HAWAII DEEP WATER CABLE PROGRAM

PHASE II

CABLE CATENARY STUDY

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CABLE CATENARY STUDY

Prepared by

Pirelli Cable Corporation
and
Societa Cavi Pirelli

Prepared for

The Ralph M. Parsons Company,
Hawaiian Electric Co., Inc.
and the
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CABLE "CATENARY" STUDY

INTRODUCTION

The "catenary" study for the Hawaii Deep Water Cable (HDWC) Program is applicable to the environmental conditions that Cable No. 116 will experience at the bottom of the Alenuihaha Channel. Based on the present limited knowledge of the bottom surface, the possibility that the cable may be supported off the ground by an outcrop or may hang between two outcrops or barrier reefs must be considered. Under these conditions, the cable will be subjected to the following:

- Forming itself into a curved configuration of relatively small radius on the supporting outcrop(s)
- Low frequency alternate lateral displacements due to tidal currents
- High frequency vibrations in the vertical plane due to vortex shedding phenomenon

The first condition may damage the cable during the deployment operation. The second and third occurrences may cause damage to the cable during its life due to mechanical fatigue of the lead sheath (1).

This study is divided into two parts. The first part addresses itself to the bending radius of the cable in its rod-like curvature on the outcrops of the bottom. The second part relates to the mechanical fatigue life of the lead sheath when the cable is subjected to the action of the water currents producing the above mentioned cable movements.

This study has been performed using the following main cable characteristics:

- Static flexural rigidity - EJs
- Dynamic flexural rigidity - EJ_d
- Cable bottom tension - To

In order to derive approximate limiting conditions for Cable No. 116, considering the present lack of experimental data on the mechanical characteristics of this cable, the mechanical characteristics measured on the Messina and Vancouver cables have been utilized in this study. Table 1 lists these mechanical characteristics and other parameters utilized in the calculations. The actual limiting conditions applicable to Cable No. 116 can be readily calculated when the mechanical characteristics for this cable have been determined.

This study makes reference to the speeds of the water currents surveyed in the Channel in (4).

CONCLUSIONS

The following conclusions of the "catenary" study are based upon the use of cable mechanical characteristics, identified in Table 1, for the previously manufactured and tested Messina and Vancouver cables. The maximum height of outcrop and span lengths applicable to Cable No. 116 will be calculated after this cable has been manufactured and its mechanical characteristics determined. It is anticipated that the values for Cable No. 116 will not be significantly different than indicated herein:

In order to observe the minimum permissible bending radius of 1.5 m:

- The maximum height (h) of outcrop or other bottom irregularity to which the cable can be subjected without damage is 4 m (13.1 ft)
- The critical (longest) span length (L) for a bottom tension (To) of 3000 kg (6600 lb) under static conditions is 60 m (196.8 ft)

In order to have a duration of life of 30 years:

- The critical span length for a bottom tension (To) of 3000 kg (6600 lb) with the cable subjected to oscillations due to tidal currents is 40 m (131 ft)
- The critical span length for a bottom tension (To) of 3000 kg (6600 lb) with the cable subjected to vibrations due to vortex shedding is practically infinite, i.e. the cable does not vibrate.

Based on the above conclusions, the following observations can be made:

- The bending radius of the suspended cable due to a single outcrop or other bottom irregularity is a controlling factor
- The critical span length for the cable subjected to oscillations due to tidal currents is more restrictive than the critical span length due to vortex shedding vibrations and the critical span length under static conditions.

PART I

STATIC BEHAVIOR OF THE CABLE

The purpose of this part of the study is to investigate the bending radius of the cable when suspended in a rod-like curvature on the outcrops of the bottom. Referring to the situation shown in Figure 1, the geometrical configuration of the cable may be described by the following formulae: (2)

$$h = \frac{WL^2}{2To} - \frac{WL}{To\sqrt{\frac{To}{EJ_s}}} \qquad (1)$$

$$R = \frac{To}{W\left(1-\sqrt{\frac{To}{EJ_s}} \cdot L\right)} \qquad (2)$$

Where:

EJs = static flexural rigidity
W = cable weight in water
To = bottom tension of the cable
L = span length
h = height of outcrop or surface irregularity

For the practical range of values of static rigidity and bottom tension for this type submarine cable, the second term in (1) can be disregarded. Assuming moreover that $\sqrt{\frac{To}{EJ_s}} \cdot L >> 1$,

(which applies for L greater than a few meters) formulae (1) and (2) can be combined to yield formula (3):

$$|R| = \sqrt{\frac{EJ_s}{2hw}} \qquad (3)$$

R is therefore independent of the bottom tension.

Figure 2 is a plot of cable bending radius R at the point of contact with an outcrop as a function of height of outcrop and static flexural rigidity. Using this figure, it is possible to obtain the maximum permissible height of outcrop at the minimum bending radius of the cable at different static flexural rigidity values. Table 2 lists the maximum heights read from Figure 2 in correspondence with the minimum bending radius of 1.5 m (5.0 ft). The minimum bending radius of 1.5 m (5.0 ft) for the Messina and Vancouver cables applies to a single bend of the cable under typical bottom tension values.

Another possible bottom surface condition can exist where, for example, the cable will be supported in a free span by two outcrops or where it is necessary to cross a channel between barrier reefs. Such a situation is shown in Figure 3. Equations (1) and (2) are valid for this situation with the substitution of L/2 for L where L is now the distance between the two support points and h is the sag. The following formulae can be applied to this situation:

$$h = \frac{WL^2}{8To} \tag{4}$$

$$\bar{R} = \frac{To}{W(1-\sqrt{\frac{To}{EJ_s}} \cdot \frac{L}{2})} \tag{5}$$

where the second term of (1) has been disregarded

Figures 4, 5 and 6 show the bending radius R as a function of the span length L for three different values of static flexural rigidity calculated in accordance with the above formulae. From these figures it is possible to obtain the maximum span length at the minimum permissible bending radius. These values are also listed in Table 3. Figure 7 shows the value of the sag h formed by the cable as a function of span length L and bottom tension To.

Employing the mechanical characteristics of the Messina and Vancouver cables, the constraints with regard to the capability of the cable to hang between two outcrops or to cross channels can be determined. Therefore, assuming a static flexural rigidity EJs = 500 kg.m^2 (11,834 lb.ft^2) and a minimum bending radius R = 1.5 m (5.0 ft), as shown in Table 1, and employing Figures 2, 4, 5 and 6 or with Tables 2 and 3, the following results are obtained:

- maximum permissible height of outcrop, h = 4 m(13.1 ft)
- maximum permissible span length at To = 3000 kg(6600 ft), L=60m(1968 ft)

These constraints are considered to be limiting when compared with the heights of outcrops and span lengths of reef channels detected on the bottom. (3) Therefore the bending radius appears to a controlling parameter in the "catenary" study.

TABLE 1

CABLE CHARACTERISTICS AND PARAMETERS FOR MESSINA AND VANCOUVER CABLES

Static Flexural Rigidity	EJ_s	500 kg-m^2(11,834 lb-ft^2)
Dynamic Flexural Rigidity	EJ_d	25,000 kg-m^2(591,712 lb-ft^2)
Bottom Tension	To	500-5000 kg(1,100-11,000 lb)
Minimum Bending Radius	R	1.5 m*(5.0 ft)
Intrinsic Mechanical Damping	r/r_c	0.06
Drag Coefficient	C_d	1.2
Ratio of Bottom to Surface Current Velocity	S_r	1/3
Equivalent Mass Coefficient	Ceq	2

* This value applies to a single bend of the cable under typical bottom tensions.

TABLE 2

MAXIMUM PERMISSIBLE HEIGHT OF OUTCROP FOR A MINIMUM BENDING RADIUS OF 1.5 m UNDER STATIC CONDITION [1]

MINIMUM BENDING RADIUS R (m)	STATIC FLEXURAL RIGIDITY EJs ($kg-m^2$)($lb-ft^2$)	OUTCROP HEIGHT h (m) (ft.)
	500(11,834 $lb-ft^2$)	4(13.1 ft)
1.5(5.0 ft)	1000(23,668 $lb-ft^2$)	8(26.2 ft)
	1500(35,503 $lb-ft^2$)	12(39.3 ft)

[1] Refer to Figures 1 and 2.

TABLE 3

TABULATION OF CRITICAL SPAN LENGTHS

FOR A MINIMUM BENDING RADIUS OF 1.5 m

UNDER STATIC CONDITION [1]

MINIMUM BENDING RADIUS R (m)	STATIC FLEXURAL RIGIDITY EJs $(kg\text{-}m^2)$ $(lb\text{-}ft^2)$	BOTTOM TENSION T (kg) (lb)	SPAN LENGTH L (m) (ft)
1.5(5.0 ft)	500(11,834 $lb\text{-}ft^2$)	500(1100 lb) 3000(6600 lb) 5000(11,000 lb) 10,000(22,000 lb)	25(82 ft) 60(196.8 ft) 78(255.8 ft) 110(360.8 ft)
1.5(5.0 ft)	1000(23,668 $lb\text{-}ft^2$)	500(1100 lb) 3000(6600 lb) 5000(11,000 lb) 10,000(22,000 lb)	35(114.8 ft) 86(282.1 ft) 110(360.8 ft) 156(511.7 ft)
1.5(5.0 ft)	1500(35,503 $lb\text{-}ft^2$)	500(1100 lb) 3000(6600 lb) 5000(11,000 lb) 10,000(22,000 lb)	43(141 ft) 105(344.4 ft) 135(442.8 ft) 191(626.5 ft)

1 Refer to Figures 3, 4, 5 & 6

PART 2

DYNAMIC BEHAVIOR OF THE CABLE

The dynamic behavior of the cable can be categorized by two distinct phenomena, namely:

- Low frequency oscillations (2 cycles per day) due to tidal currents

- High frequency vibrations (>1 Hz) due to vortex shedding

These phenomena are responsible for fatigue of the lead sheath of the cable during its life with eventual critical damage. In this regard, the lead sheath is the weakest component of the cable.

The first phenomena, i.e. oscillations due to tidal currents, causes lateral displacements of the cable while the second phenomena, i.e. vibrations due to vortex shedding, generates vibrations in the cable in the vertical plane. Since the lead sheath deformations due to the two phenomena occur in two different planes, as a first approximation, it is possible to separately consider the two phenomena without superimposing their respective stresses.

This study refers to a rodlike cable curve which is suspended on two adjacent obstacles at the same or at different height (see Fig. 8). In fact, the strains due to the two phenomena are almost independent of the static configuration of the cable.

The tension To on the cable does not appreciably change during the vibrations and oscillations.

In order to evaluate the expected damage of the lead sheath due to each phenomenon, two statistic variables must be taken into consideration:

1) the number of cycles to breakage of the lead sheath

2) the probabilistic distribution of the current speeds at the channel bottom

According to Pirelli laboratory measurements, the number of cycles to breakage of the lead sheath is given by a hyperbolic law (7).

$$N_b = Na \cdot f^{1/3} \left[\sinh \frac{4.65 \times 10^{-3}}{\Delta\varepsilon} \right]^{1.27}$$

where at the 95% confidence level, Na = 630, f is the oscillation or vibration frequency in cycles per hour and $\Delta\varepsilon$ is the strain variation due to a complete vibration or oscillation cycle (peak to peak amplitude).

With regard to Item 2 above, the current speeds to be estimated are in accordance with the following:

Tidal Current Speeds

The maximum current speed in each quarter of the tidal cycle (the horizontal to and fro tidal current corresponds to alternating cycles of rising and falling of the ocean surface). More precisely, the distribution of the square of the maximum current speeds has been considered since the force applied to the cable by the tidal current depends on the square of the speed. This force has been assumed as the correct operational random variable.

Vortex Shedding Speeds

The daily current speed distribution, represents all of the current speeds appearing during a representative day of the life of the lead sheath.

In order to evaluate the two distributions, the data collected in report (4) in the tables of "maximum daily speeds" and "distribution frequency", respectively, have been used.

Only the current speed directions across the cable line have been considered in the "distribution frequency" tables. Said directions are 30-90 and 210-270 true degrees. The values of current speeds refer to a water depth of 10.7 m (35 ft). Since tidal oscillations and vortex shedding vibrations depend on bottom current speeds in the proximity of the cable span, it is common practice (2) to refer these current speeds to that near the surface of the sea i.e. a ratio of Vb/Vs. This is due to the following reasons:

- The current speeds near the sea surface are easily measureable and they are reported in many nautical tables.

- The bottom current speeds are strongly influenced by the sea bottom configuration which may be assumed as a constant characteristic for relatively large areas. A few measurements can be used to characterize the ratio of Vb/Vs due to sea botton configuration.

From the data collected in report (5) Section 5, it appeared that the ratio of Vb/Vs might be in the order of 1/3 (26 cm/sec) (0.5 knots) at the bottom compared to 78 cm/sec (1.5 kts) at the surface. From an analogous survey conducted in the Messina Strait the same ratio was observed. However, recent surveys of bottom current speeds indicate that the ratio of bottom current speed to surface current speed, Vb/Vs is in the order of 0.40.

Several different speed distributions were considered in the present study for each phenomenon. The first one is related to the surveyed current speeds at a water depth of 10.7 m (35 ft.). Data plotted in Figures 13, 14 & 15 for tidal current oscillations and Figures 18, 19 and 20 for vortex shedding vibration are for the surface speed and for bottom speeds of 1/2 and 1/3 of the surface speed, respectfully. The calculated data in Tables 4 and 5 also include ratios of Vb/Vs of 1/1.5 and 1/2.5.

Figures 9, 10, 11 and 12 show the probabilistic distributions obtained from the collected data by using the Weibull statistics.

Figure 9 refers to the cumulative distribution of the daily speed.
Figure 10 refers to the density of probability distribution of the daily speed.

The average daily speed is V = 37.5 cm/sec (0.75 kts) (See Figures 10 and 11).

