven times that suggested by MacRae [5] and Wyllie and Munn [15] as the critical slide velocity. The critical slide velocity of 0.5 mm/min was predicted 12.3 hours before failure.

A criterion can be set for prediction of the time of critical slide velocity. The last velocities, plotted in Figures 2 and 3, show that there was a drastic increase in velocity from 0.1 to 0.33 mm/min, at t=357885 minutes. This increase can be regarded as the initiation of a third stage of the accelerating creep process. The power and exponential laws show that the velocity reached a threshold value of 0.1 mm/min, respectively 34 and 23.3 hours before failure. There are only three displacement measurements available after this threshold and before the moment of failure, so only a rough estimation of velocity prior to failure can be made. From these measurements, 2 velocities and their corresponding times are calculated. By passing power and exponential lines through these 2 points, velocities before failure may be estimated. The critical slide velocity of 0.5 mm/min corresponded to 8 hours and 23 minutes before failure for the power law, and, 8 hours and 38 minutes for the exponential line. Velocities at the time of failure were also calculated as 1.35 and 1.43 mm/min by the power and exponential laws, respectively.

A prediction of the time of the second threshold velocity can be made from the second accelerating creep stage. Displacement records show that this stage started at t=340680 minutes, equivalent to 2:00 P.M October 29 , 1979. The power law fit showed that this stage ended at t=356560 minutes, 34 hours before failure. The total time span of this stage is 11 days. A velocity of 0.02 mm/min marks the initiation of the second accelerating creep stage. The small number of observations does not allow satisfactory prediction of the threshold velocity of 0.1 mm/min.

CONCLUSIONS

The conclusions from this paper are directly applicable only to slope movements similar to that in the 51-B-2 pit. They may be extended to other coal mines in the Canadian Rockies with similar geology and groundwater conditions.

When accelerating creep is considered in 2 stages, the power and exponential laws underestimate displacement rates at times close to failure. Our 3 accelerating creep stages allow prediction of the time of the critical slide velocity, when evacuation of pit personnel and equipment should begin. The threshold velocity of 0.02 mm/min marked the initiation of the second accelerating creep stage. At the initiation of a third accelerating creep stage, a threshold velocity of 0.1 mm/min was observed, approximately 34 hours before failure. The few observations from the third stage showed that the critical slide velocity of 0.5 mm/min occurred 8.5 hours before failure.

The generalized Saito law rather than the pure Saito law was found to be the better description of all the data when t_f was known. A procedure for t_f prediction was presented. With a preset upper limit Durbin Watson statistic, the program will stop computation as soon as the upper limit of either Durbin Watson statistic or t_f is reached. The time to failure, t_f, is a variable within a wide range, t_f could not be precisely determined in contradiction of Saito's claims [10 and 11] for other slope movements. The upper limit of the range of acceptable values for t_f was 168 days after the actual time of failure.

Zavodni and Broadbent's laws may be applicable with three accelerating creep stages instead of the two they have proposed. Taking into account the third accelerating creep stage, the velocity reached to its critical value of 0.5 mm/min, 12.4 hours prior to failure.

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Table 1 Results of analysis of the displacements

LAW	POWER	EXPONENTIAL	SAITO
INTERCEPT	-51.4	-10.4	6.460
±INTERCEPT 90%	16.9	1.57	2.022
SLOPE	3.7	0.0000194	-1.116
±SLOPE 90%	1.352	0.0000055	0.197
DW CALCULATED	0.742*	0.915*	1.605
TSS CALCULATED	22.2	35.8	94.52
I	26	26	26

DW = DURBIN WATSON STATISTIC
TSS = TEST OF SLOPE SIGNIFICANCE
* = FAILS AT 5% LEVEL

Table 2 Results of analysis of the displacements - stage 1 observations

LAW	POWER	EXPONENTIAL	SAITO
INTERCEPT	-20.43	-8.2	3.849
±INTERCEPT 90%	19.32	1.9	10.584
SLOPE	1.124	0.0000071	-0.906
±SLOPE 90%	1.577	0.0000081	0.911
DW CALCULATED	1.506	1.58	1.623
TSS CALCULATED	1.638*	2.514*	3.193*
I	13	13	13

