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Computer Aided Drainage Design Modeling for Urban Areas

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Abstract: Due to rapid urbanization the existing drainage system did not serve the purpose of local needs properly. Hence, it is needed in advance to evaluate critically all the parameters that are related to drainage. With the intention of meeting the desired needs for a locality, a drainage design model was developed in this study. The model complies with the Rational formula and Manning's equation. Moreover, two concepts were used in developing the model i.e. most efficient section concept and section factor concept. A computer code was developed for the model which covers both concepts as well as checking the Minimum Permissible Velocity (MPV).

Key words: Drain size, design discharge, most efficient section method, section factor method

INTRODUCTION

In order to design a drainage system that complies with the Rational formula and Manning's equation, designers are often required to carry out a tedious and time consuming iteration procedure. Failure of the current technical approach such as upstream blockage, flooding, submergence etc. to meet the challenge often leads to failure of the existing drainage system. The primary reasons of failure of the drains are lack of sufficient data for discharge calculation and inappropriate design procedure. Factors affecting the drainage design include extent of rainfall, nature of surface, intensity of rainfall, catchment area, shape and slope of a catchment, obstructions and antecedent conditions etc. Moreover, the runoff coefficient and Manning's roughness coefficient needed to be considered.

All these factors make a clear difference from one locality to another for using the type, size, shape, material choosing and technology for the construction of a drain. But due to the lack of appropriate field data of different parameters often leads to implement inappropriate options, which makes the drainage system unsuitable for a locality. So it is needed to develop a proper design procedure for designing drains.

DESIGN DISCHARGE

The determination of design discharge is the prime concern in the development of a drainage network. It includes storm water discharge; domestic and non-domestic water discharge etc. Non-domestic waters are mainly institutional demand of water, commercial or industrial demand and fire demand etc. All contributes a significant quantity of water to be drained out. The rational formula used to estimate the storm water discharges is[1]:

$$Q_1 = FCiA_c \qquad (1)$$

where, Q_1 = peak discharge for a particular storm ($m^3\ sec^{-1}$), C = runoff coefficient, i = rainfall intensity ($mm\ h^{-1}$), A_c = area of the catchment (m^2) and F = a factor of proportionality depends on A_c and i. The values of F can be taken as 0.278 when A is in km^2 and i in $mm\ h^{-1}$ and 1.0 when A is in m^2 and i in $m\ s^{-1}$.

The runoff coefficient (C) should logically be an average weighted value in accordance with the geometric configuration of the area to be drained. The choice of suitable runoff coefficient is difficult not only by the existing condition but also by the uncertainties of change in evolving urban complexes. The average values of C that have been commonly used for various surfaces by Ahmed and Rahman[2]. Using those values for catchments with composite land use or surface characteristics, a weighted value of C can be adopted using the following Eq.[3]:

$$C_w = \frac{\sum_{j=1}^{k} C_j A_{cj}}{A_c} \qquad (2)$$

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Where, C_w = weighted runoff coefficient, C_j = runoff coefficient for the area with land use j, A_{cj} = catchment area with land use j and k = number of land use types within the catchment.

Rainfall intensity (i) can be calculated by rational method developed by Talbot[4].

$$i = a/(t_c + b) \quad (3)$$

Where, t_c = time of concentration (mm) and a, b = constants based on characteristics of the area.

The time of concentration (t_c) can be estimated by Bransby-Williams formula which is as follows[2]:

$$t_c = F_1L/A_c^{0.1}S^{0.2} \quad (4)$$

Where, F_1 = a factor of proportionality which is 58.5 when A in km^2 and 92.7 when A in hectares, L = main stream length (km) and S = main stream slope (m km^{-1}).