Figure 11 shows the cumulative distribution of Δv^2 (proportional to the total force applied by the current) and finally Figure 12 shows the density of probability distribution of Δv^2.

The average total force per unit of cable length is F=7 kg/m (4.7 lb/ft) (see Figures 10 and 11 and Formula 8).

The cumulative distributions shown in Figures 9 and 11 represent the probability that the random variable falls into a given range of values. As an example, from Figure 9 the daily speed is less than 12 cm/sec (0.2 kts) in 10% of the cases. The area under the probability density distribution curve represents the probability that the speed belongs to a suitable range of values. Referring to the same example shown above, from Figure 10 the daily speed is less than 12 cm/sec(0.2 kts) in 0.0166 x 12/2 x 100 = 10% of the cases.

Note that the reduction of the speeds by a constant factor leaves the shape of the speed distribution unchanged.

FATIGUE DUE TO TIDAL CURRENT OSCILLATIONS

Referring to the configuration shown in Figure 8, the strain variation of the lead sheath due to two successive lateral displacements of the cable can be calculated with the following formulae:

$$\Delta\varepsilon = \frac{Ds}{2} \cdot \frac{F}{To} \left(1 - \sqrt{\frac{To}{EJ_s}} \cdot \frac{L}{2}\right) \qquad (7)$$

$$F = \frac{1}{2}\rho \cdot C_d \cdot D \cdot \Delta v^2 \qquad (8)$$

where:

F = total force per unit length of the cable during the 12 hours of a tidal cycle

D_s = lead sheath diameter

ρ = water density

D = overall diameter of the cable

$\Delta v^2 = v_t^2 + v_f^2$ is the sum of the square maximum current speeds in each quarter of cycle of the tide, v_t and v_f are the to-and-fro current speeds

C_d = drag coefficient (see Table 1)

The other symbols have the meaning indicated previously.

By using the total square speed distribution shown in Figures 11 and 12, it is possible to calculate the expected force due to the water current (Equation 8) and the expected strain variation of the lead sheath (Equation 7).

The expected strain variation of the lead sheath permits the evaluation of the number of cycles at cracking of the lead sheath and consequently its life duration considering the frequency of the tidal currents at 2 cycles/day. Refer to Figure 22 for number of cycles to failure as a function of cyclic strain change. This figure shows the number of cycles to failure for the lead sheath as a power law function, employed in the previous report, and as a hyperbolic function employed in the most recent investigation.

Figures 13, 14 and 15 show the critical span length of the suspended cable as a function of static flexural rigidity EJ_s and bottom tension To. These figures refer to the tidal speed at the surface and at 1/2 and 1/3 of said speed, respectively.

The critical spans have been calculated for 30 years of expected life of the lead sheath.

In order to determine a representative value for the critical span length of Cable No. 116 subjected to the tidal oscillations, it is necessary to refer to the mechanical parameters of the Messina and Vancouver cables.

Therefore, by assuming a static flexural rigidity EJ_s = 500 kg.m^2 (11,834 lb.ft^2) and an average bottom tension T_o = 3000 kg (6600 lb), from Figures 13, 14 and 15 and Table 4, the following critical span lengths are obtained:

- bottom speed $v = 1/2\ v_s$ L = 26 m (85.3 ft)
- bottom speed $v = 1/2.5\ v_s$ L = 40 m (131 ft)
- bottom speed $v = 1/3\ v_s$ L = 56 m (184 ft)

where v_s is the current speed at the surface.

Comparision of the data in Figures 13, 14 and 15 and Table 4 indicates that the bottom tension of the cable strongly influences the critical span length for a given ratio of Vb/Vs.

From these results and recent surveys of bottom current speed, the average value of critical span length has been taken as 40 m (131 ft) for the critical span length.

FATIGUE DUE TO VORTEX SHEDDING VIBRATIONS

The vortex shedding phenomenon is strictly related to the concept of boundary layer (still water) which develops around the cable when a continuous water current flows over it in the transverse direction.

Figure 16 shows the cross section of a cable subjected to a continuous water current. The portion of water closest to the surface of the cable adheres to it owing to viscosity forces and surface roughness and forms a still layer around it. This layer grows until its energy exceeds that due to the viscosity forces. At this point, part of the still layer detaches, giving rise to a vortex. The vortices always detach at the same points (S in Figure 16), where they give rise to a depression and consequently to a displacement of the cable in the vertical direction.

When the cable is kept firm, the vortices randomly detach at a frequency f given by the Strouhal formulae:

$$f = 0.2 \frac{v}{D} \tag{9}$$

where: 0.2 = Strouhal coefficient (for a cylindrical body in water)
v = water speed
D = cable overall diameter

If the cable is free to move being suspended in a rodlike curve (Figure 8) and starts to vibrate due to vortex shedding, the vibration synchronizes the shedding of the vortices and the phenomenon becomes self sustaining. Moreover the vibration does not cease even if the speed of the water current changes in a suitable range of values known as the synchronization range (6). The vibration amplitude tends to diminish as the Reynold's number "Re" approaches its critical value of about $2x10^5$ for a smooth cylinder. On the other hand, the critical value depends on the roughness of the cable surface, i.e. it decreases as the roughness increases. The results of extensive experimental work carried out on the occasion of the Messina cable laying and reported in (6) show that the difference between a smooth and rough cable is not important, at least in the range of Reynold's numbers analyzed and close to the numbers of practical interest.

From this experimental work, the maximum energies introduced in the cable by the water current under different conditions were measured and are reported in Figure 17.

Starting from the values of energy introduced by the current and energy dissipated from the cable, the maximum peak-to-peak amplitudes of vibration of the Cable No. 116 have been computed for the whole range of daily speeds previously analyzed and for different suspension span lengths.

From the vibration amplitude, the strain variations and the number of cycles at breakage of the lead sheath (Equation 6) have been computed. The comparison between this number and the number of vibration cycles in a day gives the duration life of the cable. The number of vibrations in a day depends, of course, on the speed distribution (Figures 9 and 10) and on the frequency of vibration of the cable.

The main parameters involved in such evaluation are:

- Overall diameter of the cable
- Diameter of the lead sheath
- Dynamic flexural rigidity of the cable
- Dry weight of the cable

- Equivalent mass coefficient for the evaluation of the mass added to the cable by the mass of the water moved during the vibrations (see Table 1)
- Daily speed probabilistic distribution
- Bottom tension
- Structural intrinsic damping of the cable for the evaluation of the energy dissipated by the cable (see Table 1)
- Fatigue life hyperbolic law (eq. (6))

Figures 18, 19 and 20 indicate critical span length as a function of the dynamic flexural rigidity EJ_d and bottom tension To.

Figure 18 refers to the daily speed distribution sampled at the surface of the water (Figures 9 and 10), while Figures 19 and 20 refer to the same speed reduced by a factor of 1/2 and 1/3, respectively. These critical span lengths have been determined for duration life of 30 years of the cable lead sheath.

As can be seen in Figure 21 showing the life of Cable No. 116 as a function of the situations considered, the critical span length is practically a threshold value between the case of vibrating cable and the case of non vibrating cable.

In order to determine a representative value for the critical span length of Cable No. 116 subjected to the vortex shedding vibrations, it is necessary to refer to the mechanical parameters of the Messina and Vancouver cables. Therefore, by assuming a dynamic flexural rigidity $EJ_d = 25000$ kg.m^2 (591,712 lb.ft^2) (see Table 1) and an average bottom tension To = 3000 kg (6600 lb), from Figures 18, 19 and 20 and Table 5, the following critical span lengths are obtained:

- bottom speed $v = 1/2\ v_s$ L = 26 m (85 ft)
- bottom speed $v = 1/2.5\ v_s$ L is practically infinite, i.e. cable does not vibrate
- bottom speed $v = 1/3\ v_s$ L is practically infinite, i.e. cable does not vibrate

v_s is the current speed at the water surface.

Comparison of the data in Figures 18, 19 and 20 and Table 5 indicates that the bottom tension of the cable strongly influences the critical span length for a given ration of Vb/Vs.

From these results it is apparent that the cable will not vibrate due to the vortex shedding phenomenon at any practical span length.

Comparison of the data in Tables 4 and 5 indicates the controlling phenomena, i.e. oscillations due to tidal current or vibrations due to vortex shedding.

COMPUTER PROGRAM FOR CALCULATING THE CRITICAL SPAN LENGTHS

The critical span lengths for tidal current and vortex shedding phenomena have been computed using a computer program.

Attachment 1 is a list of the results obtained for one of the cases considered, together with the data used.

TABLE 4

TABULATION OF CRITICAL SPAN LENGTHS

UNDER TIDAL CURRENTS

$EJ_s = 500$ kg-m^2

Fatigue life: 30 years
Average total square speed: 0.99 m^2/sec^2 (3.75 knots^2)
Shape distribution parameter: 1.86

Vb/Vs*	Bottom Tension To (kg)						
	1000	2000	3000	5000	6000	8000	10,000
1	5	6	7	8	9	11	12
1/1.5	9.5	12	15	17	20	23	26
1/2	16	21	26	31	36	41	46
1/2.5	24	33	40	47	55	64	71
1/3	34	45	56	77	79	91	102

* Vs = Surface current speed
See Figures 13, 14 and 15

TABLE 5

TABULATION OF CRITICAL SPAN LENGTHS

UNDER VORTEX SHEDDING

$EJ_d = 25{,}000\ kg\text{-}m^2$

Fatigue life: 30 years
Average daily speed: 0.37 m/sec (0.73 knots)
Shape distribution parameter: 1.68

Vb/Vs*	Bottom Tension To (kg)						
	1000	2000	3000	5000	6000	8000	10,000
1	12	12	12	13	13	14	15
1/1.5	15	15	16	18	19	21	23
1/2	19	19	21	26	28	31	35
1/2.5	22	25	(**)	--	--	--	--
1/3	--	--	--	--	--	--	--

* Vs = Surface current speed
See Figures 18, 19 and 20

(**) - Indicates a practically infinite value

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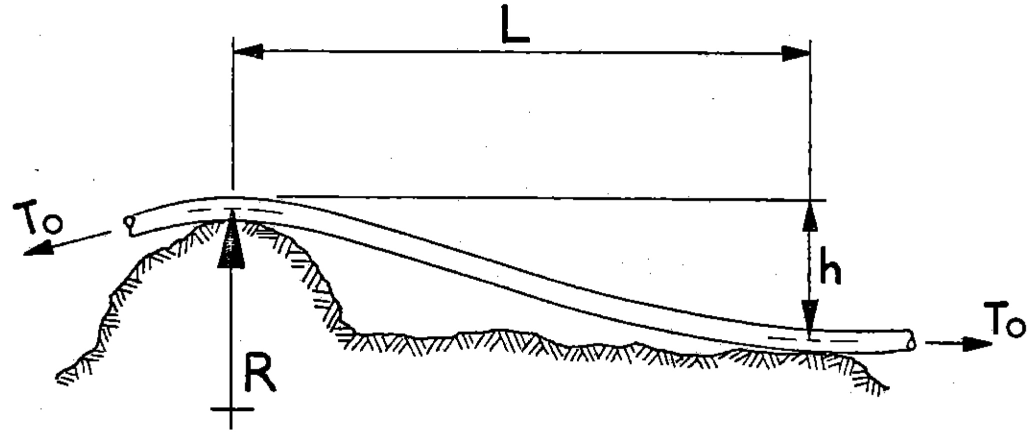

