Research Report

EVERGREEN POINT BRIDGE
MAINTENANCE PROBLEMS

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16. Abstract

This report reflects a year of calms with little addition to the data base. Pressure transducers were placed and an analytical scheme is reported. This scheme was subseqently used in the final work.

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EVERGREEN POINT BRIDGE MAINTENANCE PROBLEMS

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PROGRESS REPORT
(Third Annual Report)

Research Project Y-1640
Phase III

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INTRODUCTION

This year's work (1976-77) has had three phases:

1) Maintenance of instrumentation

2) New instrumentation

3) Analytical work

The phase involving field instruments was limited. However, it must be pointed out that costs were not diminished because of this condition. Preparedness without measurements is as expensive as preparedness with measurements. Appendix A displays the reduced data obtained in the year.

The first two phases above were handled by the Research Engineer, Mr. Derald Christensen. Mr. Christensen as well as Messrs. Bright and Vasu were involved in the analysis. The project was under the direct supervision of the Principal Investigator.

MAINTENANCE

The state of preparedness necessary to complete a set of measurements was maintained over the year. In particular, in the Fall, the electronics were completely checked. Even though nothing had changed in the Summer, it was found that the noise had risen beyond a tolerable level. Thus, resulted a considerable rewiring and reseating of some gages.

Changes in anchor cable lengths to off-set water level alterations in the lake were made without prior warning to this project. In each case bending a fracture of the 20" arms of the displacement transducers occurred. These were reinstalled.

NEW INSTRUMENTATION

In March 1977, nine pressure transducers were installed in a linear array along the south face of the bridge. The array starts approximately 400 feet west of the control tower, with the individual transducers positioned at 11 1/2 foot intervals at a location five feet below the still water level. The pressure transducers were originally purchased for the Hood Canal floating bridge project and required rebuilding and recalibration for the present use.

The pressure transducers were mounted in water tight housings attached to 1 1/2 inch galvanized pipes. The pipes are about 14 feet long with an arm at the lower end, placed under the submerged edge of the bridge. The upper end was attached to a turnbuckle which was in turn bolted to the lower support bolts of the wave deflectors. This provides a very simple and inexpensive installation, at a total cost of less than $300. Figure 1 shows the location and Figure 2 the housing arrangement. This arrangement was built in the Civil Engineering Department shop.

The pressure transducers were wired into the channel locations given in Figure 1. It was found from earlier data analysis that instrumenting adjacent tension rods was not necessary and that they could be averaged together. This released six channels. The other three necessary for the transducers were provided by channel 34, the center lock, and the original wave transducer channels. This special data can be recorded separately on a spare digital cassette recorder that will be available.

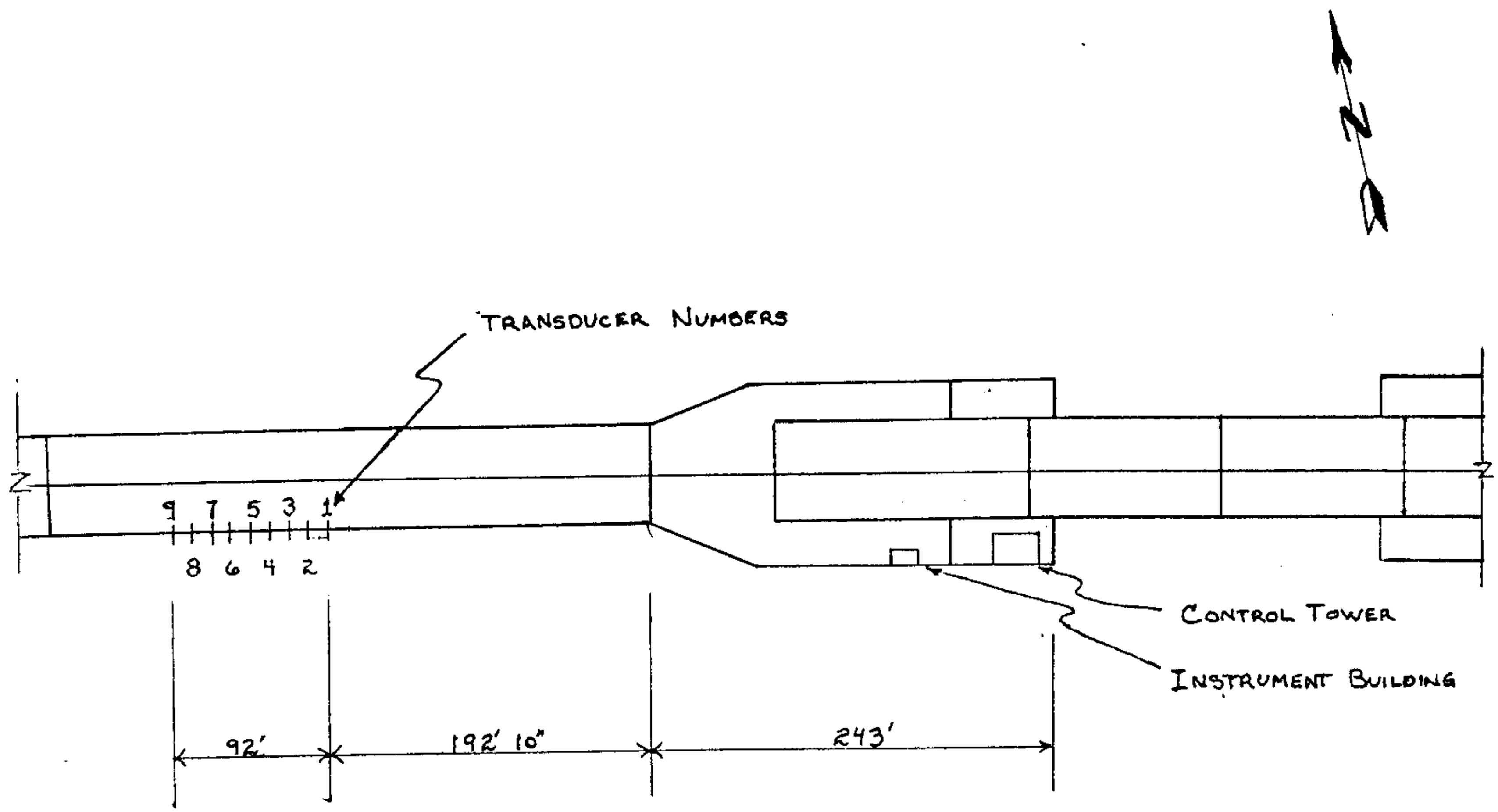
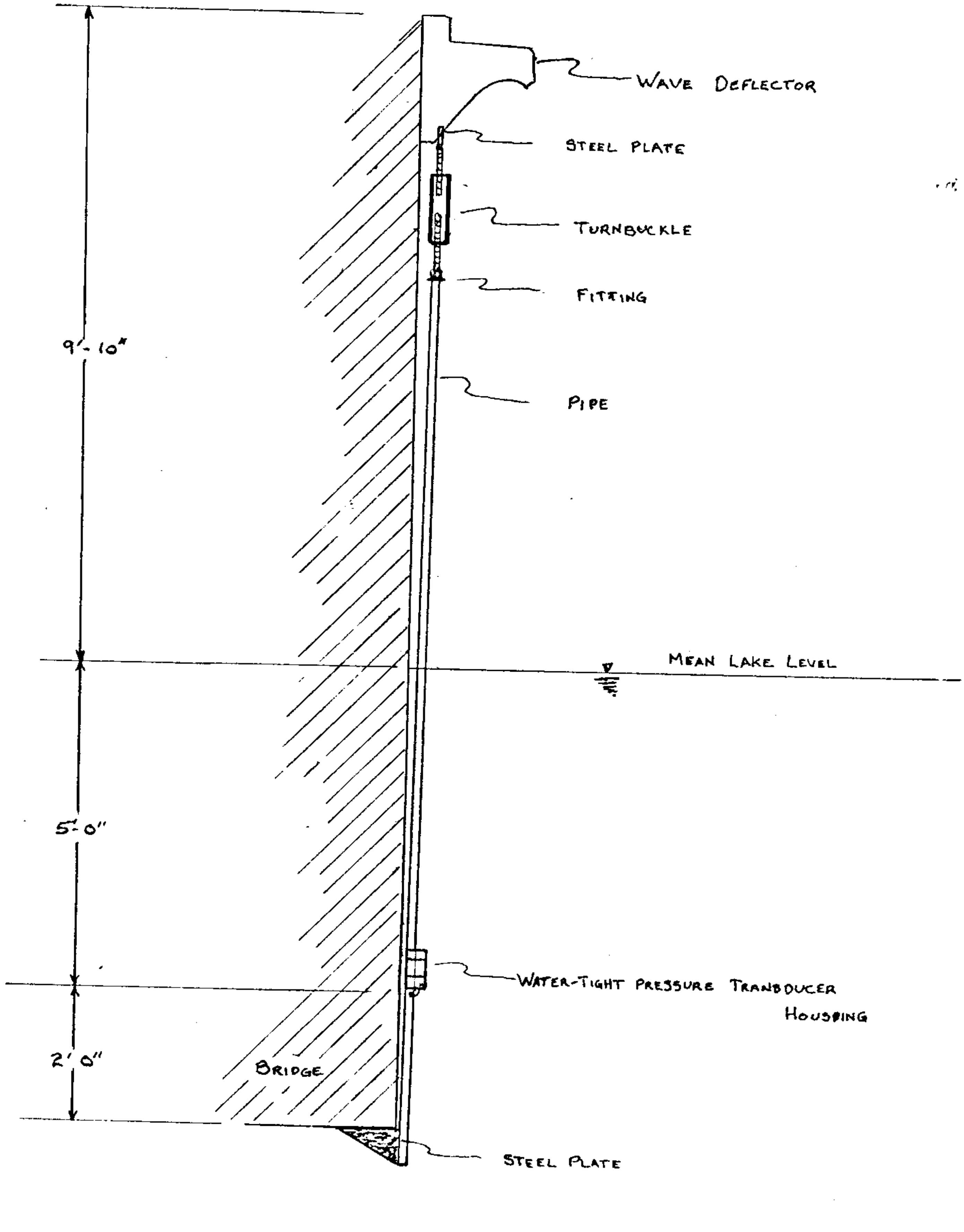


FIG. 1

TRANSDUCER LOCATION



TRANSDUCER SUPPORTS

FIG. 2

The main objective of this project is to provide the background material for a graduate student thesis project. The purpose of the thesis is to study the effective crest lengths of random water waves on the vertical sides of the bridge as a function of wind speed and direction. It has been shown that the effective crest lengths play a major role in defining the amount of energy that is being transmitted from the waves to this type of structure. (Ref. 1)

If a realistic relationship between the effective crest lengths and the wind speed and direction can be found, a better understanding of the relationship between the wind conditions and stress levels on the major structural components of the bridge can be obtained. In particular, the critical drawspan components stresses will be more readily predicted.

Appendix B gives the calibration information of the transducers.

ANALYTICAL WORK

The analytical work for the year has fallen into the development of theory and the application with respect to existing data. Thus, for the twelve vertical trunnions 1V1, 1V2, 2V1, 2V2, 3V1, 3V2, 4V1, 4V2, estimates of fatigue life were obtained. This section of this report deals with such matters. First a revised fatigue life prediction theory is presented. This modifies the theory of reference 3 to allow direct predictions on limited data - none of it at high wind speeds.

