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WIND LOADS ON TRANSMISSION LINE TOWERS

by

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SUMMARY

Wind tunnel tests on sections from two of the standard suspension type transmission line towers, (one a 220 kV single circuit tower, the other a 500 kV DC tower) are described. The variation of drag coefficient of the tower models at different angles of attack are presented and compared with results given by Cohen and Perrin (1957) and Birjulin (1960). By removing the leeward sides of the model tower, it was possible to determine the drag forces acting separately on the windward and leeward members of such a lattice structure, so that a shielding factor could be determined. These results are presented for tower sections having different solidity ratios. The results confirmed the design criteria used by the New Zealand Electricity Department for the design of square planform tower sections, except for base sections of the tower, where the wind loads might be underestimated if drag coefficient was assumed to be invariant with solidity ratio. The wind loads on the more complex, single circuit top sections were also found to be greater than that predicted by the N.Z.E.D. design criteria.

The results demonstrate that the N.Z. Draft Code would yield a conservative design for square planform lattice structures.

Maximum gust records obtained from thirty maximum gust recorders maintained by the N.Z.E.D. in the Canterbury and North Otago areas are also presented. These suggest that either, or both, the 'wind map' established for New Zealand and the topographical factor recommended in the draft N.Z. standard might cause wind speeds to be underestimated in exposed areas, where in fact transmission lines are often constructed. The maximum gust results themselves, however, need to be treated with caution and a recommendation is made that more long term data is needed.

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INTRODUCTION

A transmission line, comprising the supporting towers and the conductors strung between them, is an expensive piece of capital equipment. A single tower costs typically NZ$3000 to NZ$15,000 to erect, depending on type. More importantly the security of the electrical supply, which comprises 20 per cent of New Zealand's total energy consumption, depends upon the integrity of the towers and conductors. The loss of supply or "outage" as it is sometimes known, caused by the failure of a tower and/or fractured conductor, costs approximately NZ$100 to NZ$200 per megawatt per day. This actual cost obviously depends upon the location of the breakdown and the type and location of the power plant used to 'replace' this 'lost' source of electrical power. This means that the breakdown of a transmission line normally carrying 250 megawatts could cost between $ 25,000 and $ 50,000 every day it was out of service.

Towers and transmission lines, of necessity, frequently pass over very exposed terrain; it is well known that hills and valleys cause accelerations of the ground level wind, so that wind loads are increased and are proportional to the square of the increased velocity. A hill or escarpment can increase the ground level wind speed by up to 1.5 times, thus increasing the wind load by up to 2.25 times that prevailing on nearby level ground. (Bowen and Lindley 1974, Stodhart 1973 and Shellard 1963)

The wind can effect a transmission line and its supporting towers in several ways. The principal effects of wind forces are : a) the 'static drag loads' on all components equal to $C_D.\frac{1}{2}\rho U^2 A$. b) Aeolian Vibration of the conductors; usually a high frequency (5 to 120 Hz) low amplitutde phenomena. c) Galloping of the conductors; usually a low frequency (e.g. 8 sec/cycle), high amplitude phenomena, one of the most publicised examples of which was the conductor oscillation of the 275 kV crossing over the Severn and Wye rivers in the U.K., and described by Davis, Richards and Scriven (1963), and d) Sub conductor oscillation which is a medium frequency (1 to 2 Hz) small amplitude oscillation.

This paper will deal only with the static 'drag' loads on the towers, and looks at part of a problem that arose out of a series of tower failures in New Zealand during the period 1963 to 1968. Altogether 29 towers of various types failed during this period at the various locations numbered 1 to 7 on the gust speed map of New Zealand shown in Fig. 1. Fig. 2 gives some idea of the appearance of a tower damaged by excessive winds. During the last 30 years the New Zealand Electricity Department has changed its specifications with regard to allowable wind loads several times - each time as a result of new overseas data coming to hand. Table 1 gives brief details of these specifications as they have changed with time. Almost all of the towers that failed had been designed according to the 1957-1963 Specifications. The specifications were immediately amended and upgraded as the table shows and there have been no tower failures since 1968. It was the aim of the project described here to investigate the static wind loads on towers built by the New Zealand Electricity Department, to determine how realistic the specifications now were. Details are given in the following sections of experiments performed on models of towers that had failed.