DW = DURBIN WATSON STATISTIC
TSS = TEST OF SLOPE SIGNIFICANCE
* = FAILS AT 5% LEVEL

Table 3 Results of analysis of the displacements - stage 2 observations

LAW	POWER	EXPONENTIAL	SAITO
INTERCEPT	-534.07	-44.81	3.251
±INTERCEPT 90%	246.02	25.36	2.710
SLOPE	41.59	0.000119	-0.731
±SLOPE 90%	19.26	0.000071	0.313
DW CALCULATED	1.698	1.708	2.531
TSS CALCULATED	8.775	8.874	17.90
I	12	12	12

DW = DURBIN WATSON STATISTICS
TSS = TEST OF SLOPE SIGNIFICANCE

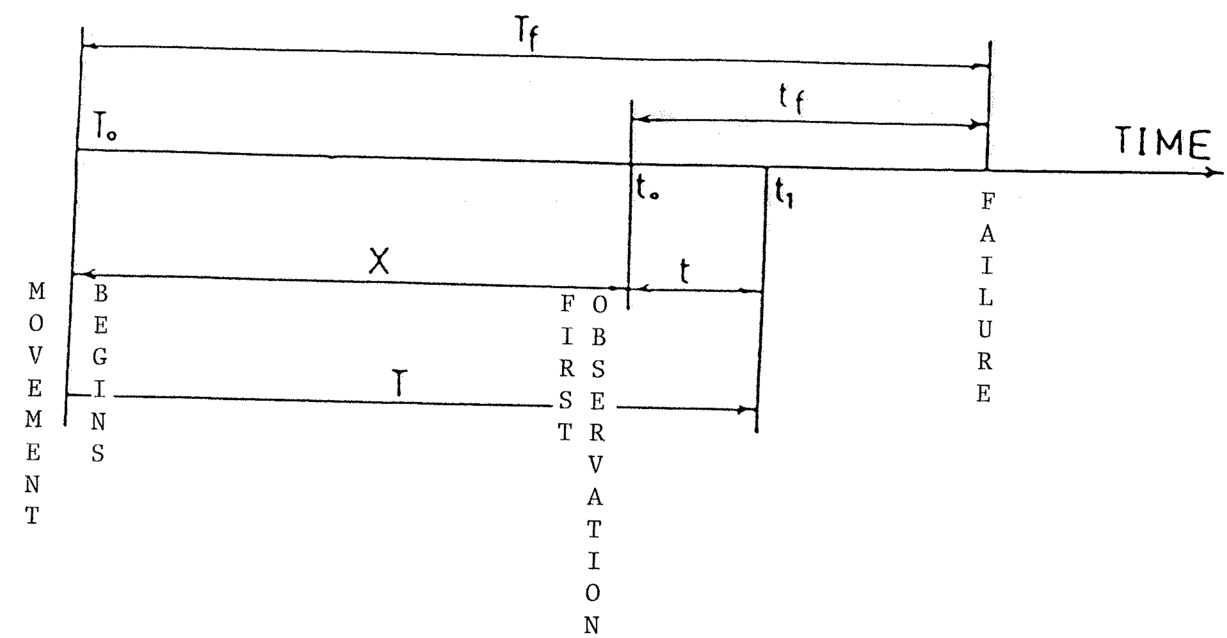

Figure 1 Times definitions

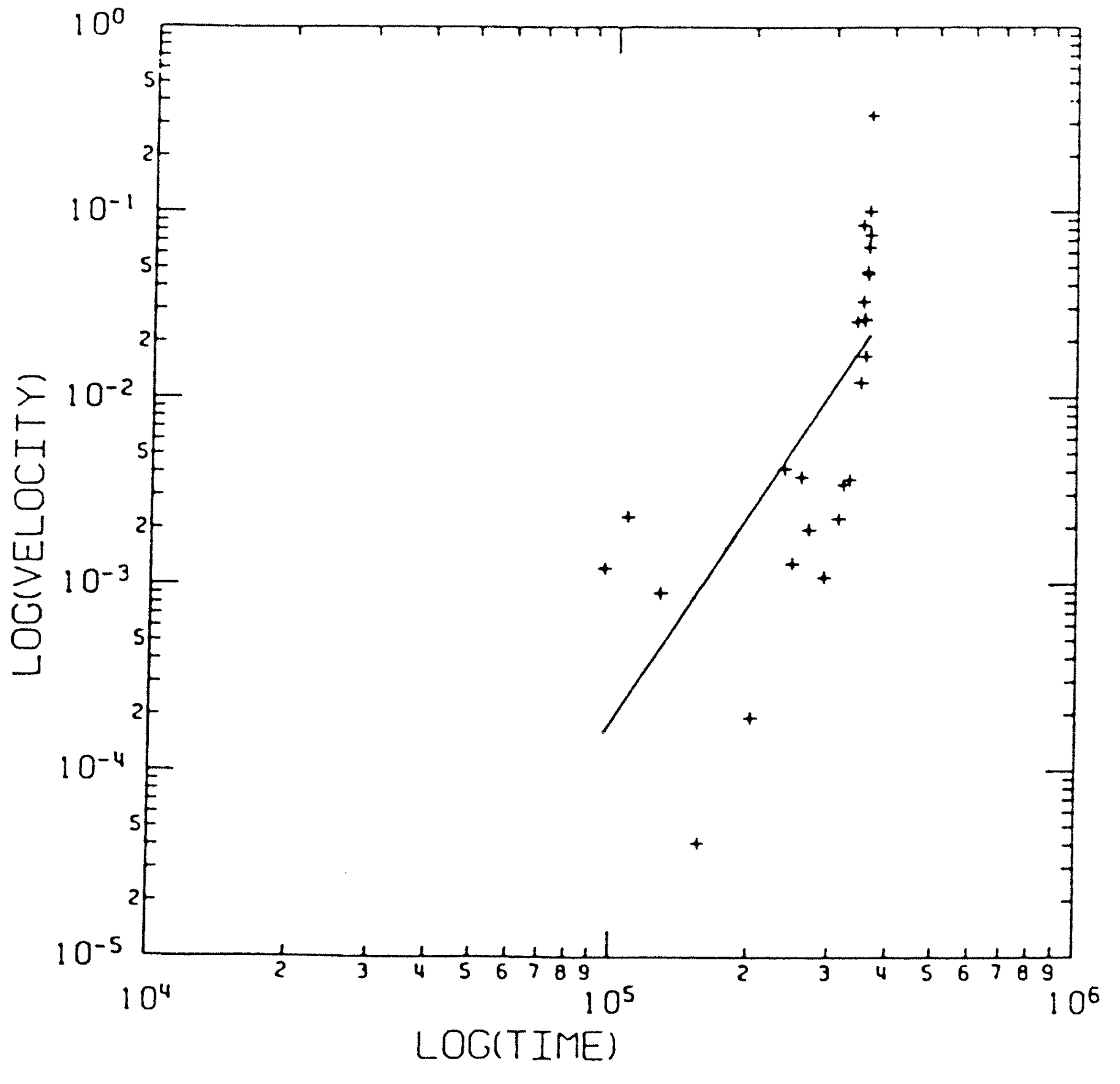

Figure 2 Power law fit to the displacements (velocity:mm/min , time:min)

