Review of Hydraulic Design of U-shaped and Half-round Channels on Slopes

GEO Report No. 320

R.P.H. Law & F.W.Y. Ko

Geotechnical Engineering Office
Civil Engineering and Development Department
The Government of the Hong Kong
Special Administrative Region

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This report was originally produced in June 2014
as GEO Technical Note No. TN 3/2014

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First published, July 2016

Prepared by:

Geotechnical Engineering Office,
Civil Engineering and Development Department,
Civil Engineering and Development Building,
101 Princess Margaret Road,
Homantin, Kowloon,
Hong Kong.

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Preface

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H.N. Wong
Head, Geotechnical Engineering Office
July 2016

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Foreword

This Technical Note presents a review of the design methodology for both U-shaped and half-round channels given in Section 8.3.4 and Figure 8.7 of the Geotechnical Manual for Slopes (Second Edition). An updated technical guidance on the hydraulic design of U-shaped and half-round channels on slopes are provided.

The study was carried out by Mr R.P.H. Law, under the supervision of Ms F.W.Y. Ko and myself. The Drafting Unit of the Standards and Testing Division assisted in formatting this report. All contributions are gratefully acknowledged.

Y.K. Shiu
Chief Geotechnical Engineer/Standards and Testing

Abstract

Second paragraph of Section 8.3.4 of the Geotechnical Manual for Slopes (Second Edition) recommends the use of Manning's formula, with a maximum permissible velocity of 4 m/s and a roughness factor of 0.013, for design of U-shaped and half-round channels on slopes. A chart is provided in Figure 8.7 of the Manual for the rapid design of channels. It further recommends that channels larger than 600 mm may be designed using the charts developed by Ackers (1969), which are based on the Colebrook-White equation.

This Technical Note presents a review of the design methodology for both U-shaped and half-round channels given in Section 8.3.4 and Figure 8.7 of the Geotechnical Manual for Slopes (Second Edition). It is found that the use of Manning's formula and Colebrook-White equation for design of U-shaped and half-round channels is still valid and consistent with the local practice in surface channel design. Nevertheless, discrepancies have been found between the design curves in the chart given in Figure 8.7 and the results of the Manning's formula. An update to the design methodology, together with a revised chart for the rapid design of channels, for both U-shaped and half-round channels is recommended.

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1 Introduction

Second paragraph of Section 8.3.4 of the Geotechnical Manual for Slopes (Second Edition) (GCO, 1984) recommends the use of Manning's formula, with a maximum permissible velocity of 4 m/s and a roughness factor of 0.013, for design of U-shaped and half-round channels on slopes. A chart is provided in Figure 8.7 of the Manual for the rapid design of channels. It further recommends that channels larger than 600 mm may be designed using the charts developed by Ackers (1969), which are based on the Colebrook-White equation.

In 2013, a consulting firm enquired in writing about the derivation of the chart shown in Figure 8.7 of GCO (1984). They had attempted to reproduce the chart for U-shaped channels using the Manning's formula presented in Equation 8.3 of GCO (1984). By trial and error, they observed that the chart for U-shaped channels is in general consistent with the following assumptions, except for 375 mm U-shaped channel:

(a) Manning's roughness factor of 0.0117 (= 0.9 × 0.013); and

(b) freeboard equal to approximately 15% of the channel size.

Section 8.3.4 of GCO (1984) however recommends the use of a roughness factor of 0.013. There is no indication in GCO (1984) that freeboard should be considered in the determination of the flow capacities of channels.

The enquiries have prompted a detailed review of the technical basis and accuracy of the chart presented in Figure 8.7 of GCO (1984). This Technical Note presents the details and the results of the review, along with recommendations for improvements in respect of hydraulic design of U-shaped and half-round channels.

2 Background for the Chart for Rapid Design of Channels

The chart for the rapid design of channels first appeared in the Geotechnical Manual for Slopes (First Edition) (GCO, 1979) as Figure 8.6, without the accompanying Manning's formula. It was repeated in GCO (1984) as Figure 8.7 and along with it, the Manning's formula is supplemented in Equation 8.3. The charts in both GCO (1979) and GCO (1984) are reproduced in Figures 2.1 and 2.2 respectively for reference. The derivations of the design curves given in the charts cannot be traced.

