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## Numerical modeling for the urban drainage gallery systems design

### *Modelagem numérica para o projeto de redes de galerias de drenagem urbana*

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## ABSTRACT

Considering the frequent flooding of urban centers, the financial limitations and the inefficient management of Urban Drainage (UD) systems in Brazilian municipalities, it is necessary that projects be developed efficiently. These objectives are achieved with the correct definition of the diameter and galleries slope, resulting in adequate hydraulic ratios. It is also necessary to guarantee the flow without backwater, by verifying the energy grade line along the network. There are software capable of assisting the calculation, which, however, do not report optimized solutions. A vector-based numerical modeling is presented for the optimized sizing of a UD gallery system. This model was applied in an area and its results were compared with those obtained by two software in the Brazilian market. It is demonstrated the optimization developed contributes to increases the efficiency in the design. The main scientific contributions are: to characterize and model the typical design slopes, to obtain the optimum slope combined with the smaller diameter; to explore the potential of the hydraulic ratios above those normally employed, with positive effects on the definition of {D, ig} and the economy in the system; and to implement a recursive solution from a cycle of interdependent information, ensuring accuracy of results.

**Keywords:** Urban drainage, Optimum slope, Rainwater design.

## RESUMO

Considerando as frequentes inundações dos centros urbanos, as limitações financeiras e a gestão ineficiente dos sistemas de Drenagem Urbana (DU) dos municípios brasileiros, é necessário que projetos sejam desenvolvidos com eficiência e economia. Estes objetivos são alcançados com a correta definição do diâmetro nominal e da declividade das galerias, que resultem em relações hidráulicas adequadas. Deve-se ainda garantir o escoamento sem a presença de remanso, verificando a linha de energia ao longo da rede. Existem softwares capazes de auxiliar no dimensionamento da rede, que, porém, não reportam soluções otimizadas. Apresenta-se uma modelagem numérica vetorial para o dimensionamento automático e otimizado de um sistema de galerias de DU. Aplicou-se esta modelagem num projeto e seus resultados foram comparados com os obtidos por dois softwares existentes no mercado brasileiro. Demonstra-se que a otimização desenvolvida contribui para aumentos de eficiência e economia nos projetos. As principais contribuições científicas são: caracterizar e modelar as declividades típicas de projeto, para obter a declividade ótima combinada com o menor diâmetro; explorar o potencial das lâminas d'água acima das normalmente empregadas, com reflexos positivos na definição de {D, ig} e na economia na implantação do sistema; e implementar uma solução recursiva a partir de um ciclo de informações interdependentes, garantindo precisão dos resultados.

**Palavras-chave:** Drenagem urbana; Declividade ótima; Dimensionamento de galerias de águas pluviais.

## INTRODUCTION

The fast cities' growth and the lack of urban territorial plan have increased the surface runoff due to sealing, overloading urban drainage systems (MACEDO et al., 2018). Flood scenarios resulting this urbanization are common in Brazilian cities, which can cause an increase of up to 139% volume drained and up to 165% in the peak flow of hydrogram according to the execution performed by Chang, Pinheiro and Lopes (2015).

The urban micro drainage systems are designed to dimension and lead surface runoffs up to the macro drainage system for a project rain, with duration time (td) equal to concentration time (tc) and return period (T) between 2 and 10 years (SMITH, 2006). In initial stretches of these systems, rainwater covers the gutter to the limit of its capacity, when caught by inlets (BLs) (DIOGO; SCIAMMARELLA, 2008). An underground tubular network begins, hereinafter called galleries systems, normally constituted by pre-shaped concrete pipe, interconnected by junction boxes (CLs) and manholes (PVs) (ABTC, 2008).

Once outflow, roughness and slope are known, the diameter of the gallery can be calculated as a free duct as operating in full section. It was also calculated the flow speed and travel time determining tc to downstream in order to obtain a new design rain and the subsequent stretches flow, considering the increase in contribution areas (BEDIENT; HUBER; VIEUX, 2008).

The final design should aim to optimize diameters and slopes, to minimize costs, maximizing the resulting global benefits. It is fundamental to elaborate the gallery system hydraulic design, with the purpose of analyze the variation of energy grade line (LE) along the network (DIOGO, 2016). In the hydraulic design, considering the steady uniform flow, it follows the positioning of the LE, which allows to obtain a hydraulically balanced system, whenever the value of energy is equal or superior to the downstream, using as reference a PV. Otherwise, a step should be introduced in the PV output to compensate the verified energy difference. However, those steps increase the network deepening, being opportune to review the slopes practiced at each stretch (FHWA, 2009).

This verification of the hydraulic performance of an urban drainage system (DU) is essential to avoid overload, according to Batista and Boldrin (2018), and it is appropriate to implement compensatory measures to prevent or minimize local flood stemming of urbanization impacts (SILVA JÚNIOR; SILVA; CABRAL, 2017). Thus an optimization of the gallery's nominal diameter (D) and the longitudinal slope (ig) should be performed, which values varies between minimum and maximum limits, establishing efficiency indicators, defining the height of hydraulic grade line (h), flow velocity (V), energy (E), steps (d) and depths of the inferior internal generatrix (invert) of upstream and downstream galleries (PGIM and PGIJ).

The present paper aims to propose a vector-based numerical modeling for the automatic sizing of a DU gallery system, by allowing optimization the pair {D, ig} of each stretch throughout the network. The acquisition process of this pair meets established hydraulic and geometrical parameters, with a verification of the energy grade lines in the PVs and the exploration of h/D ratio beyond the usually practiced limits, allowing the recovery of the system depth, including the occurrence of eventual introduced steps.

## METHODOLOGY

The characterization of a DU gallery system is presented in the subsequent sections, including the definition of its constituent elements. Next, a bibliographic review of the hydraulic sizing criteria was carried out, with a vectorial approach, including the proposition of a new polynomial to obtain the h/D ratio up to the maximum flow limit, which allows sizing optimization. A summary of the technical characteristics of existing software for DU network sizing is presented.

### Characterization of a gallery system

The Figure 1 illustrates a network segment, where gallery stretch 3-4, between PV3 (PVM) and PV4 (PVJ), of length  $L_{3-4}$ , constant slope  $ig_{3-4}$  and diameter  $D_{3-4}$ , carries an outflow of  $Q_{3-4}$ . It is noticed that the stretch 3-4 receives contributions from adjacent stretches, identified as 2-3 and 6-3 that connect to the PVM (PV3). These upstream stretches transfer to downstream properties such as: accumulated area, concentration time and a range of hydraulic and geometrical parameters, which directly influence the subsequent stretch of design.

### Usual procedure to determine the diameter of the galleries

At each stretch t, the outflow  $Q$  ( $m^3/s$ ) is calculated according to Equation 1 as a function of rainfall intensity  $I$  in mm/h (Equation 2), which concerns the cumulative weighted area  $A$  (ha), considering a duration  $td$  (min) equal to the stretch (t) concentration time  $tc$  (min) and a return period  $T$  (years), according to the Rational Method (CETESB, 1980).

$$Q_t = \frac{I_t A_t}{360} \quad (1)$$

$$I_t = \frac{kT^a}{(td_t + b)^c} \quad (2)$$

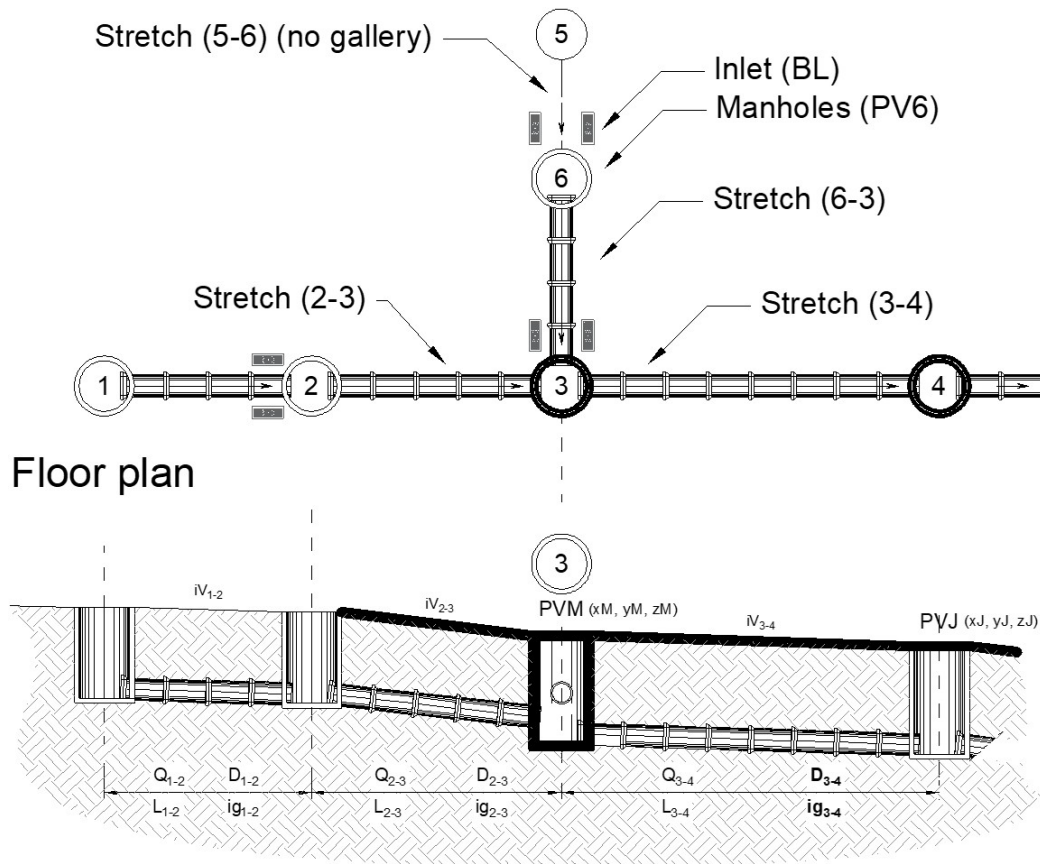
where  $k$ ,  $a$ ,  $b$ ,  $c$  are the setting parameters of the design location.