FIG.1 Configuration of Cable Positioned on an Outcrop

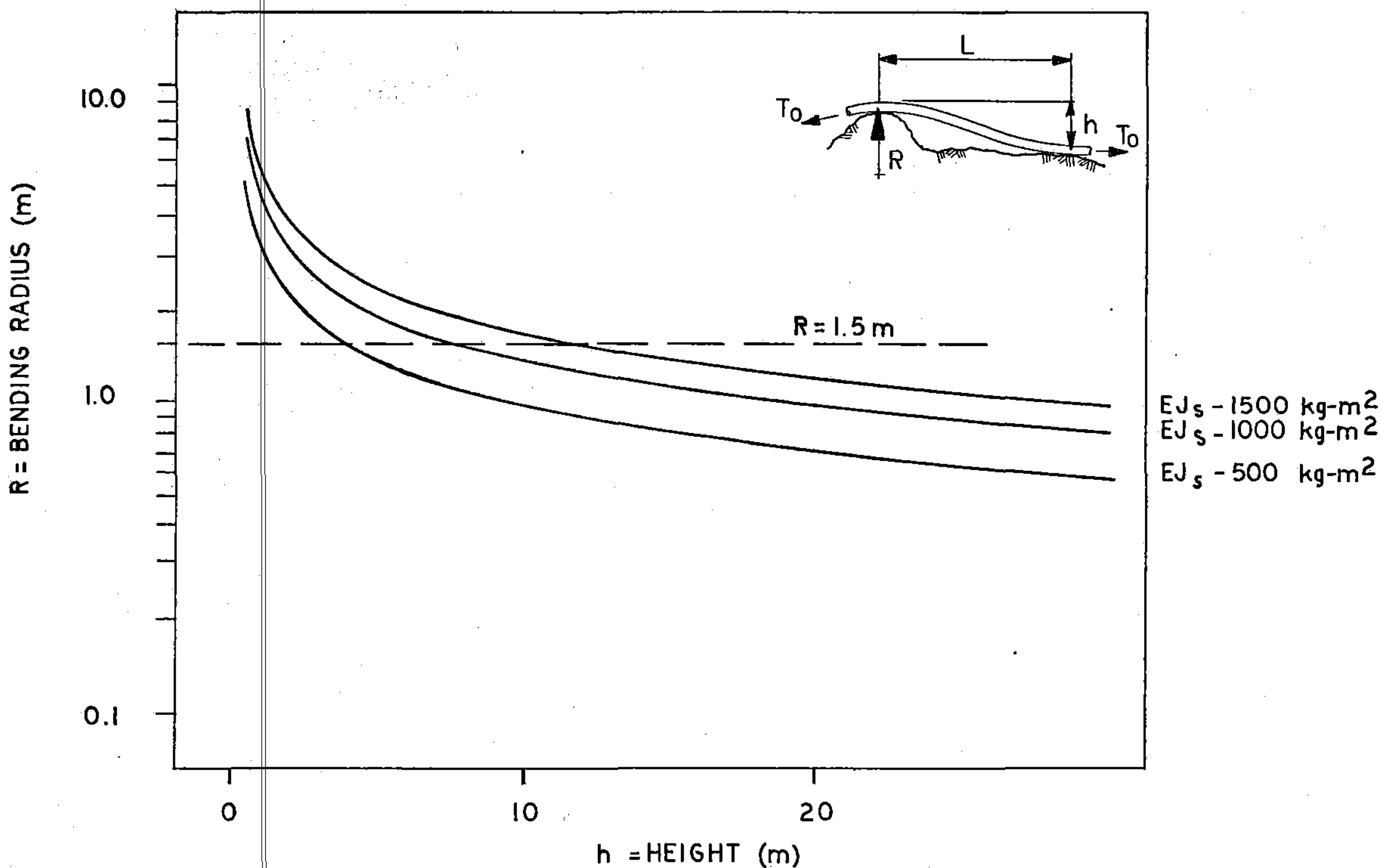

FIG.2 Bending Radius of Cable at Outcrop - Single Support Point

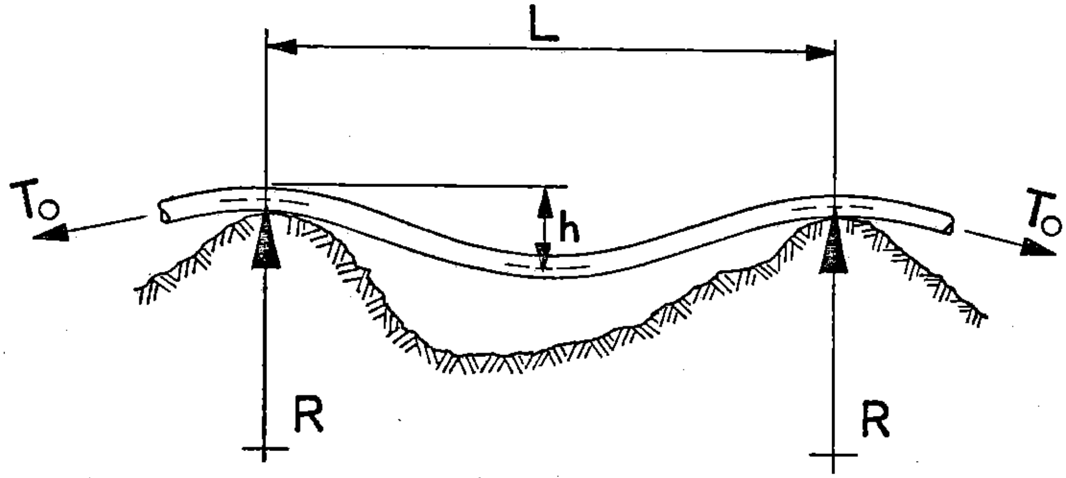

FIG.3 Configuration of Cable Suspended
on Two Outcrops at Same Height

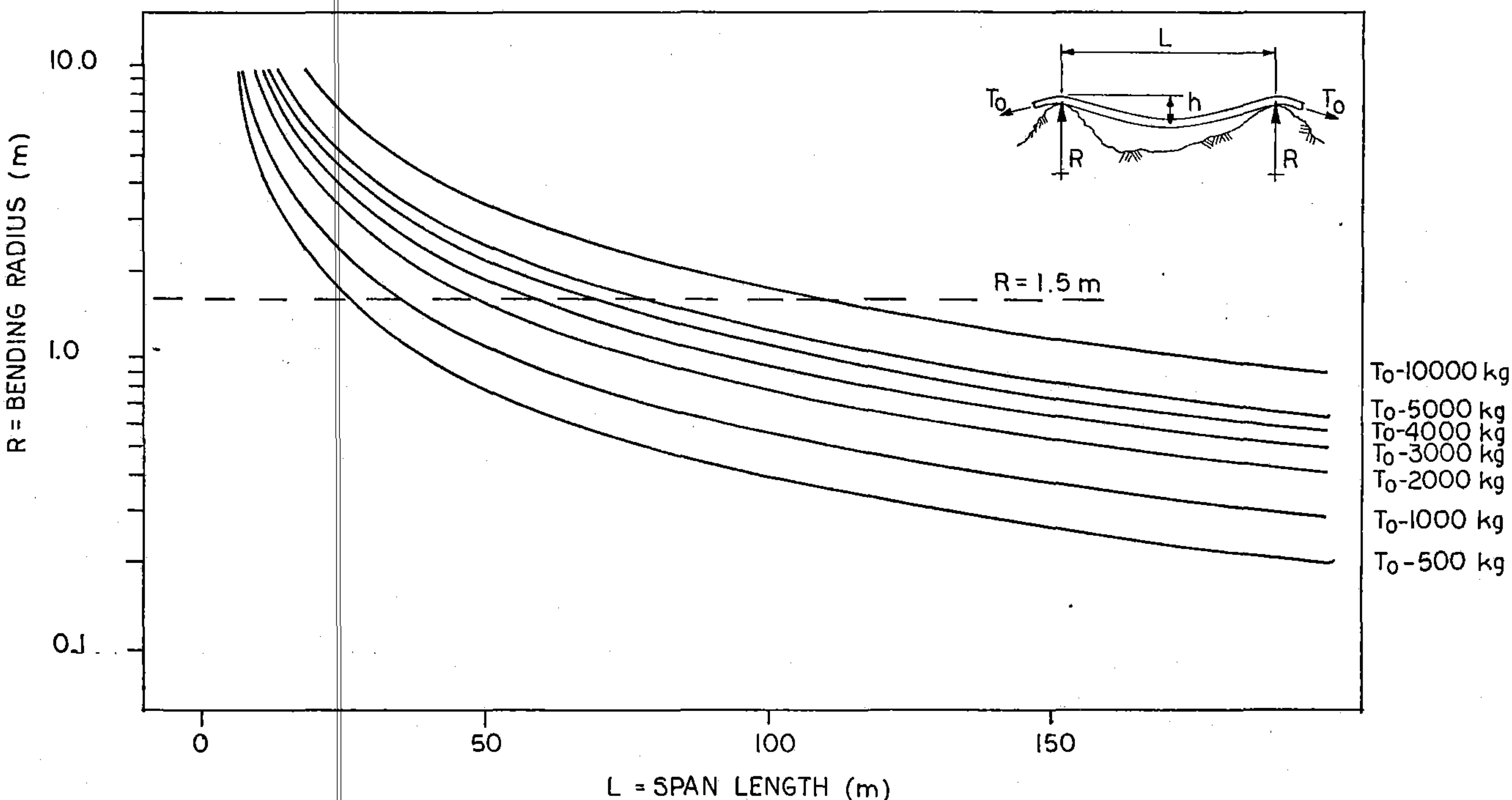

FIG.4 Bending Radius of Cable at Outcrops - Two Support Points
Static Flexural Rigidity EJ_s = 500 kg-m^2

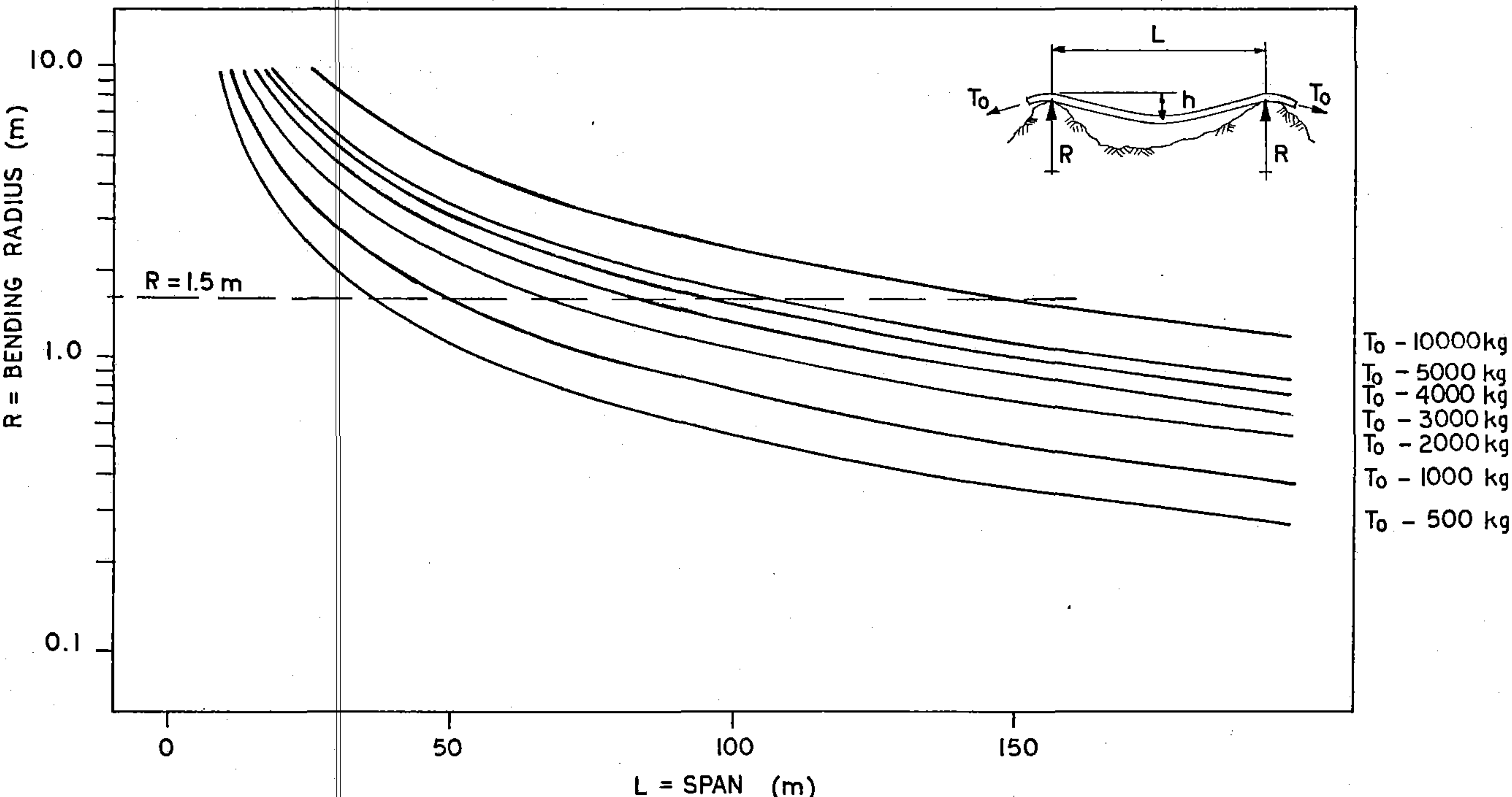

FIG.5 Bending Radius of Cable at Outcrops - Two Support Points
Static Flexural Rigidity $EJ_s = 1000$ kg-m^2

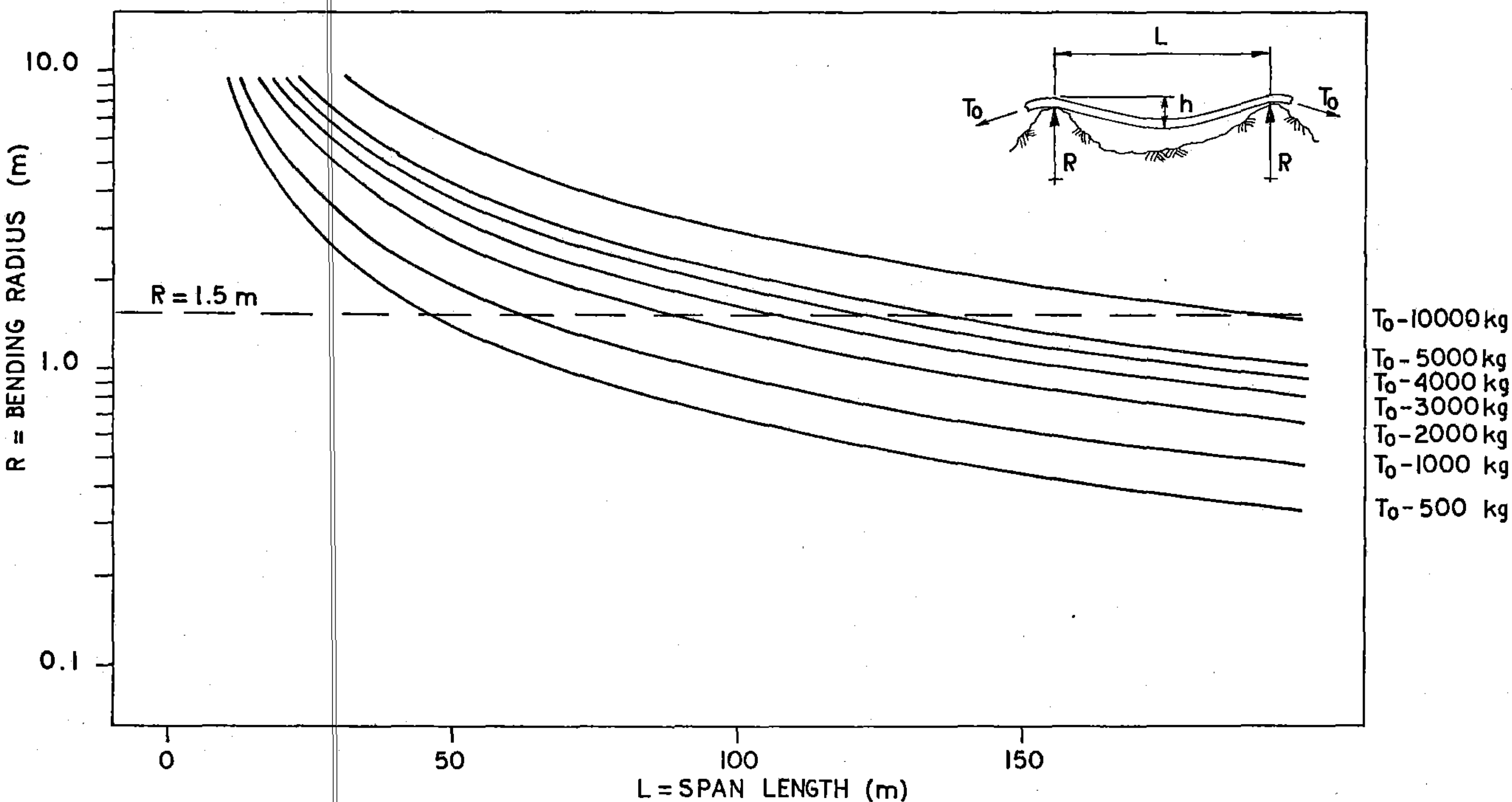

FIG. 6 Bending Radius of Cable at Outcrops - Two Support Points
Static Flexural Rigidity $EJ_s = 1500$ kg-m^2

