Paper· 130

DETERMINING MINIMUM COST CROSS-SECTIONS FOR LINED CHANNELS

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ABSTRACT

Reducing channel lining costs involves not only utilization of low cost materials, but also optimally using these materials to convey the required flow. A mathematical treatment is presented for determining the minimum cost crosssectional shape and dimensions which will fulfill the hydraulic requirements, according to Manning's equation, for various bed and side wall material costs.

A practical example of lined watercourse design is given to explain the utilization of the results. Nomographs are presented to simplify the minimum cost design process.

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1.0 INTRODUCTION

In lined channels, the material costs are usually only a function of the volume of material used. On a per unit length basis, costs will be a function of the crossection area of lining material. The capacity of a given channel also depends upon the crossectional shape. By utilizing these two relationships, minimum cost crossections can be determined.

For our purposes, the different lining techniques being tested and installed in Pakistan will be divided into three cases.

I) Partial linings with no bottom;
II) Linings where the same type and thickness of material is used on the bottom and sides; and
III) Linings where the costs of bottom and sides materials are different.

In the first case, a minimized cost cannot be derived because there is no cost associated with bottom width. The section should be as wide and shallow as is practical. If the silt covered channel bottoms have low infiltration rates, as is often the case, this case represents a practical, low cost alternative.

In case two, the cost of material for a given required thickness will be proportional to the length of the wetted perimeter. The objective will be to minimize the wetted perimeter required to achieve the required capacity. A common example of this case are poured concrete trapezoidal channels.

The third case will be the most complex. The costs will vary with different shapes and dimensions; all of which have the same capacity. For example, any number of combinations of bottom widths and depths in a rectangular channel will convey the same amount of water, but only one will minimize the costs.

2.0 BASIC EQUATIONS

The flow capacity of a channel is determined by Manning's Equation:

$$Q = (1/n)AR^{2/3}S^{1/2} \qquad (1)$$

Where Q = flow rate (m^3/sec)
n = roughness coefficient (between .015 - .02 for lined channels)
A = crossectional flow area (m^2)
R = hydraulic radius = A/WP (m)
WP = wetted perimeter (m)
S = slope (m/m)

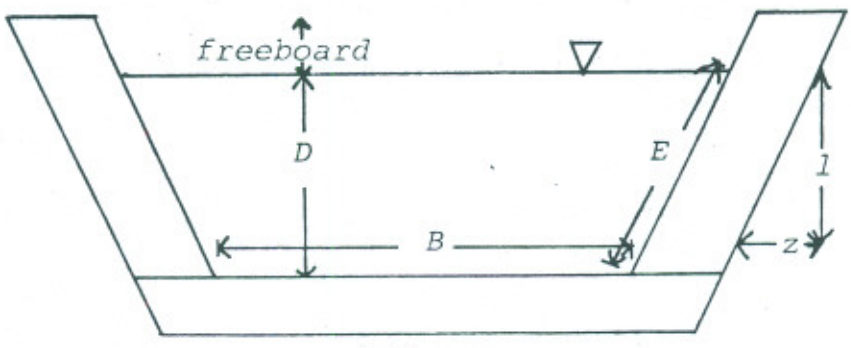
For a given channel, Q, n, and s are generally established by the local conditions. The design parameters the engineer must determine are A and R, such that:

$$AR^{2/3} = \frac{Qn}{S^{1/2}} \qquad (2)$$

The left side of equation 2 will be termed the hydraulic section, and will be used to indicate the geometrical capacity of the channel. The objective will be to minimize costs for a given required hydraulic section.

Material costs, as stated, are usually a function of the volume of material used. If thickness requirements of the respective materials are specified, then costs on a unit length basis will be a function of length of the wetted perimeter constructed of that material. Figure 1 illustrates the cost calculation for a trapezoidal channel where the base and side material costs are different.

Figure 1. Definition of dimensional terms used in cost calculations for trapezoidal channels.



$$C = bB + 2dE + k \qquad (3)$$

$$C = bB + 2dD\sqrt{z^2+1} + k \qquad (4)$$

Where

C = unit cost (Rs/m length)
B = bottom width
D = depth (m)
E = length of sides (m)
z = side slope
b = unit cost of base material (Rs/m of width)
d = unit cost of side materials (Rs/m length of side)
k = a constant to take into consideration costs of freeboard materials, corners, etc. (Rs)

0 A MINIMUM COST ANALYSIS OF THE SEPERATE CASES

I: Partial Linings with no Bottoms

As stated, since there is no cost associated with om width, this case cannot be optimized to minimize costs.

II: Linings Where the Costs of Base and Side Materials are Equal

For this case, cost is a function of wetted peri- r, and the objective is to minimize the wetted perimeter a given hydraulic section, or maximize the hydraulic section, ^{3}, for a given wetted perimeter.

Since:

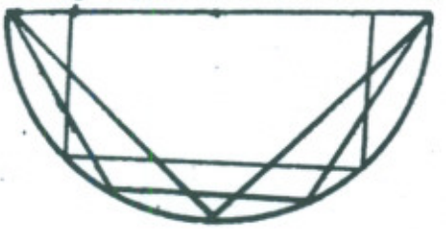
$$\frac{AR^{2/3}}{WP} = \frac{A \cdot \frac{A^{2/3}}{WP^{2/3}}}{WP} = \left(\frac{A}{WP}\right)^{5/3} = R^{5/3} \qquad (5)$$

roblem reduces to that of maximizing the hydraulic radius termining the minimum wetted perimeter that can encompass en area. The maximum obtainable hydraulic radius for any tric shape is D/2 (Albertson et al., 1960).

A half circle is the most efficient hydraulic on. The minimum wetted perimeter for any other shape will when the sides are proportioned such that the shape can

be inscribed by a semicircle (Albertson et al., 1960), as shown in Figure 2.

Figure 2. Hydraulically Optimum Crossectional Shapes



AS the number of sides decrease, the length of wetted perimeter required for a given hydraulic section increases. Table 1 gives a comparison of the wetted perimeter lengths required to achieve a hydraulic section of 0.1 for each of the shapes shown in Figure 2.

Table 1. Minimum wetted perimeter required to give a hydraulic section of $AR^{2/3} = 0.1$ for various geometric shapes.

Geometric Shape	Minimum Wetted Perimeter	% of Half Circle WP Value
half circle	1.33 m	100 %
trapezoid	1.41 m	106 %
rectangle	1.55 m	117 %
triangle	1.55 m	117 %

Table 1 indicates that required wetted perimeters increase 6% from a semicircular to a trapezoidal section and 10% from the optimum trapezoidal to a rectangular section. If material costs vary only with wetted perimeter, they will likewise increase. Of course, differences in labor and installatic costs between these sectional shapes could overshadow this difference in material costs.