PERIOD	CONDUCTOR LOADS (lb/ft^2)	TOWER LOADS (lb/ft^2)	SHIELDING FACTOR	FACTOR OF SAFETY	FACTOR OF SAFETY FOR THE BROKEN WIRE CASE
Pre 1944	18.0	30.0	1.5	1.8	1.8
1944-1957 (1)	12.0	30.0	1.5	1.65	1.65
1957-1963 (2)	7.5	30.0	1.5	1.65	1.2 (3)
1963-1968 (4)	10.0	30.0	1.75	2.0	1.5
Post 1968	10.0	40.0	1.75	2.0	1.5

TABLE 1. Historical development of N.Z. Electricity Department specifications for wind loading on towers and conductors

NOTES:

1) Longer conductor spans introduced and the concept of gust reduction factor (= 0.66 in this case) introduced thereby reducing wind loading on conductor spans.
2) Gust reduction factor reduced to 0.42 as a result of overseas data supporting such a reduction.
3) Broken wire case safety factor reduced. (See Dickens (1965), Mckenzie (1960)).
4) Conductor loads increased as a result of tower failures on Aviemore-Benmore and Benmore-Islington lines which had both been designed to 1957-1963 specification

TOWER MODELS

The tower models were of the standard suspension type and representative of those found* on the

a) Islington-Twizel 220 kV single circuit line (as shown in Fig.3),

b) Benmore-Haywards 500 kV direct current line (as shown in Fig. 4).

From flat plate drag coefficient data given by Sachs (1972) it was established that a Reynolds number greater than 10^4 (based on the angle flange dimensions of the smallest tower model member) must be reached in wind tunnel tests before the drag coefficient becomes independent of Reynolds number. The size of the tunnel working section limited the models to a scale of one tenth full size.

To obtain sharp edged angle sections for the models, extruded aluminium ($\frac{1}{2}$" x $\frac{1}{2}$") angle was used for the modelling material. This was sawn and filed down to have the necessary scaled dimensions.

The 500 kV tower was modelled in three sections and the top half of the 220 kV single circuit tower was modelled in two sections. To minimise end effects, the two lower sections of the 500 kV tower and the lower section of the 220 kV tower were constructed to leave minimum clearance between model and the tunnel roof.

Table 2 gives the solidity ratios for both normal and adjacent tower faces where the adjacent face is that in a plane perpendicular to the conductor line.

MODEL	A_1 NORMAL ϕ	A_2 ADJACENT ϕ	MODEL LEG ANGLE FLANGE DIMENSION (METRES)
DC/Top section	0.214	0.194	0.008
DC/Middle section	0.138	0.133	0.008
DC/Bottom section	0.103	0.103	0.008
SC/Top section	0.236	0.279	0.0064
SC/Middle section	0.124	0.191	0.008

TABLE 2. Model Tower Data

EXPERIMENTAL DETAILS

The University of Canterbury's closed circuit, low speed wind tunnel (Stevenson 1968) was used for all model tests. The tunnel has an 8 ft. 4 ins. long, 4 ft x 3 ft working section in which uniform velocities across the section of up to 165 ft/sec can be achieved. A three-

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* These transmission lines were designed and built about 1960 and suffered several tower failures soon after construction. The single circuit towers being particularly prone to damage.

component mechanical balance fitted with a 3 ft. 6 ins. diameter turntable flush with the floor of the working section was calibrated and used to measure drag in the direction of the airflow. Drag measurements for each model were taken at several air speeds up to the maximum possible, to establish that the model was in the range where drag coefficient was independent of Reynolds number. The variation of drag with angle of yaw was also measured and the leeward and side frames of the models were removed in stages to determine the shielding factor for each model. Finally the suspension arms were removed from the DC/Top section to determine their equivalent drag coefficient. Complete details of these experiments have been given by Willis (1974)

RESULTS AND DISCUSSION

Drag coefficients for the tower models of square planform, in two-dimensional flow, are shown plotted against solidity ratio in Figs. 5 and 6. Other data collated and corrected for three-dimensional effects by Cohen and Perrin (1957) together with Birjulin's (1960) experimental results for tower sections in two-dimensional flow, are plotted in the same figure. The Draft New Zealand standard (1973) for wind loads on planform towers and the two alternative N.Z.E.D. bases according to McKenzie (1960) of

$$\left.\begin{array}{r}\text{tower wind pressure (P)} = 0.0051\ V^2\\ \text{and tower wind pressure (P)} = 0.0043\ V^2\end{array}\right)\ \text{times a shielding factor of 1.75}$$

are also shown. The New Zealand standard is seen to be 10 to 20 per cent conservative when compared with Cohen and Perrin's fitted curve.

Fig. 7 is a plot of Composite Drag coefficient against Reynolds number for the three DC tower models. The solid lines signifying the limiting Reynolds number for the experiments which are seen to be in the Reynolds number independent range above 2×10^4. All subsequent tests were performed at the maximum Reynolds number possible.

Fig. 8 shows the variation of drag coefficient with wind angle of yaw. The results would suggest that the factor of 1.2, as proposed in the draft New Zealand standard for angles of yaw other than 0^0 is conservative for the lower solidity ratios encountered in N.Z. Electricity Department transmission line towers.