The next part considers the relation between short term and long term strains. Here the relationship between short term wind and strain is developed by a regression process. The wind is taken vertically and the strains related to wind speed and direction. It was tempting to go further and include the fetch in the analysis. However, the actual fetch was not measured. When the wind direction was plotted on the local map and hence the distance to land determined, a theoretical fetch was obtained. This presumed that the wind and wave directions conincided and that no deviation of wave direction occurred. These assumptions were probably not valid. The inclusion of such a hypothetical fetch into the regression improved correlations marginally but resulted in a negative exponent on the fetch term. This physically impossible effect suggests that the information available was not appropriate for the inclusion of the fetch term.

Also developed in the regression work are the correlations by which the adequacy of the analysis may be judged.

The final analytical step involves the development of the long term wind data as a distribution. Here two possibilities occurred. The long term measurements on the Evergreen Point Bridge were complete but only recorded at 8 hourly intervals. However, the Sand Point site measurements were made at hourly intervals but revealed speeds which were smaller than on the bridge. A future task will involve determining a relation between the two so that the duration of the wind on bridge can be properly taken into account. In all this work a long-term data maximum entropy methods were employed.

The final part of the analytical work involved applying to the theory to the trunnion rod and wind data. Using posed S-N curves various predictions of fatigue life were made. Two shortcomings were evident. First the S-N curve employed was critical and confidence can only be assured when fatigue results on the actual members are available. Second, the average time for which wind speeds were sustained could only be guessed. Dramatically different fatigue lives were evident depending on whether a single or eight hours was used. These two matters are critical features of the 1977-78 work. The first will be dealt with by laboratory experiments, the second by comparing the chronological measurements from the bridge and Sand Point. It must be pointed out, the second problem is only important in the design process. In that process an estimate of expected life is important. In the maintenance problem where the residual life is required and where full wind signals over the previous life exist, the proposed methodology is adequate.

One difficult part of the practical example is the determination of the signals which reflect stationary conditions. This decision process is developed in the re[illegible] where 71 available signals are reduced to 19 stationary ones.

FATIGUE LIFE PREDICTION THEORY

It was initially intended to use Brown's (1976) development of fatigue life expectancy in this work. That theory was based on Miner's hypothesis where failure occurs when

$$\sum_i \frac{n_i}{N_i} = 1 \qquad (1)$$

where n_i is the number of actual cycles at oscillatory stress range $\pm S_i$ and N_i the number of cycles to cause failure at that range. The various n_i can be expressed as

$$n_i = \alpha_i \ T_f \ f_i \qquad (2)$$

where α_i is the proportion of the time and f_i the frequency of oscillation at $\pm S_i$. T_f is the total time to failure of the part and is described by

$$T_f = [\sum_i \frac{\alpha_i f_i}{N_i}]^{-1} \qquad (3)$$

The treatment proposed was to examine and analyze the measurements of strain to determine $\alpha_i f_i$. The process involved the second moment of the hourly data, m_2 providing the strain variance in the form

$$\sigma^2(\varepsilon) = m_2 \qquad (4)$$

Time, and hence frequency was introduced by the stationary process correlation

$$C(\tau) = \int_{-\infty}^{\infty} D(f) \ e^{\ i2\pi f\tau} \ df \qquad (5)$$

with inverse

$$D(f) = \int_{-\infty}^{\infty} C(\tau) \ e^{-i2\pi f\tau} d\tau \qquad (6)$$

D(f), the two-sided spectral density function, is related to the one-sided spectral density function for positive frequency by

$$G(f) = 2\,D(f); \quad o \le f \le \infty$$
$$= 0 \quad ; \quad f < 0 \tag{7}$$

which is related to the variance by

$$\sigma^2 = \int_o^\infty G(f)\,df \tag{8}$$

where G(f) represents the frequency content of $\varepsilon(t)$. For the j^{th} sample, the standard deviation is σ and frequencies for strains of $k\,\sigma_j$ are considered. For k = 1

$$f_j\ (k=1) = \frac{1}{\sigma_j^2} \int_o^\infty f\,G(f)\,df \tag{9}$$

and if frequencies and probabilities of peak magnitudes are related by

$$\frac{f_j\ (k)}{f_j\ (1)} = \frac{p_j\ (k)}{p_j\ (1)} \tag{10}$$

then $f_j(k)$ can be obtained from the probabilities. For a narrow banded signal and $\varepsilon(t)$ normally distributed about zero mean then the probability density for the peak magnitudes is given by the Rayleigh distribution, (Lin, 1967),

$$p_j\ (\varepsilon = k\sigma_j) = \frac{k}{\sigma_j}\, e^{-k^2/2} \tag{11}$$

then from (10)

$$f_j\ (k) = \frac{k}{\sigma_j^2}\, e^{-\frac{1}{2}(k^2-1)} \int_o^\infty f\,G(f)\,df \tag{12}$$

The analysis of adequate signals for strains in the above manner could lead to inclusion in (3) and the determination of T_f provided stress (S_i) was linearly related to strain (ε_i). At first it was expected that the 71 hourly recordings would provide a sufficient base for such an activity. However, in the conversion of single year to long term strain information only 19 of the 71 readings could be retained for reasons described later. This suggested using Clough and Penzien's, (1975) direct approach as follows:

For (1) the continuous expression

$$1 = \int_0^\infty \frac{n(s)}{N(s)}\, ds \qquad (13)$$

is introduced where

$$n(s) = \frac{\omega T_f}{2\pi}\, p(s) \qquad (14)$$

$$p(s) = \frac{S}{\sigma_s^2}\, e^{-s^2/\sigma_s^2} \qquad (15)$$

Here $\frac{\omega T_f}{2\pi}$ is the total number of cycles at frequency ω to failure and p(s) is the Rayleigh distribution, applicable for a narrow band process.

Then

$$T_f = \left[\frac{\omega}{2\pi\sigma_s^2} \int_0^\infty \frac{S}{N(S)}\, e^{-S^2/\sigma_s^2}\, ds\right]^{-1} \qquad (16)$$

Such a result is more direct than originally proposed and is suited for a limited data base.

The form of N_i or N(S) in both approaches must be obtained from the S-N curve of the component. A familiar form often used is

$$N(S) = \left(\frac{S_1}{S}\right)^b N_1 \qquad (17)$$

When S_1 is the known stress level and N_1 is the cycles at stress S_1, then the quadrature of (16) may be completed as

$$T_f = \frac{2\pi N_1}{\omega} \left(\frac{S_1}{\sigma_s}\right)^b \frac{2^{-b/2}}{(b/2)!} \tag{18}$$

In this case, σ_s is a proportion of $\sigma(\varepsilon)$ of (4) and, with ω, is directly obtained from the measured data. S_1, N_1 and b are from the posed S-N curve. The initial method, in the light of sufficient data, would allow a more accurate estimation of the ω term.

ANALYSIS OF FIELD MEASUREMENT

In order to obtain long term strain information from limited strain data, three forms of analysis are performed. First, the short term wind and strain data are related by a regression process. Then the long term discrete wind information is analyzed to give a long term wind distribution. Finally, the relation between wind and strain is introduced into the long term strain estimate. This final step is direct. The first two analytical processes are described here.

1. Regression analysis of wind-strain data.

In general, regression analysis is a statistical procedure in which a relationship between two or more items, called variables, are expressed in an optimum mathematical form subject to specified criteria. In the work of this study, the measured signal strain was analyzed to find

$$\varepsilon = f(W) \tag{19}$$

Subsequently, it was found that good correlation between wind speed and strain was not possible. Another factor, the direction of wind, was included in the form

$$\varepsilon = f(W, \theta) \tag{20}$$

The above relation was written after regression analyses as

$$\varepsilon = k\, W^{b_1} \Theta^{b_2} \tag{21}$$

where $\Theta = \text{Cos}\ \theta$

This becomes

$$\log \varepsilon = \log k + b_1 \log W + b_2 \log \Theta \tag{22}$$

$$\log \varepsilon = Y \qquad \log W = X_1$$

$$\log k = b_o \qquad \log \Theta = X_2$$

then equation (22) may be written in the form

$$Y = \sum_{i=o}^{2} b_i X_i \tag{23}$$

Equation (23) is the linear model used in regression analysis to predict strain

To estimate the coefficients b_o, b_1, b_2, the method of least squares was used. This method assumes that the best approximation of the actual function is the one in which the minimum sum of squared normal deviation exists. The deviations are the differences between each observed Y_i and the calculated Y_i^c where $i = 1,2\ldots n$. Thus letting $d_i = Y_i - Y_i^c$, the coefficients of Y_i^c are obtained by determining the situation where

$$\min \sum_{i=1}^{n} d_i^2 \tag{24}$$

is yielded. This is accomplished by taking the partial derivatives of $\sum_{i=1}^{n} d_i^2$ with respect to each parameter and setting the results equal to 0. Thus, a set of simultaneous equations are generated and are called the normal equations. Solving these for the coefficient gives us the least square curve for a given data sample and chosen functional form.

In the particular case of this study, if the observed value is Y_i and the calculated value is Y_i^c then

$$Y_i^c = b_o + b_1 x_1 + b_2 x_2 \tag{25}$$

The sum of the normal deviation for all observation in the data sample (i=1,2..n) is

$$\sum_{i=1}^{n} d_i^2 = \sum_{i=1}^{n} (Y_i - Y_i^c)^2 = \sum_{i=1}^{n} (Y_i - b_o - b_1 x_{1_i} - b_2 x_{2_i})^2 \tag{26}$$

Taking partial derivative with respect b_o, b_1, b_2 and setting them equal to zero results in the normal equations.

$$\frac{\partial \sum_{i=1}^{n} d_i^2}{\partial b_o} = \sum_{i=1}^{n} 2 (Y_i - b_o - b_1 x_{1_i} - b_2 x_{2_i})(-1) = 0$$

$$\frac{\partial \sum_{i=1}^{n} d_i^2}{\partial b_1} = \sum_{i=1}^{n} 2 (Y_i - b_o - b_1 x_{1_i} - b_2 x_{2_i})(-x_1) = 0 \tag{27}$$

$$\frac{\partial \sum_{i=1}^{n} d_i^2}{\partial b_2} = \sum_{i=1}^{n} 2 (Y_i - b_o - b_1 x_{1_i} - b_2 x_{2_i})(-x_2) = 0$$

Rearranging the above we get

$$\sum_i Y_i = b_o n + b_1 \sum_i x_{1_i} + b_2 x_{2_i}$$

$$\sum_i x_{1_i} Y_i = b_o \sum_i x_{1_i} + b_1 \sum_i x_{1_i}^2 + b_2 \sum_i x_{1_i} x_{2_i} \tag{28}$$

$$\sum_i x_{2_i} Y_i = b_o \sum_i x_{2_i} + b_1 \sum_i x_{1_i} x_{2_i} + b_2 \sum_i x_{2_i}^2$$

Solution of Equation (28) gives the values of the coefficients.

To evaluate the validity of the solution certain standard tests are used. Four tests are now described.

A. Correlation Matrix

This matrix describes the correlation coefficients for all combination of variables, independent and dependent. The correlation coefficient expresses the degree of association between two or more variables. This gives insight into the relationship within the data.