The trapezoidal shape with the minimum hydraulic radius is a half hexagon where $D = \sqrt{3}/2\ B$ and $z = 1/\sqrt{3}$. If a trapezoidal section with side slopes other than the optimum are desired, the hydraulic radius will be minimized when:

$$D = \frac{B}{2(\sqrt{z^2+1} - z} \quad \text{(Albertson et al., 1960)} \quad (6)$$

For example, if it is desired to construct a section with a 1:1 side slope ($z = 1$), then $D = 1.21\ B$ will give the least wetted perimeter and the lowest cost. Its wetted perimeter will be about 4% longer than that for the optimum trapezoidal section. Equation 6 can also be used to design trapezoidal sections to reduce losses in earthen watercourses if it is found that losses are strictly a function of wetted perimeter length.

The basic optimum dimensions required for the design of each crossectional shape can be computed. The formulas for the half circle, rectangle, and trapezoid are given in Table 2. The derivations for these equations are given in Appendix 1.

Table 2. Formulas for designing minimum cost half circle, rectangle, and trapezoidal sections.

Shape	Formula
Half circle	$D = 1.00\left(\frac{Qn}{S^{1/2}}\right)^{3/8}$
Rectangle	$B = 1.83\left(\frac{Qn}{S^{1/2}}\right)^{3/8}$ with $D = B/2$
Trapezoidal	$B = 1.12\left(\frac{Qn}{S^{1/2}}\right)^{3/8}$ with $D = \frac{\sqrt{3}B}{2}$ and $Z = 1/\sqrt{3}$

Case III: Linings Where Costs of Base and Side Materials are Different

In order to determine minimum cost crossections where different material costs are involved, the equation for the hydraulic section $AR^{2/3}$, must be solved such that the cost function is minimized. Mathematically this problem is the same as the classical microeconomic problem of minimizing production costs through input (i.e. capital and labor) substitution. Our "production function" is the equation for the hydraulic section. Our inputs are the crossectional dimensions.

The basic solution technique involves determining the input mixture at which the ratio of the marginal products equals the ratio of the marginal costs.

This mix can be determined for any number of inputs utilizing the Lagrange Multiplier technique, although the mathematics can become very complex. Computer optimization techniques are possible for complex problems.

The only lined channel crossectional shapes presently being installed or considered utilizing multiple materials in Pakistan are rectangular or trapezoidal. The equation for the hydraulic section of a trapezoidal channel is:

$$AR^{2/3} = \frac{(BD + zD^2)^{5/3}}{(B + 2D\sqrt{z^2+1})^{2/3}} \qquad (7)$$

where the parameters are as defined in Figure 1. The cost function is given in equation 4. The rectangular section is the special case where $z = 0$. Although the minimum cost combination can be determined with three input parameters, the algebra involved in the solving of the three simultaneous equations becomes extremely complex.

It was consequently decided to treat the side slope as a constant reducing the problem to one with only two variables. By solving the same problem for a number of side slopes, the optimum side slope and dimensions can be iteratively determined. Under most practical conditions, the choice of side slope is somewhat constrained by the materials and methods employed.

The optimization method involves determining the dimension combination such that the marginal change in hydraulic section is equal to the marginal changes in costs (equation 8) and the equation for the hydraulic section (equation 2) is satisfied.

$$\frac{\frac{\partial (AR^{2/3})}{\partial B}}{\frac{\partial (AR^{2/3})}{\partial D}} = \frac{\frac{\partial C}{\partial B}}{\frac{\partial C}{\partial D}} \qquad (8)$$

$$AR^{2/3} = \frac{Qn}{S^{1/2}} \qquad (2)$$

Thus we have two simultaneous equations with which to determine the minimum cost combination of B and D.

The algebra involved in solving these equations for trapezoidal channels is given in Appendix 2. The solution is:

$$B = \left[\frac{[1 + 2\sqrt{z^2+1}\ (D/B)]^2}{[(D/B) + z(D/B)^2]^5} \left(\frac{Qn}{S^{1/2}}\right)^3 \right]^{1/8} \qquad (9)$$

Where:

$$D/B = \frac{e + \sqrt{e^2 + 20(b/d)a}}{2a} \qquad (10)$$

And:

$$e = 6\sqrt{z^2+1}\ ((b/d) - 1) + 10z(b/d)$$

$$a = 20(z^2+1) - 4z\sqrt{z^2+1}\ (1 + 4(b/d))$$

By inserting the desired side slope and side cost to base cost ratio (b/d) into these equations, the minimum cost bottom width and depth can be determined. By solving the equations for several z values, the minimum cost side slope can also be found. Once the desired dimensions are determined the unit material cost of the channel can be calculated with equation 4.

Most lined channels presently being constructed in Pakistan are rectangular. Under this condition, z = 0, and equations 9 and 10 reduce to:

$$B = \left[\frac{[1 + 2(D/B)]^2}{(D/B)^5} \left(\frac{Qn}{S^{1/2}} \right)^3 \right]^{1/8} \qquad (11)$$

Where:

$$D/B = \frac{e_o + \sqrt{e_o^2 + 400(b/d)}}{40} \qquad (12)$$

And:

$$e_o = 6[(b/d) - 1]$$

The optimum dimensions can also be determined graphically by plotting equations 7 and 10 for various values of z and choosing the point where the appropriate lines cross. Figures 3, 4, 5, 6, and 7 are plots of these equations for z = 0, 0.33, 0.5, 0.67, and 1.0 respectively.

To utilize the figures, first choose the figure with the desired z value. Then calculate the hydraulic section (equation 2), and follow this $AR^{2/3}$ line until it crosses the line eminating from the origin which represents the desired material cost ratio (b/d).

The point where the two lines cross represent the minimum cost B and D values on the two axes. Total costs can be found by inserting these B and D values into equation 4.

If this B and D combination is for some reason undesireable, alternative combinations which fulfill the hydraulic requirements can be found by moving along the $AR^{2/3}$ line in either direction. Again, total costs can be calculated by plugging the chosen B and D values into equation 4.

