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WT4 Millimeter Waveguide System:

Route Engineering and Sheath Installation

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This paper discusses route engineering for the WT4 waveguide transmission system stressing differences from cable system engineering caused by the dependence of loss on curvature. It is shown that the stiffness of the waveguide sheath, while tending to limit axis curvature of the installed waveguide, also constrains the design of the trench. A simplified method of designing trench-bottom profiles compatible with natural shapes of the sheath is described. Pipeline-like installation methods are shown to be adequate for the sheath and a demonstration of their practicality in a field evaluation test is discussed.

I. INTRODUCTION

The goal of route engineering for any transmission system is to select the route layout which minimizes the total installed cost of the system while meeting other physical and legal constraints. Specific goals of route engineering for a WT4 waveguide system are the siting of repeater buildings on suitable property and the design and staking out of a trench centerline along a right of way for which easements can be obtained. The trench design must meet the conditions that it has a shape satisfactory for emplacement of a waveguide sheath and that it can be excavated economically by conventional trenching machinery.

The transmission medium for a waveguide system differs from that for a cable system in two respects which strongly influence route engineering. First, the loss depends on the number, extent, and severity of route bends as well as the length of the route and, second, the mechanical (beamlike) properties of the waveguide and its sheath restrict the class of feasible route shapes. The siting of repeater stations for waveguide systems exerts somewhat less constraint on route selection than does the siting of manholes for coaxial cable systems in that difficulties engendered by the relatively large buildings are more than offset by avoiding the problems involved in providing access to manholes at 1-mile spacings for cable systems.

The sheathed-waveguide medium, sheath and waveguide terminations at repeater buildings, route engineering rules, and installation methods for the WT4 system were developed concurrently to ensure economical installation with low transmission loss by exploiting and enhancing the beam stiffness of the waveguide tubing. Companion papers in this issue discuss the relationship between waveguide loss and curvature,[1,2] the design of repeater buildings,[3] and the design of the sheathed-waveguide medium.[4] This paper will provide a brief review of the route engineering process and of methods for siting repeater stations with a more detailed discussion of the design of trench-bottom profiles.

Installation of the WT4 transmission medium is a two-step process. An outer sheath consisting of a nominal 5½ inch (14 cm) pipe is installed first using pipeline technology with only minor modifications. The waveguide is then inserted into the sheath by a specially developed insertion system.[5] The sheath installation methods developed for the WT4 system result in the economical joining and burial of the sheath and provide a satisfactory environment for the insertion of WT4 waveguide. A brief review of the sheath installation process emphasizes differences between cable and waveguide installation as well as deviations from usual pipeline procedures.

II. ROUTE ENGINEERING

2.1 Introduction

Route engineering methods for waveguide systems have evolved from methods used for coaxial cable systems in a manner dictated by the different electrical and mechanical properties of the new medium. A field evaluation test of the WT4 system[6] provided a data base for the determination of loss-curvature relationships for the sheathed-waveguide medium while beam theory provided an understanding of the connection between waveguide curvature and installation parameters.

Route engineering is an iterative process since the optimum route must be chosen on the basis of cost comparisons requiring data which cannot be obtained until a route has been at least tentatively selected. The process starts with an initial cost estimate based on an estimated route length which is established in the first, or exploratory, phase of route engineering. Estimates of route length and location are refined in two succeeding stages: the preliminary and detailed engineering phases.

2.2 Exploratory and preliminary engineering phases

The exploratory phase is based on a map study of the area between main stations. Its objective is to select a corridor joining the stations and having sufficient width that there is a virtual certainty of finding a usable right of way within the corridor. Potential obstacles are plotted on the map and the location of the corridor is chosen to avoid them. The length of the center line of the corridor is determined from the map with an allowance for route refinement.

Principal components of the cost of the system are the costs of the transmission medium and the repeater stations. The medium cost has three components which can be estimated: the costs of right of way, materials, and construction. The required number of repeater stations will be determined by the total loss in the waveguide medium between main stations. Since the loss depends upon the curvatures of the as-yet unspecified route, it cannot be calculated at this stage and the number of repeaters must be estimated by dividing the corridor length by an average spacing. This spacing should be conservatively short to allow for possible extreme conditions which might be encountered along the final route. The average repeater spacing recommended for cost estimating is 31 miles (50 km).

In the preliminary engineering phase the previously selected corridor is narrowed to a swath approximately 2 miles wide on the basis of a more detailed map study. The objective is to confirm the feasibility of constructing a WT4 system in the narrower corridor and to update cost estimates. The map study is supplemented by field work to confirm the nature and extent of all obstacles indicated by the map study or by consultation with various planning authorities. In addition, a broad environmental study is carried out by Bell System personnel to identify environmentally sensitive areas. Repeater station and medium costs must again be estimated on the basis of the length of the corridor centerline.

2.3 Detailed engineering overview

The objective of the detailed engineering phase of route engineering is the issuance of construction specifications covering installation of the sheath. Detailed engineering commences with a continuation of the map study carried out in the preliminary engineering phase. Aerial surveys are obtained at this stage to serve as a basis for a detailed layout of the route and to provide ground profile information needed for design of the trench-bottom profile. From the trial layout, losses can be calculated to determine whether the trial repeater spans are acceptable. The route layout is acceptable if the following conditions are met: (*i*) None of the waveguide runs between repeater stations have losses which exceed the loss allowance; (*ii*) the real estate can be purchased or easements obtained; and (*iii*) the layout yields the least-cost system between main stations. Methods of loss calculation and repeater station siting will be discussed below as will sheath properties and plan and profile design.

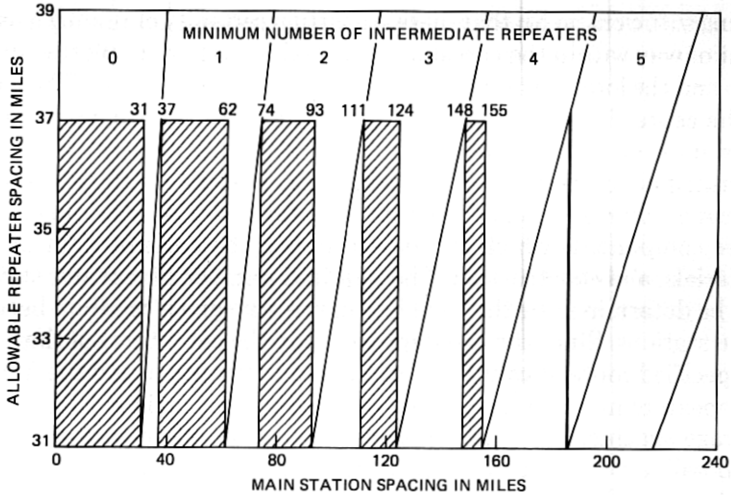


Fig. 1—Minimum number of intermediate repeaters.