For two variables the coefficient of correlation is

$$\rho_{12} = \frac{1/n \sum_{i}^{n} (x_{1_i}-\bar{x}_1)(x_{2_i}-\bar{x}_2)}{\sigma_{x1} \ \sigma_{x2}} \tag{29}$$

where

$i = 1,2,3,\ldots.n$

x_1 = independent variable 1

x_2 = independent variable 2

σ_{x1} = Std. deviation of x_1

σ_{x2} = Std. deviation of x_2

n = number of observation

The value lies between $-1 \leq \rho \geq 1$

In general, the correlation matrix for all combinations is

$$\rho_{ij} = \begin{bmatrix} \rho_{11} & & \cdots\cdots\cdots\cdots \\ \rho_{21} & \rho_{22} & \cdots\cdots\cdots\cdots \\ \rho_{i_1} & \rho_{i_2} \ \rho_{i_3} & \cdots \ \rho_{i_j} \end{bmatrix} \tag{30}$$

where $\rho_{11} = \rho_{22} = 1$

and ρ_{ij} $(i \neq j)$ is the correlation between variables i and j.

B. "R" (Multiple Correlation Coefficient)

This indicates the degree of association between independent and dependent variables in the equation. The higher the value of "R" the greater the reliability of the association.

The quantity "R" is given by

$$R = \pm \frac{\text{Explained variation}}{\text{total variation}} = \pm \frac{\Sigma(Y_{est}-\bar{Y})^2}{\Sigma(Y-\bar{Y})^2} \tag{31}$$

Y = True value of the measured strain

Y_{est} = Estimated value of the strain using the calculated coefficients

The value of "R" varies between -1 and +1.

C. Standard Error of Estimate

This indicates the degree of variation of the data about the regression line established. Mathematically, it is a measure of the error to be expected in predicting the dependent variable from the measured independent variable in the equation. It is expressed as a percent of the mean observed value of the dependent variable and has the form

$$\frac{\text{standard error of estimate}}{\text{mean of the observed value of Y}} \times 100 \qquad (32)$$

D. "t" Test

This indicates the significance of the regression coefficient of each independent variable in a regression equation. In general "t" must have at least 2.0 for significance.

Indepent variables which have a computed"t"less than 2.0 do not have a significant relationship within the dependent variable and therefore have to be deleted. The t value is given by the quotient.

$$t = \frac{\text{regression coefficient}}{\text{standard error of coefficient}} \qquad (33)$$

2. Long-Term Wind

The long-term wind data obtained from the State Highway Department was analyzed to determine the wind distribution. The principal of maximum entropy was used to determine this distribution. A distribution function f(x) is chosen such that it maximizes the entropy subject to constraints on the data.

This

$$H = -\int_a^b f(x) \ln f(x)\, dx \tag{34}$$

is maximized subject to constraints

$$\int_a^b f(x)dx - 1 = 0$$

$$\int_a^b x^k f(x)dx - m_k = 0 \tag{35}$$

$$f(x) \geq 0 \qquad a \leq x \leq b$$

where m_k is the k^{th} moment of the data. The analysis is by introducing the Lagrangian multipliers λj, $j=0$ to n and restricting k to two parameters, mean and variance. Then the distribution function is

$$f(x) = \exp(-\lambda_o-\lambda_1 x-\lambda_2 x^2) \tag{36}$$

where

$$\lambda_o = \frac{m^2}{2\sigma^2} + \ln \sigma\sqrt{2\pi} = \ln dx$$

$$\lambda 1 = -\frac{m}{\sigma^2}$$

$$\lambda_2 = \frac{1}{2\sigma^2}$$

FATIGUE LIFE PREDICTION

1. Long-Term Wind Data:

Wind data from the Evergreen Point Bridge (Table 1) and Sand Point (Table 2) was analyzed by the maximum entropy approach. The information of Table 1 was from hourly measurements at 8-hour intervals and Table 2 from hourly measurements.

2. Wind-Strain Correlation:

The 71 records of wind speed and strains shown in Table 4 were analyzed to determine an interrelationship. It was seen from the low value in the partial correlation co-efficient of 0.3 that the wind speed was not the only factor contributing towards the inducement of strain in the vertical trunnion rods. Another important factor was the direction of wind. The partial correlation co-efficient of the fitted equation was around 0.4 to 0.5 when wind speed and direction were included. This low value was due to the non-stationarity of the record. To eliminate non-stationary records the complete data was studied in the following way:

a) Records in the first three hours of a storm were rejected.

b) Records in a storm where the strains had increased and the wind speed decreased relative to the previous record were rejected.

Using a) the 71 records of Table 3 were reduced to 24 of Table 4.

Using b) the 24 records of Table 4 were reduced to 19 records of Table 5. In this way , a conservative data base for stationary events was obtained.

Only 19 records were available for the regression analysis. These 19 records were analyzed, the partial correlation coefficient of the fitted equation for the vertical trunnion was between 0.75 to 0.82. This was vastly superior to values obtained from wind alone, and is acceptable.

To improve the correlation further the fetch values were estimated for the corresponding wind direction and considered as another variable in the regression analysis. The partial correlation coefficient increased by small amounts, but the coefficient produced a negative exponential. Hence, the fetch was eliminated on physical grounds even though it improved the partial correlation coefficient.

Table 6 contains the correlation matrix of all variables. Correlation between the wind and strain is about 0.8. The correlation between the two adjacent rods is around 0.99 which indicates the spatial uniformity of the data. Table 7 contains the typical regression analysis for rod IVI showing the statistics and the coefficient of the regression equation. Fig. 4. shows a plot of actual values and the estimated function for trunnion IVI. Table 8 tabulates the regression equation for all the vertical trunnions.

TABLE 1. PERCENTAGE FREQUENCY DISTRIBUTION OF EVERGREEN POINT FLOATING BRIDGE WIND DATA

March 1964-June 1975

Speed in m.p.h.	0-10	10-20	20-30	30-40	40-50	50-60	60-70	Over 70	TOTAL
Direction N	884.0 7.3	384.0 3.2	27.0 0.2	1.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	1296.0 10.7
NE	1050.0 8.7	302.0 2.5	10.0 0.1	0.0 0.0	1.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	1371.0 11.3
NW	354.0 2.9	213.0 1.8	24.0 0.2	6.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	597.0 4.9
S	918.0 7.6	1356.0 11.2	848.0 7.0	484.0 4.0	129.0 1.1	26.0 0.2	5.0 0.0	3.0 0.0	3769.0 31.0
SE	801.0 6.6	544.0 4.5	179.0 1.5	59.0 0.5	15.0 0.1	2.0 0.0	0.0 0.0	0.0 0.0	1600.0 13.2
SW	368.0 3.0	406.0 3.3	264.0 2.2	124.0 1.0	36.0 0.3	6.0 0.0	3.0 0.0	0.0 0.0	1207.0 9.9
E	193.0 1.6	40.0 0.3	6.0 0.0	1.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	245.0 2.0
W	199.0 1.6	21.0 0.2	5.0 0.0	1.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	0.0 0.0	226.0 1.9
Calm and others	1744.0 14.4	76.0 0.6	13.0 0.1	4.0 0.0	1.0 0.0	0.0 0.0	1.0 0.0	0.0 0.0	1839.0 15.1
Total	6524.0 53.7	3342.0 27.5	1376.0 11.3	680.0 5.6	182.0 1.5	34.0 0.3	9.0 0.1	3.0 0.0	12,150.0 100.0

TOTAL 12,150 VALUES

Table 2. Summary of Wind Record - Sand Point - May 1949 Through April 1964

Frequency of Wind Speed Groups (Knots)

Wind Dr.	3-7	8-12	13-20	21-30	31-40	>40	Calm	Total
N	9910	3147	352	8				13419
NNE	2626	427	26	1				3089
NE	4009	316	13	1				4339
ENE	2287	222	10					2519
E	2439	300	33					2772
ESE	1394	312	101	9				1818
SE	3439	704	137	5				4285
SSE	4454	1824	348	12				6630
S	11757	9978	3690	197	4			25616
SSW	5246	4907	2352	168	2			12675
SW	2975	1242	376	22				4615
WSW	630	176	24					830
W	594	71	3					688
WNW	372	48	4					424
NW	3086	787	71	4				3948
NNW	10802	3853	435	27				15117
Calm	-	-	-	-	-	-	28312	28312
Total	66010	28316	7975	454	6	0	28312	131073
% of Total	50.4	21.6	6.1	0.3	0.0	0.0	21.6	100.0

TABLE 3. MEAN WIND SPEED VERSUS STD DEV OF STRAINS

RAW DATA

NO	WIND	STD WIND	FETCH	DUR	COS	1V1	1V2	2V1	2V2	3V1	3V2	3V3	3V4	4V1	4V2	4V3	4V4
1	20.42	3.89	2.52	1	1.000	18.0	31.7	18.6	19.2	17.6	16.9	6.9	.0	15.4	15.8	11.2	9.7
2	24.88	2.28	2.60	1	.862	23.2	37.4	22.4	23.6	20.2	20.6	11.4	10.8	18.5	18.8	11.9	10.1
3	24.24	2.51	2.60	1	.983	76.6	236.0	28.3	29.3	24.2	24.4	14.6	13.9	24.9	25.1	16.5	13.7
4	27.12	2.69	1.00	2	.762	39.9	76.7	39.3	40.8	31.6	31.2	18.6	18.0	31.9	31.6	20.7	18.0
5	29.99	3.09	2.53	3	.937	51.0	97.8	49.8	51.2	42.7	41.5	25.5	24.6	41.2	40.6	31.4	27.0
6	29.03	2.61	2.53	4	.937	37.2	71.9	37.2	39.0	33.6	32.7	19.2	18.4	34.0	33.5	21.7	18.2
7	28.71	2.76	2.53	5	.983	52.2	100.3	50.0	52.0	47.6	46.0	25.8	24.9	45.9	44.9	34.9	30.9
8	19.46	2.97	2.60	1	.862	30.3	.0	33.2	34.8	25.9	24.9	10.1	9.6	25.1	27.0	21.2	14.5
9	24.24	2.98	2.53	2	.937	50.8	.0	55.0	56.5	48.4	47.0	25.5	24.8	45.4	46.4	31.5	24.8
10	24.88	2.33	2.52	3	1.000	70.3	.0	73.4	75.4	64.2	63.6	34.5	33.5	62.0	62.2	37.6	32.9
11	24.56	2.90	2.52	4	1.000	81.9	.0	85.3	87.2	71.6	69.9	37.5	36.8	68.8	69.0	42.3	37.7
12	15.95	4.39	2.52	5	.983	28.3	.0	30.6	32.5	25.9	26.0	11.6	11.3	26.1	28.4	19.6	16.2
13	18.18	3.80	1.72	1	.943	20.2	.0	17.8	21.0	17.8	17.5	6.0	5.5	14.8	15.1	11.9	8.4
14	24.88	3.08	2.53	2	.937	36.9	.0	39.2	41.6	37.9	36.5	17.2	16.9	31.9	32.8	25.7	18.7
15	28.71	2.98	2.52	3	1.000	89.0	.0	92.6	94.0	86.8	84.4	41.4	40.1	78.6	78.9	47.3	41.6
16	28.71	3.60	2.52	4	1.000	118.7	.0	117.7	119.4	102.6	100.7	48.3	47.4	98.2	98.8	61.8	56.2
17	21.69	2.13	2.52	1	.983	31.9	.0	31.4	32.7	24.5	23.6	9.5	8.7	23.3	24.4	16.5	15.4
18	20.74	1.80	2.52	2	.983	28.7	.0	28.4	29.3	23.4	23.6	9.9	8.9	22.2	23.7	16.3	14.9
19	22.01	2.74	2.57	3	.986	38.0	.0	38.7	39.9	33.9	33.4	18.2	17.3	33.1	33.3	22.8	21.9
20	26.16	2.40	2.52	4	1.000	41.2	.0	40.9	42.0	36.5	36.2	20.1	19.5	33.2	34.9	23.3	22.3
21	29.35	3.74	2.52	5	1.000	111.6	.0	113.6	114.9	93.5	93.0	50.4	49.0	91.2	92.3	59.2	52.9
22	23.61	2.01	2.52	6	.983	72.5	.0	76.9	79.1	63.7	64.3	34.1	33.1	60.1	60.6	38.0	31.5
23	23.29	3.62	1.00	1	.762	26.8	.0	26.0	28.7	21.9	21.5	10.4	9.8	20.1	21.1	18.7	13.1
24	24.88	2.12	2.57	2	.986	27.8	.0	25.0	29.7	20.7	20.3	8.2	8.0	19.0	20.4	14.3	12.4
25	22.65	3.12	1.72	3	.943	26.4	.0	25.2	29.2	22.4	22.2	10.4	9.7	20.6	21.1	15.8	14.8
26	22.65	3.36	1.72	4	.983	36.4	.0	35.5	40.9	30.2	30.3	14.5	14.7	27.0	29.5	21.4	15.6
27	21.37	2.19	2.53	5	.937	25.0	.0	23.0	27.5	21.7	21.4	9.4	8.2	17.6	20.3	17.2	10.5
28	28.07	2.89	2.53	6	.983	92.6	.0	96.0	97.4	73.5	73.4	39.3	38.2	71.8	72.9	45.8	30.8
29	24.88	2.63	2.53	1	.983	39.0	.0	.0	43.2	38.5	40.2	21.0	20.6	34.5	36.5	27.3	21.0
30	25.52	2.44	2.52	2	1.000	49.8	.0	.0	57.5	44.8	46.7	25.4	24.9	42.4	43.1	29.9	23.3
31	8.29	1.40	1.00	3	.762	9.2	.0	.0	18.0	7.4	11.1	14.0	10.5	5.5	7.1	18.9	29.1
32	24.88	2.26	2.57	1	.986	42.1	.0	40.0	41.7	42.3	40.9	22.7	22.1	35.5	36.6	26.3	21.5
33	25.52	2.32	2.57	2	.986	58.7	.0	57.7	59.0	56.6	54.1	25.6	25.1	47.0	47.1	32.4	26.0
34	25.52	2.51	2.52	3	1.000	71.9	.0	77.9	78.6	68.3	65.4	31.5	30.6	56.8	57.3	37.5	29.0
35	24.24	3.03	2.52	1	1.000	27.3	44.2	25.7	26.7	25.1	24.4	13.0	12.6	21.8	22.0	14.9	11.5