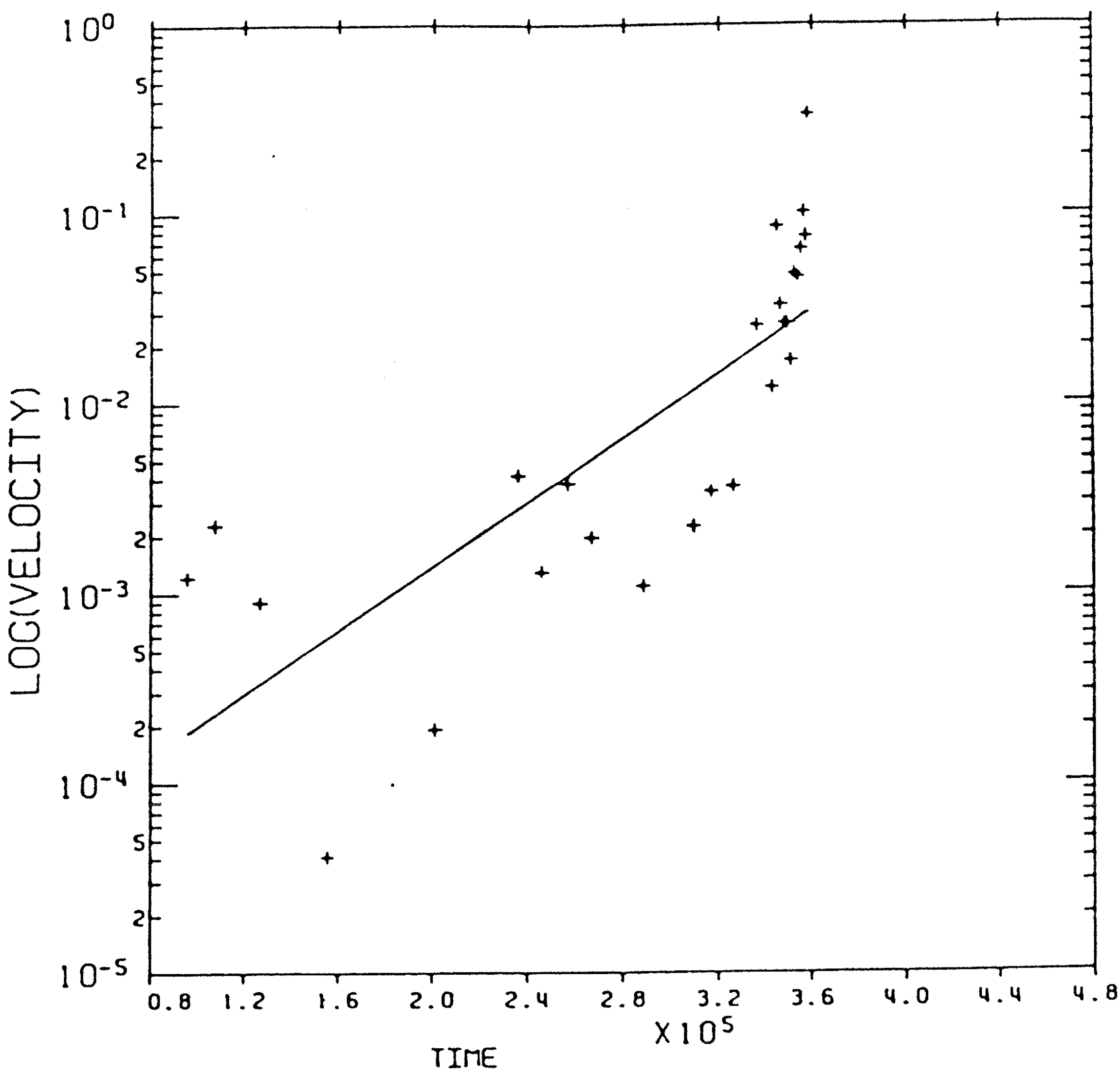

Figure 3 Exponential law fit to the displacements (velocity:mm/min , time:min)