To be able to carry this outflow  $Q$  ( $m^3/s$ ), the gallery must have a calculated diameter  $D_c$  (m), considering a slope  $ig$  (m/m), initially equal to the via slope ( $iv$ ), and a Manning roughness coefficient ( $s/m^{1/3}$ ), according to Equation 3 (combined expression of continuity and Manning speed).

$$D_{c_t} = 1.55 \left( \frac{Q_t n}{\sqrt{ig_t}} \right)^{3/8} \quad (3)$$

From  $D_c$ , the nominal diameter  $D$  (m) is chosen suited to commercial availability, and the flow  $Q_c$  ( $m^3/s$ ) at full section (Equation 4) is calculated, considering the same gallery initial slope  $ig$  (m/m). This slope is not usually reviewed and often does not meet the requirements of the system hydraulic efficiency and economy.

$$Q_{c_t} = 0.31 \frac{D_t^{8/3}}{n} \sqrt{ig_t} \quad (4)$$



**Figure 1.** Gallery system characterization.

The  $Q/Q_c$  ratio is established from the use of nomograms or tables (Figure 2). The  $h/D$  ratio (water depth/nominal diameter) and the  $V/V_c$  ratio are obtained, which determine the flow condition in partially filled circular ducts. This consultation procedure leads the engineer to accept the initial solutions, without the concern of matching or optimizing the found one.

### Obtaining the theta angle in partially filled circular ducts

In order to streamline the calculations to obtain  $h/D$  and  $V/V_c$ , Saatçi (1990) presented a mathematical solution to obtain the angle  $\theta$  (Equation 6) from variable  $K$  (Equation 5), which is a function of adopted  $D$  and  $ig$ .

$$K = \frac{Q_n}{D^{3/8} \sqrt{ig}} \quad (5)$$

$$\theta = \frac{3\pi}{2} \sqrt{1 - \sqrt{1 - \sqrt{\pi K}}} \quad (6)$$

Instead of using Equation 6, Menezes Filho and Costa, (2012) developed a degree 5 polynomial (Equation 7), to calculate  $\theta$  using the same variable  $K$ , resulting a determination coefficient  $R^2 = 0.9998$ .

$$\theta = 5915.8K^5 - 5201.2K^4 + 1786.6K^3 - 298.89K^2 + 32.113K + 1.1487 \quad (7)$$

In both studies, the range of variation allowed for  $\theta$  is from 100 to 265°, corresponding to the range  $0.10 \leq h/D \leq 0.85$ . From  $\theta$ ,  $h/D$  ratio is calculated using Equation 8.

$$\frac{h}{D} = \frac{1}{2} \left( 1 - \cos \frac{\theta}{2} \right) \quad (8)$$

In accordance to UDFCD (2016) and FHWA (2009), the sizing in which  $h/D \leq 0.85$  is conservative, and it is possible to exceed this limit up to 0.94 (beyond the limit proposed in equations 6 and 7), where  $Q/Q_c$  ratio is maximum (1.0757). The free duct condition remains in that ratio (Figure 2), allowing the reduction of  $ig$  (smaller excavated volume), or to increase the gallery flow capacity, or even to adopt smaller nominal diameters.

A new polynomial approximation (Equation 9), direct function of  $Q/Q_c$  is proposed, in the range of  $0 \leq Q/Q_c \leq 1.0757$ , corresponding to  $0 \leq h/D \leq 0.938$ . This degree 3 polynomial, generated by MS Excel software (Least Squares Method), depicts the behavior  $h/D = F(Q/Q_c)$  and results  $R^2 = 0.9972$ . With  $h/D$ ,  $\theta$  is calculated using Equation 10.

$$\frac{h}{D} = 1.0178 \left( \frac{Q}{Q_c} \right)^3 - 1.7820 \left( \frac{Q}{Q_c} \right)^2 + 1.5359 \left( \frac{Q}{Q_c} \right) + 0.0576 \quad (9)$$

$$\theta = 2 \arccos \left( 1 - 2 \frac{h}{D} \right) \quad (10)$$

Table 1 presents the h/D ratio obtained by Saatçi (1990), Menezes Filho and Costa (2012) and by the authors, for a gallery with D=500mm, ig=2%, n=0.013, varying Q from 0.1 to 0.574m<sup>3</sup>/s. For Q/Qc=1.0757, Equation 9 results in h/D=0.915. This difference is not significant for design conditions.

The velocity V, in a partially filled circular duct, can be obtained through Equation 11 (originated from Manning). With h/D and V of each stretch t, the specific energy within the gallery is calculated and the position of the energy grade line (LE) is determined in relation to the gallery inferior generatrix along the system. It is essential to verify the elevation of the LE, in order to ensure the flow conditions in permanent and uniform regime without the presence of backwater (CHIN, 2006).

$$V_t = \frac{1}{n} \left( \frac{D_t}{4} \left( 1 - \frac{\sin \theta}{\theta} \right) \right)^{2/3} \sqrt{ig_t} \quad (11)$$

### INTEGRATING VARIABLES OF A GALLERY SYSTEM

In order to enable the implementation of algorithms for a DU network sizing, a set of variables was systematized, including those coming from the contribution stretches, that enable the transfer of information for downstream, allowing a systemic approach of the network.

#### Values from the contribution stretches

In the Rational Method, the flow calculation is performed stretch by stretch considering the contributing accumulated weighted area and the rainfall intensity, for a duration time equal to the concentration time (CETESB, 1980). The outflow in this

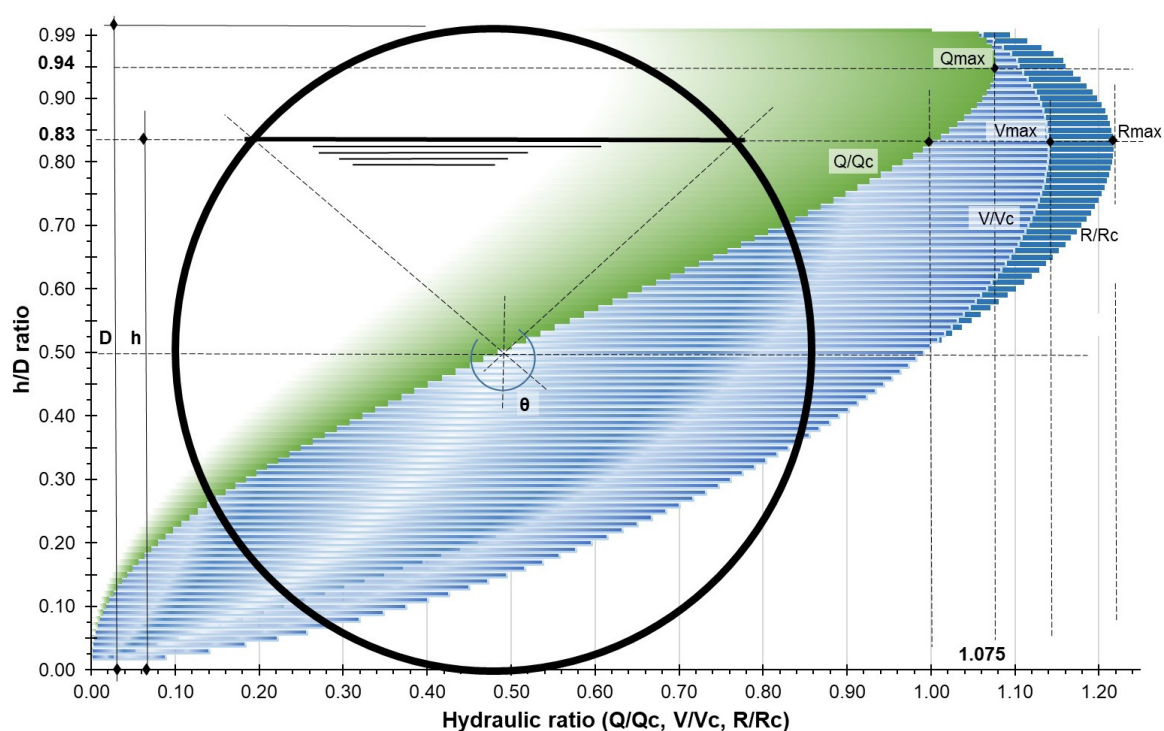


Figure 2. Hydraulic ratios of partially filled circular ducts.