Contd ....

MEAN WIND SPEED VERSUS STD DEV OF STRAINS

RAW DATA

ND	WIND	STD WIND	FETCH	DUR	COS	1V1	1V2	2V1	2V2	3V1	3V2	3V3	3V4	4V1	4V2	4V3	4V4
36	28.07	3.50	2.52	1	.983	15.9	24.0	14.2	16.0	13.9	14.1	7.2	7.2	12.7	12.6	10.0	7.4
37	23.29	2.99	2.57	2	.986	31.8	58.5	32.0	34.6	28.0	28.0	15.8	15.3	25.7	25.9	17.3	13.4
38	23.61	2.16	2.60	3	.862	28.0	52.8	28.6	31.5	24.6	24.6	13.0	12.8	19.9	20.8	15.7	11.9
39	24.56	5.57	2.57	1	.986	17.1	29.6	19.0	21.6	22.7	22.0	8.3	8.0	15.6	16.1	10.2	9.0
40	18.18	6.83	1.28	2	.871	6.6	11.2	5.9	6.7	7.0	7.3	3.4	3.9	5.6	5.8	6.0	5.2
41	22.97	2.84	1.28	1	.983	22.9	43.5	24.1	27.6	23.8	24.0	12.9	12.4	18.8	20.2	14.8	12.5
42	25.52	3.92	2.57	2	.986	19.9	37.0	20.0	22.8	19.7	19.7	9.1	8.9	15.7	16.6	11.4	9.7
43	28.71	3.19	2.57	1	.983	17.8	27.4	17.3	19.7	18.2	18.4	7.8	7.7	15.0	16.0	10.5	8.3
44	29.67	2.84	2.53	2	.937	61.3	116.1	58.4	61.5	56.1	55.1	26.4	25.6	52.1	52.2	31.7	28.1
45	28.71	3.25	2.53	3	.937	48.3	90.0	50.3	53.1	43.1	42.3	18.6	17.9	37.5	37.5	22.1	19.1
46	28.07	3.59	2.53	4	.937	38.1	72.4	41.6	44.2	37.4	37.0	15.6	15.1	31.4	30.9	18.7	15.6
47	33.49	3.62	2.52	5	1.000	63.2	120.0	64.7	66.9	61.7	60.8	26.7	25.6	57.5	56.3	34.1	30.1
48	27.75	4.09	2.57	6	.986	29.9	55.5	30.1	32.6	29.7	30.1	13.9	13.2	24.1	24.1	16.1	13.1
49	29.03	2.94	2.57	1	.983	30.6	57.4	33.5	35.8	26.7	27.4	13.6	13.1	21.7	21.9	15.7	12.6
50	27.12	2.76	2.53	2	.937	35.6	66.9	38.3	40.5	32.0	32.5	16.1	15.7	27.5	27.4	18.4	15.4
51	29.99	3.21	2.53	3	.937	66.0	126.7	63.8	64.5	62.9	61.6	30.4	29.5	60.7	58.8	39.5	35.9
52	25.52	2.61	1.72	4	.943	25.0	47.3	27.0	28.3	22.0	22.6	12.6	12.2	18.9	19.5	14.8	11.8
53	22.65	2.24	2.57	5	.986	23.4	44.5	24.0	25.5	21.4	21.8	11.5	11.3	19.0	19.1	13.8	11.1
54	24.56	3.58	2.57	6	.986	21.1	39.6	21.7	23.9	19.8	20.5	12.1	11.9	16.9	16.8	12.9	10.9
55	26.48	2.76	2.52	7	1.000	42.7	76.5	44.6	47.5	39.4	39.4	19.2	18.9	36.0	35.6	22.4	20.4
56	22.33	3.61	2.52	1	.983	11.8	17.5	11.7	14.5	13.6	13.9	4.7	5.0	9.4	10.1	8.1	6.7
57	29.99	4.27	.50	1	.638	31.4	50.7	30.8	33.1	29.6	30.4	14.4	14.4	25.3	25.4	16.7	14.0
58	24.88	3.52	2.53	2	.937	32.4	55.9	32.5	34.6	30.5	30.8	13.8	13.4	26.2	27.2	17.4	14.5
59	20.74	4.43	2.52	1	1.000	17.8	32.0	17.6	19.2	17.1	17.5	8.8	9.0	14.1	15.3	12.1	9.4
60	25.20	3.34	.50	2	.638	22.2	39.3	24.2	26.6	21.3	21.8	10.1	10.1	17.6	18.7	13.2	11.1
61	29.99	4.11	.50	3	.169	53.9	101.6	55.8	57.6	47.2	46.9	21.0	20.5	44.2	43.7	27.1	23.3
62	33.81	4.60	1.00	4	.762	77.0	146.0	71.6	72.5	63.9	62.7	31.5	30.9	66.0	63.4	38.4	34.5
63	30.62	3.73	1.00	5	.762	66.2	126.3	66.6	66.6	58.1	57.0	27.1	26.5	59.9	57.9	33.8	30.0
64	22.65	2.99	2.53	6	.937	33.1	63.2	33.7	35.3	34.4	34.6	16.5	16.1	31.3	31.1	19.2	15.8
65	21.69	3.04	.50	7	.004	9.3	14.6	8.3	9.7	7.8	8.5	4.6	3.2	6.8	7.8	6.4	5.4
66	25.52	5.44	1.72	1	.943	45.2	85.8	45.0	46.5	39.1	39.5	18.8	18.6	36.7	36.5	22.4	18.9
67	26.48	4.89	2.57	2	.986	31.6	59.5	32.3	34.4	27.8	28.5	14.2	14.1	24.7	24.8	15.5	12.4
68	31.26	3.75	2.57	3	.983	53.4	100.0	52.0	53.4	44.7	45.4	23.5	23.0	42.6	41.9	25.4	22.4
69	27.12	3.46	2.57	4	.986	39.0	71.9	39.2	42.3	35.7	36.6	18.1	17.8	31.9	31.7	18.8	16.2
70	24.88	3.38	2.57	5	.986	24.8	46.5	24.5	27.0	24.2	24.8	11.6	11.4	20.8	21.0	14.5	11.6
71	21.69	3.11	2.52	6	1.000	31.2	59.4	30.6	33.1	29.5	30.2	15.0	15.0	26.1	26.0	17.1	14.7

NA2:= 42 NSS = 24

TABLE 4. MEAN WIND SPEED VERSUS STD DEV OF STRAINS

REDUCED DATA

NO	RC	WIND	STD WIND	FETCH	DUR	COS	1V1	1V2	2V1	2V2	3V1	3V2	3V3	3V4	4V1	4V2	4V3	4V4
1	6	29.03	2.61	2.53	4	.937	37.2	71.9	37.2	39.0	33.6	32.7	19.2	18.4	34.0	33.5	21.7	18.2
2	7	28.71	2.76	2.53	5	.983	52.2	100.3	50.0	52.0	47.6	46.0	25.8	24.9	45.9	44.9	34.9	30.9
3	11	24.56	2.90	2.52	4	1.000	81.9	.0	85.3	87.2	71.6	69.9	37.5	36.8	68.8	69.0	42.3	37.7
4	16	28.71	3.60	2.52	4	1.000	118.7	.0	117.7	119.4	102.6	100.7	48.3	47.4	98.2	98.8	61.8	56.2
5	20	26.16	2.40	2.52	4	1.000	41.2	.0	40.9	42.0	36.5	36.2	20.1	19.5	33.2	34.9	23.3	22.3
6	21	29.35	3.74	2.52	5	1.000	111.6	.0	113.8	114.9	93.5	93.0	50.4	49.0	91.2	92.3	59.2	52.9
7	22	23.61	2.01	2.52	6	.983	72.5	.0	76.9	79.1	63.7	64.3	34.1	33.1	60.1	60.6	36.0	31.5
8	26	22.65	3.36	1.72	4	.983	36.4	.0	35.5	40.9	30.2	30.3	14.5	14.7	27.0	29.5	21.4	15.6
9	27	21.37	2.19	2.53	5	.937	25.0	.0	23.0	27.5	21.7	21.4	9.4	8.2	17.6	20.3	17.2	10.5
10	28	28.07	2.89	2.53	6	.983	92.6	.0	96.0	97.4	73.5	73.4	39.3	38.2	71.8	72.9	45.8	38.8
11	46	28.07	3.59	2.53	4	.937	38.1	72.4	41.6	44.2	37.4	37.0	15.6	15.1	31.4	30.9	18.7	15.6
12	47	33.49	3.62	2.52	5	1.000	63.2	120.0	64.7	66.9	61.7	60.8	26.7	25.6	57.5	56.3	34.1	30.1
13	48	27.75	4.09	2.57	6	.986	29.9	55.5	30.1	32.6	29.7	30.1	13.9	13.2	24.1	24.1	16.1	13.1
14	52	25.52	2.61	1.72	4	.943	25.0	47.3	27.0	28.3	22.0	22.6	12.6	12.2	18.9	19.5	14.8	11.8
15	53	22.65	2.24	2.57	5	.986	23.4	44.5	24.0	25.5	21.4	21.8	11.5	11.3	19.0	19.1	13.8	11.1
16	54	24.56	3.58	2.57	6	.986	21.1	39.6	21.7	23.9	19.8	20.5	12.1	11.9	16.8	16.8	12.9	10.9
17	55	26.48	2.76	2.52	7	1.000	42.7	78.5	44.6	47.5	39.4	39.4	19.2	18.9	36.0	35.6	22.4	20.4
18	62	33.81	4.60	1.00	4	.762	77.0	146.0	71.6	72.5	63.9	62.7	31.5	30.9	66.0	63.4	38.4	34.5
19	63	30.62	3.73	1.00	5	.762	66.2	126.3	66.6	66.6	58.1	57.0	27.1	26.5	59.9	57.9	33.8	30.0
20	64	22.65	2.99	2.53	6	.937	33.1	63.2	33.7	36.3	34.4	34.6	16.5	16.1	31.3	31.1	19.2	15.8
21	65	21.69	3.04	.50	7	.004	9.3	14.6	8.3	9.7	7.8	8.5	4.6	3.2	6.8	7.8	6.4	5.4
22	69	27.12	3.46	2.57	4	.986	39.0	71.9	39.2	42.3	35.7	36.6	18.1	17.8	31.9	31.7	18.8	16.2
23	70	24.88	3.38	2.57	5	.986	24.8	46.5	24.5	27.0	24.2	24.8	11.6	11.4	20.8	21.0	14.5	11.6
24	71	21.69	3.11	2.52	6	1.000	31.2	59.4	30.6	33.1	29.5	30.2	15.0	15.0	26.1	26.0	17.1	14.7