However, according to Badiul Alam[5], the time of concentration (t_c) can also be calculated by summing up of the overland flow time (T_i), the upstream channel flow time (T_n) and the channel flow time (T_t). Depending on the overland travel distance, land topography and characteristics, the overland flow time varies between 5 and 15 min. According to McCuen[3], the channel flow time can be estimated from the hydraulic properties of the drainage channel as:

$$T_n = L_{cu}/60V_u \text{ and } T_t = L_c/60V \quad (5)$$

Where, T_n = flow time in upstream channel (min), L_{cu} = length of upstream channel (m), V_u = flow velocity in upstream channel (m s^{-1}), T_t = channel flow time (min), L_c = length of the channel (m) and V = flow velocity (m s^{-1}).

The domestic and non-domestic water discharges can be calculated by finding out water needed for each person. After adding the water demand of different types (i.e. industrial, commercial, institutional or fire demands etc), the gross water discharge can be obtained. Then the amount is divided by the population of the concerned area which will give equivalent per capita water demand. Thus both the domestic and non-domestic needs can be expressed with relation to population. If the total population of the town is ascertained, the water demand of the community per day can be assessed and this will be the ultimate water discharge from domestic and non-domestic sources.

DEVELOPMENT OF THE MODEL

In this study, four types of channel geometry have been considered. Three of these (rectangular, triangular and trapezoidal) are for channel sections and another one (circular) is for sewer sections. All types of channel sections except circular section can be determined through two methods: Most efficient section method and section factor method. Since circular section itself is a most efficient section, so this section is determined in this study only through section factor method.

From the most efficient section method, channel sections (width, depth) can be determined using different equations for different channel geometry. On the other hand, using section factor method, hydraulic depth can be determined by trial and error method for a fixed bed width and slope.

Most efficient section method: In order to accommodate the design discharge Q, the size and bed slope of a drainage channel are to be determined based on the Manning's equation, which is as follows:

$$Q = AR^{2/3}S^{1/2} / n = A^{5/3}S^{1/2} /nP^{2/3} \quad (6)$$

Where, Q= design discharge (m^3 sec^{-1}), A = flow area or cross sectional area (m^2), R = hydraulic radius (m), P = wetted perimeter and n = Manning's roughness coefficient.

Now, for known values of n and S, the discharge will be maximum for a given cross-sectional area, when the wetted perimeter is minimum. Such a cross section is known as the most efficient hydraulic section. Obviously, the circular section is the most efficient section since a circle has the least perimeter for a given area. But for practical considerations i.e. ease of construction, steepest stable slope in the soil etc rule out the adoption of circular section in most drainage channels and used effectively for sewer sections only. Hence the optimization problem is of determining the most efficient hydraulic section for a given shape. It is to be noted that a minimum wetted perimeter means the minimum length of lining also.

Now Eq. 6 can also be written as:

$$P = S^{3/4}A^{5/2}/Q^{3/2}n^{3/2} = k_1A^{5/2} \quad (7)$$

Here, k_1 is a constant for given Q, n and S and equal to $[S^{3/4}/(Qn)^{3/2}]$. A minimum wetted perimeter also means a minimum cross sectional area and thus a minimum value of excavation also. Hence the most efficient section really implies a minimum cost of excavation as well as of lining.

Most efficient rectangular section: Consider a rectangular section of width B and depth h, whose, $A = Bh$ and $P = B + 2h = A/h + 2h$.

For obtaining the most efficient section, differentiation of P with respect to h i.e. (dP/dh) must be equal to zero.
So,

$$dP/dh = 0 \quad \text{or,} \quad -A/h^2 + 2 = 0$$

$$\text{or, } A = 2h^2 \quad \text{or, } B = 2h$$

Thus the width must be equal to twice the depth for the most efficient rectangular section.

The hydraulic radius R becomes,
$R = Bh/(B+2h) = h/2$ since $B = 2h$
Now the Manning's equation becomes,

$$\begin{aligned} Q &= AR^{2/3}S^{1/2}/n \\ &= 2h \times h \times h^{2/3} \times (1/2)^{2/3} \times S^{1/2}/n \\ &= 1.2599 \times h^{8/3} \times S^{1/2}/n \end{aligned} \tag{8}$$

