New approach for the computation of Flow velocity in partially filled pipes Arranged In parallel

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ABSTRACT

In this paper, a new approach is presented for the computation of the flow velocity in pipes arranged in parallel based on analytic development. This parameter is needed to trail error procedures to be solved, and have big important in flow measurement and design of drainage network, where the flow is mostly flowing in free surface flow. A new method is elaborated to eliminate the need for trial methods, where the computation of the flow velocity become easy, simple and direct with zero deviation compared to Manning equation and others approaches such as Saatçi(1990) and Akgiray (2005) which have been considered as the best approaches but after investigation these approaches are lack accuracy and do not cover the entire range of : $0° \leq \theta \leq 360°$

Key words: Flow velocity, free surface flow, uniform and steady flow, Circular pipe, Manning equation.

Introduction

Flow velocity calculation is an important task for hydraulic engineers in the design of conveyance open channels for irrigation, drainage, and sewage network. Sewer and drainage are frequently flowing in free surface flow, in order to avoid the decrease of the flow cross-sectional area and thereby the decrease of the flow efficiency. Manning model is already considerate as the best to describe the free surface flow. A number of authors are discussed the model such as (chow 1959),(Henderson 1966),(Metcalf & Eddy, 1981),(Carlier, 1985), ,(Hager ,2010) and other. Circular shape is the prefer form for sewer system design. Sub-watersheds can be arranged in series form or in parallel; similarly the pipes of the sewer and drainage system can be arranged in series or in parallel form. Using Manning equation the computation of the flow velocity and water surface angle is not direct and need to trial method and heavy computation. Based on Manning model, a number of researches are trying to propose explicit solution for the free surface flow computation, among the interesting approaches: (Saâtçi, 1990), (Giroud and al, 2000), (Akgray 2004 and 2005) which have trying to eliminate the need to the trial methods, Where the water surface angle range is between 0 and 302.41°. In this study and based on Manning model we will propose a new approach, much simple and more accuracy than the other methods for the computation of the flow velocity partially filled pipes arranged in parallel form, for all the range of surface water angle :$0° \leq \theta \leq 360°$, where the maximum deviation is zero.

Theory

Manning equation:

For a long time Manning equation (Manning, 1891), is already considered as the best formula to compute free surface flow due to its simplicity. The Manning equation can be used for uniform flow in pipe. Graphs (camp, 1946), (Swarna, V. and Modak, P., 1990) and tables are established to facilitate the application of Manning equation for the estimation of the flow characteristics (Terence J, 1991). Manning equation can be written as follow:

$$Q = \frac{1}{n} R_h^{2/3} A S^{1/2} \tag{1}$$

$$V = \frac{1}{n} R_h^{2/3} S^{1/2} \tag{2}$$

Where:

Q: Flow rate in m3/s,
R_h: Hydraulic radius,
n: Pipe roughness coefficient (Manning n),
A: cross sectional flow area,
S: slope of pipe bottom, dimensionless,
V: flow velocity m/s,

To use the Manning model some hypothesis must be assumed: Flow must be steady and uniform, where the slope, cross-sectional flow area, velocity are not related to time, and constant in the length of pipe being analysed (Carlier, 1985).

The two equations (1) and (2), can be rewritten as function of the water surface angle of the pipe as shown in figure 01 as follow:

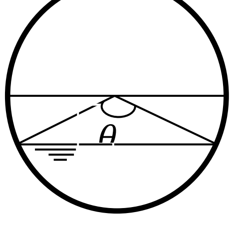

Figure 01: Water surface angle

$$Q = \frac{1}{n}\left(\frac{D^8}{2^{13}}\right)^{1/3}\left[\frac{(\theta - \sin\theta)^5}{\theta^2}\right]^{1/3} S^{1/2} \quad (3)$$

$$V = \frac{1}{n}\left(\frac{D}{4}\right)^{2/3}\left[\frac{(\theta - \sin\theta)}{\theta}\right]^{2/3} S^{1/2} \quad (4)$$

$$A = \frac{D^2}{8}\left(\theta - Sin(\theta)\right) \quad (05)$$

$$P = \theta\frac{D}{2} \quad (06)$$

$$R_h = \frac{A}{P} = \frac{D}{4}\left(1 - \frac{\sin(\theta)}{\theta}\right) \quad (07)$$

Where:

- D : pipe diameter,
- P : wetted perimeter,
- θ : Water surface angle.