The drag measured for the suspension arms of DC/Top was only about 25 per cent of the value to be expected if they were situated away from the influence of the tower, i.e. C_D for both arms based on the projected area of one arm was 0.67 c.f. $C_D = 2.90$ for a square planform tower section.

Fig. 9 is a plot of shielding factor versus solidity ratio with the experimental values for the 3 D.C. model tower sections plotted and the draft New Zealand standard, Cohen and Perrin curves being included for comparison. The present N.Z. Electricity Department specification for shielding factor is 1.75 (sse Table 1), and this is seen to be on the conservative side for the middle and top sections of the d.c. tower but low for the lower solidity base section. The draft New Zealand standard is seen to be conservative for all three sections.

Wind loads on the two single circuit model tower sections were significantly greater than those predicted by the N.Z. Electricity Department design basis as illustrated by Table 3 and Fig.10.

	N.Z.E.D. DESIGN BASIS	SC/1	SC/2
C_D ($\alpha = 0$)	2.90	4.68	3.99
%	100	161	138
C_D ($\alpha = 15^0$)	2.90	6.52	4.48
%	100	225	155

TABLE 3. Showing comparison between N.Z. Electricity Department design basis and single circuit results.

TABLE 4 Maximum Gust Values from New Zealand Electricity Department Records for the period August 1969 to April 1972*

Tower Identification		Recording Period	August 1969 to April 1970	Sept. 1970 to March 1971	May 1971 to April* 1972	Maximum Gust (m.p.h.)	Calibration Adjusted Maximum Gust m.p.h. (m/sec.)
			All recordings given in m.p.h.				
B-H	Timaru Area	177	65	120+	120+	120+	105+ (46.9+)
		190	120+	120+	110	120+	105+ (46.9+)
		204	120+	95	110	120+	105+ (46.9+)
		297	55	70	100	100	92 (41.1)
		370	100	120+	100	120+	105+ (46.9+)
		456	60	100	90	100	92 (41.1)
		522	90	90	-	90	83 (37.1)
		547	-	-	90	90	83 (37.1)
		944	80	80	100	100	92 (41.1)
	Hanmer Area	983	105	120+	120+	120+	105+ (46.9+)
		1129	98	80	120+	120+	105+ (46.9+)
		1159	120	120+	120+	120+	105+ (46.9+)
I-K	Hanmer Area	259	-	100	100	100	92 (41.1)
		305	55	60	85	85	80 (35.8)
		Depot	120	100	110	120	105 (46.9)
		339	75	110	115	115	100 (44.7)
		456	70	77	85	85	80 (35.8)
		494	65	70	80	80	76 (34.0)
I-T	All in Timaru Area	5	35	90	-	90	83 (37.1)
		154	60	90	40	90	83 (37.1)
		197	-	-	70	70	65 (29.0)
		212	120+	-	-	120+	105+ (46.9+)
		222	-	-	90	90	83 (37.1)
		224	100+	100	-	100+	92+ (41.1+)
		234	100	-	80	100	92 (41.1)
		235	65	-	-	65	60 (26.8)
		333	60	95	-	95	87 (38.9)
		334	-	-	120+	120+	105+ (46.9+)
		398	-	-	70	70	65 (29.0)

KEY: Read - to mean not reset during that period

Read B-H to mean Benmore-Hayward 500 kV DC Line

Read I-K to mean Islington-Kikiwa 220 kV Line

Read I-T tc mean Islington-Twizel 220 kV Line

* Records for August 1969 to March 1972 for Timaru Area

As these sections are specialised shapes, no general information was available from the literature with which to compare the results. However, for airflow normal to A_1 it is possible to treat SC/Middle as having four faces, considering a shielding factor to apply to each face. This computation yielded values of the front face C_D and shielding factors that were found to be lower than would normally be predicted for the given solidity ratio. The conclusion being, that if an overall C_D was derived from the draft New Zealand standard on this basis, the wind load would be overestimated.

MAXIMUM GUST DATA

The integrity of a transmission line and tower depends not only on the designer's ability to predict drag coefficient and shielding factor, but also to predict the maximum gust that the structure is likely to meet in its lifetime. In general, the designer of any structure must rely on a gust contour map such as that produced by de Lisle (1965) and shown in Fig. 1. He uses this to determine the maximum gust the structure is likely to see in a period of 50 years. The contour lines of Fig. 1 are necessarily extrapolated from observations of a limited number of Meteorological Service observation stations, which are usually located in the vicinity of towns and cities. Unfortunately the transmission line is often constructed in areas where no wind data has ever been collected, and in regions where, because of topographical effects, the wind velocities are much higher than those recorded in the towns. The N.Z. Electricity Department has endeavoured to supplement the Meteorological Service data by maintaining more than thirty maximum gust recorders in the Canterbury - North Otago district. The locations of these recorders is shown in Fig. 11; data from them has been collected since 1969. The gust recorder consists of a pressure plate acting against a spring with a slider behind the pressure plate recording the maximum gust occurring in a given period (i.e. since it was last reset). Two such recorders have been calibrated (by the Aeronautical Research Laboratories, Melbourne, Australia) in a wind tunnel at velocities up to 80 m/s (180 m.p.h.) A typical calibration curve is given in Fig. 12 taken from N.Z. Electricity Department files (1969). The calibrations showed that the recording slide crept back under pressure of the wind at indicated wind speeds in excess of 54m/sec. (120 m.p.h.) and that the wind speed is overestimated at speeds above 34 m/sec. (76 m.p.h.)