Most efficient triangular section: Consider a triangular section with side slope z:1 and depth h, whose area becomes, $A = zh^2$ and perimeter,

$$P = 2\sqrt{(z^2+1)}*h = 2\sqrt{(z^2+1)}*(A/z)^{1/2}$$

$$\text{or,} \quad P^2 = 4*(z^2+1)*A/z = 4(z+1/z)A$$

For this section to be most efficient, P should be minimum for given A or dP/dh= 0. Differentiating the above equation with respect to z becomes

$$2PdP/dz = 0 = (4 - 4/z^2)A, \text{ So, } z = 1.0 \text{ as } A \neq 0$$

Thus, a triangular section with a central angle of 90^0 is the most efficient section. If OA is the perpendicular from the mid point on the water surface to the side of the channel, then $OA = h/\sqrt{2}$. It can then be shown that a semicircle with O as center and $h/\sqrt{2}$ as radius is tangential to the two sides becomes the most efficient triangular section.

The hydraulic radius can be written as:

$$R = zh/2\sqrt{(z^2+1)} = h/2\sqrt{2}, \text{ since } z = 1.0$$

Hence, the Manning's equation becomes,

$$\begin{aligned} Q &= AR^{2/3}S^{1/2}/n \\ &= zh^2 \times (h/2\sqrt{2})^{2/3} \times S^{1/2}/n \\ &= 0.125 \times h^{8/3} \times S^{1/2}/n \end{aligned} \tag{9}$$

Most efficient trapezoidal section: Again, consider a trapezoidal section with side slope z: 1, bottom width B and depth h. The area and the perimeter of this section becomes

$$\begin{aligned} A = (B+zh)\,h \text{ and } P &= B + 2h\sqrt{(z^2+1)} \\ &= A/h - zh + 2h\sqrt{(z^2+1)} \end{aligned}$$

$$\text{or,} \quad P = A/h + h\{2\sqrt{(z2+1)}-z\} \tag{10}$$

Considering A and z to be constant, differentiation of the above equation with respect to h and setting the differential to zero will satisfy the condition for the most efficient section,

$$\text{i.e.} \quad -A/h^2 + 2\sqrt{(z^2+1)} - z = 0$$

$$\text{or} \quad (B + zh) = \{2\sqrt{(z^2+1)} - z)h$$

$$\text{or} \quad B = 2\{\sqrt{(z^2+1)} - z\}h$$

The water surface width (top width), $T = B + 2zh = 2\sqrt{(z^2+1)}h$ = 2 x length of the sloping side, so, the top width is equal to twice the length of sloping side for a trapezoidal section. Now if OQ is the perpendicular from the mid point on the water surface (O) to the side of the channel and OP is the half of the top width, then

$$\begin{aligned} OQ = OP\,\text{Sin}\theta &= T/2 * 1/\sqrt{(z^2+1)} \\ &= 2\{\sqrt{(z^2+1)}*h\}/2 * 1/\sqrt{(z^2+1)} = h \end{aligned}$$

Thus a semi circle with O as center and h as radius is tangential to the bed and sides is the most efficient trapezoidal section.

The hydraulic radius R of that section becomes, $R = (B + zh)h/\{B + 2\sqrt{(z^2+1)}h\}$
Substituting B in this equation, R becomes h/2.

Again, If the side slope is assumed to be variable and A and h are constant, the condition for the most efficient trapezoidal section becomes $dP/dz = 0$. Thus Eq. 10 can be written as, $h*2*2z/2\sqrt{(z^2+1)} - h = 0$ or, $2z = \sqrt{(z^2+1)}$ or $z = 1/\sqrt{3}$ = o.57735, Thus, width

$$B = 2\{\sqrt{(z^2+1)} - z\}h = 2(\sqrt{1.333} - 0.57735)h = 1.15467h$$

$$\text{And, } A = (B+Zh)h = (1.15467h+0.5775h) = 1.728h$$

Hence the Manning's equation becomes,

$$\begin{aligned} Q &= 1.728h^2 \times (h/2)^{2/3} \times S^{1/2}/n \\ &= 1.091124h^{2.667} \times S^{1/2}/n \end{aligned} \tag{11}$$