Additional costs involved in moving away from the optimum dimension combination can also be determined graphically. Draw a line through the optimum point (where the $AR^{2/3}$ and (b/d) lines cross), tangent to the $AR^{2/3}$ curve until it crosses the B axis. Then extend a line from the chosen dimensions, parallel to the first line, until it also crosses the B axis. The difference in the two B_o values on the axis (ΔB_o) times the unit cost of B, will give the additional costs (ΔC).

$$\Delta C = b(\Delta B_o) \qquad (13)$$

4.0 A PRACTICAL EXAMPLE OF LINED CHANNEL DESI

It is desired to line a 500 meter section of wate course channel near a heavily trafficked area to avoid deterioration of the banks and reduce water losses. The design slope of the section is .0004. The design flow is .06 m^3/sec (about 2 csc). The roughness coefficient, n, will be taken as 0.017 for lined channels. Thus the hydraulic section, $AR^{2/3} = Qn/S^{1/2} = 0.051$.

The material costs at the construction site are:

Bricks:	*Rs 250 per 1000*
Cement:	*Rs 30 per bag*
Sand:	*Rs 30 per m^3*
Aggregate:	*Rs 100 per m^3*

At these rates, 1:2:4 concrete will cost about Rs 300/m^3 and brick masonry about Rs 225/m^3.

Because the construction site involves some fill area and is in coarse textured soils, it was decided that construction with no base is not desireable.

The crossectional shape with the smallest wetted perimeter is the semicircle. This shape can be made by RCC pipe manufacturers at a price of about Rs 75 per meter diamete per meter length at the factory. Our channel requires a depth of:

$$D = 1.00\left(\frac{Qn}{S^{1/2}}\right)^{3/8} = .33 \text{ m}$$

or a diameter of 0.66 m, and would cost Rs 50 per meter. Free board requirements (15 cm) would increase the cost, and would be difficult to install. Transport would further increase the price.

If section length were sufficiently long, the concrete pipe making machine could be moved to the field, eliminating the need for reinforcement and reducing transport costs. Material costs could be reduced to about Rs 28/m with

6cm thick 1:1½:3 concrete and 15 cm freeboard (which would be attached later). Labor costs would be relatively high.

The next lowest wetted perimeter alternative is the trapezoidal section given in Table 2. The required dimensions would be B = .37 m, z = .58, and D = .48 including freeboard. Material costs of a 8 cm thick 1:2:4 poured in place concrete lining would be about Rs 35/m. The form costs would be extra, but forms could be reused for other sections. Labor costs will depend upon the process and equipment utilized and supervision.

The commonly used lining material in Pakistan is brick masonry both in one and two brick (11 and 23 cm respectively) wall thickness. Although brick masonry bottoms are commonly used, a rigid base such as poured concrete, will greatly add to the strength and stability of the section, especially in fill areas where compaction will be a problem. Cost parameters for such sections would be:

11 cm wall thickness	23 cm wall thickness
b = Rs 24/m^{2*}	b = Rs 24/m^{2*}
d = Rs 26/m^2	d = Rs 52/m^2
k = Rs 17/m**	k = Rs 30/m**

* 1:2:4 concrete 8 cm thick

** $z = 0$ (rectangular section)
for $z \neq 0$; k = Rs $9.4 + 7.8(\sqrt{z^2+1})$ for 11 cm walls
and k = Rs $14.9 + 15.5(\sqrt{z^2+1})$ for 23 cm walls.

Because vertical side walls are easier to construct it was decided to first calculate the minimum costs of a rectangular section. The optimum dimensions and costs are determined from Figure 3 and/or Equations 11, 12, and 4 to be:

11 cm wall thickness	23 cm wall thickness
B = .62 m	B = .83 m
D = .29 m	D = .22 m
C = Rs 47/m	C = Rs 73/m

In order to check how much the costs can be reduced by utilizing sloping sides, Equations 9, 10, and 4 were itera-

tively solved for varying z values. It was found that, with 11 cm walls, the minimum cost side slope is with z = .35, and costs are reduced by Rs 1.5/m or about 3%. With 23 cm walls, the minimum cost side slope is at z = .2 and costs are reduced by Rs 0.5/m or less than 1%. The reduction in material costs for both cases was deemed insufficient to out-weigh the extra labor and supervisory costs that would be involved in making sloping sides.

There is an advantage to sloping side walls which will, under some conditions increase their economy. The weight of sloping side walls opposes the back pressure from the soil outside the watercourse. Thin-walled linings will fail most often as a result of this back pressure, especially if they are built in cut areas or adjacent to road ways and/or the surrounding soil is often saturated. If the side walls are sloping, less strength is required in the walls to oppose this force, and thinner, lower cost wall materials can be used.

Since the lined section is passing through a heavily trafficked area, it is desireable to keep the bottom width as narrow as possible so that crossing is easier and so that animals will be less likely to enter and damage the water-course.

The costs associated with other than optimum dimensions were calculated and are shown in Figure 8. It can be seen from this fugure, or from studying Figure 3, that costs increase slowly at first, and then more and more rapidly as the dimensions vary from the optimum. Decreasing B by 0.22 m to 0.40 m would increase costs by 9% with 11 cm wall thickness lining. Decreasing to 0.5 m would involve only 2% additional costs. With 23 cm lining, decreasing B from 0.83 to 0.40 increases cost by 22% to B = 0.5, by 9%.

If culverts would eliminate most of the inconvenience created by a wider section, it would be cheaper to install a slab walking culvert (which would cost less than Rs 100) each 50 meters than to reduce the bottom width of a 11 cm lining from B = 0.5 m to B = 0.4 m.

Again, the back pressure must be considered when determining the dimensions. As depth increases, the back pressure force on the walls increase and a stronger, thicker wall must be designed. So, depth should be maintained as small as is practical. It should be remembered that 0.15 m of free board is added to the calculated depth (D) to get actual wall height.