COMPARISON WITH BASIC WIND SPEEDS GIVEN IN THE DRAFT N.Z. STANDARD

Calibration corrected, yearly maximum gust readings from the recorders for the period 1969-72 are shown in Table 4. The maximum reliable indicated wind speed of 120 m.p.h. when adjusted for instrument calibration gives a maximum reliable true speed of 47 m sec^{-1} (105 m.p.h.). Readings over this value are suffixed with a + sign.

A maximum gust with a 50 year return period cannot be determined from this gust recorder data because:

a) normally a 10 year recording period is required. (see de Lisle, 1965);
b) of unreliable gust recorder readings in the high wind speed range.

However, it is reasonable to expect the maximum gust recordings shown in Table 4 to be generally below the level of a five year return period gust, and considerably below the level of a 50 year return period gust. An indication of the difference between a five year and 50 year return period maximum gust is given in Fig.13 taken from Shellard (1958, 1963)

The basic 50 year return period maximum gust for the Canterbury area is 40 m sec^{-1} (90 m.p.h.) (Fig. 1). This may be factored, according to the draft N.Z. standard (1973) by 1.2 to account for acceleration of winds over hills and through gullies. This gives a maximum gust value of $40 \times 1.2 = 48$ m sec^{-1} (107 m.p.h.)

Comparing this figure (and remembering that it represents a 50 year return period gust) with the maximum gust data (covering a five year period at most) of Table 4, suggests that, either the maximum wind speeds occurring in remote Canterbury areas are considerably greater than Fig. 1 indicates or that the topographical factor of 1.2 given in the code is too low. It is more likely a combination of both these factors

Whatever the case, it points to the need for caution in using the maximum gust data available until further long term measurements of hourly mean and maximum wind velocities are obtained from open sites.

REFERENCES

Birjulin, A.P., Burgsdorf, V.V. and Makhlin, B.J. 1960: Wind loads on overhead lines, C.I.G.R.E. Paper No. 225.

Bowen, A.J.B. and Lindley, D. 1974 (Dec.): "Measurements of the Mean Wind Flow over Various Escarpment Shapes" 5th Australasian Conference on Hydraulics and Fluid Mechanics, Christchurch, New Zealand.

Cohen, E and Perrin, J. 1957: Design of multilevel guyed towers; wind loading, Journ. Struct. Div. Proc. Amer. Soc. Civil Eng., ST5, Paper 1355

Davis, D.A., Richards, D.J.W. and Scriven, R.A. 1963(Jan.) "Investigation of Conductor Oscillation on the 275kV crossing over the Rivers Severn and Wye", Proc. I.E.E. vol.110 No.1.

de Lisle, J.F. 1965: Extreme Surface Winds in New Zealand" N.Z. Journ. of Sci. 8, pp 422-430.

Dickens, T.A. 1965: "A Direct Current Transmission Line", N.Z. Engineering, April, pp 121-130.

Mckenzie, E.B. 1960: "Transmission Line Mechanical Design" N.Z. Engineering, October.

N.Z. Standard 1973: "Explanatory Notes on the Draft N.Z. Standard Code of Practice for General Structural Design" Part 3: Wind Loadings, DZ 4203/303N/1973.

N.Z. Electricity Department 1969: "N.Z.E.D. Christchurch District Office Files" 29/8/1 and 29/8/2.

Sachs, P. 1972: "Wind Forces in Engineering" Pergamon Press.

Shellard, H.C. 1958: "Extreme Wind Speeds over Great Britain and Northern Ireland", Meteor. Mag. vol 87 p 257

—"— 1963 (June): "The Estimation of Design Wind Speeds", Symposium on "Wind Effects on Buildings and Structures" National Physical Laboratory, U.K.

Stevenson, D.C. 1968: "The University of Canterbury Wind Tunnel' N.Z. Engineering, 15 Oct., pp 403-407.

Stodhart, A.H. 1973 (Dec.) "Wind Data for Wind Driven Plant" Wind Energy Conversion Systems Workshop Proceedings N.S.F./R.A./W-73-006 N.S.F./ N.A.S.A. Washington D.C., U.S.A.