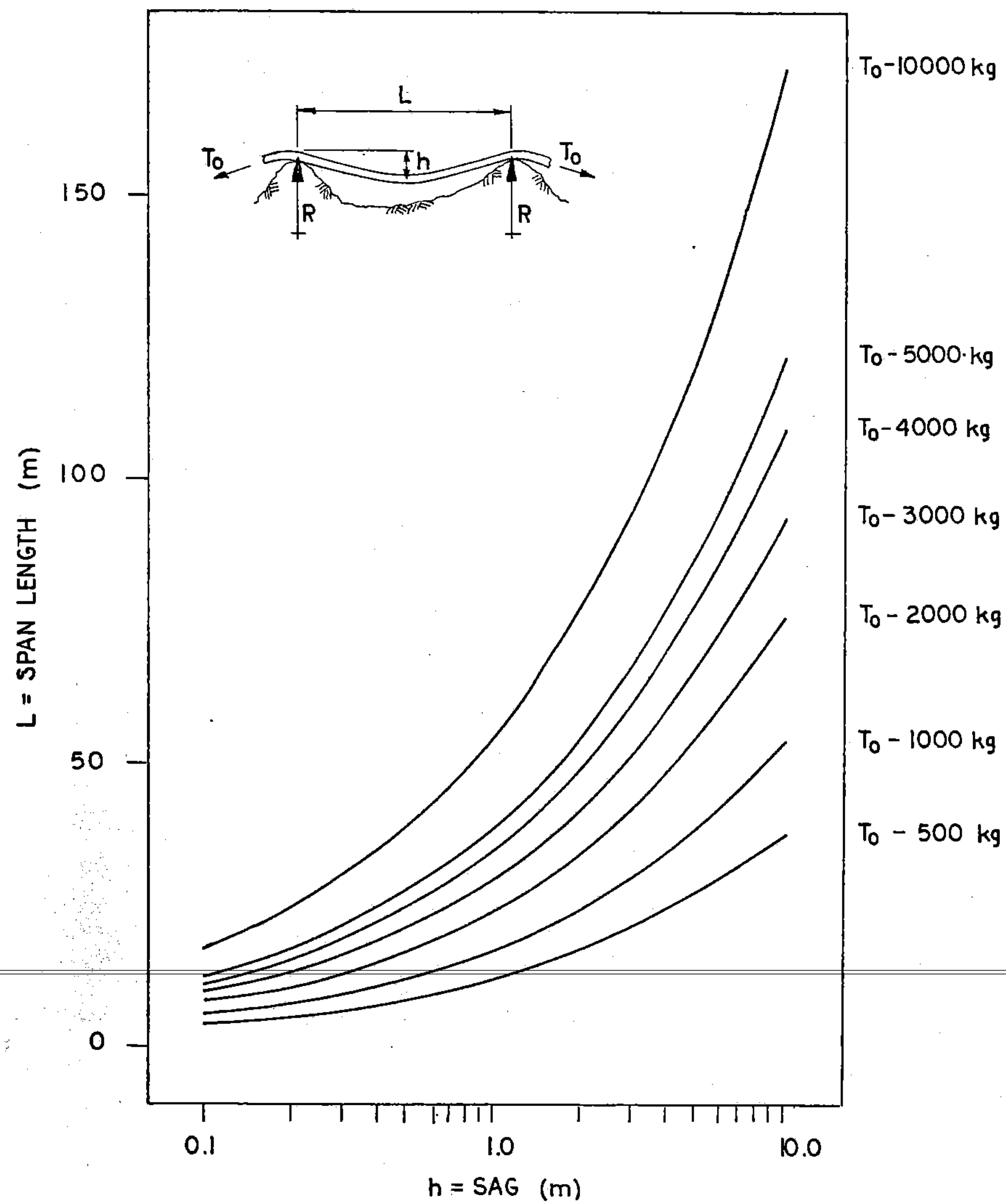

FIG.7 Sag of Cable as a Function of Span Length

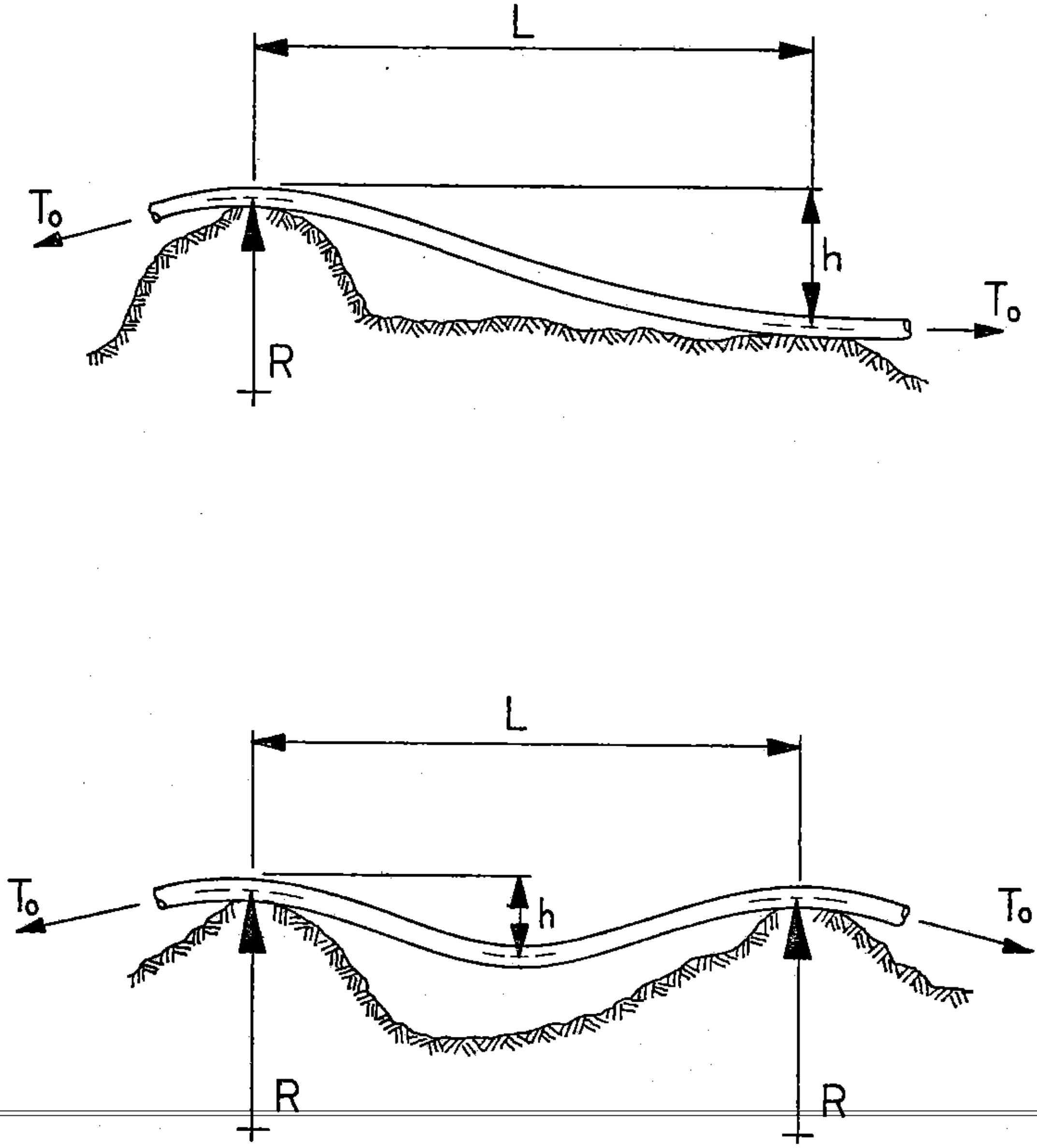

FIG.8 Equivalent Configurations of Cable for Tidal Current and Vortex Shedding.