According to the equations mentioned above, the computation of the flow velocity is not direct, which need iterative methods. A number of authors have trying to propose approximate approaches to eliminate the need of trial procedures, where the interesting approaches are Saatçi (Saatçi, 1990), Giroud (Giroud and al, 2000) and Akgiray (Akgiray , 2005). Saatçi approach is based on two steps; first we estimate the water surface angle using the following formula:

$$\theta_{Saatçi} = \frac{3\pi}{2}\sqrt{1 - \sqrt{1 - \sqrt{\frac{\pi Q n}{D^{8/3} S^{0.5}}}}} \quad (08)$$

Secondly, using equation (4), the flow velocity can be calculated. Saatçi equations not able to be used for all range of θ, Where it can only used for range: $\theta \leq 265°$ (Saatçi, 1990).

Giroud(Giroud and al, 2000) and Akgiray (Akgiray, 2005) have also propose approaches in order to improve Saatçi equation, where Giroud model is consist to propose direct relationship between average flow velocity and flow rate for θ between 0 and 301.41°, where they have estimated the maximum deviation less than 3%.

As well, Akgiray have trying to improve more the approaches proposed before, where he have proposed an explicit approximate solutions from Manning equation for four types of problems:

1. Given Q, D, and S, find h/D and (or) V,
2. Given Q, D and V, find h/D and (or) S,

3. Given V, D and S, find h/D and (or) Q,
4. Given Q, V and S, find h/D and (or) D.

The four problems mentioned above are studied for two cases, when Manning coefficient n is constant, and for n varies with the depth flow as documented by Camp (Camp, 1946), but both are considered as known parameters. In this research, we interest for the first problem, where author (Akgiray, 2005) have propose the following equations to evaluate water surface angle:

$$\theta = 2 \times 6^{5/13} K^{3/13} \left(1 + \left(sin^{-1}(2.98K)\right)^{0.8} - 2K^{0.946}\right) \qquad (09)$$

Where:

$$K = \frac{Qn}{D^{8/3} S^{0.5}} \qquad (10)$$

The equation (09) is proposed for θ between 0° and 301.41° with maximum error equal to 0.72%. The flow velocity can be estimated according to the equations (09) and (04) where the maximum deviation is 0.29%.

New approach

Flow velocity

1.1.Subwatershed arranged in parallel

Subwatersheds may be arranged whether in series form or in parallel, in this study we will focused on the second case, where the pipes are arranged in parallel as shown in figure 02:

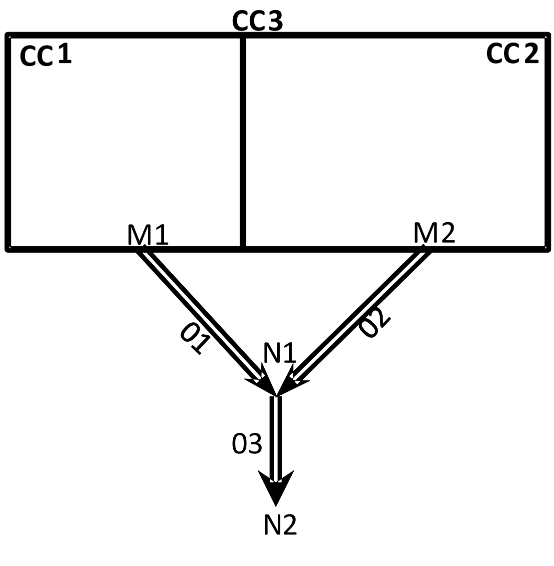

Figure 02: Subwatershed and pipes arranged in parallel.