III. LOSS CALCULATIONS AND REPEATER SITING

3.1 Introduction

Main station spans for WT4 systems, as for coaxial cable systems, will range from a few tens of miles to several hundred miles. Repeater station spacings will range from 31 miles (50 km) in very difficult terrain to 37 miles (60 km) in relatively gentle terrain and on super-highway rights-of-way.[7] Figure 1 shows the minimum number of intermediate repeater stations required as a function of main station span and maximum allowable repeater station spacing. The solid inclined lines represent limiting combinations of repeater spacing and main station span which necessitate a given minimum number of intermediate repeaters. Combinations of spacing and span lying in the regions between these lines require, as a minimum, the number of repeaters corresponding to the line forming the right boundary of the region. For main station spans lying in the cross-hatched areas of Fig. 1, the minimum number of intermediate repeaters required will be independent of maximum allowable repeater spacing over the normal range of 31 to 37 miles and loss calculations can be expected to confirm the acceptability of a trial layout based on the given number of repeaters. For combinations of main station span and maximum allowable repeater spacing which plot between the cross-hatched areas and near the inclined lines, loss calculations may show the need for an additional repeater if the estimated value of allowable repeater spacing was not sufficiently conservative. The need for this additional repeater may usually be obviated by a relatively small decrease in route length or by a decrease in loss effected by eliminating plan bends or by avoiding rough terrain. A trial-and-error process based on the foregoing discussion will suffice for the initial choice of repeater sites for main station spans up to about 150 miles (240 km). For longer spans it may be desirable to use a computerized method of siting repeaters which is described below. In either case it is necessary to calculate losses for all segments of the route at some stage of the route engineering process.

3.2 Loss calculations

Complete route information in both the plan and profile planes is required for the calculation of losses. The data required for each plan bend, derivable from a layout of the proposed route, is: (*i*) location, (*ii*) radius of curvature, and (*iii*) angle. The sheath profile, as designed by means of the beam curve profiling technique discussed below, provides the following required profile bend data: (*i*) location, (*ii*) change in grade, and (*iii*) sign of grade change. Locations are given as surveyor's "stations" which represent length in feet from an arbitrary reference. This route information is input to a set of loss programs which calculate total loss for each ½-mile segment of the route for use in hand calculation of cumulative loss for each trial repeater span or for input to a repeater siting program. The total losses include, in addition to the loss contributions of the plan and profile bends, statistical estimates of all other contributors.

3.3 Repeater siting

A repeater siting program, having as inputs the main station span and the losses for each route segment, determines trial repeater sites with allowed ranges. The route engineer attempts to fix the actual repeater sites within the allowed ranges according to the following guidelines: (*i*) repeaters should be sited where there is access for maintenance and repair via an all-weather road, (*ii*) zoning regulations must permit construction of a repeater building, (*iii*) repeater sites must have commercial electrical power available to them, and (*iv*) it is desirable to site repeaters near property lines.

3.4 Repeater spacing—route selection trade-offs

For each main station span with N repeaters, there is some total "slack" in miles which represents the difference between the maximum distance which those N repeaters could have spanned and the actual right-of-way length. The right-of-way length for a span may be such that the total slack is a large percentage of the repeater spacing. If, in addition, the route contains many bends, then repeater spacing will be controlled by the loss at the high frequency end of the transmission band. In this case, it may be cost-effective to modify the route in order to eliminate the need for an underutilized repeater. The loss at the high end of the band can be reduced by eliminating some of the route bends since they cause large losses.

Another reason for modifying the route may be the fact that constraints imposed by special right-of-way conditions have led to the need for manually sited repeaters which may have partitioned the route in such a way that an "extra" repeater is required. One solution is to reroute in order to avoid these special right-of-way conditions altogether and thus eliminate the "extra" repeater. When this is not possible and when the repeater spacing is controlled by the loss at the high end of the band, another solution may be to eliminate enough route loss to drop the "extra" repeater.

To test whether a reroute which eliminates some route bends is worthwhile, route losses for the reroute are calculated and the repeater siting process is again performed in order to check on the number of repeaters needed.

IV. SHEATH PROPERTIES AND TRENCH PROFILE DESIGN

4.1 Introduction

The degrading effects of waveguide-axis curvature on the transmission properties of a waveguide system have been discussed in other papers in this issue.[1,2,4] The only curvature contribution controlled by route engineering is that inherent in the designed sheath configuration. If the designed profile of a trench bottom is such that the sheath can conform to the profile under its own weight and the trench bottom is excavated perfectly to the designed profile, then the sheath will be supported everywhere and soil forces can have no effect in degrading the sheath-axis curvature. Because of the practicalities of trench excavation there will in fact be trench-bottom roughness which will cause the as-excavated trench-bottom profile to deviate from the designed profile. This deviation will result in the sheath having unsupported spans of varying lengths and the weight of the backfilled soil will force the sheath down in these areas to some extent, giving additional sheath axis curvature. If, in addition, the sheath with no soil load cannot conform perfectly to the designed profile, then there will be additional curvature contributions resulting from the backfill acting on any designed-in spans. It is therefore essential that trench-bottom profiles be designed for good gravity conformance of the sheath and that they be so staked out as to facilitate excavation with sufficient precision by conventional methods. Trench-bottom profiles consisting only of straight line segments can satisfy these conditions by exploiting the natural shapes of the pipe as determined by its elastic properties and the gravity loading.

4.2 Sheath properties

The WT4 sheath consists of $5\frac{9}{16}$-inch-diameter line pipe procured from the pipe mill in lengths, called "joints," which are approximately 60 feet (18 m) long. When many straight joints are precisely butt-welded together the result is a very long pipe which behaves like a beam loaded by its own weight and which would, if unconstrained in a gravity-free environment, be straight. If the pipe were to be placed in a straight trench with a bottom having an arbitrary (vertical) profile it would generally not conform perfectly, would have unsupported spans of various lengths with concentrated support reactions, and would have axis curvature which varied with distance along the pipe. Nevertheless the shape of the profile of the sheath axis would be a characteristic planar beam curve having no discontinuities in displacement, slope, or curvature. A satisfactory sheath profile would, in addition to these desirable properties, have no radii of curvature smaller than a specified minimum which should, of course, be somewhat larger than the radius at which the pipe takes a permanent set.

Similarly, a long length of pipe under the action of gravity and friction on a smooth horizontal surface could take on various planar shapes depending on the manner in which it was placed. In a trench of arbitrary plan having a smooth horizontal bottom, and sufficient width to prevent contact of the sheath with the trench wall, there would be no concentrated horizontal forces acting on the sheath. In addition, since the coefficient of friction between the soil and the sheath can be expected to be less than unity, the horizontal frictional force per unit length normal to the pipe axis will be less than the unit weight of the pipe. For these reasons a plan bend will tend to have more gentle curvature transitions than a vertical bend having the same minimum radius. Because of the less-than-unity coefficient of friction, this will be true even in the case of nonplanar bends which may have concentrated frictional reactions corresponding to concentrated support reactions.

The requirements on axis geometry for a practical transmission waveguide are satisfied by the sheath shapes described above. This leads to the conclusion that sheath sections joined appropriately and laid in trenches with reasonable profile and plan-bend configurations provide, fortuitiously, an eminently satisfactory environment for the insertion of WT4 waveguide.

4.3 Minimum bend radius

As a basis for the design of sheath configurations it is necessary to establish an allowable minimum bend radius. From the mechanical viewpoint this minimum is limited by two factors: (*i*) the yield stress of the sheath pipe and (*ii*) the limited elastic range of the roller support springs which deflect in bends under the action of thermal axial forces in the waveguide. The purchase of more expensive high-strength pipe can decrease the allowable minimum bend radius of the sheath but the solution of the roller support loading problem is either to increase the stiffness, and thereby decrease the mechanical filtering capability, or to increase the pipe diameter which of course increases the stresses in bending for a given bend radius. These considerations and the fact that route bend losses increase sharply with curvature argue for a large minimum bend radius.

