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DESIGN OF PRESSURIZED PIPE-WEIR USING THE ROUGH MODEL METHOD (RMM)

DIMENSIONNEMENT D'UNE CONDUITE DEVERSOIR SOUS PRESSION PAR LA METHODE DU MODELE RUGUEUX (MMR)

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ABSTRACT

The rough model method (RMM) is explained through its application to the design of a pressurized pipe-weir, widely used in practice. The three basic equations of turbulent flow are firstly applied to define explicitly the geometric elements of a referential rough model characterized by an arbitrary assigned relative roughness value. The required linear dimensions of the studied conduit are then easily deduced by multiplying the homologues linear dimensions of the rough model by a non-dimensional correction factor. The friction factor is not indispensable when applying the RMM, unlike current design methods. Resulting RMM equations are not only explicit but are also valid in the entire domain of turbulent flow.

Keywords: Discharge, Energy slope, Pressurized conduit, Pipe-weir, Rough Model Method, Turbulent flow.

RESUME

La méthode du modèle rugueux de référence (MMR) est démontrée par son application au dimensionnement d'une conduite déversoir sous pression, cette derniere est largement utilisé dans la pratique. Les trois équations de base de l'écoulement turbulent sont tout d'abord appliquées pour définir explicitement les éléments géométriques d'un modèle rugueux de référence caractérisé par une valeur arbitraire de la rugosité relative. Les dimensions linéaires requises de la conduite étudiée sont alors facilement déduites en multipliant les dimensions linéaires correspondantes du modèle rugueux de référence par un facteur de correction adimensionnel. La connaissance du coefficient de frottement n'est pas indispensable pour l'application de la MMR, contrairement aux méthodes de dimensionnement classiques. Les équations de la MMR résultantes sont non seulement explicites, mais valables également dans tout le domaine des écoulements turbulents.

Mots clés : Débit, pente hydraulique, conduite sous pression, conduite déversoir, méthode du modèle rugueux de référence, écoulement turbulent.

INTRODUCTION

In turbulent flows, three types of problems are presented in the hydraulics engineer's practice. The first type is the calculation of pipeline flow. Generally, this problem can be explicitly resolved by combining *Dacy-Wesbach's* relationship and this of *Colebrook-White* who express respectively pressure loss gradient and friction coefficient. The second one consists to calculate pressure loss gradient. This computation is an implicit issue since it needs the application of *Darcy-Weisbach*,s ' relationship which uses friction coefficient f whose expression being itself implicit For this reason, some authors propose approximate relations for determination of friction coefficient, notably for pipes (Swamee & Jain 1976, Achour & Bedjaoui 2006, 2012). The third one responds to the sizing need and consists to evaluate linear dimension from known values that govern the flow. The majority of non-circular pipelines, dimensioning is complex and basic relations are implicit (Swamee.P & Swamee.N, 2008). Existing studies relating to computation of pipes dimensions are not numerous. They propose either a burdensome graphical resolution or iterative resolutions based all on the resistance coefficient to a constant flow (Chow 1973, French 1986, Sinniger 1989). A particular case of flow under pressure, determination of linear dimension is based on *Darcy-Weisbach*'s equation which gives pressure loss gradient. This equation with those of *Colebrook-white* and *Reynolds* form the three basic equations of the turbulent flow. The challenge resides in the use of friction flow which is determined by the relation of Colebrook-*white* (Colebrook 1937, Moody 1944, Swamee 1976). Because in this last relationship, the friction coefficient is depending on Reynolds' number, this is itself depending on the linear dimension. Referring to the bibliography, we can affirm that no explicit method is presently available for pipes dimensioning. Linear dimensions determination will be resolved in the present study by a rigorous theory based on the three relationships already quoted, particularly *Darcy-Weisbach*'s relationship. To avoid friction coefficient problem, this relation will be applied to a rough reference model whose friction coefficient has a constant value in the rough turbulent field. Explicit relationships, to find linear dimensions of the rough model, will be deducted from this approach. Real dimensions are then obtained thanks to the dimensionless correction factor. This method is the method of reference model which has been proven in the recent past by its simplicity and its efficiency (Achour & Bedjaoui 2006, Achour 2013, Riabi 2014). The resulting relations of RMM. are not only explicit but are also applicable in the whole of the flow field which corresponds to Reynolds number upper or equal to 2300 and relative roughness varying in a wide range [0; 0,05]. This method is applied in the present study, to linear dimensions determination of weirs pipes. These pipes, very used in the practice as collector sewers or stormwater weirs are intended to evacuate in event of stormwater the additional high flows towards natural areas without treatment. Figure 1 represents this pipe; its base has been enlarged to allow the evacuation of an important flow under low height (Guerée & Gomella & Balette 1972, Tabasarah & Hanisch & Muller 1974). The study of such pipe enhances the bibliography of flow under pressure of existing studies.