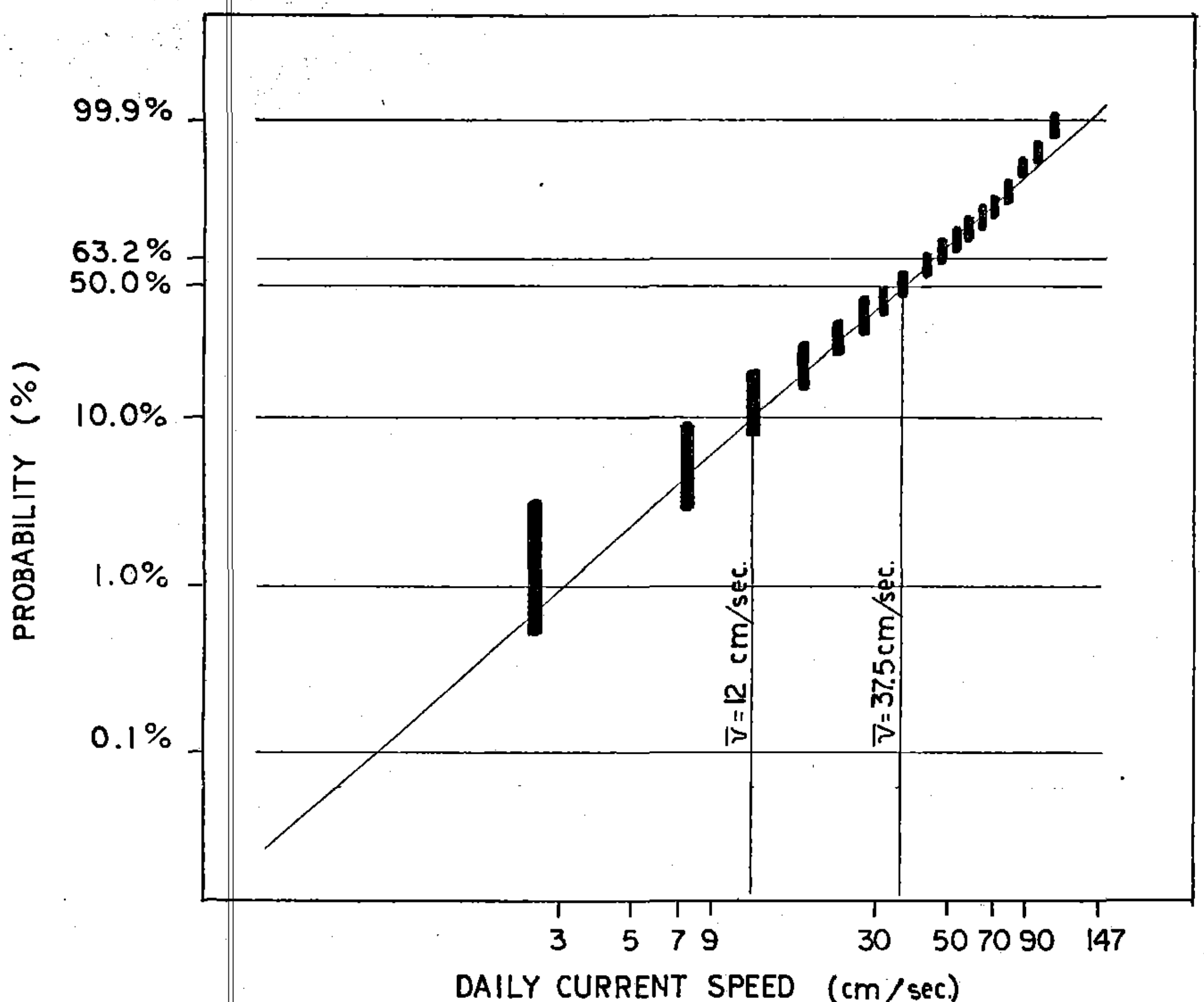

FIG.9 Cumulative Probability - Daily Current Distribution at the surface

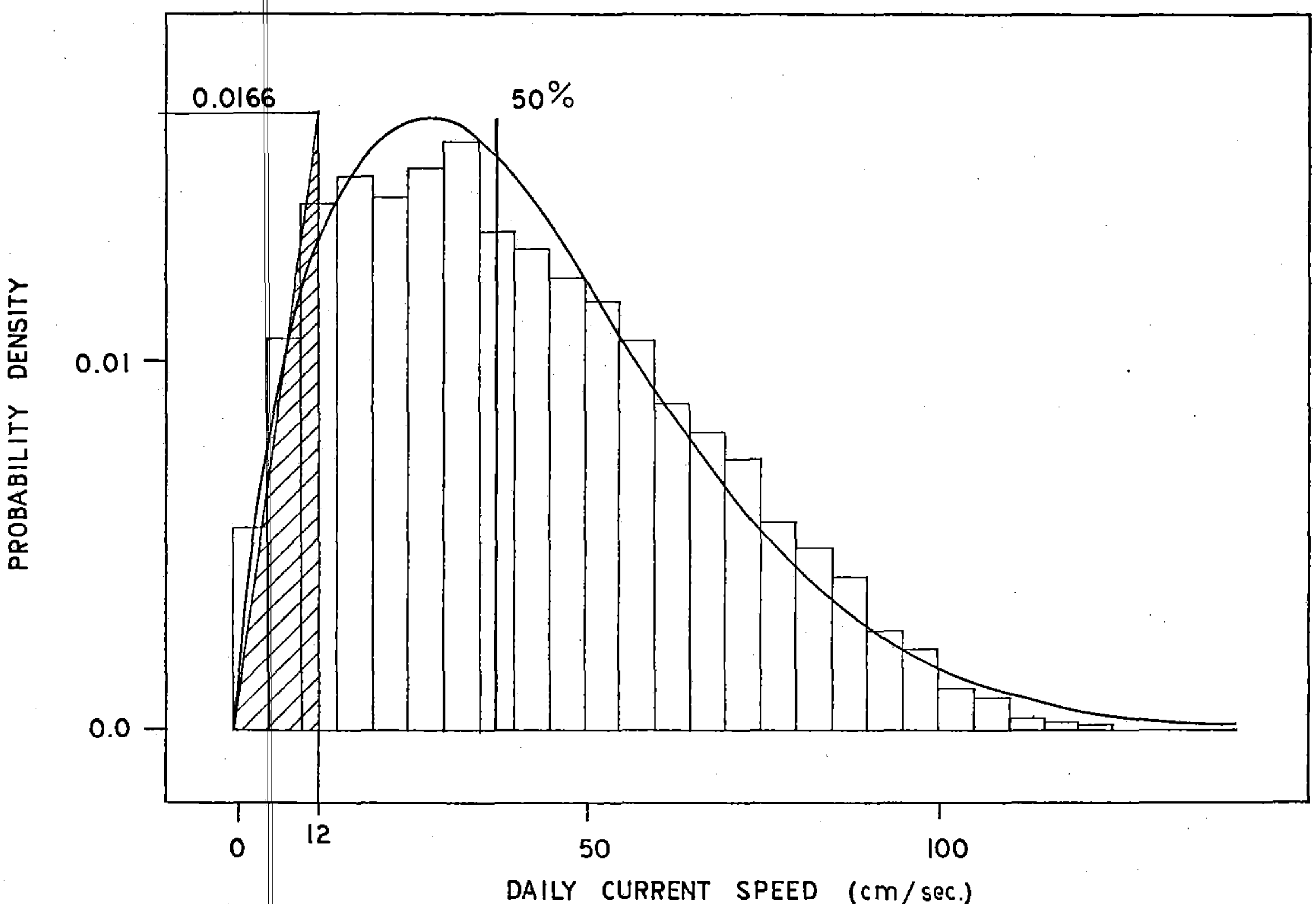

FIG.10 Probability Density of Daily Current Speed Distribution at the Surface

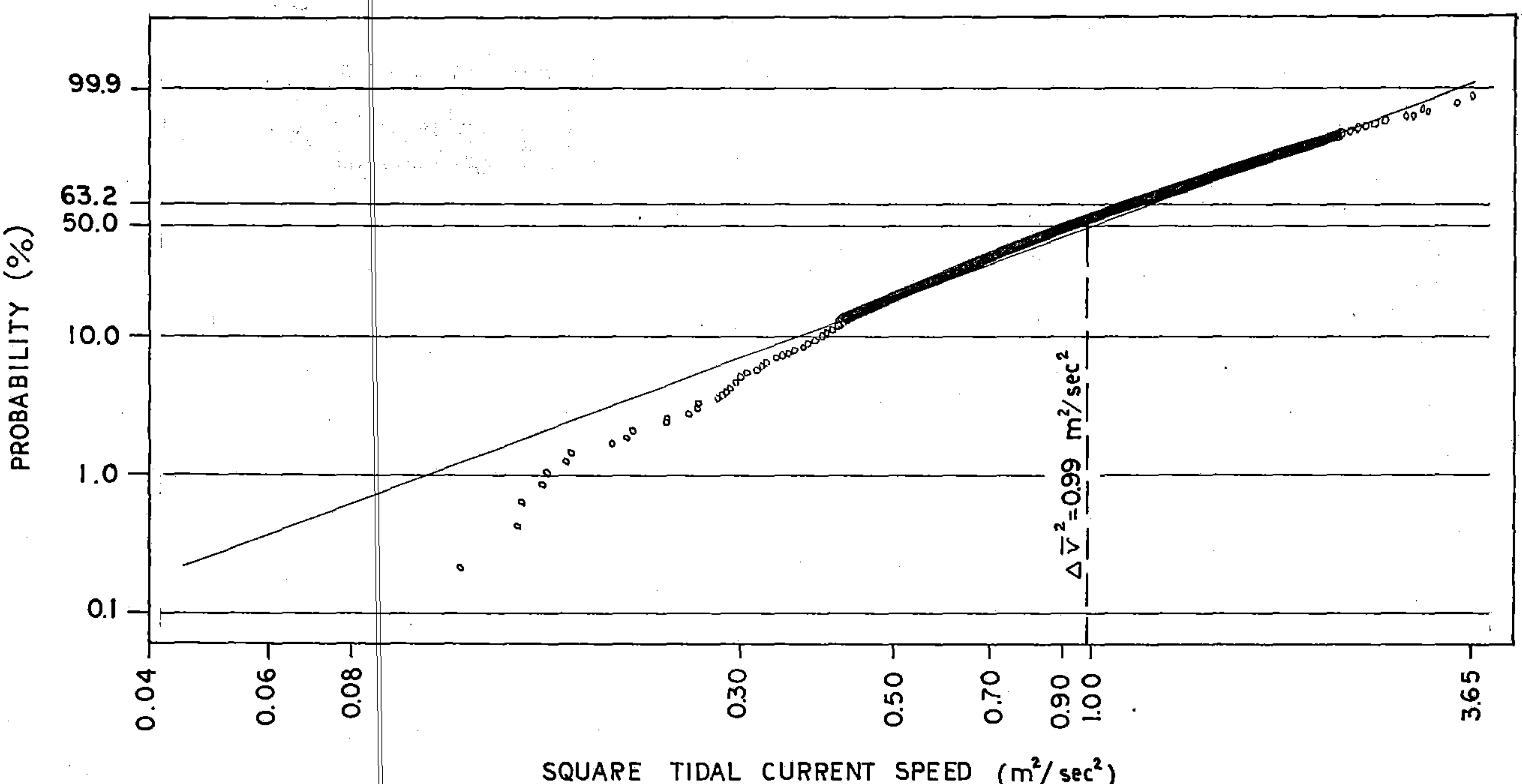

FIG.11 Cumulative Probability of the Total Square of the Maximum Speed (Tidal Current Speed) Distribution

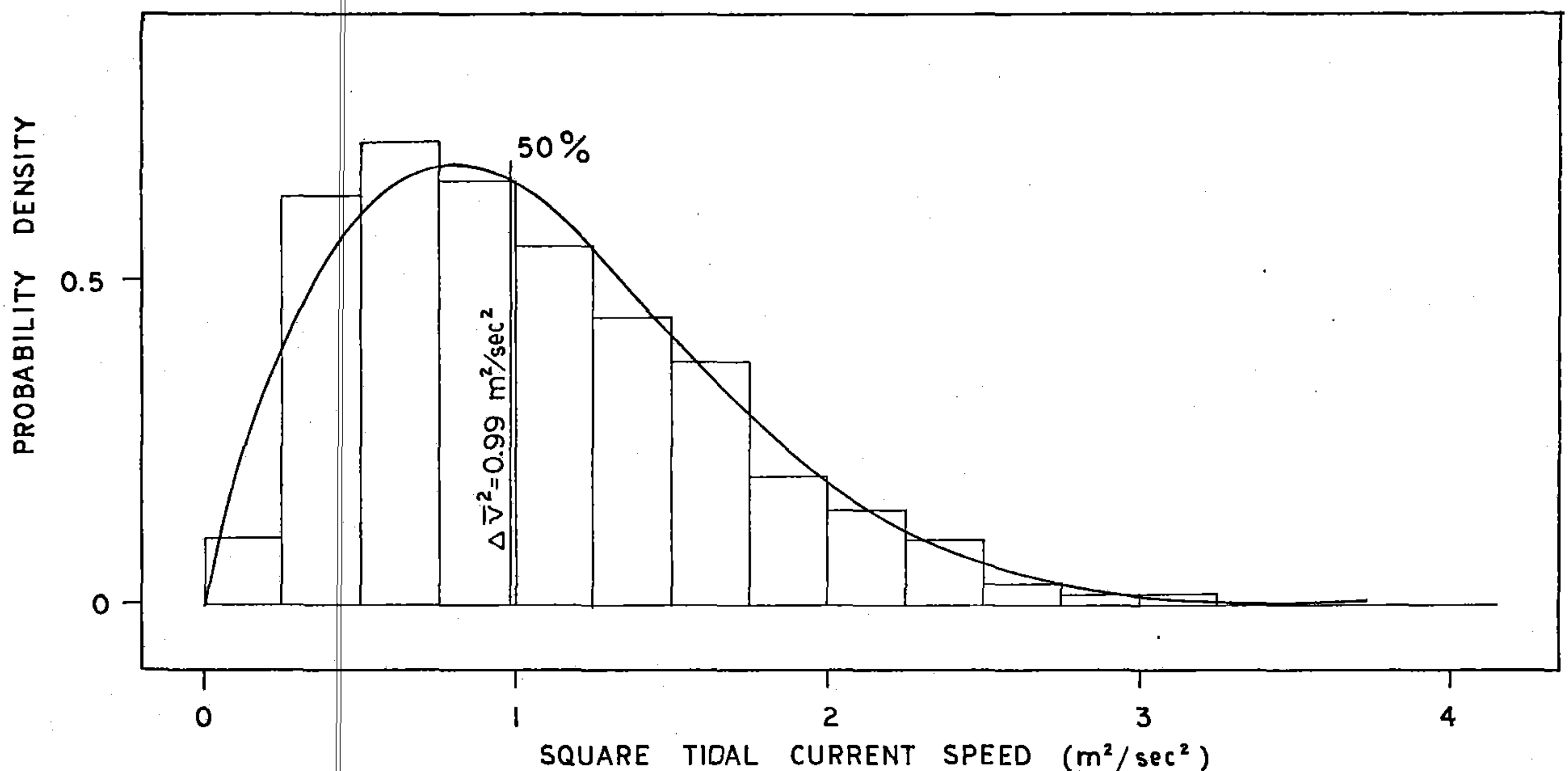

FIG.12 Probability Density of the Total Square of the Maximum Speed at the Surface Distribution

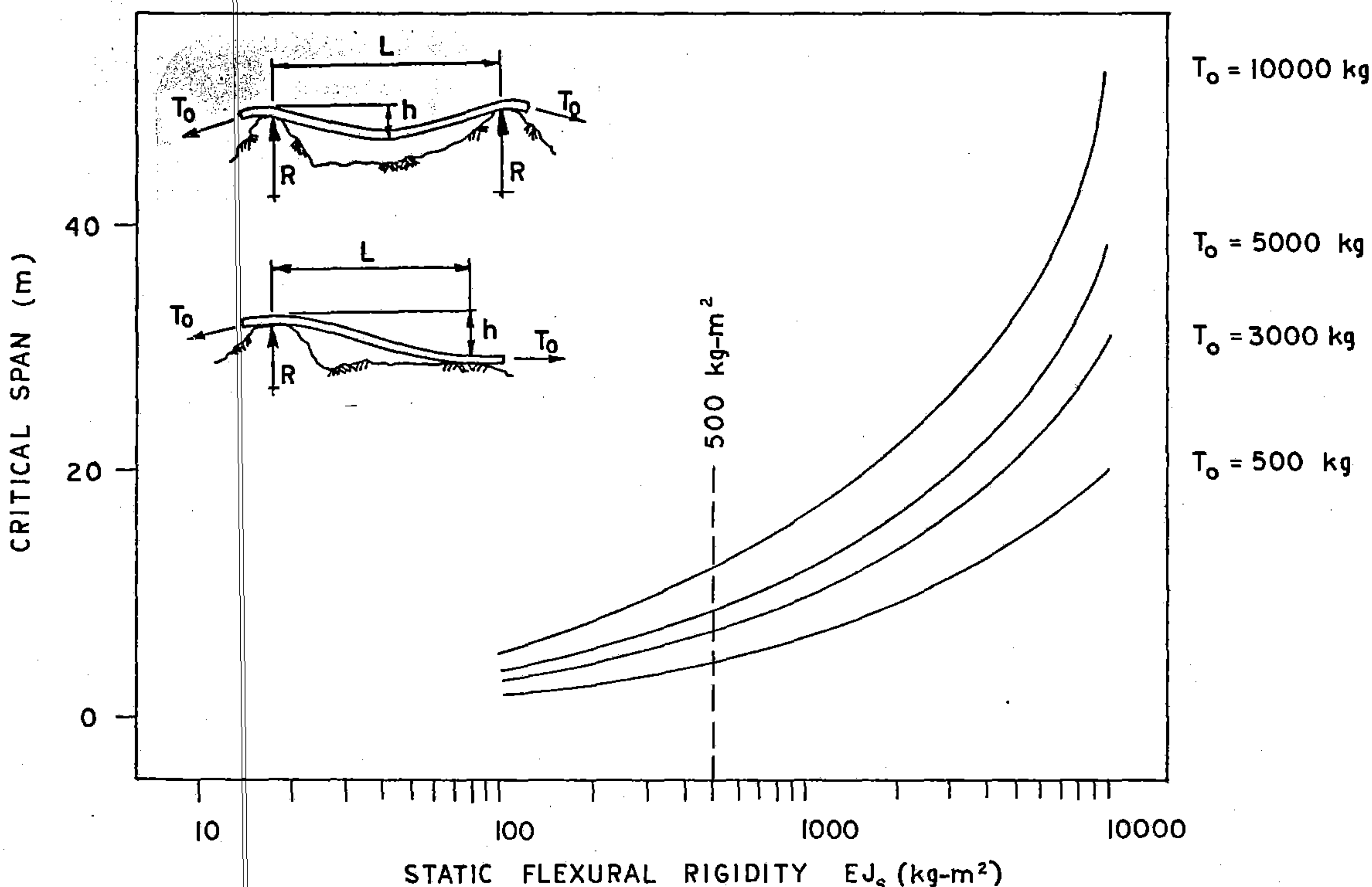

FIG.13 Critical Span Lengths for the Tidal Current Oscillation.
Tidal Current Speed Measured at the Surface.