Large minimum radii have, however, undesirable effects in both plan and profile layout. In the plan situation the fact that property boundaries are normally straight lines which meet at various angles makes it impossible to confine the right-of-way sufficiently close to the property boundaries when a large-radius large-angle bend is made. Since building cannot be permitted on the right-of-way, such a bend may necessitate purchase of one or more house lots even though the remainder of the right-of-way is obtained on an easement basis. In the vertical situation the restriction of the minimum radius to a large value results in additional excavation at changes in grade. For the WT4 field evaluation test these considerations led to the specification of a maximum allowable curvature, resulting from the vectorial addition of plan and profile curvatures, corresponding to a radius of curvature of 250 feet (75 m).

4.4 Sheath profile design requirements

In addition to meeting the minimum-bend-radius criterion, a waveguide trench-bottom profile must also allow for a minimum depth of cover over the sheath. Analysis of failure rates on small-diameter pipelines and communication cables as a function of depth of burial indicates that there is a significant decrease in failure rate as the depth of cover is increased in the range from 3 to 4 feet (0.9 to 1.2 m). Also the average maximum annual temperature excursion decreases with increased depth of cover. Lower temperature excursions of course mean smaller excursions of thermal stress in the waveguide. On the basis of these considerations, a minimum depth of cover of 3.5 feet (1 m) was specified for the WT4 sheath.

In general terms the problem of designing a trench-bottom profile for a given ground profile consists of meeting both the minimum-cover requirement and the minimum-radius requirement while minimizing in some sense both the sheath-axis curvature and the total excavation. For a variety of reasons this problem is not subject to solution by mathematical modeling. First, the soil-sheath interaction is basically nonlinear because the sheath support reaction forces can take on any positive value but cannot go negative. Secondly, the cost function for curvature is very difficult to define because of its own nonlinearity and because of the complex interactions of the cost of loss with the other cost factors in the total route engineering problem. In addition, a reasonable cost function for excavation depth is not available.

Besides the intractability of the mathematical solution, there are other reasons for taking a simpler approach. It is desirable to use natural low-loss beam shapes for trench-bottom profiles, to employ design procedures which are appropriate for the personnel who will execute the design, and to call for trench shapes which are easily produced by contractors. Before proceeding to a detailed exposition of a method of designing trench-bottom profiles which satisfy these requirements, we will attempt to provide some physical feeling for the effect of the sheath stiffness in limiting ground conformance.

4.5 Sinusoidal profiles and pick-up curves

Sinusoidal ground profiles are not particularly common in nature and because of their periodicity are inimical to good waveguide performance. Nevertheless, the consideration of hypothetical sinusoidal ground profiles can provide a good physical basis for the evaluation of the magnitude of trench-bottom roughness relative to the amplitude of sinusoidal profiles to which the sheath could conform under gravity. It is noted in Appendix A that a useful parameter for characterizing the bending behavior of beams is a bending characteristic length λ defined by the relationship

$$\lambda = \sqrt[3]{EI/w}$$

where EI = bending stiffness and w = weight per unit length. The WT4 sheath pipe will conform to a sinusoidal profile of a given amplitude provided that the maximum force-per-unit-length required to deform the sheath to a sinusoid of that amplitude is no greater than the weight per-unit-length of the pipe. The relationship among amplitude, wavelength, and bending characteristic length for the limiting case of contact is shown in Appendix A to be

$$y_{o(\max)} = \frac{\lambda}{(2\pi)^4}\left(\frac{L}{\lambda}\right)^4$$

or, for WT4 sheath with $y_{o(\max)}$ and L in feet,

$$y_{o(\max)} = 3 \times 10^{-9} L^4$$

where $Y_{o(\max)}$ = maximum amplitude for full contact and L = wavelength. This result is plotted in Fig. 2, where all combinations of (double) amplitude and wavelength lying below the solid line represent ground profiles to which the WT4 sheath would conform everywhere.

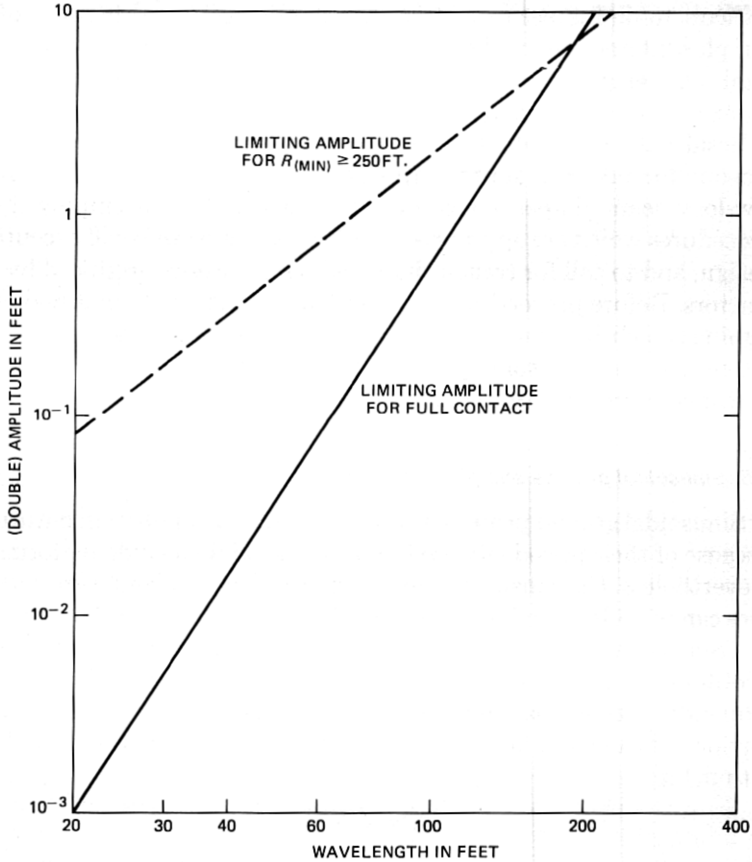


Fig. 2—WT4 sheath on sinusoidal profile.

The minimum radius of curvature of a sinusoidal configuration is also a function of its amplitude. In Appendix A there is derived, for the amplitude at which the minimum radius of curvature is the value R_0, the expression

$$y_{o(R_o)} = \frac{1}{(2\pi)^2} \frac{L^2}{R_o}$$

which, for WT4 sheath, can also be written

$$y_{o(250)} = 10^{-4} L^2$$

for a minimum radius of 250 feet (75 m) and for $y_{o(250)}$ and L in feet. This expression is also plotted in Fig. 2.

For a wavelength of 60 feet (18 m) Fig. 2 shows that a WT4 sheath will contact a sinusoidal profile everywhere only if the excursion, or double amplitude, is less than 0.93 inches (2.4 cm). The minimum radius of curvature of such a configuration would be approximately 2400 feet (720 m). For a wavelength of 200 feet (61 m) the maximum excursion for full contact would be nearly 10 feet (3.1 m) and the minimum radius would be approximately 213 feet (65 m). Study of Fig. 2 and the associated equations leads to the conclusions that (*i*) WT4 sheaths which are fully supported by nominally flat trench bottoms have very low curvatures, (*ii*) WT4 wheaths on profiles having elevation excursions of tens of feet may be fully supported if they have wavelengths of hundreds of feet. Such sheaths may, however, have radii of curvature less than 250 feet (75 m).