In the light of this analysis, this designer would recommend rectangular crossections with a 11 cm wall thickness through most of the lined section, and a 23 cm wall thickness through a portion where a roadway runs beside the watercourse. The dimensions and costs of both sections would be:

11 cm wall thickness	23 cm wall thickness
B = 0.5 m	B = 0.6 m
D = 0.36 m	D = 0.30 m
C = Rs 48/m	C = Rs 76/m

5.0 CONCLUSIONS

1) *Designing lined channels, utilizing the cost minimization techniques given can significantly reduce material costs with a small investment of the designer's time.*

2) *Even if the minimum cost design is not desireable, the additional costs involved in other crossections can be determined and used to evaluate alternatives.*

3) *Under most cost conditions, the cost reduction involved in building sloping side walls on trapezoidal channels will be small.*

REFERENCES

1) *Albertson, Maurice L., James R. Barton, and Daryl B. Simons 1960. Fluid Mechanics for Engineers. Prentice Hall. Englewood Cliffs, N.J., U.S.A.*

APPENDIX 1. *DERIVATION OF MINIMUM WETTED PERIMETER DIMENSIONS FOR VARIOUS SHAPES*

1) Semi Circle:

$$\frac{Qn}{S^{1/2}} = AR^{2/3} = \frac{\pi D^2}{2}\left(\frac{\pi D^2/2}{\pi D}\right)^{2/3} = \frac{\pi D^2}{2}(D/2)^{2/3}$$

$$= \frac{\pi}{2^{5/3}} D^{8/3}$$

$$D = \left[\frac{2^{5/3}}{\pi}\frac{Qn}{S^{1/2}}\right]^{3/8} = 1.00\left(\frac{Qn}{S^{1/2}}\right)^{3/8}$$

2) Rectangle (D = B/2):

$$\frac{Qn}{S^{1/2}} = AR^{2/3} = \frac{(BD)^{5/3}}{(B + 2D)^{2/3}} = \frac{(B(B/2))^{5/3}}{(B + B)^{2/3}} =$$

$$\frac{(1/2)^{5/3} B^{10/3}}{2^{2/3} B^{2/3}} = \frac{D^{8/3}}{2^{7/3}}$$

$$B = 2^{7/8}\left(\frac{Qn}{S^{1/2}}\right)^{3/8} = 1.83\left(\frac{Qn}{S^{1/2}}\right)^{3/8}$$

3) Trapezoid ($D = \sqrt{3}/2B$ and $Z = 1/\sqrt{3}$):

$$\frac{Qn}{S^{1/2}} = AR^{2/3} = \frac{(BD + zD^2)^{5/3}}{(B + 2D\sqrt{z^2+1})^{2/3}} =$$

$$\frac{((\sqrt{3}/2)B^2 + 1/\sqrt{3}(\sqrt{3}/2)^2 B^2)^{5/3}}{(B + 2(\sqrt{3}/2)B\sqrt{(1/\sqrt{3})^2 + 1})^{2/3}} = \frac{(\sqrt{3}/2 + \sqrt{3}/4)^{5/3} B^{10/3}}{(1 + 2(\sqrt{3}/2)(2/\sqrt{3}))^{2/3} B^{2/3}}$$

$$= \frac{(3\sqrt{3}/4)^{5/3}}{3^{2/3}} B^{8/3} = \frac{3^{11/6}}{4^{5/3}} B^{8/3}$$

$$B = \left(\frac{4^{5/3}}{3^{11/6}}\frac{Qn}{S^{1/2}}\right)^{3/8} = 1.12\left(\frac{Qn}{S^{1/2}}\right)^{3/8}$$

APPENDIX 2. *DERIVATION OF EQUATIONS 9 AND 10.*

For a trapezoidal channel:

$$AR^{2/3} = \frac{A^{5/3}}{WP^{2/3}} = \frac{(BD + ZD^2)^{5/3}}{(B + 2D\sqrt{z^2+1})^{2/3}} \qquad (7)$$

and

$$C = bB + 2dD\sqrt{z^2+1} + k \qquad (4)$$

The optimum is found where the ratio of the marginal outputs equals the ratio of the marginal costs, or where:

$$\frac{\frac{\partial (AR^{2/3})}{\partial B}}{\frac{\partial (AR^{2/3})}{\partial D}} = \frac{\frac{\partial C}{\partial B}}{\frac{\partial C}{\partial D}} \qquad (8)$$

$$\frac{\partial (AR^{2/3})}{\partial B} = \frac{(5/3)DA^{2/3}WP^{2/3} - (2/3)A^{5/3}WP^{-1/3}}{WP^{4/3}} =$$

$$(A/WP)^{2/3}[(5/3)D - (2/3)(A/WP)]$$

$$\frac{(AR^{2/3})}{D} = \frac{(5/3)(2zD + B)A^{2/3} - (2/3)(2\sqrt{z^2+1})A^{5/3}WP^{-1/3}}{WP^{4/3}} =$$

$$(A/WP)^{2/3}[(5/3)(2zD + B) - (4/3)\sqrt{z^2+1}\,(A/WP)]$$

$$\frac{\partial C}{\partial B} = b$$

$$\frac{\partial C}{\partial D} = 2d\sqrt{z^2+1}$$

Plugging into (8) above:

$$\frac{(A/WP)^{2/3}[(5/3)D - (2/3)(A/WP)]}{(A/WP)^{2/3}[(5/3)(2zD + B) - (4/3)\sqrt{z^2+1}\ (A/WP)]} = \frac{b}{2\sqrt{z^2+1}\ d}$$

$$10\sqrt{z^2+1}\ (D) - 4\sqrt{z^2+1}\ (A/WP) = 10z(b/d)D + 5(b/d)B - 4\sqrt{z^2+1}\ (b/d)(A/WP)$$

$$[10\sqrt{z^2+1} - 10z(b/d)]D + [4\sqrt{z^2+1}\ (b/d) - 4\sqrt{z^2+1}](A/WP) - 5(b/d)B = 0$$

Insert the equations for A and WP and multiply by WP:

$$10\sqrt{z^2+1}\ (BD) + 20(z^2+1)D^2 - 10z(b/a)BD - 20\sqrt{z^2+1}\ (b/a)D^2 + 4\sqrt{z^2+1}\ (b/d)BD + 4z\sqrt{z^2+1}\ (b/a)D^2 - 4\sqrt{z^2+1}\ (BD) - 4z\sqrt{z^2+1}\ (D^2) - 5(b/d)B^2 - 10\sqrt{z^2+1}\ (b/d)BD = 0$$

Grouping terms:

$$[20(z^2+1) - 4z\sqrt{z^2+1} = 16z\sqrt{z^2+1}\ (b/d)]D^2 + [6\sqrt{z^2+1} - 6\sqrt{z^2+1}\ (b/d) - 10z(b/d)]BD - 5(b/d)B^2 = 0$$

When all terms are divided by B^2, the equation becomes quadratic of the form:

$$a(D^2/B^2) = e\ (D/B) = c = 0$$

whose solution is:

$$D/B = \frac{-e \pm \sqrt{e^2 - 4ac}}{2a}$$

Plugging the terms into this equation gives:

$$D/B = \frac{[6\sqrt{z^2+1}\ (b/d - 1) + 10z(b/d)] + \sqrt{[6\sqrt{z^2+1}\ (1 - (b/d)) - 10z(b/d)]^2 + 20(b/d)[20(z^2+1) - 4z\sqrt{z^2+1}\ (1 + 4(b/d)]}}{8[5(z^2+1) - z\sqrt{z^2+1}\ (1 + 4(b/d))]} \qquad (10)$$