TABLE 5. MEAN WIND SPEED VERSUS STD DEV OF STRAINS

MODIFIED DATA

NO	RC	WIND	STD WIND	FETCH	DUR	COS	1V1	1V2	2V1	2V2	3V1	3V2	3V3	3V4	4V1	4V2	4V3	4V4
1	6	29.03	2.61	2.53	4	.937	37.2	71.9	37.2	39.0	33.6	32.7	19.2	18.4	34.0	33.5	21.7	18.2
2	7	28.71	2.76	2.53	5	.983	52.2	100.3	50.0	52.0	47.6	46.0	25.8	24.9	45.9	44.9	34.9	30.9
3	20	26.16	2.40	2.52	4	1.000	41.2	.0	40.9	42.0	36.5	36.2	20.1	19.5	33.2	34.9	23.3	22.3
4	26	22.65	3.36	1.72	4	.983	36.4	.0	35.5	40.9	30.2	30.3	14.5	14.7	27.0	29.5	21.4	15.6
5	27	21.37	2.19	2.53	5	.937	25.0	.0	23.0	27.5	21.7	21.4	9.4	8.2	17.6	20.3	17.2	10.5
6	46	28.07	3.59	2.53	4	.937	38.1	72.4	41.6	44.2	37.4	37.0	15.6	15.1	31.4	30.9	18.7	15.6
7	47	33.49	3.62	2.52	5	1.000	63.2	120.0	64.7	66.9	61.7	60.8	26.7	25.6	57.5	56.3	34.1	30.1
8	48	27.75	4.09	2.57	6	.986	29.9	55.5	30.1	32.6	29.7	30.1	13.9	13.2	24.1	24.1	16.1	13.1
9	52	25.52	2.61	1.72	4	.943	25.0	47.3	27.0	28.3	22.0	22.6	12.6	12.2	18.9	19.5	14.8	11.8
10	53	22.65	2.24	2.57	5	.986	23.4	44.5	24.0	25.5	21.4	21.8	11.5	11.3	19.0	19.1	13.8	11.1
11	54	24.56	3.58	2.57	6	.986	21.1	39.6	21.7	23.9	19.8	20.5	12.1	11.9	16.8	15.8	12.9	10.9
12	55	26.48	2.70	2.52	7	1.000	42.7	78.5	44.6	47.5	39.4	39.4	19.2	18.9	36.0	35.6	22.4	20.4
13	62	33.61	4.60	1.00	4	.762	77.0	146.0	71.6	72.5	63.9	62.7	31.5	30.9	66.0	63.4	38.4	34.5
14	63	30.62	3.73	1.00	5	.762	66.2	126.3	66.6	66.6	58.1	57.0	27.1	26.5	59.9	57.9	33.8	30.0
15	64	22.65	2.99	2.53	6	.937	33.1	63.2	33.7	36.3	34.4	34.6	16.5	16.1	31.3	31.1	19.2	15.8
16	65	21.69	3.04	.50	7	.004	9.3	14.6	8.3	9.7	7.8	8.5	4.6	3.2	6.8	7.8	6.4	5.4
17	69	27.12	3.46	2.57	4	.986	39.0	71.9	39.2	42.3	35.7	36.6	13.1	17.8	31.9	31.7	18.8	16.2
18	70	24.86	3.38	2.57	5	.986	24.8	46.5	24.5	27.0	24.2	24.8	11.6	11.4	20.8	21.0	14.5	11.6
19	71	21.69	3.11	2.52	6	1.000	31.2	59.4	30.6	33.1	29.5	30.2	15.0	15.0	26.1	26.0	17.1	14.7

NSS1 = 19

TABLE 6. CORRELATION MATRIX OF ALL VARIABLES

X(1)WIND	1.000000									
X(2)STOWIND	.567075	1.000000								
X(3)FETCH	-.125042	-.325532	1.000000							
X(4)DUR	-.366280	-.035947	-.044666	1.000000						
X(5)CGS	.133719	-.095198	.793891	-.363160	1.000000					
X(6)1V1	.849233	.485828	-.184353	-.359169	.207203	1.000000				
X(7)1V2	.887215	.505343	-.159440	-.302300	.182229	.966033	1.000000			
X(8)2V1	.861877	.476086	-.146616	-.357469	.240382	.994031	.969883	1.000000		
X(9)2V2	.845580	.475766	-.120728	-.365241	.269112	.991713	.953718	.997372	1.000000	
X(10)3V1	.859801	.484666	-.088059	-.313602	.257698	.987574	.969034	.992673	.991300	1.000000
X(11)3V2	.857592 1.000000	.497932	-.084712	-.308561	.263852	.985753	.969468	.991845	.990653	.999419
X(12)3V3	.354006 .969838	.416669 1.000000	-.086460	-.345548	.268647	.975573	.977814	.971350	.963473	.972314
X(13) 3V4	.840087 .967154	.423308 .998175	-.070837 1.000000	-.355351	.301461	.972445	.976114	.969440	.962634	.968512
X(14)4V1	.857995 .969699	.477831 .980038	-.172669 .975221	-.310593 1.000000	.187142	.992966	.977219	.990743	.984646	.991748
X(15) 4V2	.844629 .989068	.457020 .978075	-.169318 .973110	-.330857 .998134	.198348 1.000000	.995180	.967210	.991805	.988282	.991584
X(16) 4V3	.798849 .951351	.357053 .967323	-.127529 .960114	-.349521 .965895	.238018 .972979	.970223 1.000000	.921878	.956367	.956948	.958767
X(17)4V4	.825617 .956447	.370238 .984748	-.138333 .977914	-.304613 .971507	.200909 .973776	.970193 .987077	.956559 1.000000	.960198	.952813	.962185
X(18)LOGWIND	.997441 .841937	.554001 .844051	-.096073 .831484	-.374194 .840141	.158774 .826144	.831370 .781227	.876847 .811950	.847691 1.000000	.830871	.844005
X(19)LOGSTWIND	.540597 .475720	.993605 .391862	-.311780 .400004	-.004324 .451845	-.101102 .430131	.454166 .327255	.482807 .344381	.450504 .530499	.451196 1.000000	.461514
X(20)LOGFETCH	-.066200 .000689	-.286651 .000776	.981806 .022179	-.156405 -.087562	.891881 -.080991	-.089761 -.035901	-.081707 -.058612	-.050876 -.036750	-.022163 -.277597	-.003206 1.000000

Contd.....

X(21) LOGDUR									
-.362597	-.036014	-.013792	.996338	-.327433	-.348553	-.293726	-.347386	-.355077	-.298509
-.293768	-.334076	-.343891	-.297196	-.317640	-.331020	-.291258	-.371559	-.005682	-.123441
1.000000									
X(22)LOGCOS									
.260864	.017144	.659387	-.443827	.968778	.367192	.331458	.394209	.417873	.400811
.405646	.409683	.441584	.345861	.354863	.380047	.335650	.280683	-.001934	.782244
-.405910	1.000000								
X(23)LOG1V1									
.776939	.374389	.089725	-.446260	.492851	.945112	.905795	.953760	.962349	.951871
.951621	.944154	.951897	.933310	.940401	.926832	.914708	.772402	.349580	.203896
-.429760	.624384	1.000000							
X(24)LOG1V2									
.803706	.441760	.081065	-.338718	.414729	.850240	.927584	.875543	.862513	.877686
.882832	.906599	.920961	.866172	.852892	.801213	.850092	.812575	.438739	.169337
-.330700	.518798	.889108	1.000000						
X(25)LOG2V1									
.774313	.363241	.133882	-.453269	.538311	.921956	.894381	.940181	.948110	.936816
.937539	.926083	.936474	.912152	.917429	.896651	.888091	.774037	.342348	.251639
-.437111	.663841	.994972	.905229	1.000000					
X(26)LOG2V2									
.755132	.364441	.143447	-.453574	.548313	.917382	.874571	.933856	.946298	.931269
.932077	.913632	.924128	.904041	.911835	.895022	.878158	.753471	.343579	.262403
-.437058	.671642	.994987	.880159	.997733	1.000000				
X(27)LOG3V1									
.768644	.381513	.176513	-.405106	.543379	.916897	.893578	.933002	.941789	.942354
.943527	.925209	.933574	.913812	.917738	.896594	.887947	.766833	.362219	.283330
-.384509	.662968	.991575	.903736	.993679	.992567	1.000000			
X(28)LOG3V2									
.771963	.399528	.167845	-.395806	.536502	.918872	.899329	.935535	.943813	.945087
.947270	.926774	.936163	.916180	.919271	.893502	.887705	.769910	.381439	.274181
-.375802	.655637	.990300	.910470	.992906	.991190	.999447	1.000000		
X(29)LOG3V3									
.782548	.343623	.150606	-.414736	.526012	.910210	.914585	.921540	.922088	.924225
.924633	.954216	.964443	.911026	.911506	.901436	.911100	.784972	.325737	.257751
-.398302	.643067	.976190	.940734	.978192	.968368	.976809	.976806	1.000000	
X(30)LOG3V4									
.735673	.328422	.215753	-.434099	.607825	.869488	.874886	.884659	.887513	.886044
.888052	.917054	.933292	.867871	.868504	.858725	.864976	.741378	.312275	.331671
-.415259	.717215	.965068	.934929	.973711	.965025	.970918	.971023	.993148	1.000000
X(31)LOG4V1									
.785003	.374477	.112083	-.403880	.485159	.938574	.920973	.950520	.955455	.956069
.956042	.951816	.959387	.939939	.942468	.920706	.916062	.781494	.355164	.217428
-.365579	.614540	.993104	.917537	.990730	.986770	.994294	.993716	.984792	.972919
1.000000									
X(32)LOG4V2									
.772575	.355239	.092986	-.419246	.472278	.944576	.910912	.953627	.961055	.957558
.956633	.949669	.955703	.941505	.948089	.931592	.921137	.767005	.333955	.200175
-.401600	.602542	.996017	.892731	.989512	.988678	.991707	.990131	.976994	.962334
.997280	1.000000								
X(33)LOG4V3									
.741274	.280554	.086476	-.432967	.477472	.933186	.874844	.931929	.941563	.934732
.929510	.940872	.943545	.922783	.934530	.959966	.935148	.733400	.253380	.198868
-.410745	.604219	.980475	.831489	.965890	.965898	.965149	.959696	.957809	.940666
.971543	.981269	1.000000							
X(34)LOG4V4									
.767670	.316260	.060165	-.380315	.424850	.947278	.931927	.951053	.951832	.953632
.950460	.976237	.979649	.945125	.950509	.958251	.964482	.783549	.296056	.159080
-.364693	.544399	.976812	.906591	.966293	.959327	.965481	.963839	.981137	.958553
.978988	.980560	.980547	1.000000						