Willis, D.J. 1974: "Transmission Line Wind Loads at Extreme Wind Speeds" M.E. Thesis, University of Canterbury, Christchurch, New Zealand, Feb.

NOTATION

A	Projected surface area of model face
A_1	Projected surface area of tower face which is normal to the airflow perpendicular to the conductor line.
A_2	Projected surface area of the tower face adjacent to A_1
C_D	Drag coefficient = $\frac{D}{qA_1}$
D	Drag
d	Angle flange dimension
Re	Reynolds number based on the leg angle flange dimension = $\frac{Vd}{\nu}$
S	Shadow area of plane model
V	Free steam velocity
q	Dynamic pressure of free stream = $1/2\ \rho V^2$
ϕ	Solidity ratio of model = A/S
η	Shielding factor = ratio of tower drag to tower front face drag
ρ	Fluid Density
ν	Kinematic viscosity of fluid

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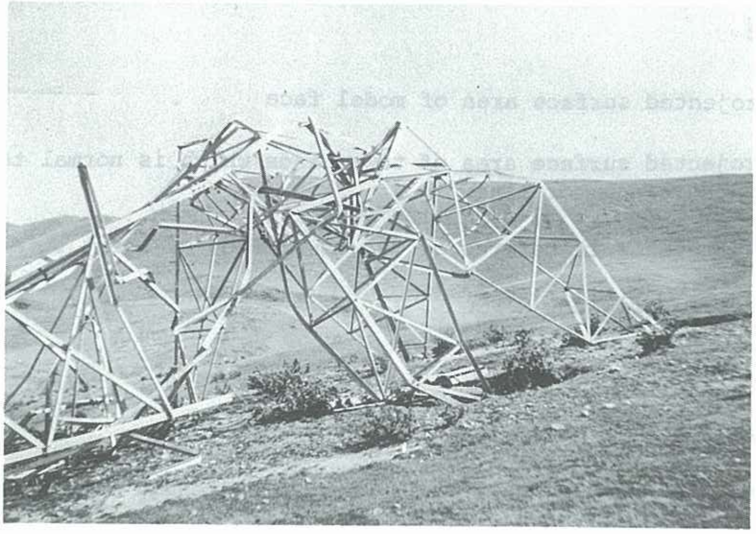