The second equation required to find the unique solution is the formula for the hydraulic section:

$$\frac{Qn}{S^{1/2}} = AR^{2/3} = \frac{A^{5/3}}{WP^{2/3}} = \frac{(BD + zD^2)^{5/3}}{(B + 2D\sqrt{z^2+1})^{2/3}}$$

This can be converted to:

$$\frac{Qn}{S^{1/2}} = \frac{[(D/B)B^2 + z(D/B)^2B^2]^{5/3}}{[B + 2(D/B)\sqrt{z^2+1}\ (B)]^{2/3}} = \frac{[(D/B) + z(D/B)^2]^{5/3}}{[1 + 2\sqrt{z^2+1}\ (D/B)]^{2/3}} B^{5/3}$$

or

$$B = \left[\frac{[1 + 2\sqrt{z^2+1}\ (D/B)]^2}{[(D/B) + z(D/B)^2]^5} \left(\frac{Qn}{S^{1/2}}\right)^3\right] \qquad (9)$$

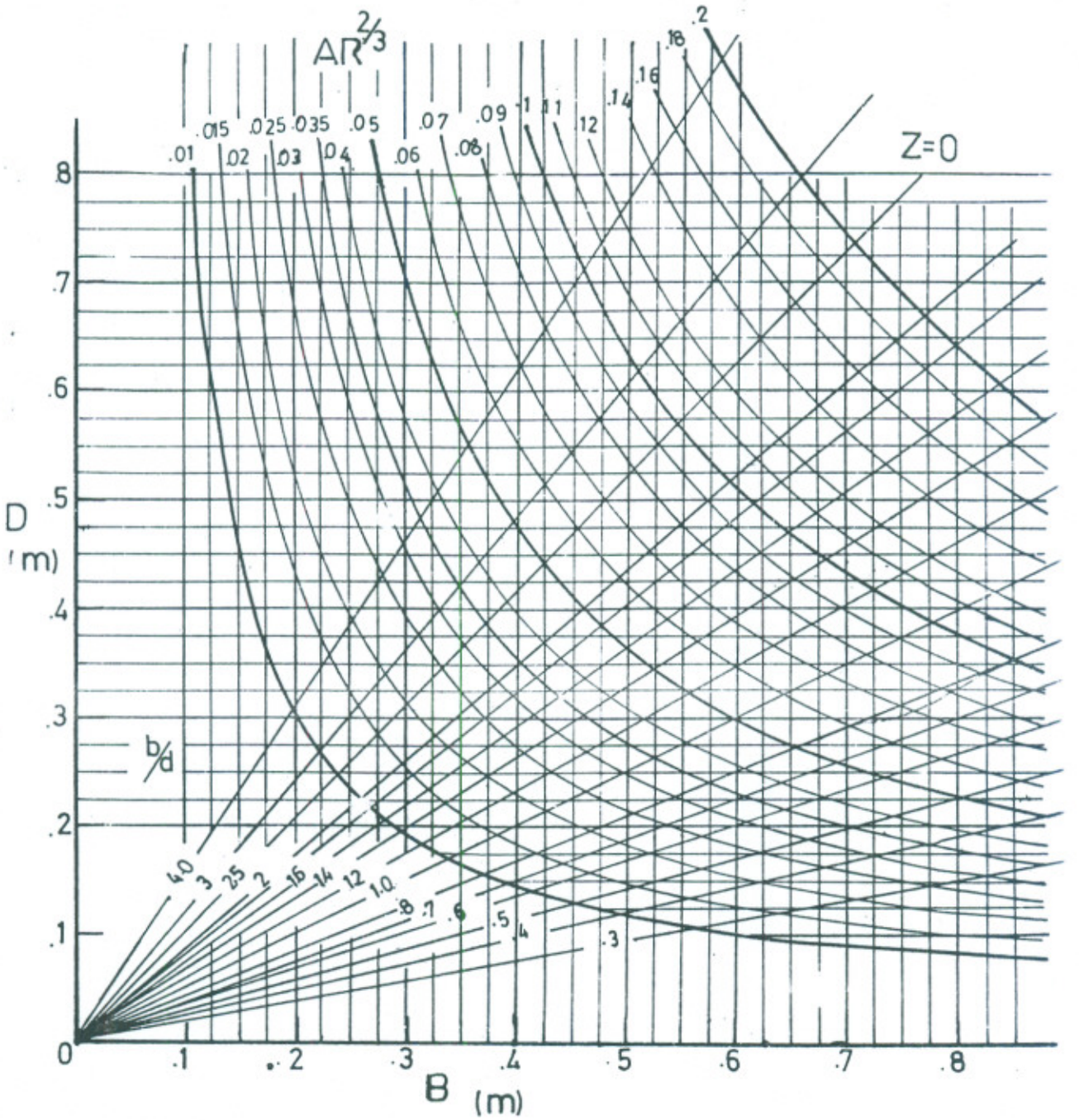
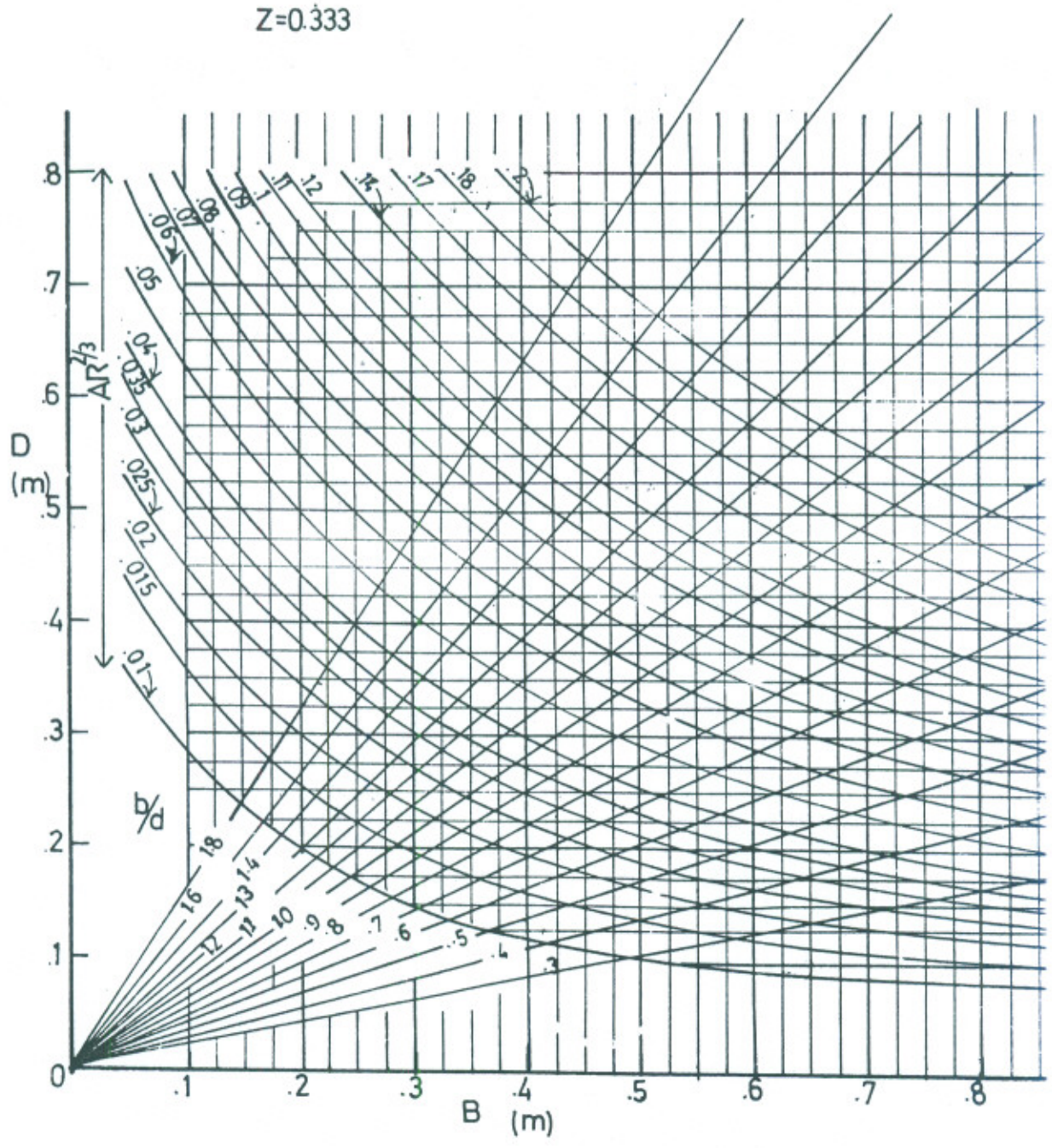