Table 1. h/D ratio calculated through presented methods.

Q	Q/Qc	θ			h/D		
		K	Equation 6	Equation 7	Saatçi	Menezes	Authors
0.100	0.187	0.058	2.327	2.304	0.30	0.30	0.29
0.200	0.375	0.117	2.874	2.829	0.43	0.42	0.44
0.300	0.562	0.175	3.305	3.284	0.54	0.54	0.54
0.400	0.749	0.233	3.714	3.741	0.64	0.65	0.64
0.500	0.936	0.292	4.199	4.266	0.75	0.77	0.77
0.520	0.974	0.304	4.336	4.413	0.78	0.80	0.80
<b>0.534</b>	<b>1.000</b>	<b>0.312</b>	<b>4.465</b>	<b>4.533</b>	<b>0.81</b>	<b>0.82</b>	<b>0.83</b>
0.545	1.021	0.318	4.670	4.640	0.85	0.84	0.85
0.550	1.030	0.321	-	-	-	-	0.86
0.560	1.049	0.327	-	-	-	-	0.88
0.570	1.067	0.333	-	-	-	-	0.90
<b>0.574</b>	<b>1.076</b>	<b>0.335</b>	-	-	-	-	<b>0.915</b>

condition is maximum, as the whole area will be contributing at the considered point.

It is presented four variables that systematize information transmitted from the contribution stretches (i), necessary for the sizing of the current stretches (t):

### Cumulative weighted area

It is the sum of the accumulated weighted areas ( $A_i$  in ha), stretch by stretch, from the contribution basins (originating the flow within the gallery of the stretch t), as defined by Equation 12:

$$A_t = \sum A_i + \sum ABL_i + AC_t \quad (12)$$

where:

- $A_i$ : cumulative weighted area of contribution stretches i conducted by galleries converging at upstream point of the stretch t,
- $ABL_i$ : cumulative weighted area corresponding to adjacent lots, captured by BLs situated at the downstream point of contribution stretch(s);
- $AC_i$ : area corresponding to a concentrated flow applied at the upstream point of stretch t.

### Concentration time (tc)

The concentration time in stretch t ( $tc_t$ ) corresponds to the highest  $tc_i$  value stemming from each of the contribution stretches (galleries, gutters, or concentrated flow) that converge at the upstream point, according to Equation 13:

$$tc_t = \text{maximum} \begin{cases} tc_i^{\text{gal}} + tpg_i \rightarrow (A_i \geq ABL_i) \\ tc_i^{\text{gutter}} + tps_i \rightarrow (A_i < ABL_i) \\ tc_i^{\text{AC}} \end{cases} \quad (13)$$

where  $tpg_i$  flow travel time in gallery of contribution stretch i, in min  
 $tps_i$  flow travel time along gutter of contribution stretch i, in min

### Inferior gallery generatrix depth (PGIC)

PGIC corresponds to the greatest depth of the inferior internal downstream generatrix (PGIJ) among the contribution stretches i, measured in relation to terrain surface.

$$PGIC_t = \text{maximum} (PGIJ_i) \quad (14)$$

### Energy grade line depth (PLEC)

PLEC corresponds to the maximum depth among the downstream energy grade lines, measured from terrain surface (PLEJ) of each of the contribution stretches i, added the value of the localized pressure drop in PV ( $hp_i$  in mca), calculated according to Equation 21.

$$PLEC_t = \text{maximum} (PLEJ_i + hp_i) \quad (15)$$

Figure 3 shows how to define these four variables for the sizing of stretch 3-4 (t), which depends on the previous sizing of contribution stretches 2-3 and 6-3, that converge on point 3. It is observed that area  $A_{3-4}$  corresponds to the sum of the contributing areas related to galleries 2-3 and 6-3, added the area from  $BL_{6-3}$ ,

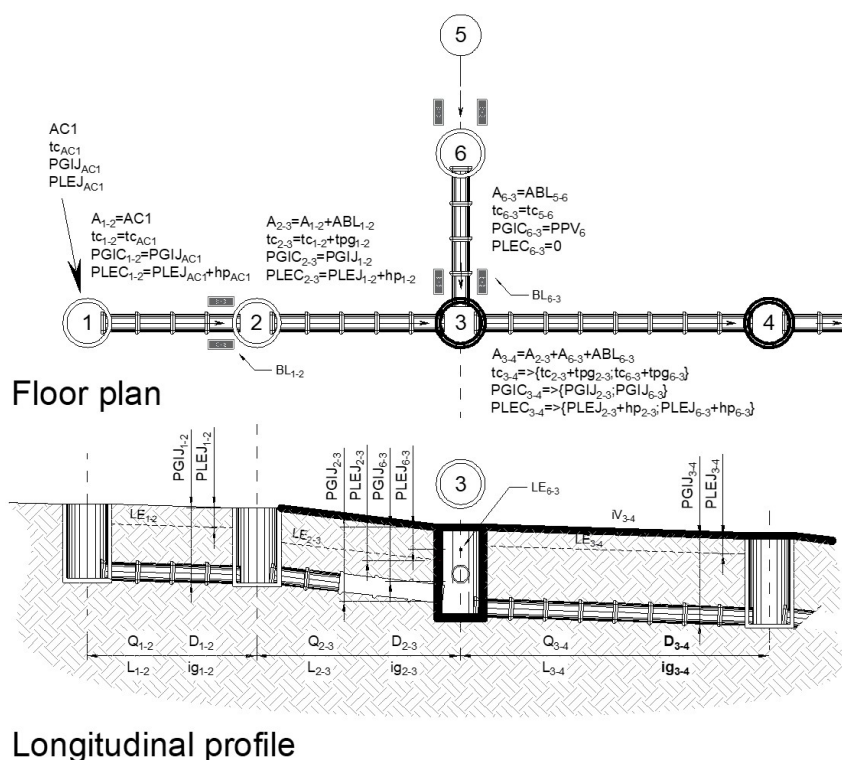


Figure 3. Information from the contribution stretches.

and the values of  $tc_{3,4}$ ,  $PGIC_{3,4}$  and  $PLEC_{3,4}$  assume the highest value of contributions, according to Equations 13, 14 and 15, respectively.

### Depth of the upstream and downstream inferior generatrix of the stretch

The depth of the inferior internal upstream generatrix (PGIM) of stretch  $t$  shall be equal to  $PGIC$ , respected to the minimum cover in accordance with Equation 16:

$$PGIM_t = \text{maximum} \begin{cases} PGIC_t \\ R_{min} + EP_t + D_t \end{cases} \quad (16)$$

Where  $EP$  is the gallery wall thickness (m), according to NBR 8890 (ABNT, 2007).

The depth of the inferior internal downstream generatrix (PGIJ) of the stretch  $t$  is calculated and must respect the minimum cover, according to Equation 17:

$$PGIJ_t = \text{maximum} \begin{cases} PGIM_t + (ig_t - iv_t)L_t \\ R_{min} + EP_t + D_t \end{cases} \quad (17)$$

Where  $iv$  is the via longitudinal slope (m/m) in the stretch  $t$ .

### Depth of stretch upstream and downstream energy grade line

The DU gallery systems are normally sized to operate as free ducts. In this condition, the hydraulic grade line (LP) is inside the duct, and the energy grade line (LE) is usually above the upper gallery generatrix, both parallel to the duct grade. Therefore, load loss distributed in one stretch is equal to the corresponding potential energy, and specific energy ( $E$ ) can be obtained by Equation 18 (adapted from BEDIENT; HUBER; VIEUX, 2008).

$$E_t = \left(\frac{h}{D}\right)_t D_t + \frac{V_t^2}{2g} \quad (18)$$

where  $(V_t^2)/2g$  is the kinetic load or velocity energy (m) in stretch  $t$ .