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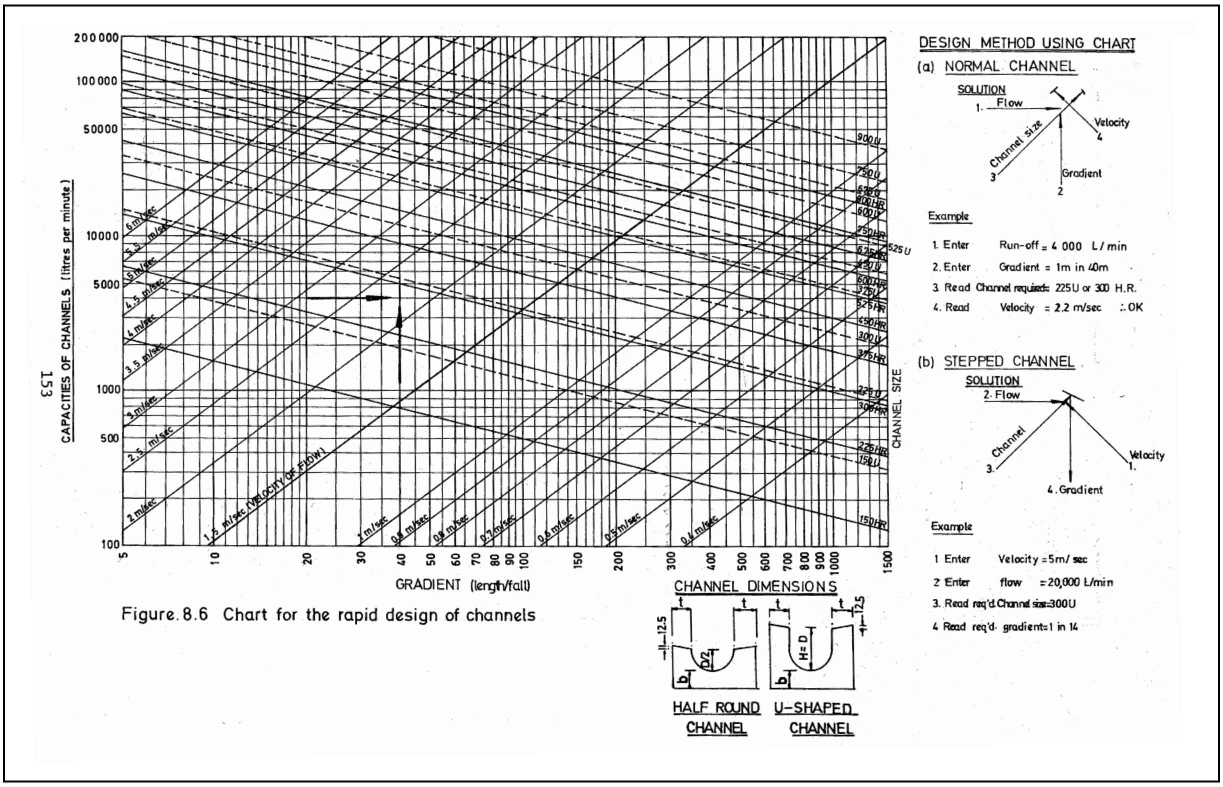

Figure 2.1 Chart for the Rapid Design of Channels in the Geotechnical Manual for Slopes (First Edition) (GCO, 1979)