FIGURE 2 TOWER DAMAGED BY EXCESSIVE WIND LOADS ON TOWER AND CONDUCTORS

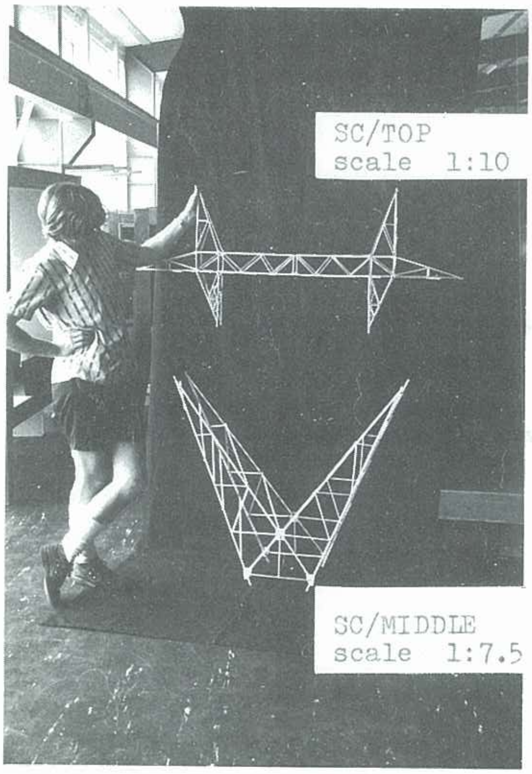


FIGURE 3 SINGLE CIRCUIT 220kV MODEL TOWER

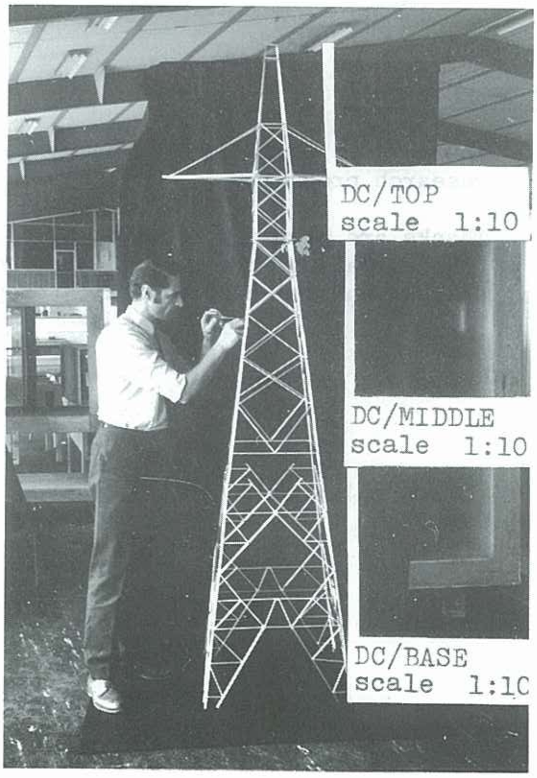


FIGURE 4 500kV D.C. MODEL TOWER

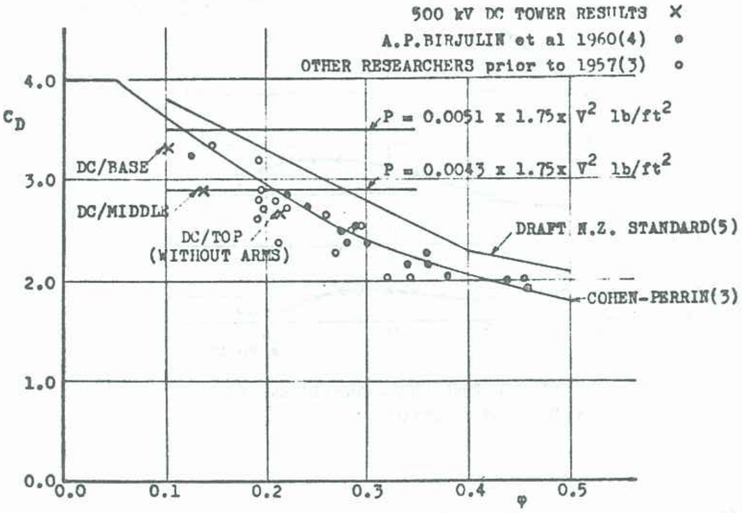


FIGURE 5 COMPOSITE TOWER DRAG COEFFICIENT VS SOLIDITY RATIO

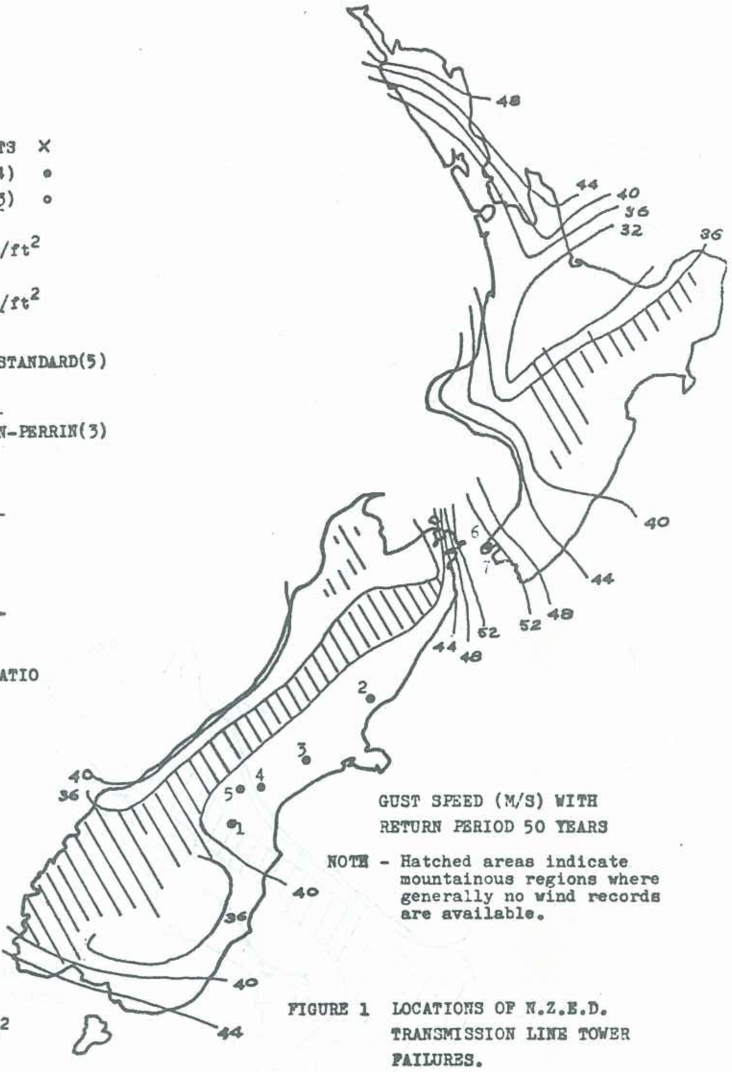


FIGURE 1 LOCATIONS OF N.Z.E.D. TRANSMISSION LINE TOWER FAILURES.