The depth of the upstream energy grade line (PLEM) of the stretch  $t$ , measured from terrain surface, is obtained by subtracting from  $PGIM$  the value of the specific energy  $E$  of that stretch:

$$PLEM_t = PGIM_t - E_t \quad (19)$$

Similarly, the depth of the downstream energy grade line (PLEJ) is calculated by Equation 20:

$$PLEJ_t = PGIJ_t - E_t \quad (20)$$

### Localized load loss in the PV

Calculating the load loss located in a PV (Equation 21) is a complex matter, and it is not the subject of this paper. However, a preliminary assessment of this loss can be performed as a function of the constant ( $K_p$ ) that reflects the angular change in the PV interior flow direction, multiplied by the kinetic load, according to Bedient et al. (2008).

$$hp_t = K_p t \frac{V_t^2}{2g} \quad (21)$$

Where  $K_p$  values defined according to Table 2.

For more rigorous assessments, it is recommended to apply the methods developed by Chang et al. (1994) and FHWA (2009), where those losses are calculated by the sum of three plots in PV: input, output and pathway setting between these two points.

### Step requirement in upstream PV

The depth of the upstream energy grade line (PLEM) of stretch  $t$  should be compared with  $PLEC$  (Equation 15) in each PV. The condition  $PLEM \geq PLEC$  leads the flow without backwater, from a higher energy point to a lower energy point. If  $PLEM < PLEC$  ( $E_{3,4} > E_{2,3}$ ), a step ( $d$ ) in PV must be introduced (Equation 22), equal to the difference of the verified energy (Figure 4).

This step ( $d_{3,4}$ ) lowers the PV output quota in relation to its input, in order to match the energy grade line ( $LE_{Corr_{3,4}} = LE_{2,3}$ ) to not occur backwater or excessive elevation of the water level in PV. If there is a step,  $PGIM$  shall be revised and  $PGIM_{Corr_{3,4}}$  must correspond to  $PGIM_{3,4}$  added step according to Equation 23.

$$d_t = PLEC_t - PLEM_t \geq 0 \quad (22)$$

$$PGIM_{Corr_t} = PGIM_t + d_t \quad (23)$$

When a step exists, it deepens the corresponding PV. Keeping  $ig$ , this depth will be propagated to downstream to the launch point. To avoid deepening the entire system, it is necessary to review  $ig$  within each stretch, with the purpose of reducing gallery longitudinal slope, making the network as shallow as possible.

The formulation presented so far allows to define  $D$ , known  $Q$ ,  $ig$ ,  $n$ , and to check galleries operating hydraulic conditions. However, it is necessary to optimize  $ig$  for each stretch, aiming to recover depths and  $h/D$  ratios. Given the presented methodology, there is all the necessary information for the sizing of a galleries network, with the automatically optimization of its slope, stretch by stretch, meeting all the presented conditions.

### TYPICAL GALLERY DESIGN SLOPES

Normally, the longitudinal slope of the via ( $iv$ ) is used as a reference to define the initial slope of a gallery stretch ( $ig$ ). However, due to topographic (almost flat or steep roads) and hydraulic constraints ( $h/D$  ratios, minimum and maximum speed

**Table 2.** Localized load loss in PVs (BEDIENT et al., 2008).

Flow direction change (degrees)	$K_p$
0	0.05
15	0.08
30	0.20
45	0.38
60	0.65
75	0.94
90	1.33

limits), and possible interference with other existing buried systems, not always  $ig=iv$  is possible.

The typical slopes of a gallery stretch allow a range of possible  $ig$  to be established. These slopes are then identified, and the respective formulations that characterize them are developed.

**Via slope (iv)**

It corresponds to the via slope (Figure 5). It is a convenient practice to adopt  $ig=iv$  to start the calculations, once this slope at first does not deepen the system. However, in almost flat, steep stretches or when there are steps,  $ig$  should be reviewed.

$$i_{v_t} = \frac{ZM_t - ZJ_t}{L_t} \tag{24}$$

where  $ZM$ ,  $ZJ$  are the quotas of the upstream and downstream stretches points (PVM, PVJ).

**Slope due to minimum cover (iRmin)**

Correspond to calculated slope (Equation 25) as a function of the minimum allowed cover ( $Rmin$ ) above the upper external gallery generatrix in the PVJ (Figure 6). It controls the minimum depth of the PVJ, in order to protect the gallery against structural damage (diametrical deformation). In specific stretches,  $Rmin$  may

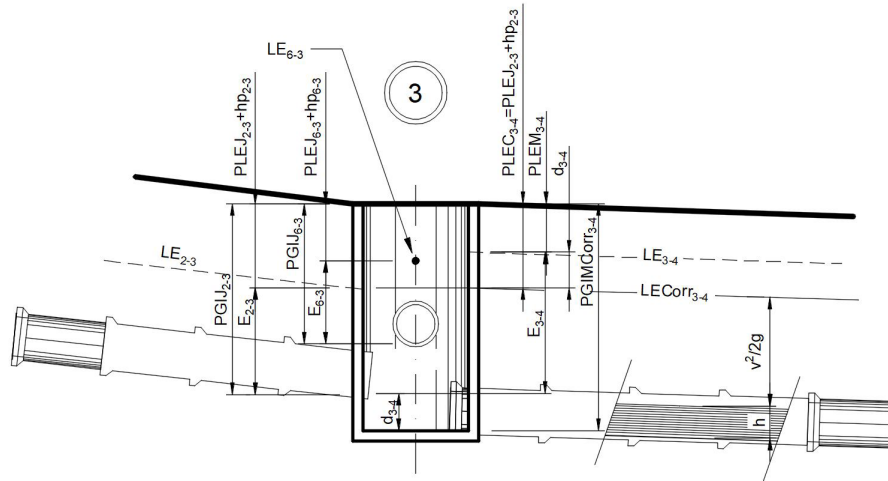


Figure 4. Comparison of LE and verification of step requirement in PV3.

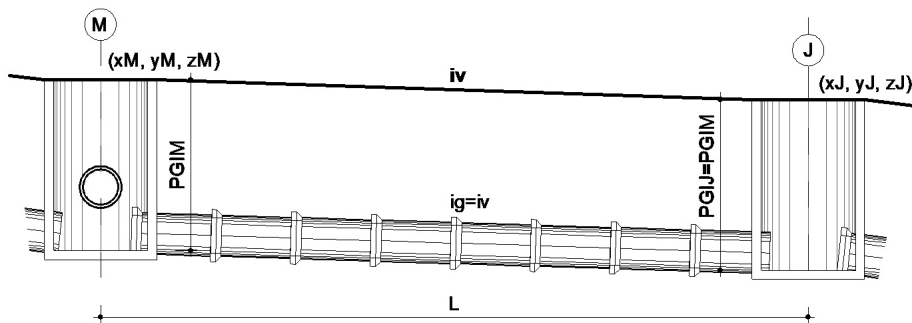


Figure 5. Gallery slope equal to the via slope.

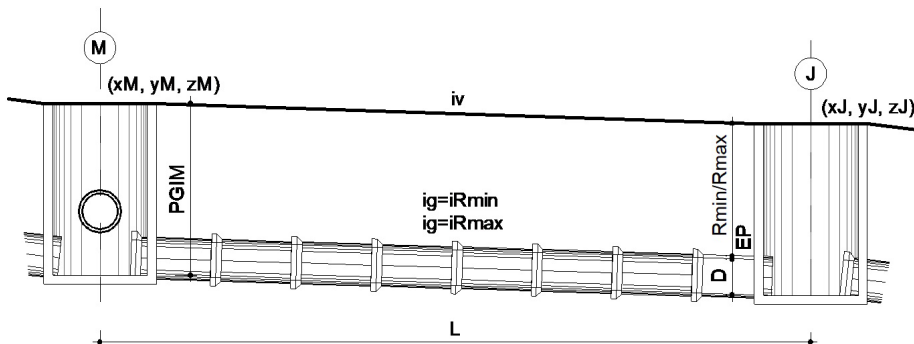


Figure 6. Gallery slope ( $iRmin$  and  $iRmax$ ).

not be met (Table 3), with additional protection for the gallery must be ensured.

$$iR_{min_t} = \frac{R_{min_t} + EP_t + D_t - PGIM_t}{L_t} + iv_t \quad (25)$$

### Slope due to maximum cover (iRmax)

It corresponds to the calculated slope (Equation 26) in a function of the tallest allowed cover (Rmax) for the gallery outer superior generatrix, in the PVJ (Figure 6). It controls the depth of the PVJ, avoiding excessive digging, backfilling, disposal material and shoring. Recommended values of Rmax are listed in Table 3.

$$iR_{max_t} = \frac{R_{max_t} + EP_t + D_t - PGIM_t}{L_t} + iv_t \quad (26)$$

### Slope due to minimum h/D (ihDmin)

It corresponds to the slope calculated according to Equation 27 (proposed by the authors), so that the gallery works in the allowed minimum h/D ratio. It is desirable to work above the half section ( $hD_{min} \geq 0.50$ ), since lower h/D characterizes underutilization of the gallery.