The axis curvature of fully supported sheaths will not be degraded by backfill loading. Sheaths on sinusoidal profiles having combinations of amplitude and wavelength lying above the solid line of Fig. 2 will have unsupported spans and thus will suffer degradation. This problem is discussed by Gretter et al.[4] On the basis of that work a maximum allowable unsupported span of 30 feet (9 m) was specified for WT4 sheath.

A satisfactory trench-bottom profile, in addition to meeting curvature and conformance requirements, must also minimize "excess" excavation beyond the nominal trench depth of 4 feet (1.2 m), which includes minimum cover plus sheath diameter. The stiffness of the sheath tends to limit the extent to which it can conform with a (downward-displaced) replica of the ground profile, and thus avoid excess excavation, while meeting other requirements. Since the limiting sinusoidal profiles are not of much use when we are concerned with an isolated profile feature, we employ another sheath configuration, referred to as a "pick-up curve," for illustrating the effect of sheath stiffness. Consider a very long length of WT4 sheath pipe lying on a horizontal plane surface. If the pipe is lifted by means of a sling at a point far from either end, there will be a symmetrical region, centered at the pick-up point, in which the sheath does not contact the ground. In Appendix B there are derived the following expressions for the extent, A, of this region of noncontact and the minimum radius of curvature, both as a function of the pick-up height, H:

$$A = 2\sqrt[4]{\frac{72EIH}{w}}$$

or

$$A = 2\lambda\sqrt[4]{\frac{72H}{\lambda}}$$

and

$$1/R(\min) = \sqrt{\frac{2wH}{EI}}$$

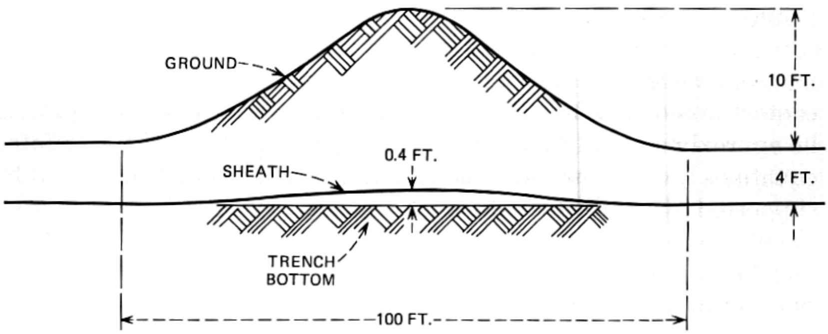


Fig. 3—Cross section through a hypothetical ridge.

or

$$1/R(\min) = \frac{1}{\lambda}\sqrt{\frac{2H}{\lambda}}$$

where, for the WT4 sheath, $\lambda = 60$ feet (18 m).

Assume that a waveguide system is to cross a rather high but narrow ridge lying in an area that is otherwise completely flat. The question arises as to how much excavation can be saved by attempting to make the trench bottom profile follow the ground profile as closely as permitted by the stiffness and by radius requirements. Figure 3 shows a cross section through a hypothetical ridge which is 10 feet (3 m) high and 100 feet (30 m) wide at its base. The figure is drawn with a 5-to-1 vertical scale exaggeration in order to make the pick-up height visible. The trench is excavated so that its bottom is 4 feet (1.2 m) below the level of the plane surface on which the ridge is located. A length of WT4 sheath lying on the trench bottom has been lifted to such a height that the touch-down points lie at the extreme edges of the ridge. If the sheath were to be lifted any higher the depth of cover requirement would be violated at these points. It is obvious from the scaled drawing that the amount of excavation to be saved by employing this sheath profile, in place of the straight line, is not worth the extra surveying and staking effort particularly in view of the additional curvature introduced into the sheath.

4.6 Conventional route design

Route layout work for Bell System right-of-way projects is frequently contracted out to engineering concerns which handle the complete surveying and drafting job. In highway work, at least for low-speed highways, it is normal for surveyors to use circular arcs for horizontal curves. Similarly, parabolas are used as vertical curves for joining grade tangents. Neither of these curves is strictly applicable for laying out waveguide trenches because they are not characteristic shapes for beams with the support and loading conditions encountered by WT4 sheath.

Consider a plan bend which is laid out as two tangents connected by a circular arc. If the trench were excavated exactly to this shape, it would be necessary to apply concentrated bending moments at appropriate points in order to make the sheath lie exactly along the centerline of the trench. As a practical matter this layout is satisfactory because frictional forces can generate the necessary moment in the sheath over a distance of the order of 100 feet (30 m) with the result that the sheath, when lowered into the trench, will lie within approximately 6 inches (16 cm) of the centerline throughout a bend having a radius of 250 feet (75 m). The shapes taken by WT4 sheath, when constrained only by trench-bottom friction in plan bends, have curvatures which vary continuously from zero in the straight runs to maxima in the arcs. These so-called "curvature tapers" are very desirable from the point of view of electrical loss.

The horizontal deviations from center line in the plan case are not objectionable because backfill will not increase the existing sheath curvatures. In the vertical case, however, it is necessary to have good conformance of the pipe with the trench bottom prior to applying backfill. For small changes in slope a parabola is, to all intents and purposes, a circular arc since its curvature is nearly constant. Therefore, a sheath pipe under gravity will not conform with a parabolic vertical curve.

4.7 Beam curve profiles

Instead of designing a profile based on an arbitrary curve, we consider using the natural curves which the sheath pipe takes when it is laid on profiles consisting of intersecting grade tangents. It is shown in Appendix C that the appropriate "sag" curve for a concave upward or positive change in grade is that of an ordinary simply supported beam. Expressions are derived in this appendix for the span, the maximum curvature, and the clearance between the curve and the point of intersection of the grade tangents. If we add an additional short grade tangent which just osculates with the center of the simply supported beam, we have the configuration of Fig. 4. In this situation the maximum unsupported span is now the half length of the beam. Positive changes in grade up to 20 percent can be handled with a single sag curve of this type without exceeding the curvature limit corresponding to a 250 foot (75 m) radius.

Since the clearance between the sheath and a trench-bottom profile consisting of the three straight grade tangents would be of the order of the trench bottom roughness in a typical pipeline excavation, there is no point in calculating the actual beam profile and attempting to excavate a trench bottom of this shape. A similar observation applies to the surveyor's parabolic vertical curve. The vertical curve to be employed in the simplified method of profile design for WT4 sheath is therefore merely the straight line defined by the osculating tangent of Fig. 4. For changes in grade greater than about 9 percent, the unsupported spans will be longer than the 30 foot (9 m) allowable maximum and will be propped during construction with sand bags or other material as are similar spans elsewhere.