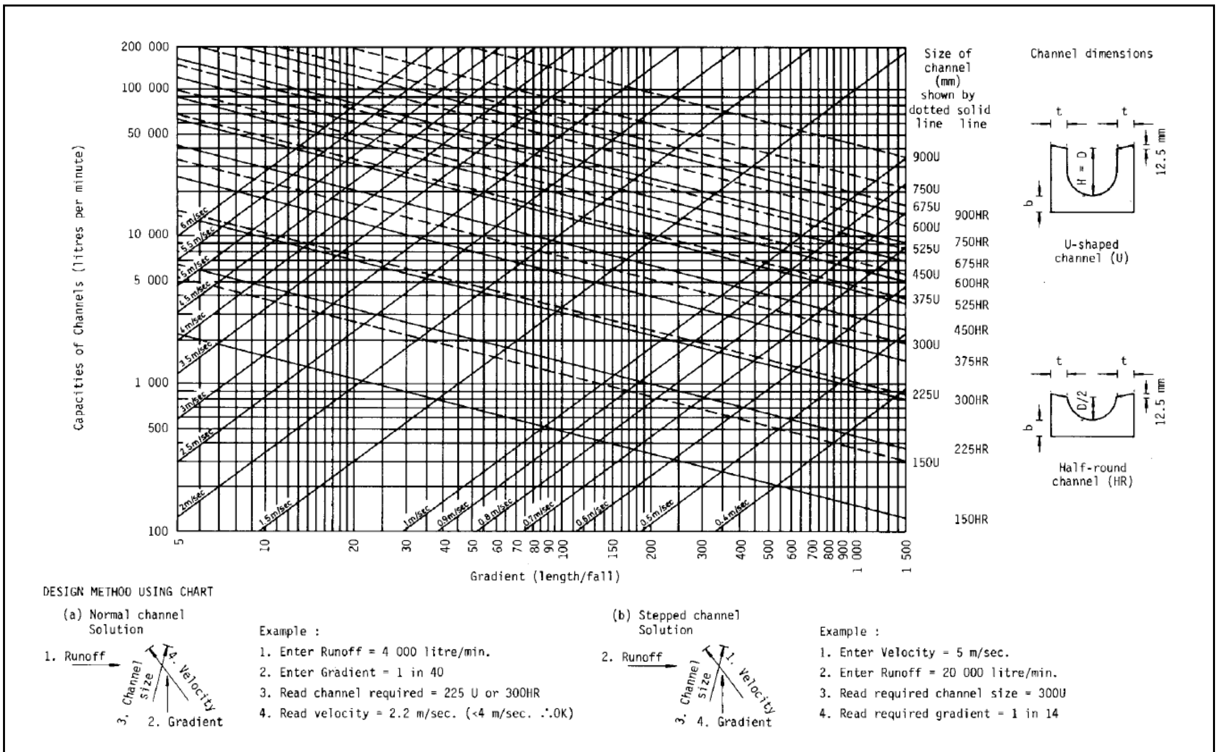

Figure 2.2 Chart for the Rapid Design of Channels in the Geotechnical Manual for Slopes (Second Edition) (GCO, 1984)

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3 Practice for Hydraulic Design of Channels

GCO (1979) and GCO (1984) recommend the use of the Manning's formula for hydraulic design of U-shaped and half-round channels which are 600 mm in diameter or less, with a maximum permissible velocity of 4 m/s and a roughness factor of 0.013. The roughness factor of 0.013 represents finished concrete surface. Channels larger than 600 mm may be designed using the Colebrook-White equation presented in the design charts given in Ackers (1969), as the open channel flows become more turbulent.

Six flow equations are provided in DSD's Stormwater Drainage Manual (DSD, 2013) for design of turbulent uniform flows in open channels. It is indicated that the Manning's formula and Colebrook-White equation are the most popular in local applications. The drainage manual also provides the design values of Manning's n and Colebrook's k_s for design use. It recommends using a roughness factor of 0.012 for the best quality of concrete lined channel and 0.014 for good quality of concrete lined channel, based on Brater & King (1976). The recommended value of 0.013 in GCO (1984) is in general consistent with the local and overseas practices. While four other common flow equations are given in the drainage manual, no recommended design values are provided. Apparently, these equations are presented for information. Details of the Manning's formula and Colebrook-White equation are discussed in Appendix A.

4 Use of Freeboard

4.1 Hong Kong Approaches

Freeboard is provided to avoid spilling over of water in open channels. By making reference to Chow (1959), GCO (1984) recommends that sufficient freeboard should be provided to contain super-elevation of water surface for flow in bends. Furthermore, it is recommended in Tang & Cheung (2007) that freeboard should be provided at curved channels with an outer bank at downslope side. Details of freeboard are proposed and they are being tested in slope works under the Landslip Prevention and Mitigation Programme.

According to DSD (2013), a 200 mm freeboard is generally considered adequate for normal condition to cover superelevations at bends and wave run-ups, if both apply. An additional margin of safety (300 mm minimum) is also recommended to account for inaccuracies in flood level computations. MTRC (2009) recommends provision of a minimum 300 mm freeboard for manholes, culverts and channels. It also provides different values of freeboard heights for various specific conditions, such as construction tolerance and superelevation of flow at bends. According to Hui et al (2006), freeboard should be provided, including the use of baffle walls where necessary, against overflow at bends.

4.2 Overseas Approaches

Guidelines on use of freeboard can also be found in overseas standards and publications. FHWA (2001) considers that freeboard of about 150 mm is generally adequate in a permanent roadside or median channel. Freeboard is however not necessary for temporary channels. BSI (1983) recommends that the amount of freeboard for valley,

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parapet and boundary wall gutters should be taken as two-fifths of the maximum depth of flow in the gutter, with an upper limit of 75 mm. The Department of the Interior (1967) states that freeboard height varies from six inches for small laterals to two feet or more for large canals. The document contains a design chart relating freeboard height and flow capacity. Based on Chow (1959), freeboards that vary from less than 5% to greater than 30% of the depth of flow are commonly used in design. Freeboard height must be increased for channels with high velocity or deflections to prevent water from spilling over.

In both local and overseas practices, freeboard is not considered in determining flow capacities of channels. It is usually provided at bends to protect against super-elevation or at locations to protect against wave action.