- The pipe M1-N1 collects water from subwatershed CC1 (which take number 1);
- The pipe M2-N1 collect water from the equivalent watershed CC2 (which take number 2);
- The pipe N1-N2 collects water from the equivalent watershed CC3(which take number 3).

$$CC_{3=}\ CC_2 + CC_1 \tag{11}$$

The flow Q can be evaluating with agree methods, like rational method or SCS method (Viessman and Lewis 2003). Four types of problems are possible to compute the flow velocity and water surface angle according to the reference pipe:

1. The Computation of V_3 as function of the pipe 01 characteristics (pipe 01 is the reference pipe).
2. The Computation of V_3 as function of the pipe 02 characteristics (pipe 02 is the reference pipe).
3. The Computation of V_2 as function of the pipe 01 characteristics (pipe 1 is the reference pipe).
4. The Computation of V_1 as function of the pipe 02 characteristics (pipe 2 is the reference pipe).

Cases one and two

Flow in pipes is steady and uniform, which means the flow characteristics are constant during flow time and in space (for length of pipe being analysed). Let us to consider that pipe M2-N1(or pipe02) is the reference pipe, with known parameters, where the diameter D2, hydraulic radius Rh2, surface water angle θ2, water cross section A2, slope S2, are known data. The slop S3 and roughness n3 are considerate as known parameters for pipes N1-N2 (or pie03).

Many Authors considered that Manning equation (Manning 1889) is the best model to describe the free surface flow (Chow 1959), (Saatçi 1990), (Carlier 1985), (Akgray 2004 and 2005), (prabhata and Swamee 1994 and 2004).

Equation (04) can be also written as the following forms (zeghadnia and al, 2009):

$$V = \left(\left(\frac{S^{1/2}}{n}\right)^3 \left(\frac{2Q}{D}\right)^2\right)^{1/5} \theta^{-2/5} \tag{12}$$

Where:

θ : Water surface angle in radians as shown in figure 02.

Q_1 is transported in pipe M1-N1 and produced in subwatershed CC1, Q_2 transported in pipe M2-N1 and produced in subwatershed CC2, Q_3 is transported in pipe N1-N2 and produced in subwatershed CC3

$$Q_3 > Q_1 \quad (13)$$

$$Q_3 > Q_2 \quad (14)$$

And the ratio Rq_{32} between Q_3 and Q_2 and Rq_{31} between Q_3 and Q_1, are given by the following equations:

$$\frac{Q_3}{Q_2} = Rq_{32} \quad (15)$$

$$\frac{Q_3}{Q_1} = Rq_{31} \quad (16)$$

Where:

$$Q_3 = A_3 V_3 \quad (17)$$

$$Q_1 = A_1 V_1 \quad (18)$$

From inequations (13) and (14) for just full pipe (under atmospheric pressure) we obtain the following:

$$A_3 = bA_1 \quad (19)$$

This is give:

$$D_3^2 = bD_1^2 \quad (20)$$

Similarly:

$$A_3 = aA_2 \quad (21)$$

Where:

$$D_3^2 = aD_2^2 \quad (22)$$

Based on the equations (15), (17) and (21) the ratio Rq_{32} become as:

$$Rq_{32} = \frac{aV_3}{V_2} \quad (23)$$

This yield:

$$V_3 = \frac{Rq_{32}}{a} V_2 \quad (24)$$

Using the equation (22), the equation (2) become as follow:

$$V_3 = \frac{s_3^{0.5}}{n_3} \left(\frac{D_2}{4}\right)^{2/3} a^{1/3} \quad (25)$$

$$\Rightarrow a = V_3^3 \left(\frac{n_3}{s_3^{0.5}}\right)^3 \left(\frac{4}{D_2}\right)^2 \quad (26)$$

From the combination between the equations (24) and (26) give the following:

$$V_3 = (\mathrm{rQ_{32}V_2})^{1/4} \left(\frac{S_3^{0.5}}{n_3}\right)^{3/4} \left(\frac{D_2}{4}\right)^{1/2} \tag{27}$$