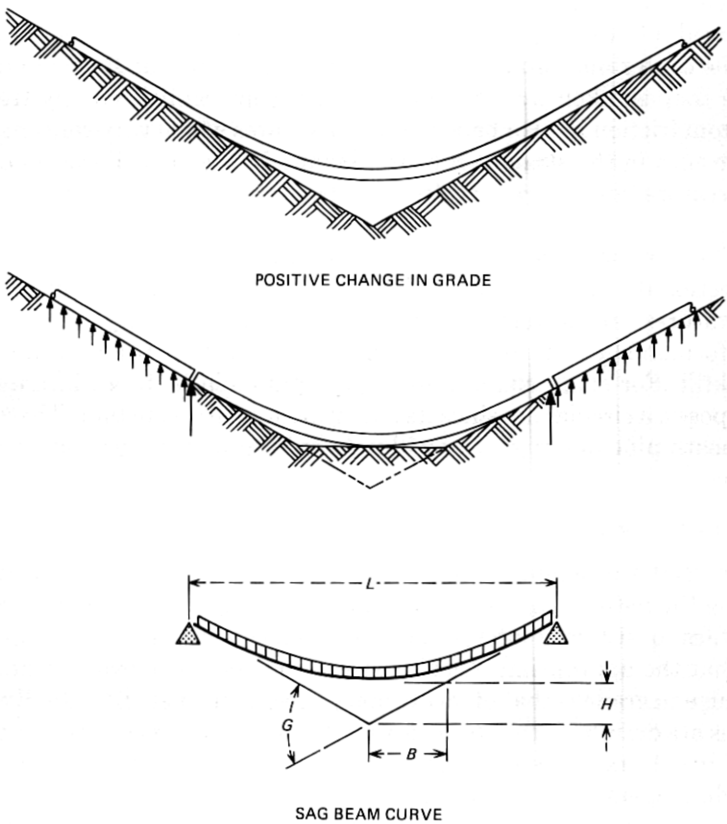
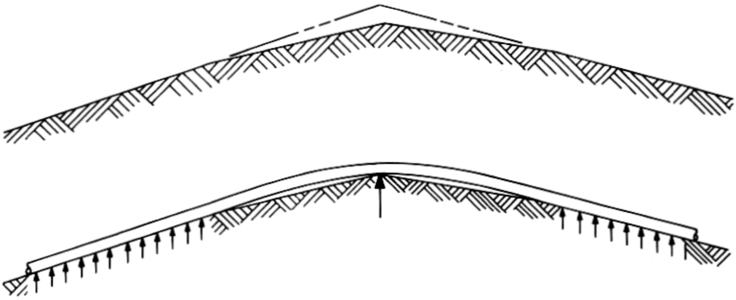


Fig. 4—WT4 sheath at positive change in grade.

In Appendix C the parameters of a "crest" curve consisting of a double cantilever are derived. The resulting configuration is shown in Fig. 5. The support point for the double cantilever lies below the point of intersection of the two original grade tangents. Therefore there are two additional short grade tangents running from the new point of intersection to the tangent points of the beam curve with the original grade tangents. In the crest situation the appropriate trench-bottom transition also consists of straight lines but the allowable maximum change in grade for a 250 foot (75 m) minimum radius of curvature is only 10 percent.



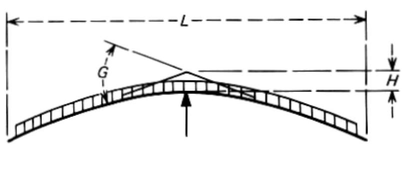


Fig. 5—WT4 sheath at negative change in grade.

4.8 Trench-bottom profile design

Design of a trench-bottom profile is generally an iterative process regardless of the type of vertical curve employed. A series of reasonably long grade tangents are initially established in some manner. The vertical curves which provide smooth transitions at each point of intersection are then calculated and plotted. The resulting profile may be unsatisfactory for a variety of reasons. It may call for excessive excavation, it may not provide sufficient cover over the pipe at all points, and one or more of the grade tangents may be too short to accommodate the half-lengths of the adjacent vertical curves. In addition, for the beam curve method, excessive curvature in the sheath pipe could occur if there were excessive changes in grade at any of the points of intersection between the originally-chosen grade tangents.

4.8.1 Beam-curve overlays

To simplify the iterative process and ensure that curvature requirements are met, a method of profiling based on transparent overlays has been developed. Beam-curve overlays for positive and negative changes in grade are shown in Fig. 6. The method is described in Appendix D.

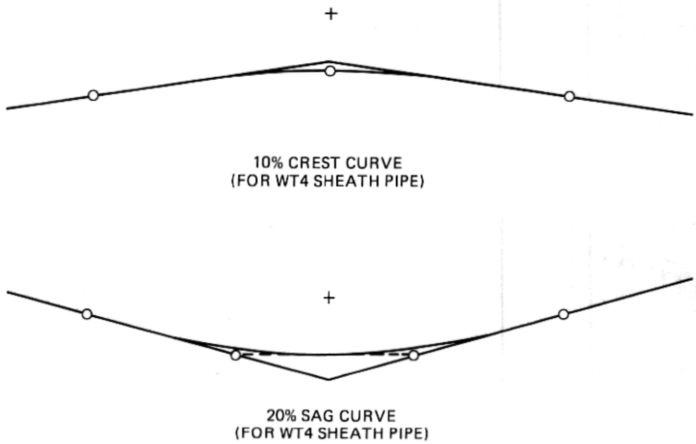


Fig. 6—Sample beam-curve overlays.

4.8.2 Constant-depth trenching

For small changes in grade, the deviations of a beam curve from its grade tangents will be smaller than the usual accuracy of excavation. Also the ground profile, consisting as it does of a series of chords, is only an approximation to the actual shape of the ground. In addition, wheel-type or ladder-type trenchers which are normally track-mounted will tend to provide some smoothing of small discrete changes in grade. For these reasons a trencher on gently rolling ground with reasonable soil conditions will normally produce a perfectly satisfactory trench bottom on a constant-depth-trenching basis. The detailed beam-curve-profiling design process therefore only needs to be used for final route profiling in areas where there are changes in grade greater than approximately 6 percent for positive changes and 3 percent for negative. These limits will of course, depend on the amount of pregrading of the right of way to be done during installation. When the beam-curve method is used the final profile information will consist of station and elevation data for the points of intersection of trench-bottom grade tangents.

4.8.3 Computerized Profiling

The trench bottom profile, in addition to being required for specifying the desired trench shape to the excavator after completion of design, would also be useful early in the route engineering process for determining curvature for loss calculations. To meet this need a method of generating beam curve profiles by computer was developed. The rationale of the approach and the resulting algorithms are described briefly in Appendix E. The input to a set of profile-modifying routines is station and elevation data for a ground profile which has been derived from photogrammetric information. One output of this set of programs is a trench bottom "pseudoprofile" which, along with a beam curve at each of its points of intersection, defines the shape of the sheath. Station, elevation, and change in grade data for each point of intersection of the pseudo profile serve as input to a variety of other proposed programs which will calculate the elevation and curvature of the profile at any point, station and elevation of the additional points of intersection for the trench bottom profile, the excess excavation as a function of distance along the trench bottom, and various statistics on excess depth and curvature.

V. SHEATH INSTALLATION

5.1 *Introduction*

Because emplacement of the sheath was expected to be the largest cost element in WT4 installation, it was an important development objective that the economical construction techniques of the pipeline industry be employed. Since the WT4 sheath consists of line pipe, joined by welding and installed prior to insertion of the waveguide, its installation is so similar to that for a gas or oil pipe that it is essentially pipelining. There are, however, two important differences between pipelining and sheath installation. First, the entire length of the sheath must be installed elastically. This prohibits the use of plastic bending for obtaining good ground conformance. Second, in order to ensure a smooth interior surface the sheath is joined by partial penetration welds in contrast with the full penetration welds used by the pipeline industry. These differences will be highlighted in the following review of the installation process.