5 Discrepancies between Design Curves and Results of Manning's Formula

As part of the review, the design curves in the chart in Figure 8.7 of GCO (1984) have been re-calculated using the Manning's formula, with a roughness factor of 0.013 and fully wetted cross-sectional area.

The Manning's formula used in the recalculation is:

$$V = \frac{1}{n} R^{0.67} S^{0.5} \quad \text{...} \quad (5.1)$$

where V = velocity (in m/s)
n = roughness factor
R = hydraulic mean depth based on a fully wetted cross-section = A/P
A = wetted cross-sectional area (in m^2)
P = wetted perimeter (in m)
S = gradient of channel.

A comparison of the re-calculated design curves and the design curves given in the chart is presented in Figure 5.1 for U-shaped channels and Figure 5.2 for half-round channels. The following major observations are made:

(a) for U-shaped channels, the flow capacities derived from the Manning's formula are higher than those obtained from the design curves for all channel sizes except for 375 mm channel, see Figure 5.1. The difference ranges between +6% and +16%. This also shows that the hydraulic mean depths (the ratio of wetted cross-sectional area to wetted perimeter) adopted in the design curves are lower than those defined in the Manning's formula; and

(b) for half-round channels, the flow capacities derived from the Manning's formula are lower than those obtained from the design curves for all channel sizes except for 300 mm channel, see Figure 5.2. The difference ranges between -5% and -15%. This indicates that the hydraulic mean

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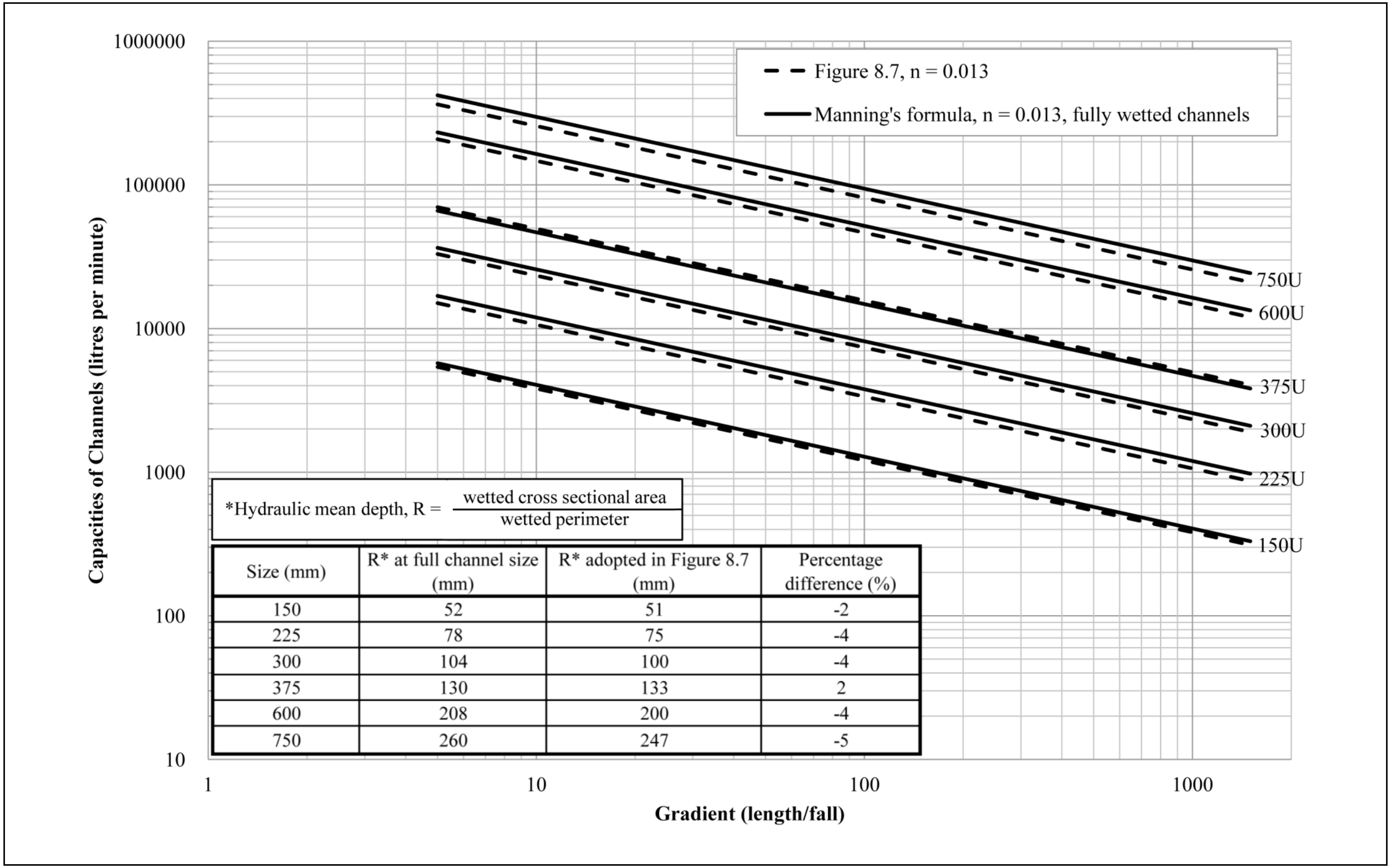

$$\text{*Hydraulic mean depth, } R = \frac{\text{wetted cross sectional area}}{\text{wetted perimeter}}$$