TABLE 7. REGRESSION ANALYSIS OF VERTICAL TRUNION – 1V1

ANALYSIS OF VERTICAL TRUNIONS

MAIN PROBLEM.... 1

SUB-PROBLEM... 1
LIST OF INDEPENDENT VARIABLES 0 18 21 22

STEP NUMBER 1

DEPENDENT VARIABLE X(23)LOGIV1 ST.ERR.OF RESIDUAL .314736

R2 = .59660 D.F. = 17

VAR NAME	COE	ST.ERR.	T-VAL	PAR.CORR.
X(0)CONST.	-5.03172	1.70374	-2.9447	
X(18)LOGWIND	2.62719	.523949	5.0142	.7724

STEP NUMBER 2

DEPENDENT VARIABLE X(23)LOGIV1 ST.ERR.OF RESIDUAL .241307

R2 = .77682 D.F. = 16

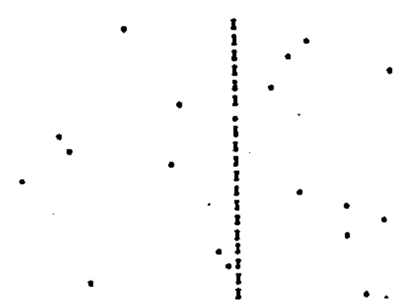
VAR NAME	COE	ST.ERR.	T-VAL	PAR.CORR.
X(0)CONST.	-3.59090	1.36955	-2.6203	
X(18)LOGWIND	2.20460	.418561	5.2671	.7964
X(22)LOGCOS	.169466	4.714652E-02	3.5945	.6684

END OF REGRESSION ANALYSIS

RESIDUAL SUM OF SQUARES .931668
VARIABLE GENERATED BY THIS REDUCED FORM EQUATION WILL BE LABELLED AS X(35)LOGIV1
COVARIANCE OPTION DELETED BECAUSE OF STEPWISE OPTION

PLOT OF RESIDUALS IN THE ABOVE REGRESSION

NO.	TRUE-Y	ESTIMATE	RESIDUAL
1)	3.616	3.818	-.2016
2)	3.955	3.802	.1535
3)	3.716	3.599	.1190
4)	3.595	3.279	.3157
5)	3.219	3.143	7.6344E-02
6)	3.640	3.744	-.1035
7)	4.146	4.144	2.3083E-03
8)	3.396	3.727	-.3293
9)	3.219	3.535	-.3160
10)	3.153	3.279	-.1267
11)	3.349	3.778	-.4286
12)	3.754	3.626	.1280
13)	4.344	4.119	.2249
14)	4.193	3.900	.2923
15)	3.500	3.271	.2288
16)	2.230	2.251	-2.0613E-02
17)	3.564	3.576	-1.2926E-02
18)	3.211	3.486	-.2756
19)	3.440	3.186	.2541



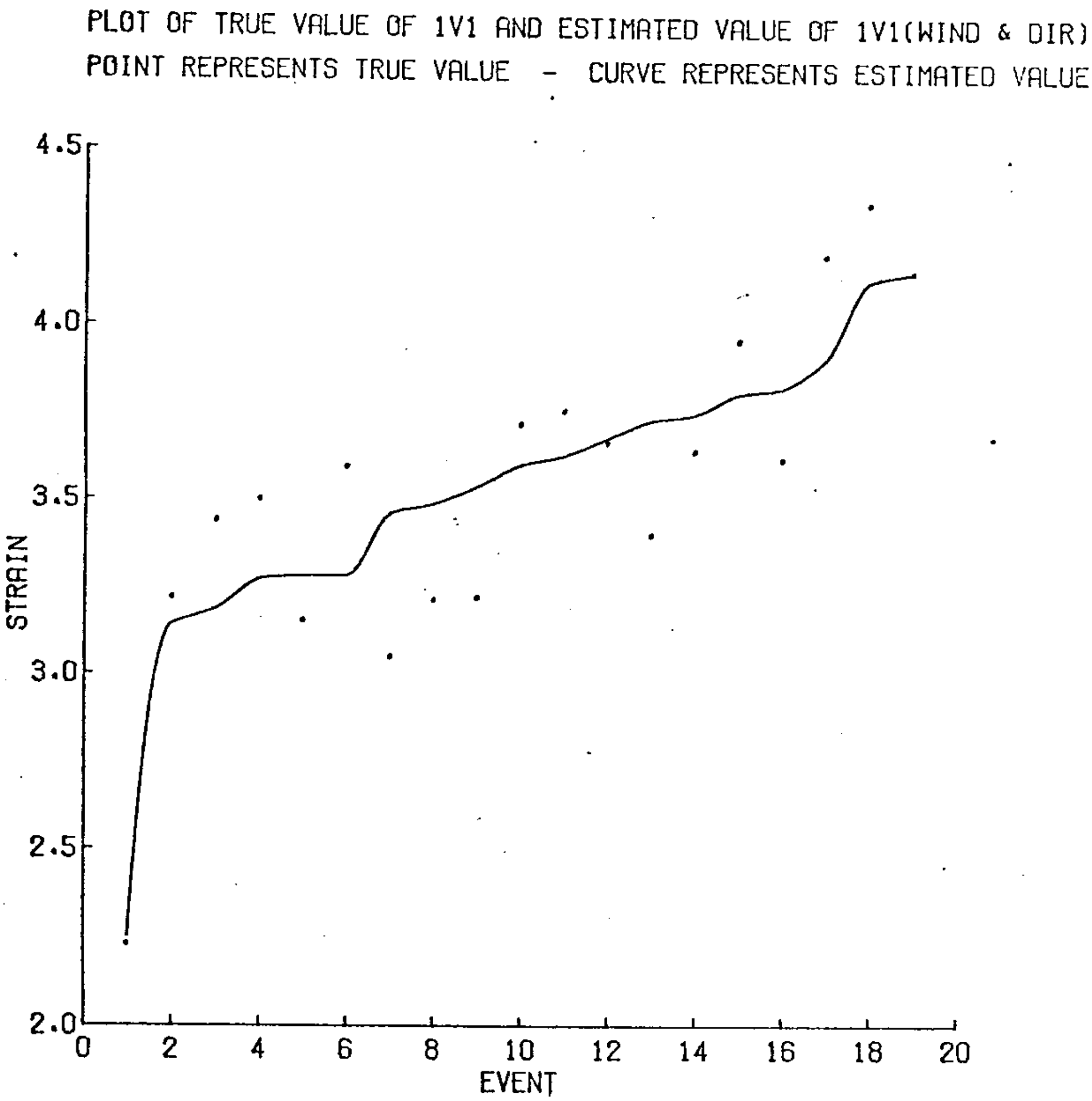


FIG 4 . COMPARSION OF ESTIMATED AND TRUE VALUE OF VERTICAL TRUNION - 1V1

TABLE 8. REGRESSION EQUATION FOR VERTICAL TRUNION

* R = Partial Correlation Coefficient of the Regression Equation*

$$Y = A\ (\text{wind})^m\ \text{Cos}^n\phi$$

Component Part	Variable Name	Coefficient	St. Err	T-Val	Par Corr	Fitted Equation
1V1	Const Log Wind Log Cos	-3.59690 2.20460 0.16946	1.36955 .41856 .04714	-2.6263 4.2471 3.5945	0.7964 0.6684	$Y = 0.0275W^{2.2056}\text{Cos}\ \phi^{0.16946}$ R = 0.77632
2V1	Const Log Wind Log Cos	-3.6630 2.22721 0.19060	1.27823 0.39065 0.04002	-2.8683 5.7013 4.3317	0.8186 0.7347	$Y = 0.0253W^{2.22721}\text{Cos}\ \phi^{0.19060}$ R = 0.81550
2V2	Const Log Wind Log Cos	-2.83395 1.99306 0.182837	1.24679 0.381043 0.04292	-2.2730 5.2305 4.2499	0.7943 0.7290	$Y = 0.0487W^{1.99306}\text{Cos}\ \phi^{0.182837}$ R = 0.79745
3V1	Const Log Wind Log Cos	-3.57290 2.17215 0.188608	1.29525 0.39585 0.04485	-2.7585 5.4875 4.2299	0.8081 0.7266	$Y = 0.0280W^{2.17215}\text{Cos}\ \phi^{0.188608}$ R = 0.80552
3V2	Const Log Wind Log Cos	-3.29443 2.08725 0.17635	1.24371 0.38010 0.04281	-2.6489 5.4913 4.1191	0.8083 0.7174	$Y = 0.0371W^{2.08725}\text{Cos}\ \phi^{0.176357}$ R = 0.80255
3V3	Const Log Wind Log Cos	-3.91809 2.06500 0.162644	1.16914 0.35731 0.04247	-3.3513 5.7793 4.0411	0.8223 0.7107	$Y = 0.0198W^{2.065}\text{Cos}\ \phi^{0.162644}$ R = 0.81005
3V4	Const Log Wind Log Cos	-4.04136 2.09450 0.22400	1.25243 0.38276 0.04311	-3.2268 5.4720 5.1584	0.8073 0.7902	$Y = 0.0175W^{2.0945}\text{Cos}\ \phi^{0.2240}$ R = 0.83089
4V1	Const Log Wind Log Cos	-4.73779 2.49710 0.182485	1.50968 0.46133 0.05197	-3.1383 5.4122 3.5133	0.7042 0.6597	$Y = 0.0086W^{2.4971}\text{Cos}\ \phi^{0.18268}$ R = 0.78015
4V2	Const Log Wind Log Cos	-4.02782 2.28220 0.16647	1.49574 0.45712 0.05149	-2.6929 4.9925 3.2331	0.7804 0.6286	$Y = 0.0178W^{2.2822}\text{Cos}\ \phi^{0.16647}$ R = 0.75098
4V3	Const Log Wind Log Cos	-2.97093 1.83708 0.14618	1.37777 0.42107 0.04742	-2.1563 4.3629 3.0822	0.7371 0.5104	$Y = 0.051W^{1.83708}\text{Cos}\ \phi^{0.14618}$ R = 0.71004
4V4	Const Log Wind Log Cos	-4.49896 2.24808 0.13009	1.45683 0.44523 0.05015	-3.0882 5.0492 2.5941	0.7838 0.5441	$Y = 0.011W^{2.24808}\text{Cos}\ \phi^{0.13009}$ R = 0.72868

ESTIMATION OF LIFE

Equation (18) was used to estimate the life of the vertical trunnions. This required the determination of ω, the oscillating frequency of the member; S, the maximum amplitude of oscillating stress; σ_s, the standard deviation of S; N, the number of cycles to failure at S and b^{-1}, the slope of the S-N curve.