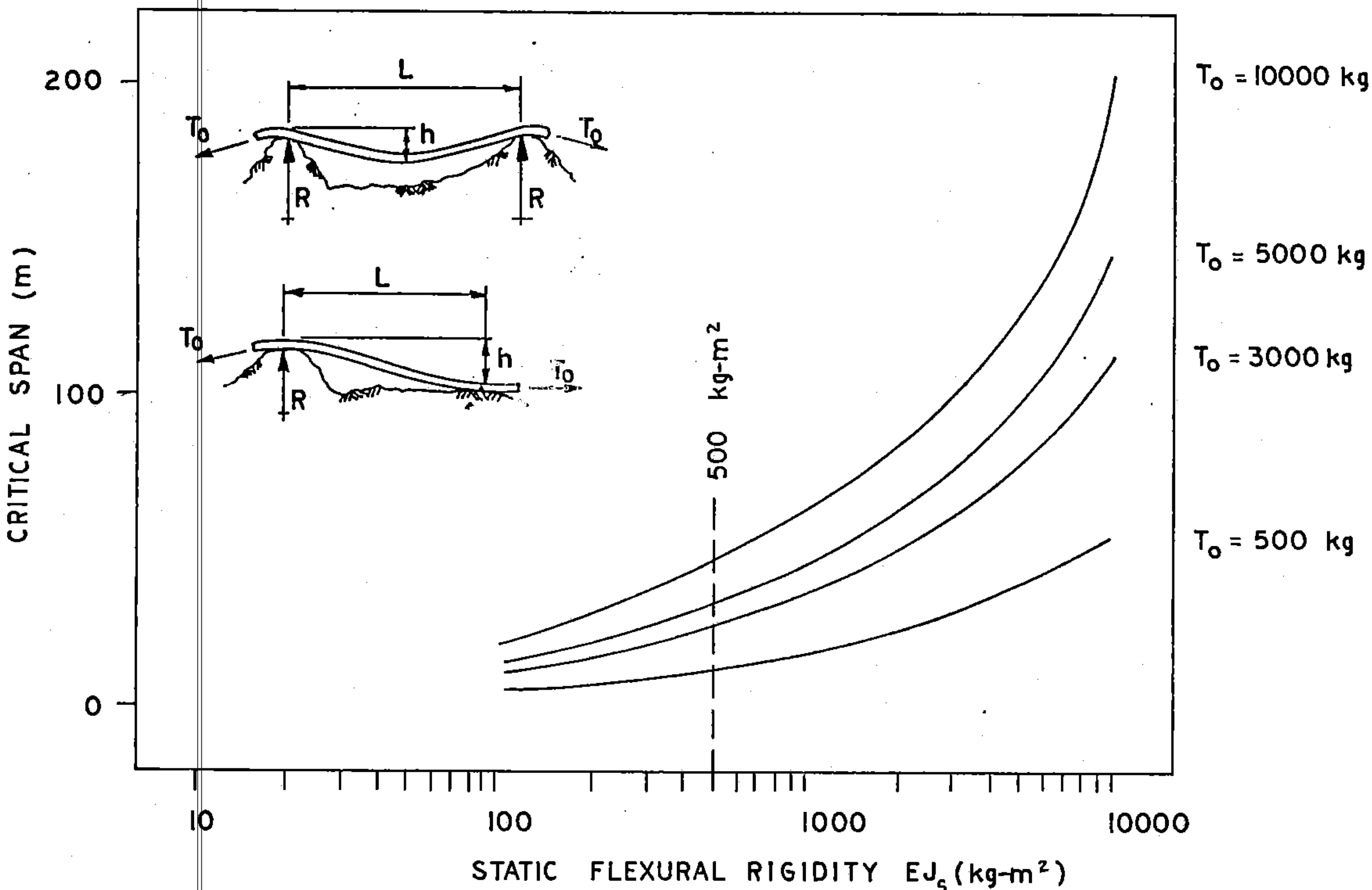

FIG.14 Critical Span Lengths for the Tidal Current Oscillation.
Tidal Current Speed One Half of that at the Surface.

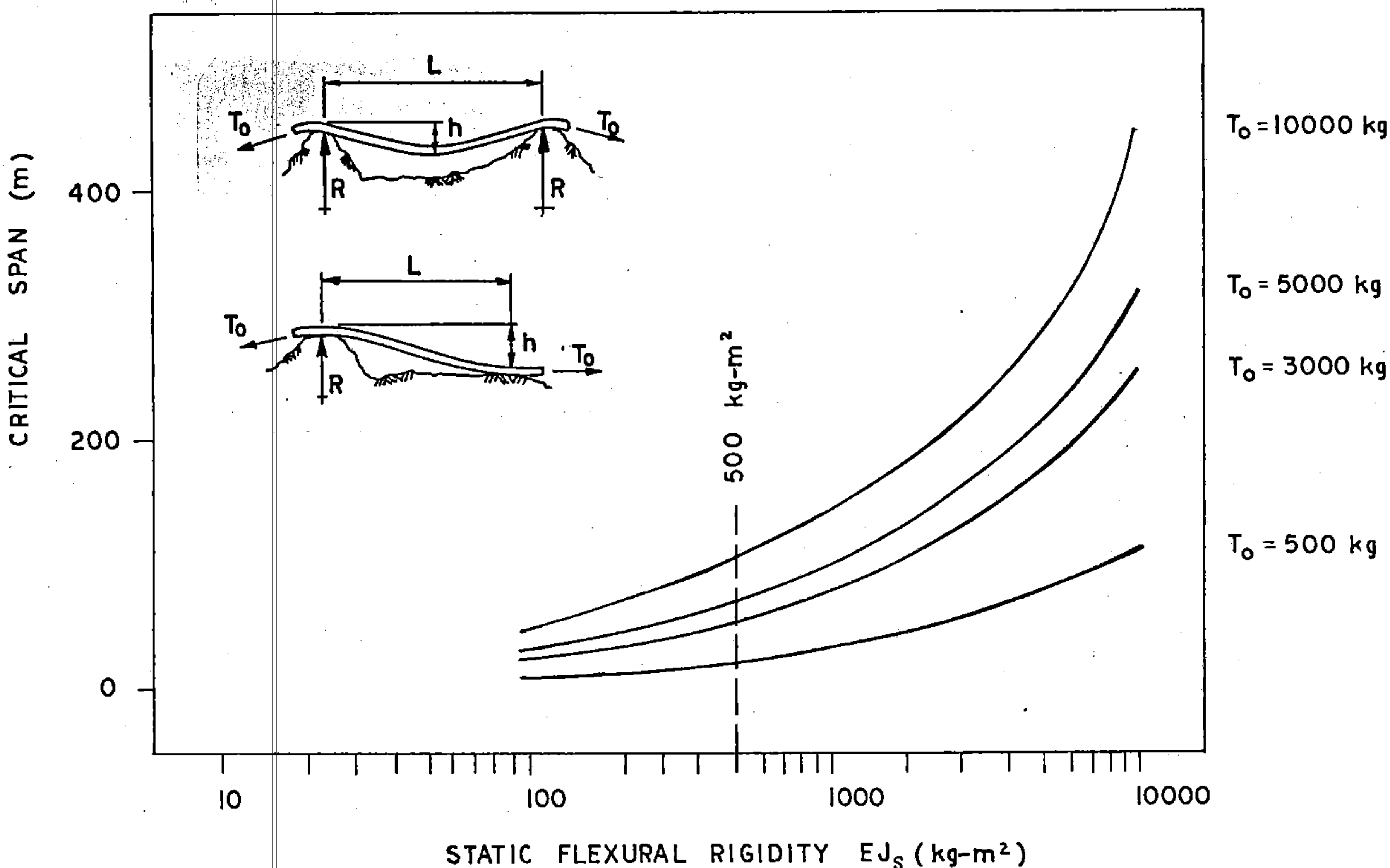

FIG.15 Critical Span Lengths for the Tidal Current Oscillation. Tidal Current Speed One Third of that at the Surface.