Figure 3. Nomograph for Determining Minimum Cost Dimensions of Small Lined Rectangular Channels (b/d = side wall cost (Rs/m^2) : base cost (Rs/m^2); and $AR^{2/3} = Qn/S^{\frac{1}{2}}$)

Figure 4. Nomograph for Determining Minimum Cost Dimensions of Small Lined Trapezoidal Channels with Side Slope (z) = 0.333; (b/d_1 = side wall cost (Rs/m^2) ÷ base cost (Rs/m^2); and $AR^{2/3} = Qn/S^{\frac{1}{2}}$)



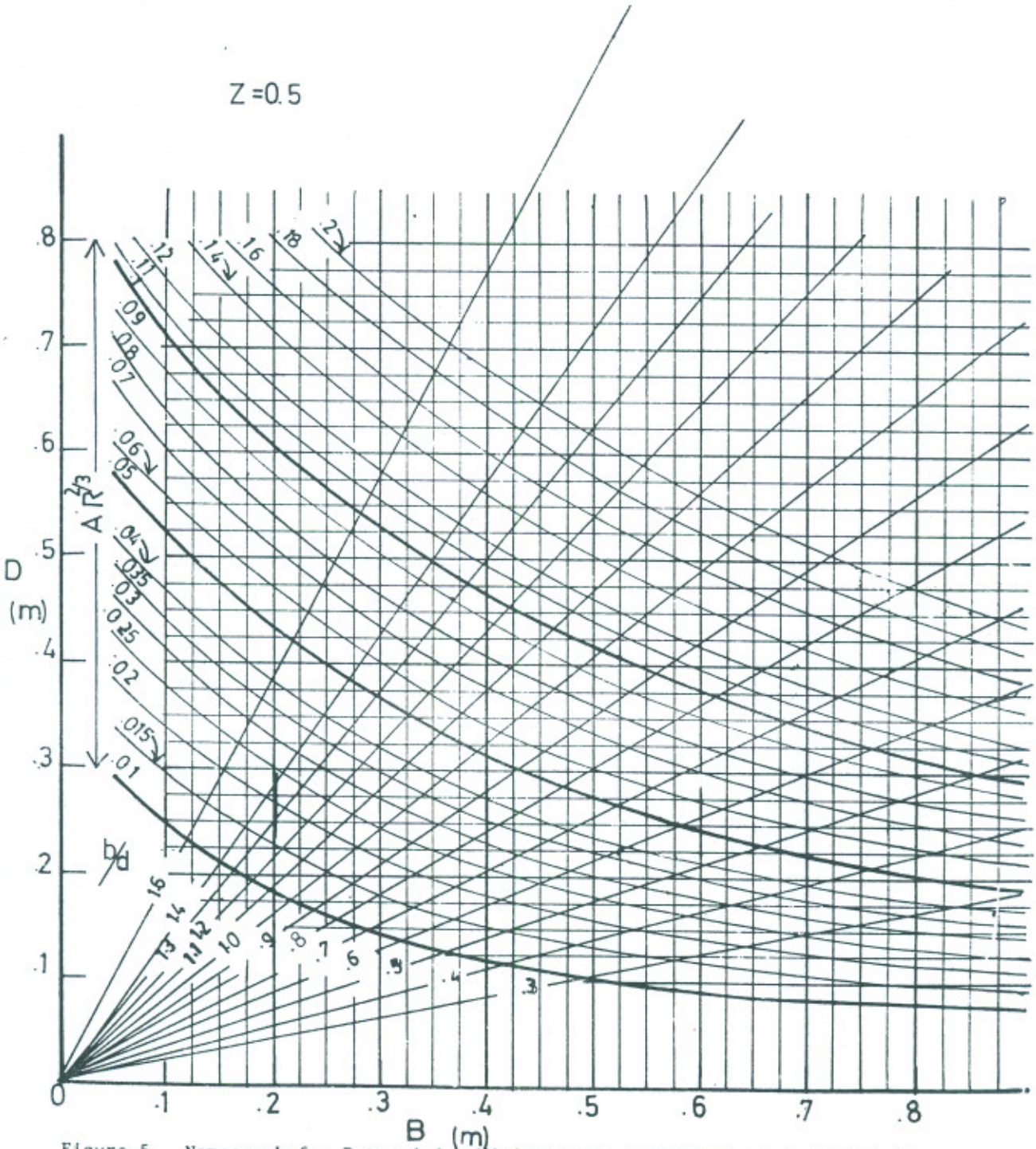


Figure 5. Nomograph for Determining Minimum Cost Dimensions of Small Lined Trapezoidal Channels with Side Slope (z) = 0.5; (b/d = side wall cost (Rs/m^2) ÷ base cost (Rs/m^2); and $AR^{2/3} = Qn/S^{1/2}$).

