APPENDIX E
CONDUCTOR SAG AND TENSION CALCULATIONS

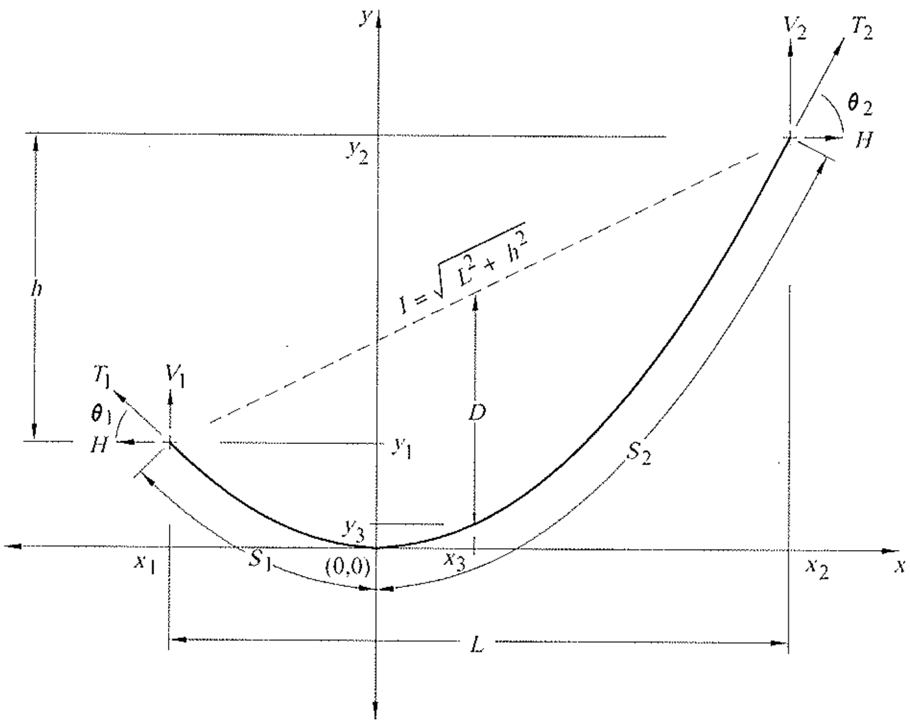

FIGURE E1 INCLINED SPAN GEOMETRY

E1 TERMINOLOGY

Level span	The conductor supports are at the same level.
Inclined span	The conductor supports are at different levels.
Suspension span	Either or both conductor supports are free to swing longitudinally (along the line).
Deadend span	Both conductor supports are terminated.
Sag	The maximum vertical departure of the catenary from a chord joining the support points (approximately mid span).
Section	That portion of an overhead line between strain structures consisting solely of intermediate suspension structures for which the ruling span concept is valid.
Ruling span	A hypothetical level deadend span used to model the tension behaviour of a section.
Tension constraint	The maximum allowable conductor tension (independent of the ruling span) for a given loading condition.
Controlling constraint 1	The tension constraint which produces the largest sags at the maximum operating temperature for a given ruling span.
Controlling constraint 2	The tension constraint which produces the longest unstressed constraint 2 conductor length for a given ruling span.

E3 INTRODUCTION

A flexible, inelastic conductor with constant load (W) per unit of arc length suspended between supports assumes the shape of a catenary—

$$y = C\left(\cosh\left(\frac{x}{C}\right) - 1\right) \text{ where the catenary constant } C = \frac{H}{W} \qquad \text{. . . E1}$$

An approximation of the catenary is the parabola which uses a constant load (W) per horizontal unit length.

$$y = \frac{x^2}{2C} \qquad \text{. . . E2}$$

For span lengths less than 0.7C, or sags less than 9% of the span length, the difference in sag between the catenary and the parabola is less than 1%.

These mathematical models are adequate for describing inelastic conductors at any given tension. To determine the tension at different loading conditions the equations should be modified for temperature, elasticity, wind pressure, ice weight and age (creep).

For all steel reinforced conductors, the use of a constant E value may result in calculated sags less than actual sags for temperatures greater than 90°C. This is subject to further research by CIGRE Study Committee 22/Working Group 12 and IEEE Subcommittee Towers, Poles and Conductors/WG '*Thermal Aspects of Overhead Conductors*'/Task Force '*Bare Conductor Sag at High Temperature*'.

E4 RULING SPAN

The ruling span, also known as the equivalent span or the mean effective span (MES), is defined as that level dead-end span whose tension behaves identically to the tension in every span of a series of suspension spans under the same loading conditions. Note that the ruling span concept can only model a uniformly loaded section, e.g. where wind or ice on one span exists but not on the other spans in the section, other more precise modeling techniques are to be adopted.

It is assumed that the insulator is free to swing along the line and long enough to equalize the tension in adjacent spans without transferring a longitudinal load onto the structure. In general, spans shorter than the ruling span tend to sag more than predicted whilst spans longer than the ruling span sag less than predicted at temperatures above the stringing temperature (assuming that the tensions were equal at stringing).

The ruling span concept may not apply to fixed pin and post insulators because the structures may not be flexible enough to equalize tensions. However, if the stringing tension is low, or the spans are short, or the spans are approximately equal, then there is little difference in tension across the insulator under identical loading conditions in each span. Therefore the risk of conductor movement through the ties and associated fretting is minimized, except for non-uniform span loading.

A value for the ruling span should be assumed before spotting structures because the actual ruling span can only be calculated after the structure locations are determined. In most cases the actual ruling span should be greater than or equal to the assumed ruling span to ensure the design clearances. However, the situation sometimes arises (for large ruling spans when the controlling constraint is associated with a heavy loading condition) where the tension decreases with increasing ruling spans at the maximum operating temperature. Under these circumstances the actual ruling span should be less than or equal to the assumed ruling span.