5.2 *Staking, clearing, and trenching*

After purchase of the right-of-way for a WT4 system the trench center line and the clearing limits are staked out. The right of way is then cleared and destumped. In pipelining it is customary to pregrade the right of way in order to smooth out irregularities of the profile as well as to provide a better working surface for vehicles. Pregrading will also be used for WT4. After pregrading, the trench center line is restaked. Plan bends are staked out as a series of chords and the profile consists only of straight grade tangents. The trench is excavated by means of wheel-type trenchers or backhoes depending on the soil properties. The principal requirement for the excavation in addition to the large-radius bends and, in some cases somewhat deeper cuts, is that the bottom be sufficiently smooth for the pipe to be properly supported. Sheath support is discussed below in connection with lowering in of the sheath. Padding of the trench bottom with sand or other acceptable material is only required where rock is encountered.

On a pipeline job the trench is usually excavated to a constant depth from the pregraded surface. In gently rolling country the resulting trench profile would normally be satisfactory for either a waveguide sheath or a pipeline in that the pipe would conform well with the trench bottom under its own weight. In rough terrain the trench bottom, if prepared in this manner, would have excess curvature and abrupt changes in grade which would prevent a straight pipe string from conforming elastically. In pipelining the abrupt changes in grade as well as the plan bends are handled by plastic bending of the pipe to a radius of a few feet. The bends are specified in location and magnitude by a bending engineer who marks the information on the joints of pipe before they are welded together. The fact that this procedure cannot be used in the installation of WT4 sheath should cause no serious problems for the pipeline contractor since the trench will have been staked out in both plan and profile to a configuration which takes into account the natural elastic behavior of the sheath. The skills of the bending engineer should make it easy to adapt to beam-curve profiles and to handling the problem of providing grade reference for excavators by means of various commercially available systems. Additionally many pipeliners have had experience with a method of installation, referred to as "free stressing," in which the pipe is installed without prebending.

5.3 Sheath handling and joining

The lengths of sheath are "strung" along the edge of the right-of-way (either before or after trenching) as shown in Fig. 7. As in pipelining, the next step in sheath installation after completion of the trench is joining of the pipe. Lengths of sheath are lifted by a tractor-mounted side boom, the ends are simply butted together, and a partial-penetration weld is made. The sheath is easily aligned with an outside line-up clamp and the joint requires few weld passes, no x-ray inspection, and only minimal testing. Although the welding procedure differs from that employed in pipelining, the difference is principally psychological in that experienced welders find it difficult to believe that they are required to make a type of weld which would be cause for instant dismissal on a conventional pipeline job. Once this obstacle is overcome the ease of line-up resulting from the fact that the two lengths of pipe are butted tightly together and the relative freedom from the danger of "burn through" inherent in the partial penetration weld should combine to increase production rates over those achieved in pipelining.

5.4 Lowering-in and backfilling

The continuous string of welded pipe is lowered into the trench by a side boom equipped with a roller sling as shown in Fig. 8. Before the

Fig. 7—Sheath strung along right of way.

Fig. 8—Sheath being lowered into trench.

trench is backfilled a visual inspection is made for conformance of the sheath with the trench bottom to ensure that the sheath is properly supported. The requirement for sheath support is that there be no unsupported spans longer than 30 feet (9 m). This support requirement for WT4 sheath is no more severe than normal bedding requirements for pipelines. Because of its stiffness properties the sheath constitutes an inspection "spline" for checking the trench bottom. Unacceptable spans are immediately apparent and are propped with sand bags, tamped soil, or other suitable material. After visual inspection and propping of any excessively long spans the trench is backfilled conventionally.

5.5 Conclusion

Upon completion of a repeater-to-repeater length of sheath, the pipe is cleaned, dried, and pressure tested. Cleaning and drying are accomplished by blowing plugs through the pipe by means of dry air or dry nitrogen. In the field evaluation test 8.5 miles of sheath were installed, tested, cleaned, and dried as described above.

Curvature contributions of the sheath installation process, in addition to trench-bottom roughness, include contributions to sheath-axis tilt and offset which may be introduced by faulty line-up during sheath joining, the small-radius bends which would remain in the pipe if it were plastically yielded by handling, and such defects as excess ovality or dents in the pipe, also caused by mishandling during installation. All of these contributions can be minimized by well written installation specifications and good inspection practices. It is expected that future waveguide sheath installations will be inspected prior to acceptance by means of a sheath inspection gauge which, in addition to locating dents, will print out data on all radii of curvature below 300 ft and all tilts and offsets above specified values.

VI. SUMMARY

In a review of the route engineering process for WT4 systems the effect on repeater spacing of the dependence of loss on curvature was discussed. Proposed methods of route layout using initial and improved estimates of repeater spacing were given. It was shown that these methods should suffice for short main station spans where the large ratio of repeater station spacing to main station spacing restricts the possibility of eliminating repeaters by decreasing loss or route mileage. Methods of calculating losses to confirm repeater spacing and for use in designing routes for long main station spans with few constraints on repeater siting were outlined. The elastic properties of the sheathed waveguide medium were discussed at some length in order to provide a feeling for profile design and for problems of obtaining ground conformance. A method of designing trench bottom profiles consisting only of straight lines was discussed. Computerized methods which are under development for profile design, loss calculation, and repeater siting were outlined.

The installation process for WT4 sheath was briefly described with emphasis on two ways in which it differs from pipeline procedure. Experience gained in the field evaluation test indicates that these differences should not cause the cost of installation of waveguide sheath to be any higher than that of a similar-sized pipe in similar soil and topographical conditions, except for the additional right-of-way costs incidental to the large-radius plan bends and the extra excavation required in some cases to create acceptable profiles. The fact that the sheath for the field evaluation test was installed by a pipeline contractor supervised by personnel of AT&T Long Lines Department, Northeast Area, has shown the practicality of the installation methods.

ACKNOWLEDGMENTS

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APPENDIX A

WT4 sheath on sinusoidal profiles

Consider an infinitely long straight weightless pipe subjected to a planar normal loading which varies sinusoidally along the pipe axis. If the wavelength of the loading is long compared with the diameter of the pipe, it will deform in bending with a sinusoidal deformation of the same wavelength. Let the displacement of the pipe axis be given by

$$y = y_o \sin (2\pi z/L) \tag{1}$$

and the loading by

$$P = P_o \sin (2\pi z/L) \tag{2}$$

where z = axial length coordinate and L = wavelength. From the beam equation

$$EIy^{\text{IV}} = P(z) \tag{3}$$

we have

$$EI\left(\frac{2\pi}{L}\right)^4 y_o \sin (2\pi z/L) = P_o \sin (2\pi z/L)$$

or

$$y_o = \left(\frac{L}{2\pi}\right)^4 \frac{P_o}{EI} \tag{4}$$

A real beam, such as the WT4 sheath, will contact a sinusoidal ground profile everywhere if its amplitude is given by eq. (4) and the amplitude of the required loading meets the condition

$$|P_o| \leqslant w \tag{5}$$

where w = beam weight per unit length. Combining (4) with (5) gives the maximum amplitude for full contact as

$$y_{o(\max)} = \left(\frac{L}{2\pi}\right)^4 \left(\frac{w}{EI}\right) \tag{6}$$

Since the quantity (w/EI) has the dimension of inverse length cubed we write

$$\lambda = \sqrt[3]{EI/w} \tag{7}$$

and thus define a useful bending characteristic length λ. In terms of λ (6) becomes

$$y_{o(\max)} = \frac{\lambda}{(2\pi)^4} \left(\frac{L}{\lambda}\right)^4 \tag{8}$$

Since λ is very nearly 60 feet (18 m) for WT4 sheath, this can be written

$$y_{o(\max)} = 3 \times 10^{-9} L^4$$

for $y_{o(\max)}$ and L in feet.