BASIC EQUATIONS

The fundamental relationships on which study is based are hydraulic equations well known and easy to know, equation of *Darcy-Weisbach*, equation of *Colebrook-White* and this of *Reynolds* number the gradient of pipe pressure loss is given by *Darcy-Weisbach's* relationship

$$J = \frac{f}{D_h} \frac{Q^2}{2gA^2} \tag{1}$$

Where Q is the discharge, g is the acceleration due to gravity, A is the wetted area, D_h is the hydraulic diameter and f is the friction coefficient given by the well-known Colebrook-White formula.

$$\frac{1}{\sqrt{f}}=-2\log\left(\frac{\varepsilon/D_h}{3,7}+\frac{2,51}{R\sqrt{f}}\right) \tag{2}$$

Where ε is the absolute roughness and ε the Reynolds'number expressed by:

$$R=\frac{4Q}{P\nu} \tag{3}$$

Where ν is the kinematic viscosity and P is the wetted perimeter.

Piping's geometric characteristics.

The pipe in the form of spillway considered in the present study is that presented in the above figure 1. Piping is characterized by its height *H* and its width *D*.

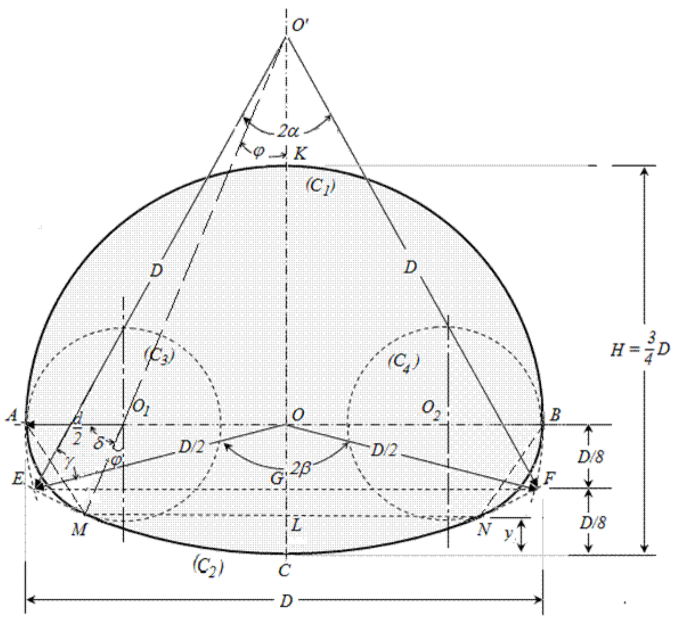

Figure 1 : Template definition of the spillway pipeline.

i. On-axis AB of the circle (*C1*), we trace the centre O_1 of the circle (*C3*) of diameter d tangent to circles (*C1*) and (*C2*).

ii. Repeating the same tracing from the point O_2 for the circle (*C4*) identical to (*C3*) and also tangent to circles (*C*1) and (*C2*).

iii. SO, arcs *MCN* of the circle (C_2), *MA* of the circle (C_3), *AKB* of the circle (C_1) and *BN* of the circle (C_4) form the contour AKBNCMA of the right section considered. This right section is this of the spillway pipeline. Its height is $\overline{CK}$ and maximal width $\overline{AB} = D$

Figure 1 of the section obtained suggests the following notes:

1. In the triangle EO'O we have :

$$\cos\alpha = \cos\left(EO'O\right) = \frac{\left(\overline{EO'}\right)^2 + \left(\overline{OO'}\right)^2 - \left(\overline{EO}\right)^2}{2\times\left(\overline{EO'}\right)\times\left(\overline{OO'}\right)} = \frac{D^2 + \left(3D/4\right)^2 - \left(D/2\right)^2}{2\times D\times\left(3D/4\right)}$$

$$= \frac{1+\frac{9}{16}-\frac{1}{4}}{3/2} = \frac{7}{8}$$

$$\alpha = 0,505361\,rd \tag{4}$$

$$\cos\gamma = \cos\left(OEO'\right) = \frac{\left(\overline{EO'}\right)^2 + \left(\overline{EO}\right)^2 - \left(\overline{OO'}\right)^2}{2\times\overline{EO'}\times\overline{EO}} = \frac{D^2 + \left(D/2\right)^2 - \left(3D/4\right)^2}{2\times D\times\left(D/2\right)}$$

$$= 1+\frac{1}{4}-\frac{9}{16} = \frac{11}{16}$$

$$\gamma = 0,812756\,rd \tag{5}$$

The angle EOO' is then equal to:

$$EOO' = \left(\pi-\alpha-\beta\right) = \left(\pi - 0,505361 - 0,812756\right)$$

$$EOO' = 1,823477\,rd \tag{6}$$

We also have the angle that is equal to:

$$\beta = EOC = \left(\pi - EOO'\right) = \pi - 1,823477$$

$$\beta = 1,318116\,rd \tag{7}$$

In the triangle *EOG* we have:

$$\overline{EG} = \frac{\overline{EF}}{2} = D\sin\alpha \Rightarrow EF = 2D\sin\alpha = 2\times D\times\sin\left(0,505361\right)$$
$$EF = 0,968246D \tag{8}$$

We also have:

$$\sin\left(\frac{\pi}{2}-\beta\right) = \frac{\overline{OG}}{\overline{EO}} \Rightarrow OG = \overline{EO}\sin\left(\frac{\pi}{2}-\beta\right) = \frac{D}{2}\times\sin\left(\frac{\pi}{2}-1,318116\right)$$
$$= 0,125D$$
$$\overline{OG} = D/8 \tag{9}$$

Similarly we have:

$$\overline{OC} = \overline{O'C} - \overline{O'O} = D - \frac{3D}{4}$$
$$\overline{OC} = D/4 \tag{10}$$

with relations (9) and (10), we obtain:

$$\overline{GC} = \overline{OC} - \overline{OG} = \frac{D}{4} - \frac{D}{8}$$
$$\overline{GC} = D/8 \tag{11}$$

2. The circle *(C3)* of diameter *d* is tangent to the point A at the circle *(C1)* and at the point *M* at the circle *(C2)*. Then determine what is the diameter *d* of such a circle.

Let the point O_1 that is the intersection of the rays $\overline{OA}$ and $\overline{O'M}$ of the respectives circles (C1) and (C2). If the circle (C3) of radius $\overline{O_1A} = d/2$ is tangent, at point A, to the circle (C1), we have:

$$\overline{O_1A} = d/2 = \overline{OA} - \overline{OO_1} = D/2 - \overline{OO_1} \tag{12}$$

If this same circle (C3) of diameter $\overline{O_1M} = d/2$ is tangent, at the point *M*, to the circle (C2), we have:

$$\overline{O_1M} = d/2 = \overline{O'M} - \overline{O'O_1} = D - \overline{O'O_1} \tag{13}$$

From these two last relations we deduce:

$$D/2 - \overline{OO_1} = D - \overline{O'O_1}$$

Then

$$\overline{OO_1} = \overline{O'O_1} - D/2 \tag{14}$$

On the other hand in the right triangle $O'OO_1$ we can write:

$$\overline{O'O}^2 + \overline{OO_1}^2 = \overline{O'O_1}^2 \tag{15}$$

Using the relation (14), and knowing that $\overline{O'O} = \frac{3}{4}D$ (point ***ii***), the expression (15) becomes:

$$\left(\frac{3}{4}D\right)^2 + \left(\overline{O'O_1} - D/2\right)^2 = \overline{O'O_1}^2$$

By developing this last expression we obtain:

$$\frac{9D^2}{16} + \frac{D^2}{4} - D\overline{O'O_1} = 0 \quad \Rightarrow \quad \overline{O'O_1} = \frac{13}{16}D \tag{16}$$

From relations (13) and (16) we deduce:

$$\overline{O_1M} = d/2 = D - \overline{O'O_1} = D - \frac{13}{16}D$$

After calculation, the value of d is equal to:

$$d = \frac{3}{8}D \tag{17}$$

Similarly using the relations (12), (14) and (16) we obtain:

$$\overline{O_1A} = \frac{d}{2} = \frac{D}{2} - \overline{OO_1} = \frac{D}{2} - \left(\frac{13D}{16} - \frac{D}{2}\right)$$