The channel depth can directly be obtained from Eq. 8, 9 and 11 after inputting appropriate n, Q and

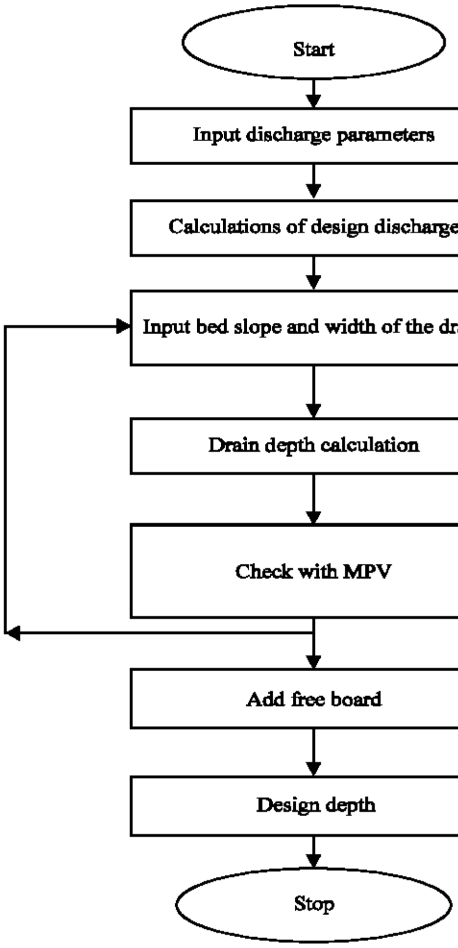

Fig. 1: Flow chart of drainage design model by section factor method

S values. The section will be fixed after checking with MPV and adding the free board in order to reduce overtopping of the flow. MPV will also prevent siltation and retains the channel section stable.

Section factor method: The section factor concept based on the hypothesis that the section factor ($AR^{2/3}$) depends on the geometry of the water area. Thus for a given conditions of n and Q, there is only one possible depth for maintaining uniform flow provided that the value of section factor always increases with increases in depth.

Through this method, the drain size of different types of channel sections can be calculated by trial and error. First, a width and side slope is assumed and calculate the values of ($nQ/\sqrt{S}$) which is equivalent to the section factor $AR^{2/3}$ (Eq. 6). Now, a value of depth of flow (h) should be considered and corresponding section factor has to be calculated. The depth will be fixed after several iteration when the section factors become very close with the previous calculated value. Finally the section will be fixed after checking with MPV and adding the free board. Figure 1 shows the flow chart of drainage design model by this method.

MODEL APPLICATION

In order to check the validity, the developed models applied in a location with appropriate field data and compare the results with an existing drain.

Study area: To justify the validity of the model, the study area selected is Sylhet, Bangladesh. A large number of natural and artificial khals and drains (Locally called as Chara) passes through this city and finally have reached in the Surma River. But for easing the calculation, a single drain is considered which is originated from Malani chara and passes through several locations and finally has fallen into the Surma River. During monsoon period generally heavy rainfall occurs in Sylhet city and this creats environmental hazards by overflowing after heavy rainfall.

Design discharge estimation: A uniform rectangular stretch from Malani chara to Kanishail is considered for validation. The catchment area of this stretch is about 40 ha, mainstream length 2 km, mainstream slope 1 m km^{-1} and maximum distance of inlet from extreme point of catchments is 600 m. Using this slope (0.001), the developed Eq. 8, 9 and 11 becomes as follows:

- For rectangular section: $h = 3.3482\ (nQ)^{0.37495313}$
- For triangular section: $h = 4.7350\ (nQ)^{0.37495313}$
- For trapezoidal section: $h = 3.53694\ (nQ)^{0.37495313}$

Now using Eq. 4, t_c is found as 128.2 min. Again, considering T_i as 10 min, velocity over the surface as 0.3 m s^{-1}, velocity through the drain as 2.5 m s^{-1} and using the equation described in section 2, the t_c is found as 63.33 min. Since two values of t_c varied significantly, an average value of t_c = 92.43 min has been considered here. The rainfall intensity becomes 63.22 mm h^{-1}, considering the formula proposed by JICA for Bangladesh[6]. As Sylhet being a middle class residential area, the runoff coefficient is considered as 0.4. Hence, the storm water is estimated as 2.8266 $m^3\ sec^{-1}$.