$$ihD_{min_t} = \left( \frac{Q_t n}{\varpi Ac Rc^{2/3}} \right)^2 \quad (27)$$

Where  $\frac{h}{D} = hD_{min}$

$\varpi = \left( 1 - \frac{\sin \theta}{\theta} \right)^{5/3} \frac{\theta}{2\pi}$ , where  $\theta$  is obtained according to Equation 10

for hDmin.

$$Ac = \frac{\delta D_t^2}{4}, \quad Rc = \frac{D_t}{4}$$

### Slope due to h/D=0.83 (ihD83)

It is the slope calculated according to Equation 28, where velocity reaches its maximum value (Figure 2). Although the gallery is in a partially full condition ( $h/D=0.83$ ), it has the same capacity of the full section ( $Q/Q_c=1.00$ ).

$$ihD83_t = \left( \frac{Q_t n}{Ac Rc^{2/3}} \right)^2 \quad (28)$$

### Slope due to maximum flow (ihDmax)

It is the slope calculated in accordance with Equation 29 (proposed by the authors), with the gallery flow working at h/D=0.94 ratio, where the flow is maximum ( $Q/Q_c=1.076$ ). It is the smallest design slope capable of carrying Q in a free duct condition (UDFCD, 2016). Recommended values for hDmax is introduced in Table 3, which condition the value of  $\varpi$ .

$$ihD_{max_t} = \left( \frac{Q_t n}{\varpi Ac Rc^{2/3}} \right)^2 \quad (29)$$

Where  $\frac{h}{D} = hD_{max}$

### Slope due to minimum speed (iVmin)

It corresponds to the slope characterized by the flow at minimum allowed speed (Equation 30, proposed by the authors). Recommended values of Vmin are presented in Table 3, in order to control the siltation in the gallery, being necessary to define h/D where it is intended, to calculate  $\theta$ .

$$iV_{min_t} = \left( \frac{nV_{min}}{\left( \frac{D_t}{4} \left( 1 - \frac{\sin \theta}{\theta} \right) \right)^{2/3}} \right)^2 \quad (30)$$

**Table 3.** Recommended limits for gallery sizing.

Reference	Velocity (m/s)		Cover (m)		h/D ratio	
	Vmin	Vmax	Rmin	Rmax	hDmin	hDmax
<b>Authors</b>	<b>0.75</b>	<b>7.00</b>	<b>1.00</b>	<b>4.00</b>	<b>0.50</b>	<b>0.94</b>
Diogo and Sciammarella (2008)	0.75	5.00	$0.6 + \frac{(D-0.4)}{0.1} 0.05$	-	0.20	0.85
FHWA (2009)	0.60 a 0.90	6.00	0.9	-	-	0.83 a 0.93
Inouye (2009)	0.75	6.00	1.00	5.00-D	-	-
Belo Horizonte (2017)	0.75	7.50	0.80	-	-	0.80
Rio de Janeiro (2010)	0.80	5.00	$D + D/2 + 0.40$	-	-	0.85
Goiânia (2005)	0.75	5.00	-	-	-	0.85 a 0.90
Joinville (2011)	0.80	4.00	0.80	-	-	0.75
Porto Alegre (2005)	0.80	4.00	1.00	-	-	-
São Paulo (2012)	0.60	5.00	1.00	-	-	-
SUDERHSA (2002)	0.60	5.00	1.00	-	-	-
UDFCD (2016)	1.00	6.10	-	-	-	Full



### Slope due to maximum speed (iVmax)

It is the slope characterized by the flow at maximum allowed speed (Equation 31, proposed by the authors). Recommended values of Vmax are presented in Table 3, to minimize abrasive wear of the gallery's inner walls. It is necessary to define h/D where it is intended to calculate  $\theta$ .

$$iV_{max_t} = \left( \frac{nV_{max}}{\left( \frac{D_t}{4} \left( 1 - \frac{\sin\theta}{\theta} \right) \right)^{\frac{2}{3}}} \right)^2 \quad (31)$$

### DEFINITION OF SLOPE RANGE

In order to make a decision concerning which  $ig$  to adopt, a range of gallery slopes is defined at each stretch, which establishes limits that allow a flexibility in choosing the optimum slope. The smallest possible  $ig$  slope for a stretch is that in which the following condition (Equation 32) is observed:

$$ig_{min} = \text{maximum} \begin{cases} iR_{min} \\ ihD_{max} \end{cases} \quad (32)$$

Similarly, considering that the maximum cover must be respected and that the gallery cannot operate below  $hD_{min}$ , the maximum limit of  $ig$  is (Equation 33):

$$ig_{max} = \text{minimum} \begin{cases} iR_{max} \\ ihD_{min} \end{cases} \quad (33)$$

Thus, the gallery slope ( $ig$ ) of a given stretch will be in the range between  $ig_{min}$  and  $ig_{max}$  (Figure 7), as long as the speed meets the minimum and maximum limits established under the control conditions. Thereby, a DU network sizing is solved by assigning an  $ig$  value within this range. Nevertheless, it must be optimized.

### DESIGN SLOPE OPTIMIZATION

It is proposed a vector-based numerical solution for optimal determination of  $ig$  at each stretch of a gallery system, where the hydraulic factors, energy, step, cover, depth and other limits established under the control conditions are considered. It is observed that the calculation of diameter in function of slope (Equation 3) and the slope in function of diameter (see section Typical Gallery Design Slopes) creates a situation of recursiveness in the sizing process.

The search for optimal slope assumes a complex scenario, where several factors contribute to its definition, many of them dependent on that slope, not yet calculated. Therefore, the optimization of the pair  $\{D, ig\}$  in the context of sizing a DU network suggests the need for an automatic-interactive calculation process. Any change in  $ig$  will affects the upstream PV (as it modifies energy, possibly interfering with the steps) beyond propagating for downstream to the launch point.

Given this scenario and considering automatic decision making, the optimal slope should be as low as possible ( $ig_{min}$ , Equation 32). This slope provides maximum hydraulic performance, meets minimum coverage and speed, by contributing to savings in network execution. The flowchart of Figure 8 summarizes the process of automatically obtaining the pair  $\{D, ig\}$  for each stretch of a galleries system.

### SOFTWARE FOR DU NETWORK SIZING

There are several software available concerning DU sizing. Among them are: SUwin, Pró-Saneamento, Drenar, UFC8, SWMM, and StormCAD V8i. A summary of its main features is presented in Table 4. The Rational Method is used in some of those software, and the hydraulic calculation of network galleries can be performed under steady uniform flow as a free duct, being uncommon the sizing in forced duct condition.

Though it is important to evaluate energy grade line (LE) behavior throughout the system to ensure free duct condition without backwater. This evaluation is carried out in different

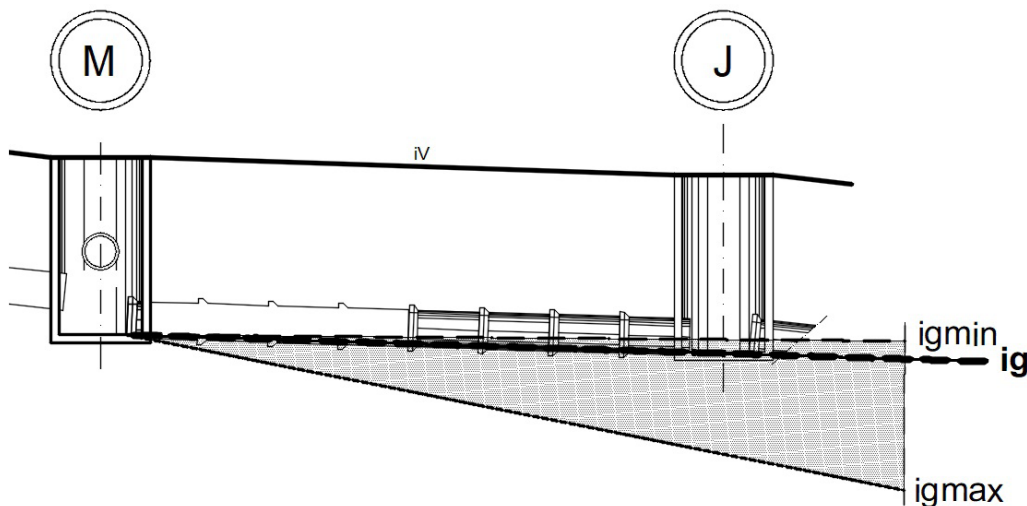


Figure 7. Range of the gallery slope in a stretch.