Size (mm)	R* at full channel size (mm)	R* adopted in Figure 8.7 (mm)	Percentage difference (%)
150	52	51	-2
225	78	75	-4
300	104	100	-4
375	130	133	2
600	208	200	-4
750	260	247	-5

Figure 5.1 Comparison between the Re-calculated Design Curves and the Original Design Curves in Figure 8.7 of GCO (1984) for U-shaped Channels

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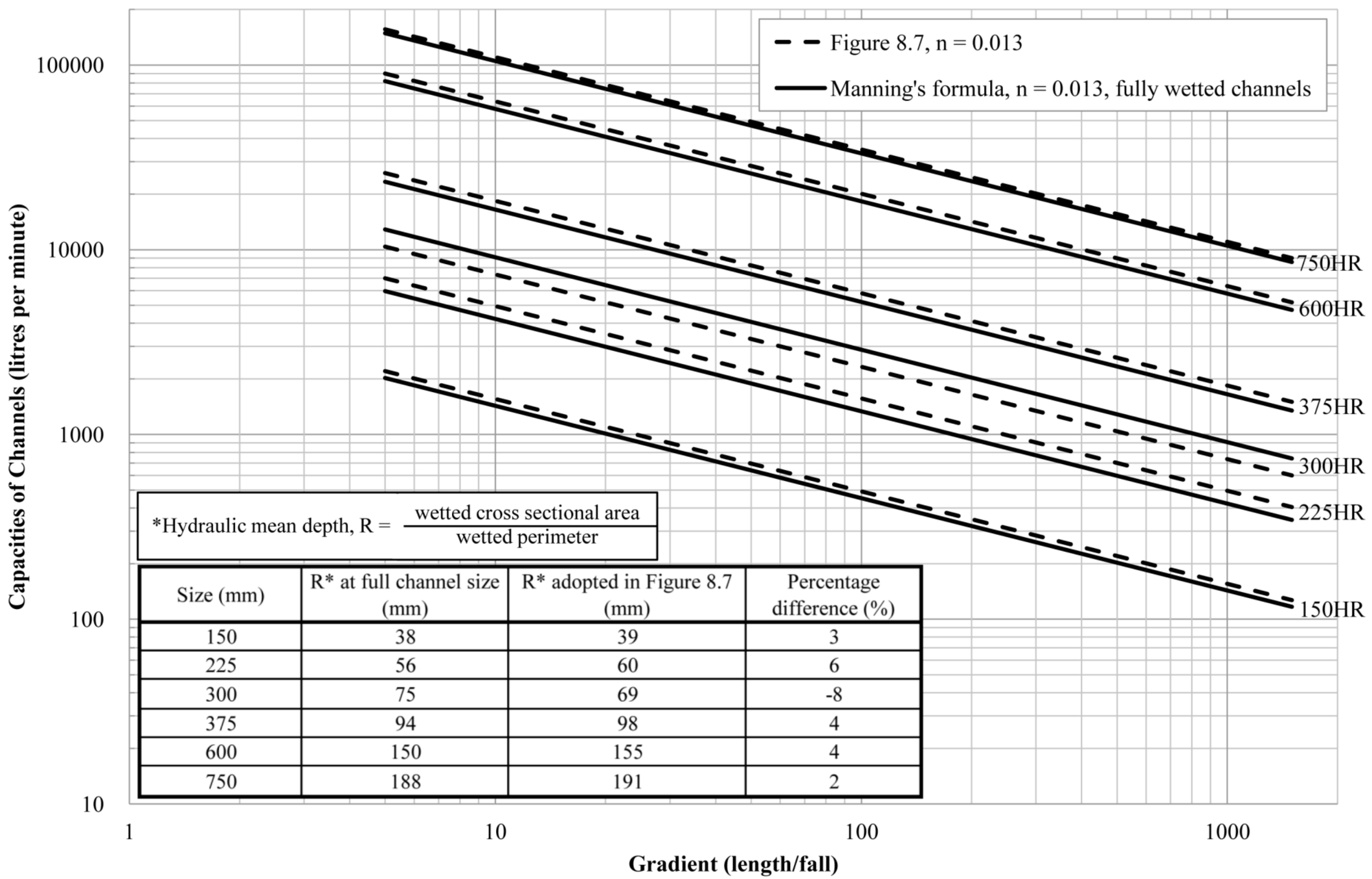