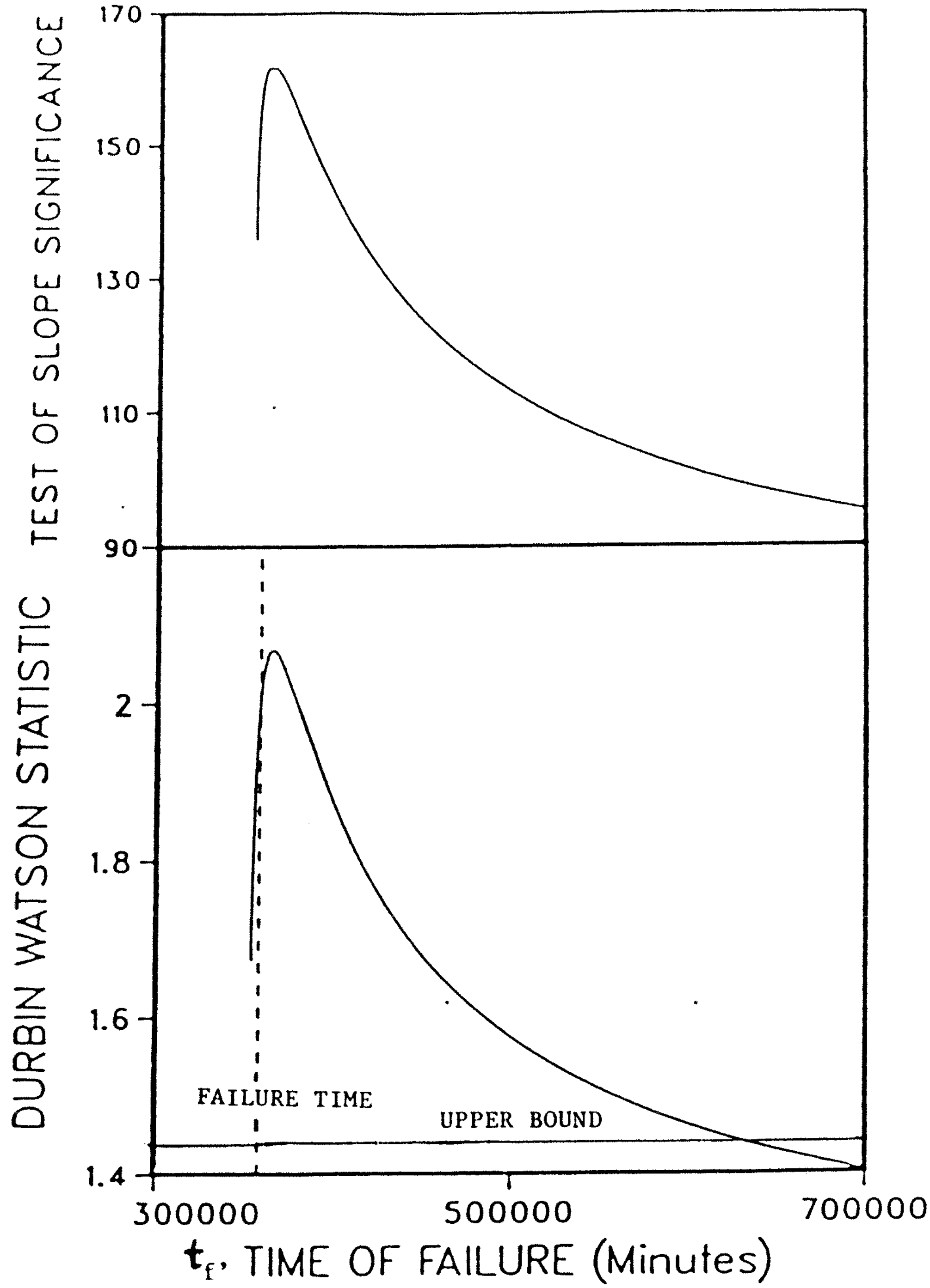

Figure 4 Saito fit statistics showing the effect of variation in t_f, the time of failure