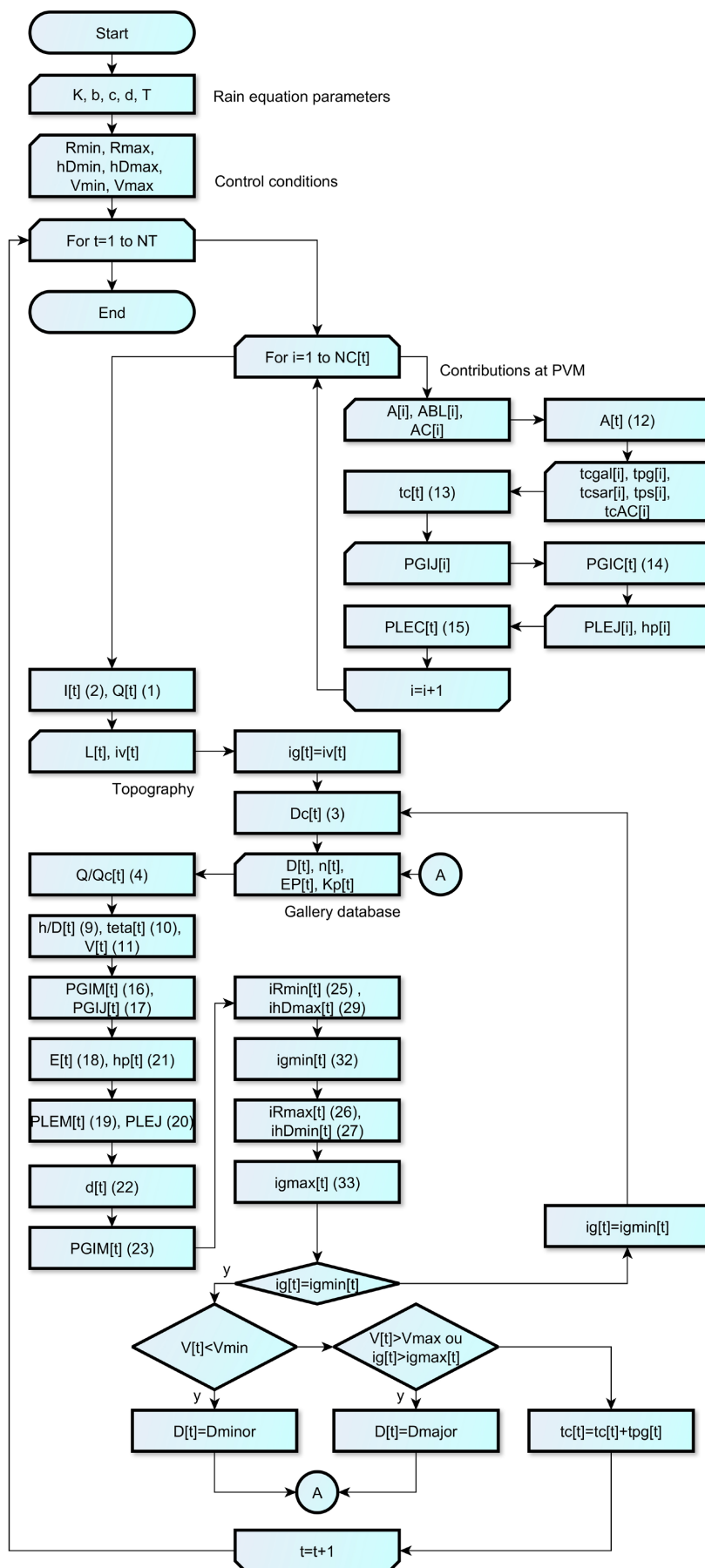


Figure 8. Flowchart for the calculation of  $\{D, ig\}$  of a galleries network.

**Table 4.** Software for urban drainage network sizing.

Software/Company	Main features
<b>SUwin</b> (TOTALCAD, 2019)	It is a stand-alone software, allowing to sizing the rainwater urban network. From the reading of the level curves of the topographic plant and the contribution areas definition, rainfall intensity, it calculates flow and size the network. It facilitates calculation of all parameters: flow, speed, waterline height, etc, within minimum and maximum defined limits. It emits a pipe geometry report of network stretches, indicating length, slope, pipe and ground quotas, and material quantitative. Regarding LE calculation, it recognizes that the best way of analyze the system hydraulic behavior is searching the LE equalization within confluent collectors on PVs. However, SUwinBR software cannot verify it, but adopts the LPs coincidence to a height of 80% of galleries diameters. According to TotalCad (2019), this balance defined by geometry is easier to establish and its results are next to LE method. It also generates plan and longitudinal profiles as well the calculation memory.
<b>Pró-Saneamento V16</b> (MULTIPLUS, 2019)	Calculates, checks and sizes sewer systems, water supply, rainwater drainage. It is an AutoCAD application and performs level curves recognition of topography plant. After rainwater network tracing, with location of PVs, gutter, BLs (interlinked by galleries), it is possible to pre-size the diameters and to create the hydraulic calculation spreadsheet through the Rational Method. It does not mention any step calculation methodology or fall tubes.
<b>Drenar</b> (SANEGRAPH, 2019)	It has a graphic interface with AutoCAD 2016 and IntelliCAD. Using the topographic and urban plants, it is possible to delimit the contribution areas, insert PVs, gutters, BLs and define network outline. These information combined with the hydrological parameters allows to calculate the outflow using the Rational Method. The software allows the definition of several parameters stretch by stretch, with maximum hydraulic grade line, minimum slope, and to control backwater (steps), considering LP or up to 100%LE, among other factors. Afterwards calculation, it is possible to create longitudinal network profile, to list materials, to raise quantitative and other information in order to implement the project.
<b>UFC8</b> (LHC/UFC, 2019)	Developed by UFC Hydraulic Laboratory, it is implement in AutoLIST, VBA and Visual Basic for AutoCAD, similar to Drenar concerning elements insertion of DU system. From hydrologic parameters, using the Rational Method, UFC8 has an interface with SWMM, appropriate to calculate and simulate flow in DU networks, using Saint-Venant equations, controlling backwater through LP analysis.
<b>SWMM</b> (EPA, 2019)	Storm Water Management Model was created by American Environment Protection Agency (EPA). Since it is a free and easy to use software, is used all over the world for planning, analysis and sizing storm drainage systems. The user inserts existing input parameters such as temporally distributed rain, basin features and the hydraulic structures. The model provides quantitative and qualitative data in the considered stretch represented by tables or graphics. The last updates include the capacity of simulating compensatory techniques, what makes the model useful for urban basins.
<b>StormCAD V8i</b> (BENTLEY SYSTEMS, 2019)	It is a tool for design and analysis of a DU system. The model assumes steady uniform flow along the stretches. It defines all gradually varied flow profiles and follows the system hydraulic gradient. It also allows users to insert maximum and minimum parameters, such as: speed, slope and cover. Moreover, the user can specify a method for flow analysis in the PVs. The estimated flow of the hydraulic basin are carried out using the Rational Method. The rainfall data can be inserted as IDF equation. It allows the use of many equations to calculate energy loss along the system (Manning, Ganguilet-Kutter, Hazen-Williams, Darcy-Weissbach).

ways, depending on the calculation methodology employed by the software. Normally, the hydraulic conditions of the upstream and downstream galleries in a PV are compared and steps are eventually introduced to promote the coincidence of: the upper duct generatrix (geometric), the hydraulic ( $LP=h$ ) or the energy grade lines ( $LE=h+V^2/2g$ ). Comparison of LE is the most appropriate procedure, however it requires greater computational effort due to the more complex iteration mechanisms, as shown in the flowchart of Figure 8. Regarding the optimization of the resulting calculation, especially for the  $\{D, ig\}$  pair, none mention is made in those software.

In the case of UFC8, which uses SWMM to simulate non-steady unidirectional flow conditions, the *Saint Venant* equations allow to match energy along the network simultaneously and interconnectedly. In this procedure, the flow is expressed in a hydrograph, which can be compared or added to that of another stretch, by eliminating the need to consider travel time. As the velocity is variable along a gallery stretch, tc values obtained by methods that consider steady and uniform flow are inaccurate.

## APPLICATION

In order to show the potential of optimization of  $\{D, ig\}$ , the authors proposed modeling was applied in a DU design. The floor plan of Figure 9 presents an allotment of 11.55ha, with the division of the blocks and their respective contributing areas, the quoted analysis points, the superficial flow direction and the layout of the gallery network.

From the analysis points, the lengths and the slopes of each stretch are determined. The division of the contributing areas, the surface runoff coefficient, the rain equation and other design parameters allow the outflow (Q) calculation by the Rational Method up to point 057 (launch point). BLs are positioned next to the upstream PVs (not shown in Figure 9) of each gallery stretch. The network defined by points 013 to 057 is called “main”, and the network 023-054 and 033-056, “secondary”. At points 054 and 056, the main network receives the contributions from the secondary networks.