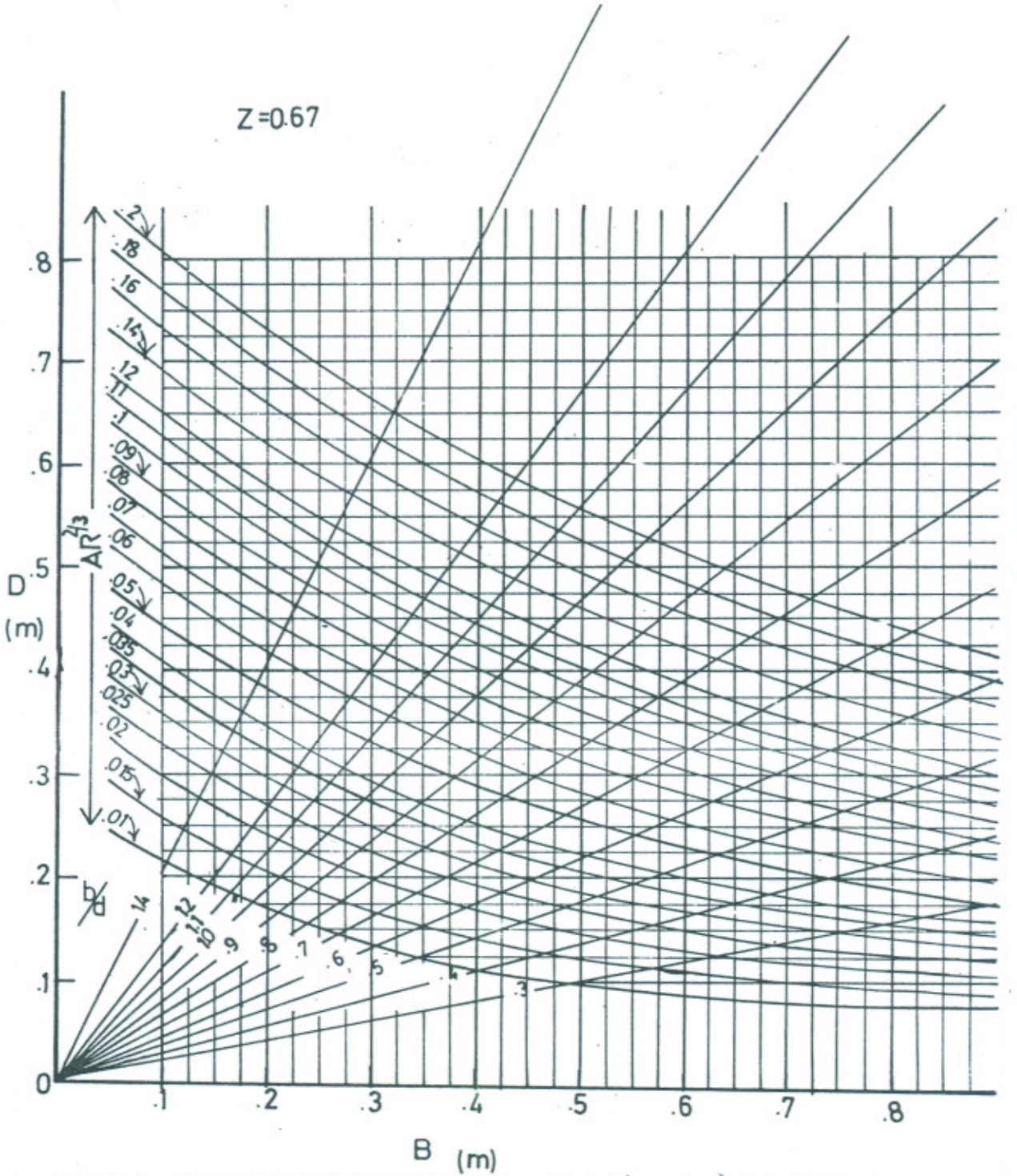


Figure 6. Nomograph for Determining Minimum Cost Dimensions of Small Lined Trapezoidal Channels with Side Slope (z) = 0.67; (b/d = side wall cost (Rs/m^2) ÷ base cost (Rs/m^2); and $AR^{2/3} = Qn/S^{\frac{1}{2}}$).