The frequency of oscillation, ω, was estimated from the empirical relation (1)

$$\omega = k \quad F^{-0.31} \quad u^{-0.38} \tag{37}$$

where k = 171.1 F = fetch in ft. u = wind speed (ft/sec)

The regression equation obtained gives values of standard deviation of strains from known wind speed and direction. Thus σ_s, standard deviation of stress, is obtained directly by introducing the long term wind data into the regression equation. The harmonic stress amplitude or actual stress is determined as $3\sigma_s$, in addition the prestress force of 12.85 ksi in the rods. This means that S includes 99% of the expected stress range. N, S and b are obtained from a posed S-N (Fig. 5) curve for the material of member based on its mechanical properties (Appendix) assuming that it takes 1 million cycles at 30 ksi and 1/4 cycle at 137. 4 ksi.

These matters are illustrated in the following example for vertical trunnion 1V1.

1) Calculation of strain

Wird speed:	55.00 mph	Fetch = F =	3.55 miles
Direction:	South = 0°	E =	31.25×10^6 psi

Using the regression equation of 1V1 from Table 9

$$\sigma_\varepsilon = 0.275\ W^{2.204}\ \mathrm{Cos}^{0.169} = 188.2 \text{ micro strain}$$

$$\sigma_s \approx 188.22 \times 31.25/1000.0 = 5.882 \text{ kip/in}^2$$

$$S = 5.882 \times 3 + 12.85 = 30.52 \text{ kip/in}^2$$

2) Estimation of cycles

To estimate the cycles to failure for S (harmonic stress amplitude) from the posed S-N curve, an equation of the form was employed.

$$\overline{N} = \frac{N_1 \times S_2}{(S_2 - S_1)k} - \frac{N_1 \times S}{S_2 - S_1}$$

where

N_1 = the number of cycles required at stress range of 30 ksi.

S_2 = the maximum stress range of 137.4 ksi.

S_1 = the lowest stress range of 30 ksi.

K = stress intensity factor

S = the harmonic stress amplitude attained for particular wind speed.

Thus, using above equations and from the estimated harmonic stress amplitude S of 30.52 ksi for the previous section, then

$$N = 10^{\overline{N}} = 9.357 \times 10^5 \text{ cycles}$$

3) Estimation of Oscillating Frequency (1)

$$\omega = k\ F^{-0.31}\ u^{-0.38} \approx 1.526 \text{ radian/sec}$$

4) Estimation of b

$$b = \frac{\log \underline{N}_2 - \log \underline{N}_1}{\log \underline{S}_2 - \log \underline{S}_1} \approx 4$$

5) Time of Failure

$$T_f = \frac{2\pi N}{\omega} \left(\frac{S}{\sigma_s} \right)^b \frac{2^{-b/2}}{(b/2)!}$$

$$= 7.753 \times 10^7 \text{ sec}$$

$$= 24.55 \text{ years}$$

6) Percent Damage

no. of occurrence of that particular wind = 26

no. of years = 10 years

no. of occurrence for 1 year = 2.6 hours

$$\% \text{ damage for one year} = \frac{2.6 \times 100}{24.55 \times 365 \times 24}$$