From (1) we obtain

$$y'' = -\left(\frac{2\pi}{L}\right)^2 y_o \sin(2\pi z/L) \tag{9}$$

which, with the usual small slope assumption of elementary beam theory, is taken to be the curvature. Since the curvature will also be sinusoidally distributed we write

$$\rho = \rho_o \sin(2\pi z/L) \tag{10}$$

where

$$\rho = \text{curvature} = |-y''|. \tag{11}$$

From (9), (10), and (11) we obtain

$$\rho_o = \left(\frac{2\pi}{L}\right)^2 y_o \tag{12}$$

Since the minimum radius of curvature will correspond to the curvature amplitude of a sinusoidal configuration we have

$$1/\rho_o = R(\min) \tag{13}$$

which, with (12), gives

$$y_{o(R_o)} = \left(\frac{1}{2\pi}\right)^2 \frac{L^2}{R_o} \tag{14}$$

for the maximum amplitude of a sinusoidal configuration having a minimum radius of curvature R_o. For a minimum radius of curvature of 250 feet (75 m) and for $y_o(R_o)$ and L in feet this becomes

$$y_{o\,(250)} = 10^{-4} L^2$$

Equating the limiting amplitudes given by (8) and (14) and solving for L yields the expression

$$L = 2\pi\lambda \sqrt{\frac{\lambda}{R_o}} \tag{15}$$

for the wavelength at which the limits coincide. For shorter wavelengths the radius of curvature will be greater than the allowable minimum for any sheath which is fully supported by a sinusoidal profile.

APPENDIX B

Pick-up curves for WT4 sheath

Consider a long straight length of WT4 sheath lying on a horizontal plane surface. If a lifting force is applied to the sheath at its center, a symmetrical region of the sheath will leave contact with the surface. Since the beam has zero end slope and curvature at the "touch down" points we consider the lifted region to be a simply supported beam of length A, bending stiffness EI, and weight per unit length w. The end slope due to the lifting force F acting alone is given by

$$\theta_F = \frac{1}{16}\frac{FA^2}{EI}$$

while that for the beam weight alone is

$$\theta_w = -\frac{1}{24}\frac{wA^3}{EI}$$

By superposition the sum of these end slopes must be zero which leads to

$$F = \frac{2}{3} wA \tag{16}$$

Also by superposition, the height H of the beam at the force F is given by the sum of the deflections due to the force F and the weight

$$\delta_F = \frac{1}{48}\frac{FA^2}{EI}$$

and

$$\delta_w = -\frac{5}{384}\frac{wA^4}{EI}$$

which, with (16), when added yield

$$H = \frac{wA^4}{1152\,EI} \tag{17}$$

or

$$H = \frac{\lambda}{1152}\left(\frac{A}{\lambda}\right)^4 \tag{18}$$

where

$$\lambda = \sqrt[3]{EI/w}$$

Solving (17) for A in terms of H gives

$$A = 2\sqrt[4]{\frac{72\,EIH}{w}} \tag{19}$$

or

$$A = 2\lambda\sqrt[4]{\frac{72H}{\lambda}} \tag{20}$$

The bending moment is maximum at the load F and is given by

$$M_{(\max)} = \frac{wA^2}{24} \tag{21}$$

From the beam equation in terms of radius of curvature we have

$$EI/R_{(\min)} = M_{(\max)}$$

which with (21) gives

$$\frac{1}{R_{(\min)}} = \frac{1}{24}\frac{wA^2}{EI} \tag{22}$$

or

$$\frac{1}{R_{(\min)}} = \frac{1}{24}\frac{A^2}{\lambda^3} \tag{23}$$

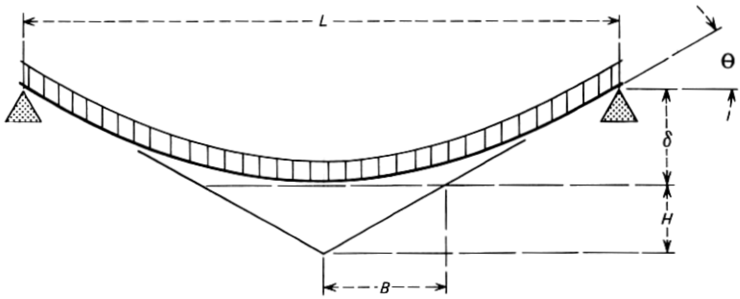

Fig. 9—WT4 sheath on simple supports.

Using (19) squared, the latter equations can be put into the forms

$$\frac{1}{R_{(\min)}} = \sqrt{\frac{2wH}{EI}} \tag{24}$$

and

$$\frac{1}{R_{(\min)}} = \frac{1}{\lambda}\sqrt{\frac{2H}{\lambda}} \tag{25}$$

respectively.

APPENDIX C

Derivation of beam curve formulae

Consider a V-shaped gully formed by two plane surfaces which intersect in a horizontal line. If a long beam, such as a length of WT4 sheath, is laid across the gully it will conform with the plane surfaces except near their intersection. The suspended portion will have the shape and the reactions of a beam on simple supports with end slopes equal to one half the change in grade. Figure 9 represents a length of WT4 sheath on simple supports and defines nomenclature for derivation of the sag beam-curve formulae.

Since the end slope angle θ is equal to one half of the fractional change in grade we have,

$$\theta = (1/2)(G/100) = G/200$$

where G = change of grade in percent.

From the geometry of Fig. 9 we obtain

$$B = H/\theta$$

and

$$H = (L/2)\theta - \delta$$

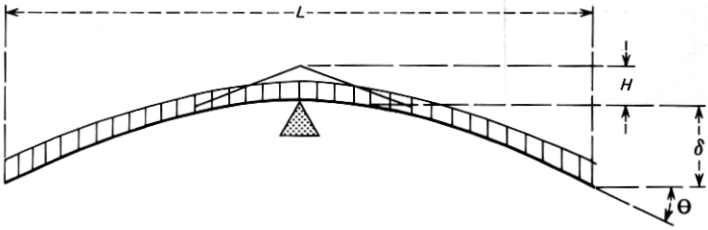

Fig. 10—WT4 sheath as double cantilever.