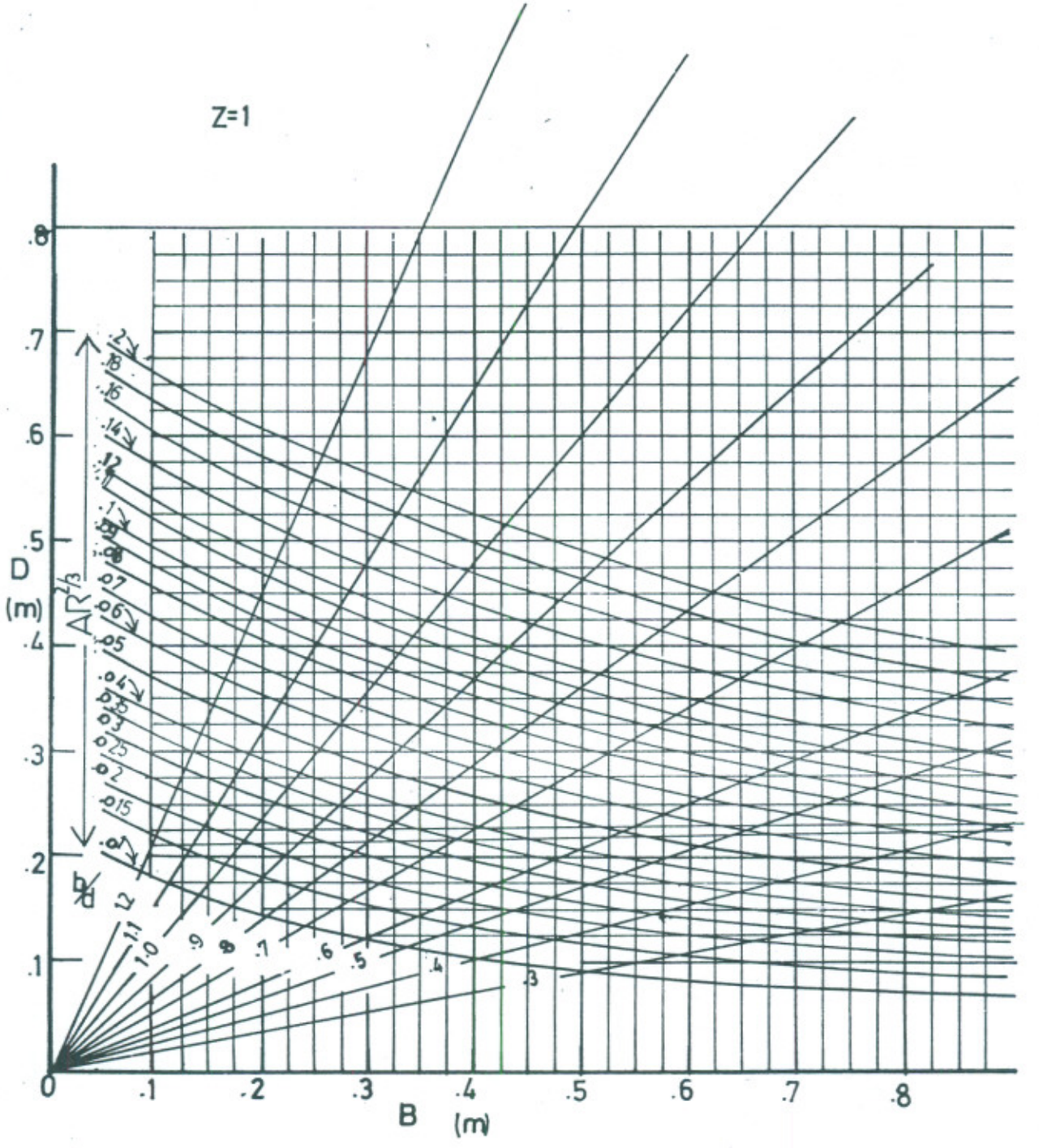
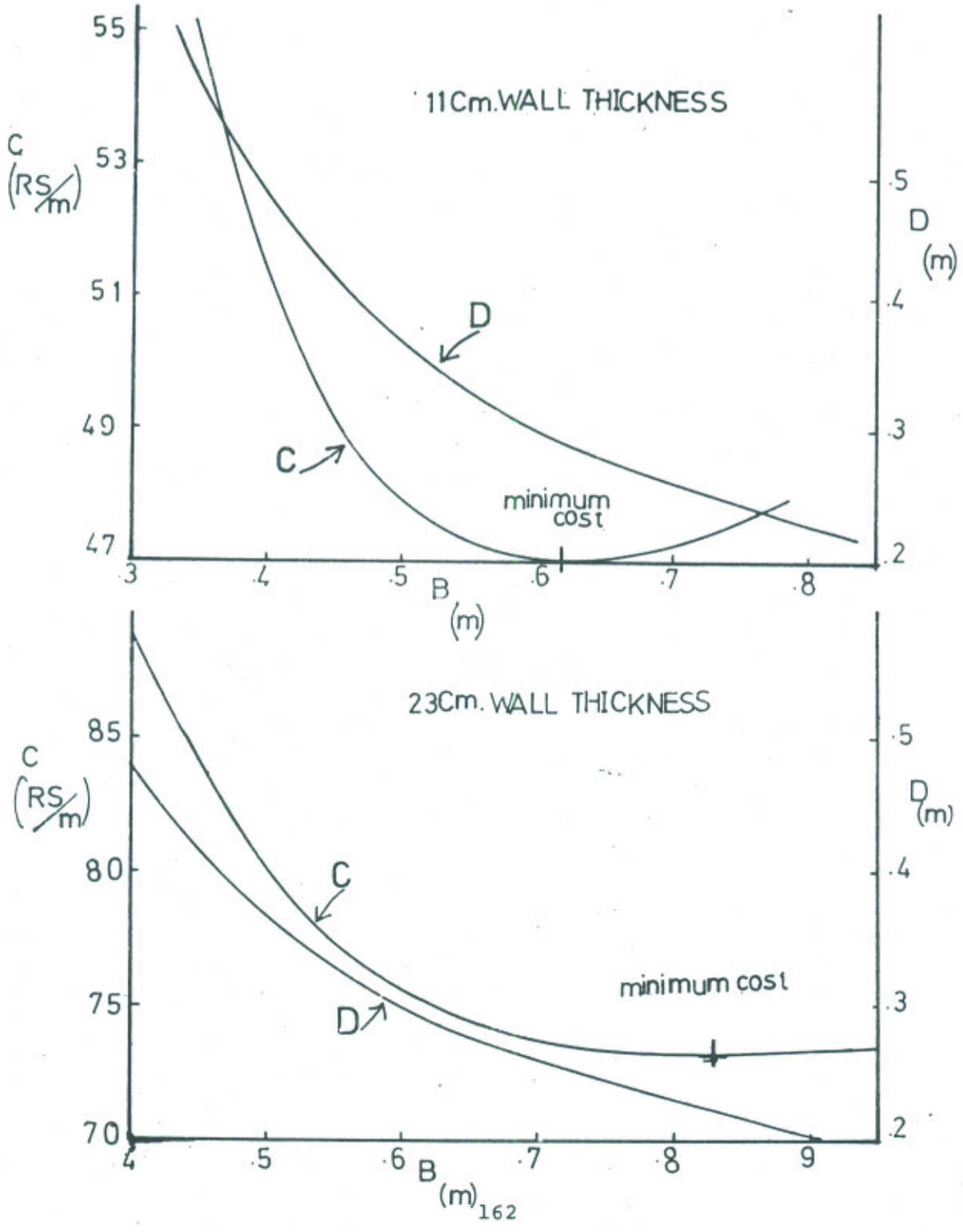


Figure 7. Nomograph for Determining Minimum Cost Dimensions of Small Lined Trapezoidal Channels with Side Slope (z) = 1; (b/d = side wall cost (Rs/m^2) ÷ base cost (Rs/m^2); and $AR^{2/3} = Qn/S^{\frac{1}{2}}$).

Figure 8. Cost (C) vs. Bed Width (B) for 11 cm and 23 cm Wall Thickness Rectangular Channel for the Practical Example Watercourse.



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