$$= 0.0000268$$

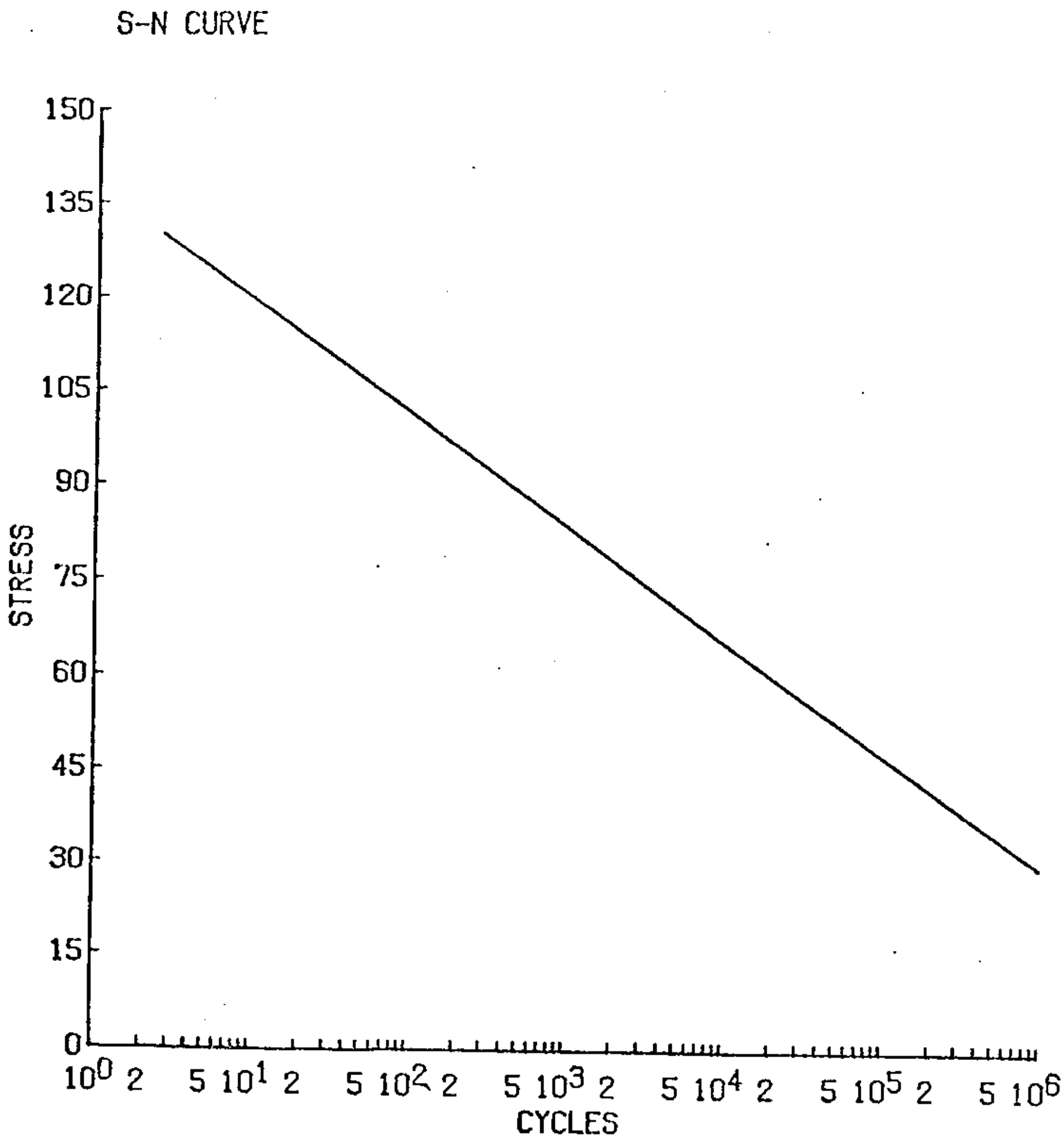


FIG 5. POSED S-N CURVE

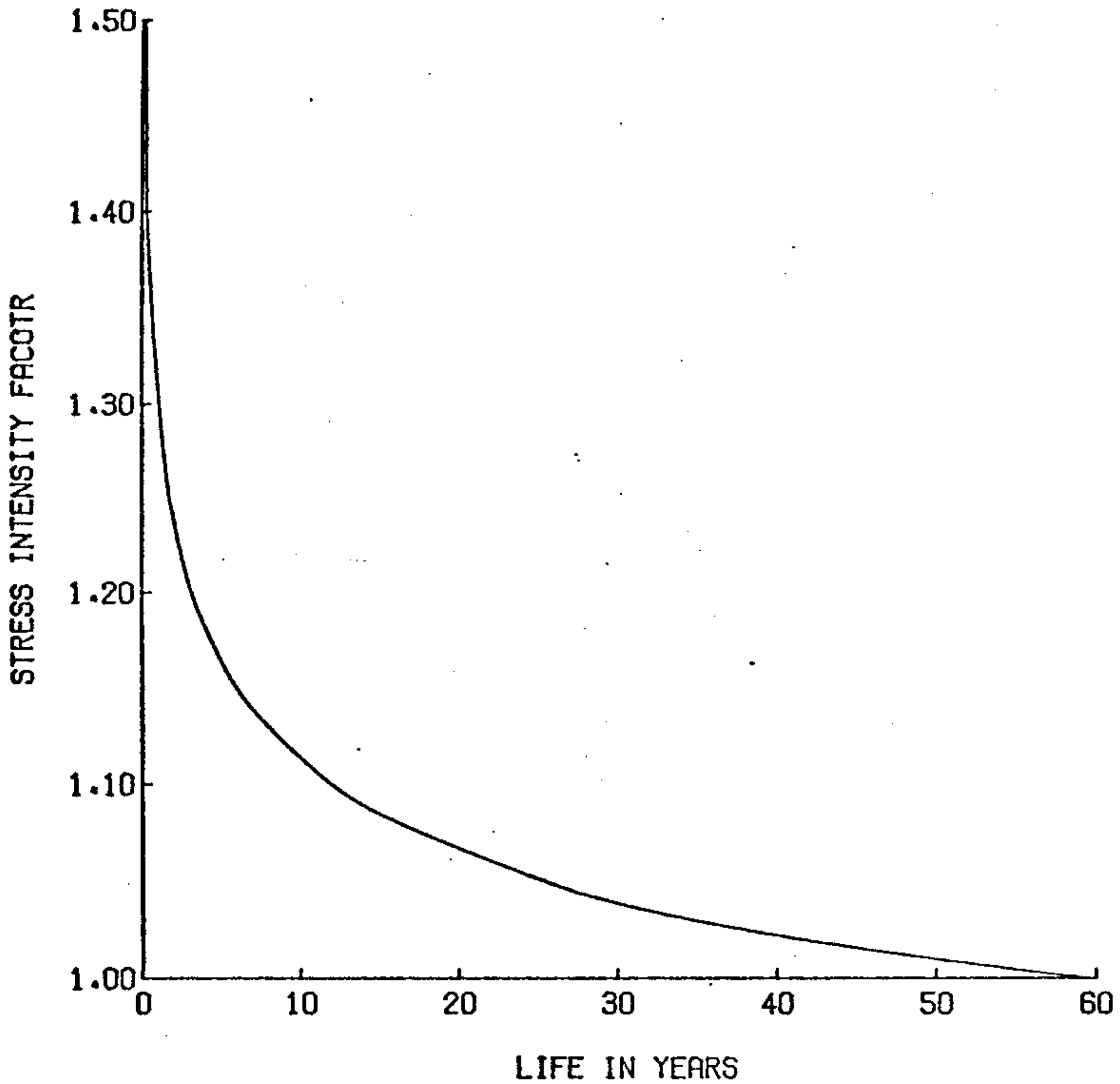


FIG 6. ESTIMATION OF LIFE FOR VERTICAL TRUNION-1V1

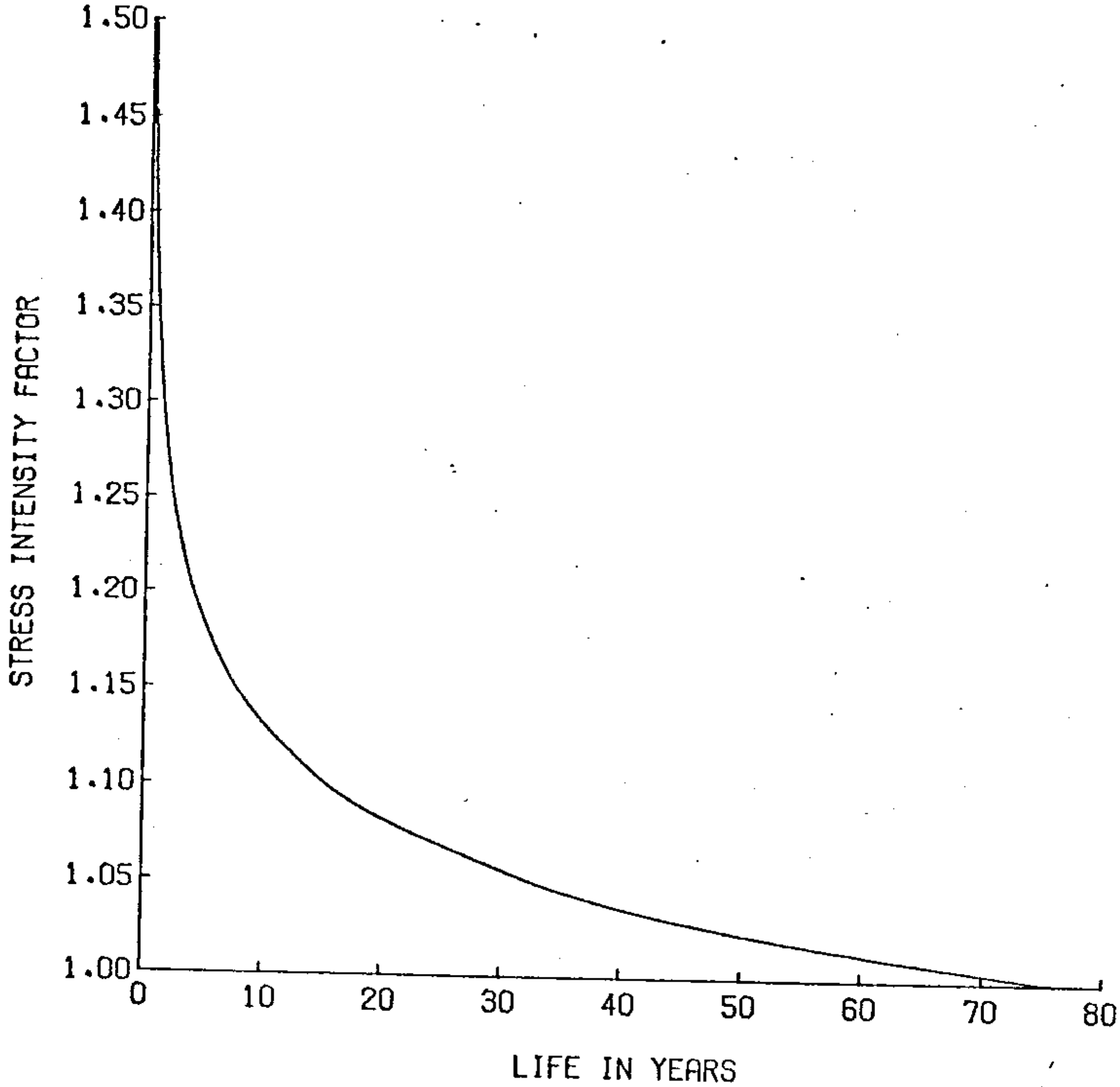


FIG 7. ESTIMATION OF LIFE FOR VERTICAL TRUNIONS (AVERAGE)

TABLE 9: ESTIMATION OF LIFE

EVERGREEN POINT BRIDGE

STRESS INTENSITY	LIFE IN YEAR (ONE HOUR DURATION)											
	1V1	2V1	2V2	3V1	3V2	3V3	3V4	4V1	4V2	4V3	4V4	Average
1.0	58.67	54.16	79.33	90.27	112.20	1485.8	1562.5	49.93	95.77	1160.9	906.5	75.4
1.05	25.28	23.34	34.19	38.90	48.36	640.3	673.45	21.52	51.27	500.3	390.7	32.5
1.1	11.76	10.86	15.91	18.10	22.50	297.9	313.3	10.01	19.20	232.3	181.7	15.4
1.15	5.85	5.40	7.91	9.0	11.19	148.16	155.7	4.97	9.50	115.7	90.40	7.5
1.2	3.08	2.84	4.17	4.74	5.89	78.09	82.13	2.69	5.03	51.02	57.06	3.9
1.25	1.71	1.58	2.31	2.63	3.27	43.3	45.57	1.45	2.75	33.85	26.43	2.2
1.3	0.9	0.9	1.54	1.52	1.9	25.13	26.45	0.86	1.62	19.65	15.36	1.2

SAND POINT

STRESS INTENSITY	LIFE IN YEARS (ONE HOUR DURATION)										
	1V1	2V1	2V2	3V1	3V2	3V3	3V4	4V1	4V2	4V3	4V4
1.0	106.5	102.1	107.4	140.1	165.8	2061.1	2223.7	135.6	181.6	1270.8	1520.5
1.05	45.9	44.0	46.3	64.7	71.4	888.3	958.4	58.4	78.2	547.7	655.3
1.10	21.3	20.4	21.5	20.1	22.1	41.2	445.9	27.2	36.4	254.8	304.9
1.15	10.6	10.1	10.7	14.9	16.5	205.5	221.7	13.5	18.1	126.7	151.6
1.2	5.6	5.3	5.6	7.8	8.7	108.3	116.8	7.1	9.5	66.8	79.9
1.25	3.1	2.9	3.1	4.3	4.8	60.1	54.8	3.9	5.2	37.0	44.3
1.3	1.8	1.7	1.8	2.5	2.8	34.8	37.6	2.2	3.07	21.5	25.7

Using the long-term wind data read on the Evergreen Point Bridge and assuming that every wind measured lasted for 8 hours (the frequency of measurement), then the estimated life of the trunnion 1V1 was 8 years. However, if it is assumed that the measured winds only persisted for a single hour, then the estimated life increased to 58 years. This figure was reduced to 6 years when the maximum static strength was reduced by 15%. Similar results are obtained for the other interior trunnions (1VI, 2V1, 2V2, 3V1, 3V2, 4V1, 4V2 on Fig. 1). These are given in Table 9 .

Using the long-term data for wind obtained at 1 hour frequency at Sand Point and assuming a single hour duration of measured wind, the estimated life of 1V1 was higher than the 1 hour assumption from the Evergreen Point measurements, as given above (Table 9).

In a way a paradox exists. The long-term measurements on the Bridge are not at the same frequency as the short-term measurements and therefore are not so attractive for the determination of cycles of loading N. However, the Sand Point measurements are 1 hour frequency but the amplitude of wind speeds is much lower than on Bridge.

The approach favored here is to utilize the long-term Bridge data, but treating the duration of wind as an undetermined value. Thus, the life lies between 8 years and 58 years. This can be resolved by obtaining the chronological data for the Sand Point and determining the statistics of wind duration.

As a final look at the results, Fig. 6 shows the estimation of life for trunnion 1V1 using Evergreen Point Bridge long-term wind data with a single hour duration for various values of structural static strength defined by the material strength divided by the stress intensity factor. Fig. 7 shows average estimation of life for all members obtained by averaging the regression coefficients of Table 8.

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APPENDIX B

PRESSURE TRANSDUCER INFORMATION

Calibration Factors

TRANSDUCER NUMBER	CHANNEL NUMBER	SLOPE (ft/V)	SCALING FACTOR (IN./Count)
1	22	0.91	-.341
2	24	1.96	-.735
3	40	2.01	-.754
4	28	0.88	-.330
5	30	1.10	-.413
6	32	1.07	-.401
7	34	-1.08	+.405
8	39	1.74	-.653
9	26	1.79	-.671

APPENDIX C

MATERIAL PROPERTY OF VERTICAL TRUNION

Cardinal
FOUNDRY & SUPPLY COMPANY
DIVISION OF PRODUCTION EXPERTS, INC.
THREADING DIVISION
5200 HARVARD AVENUE
PHONE 216 / 341 5700
CLEVELAND, OHIO 44105

TO:
WASHINGTON DEPT OF HIGHWAYS
10833 Northrup Way N. E.
Bellevue Washington 98004
Attn: L. Waite

REPORT OF CHEMICAL AND PHYSICAL TEST

DESCRIPTION OF MATERIAL AND SPECIFICATIONS

ITEM NO	QUANTITY	DESCRIPTION	CUSTOMER ORDER NO	OUR ORDER NO	SPECIFICATION	SHIPPING DATE
1	10	3" - 8 x 17' B7	F624089	CF 22239	ASTM A193 B7	7/30/76
		Double end stud				
		6" Thread one end				
		15" Thread one end				

CHEMICAL ANALYSIS

ITEM NO	GRADE	HEAT NO	C	Mn	P	S	Si	Ni	Cr	Mo	V	
1	A-4140	193704	.42	.93	.018	.025	.26		.98	.19		

MECHANICAL PROPERTIES

ITEM NO.	TENSILE STRENGTH PSI	YIELD STRENGTH PSI	PROOF LOAD LBS	ELONGATION PERCENT IN 2"	PERCENT RED AREA	HARDNESS BHN	HARDNESS R/C	MINIMUM TEMPERING TEMP
1	137,400	111,740		19.5	58.4	280		1100°F

Modulus of Elasticity = 31.25×10^6 psi

We hereby certify that the foregoing is a true copy of the data as furnished to us by the producing mill or the data as obtained in the laboratory of Cardinal Foundry.

CARDINAL FOUNDRY & SUPPLY CO.

Quality Control Supervisor

NOTARIAL SEAL CUYAHOGA COUNTY

18th AUG 76

RICHARD R. [illegible]
NOTARY PUBLIC
[illegible]

TRANSDUCER CALIBRATION DATA:

EGB 1:

ft	V
4.69	-5.04
3.30	-3.48
2.12	-2.18
1.09	-1.09

EGB 2

ft	V
4.86	-2.03
4.02	-1.55
1.99	-0.49
0.88	+0.024
0.19	+0.35

EGB 2

ft	V
4.35	-2.16
2.37	-1.12
0.90	-0.41
0.20	-0.10

EGB 3

ft	V
4.32	-3.35
2.24	-1.87
0.75	-0.97
0.14	-0.62

EGB 4

ft	V
4.55	-5.19
3.25	-3.63
2.05	-2.19
0.83	-0.90
0.13	-0.18

EGB 5

ft	V
3.84	-3.54
2.54	-2.29
1.29	-1.14
0.18	-0.21

EGB 6

ft	V
5.02	+4.17
3.90	+2.99
2.74	+1.76
0.85	+0.03
0.13	-0.30

EGB 6

ft	V
4.61	+4.24
3.35	+2.92
1.78	+1.33
0.16	+0.17

EGB 7

ft	V
4.65	-0.35
2.98	+1.27
1.81	+2.38
0.54	+3.46
0.17	+3.79

EGB 8

ft	V
4.81	-2.91
3.24	-1.96
2.09	-1.29
0.96	-0.66
0.18	-0.25

EGB 9

ft	V
4.68	-2.68
3.30	-1.85
2.15	-1.17
0.88	-0.51
0.15	-0.15