Size (mm)	R* at full channel size (mm)	R* adopted in Figure 8.7 (mm)	Percentage difference (%)
150	38	39	3
225	56	60	6
300	75	69	-8
375	94	98	4
600	150	155	4
750	188	191	2

Figure 5.2 Comparison between the Re-calculated Design Curves and the Original Design Curves in Figure 8.7 of GCO (1984) for Half-round Channels

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depths adopted in the design curves are higher than those defined in the Manning's formula.

Based on the above comparison, there are discrepancies between the design curves and the results of the Manning's formula. The probable reason for the discrepancies is that the hydraulic mean depths used by the design curves differ from those defined in the Manning's formula.

It is also found that using a nomograph to solve the Manning's formula generates the same observations as above. There is no difference between the use of a nomograph and a calculator/computer in solving the Manning's formula.

6 Discussion

For the two assumptions mentioned in Section 1 above, assumption (a) for a 10% reduction of the roughness factor in solving the Manning's formula is not justifiable. In addition, assumption (b) for allowance for freeboard in solving the Manning's formula is not valid.

Based on the present understanding, the chart given in Figure 8.7 of GCO (1984) cannot be reproduced using the Manning's formula. It is not clear how it was derived, or it may have been mistakenly produced.

Both GCO (1979) and GCO (1984) recommend the use of Manning's formula for channels up to 600 mm. GCO (1984) further recommends that Colebrook-White equation (Ackers, 1969) may be used for channels larger than 600 mm. These recommendations are consistent with those given in DSD (2013). Therefore, the use of Manning's formula and Colebrook-White equation in GCO (1984) for design of surface channels is valid.

7 Recommendations

U-shaped and half-round channels up to 600 mm should be designed in accordance with Figure 7.1. Alternatively, assuming a maximum permissible velocity of 4 m/s and a roughness factor of 0.013, Manning's formula (see Equation 5.1) can be used.

Channels larger than 600 mm may be designed using the Colebrook-White equation presented in the design charts in HR Wallingford (2006), which is an updated version of Ackers (1969).

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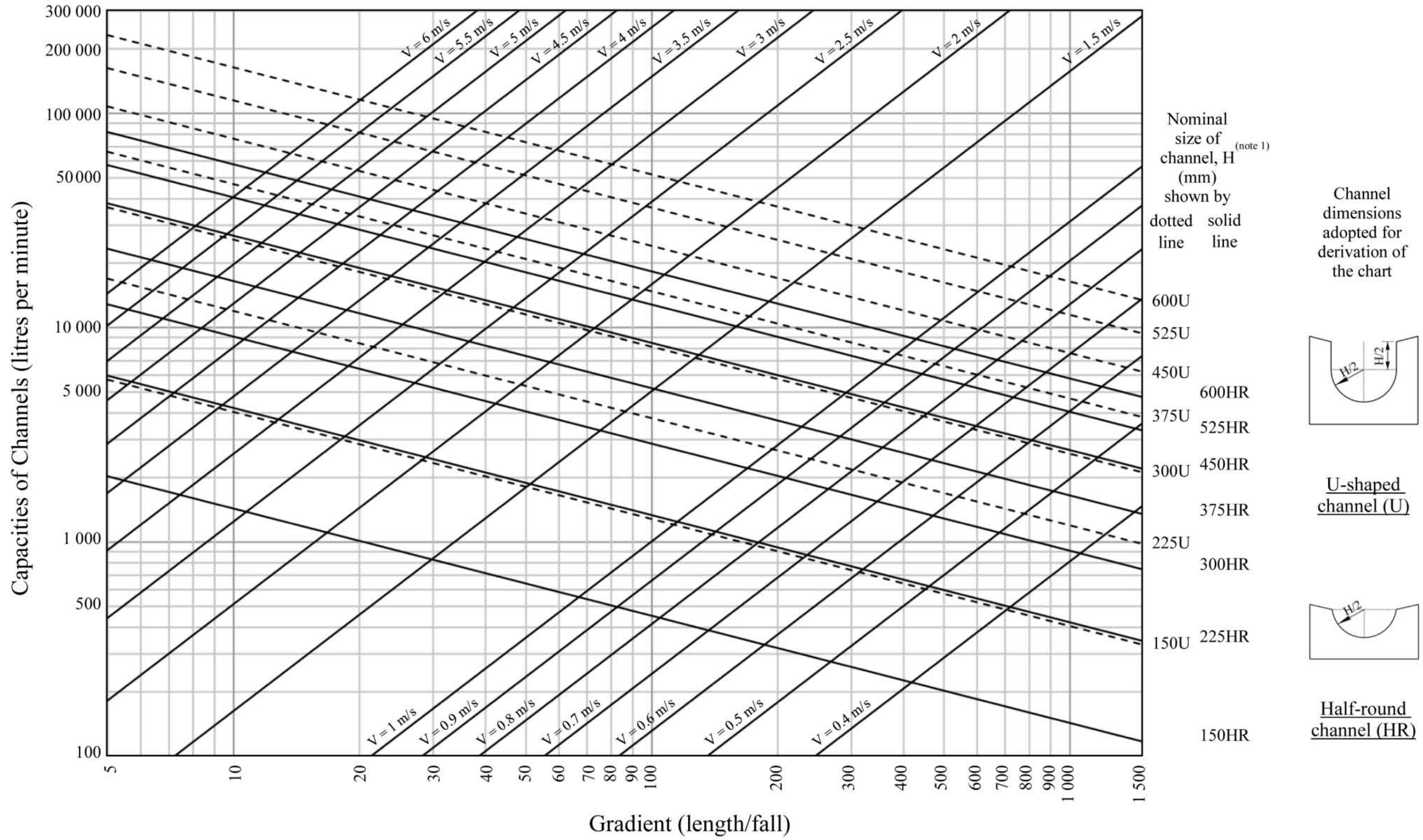