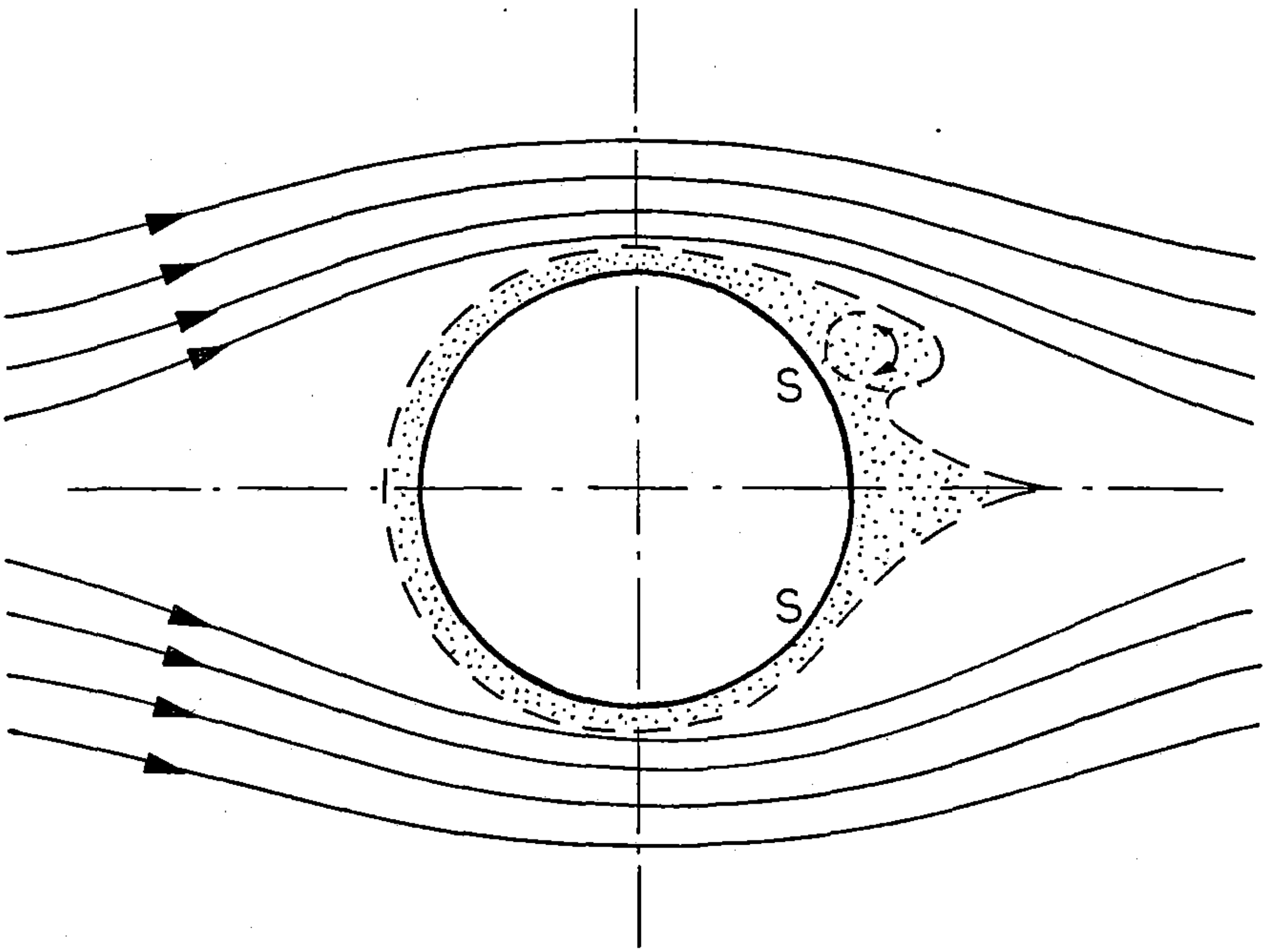

FIG.16 Vortex Formation Around Cable Immersed in a Continuous Current Flow

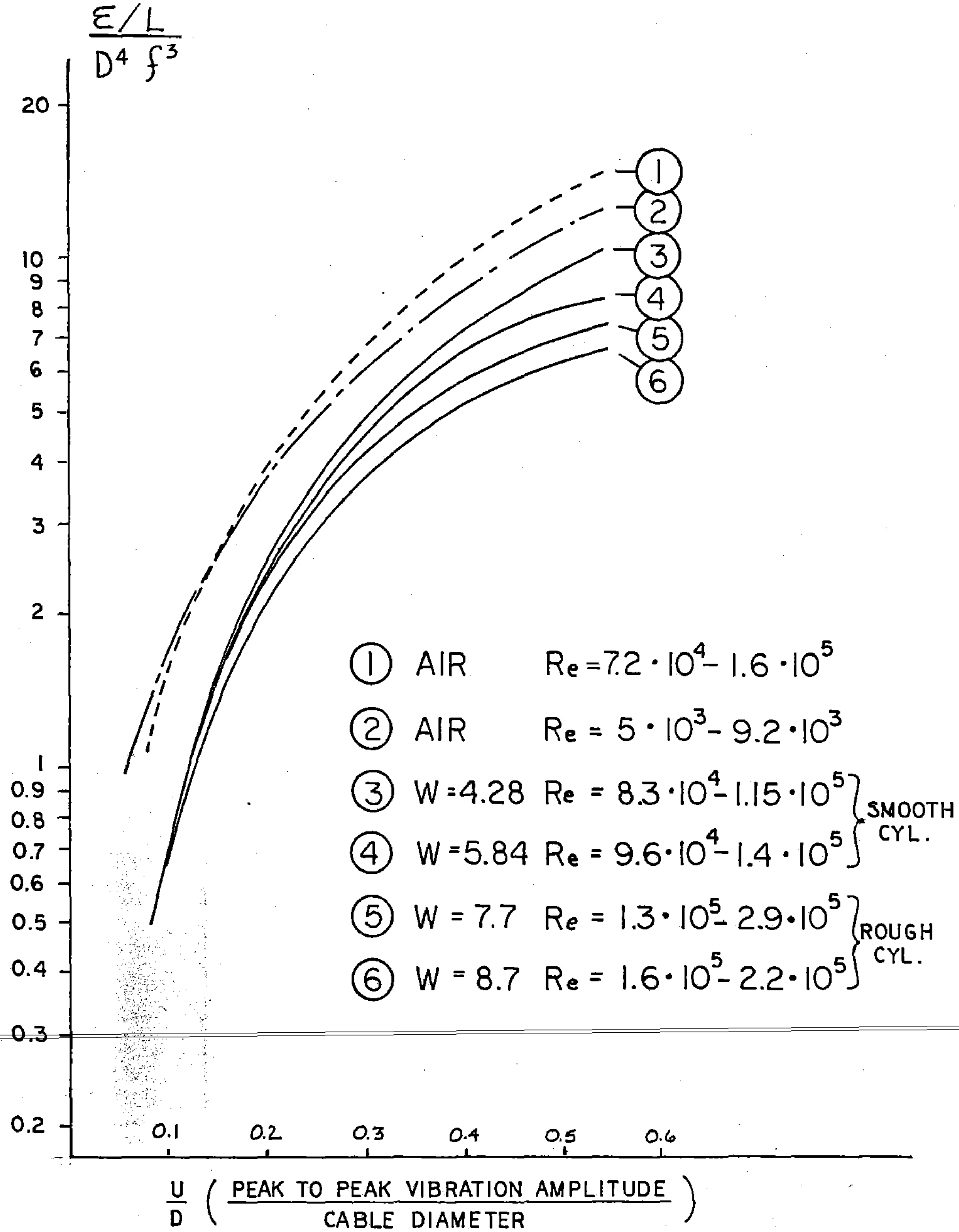

FIG. 17 Maximum Energy Introduced Into a Cable Values Referred to Air Energy ε is in the Farquharson Notation

NOTE: The energy can be referred to the water by multiplying by the ratio between water density and air density (6).

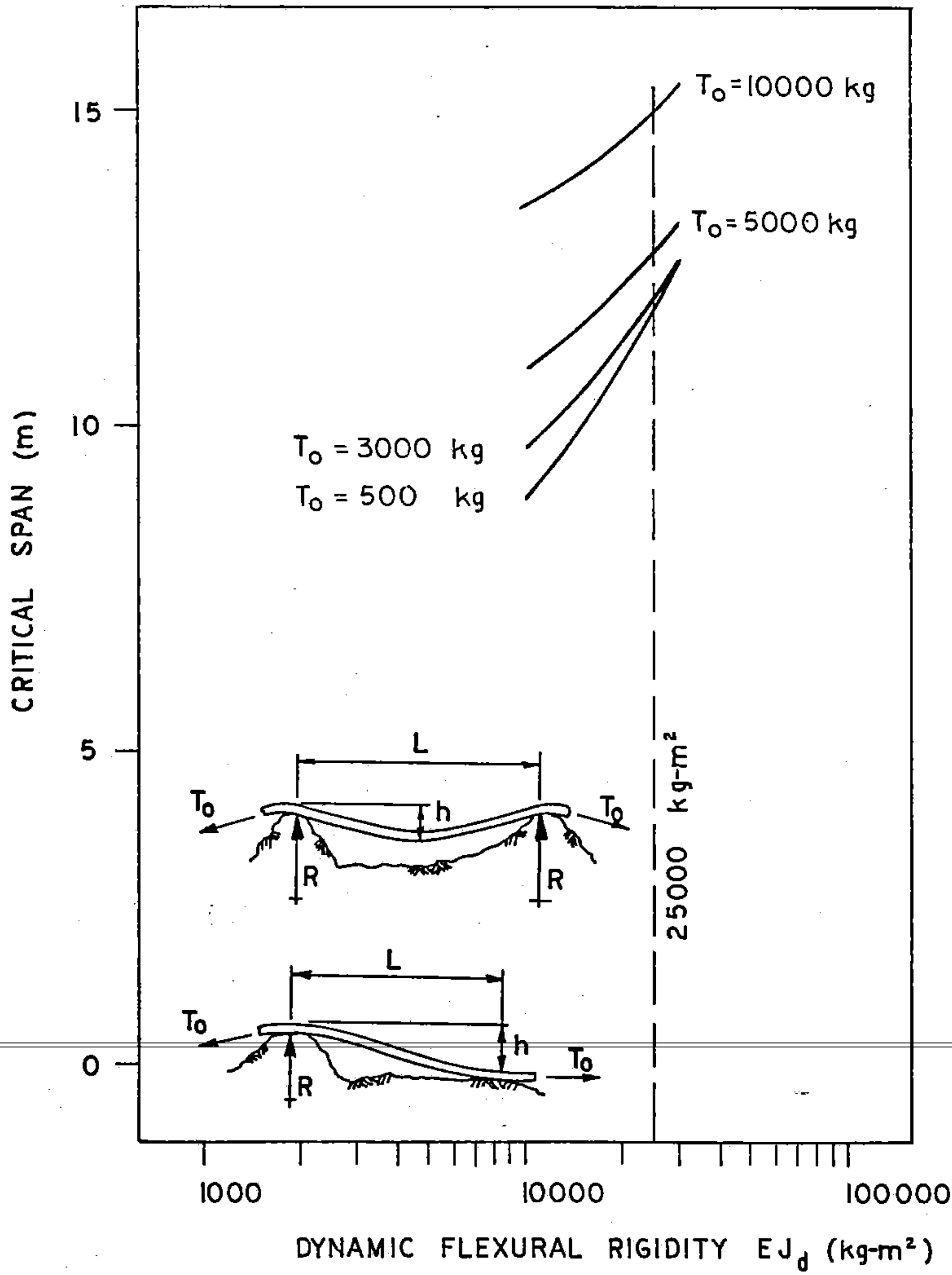

FIG.18 Critical Span Lengths for Vortex Shedding Vibrations Daily Current Speed Measured at the Surface

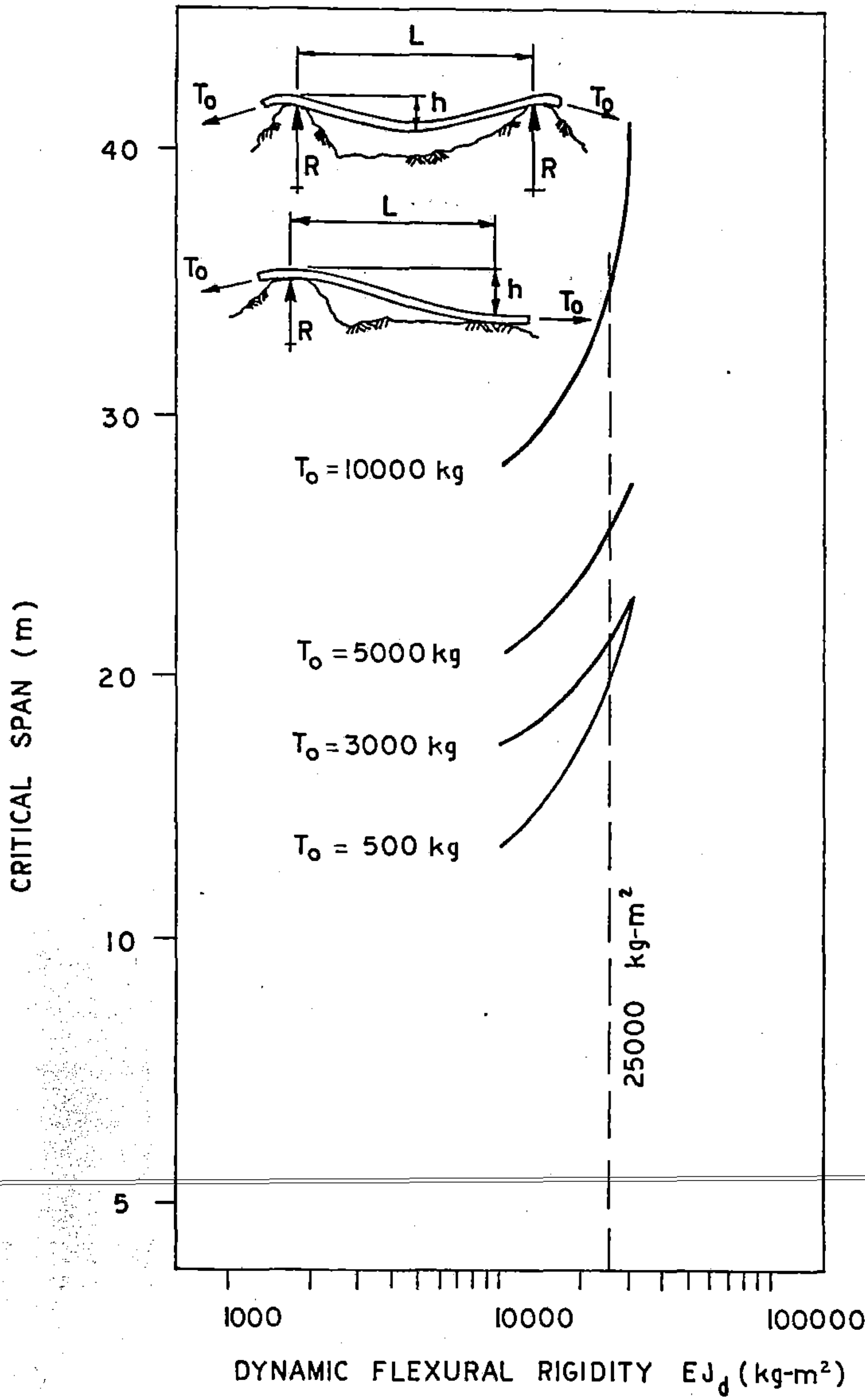

FIG.19 Critical Span Lengths for Vortex Shedding Vibrations
Daily Current Speed One Half of that at the Surface

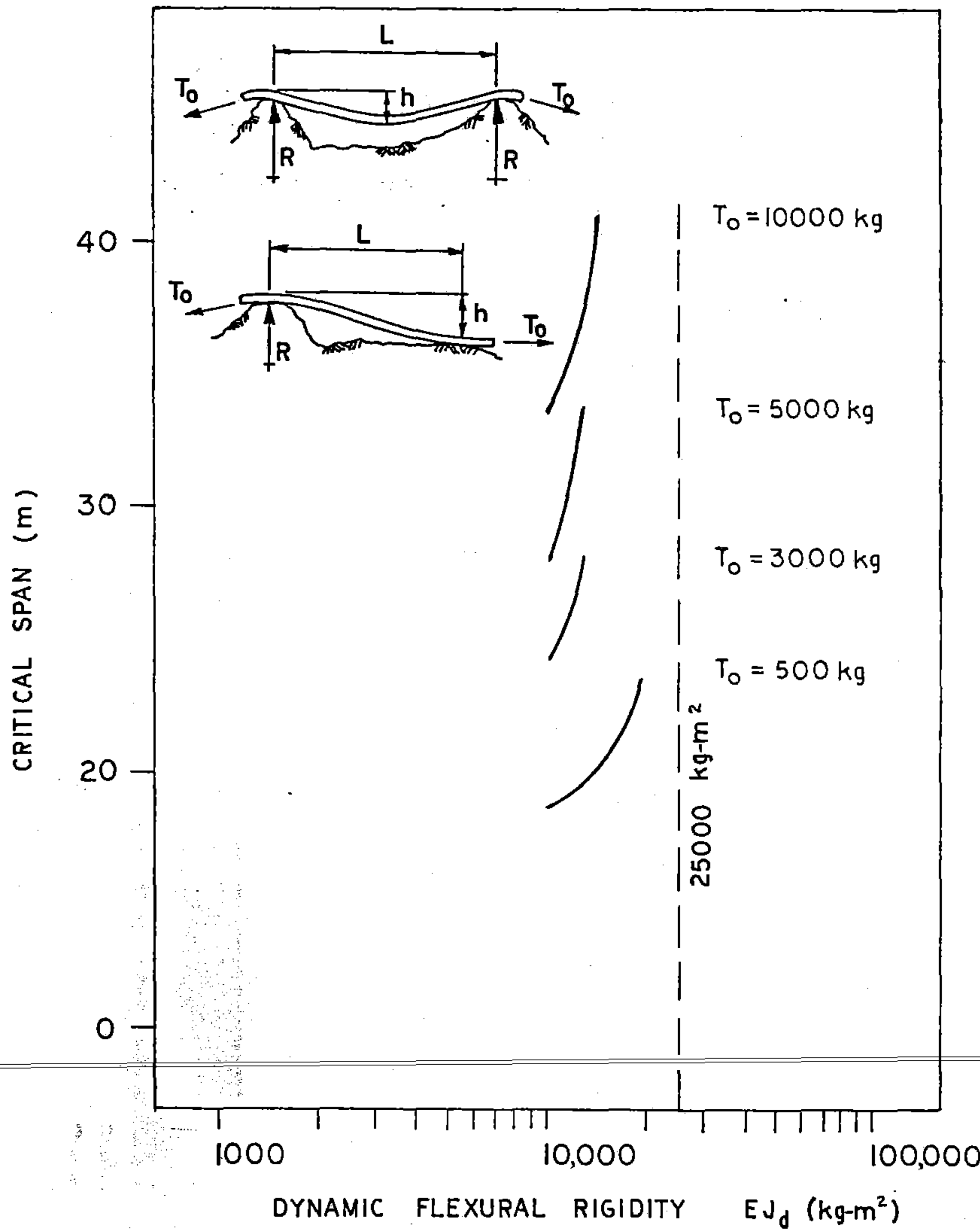

FIG.20 Critical Span Lengths for Vortex Shedding Vibrations
Daily Current Speed One Third of that at the Surface