The following design parameters were adopted, disregarding the localized load loss in PVs:

$k = 3510.00$   
 $a = 0.227$   
 $b = 29.32$   
 $c = 0.995$  (Equation 2, IDF parameters)  
 $T = 10$  (years)  
 $t_d = t_c$  (min)  
 $C = 0.70$  (surface runoff coefficient)  
 $D$  for precast concrete galleries (ABNT, 2007).  
 $n = 0.013$  (for precast concrete galleries)

The concentration time ( $t_c$ ) was calculated from an initial superficial flow time of 10 minutes ( $T_{ES}=10\text{min}$ ), added gutter (TPS) and/or gallery (TPG) travel time, which were calculated stretch by stretch using the Manning equation.

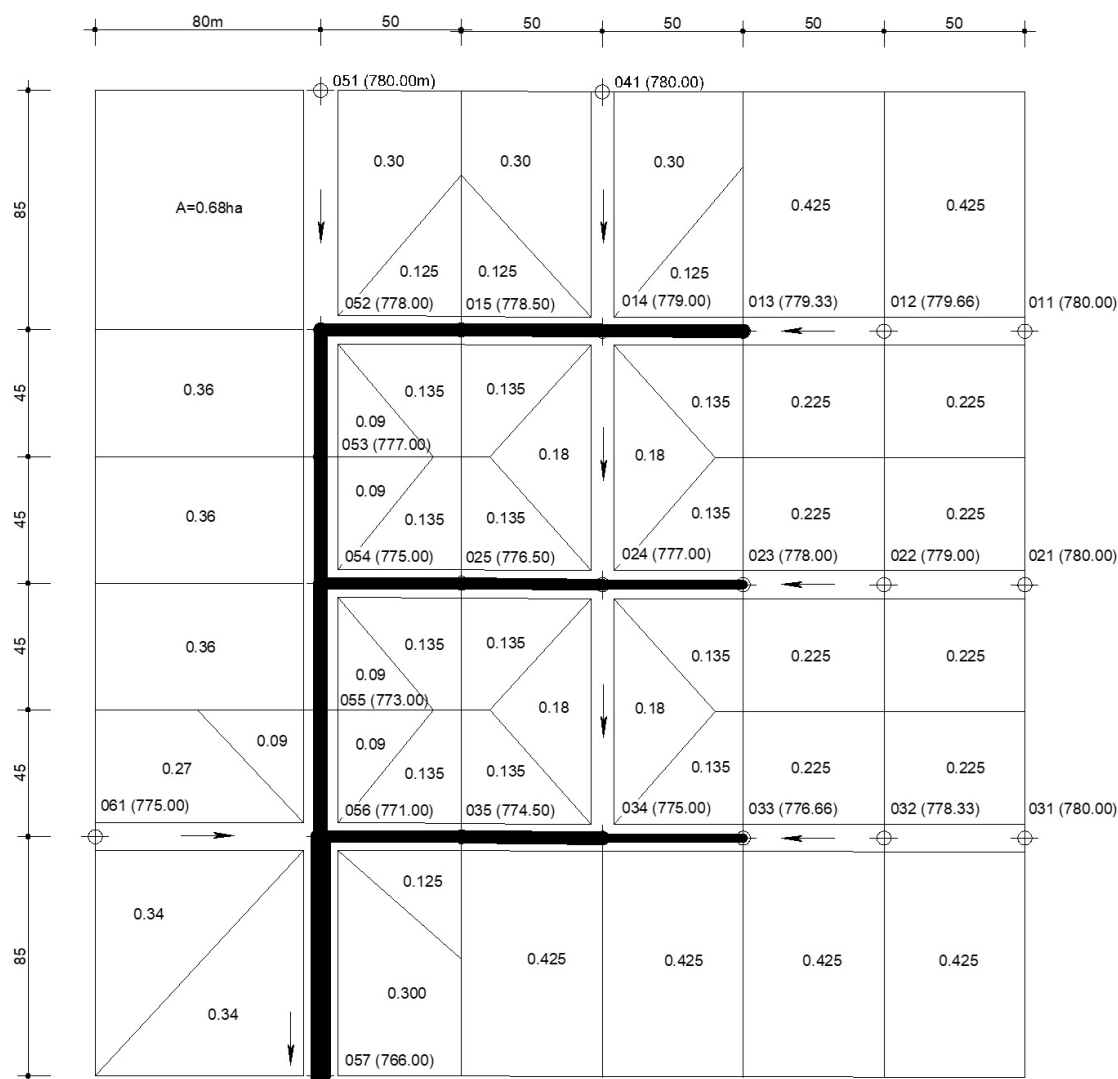
That gallery network, consisted of 14 stretches with different longitudinal slopes, was sized using three software applications, and their results compared, by using the same design parameters mentioned above. In addition to the spreadsheet implemented by the authors, it was chosen two software developed in Brazil, due to license availability, reliability, and large performance. The alternative are:

- A: MS-Excel Spreadsheet (by the authors, with LE)
- B: UFC8 Program (UFC, com LP)
- C: Drenar Program (Sanegraph, with LP)
- D: Drenar Program (Sanegraph, with LE)

Table 5 presents the control conditions used in each of the alternatives.

**Table 5.** Alternative control conditions.

Alt.	Velocity (m/s)		Cover (m)		h/D ratio		Allow <D downstream	Step sizing method
	Vmin	Vmax	Rmin	Rmax	hDmin	hDmax		
A	0.75	7.00	1.00	4.00	0.50	0.94	Yes	LE
B	0.75	7.00	1.00	-	-	1.00	Yes	LP
C	0.80	7.00	1.00	-	-	0.85	No	LP
D	0.80	7.00	1.00	-	-	0.90	No	0.75LE



**Figure 9.** Floor plan of the design area and the corresponding gallery network.



$R_{min}$  and  $R_{max}$ ,  $V_{min}$  and  $V_{max}$ ,  $hD_{min}$  and  $hD_{max}$  ratios. This spectrum supports the determination of  $ig$  (col. 14), which approaches  $ig_{min}$  at each iteration.

Known  $\{D, ig\}$ , the depth of upstream (PGIM) and downstream (PGIJ) gallery inferior generatrix of a stretch (col. 15 and 16) is determined. The upstream (col. 17) and downstream (col. 18) cover are also obtained, which must meet the established values in the control conditions. Columns 19 to 23 present the calculated hydraulic parameters that permit the determination of the stretch specific energy (col. 24), that when compared with the contribution's energy, allows to verify the need for a step (col. 25). If a step exists, its value will be added to PGIC (the higher PGIJ of contributions), so that the stretch PGIM is updated (Figure 4).

At the bottom line of each alternative, we highlight the efficiency indicators, related to the average diameter and slope (weighted by the stretch length), the average depth of the inferior downstream generatrix, the average  $h/D$  ratio, and the sum of the steps along the network. Also, the differences of the efficiency indicators in relation to alternative A is highlighted. However, the difference shown in column 16 refers to the recovery of the average depth of the inferior downstream generatrix relative to its upstream, including alternative A.

## DISCUSSION OF RESULTS

Based on the results presented in Figure 10 for each of the four alternatives, the values obtained are analyzed, discussed and compared, by selecting some relevant design stretches.

The alternatives B, C and D do not consider the wall thickness of the ducts for the purposes of cover verification, with a reflection on excavation costs, which was considered in alternative A.

### Stretch 013-014

It is necessary a  $D_c=513\text{mm}$  gallery to conduct  $Q=364\text{L/s}$  in alternative A. In this case, normally,  $D=600\text{mm}$  is used. However, it is feasible to define  $D=500\text{mm}$ , with  $ig=0.81\%$ . This slope corresponds to the highest value between that referring to the minimum cover ( $iR_{min}=0.66\%$ ) and where the  $h/D$  ratio is maximum ( $ihD_{max}=0.81\%$ ), as expressed in Equation 32.  $Q$  is conducted in  $h/D=0.91$  condition, with a 7.5% increase in flow capacity over the full duct.

In the alternatives B, C and D were used  $D=600\text{mm}$  as usual sizing practice, due to the absence of the recursive process of obtaining  $\{D, ig\}$ . The gallery slope, as expected, was  $ig=iv$ , resulting lower  $h/D$  ratio: 0.72, 0.66 e 0.66, respectively (Figure 10).

### Stretches 014-015 to 053-054

In alternative A, in all these stretches, the diameter employed was  $D=600\text{mm}$ , lower than the calculated ones ( $D_c$ , col. 4), and  $ig=ihD_{max}$  making all  $h/D=0.91$ . The introduced steps were recovered by optimizing  $\{D, ig\}$  in all stretches, so that the downstream cover approached its minimum limit.