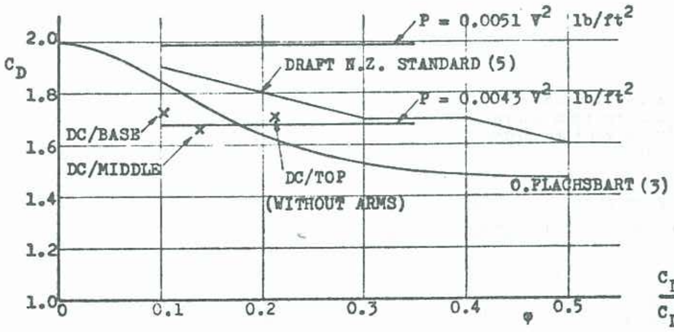


FIGURE 6 TOWER FRONT FACE DRAG COEFFICIENT VS SOLIDITY RATIO

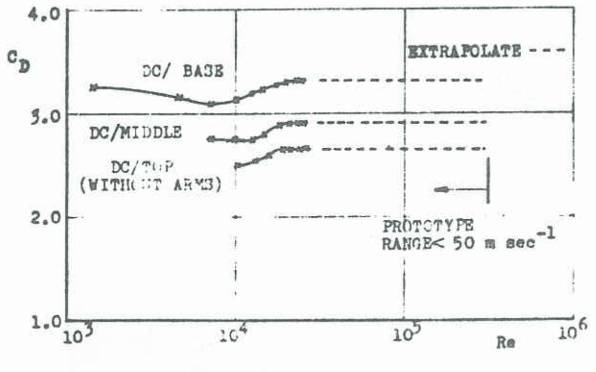


FIGURE 7 COMPOSITE DRAG COEFFICIENT VS REYNOLDS NUMBER

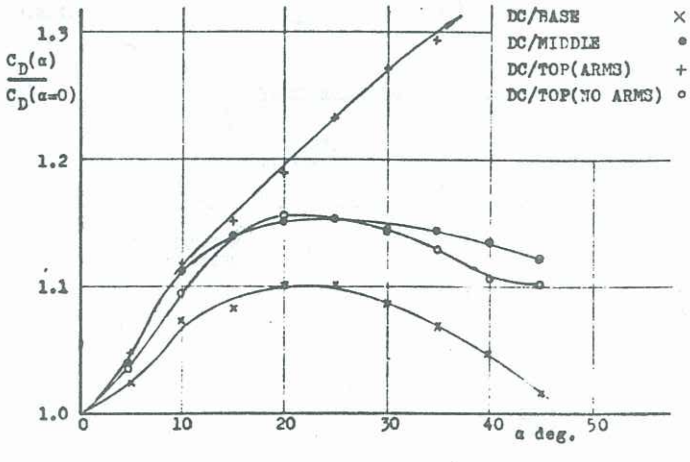


FIGURE 8 RELATIVE COMPOSITE DRAG COEFFICIENT VS WIND ANGLE OF ATTACK

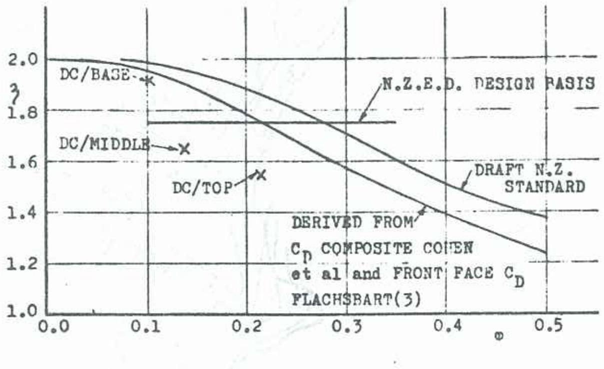


FIGURE 9 SHIELDING FACTOR VS SOLIDITY RATIO

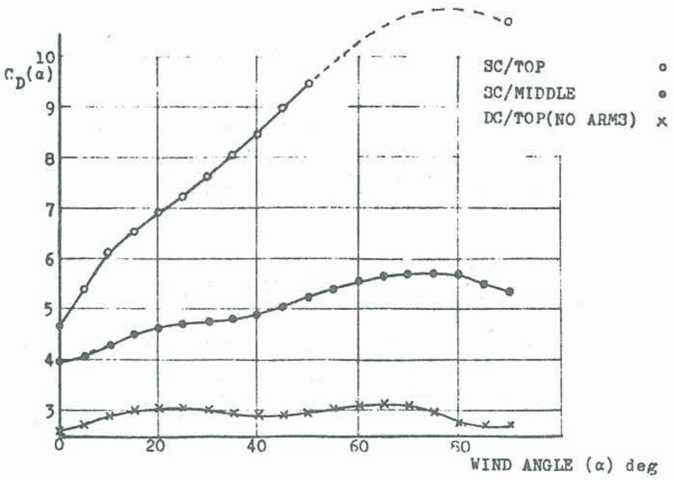
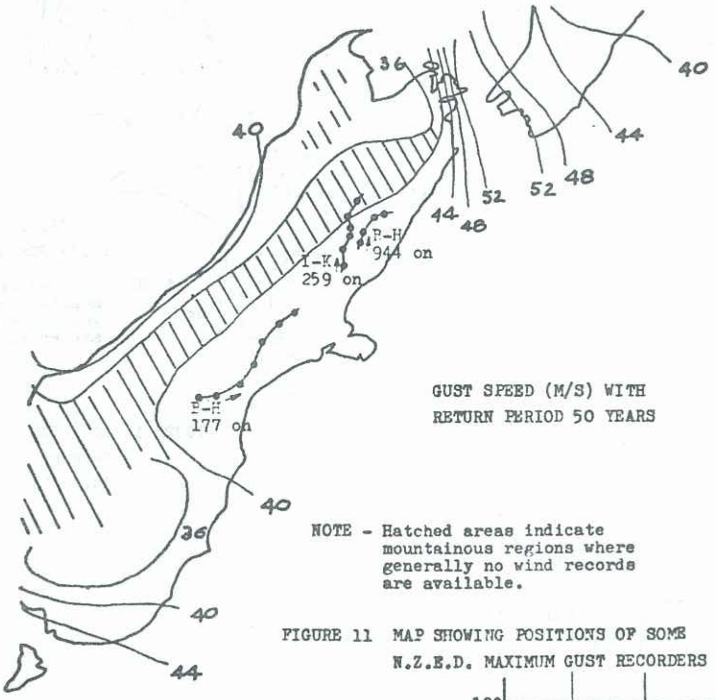