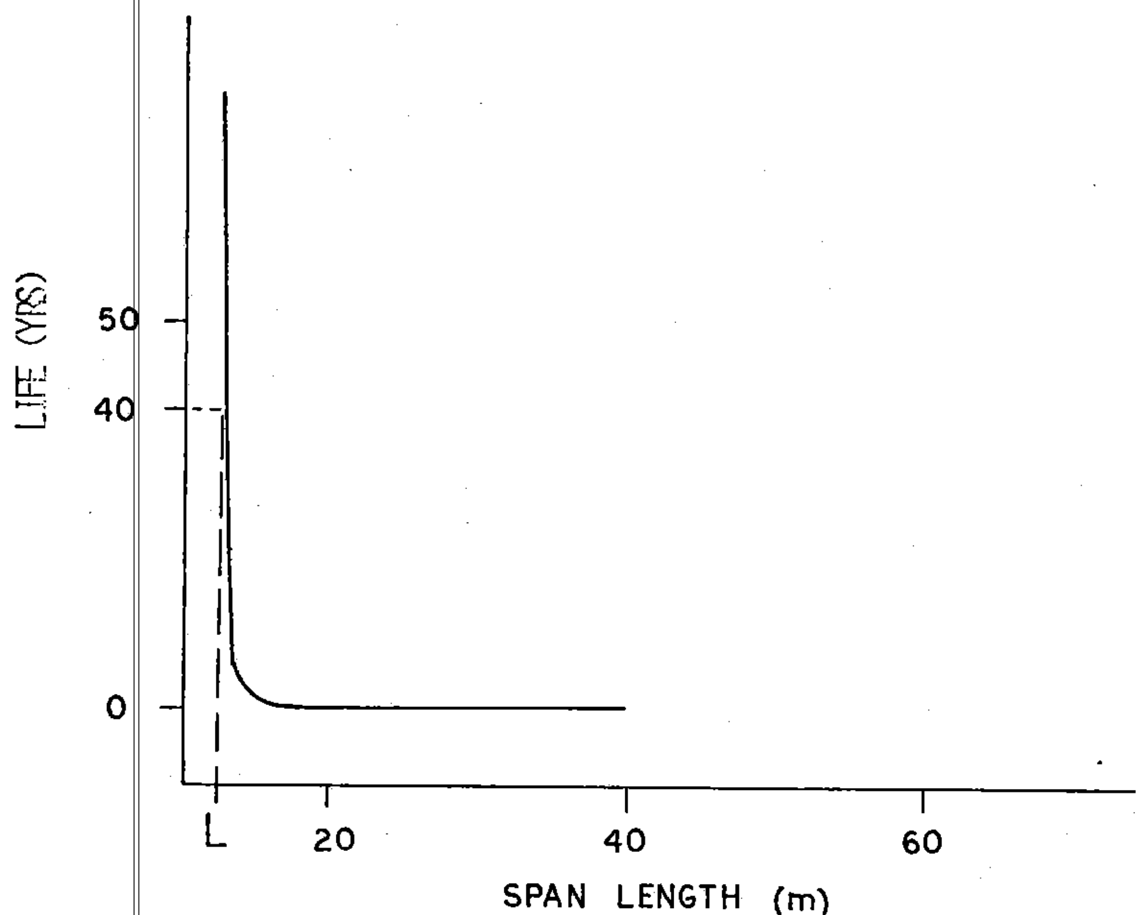

FIG.21 Critical Span as Threshold Value Between Cases of Vibrating Cable and Non-Vibrating Cable

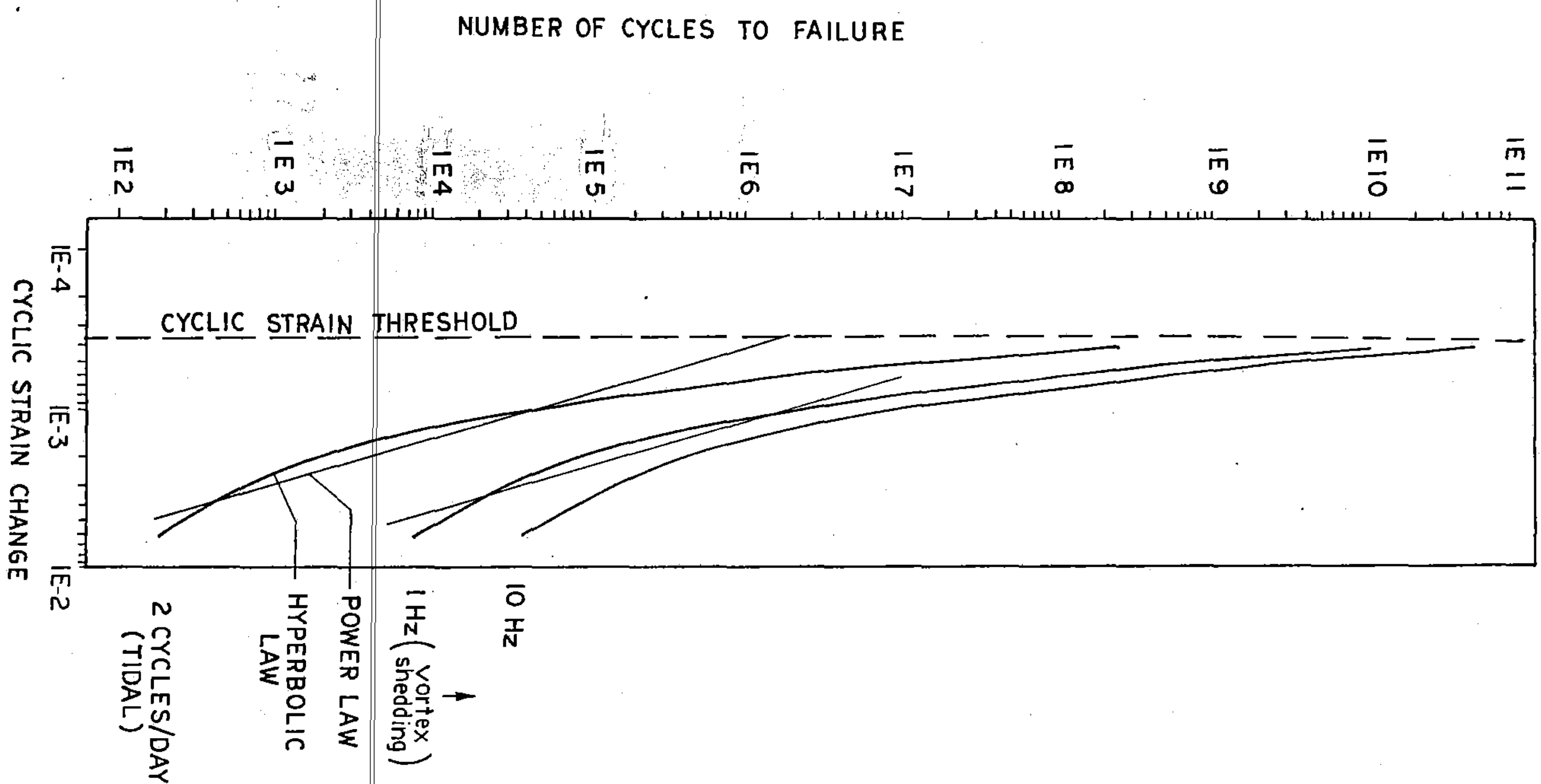

FIG. 22 Comparison of Lead Alloy E Life Curves Obtained With Power Law and Hyperbolic Law Functions

ATTACHMENT 1

CABLE ELEMENTS

ELEMENT	ELEMENTS NUMBER	D.INT. (MM)	D.EST. (MM)	E YOUNG'S (KG/MM2)
TUBULAR CONDUCTOR AL	1	25.000	51.900	7000.00
TUBULAR LEAD	1	76.760	83.360	1500.00
ARMOUR INT.	29	97.710	103.710	21000.00
ARMOUR EXT.	31	106.910	112.910	21000.00
POLYPROPILENE YARN	1	112.910	119.510	55.00

CABLE CHARACTERISTICS

EXTERNAL DIAMETER= 119.51(MM)
WEIGHT= 37.09(KG/M)
DYNAMIC FLEXURAL RIGIDITY=10000.0(KG*M**2)
STATIC FLEXURAL RIGIDITY= 100.0(KG*M**2)
BOTTOM TENSION=10000(KG)
INTRINSIC DAMPING= 0.060
SPAN REFERENCE LENGTH= 19.5(M)
EQUIVALENT DAMPING= 1.45E+07(JOULES)
DRAG COEFFICIENT= 1.2

SEA STREAM

TYPE=LAMINAR
VISCOSITY= 1.60E-06(M**2/SEC)
EQUIVALENT MASS COEFFICIENT= 2.0
SYNCHRONIZATION COEFFICIENT= 0.20

STREAM SPEED DISTRIBUTION

SPEED AT 63.2% OF PROBABILITY= 0.453(KNOTS)
SHAPE EXPONENT= 1.680

SQUARE TIDAL SPEED DISTRIBUTION

SQUARE SPEED AT 63.2% OF PROBABILITY= 1.145(KNOTS**2)
SHAPE EXPONENT= 1.860

RESULTS

CRITICAL SPAN FOR VORTEX SHEDDING

FREQ. (HZ)	SPEED (KNOTS)	REY	PROB (%)	AMP. (MM)	EPS (E-6)	SPAN (M)	LIFE (YEARS)	PCW (W/M)
1.360	1.58	6.1E+04	0.0	96.7	854.1	30.5	11.4	10.3
1.373	1.60	6.1E+04	0.0	96.4	858.9	30.2	12.6	10.6
1.386	1.61	6.2E+04	0.0	96.1	863.7	29.9	13.9	10.9
1.398	1.63	6.2E+04	0.0	95.8	868.4	29.7	15.5	11.2
1.411	1.64	6.3E+04	0.0	95.5	873.3	29.4	17.2	11.5
1.424	1.66	6.4E+04	0.0	95.2	878.1	29.2	19.1	11.9
1.436	1.67	6.4E+04	0.0	94.9	883.1	28.9	21.9	12.2
1.449	1.68	6.5E+04	0.0	94.6	888.3	28.7	23.7	12.6
1.462	1.70	6.5E+04	0.0	94.4	893.5	28.4	26.3	12.9
1.474	1.71	6.6E+04	0.0	94.1	899.0	28.2	29.4	13.3
1.487	1.73	6.6E+04	0.0	93.9	904.5	28.0	32.7	13.7
1.499	1.74	6.7E+04	0.0	93.7	910.2	27.8	36.5	14.1
1.512	1.76	6.7E+04	0.0	93.5	916.1	27.5	40.7	14.5
1.525	1.77	6.8E+04	0.0	93.2	921.1	27.3	45.6	14.8
1.537	1.79	6.9E+04	0.0	93.1	928.1	27.1	50.9	15.3
1.550	1.80	6.9E+04	0.0	93.0	934.2	26.9	56.9	15.7
1.563	1.82	7.0E+04	0.0	92.8	940.5	26.7	63.7	16.2
1.575	1.83	7.0E+04	0.0	92.6	946.7	26.5	71.4	16.6
1.588	1.85	7.1E+04	0.0	92.5	953.2	26.3	80.0	17.1
1.601	1.86	7.1E+04	0.0	92.3	959.6	26.1	89.7	17.6
1.613	1.88	7.2E+04	0.0	92.2	966.1	25.9	100.8	18.0
1.626	1.89	7.3E+04	0.0	92.0	972.6	25.7	113.4	18.5
1.638	1.90	7.3E+04	0.0	91.9	979.2	25.5	127.5	19.0
1.651	1.92	7.4E+04	0.0	91.7	985.8	25.3	143.7	19.5
1.664	1.93	7.4E+04	0.0	91.6	992.5	25.2	162.0	20.0

CRITICAL SPAN FOR TIDAL STREAM

SPAN (M)	LIFE (YEARS)	EPS (E-6)
15.5	99.3	345.8
15.6	96.3	348.1
15.7	93.4	350.3
15.8	90.7	352.6
15.9	88.0	354.9
16.0	85.5	357.1
16.1	83.0	359.4
16.2	80.6	361.6
16.3	78.4	363.9
16.4	76.2	366.2
16.5	74.1	368.4
16.6	72.1	370.7
16.7	70.1	372.9
16.8	68.3	375.2
16.9	66.5	377.5
17.0	64.7	379.7
17.1	63.0	382.0
17.2	61.4	384.2
17.3	59.9	386.5
17.4	58.3	388.8
17.5	56.9	391.0
17.6	55.5	393.3
17.7	54.1	395.5
17.8	52.8	397.8
17.9	51.5	400.1
18.0	50.3	402.3
18.1	49.1	404.6
18.2	48.0	406.8
18.3	46.9	409.1
18.4	45.8	411.4
18.5	44.8	413.6
18.6	43.8	415.9
18.7	42.8	418.1
18.8	41.8	420.4
18.9	40.9	422.7
19.0	40.0	424.9
19.1	39.2	427.2
19.2	38.3	429.4
19.3	37.5	431.7
19.4	36.7	434.0
19.5	36.0	436.2
19.6	35.2	438.5
19.7	34.5	440.7
19.8	33.8	443.0
19.9	33.1	445.3
20.0	32.5	447.5
20.1	31.8	449.8
20.2	31.2	452.0
20.3	30.6	454.3
20.4	30.0	456.6
20.5	29.4	458.8