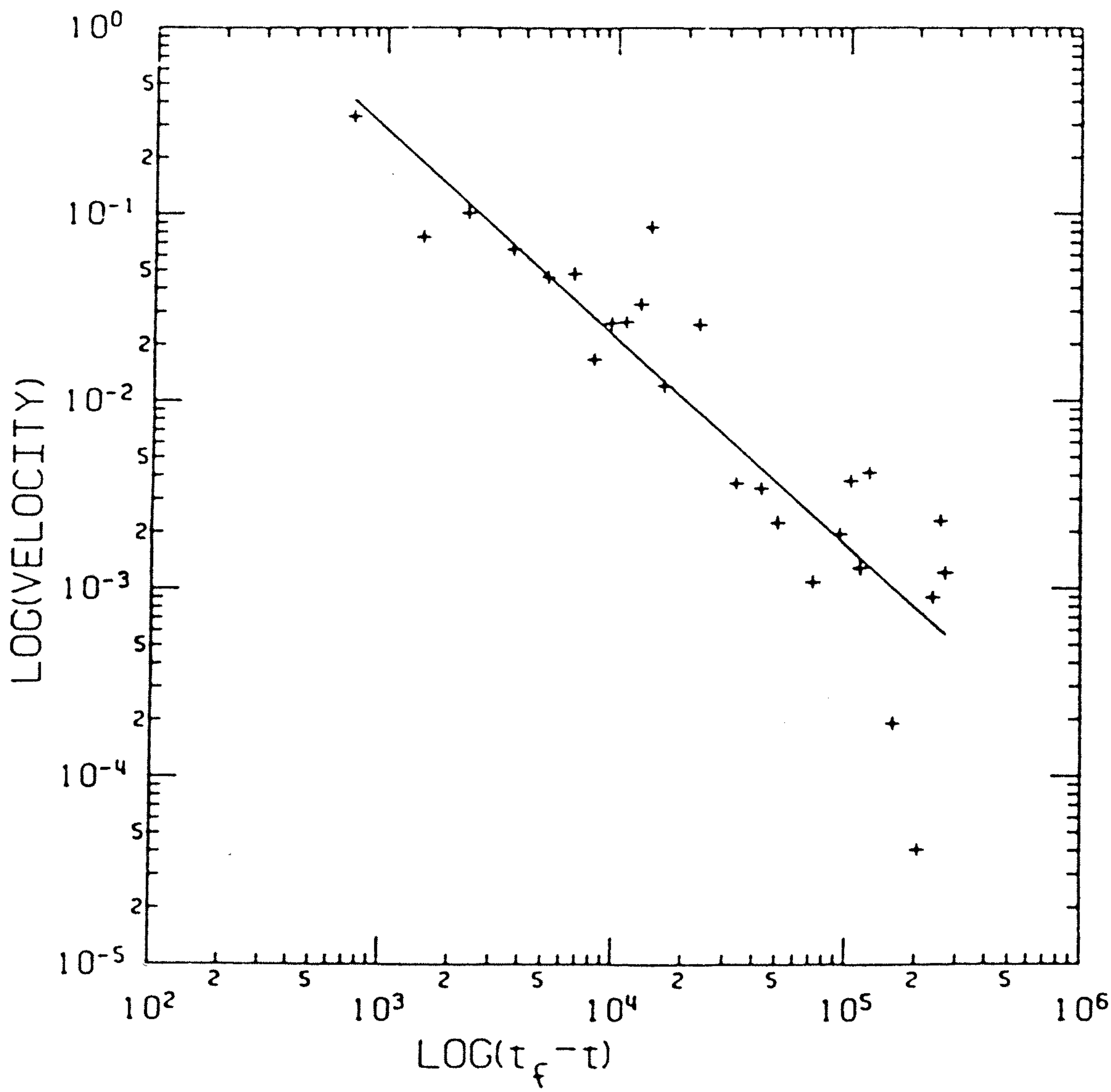

Figure 5 Saito fit to the displacements (velocity:mm/min , time:min)