FIGURE 10 COMPOSITE TOWER DRAG COEFFICIENT VS WIND ANGLE OF ATTACK



NOTE - Hatched areas indicate mountainous regions where generally no wind records are available.

FIGURE 11 MAP SHOWING POSITIONS OF SOME N.Z.E.D. MAXIMUM GUST RECORDERS

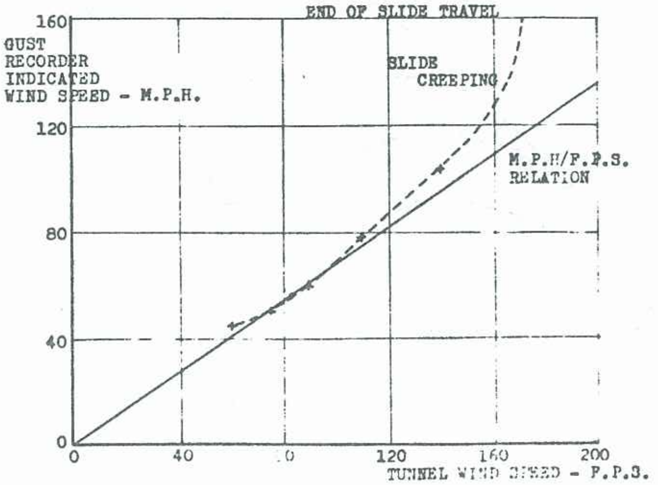


FIGURE 12 GUST RECORDER CALIBRATION

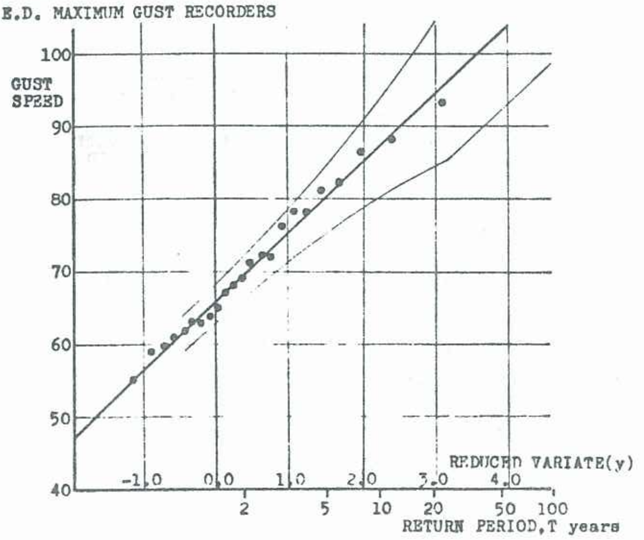


FIGURE 13 STATISTICAL ANALYSIS OF LONG TERM WIND SPEED RECORDS TO DETERMINE THE REQUIRED RETURN PERIOD FOR A GIVEN MAXIMUM GUST