The fundamental beam equation relates bending stiffness, curvature (reciprocal of radius of curvature), and bending moment as follows

$$(EI)/R = M$$

and, for the minimum radius,

$$M_{(\max)} = (EI)/R_{(\min)}$$

With the above relationships, and others from elementary beam theory, there can readily be obtained expressions for L, $R_{(\min)}$, B, and H as follows:

$$L/\lambda = 2(3G/200)^{1/3}$$

$$R_{(\min)}/\lambda = 2(3G/200)^{-2/3}$$

$$B/\lambda = (3/8)(3G/200)^{1/3}$$

and

$$H/\lambda = (1/8)(3G/200)^{4/3}$$

where

$$\lambda = \sqrt[3]{(EI/w)}$$

Figure 10 depicts a length of WT4 sheath balanced at its midpoint on a simple support which is located a distance H below the point of intersection of a pair of grade tangents. The beam will be tangent at its ends with the grade tangents for a change in grade equal to twice the end slope of the beam. Inspection of Fig. 10 yields

$$H = (L/2)\theta - \delta$$

Appropriate combination of this relationship with the fundamental beam equation and others from elementary beam theory will produce expressions for L, $R_{(\max)}$, and H for the double cantilever as follows:

$$L/\lambda = 2(3G/100)^{1/3}$$

$$R_{(\max)}/\lambda = 2(3G/100)^{-2/3}$$

$$H/\lambda = (1/24)(3G/100)^{4/3}$$

Numerical values can be obtained for WT4 sheath by setting λ equal to 60 feet (18 m).

APPENDIX D

Beam-curve profiling with transparent overlays

Formulae for beam curves to be used at grade changes in trench-bottom profiles for WT4 sheath were derived in Appendix C. Plots of these curves to an appropriate scale on transparent plastic sheets have been made for use in designing profiles. Sag curves, for positive changes in grade, were made for changes in grade from 4 percent to 20 percent with increments of 2 percent. For the crest, or negative change-in-grade curves, the increment is 1 percent and the curves cover the range from 2 percent to 10 percent change in grade. Samples of these curves are shown in Fig. 6. For both types of curve the outer pair of small circles indicate the limit of the curved portion of the transition between grade tangents.

The other pair of circles on the sag curves mark the points of intersection of the added short (osculating) tangent with the original grade tangents. On the crest curves the central circle marks the support point for the double cantilever and thus the point of intersection of the two additional short grade tangents. On both types of curves the grade tangents which the curve joins are extended as lighter lines and there is a cross mark 4 feet (1.2 m), to scale, above the center of the curve.

The overlays are used with a ground profile which has been drawn to an appropriate scale. Although some vertical exaggeration is desirable excess vertical exaggeration tends to make the overlay curves have angles which are too large for the usual small-angle approximations to apply even though they do apply very well for the actual sheath curves. Perusal of a selection of AT&T Long Lines profile drawings which had exaggeration factors of 1, 2, 4, 5, and 10 led to a decision that a ratio of 2½ for horizontal to vertical scale would provide sufficient vertical exaggeration without occasioning problems due to angularity. Accordingly, a scale of 20 feet to the inch (240 to 1) horizontally and 8 feet to the inch (96 to 1) vertically was used.

The most straightforward way to commence the design process with beam curve overlays is to draw a "phantom" ground profile exactly 4 scale feet below the actual ground profile. By superimposing the transparent overlays in various combinations one then attempts to generate a profile which lies as closely as possible to the phantom but remains always below it. Each pair of overlays is superimposed in such a manner that the grade tangents coincide and the curved regions do not overlap. Where the ground profile has a long straight grade the overlays may be so far apart that the tangents cannot be superposed. In this case one simply makes the tangents parallel to or coincident with the straight grade in the phantom profile. Changes in grade larger than the maximum values covered by the beam curve overlays can be handled by using pairs of sag or crest curves.

After some experience with the method it is found that it is not necessary to draw the phantom ground profile. Instead the cross marks on the beam curve which indicate the 4 foot distance to the bottom of the pipe can be used directly with the ground profile to generate a trench bottom profile which meets the minimum-cover requirement.

After the optimum set of beam curves has been chosen and aligned, the points of interaction can be pricked through onto the original profile drawing. It is expected that templates will eventually be provided for drawing the actual beam curves in cases where the drawings are needed for obtaining road crossing permits.

APPENDIX E

Computer generation of WT4 trench-bottom profiles

Ground profile information for a WT4 route consists of short line segments, called "grade tangents" by surveyors, intersecting at "Points of Intersection" or PIs. The data is given in the form of station and elevation coordinates of the PIs. A series of computer programs has been developed to generate trench bottom profiles by successive modifications of a ground profile having grade tangents of arbitrary length.

Methods for generating an appropriate trench bottom profile for a given ground profile have been discussed in the body of this paper and in Appendix D. The WT4 beam curves which are used for making transitions between "long" grade tangents have lengths which range up to 80 feet (24 m). In order to avoid interference between beam curves "long" is therefore defined to be equal to or greater than 80 feet and a "pseudoprofile" is defined to consist of the long grade tangents. In order to yield a satisfactory trench bottom profile the pseudoprofile must have no positive changes in grade greater than 20 percent or negative changes in grade of magnitude greater than 10 percent and must have PIs far enough below the ground profile that no point on the bottom surface of the WT4 sheath will lie less than 4 ft below the ground profile.

Although beam curves have lengths which vary with the magnitude of the change in grade for which they provide a transition, it is assumed, for the purposes of this set of programs, that all beam curves are 80 feet (24 m) long. This assumption is made to simplify the logic of profile modifying routines and appears to lead to little excess excavation. The first steps in generating a trench-bottom profile start with the ground profile to produce a pseudoprofile which is then translated downward 4 feet (1.2 m) to provide for the minimum depth of cover.

The first profile modifying routine eliminates short grade tangents in concave downward situations. If a pair of adjacent tangents, meeting at a point of intersection with a negative change of grade, have a total length less than 160 feet (49 m) the central PI is eliminated. If one tangent is less than 80 feet long but their sum is greater than 160 feet, a new PI is established on the long tangent to create two new tangents each greater than 80 ft in length. Several applications of this routine eliminate all short grade tangents in concave downward situations. The second profile-modifying routine eliminates short grade tangents in upward concave portions of a profile by extending the tangents on each side of the short one so that they meet in a new PI below the short tangent.

A third routine decreases the magnitude of the change in grade at PIs having positive changes greater than 20 percent or negative changes greater in magnitude than 10 percent. Negative magnitudes are decreased by decreasing the elevations of the PIs at which the excess magnitudes occur.

At a positive change in grade the sheath will lie above the PI of the modified profile by the beam clearance H. If the PI does not lie below the original profile by at least an equal distance it will be necessary to lower the PI, thus increasing the change in grade. This increase may require further adjustment of the change in grade. A positive change in grade is reduced by decreasing the elevations of the PIs adjacent to the one having the excess change in grade. The decrements in elevation at the two adjacent PIs are so proportioned that the excess excavation under the two tangents which meet at the central PI are equal.

A fourth subroutine routine "spots" additional PIs (points of intersection) on long grade tangents prior to the use of the routine which reduces changes in grade by lowering PIs. If a grade tangent is longer than 160 feet a new PI is introduced at its center (or two are added 80.0 feet from the ends of the tangent) so that excavation will be minimized and no tangent will be shorter than 80.0 feet. All P.I.'s having zero change in grade, after adjustment of grade changes, are removed.

The above described programs yield a trench-bottom pseudoprofile which serves as input to other programs which generate the actual trench-bottom profile and calculate curvatures and excess depth of excavation.

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