We check that the value of d is that of the relation (17) $d = 3/8\,D$

3. In the triangle $O'O_1O$ we have:

$$\tan\varphi = \frac{\overline{OO_1}}{\overline{O'O}}$$

Using the relations (14), (16) and the value $\overline{O'O} = 3D/4$ we have:

$$\tan\varphi = \frac{\overline{OO_1}}{\overline{O'O}} = \frac{\left(\frac{13}{16}D - \frac{D}{2}\right)}{\frac{3}{4}D} = \frac{5}{12}$$

$$\varphi = 0,394791\,rd \tag{18}$$

We deduce that the angle δ is equal to:

$$\delta = AO_1M = \left(\pi/2 - \varphi\right) \tag{19}$$

4. Determine the rope $\overline{MN}$ joining the points of tangency M and N:

$$\sin\varphi = \frac{\overline{ML}}{\overline{O'M}} \Rightarrow \overline{ML} = \overline{O'M}\sin\varphi = D\sin\left(0,394791\right) = 0,384615D$$

$$\overline{MN} = 2\times\overline{ML} = 0,769231D \tag{20}$$

5. Determine the height y of the arc of circle *MN* belonging to the circle (C2).

$$\cos\varphi = \frac{\overline{O'L}}{\overline{O'M}} \Rightarrow \overline{O'L} = \overline{O'M}\cos\varphi = D\cos\left(0,394791\right) = 0,923077D$$

$$CL = y = D - \overline{O'L} = D - 0,923077D$$

$$y = 0,076923D \tag{21}$$

6. According to figure. 1, the height H of the pipe is:

$$H = \overline{KC} = \overline{KO} + \overline{OG} + \overline{GC} = \frac{D}{2} + \frac{D}{8} + \frac{D}{8}$$

$$H = 3D/4$$

Profile surface:

The total area of the profile is calculated as follows:

$$A = A_1 + A_2 + A_3$$

Where:

A_1 is the area of the circular segment *MCN* of diameter 2D and rope $\overline{MN}$:

$$A_1 = \frac{1}{2}\left(\frac{2D}{2}\right)^2\left[2\varphi - \sin\left(2\varphi\right)\right]$$

Using the relation (18) we have:

$$A_1 = \frac{1}{2}\left(\frac{2D}{2}\right)^2 \left[2\times 0,394791 - \sin\left(2\times 0,394791\right)\right] = 0,039761D^2 \quad (22)$$

A_2 is the area of the surface between the Ropes $\overline{MN}$, $\overline{AB}$, and the arcs of circles *MA* and *NB*. This surface is equal to the surface A_{21} of the trapezoid *MABN* and A_{22} the two segments of circle of strings $\overline{MN}$ and $\overline{AB}$.

$$A_2 = A_{21} + A_{22}$$

Knowing that $\overline{AB} = \mathrm{D}$, the surface A_{21} is equal using the relations (10), (20) and (21):

$$A_{21} = \frac{\overline{AB}+\overline{MN}}{2}\times\overline{LO} = \frac{\overline{AB}+\overline{MN}}{2}\times\left(\overline{OC}-y\right)$$

$$= \left(\frac{D+0,769231D}{2}\right)\times\left(\frac{D}{4}-0,076923D\right)$$

$$A_{21} = 0,153107D^2 \quad (23)$$

The surface A_{22}, segments of circles of diameter d and Ropes $\overline{MA}$ and $\overline{NB}$ is equal using (17) and (19):

$$A_{22} = 2\times\left\{\frac{1}{2}\left(\frac{d}{2}\right)^2\left[\delta-\sin\delta\right]\right\} = 2\times\left\{\frac{1}{2}\times\left(\frac{d}{2}\right)^2\left[\left(\pi/2-\varphi\right)-\sin\left(\pi/2-\varphi\right)\right]\right\}$$

$$= 2\times\left\{\frac{1}{2}\times\left(\frac{3D/8}{2}\right)^2\left[\left(\pi/2-0,394791\right)-\sin\left(\pi/2-0,394791\right)\right]\right\}$$