Note: (1) Refer to the latest CEDD Standard Drawings for the details of U-shaped (U) and half-round (HR) channels.

Figure 7.1 Chart for the Rapid Design of U-shaped and Half-round Channels up to 600 mm

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8 Conclusion

A review of the design methodology for both U-shaped and half-round channels given in Section 8.3.4 and the chart given in Figure 8.7 of GCO (1984) has been carried out. It is found that the use of Manning's formula and Colebrook-White equation for design of U-shaped and half-round channels is still valid and consistent with the local practice in surface channel design. Nevertheless, discrepancies have been found between the design curves in the chart given in Figure 8.7 of GCO (1984) and the results of the Manning's formula. An updated design methodology, together with a revised chart for the rapid design of both U-shaped and half-round channels, is recommended. The recommendations have been promulgated in the GEO Technical Guidance Note No. 43.

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Appendix A

Technical Details and Discussions of the Manning's Formula and the Colebrook's White Equation

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This Appendix provides technical information on hydraulic design of surface channel using the Manning's formula and the Colebrook-White equation. The use and limitations of the two design equations are also discussed.

A.1 Manning's Formula

The Manning's formula, in SI unit, is given below:

$$V = \frac{1}{n} R^{0.67} S^{0.5} \quad \text{(A.1)}$$

where
V = velocity (in m/s)
n = roughness factor
R = hydraulic mean depth = A/P
A = wetted cross sectional area (in m^2)
P = wetted perimeter (in m)
S = gradient of channel.

Section 8.3.4 of GCO (1984) recommends a roughness factor of 0.013, which represents finished concrete surface. In hydraulic design of surface channels on slopes, the hydraulic mean depth refers to the design flood level. The extra hydraulic mean depth as a result of the provision of freeboard and splash allowance is not considered in the calculation of design flow capacity. The same principle applies to the use of Colebrook-White equation.

The Manning's formula applies only to rough turbulent uniform flows (DSD, 2013). It is applicable for design of surface channels on slopes due to the rapid entry of rainwater into the drainage system, the potentially rough finishing of the channel surface and the relatively steep channel gradient for partial cleansing of sediments in the channel. Section 8.3.4 of GCO (1984) also specifies the use of Manning's formula for channels up to 600 mm at a permissible velocity less than 4 m/s. The Manning's formula is an empirical relationship based on limited data (HR Wallingford, 2006). The Manning's roughness factor is not dimensionless (i.e. the unit of n is $s/m^{(1/3)}$) and therefore, Equation A.1 and the suggested value of 0.013 are only applicable in SI unit.