The equation (27) allows the computation of the flow velocity in just full pipe (pipe N1-N2) as function of the reference pipe. In case of partially filled pipe the precedent formula and according to the equation (12) is rewrite as follow:

$$V_3 = \left(\frac{Q_3}{Q_2}\right)^{1/4} \left(\frac{S_3^{0.5}}{n_3}\right)^{3/4} \left(\frac{n_2}{S_2^{0.5}}\right)^{3/20} \left(\frac{2Q_2}{D_2\theta_2}\right)^{2/5} \tag{28}$$

Similarly, in the case when pipe M1-N1 is the reference pipe, the flow velocity can be calculate as follow:

$$V_3 = \left(\frac{Q_3}{Q_1}\right)^{1/4} \left(\frac{S_3^{0.5}}{n_3}\right)^{3/4} \left(\frac{n_1}{S_1^{0.5}}\right)^{3/20} \left(\frac{2Q_1}{D_1\theta_1}\right)^{2/5} \tag{29}$$

The equations (28) and (29) give the exact value of flow velocity in pipe N1-N2 as function of the parameters of the reference pipe. Both in the first or in the second case the maximum deviation is zero compared to equation (4).

Case three and four

In this case, the reference pipe characteristics are known. Here, we will write the characteristics of the first pipe using the second pipe characteristics (reference pipe) as will be shown in the following sections. Using equations (20) and (22), we obtain the following:

$$aD_2^2 = bD_1^2 \tag{30}$$

$$D_1 = \left(\frac{a}{b}\right)^{0.5} D_2 \tag{31}$$

Using equation (31) the velocity equation can be written as follow:

$$V_1 = \frac{S_1^{0.5}}{n_1} \left(\frac{D_2}{4}\right)^{2/3} \left(\frac{a}{b}\right)^{1/3} \tag{32}$$

Based on the equations (16), (17) and (19) the ratio Rq_{31} become as:

$$Rq_{31} = \frac{bV_3}{V_1} \tag{33}$$

This yield:

$$V_3 = \frac{Rq_{31}}{b} V_1 \tag{34}$$

Also, using equations (24) and (34) we get the following equation:

$$\frac{a}{b} = \frac{V_2 Q_1}{V_1 Q_2} \quad (35)$$

Where:

$$R_{q12} = \frac{Q_1}{Q_2} \quad (36)$$

Using the equations (32), (35) and (36) we can estimate the velocity using the characteristics of second pipe for just full as follow:

$$V_1 = (\mathrm{Rq}_{12}\mathrm{V}_2)^{1/4}\left(\frac{\mathrm{S}_1^{0.5}}{\mathrm{n}_1}\right)^{3/4}\left(\frac{\mathrm{D}_2}{4}\right)^{1/2} \quad (37)$$

For case of partially full pipe, and according to the equation (12), the equation (37) become as:

$$V_1 = \left(\frac{\mathrm{Q}_1}{Q_2}\right)^{1/4}\left(\frac{\mathrm{S}_1^{0.5}}{\mathrm{n}_1}\right)^{3/4}\left(\frac{n_2}{\mathrm{S}_2^{0.5}}\right)^{3/20}\left(\frac{2Q_2}{D_2\theta_2}\right)^{2/5} \quad (38)$$

The equation (38) is the best formula compared to the equation (04) and the recent approaches, where the maximum error is zero as shown in table 01. For case when pipe 01 is the reference pipe, the same result can be obtain as follow:

$$V_2 = \left(\frac{\mathrm{Q}_2}{Q_1}\right)^{1/4}\left(\frac{\mathrm{S}_2^{0.5}}{\mathrm{n}_2}\right)^{3/4}\left(\frac{n_1}{\mathrm{S}_1^{0.5}}\right)^{3/20}\left(\frac{2Q_1}{D_1\theta_1}\right)^{2/5} \quad (39)$$

1.2.Accuracy Test

From The table 01, the equation (38) is an excellent formula, where the maximum deviation is 9.8910^{-6} % $\cong 0$, Compared to Manning equation (04) and approaches of Saatçi (Saatçi, 1990), Giroud (Giroud and al, 2000) and Akgiray (Akgiray, 2005) where the maximum deviation $\frac{\Delta V}{V}$ for Saatçi equation is very lack accuracy and not applicable for the entire range of θ. As well the approach of Giroud for θ between 0 and 360 the maximum error occurs is 12.76%. For Akgiray formula, which is the most recent proposal approach, it is less accuracy too, where for the entire range of θ the maximum deviation occur is 23.80%. In other hand, the proposal approach in this study using the equation (38) for the first case or the equation (39) for the second case, is very accuracy, where the maximum error occurs is zero, this result is the best until now, where no authors before have claims that a formula can produced the same deviation compared to the equation (4).