The resultant distributed load is the vector sum of W_h and W_v

$$W = \sqrt{W_h^2 + W_v^2} \qquad \text{. . . E9}$$

The catenary constants C, C_h and C_v are functions of W, W_h and W_v respectively. C_h is used for conductor swing-out calculations, C_v is used to calculate sags and C is used for calculating tension changes.

NOTE: The value of gravitational acceleration 'g' is normally taken as 9.8067 m/s².

E6 TENSION CONSTRAINTS

Tension constraints are used to limit the horizontal tensions for one or more of the following reasons:

(a) To restrict fatigue damage caused by aeolian vibration. This constraint is frequently referred to as the everyday tension (*EDT*) constraint. The tension limit is influenced by the climate, terrain, extent of vibration protection, conductor material, conductor self damping characteristics and type of conductor support. Refer to Section 7.

(b) To give a margin of structural safety under extreme weather conditions of wind and ice.

(c) To limit the tension for short ruling spans under cold conditions. For short spans there are large variations of tension with temperature changes.

(d) To give a margin of safety for personnel performing maintenance and stringing operations which could be done under light wind conditions.

The age of the conductor at which a particular tension constraint applies should be stipulated if the creep is significant. The tension reduces as the conductor creeps. An age of 10 years is usually applied since strand settling and metallurgical creep are virtually completed in that period.

For a given ruling span only one tension constraint limits (or controls) the tensions for all other loading conditions. The controlling constraint is the most restrictive tension constraint, producing the largest sags and the least tensions for any given loading condition.

A tension constraint can alternatively be expressed as a support tension, sag, conductor stress or catenary constant. Each of these alternatives can be converted to a horizontal tension as follows:

(i) Tangential Tension (T) at a support

$$H = \frac{T}{2} + \sqrt{\left(\frac{T}{2}\right)^2 - \frac{(WL_r)^2}{8}} \text{ (based on the parabola and a level span)} \qquad \text{. . E10}$$

(ii) Sag (D)

$$H = \frac{W_v L_r^2}{8D} \text{ (based on the parabola)} \qquad \text{. . . E11}$$

(iii) Conductor stress (σ)

For an ACSR conductor with a steel to aluminium modulus ratio of three and with the aluminium and steel in tension the aluminium stress can be converted to tension using—

$$H \approx \sigma(A_a + 3A_s) \qquad \text{. . . E12}$$

For a homogeneous conductor $H = \sigma A$

It is common practice to convert the difference in creep strain ($\varepsilon_f - \varepsilon_i$) to an equivalent thermal strain (αt_c) and overtension the conductor by using a temperature lower than that which actually applies at the time of sagging. Therefore if the controlling constraint applies at say 10 years, then the final sags and tensions are calculated using equation E17 with $\varepsilon_f = \varepsilon_i = 0$ and the initial sags and tensions are determined by applying a negative temperature correction of $t_c = \frac{\varepsilon_f - \varepsilon_i}{\alpha}$ to the final sags and tensions.

E8 PHYSICAL PROPERTIES

Once a conductor tension has been determined for a section of transmission line using its ruling span in the tension change equation, the characteristics of each span in the section may be determined using the inelastic catenary or parabolic equations.

Reference Figure E1 for the variables associated with the inclined span geometry.

E8.2 Parabolic equations

$x_1 = \frac{Ch}{L} - \frac{L}{2} =$ weight span contribution to structure 1

$x_2 = \frac{Ch}{L} + \frac{L}{2} =$ negative weight span contribution to structure 2

$\frac{L}{2} =$ wind span contribution to structure 1 and structure 2

The equation for calculating the arc length of a parabola is more complex than that of the catenary, therefore a Maclaurin's series approximation of the catenary equation is used here.

$$S = I + \frac{L^4}{24C^2 I}$$

$$\Delta = S - I = \frac{L^4}{24C^2 I} = \frac{8D^2}{3I}$$

$$V_1 = -W_v x_1 = \frac{W_v L}{2} - \frac{Hh}{L}$$

$$V_2 = -W_v x_2 = \frac{W_v L}{2} + \frac{Hh}{L}$$

$$y_1 = D + \frac{h^2}{16D} - \frac{h}{2}$$

$$y_2 = D + \frac{h^2}{16D} + \frac{h}{2}$$

$$T_1 = \frac{H}{C}\sqrt{x_1^2 + C^2}$$

$$T_2 = \frac{H}{C}\sqrt{x_2^2 + C^2}$$

$$\tan\theta_1 = \frac{x_1}{C} = \frac{h - 4D}{L}$$

$$\tan\theta_2 = \frac{x_2}{C} = \frac{h + 4D}{L}$$

$x_3 = \frac{Ch}{L}$ (mid span)

$D = \frac{L^2}{8C}$ (independent of h)

$$T_a = \frac{H}{S}\left(\frac{I^2}{L} + \frac{L^3}{12C^2}\right)$$

E9.3 Variation of weight span with conductor tension (Based on parabolic simplification)

If the weight span (L_{v1}) is known for a given tension (H_1) then the weight span (L_{v2}) at any other tension (H_2) is—

$$L_{v2} = L_h + \frac{C_2}{C_1}(L_{v1} - L_h)$$

where

$$C_1 = \frac{H_1}{W_{v1}} \text{ and } C_2 = \frac{H_2}{W_{v2}}$$

Longitudinal profile drawings can be used to measure the weight spans for the plotted catenaries (e.g. the maximum operating temperature or sometimes the maximum working wind or ice load). The above formula can be used to calculate the conductor weight spans at other conditions of temperature, ice, wind or creep.