When considering LE, the introduced steps were higher than those taking into account only LP. Nonetheless, these provided greater safety concerning the flow without backwater, because a portion of the energy ( $V^2/2g$ ) should not be neglected, especially in higher speed stretches.

In other alternatives (B, C and D), the used nominal diameter was higher again ( $D=700\text{mm}$ ) and  $h/D$  ratios were lower, varying from 0.55 to 0.78. The underutilization of the employed diameters is evident, due to the lack of optimization, which ends up encumbering the system.

### Stretches 054-055

In this stretch, the main network receives the additional contribution from the secondary network (stretch 025-054). In alternative A, with  $D=700\text{mm}$  and  $ig=3.26\%$ , a  $Q=1.794\text{L/s}$  is carried with  $h/D=0.91$ .

Figure 11 illustrates a step ( $d=0.81\text{m}$ ), entered at the PV054 outlet, was necessary to level the energy grade lines of the stretches 025-054 (0.63m below terrain surface) and 054-055 (assuming 1.84m below terrain surface). This step, added the PGIJ of stretch 053-054 (1.66m), results in a PGIM=2.47m in the stretch 054-055.

If this step would not be introduced, the LE level of 054-055 stretch would be above the terrain surface, causing not only a backwater in the gallery, but flooding around PV054.

In alternative D, which considers only 75% LE,  $D=800\text{mm}$  and  $ig=4.04\%$  (higher than Alt. A) were used, resulting in  $h/D=0.60$  with step  $d=0.75\text{m}$ . In alternatives B and C, where only LP was considered, the steps were smaller, what it was expected.

### Efficiency indicators analysis

The efficiency indicators, presented in the bottom line of the different alternatives in Figure 10 allow to conclude that:

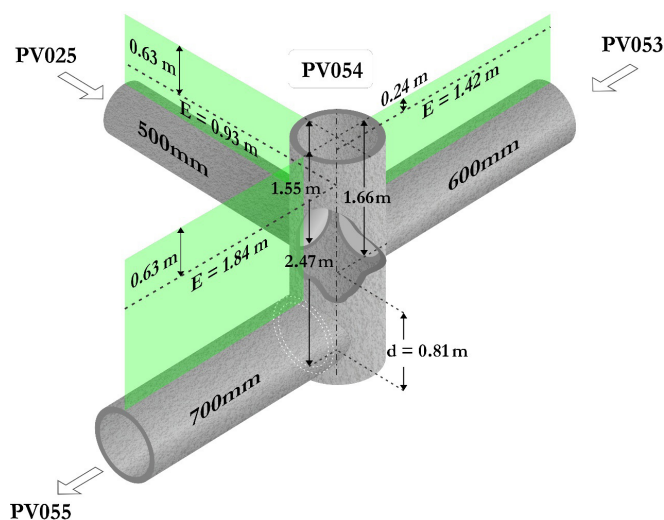


Figure 11. Energy grade line analysis at PV054.

**Table 6.** Comparative budget for gallery network implementation.

Alt.	Costs (R\$)									Dif. (%)
	Excav.	Shoring	Tamping	Cradle	Settlement	Backfilling	Compact.	Dispos.	Total	
A	6,982.40	29,114.20	3,281.44	38,171.99	110,752.09	12,065.30	14,395.18	4,860.14	<b>219,622.74</b>	
B	6,732.55	28,152.41	3,327.08	42,012.17	122,755.14	11,633.56	13,500.84	4,686.23	<b>232,799.99</b>	<b>+6.00</b>
C	6,518.90	27,168.47	3,325.22	42,986.29	125,818.51	11,264.38	12,592.16	4,537.52	<b>234,211.44</b>	<b>+6.64</b>
D	8,065.34	31,570.45	3,462.45	44,033.61	127,144.96	13,936.57	16,721.42	5,613.96	<b>250,518.73</b>	<b>+14.07</b>

- the network average diameter, calculated for alternative A is 580mm, while in subsequent alternatives, it is 622, 634 and 641mm, respectively, demonstrating that it is possible to conduct the same flow with smaller diameters.
- similarly, the average h/D ratio along the network for alternative A is 0.85, while for the other alternatives, it is 0.72, 0.65 and 0.66, respectively. This demonstrates that the developed optimization process has achieved its goals of maximizing the efficiency of DU networks.
- it is also observed that the average slope of the via is  $i_v=3.08\%$ , and of the gallery is  $i_g=2.73\%$  in alternative A (col. 13). This demonstrates the potential of steps recovery along the network, due to optimization of  $i_g$ . In the other alternatives,  $i_g$  assumed higher values.
- in alternatives A and D, in which LE was considered, there was a significant increase in the total of the steps introduced (4.12 and 6.16m). In the alternative D, which considered 75% of LE, the steps were deeper, which demonstrates once again the potential for optimization of alternative A in the recovery of these steps.
- in alternatives B and C, where only LP was considered, the steps were smaller (2.25 and 1.70m), with consequences in the depths of the galleries inferior generatrix (PGIM and PGIJ). However, it is not recommended to disregard LE, as it ensures greater safety, avoiding backwaters along the network, to ensure flowing in a free condition.

### Final considerations

Based on the specifications of the SUDECAP contract documents (BELO HORIZONTE, 2008), a comparative execution budget of the entire network was made (Figure 10) without considering the implementation of PVs and BLs, as their costs are equal in any of the alternatives. The unit cost compositions of each service were taken from SINAPI (National System of Cost Survey and Construction Industry Indexes) of August 2018 (CEF, 2018).

The comparative budget presented in Table 6 was prepared based on the composition and volume of services (excavation, shoring, tamping, cradle, settlement, backfilling, compaction and disposal area), raised from the network data (Figure 10), to the four sizing alternatives.

The costs related to tamping, cradle and settlement depend on the galleries diameter, while those related to excavation, shoring, backfilling, compaction and disposal area also include the system depth. The settlement cost alone represents approximately 50%

of the network total cost, being appropriate to reduce the nominal diameters and, consequently, the trench width.

Thus, the total cost of alternative A (Table 6) for the entire network is lower than that of alternatives B, C and D, with differences of 6.00, 6.64 and 14.07%, respectively. Although in alternative A the earth moving costs were higher, it is demonstrated that the total costs of the network execution are influenced by the results of the hydraulic optimization of the pair {D,  $i_g$ }. Other optimization criteria can be modeled in future work.

### CONCLUSIONS

In this paper, a methodology for the sizing of DU gallery networks is presented. The method consists of a vector-based numerical modeling for automatic and optimized sizing of a network, consisting of subsequent stretches, upstream contributions, whose information has been identified, characterized and systematized.

A degree 3 polynomial, direct  $Q/Q_c$  function, valid in the range  $0 \leq Q/Q_c \leq 1.076$ , is proposed to obtain h/D ratio up to 0.94. This polynomial presents sufficient accuracy for design purposes ( $R^2=0.9972$ ) and covers a wider range of h/D, usually unexplored.

Criteria are defined to determine, for each stretch: the upstream (PGIM) and downstream (PGIJ) inferior generatrix depth, based on the minimum adopted cover; the maximum depth of the inferior generatrix of downstream contributions (PGIC); and the height of the steps (d), derived from the difference between the depths of the energy grade lines in the PVs.

Typical slopes of a gallery stretch are identified, establishing a range of acceptable slopes, which provides support to the choice of the optimal design slope ( $i_g$ ). Also, a roadmap for the iterative network sizing of galleries was developed, shown in the Figure 8 flowchart, able to set the optimized {D,  $i_g$ } pair, allowing the recovery of the average system depth, due to the possible steps introduced.

Given the precarious state of the DU systems and the financial limitations of Brazilian municipalities, it is necessary the future projects to be developed with maximum efficiency and economy. These requirements are achieved by obtaining the optimized {D,  $i_g$ } pair.

A project is presented and developed using the proposed methodology and the results compared with two existing software. The results showed that the proposed numerical modeling contributes to a gain of safety, hydraulic efficiency and economy in the DU projects.

The main contributions of this paper are:

- characterize and model the typical slope of a stretch in a gallery system, with the purpose of obtaining the optimal

gallery slope, combined with the smallest nominal diameter in each stretch;

- exploit the potential of using hydraulic grade lines above those commonly utilized, with positive impacts on the definition of the optimized pair  $\{D, ig\}$  and the economy of system deployment; and
- highlight the need for the iterative solution of a gallery system, from the identification and systematization of an interdependent information cycle, capable of promoting the accuracy of the results.

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### Authors contribution

José Carlos Bohnenberger: Development of all research work, which is part of your doctoral training.

Kleos Magalhães Lenz César Júnior: Participated in the discussion and also in the work development, as a co-supervisor. Assisted in editing figures, tables and spreadsheets.

Maria Lúcia Calijuri: Participated in the discussion and in the development of the work, assisting in the general review and planning as supervisor and coordinator of the project.