Table 01: *Accuracy test of the equation (38) compared to the recent approaches and equation (4)*

θ_1 *and* θ_2	**Manning Equation (04)**	**Proposed Equation (38)**	**Error %**	**Saatçi equation Error %**	**Giroud equation Error %**	**Akgiray equation Error %**
1°	0.002175079	0.002175079	0	89.3474	0,004	3.82208E-03
2°	0.00548069	0.00548069	0	85,94367	0,004	1.83529E-03
3°	0.009410257	0.009410258	9.8968E-06	83,46836	0,005	1.30634E-03
4°	0.01380879	0.01380879	0	81,45177	0,007	3.97250E-03
5°	0.01859214	0.01859214	0	79,71937	0,009	5.74054E-03
6°	0.02370587	0.02370587	0	78,18411	0,012	8.23439E-03
7°	0.02911126	0.02911126	6.3983E-06	76,79537	0,015	1.16579E-02
8°	0.03477904	0.03477904	0	75,52073	0,018	1.50708E-02
9°	0.0406861	0.0406861	0	74,33798	0,022	1.90265E-02
19°	0.1098737	0.1098737	6.7810E-06	65,35349	0,087	8.55768E-02
20°	0.1176045	0.1176045	0	64,62856	0,096	9.48772E-02
25°	0.1579958	0.1579958	0	61,28267	0,146	0.1490910
26°	0.1663918	0.1663918	8.9554E-06	60,66024	0,158	0.1614311
27°	0.1748849	0.1748849	0	60,05098	0,169	0.1742965
28°	0.1834716	0.1834716	0	59,45406	0,182	0.1876701
29°	0.1921487	0.1921487	0	58,86872	0,194	0.2015530
30°	0.2009132	0.2009132	0	58,29429	0,207	0.2159227
56°	0.4514051	0.4514051	0	45,7916	0,636	0.7720128
57°	0.461654	0.461654	0	45,37019	0,654	0.8003723
58°	0.4719323	0.4719323	0	44,95152	0,673	0.8292488
59°	0.4822383	0.4822384	6.1799E-06	44,53543	0,692	0.8586057
60°	0.4925706	0.4925706	0	44,12185	0,710	0.8884778
61°	0.5029277	0.5029277	0	43,71062	0,729	0.9188495
62°	0.513308	0.513308	0	43,30164	0,748	0.9496996
63°	0.5237103	0.5237103	0	42,89482	0,766	0.9810618
64°	0.5341328	0.5341328	0	42,49005	0,785	1.012904
70°	0.5970176	0.5970176	0	40,09892	0,893	1.214122
71°	0.6075438	0.6075439	9.8107E-06	39,70581	0,911	1.249312
72°	0.6180795	0.6180795	0	39,31403	0,928	1.284971
89°	0.7974017	0.7974017	0	32,78585	1,178	1.958465
90°	0.8078941	0.8078941	0	32,4059	1,190	2.001798
91°	0.818373	0.818373	0	32,02603	1,200	2.045525
92°	0.8288372	0.8288372	0	31,64618	1,210	2.089636
93°	0.8392858	0.8392857	7.1018E-06	31,26629	1,220	2.134128
94°	0.8497174	0.8497174	0	30,88631	1,229	2.178987
95°	0.8601313	0.8601313	0	30,50619	1,238	2.224210
96°	0.8705262	0.8705261	6.8469E-06	30,12587	1,246	2.269811
97°	0.880901	0.880901	0	29,74532	1,253	2.315762
98°	0.8912548	0.8912548	0	29,36445	1,260	2.362076
99°	0.9015866	0.9015866	0	28,98323	1,266	2.408742
100°	0.9118952	0.9118952	0	28,60162	1,272	2.455752
110°	1.013489	1.013489	0	24,75224	1,293	2.944013
111°	1.023478	1.023478	0	24,36287	1,292	2.994553
112°	1.033432	1.033432	0	23,97251	1,289	3.045419
113°	1.04335	1.04335	0	23,5811	1,286	3.096538