Then:

$$A_{22} = 0,008892D^2 \quad (24)$$

The surface A_2 is then obtained from relations (23) and (24)

$$A_2 = A_{21} + A_{22} = 0,153107D^2 + 0,008892D^2 = 0,161999D^2 \quad (25)$$

A_3 is the area of the half circle *AKB* of the diameter *D* and rope $\overline{AB}$:

$$A_3 = \frac{1}{2}\left(\frac{\pi D^2}{4}\right) = 0,392699D^2 \quad (26)$$

The total area, using the relations (22), (25) and (26), is equal to:

$$A = A_1 + A_2 + A_3 = 0,039761D^2 + 0,161999D^2 + 0,392699D^2$$
$$A = 0,594459D^2 \tag{27}$$

Perimeter of the profile

The total perimeter of the profile is equal:

$$P = P_1 + P_2 + P_3$$

Where

P_1 is the length of the arc of circle $\overline{MN}$, this length is equal to:

$$P_1 = \left(\frac{2D}{2}\right)(2\varphi) = \frac{2\times D}{2}\times 2\times 0,394791 = 0,789582D \tag{28}$$

The P_2 is the length of the identical circular arcs *MA* and *NB*, this length is equal to:

$$P_2 = MA + NB = 2\times MA = 2\frac{d}{2}\delta = 2\frac{d}{2}(\pi/2-\varphi)$$
$$= 2\times\frac{3D/8}{2}\times(\pi/2-0,394791)$$
$$P_2 = 0,441002D \tag{29}$$

P_3 is the length of the semicircle *AKB*:

$$P_3 = AKB = \frac{1}{2}\pi D = 1,570796D \tag{30}$$

Under relations (28), (29) and (30) the total perimeter of the profile is equal to:

$$P = 2,80138D \tag{31}$$

Consequently, the hydraulic diameter D_h is equal to:

$$D_h = \frac{4A}{P} = \frac{4\times 0,594459D^2}{2,80138D}$$

Where:

$$D_h = 0,848809D \tag{32}$$

ROUGH REFERENCE MODEL

Geometric and hydraulic characteristics of the rough model can be distinguished by the symbol:" $\bar{}$ ". So, its height is designated by $\overline{H}$, its diameter by $\overline{D}$, its wetted perimeter by $\overline{P}$, etc.

The rough model considered is a spillway pipeline under pressure flow, characterized by a relative roughness $\overline{\varepsilon}/\overline{D}_h = 0,037$ arbitrarily selected. This value is so important that flow regime is fully rough turbulent. So, friction coefficient $\overline{f} = 1/16$ according to relation (5) for *Reynolds'* number $\overline{R} = R$ tending toward infinitely large value.

Application of equation (1) to the rough reference model leads to:

$$\overline{J} = \frac{\overline{f}}{\overline{D}_h}\frac{\overline{Q}^2}{2g\overline{A}^2} \tag{33}$$

By using, for rough reference model, expression of hydraulic diameter $\overline{D} = 4\overline{A}/\overline{P}$ and this of friction coefficient $\overline{f = 1/16}$ expression (33) becomes:

$$\overline{J} = \frac{1}{128g}\frac{\overline{P}}{\overline{A}^3}\overline{Q}^2 \tag{34}$$

We introduce in expression (34), relationships (27) and (31), we deduce:

$$\overline{J} = 0,104183\frac{\overline{Q}^2}{g\overline{D}^5} \tag{35}$$

If we assume $\overline{Q} = Q$ and $\overline{J} = J$, which obviously implies $\overline{D} \neq D$. The relation (35) gives:

$$\overline{D} = 0,636150\left(\frac{Q^2}{gJ}\right)^{0.2} \tag{36}$$

If values of the discharge Q and gradient of pressure loss J are given, we can explicitly determine value of $\overline{D}$ of the rough reference model.

Dimensionless correction factors of linear dimensions.

In RMM method, all linear dimensions « L » is linked to its counterpart « $\overline{L}$ » by the fundamental relationship:

$$L = \psi \overline{L} \tag{37}$$

Where ψ is a dimensionless factor of inferior value to 1 and which is given by the explicit relationship (Achour et Bedjaoui, 2006; 2012):

$$\psi = 1,35\left[-\log\left(\frac{\varepsilon/\overline{D_h}}{4,75}+\frac{8,5}{\overline{R}}\right)\right]^{-0,4} \tag{38}$$

In which $\overline{R}$ is Reynolds 'number characterizing rough reference model and whose expression is:

$$\overline{R} = \frac{4Q}{\overline{P}\nu} \tag{39}$$

Computing steps of the pipe linear dimensions

Knowing the discharge Q, the gradient of pressure loss J, the absolute roughness ε and the kinematic viscosity ν, the following steps are recommended to compute the required value of piping linear dimensions:

1. Compute diameter $\overline{D}$ of the rough model by the use of equation (36).
2. Knowing $\overline{D}$ we compute wetted perimeter $\overline{P}$ and Reynolds'number $\overline{R}$ of the rough model, using equation (31) and equation (39) respectively.
3. Compute the hydraulic diameter $\overline{D_h}$ of the rough model thanks to equation (32).
4. Thanks to relation (38) we calculate then the dimensionless correction factor of linear dimensions.
5. The diameter value is then determined by the relation $D = \psi\overline{D}$ accordingly with Eq (37).
6. The diameter D of the pipe getting determined, the height is then deduced from relation of point N°6 quoted above $H = 3D/4$.

Example

Determine the diameter of the pipe schematized in Figure 1, knowing that:

$$Q = 2,676\ m^3/s\ , \nu = 10^{-6}\ m^2/s\ ,\ J = 0,0005\ , \varepsilon = 0,0002\, m$$

1. According to equation (36), the pipe diameter of the rough reference pattern is:

$$\overline{D} = 0,636150\left(\frac{Q^2}{gJ}\right)^{0,2} = 0,636150\times\left(\frac{2,676^2}{9,81\times 0,0005}\right)^{0,2} = 2,731657\, m$$

2. The perimeter of the rough model is, according to the relation (31)

$$\overline{P} = 2,80138\overline{D} = 2,80138\times 2,731657 = 7,652409\, m$$

3. Using the relation (39) the Reynolds number $\overline{R}$ is:

$$\overline{R} = \frac{4Q}{\overline{P}\nu} = \frac{4\times 2,676}{7,652409\times 10^{-6}} = 1398775$$

4. The hydraulic diameter is, according to the relation (32)

$$\overline{D}_h = 0,848809\overline{D} = 0,848809\times 2,731657 = 2,318655\, m$$

5. According to relation (38), the dimensionless correction factor is:

$$\psi = 1,35\left[-\log\left(\frac{\varepsilon/\overline{D_h}}{4.75} + \frac{8,5}{\overline{R}}\right)\right]^{-0,4}$$

$$= 1,35\left[-\log\left(\frac{0,0002/2,318655}{4,75} + \frac{8,5}{1398775}\right)\right]^{-0,4}$$

$$\psi = 0,732226$$

6. Finally, the diameter D of the pipe is equal to:

$$D = \psi\overline{D} = 0,732226\times 2,731657 = 2,00019\, m \cong 2\, m$$

7. The height of the pipe H is equal to:

$$H = 3D/4 = 3\times 2/4 = 1,5\ m$$

8. Verification

Let's check the validity of the calculations by determining the pressure drop gradient $\overline{J}$ that must be equal to J for:

$$\overline{J} = \frac{1}{128g}\frac{\overline{P}}{\overline{A}^3}\overline{Q}^2 = J$$

Using relations (27) and (31) we have:

$$\overline{P} = 7,652409\,m$$

$$\overline{A} = 0,594459\overline{D}^2 = 0,594459 \times 2,731657^2 = 4,435823\,m^2$$

It comes then:

$$\overline{J} = \frac{1}{128g}\frac{\overline{P}}{\overline{A}^3}\overline{Q}^2 = \frac{1}{128 \times 9,81} \times \frac{7,652409}{4,435823^3} \times 2,676^2 = 0,000500 \cong 0,0005$$

CONCLUSION

Sizing the spillway pipeline considered in the present study confirms the method advantages of the rough reference model. The characteristic diameter and the pipeline height are explicitly found by a rigorous theory approach. This theory is mainly based on *Darcy-Weisbach's* relationship whose friction coefficient cannot be directly determined without a laborious iterative process.

The study is conducted in the first instance on a rough reference model characterizing by a relative roughness arbitrarily selected in the rough turbulent field such that friction coefficient would have a constant value following the Colebrook-white relationship. The characteristic diameter of the rough model is explicitly determined by the application of Darcy-Weisbach's relation from known values of the discharge *Q* and the pressure loss gradient *J*. The diameter of the pipe studied is easily obtained by multiplying the diameter of the rough reference model by a dimensionless correction factor, following the fundamental relation of the RMM. Other pipe dimensions, such as height, are deduced from the same principle.

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