Total population of the study area is 55,000 (data collected from Sylhet city corporation) and according to Chatterjee[7], water consumption rate will be 125 to 200 lpcd. Considering water consumption rate as 200 lpcd, the domestic and non-domestic discharges become 0.1273 $m^3\ sec^{-1}$. Finally, the design discharge (Q) becomes 3.5447 after adding all discharges and increased to 20% as it considered as upstream flow.

Table 1: Comparison between existing and design drain

Existing drain	**Design drain**
Depth: 1.1 m	By most efficient section method
Width: 2.065 m	Design depth: 1.27 m
X-sectional area: 2.27 m^2	Design width: 2.22 m
	X-sectional area: 2.83 m^2
	By section factor method
	Design depth: 1.43 m
	Width: 2 m
	X-sectional area: 2.86 m^2

Table 2: Comparison between the drain sizes obtained by most efficient section and section factor method for different sections

Most efficient section method	**Section factor method**
Rectangular section	Rectangular section
Design depth: 1.276 m	Design depth: 1.43 m
Width: 2.22 m	Width: 2 m
X-sectional area: 2.83 m^2	X-sectional area: 2.86 m^2
Triangular section	Triangular section
Design depth: 1.812 m	Design depth: 7.015 m
Side slope: 1	Side slope: 0.1
X-sectional area: 3.28 m^2	X-sectional area: 4.92 m^2
Trapezoidal section	Trapezoidal section
Design depth: 1.3535 m	Design depth: 1 m
Side slope: 0.57735	Side slope: 1
Width: 1.359 m	Width: 2 m
X-sectional area: 2.89 m^2	X-sectional area: 3 m^2
	Circular section
	Design depth: 1.39 m
	Diameter: 2 m
	X- sectional area: 2.33 m^2

Drainage channel design: With $Q = 3.5447$ m^3 sec^{-1} and using the most efficient section concept, the design depth and width for rectangular channel has been calculated as 1.276 and 2.22 m, respectively. Again using the section factor concept, the design depth has been calculated as 1.43 m when width has been considered as 2.00 m. For both the methods, the free board is considered as 15% of total depth and it can also be considered as factor of safety for the design. By field observation, the depth and width of the existing drain is found as 1.1 and 2.065 m. In Table 1 comparison between the existing and design drain shows that the existing drain is not adequate to discharge the calculated water that may be the main cause of flooding of this drain during monsoon period.

A comparison between both the design methods for different channel sections has also been done for a fixed discharge ($Q = 3.5447$ m^3 sec^{-1}) shown in Table 2.

CONCLUSIONS

The developed computer-aided drainage design model is a general drainage design model that can be applied to any location, which has the required input data of some parameters. The model can simulate the dimensions of different drains efficiently. From the calculation of design discharge in the study area, it is found that maximum discharge is contributed from storm water (about 80% of design discharge). So it is the dominant factor in designing drainage channel. Hence proper evaluation of hydrologic parameters related to storm water discharge is necessary for proper accomplishment of drainage channel design.

From the comparison between most efficient section methods and section factor methods, it can be seen that the most efficient method is the best suitable method as it passes the maximum water discharge through minimum cross-sectional area. However, the great advantage of most efficient method is that the developed equations are very simple and able to calculate the section size easily, but the section factor method is needed where a land constrain imposes.

- For most efficient method, the following conclusions can be drawn for different sections:
- For rectangular section: width (B) should be twice the hydraulic depth,
- For triangular section: side slope ratio should be one i.e. Z_1: $Z_2 = 1$,
- And for trapezoidal section: side slope ratio should be 0.57735 i.e. Z_1: $Z_2 = 1/\sqrt{3} = 0.57735$ and width should be multiplication of 1.15467 with hydraulic depth.

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