A.2 Colebrook-White Equation

For open channel flow as for pipe flow, the head loss ΔH over a distance Δs (along the flow direction) is given by the Darcy equation.

$$\Delta H = f \frac{\Delta s}{D_H} \frac{V^2}{2g} \quad \text{(A.2)}$$

where
f = Darcy coefficient
D_H = hydraulic diameter = $4R$
R = hydraulic mean depth = A/P
A = wetted cross sectional area (in m^2)

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P	=	wetted perimeter (in m)
V	=	velocity (in m/s)
g	=	gravitation acceleration (in m/s^2)

The Darcy coefficient (f) in the above equation could be estimated using the Colebrook-White equation (Colebrook, 1939; HR Wallingford, 2006), which is given below:

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{k_s}{3.71D_H} + \frac{2.51}{Re\sqrt{f}}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(A.3)}$$

where

f	=	Darcy coefficient
k_s	=	effective roughness
D_H	=	hydraulic diameter = $4R$
R	=	hydraulic mean depth = A/P
A	=	wetted cross sectional area (in m^2)
P	=	wetted perimeter (in m)
Re	=	Reynolds number.

The non-dimensional variables in Equation A.3 could be expressed in terms of their dimensional engineering equivalents, resulting in the following expression, which is also given in DSD (2013):

$$V = -\sqrt{32gRS}\,\log\left[\frac{k_s}{14.8R} + \frac{1.255v}{\mathrm{R}\sqrt{32gRS}}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(A.4)}$$

where

V	=	velocity (in m/s)
g	=	gravitation acceleration (in m/s^2)
R	=	hydraulic mean depth = A/P
A	=	wetted cross sectional area (in m^2)
P	=	wetted perimeter (in m)
S	=	gradient of channel
k_s	=	effective roughness
v	=	kinematic viscosity of fluid.

DSD (2013) provides a table of recommended roughness values, k_s, which is based on HR Wallingford (2006). The category "Concrete Channels" is particularly relevant to U-shaped and half-round channels on slopes. An appropriate design roughness value may be selected from the table.

The Colebrook-White equation is only applicable to turbulent uniform flows. DSD (2013) presents the Colebrook-White equation and remarks that the equation is applicable to transitional flow between rough and smooth turbulent flow. It is however mentioned in HR Wallingford (2006) that the Colebrook-White equation is applicable to virtually any surface roughness, conduit size, velocity of flow, or fluid. The following discussion shows that the argument by HR Wallingford (2006) is valid.

The roughness effects are negligible at smooth turbulent condition. Equation A.3 is reduced to the following equation by setting the effective roughness, k_s, to zero:

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$$\frac{1}{\sqrt{f}} = 2\log_{10}\left(Re\sqrt{f}\right) - 0.8 \quad \text{(A.5)}$$

This equation is equivalent to the hydraulic equation presented in HR Wallingford (2006) and Chanson (2004) for smooth turbulent flow.

On the other hand, the viscous effects are negligible at rough turbulent condition. Equation A.3 is reduced to the following equation by setting the kinematic viscosity of fluid, *v*, in Reynolds number, *Re*, to zero (i.e. setting $\frac{2.51}{Re\sqrt{f}} = 0$):

$$\frac{1}{\sqrt{f}} = 2\log_{10}\left(\frac{D_H}{2k_s}\right) + 1.74 \quad \text{(A.6)}$$

This equation is equivalent to the hydraulic equation presented in HR Wallingford (2006) and Chanson (2004) for rough turbulent flow.

It is obvious in the above discussion that the Colebrook-White equation given in DSD (2013) could be used for smooth turbulent flow, rough turbulent flow and transitional flow.

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E-mail: florenceko@cedd.gov.hk

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傳真: (852) 2714 0275
電子郵件: florenceko@cedd.gov.hk

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MAJOR GEOTECHNICAL ENGINEERING OFFICE PUBLICATIONS
土力工程處之主要刊物

GEOTECHNICAL MANUALS

Geotechnical Manual for Slopes, 2nd Edition (1984), 302 p. (English Version), (Reprinted, 2011).

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Highway Slope Manual (2000), 114 p.

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Geoguide 1	Guide to Retaining Wall Design, 2nd Edition (1993), 258 p. (Reprinted, 2007).
Geoguide 2	Guide to Site Investigation (1987), 359 p. (Reprinted, 2000).
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Geoguide 4	Guide to Cavern Engineering (1992), 148 p. (Reprinted, 1998).
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Geospec 1	Model Specification for Prestressed Ground Anchors, 2nd Edition (1989), 164 p. (Reprinted, 1997).
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GEO Publication No. 1/2011	Technical Guidelines on Landscape Treatment for Slopes (2011), 217 p.

GEOLOGICAL PUBLICATIONS

The Quaternary Geology of Hong Kong, by J.A. Fyfe, R. Shaw, S.D.G. Campbell, K.W. Lai & P.A. Kirk (2000), 210 p. plus 6 maps.

The Pre-Quaternary Geology of Hong Kong, by R.J. Sewell, S.D.G. Campbell, C.J.N. Fletcher, K.W. Lai & P.A. Kirk (2000), 181 p. plus 4 maps.

TECHNICAL GUIDANCE NOTES

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