128°	1.187246	1.187246	0	17,54957	1,150	3.895500
129°	1.196476	1.196476	0	17,13445	1,134	3.950676
130°	1.205655	1.205655	0	16,71739	1,118	4.006063
147°	1.353387	1.353387	0	9,275119	0,735	4.973069
148°	1.361549	1.361549	0	8,813026	0,706	5.031021
164°	1.483255	1.483255	0	0,9392976	0,173	5.959071
165°	1.490281	1.490281	0	0,4127013	0,135	6.016496
178°	1.575009	1.575009	0	6,898433	0,368	6.743353
179°	1.581007	1.581007	0	7,50117	0,408	6.797178
180°	1.586928	1.586928	0	8,110403	0,448	6.850616
181°	1.592774	1.592774	0	8,726289	0,487	6.903657
182°	1.598542	1.598542	0	9,348998	0,526	6.956260
183°	1.604235	1.604235	0	9,978709	0,566	7.008436
199°	1.684735	1.684735	0	21,17673	1,159	7.768579
204°	1.705757	1.705757	0	25,21011	1,319	7.970502
205°	1.709723	1.709723	0	26,05456	1,348	8.008473
220°	1.759718	1.759718	0	40,65947	1,686	8.470866
266°	1.807488	1.807488	0	561,416	0,673	8.549014
267°	1.806925	1.806925	0	not applicable	0,607	8.532533
300°	1.758345	1.758345	0	not applicable	2,694	8.254137
301°	1.756103	1.756103	0	not applicable	2,827	8.336226
302°	1.753824	1.753824	0	not applicable	2,961	8.446418
315°	1.721249	1.721249	0	not applicable	4,857	11.61676
316°	1.718545	1.718545	0	not applicable	5,013	11.90319
317°	1.715817	1.715817	0	not applicable	5,171	12.19025
318°	1.713066	1.713066	0	not applicable	5,330	12.47768
319°	1.710293	1.710293	0	not applicable	5,490	12.76533
320°	1.707498	1.707498	6.9815E-06	not applicable	5,652	13.05293
321°	1.704682	1.704682	0	not applicable	5,815	13.34037
322°	1.701847	1.701847	0	not applicable	5,979	13.62755
323°	1.698993	1.698993	0	not applicable	6,144	13.91430
324°	1.69612	1.69612	0	not applicable	6,311	14.20057
325°	1.693231	1.693231	0	not applicable	6,479	14.48628
326°	1.690325	1.690325	0	not applicable	6,647	14.77135

350°	1.617947	1.617947	0	not applicable	10,930	21.30812
351°	1.614915	1.614915	0	not applicable	11,114	21.56447
352°	1.611889	1.611889	0	not applicable	11,298	21.81933
353°	1.608871	1.60887	7.4095E-06	not applicable	11,482	22.07269
354°	1.605859	1.605859	0	not applicable	11,666	22.32451
355°	1.602857	1.602857	0	not applicable	11,850	22.57478
356°	1.599864	1.599864	7.4512E-06	not applicable	12,034	22.82348
357°	1.596881	1.596881	0	not applicable	12,218	23.07058
358°	1.593909	1.593909	0	not applicable	12,402	23.31607
359°	1.590949	1.590949	0	not applicable	12,585	23.55994
360°	1.588002	1.588002	0	not applicable	12,768	23.80213

Conclusions

This paper presents explicit equations for computation of flow velocity in circular sections partially filled based on the reference pipe, where the deviation between these equations and manning equation is zero. It is hoped that the explicit equations will be useful for designers or engineers to appropriately design open channels.

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