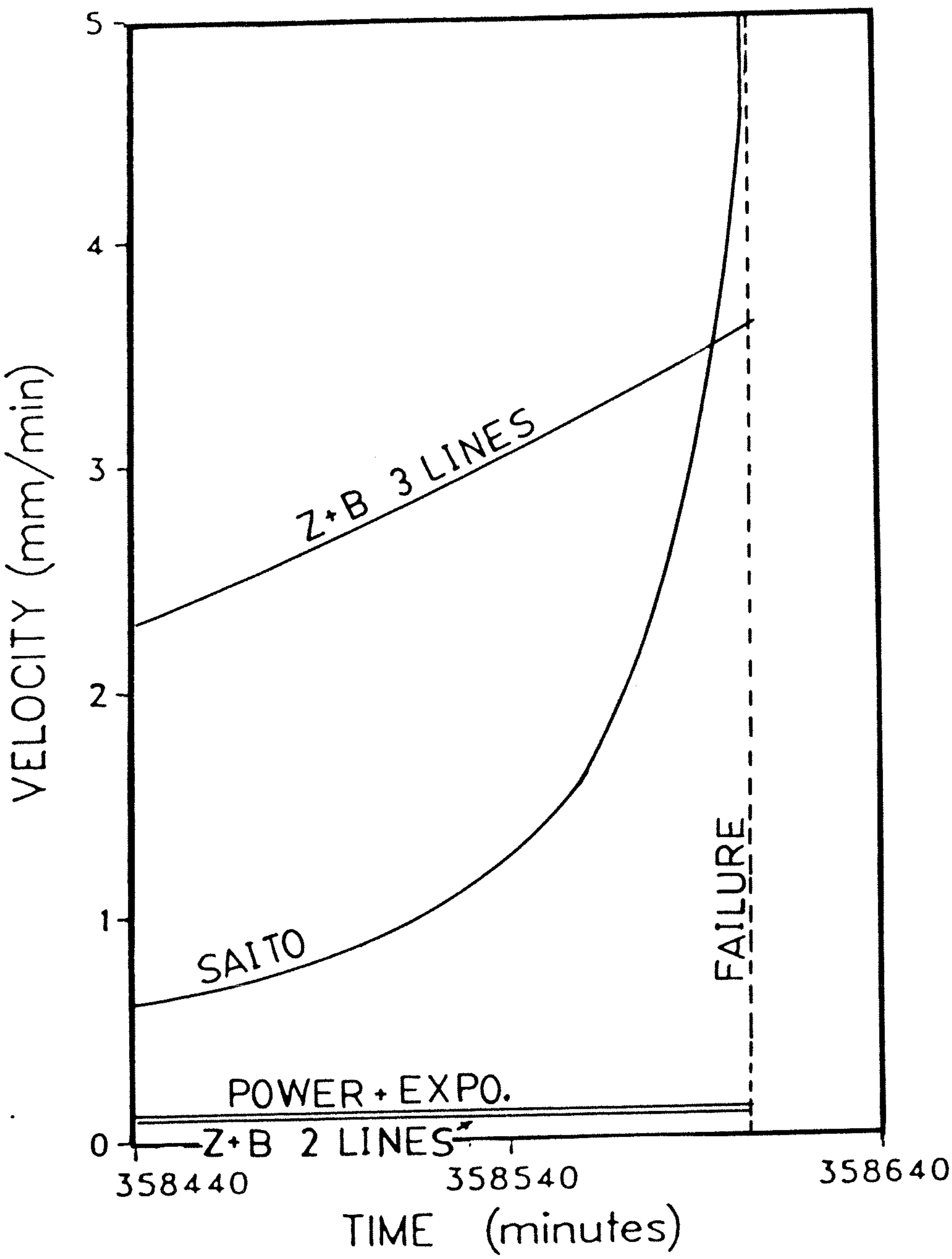

Figure 6 Comparison of laws beyond 165 minutes prior to failure