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

GEO Technical Guidance Note No. 27 (TGN 27)
Hydraulic Design of Stepped Channels on Slopes

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1. SCOPE

1.1 This Technical Guidance Note (TGN) provides technical guidance on the hydraulic design of stepped channels on slopes. It supersedes the stepped channel design methodology given in the last paragraph of Section 8.3.4 of the Geotechnical Manual for Slopes (GEO, 1984).

1.2 Any feedback on this TGN should be referred to Chief Geotechnical Engineer/ Standards and Testing of the GEO.

2. TECHNICAL POLICY

2.1 The technical recommendations promulgated in this TGN were agreed by the GEO Geotechnical Control Conference.

3. RELATED DOCUMENTS

3.1 Chanson, H. (1994). *Hydraulic Design of Stepped Cascades, Channels, Weirs and Spillways*. Pergamon, Oxford, England, 261 p.

3.2 DSD (2003). *Design of Stormwater Inlets (DSD Practice Note No. 1/2003 Version 2)*. Drainage Services Department, Hong Kong, 26 p.

3.3 GEO (1984). *Geotechnical Manual for Slopes (Second Edition)*. Geotechnical Engineering Office, Hong Kong, 295 p.

3.4 Lam, J.S. & Siu, C.K. (2004). *A Review of Hydraulic Design of Stepped Channels for Slope Drainage (GEO Discussion Note No. 1/2004)*. Geotechnical Engineering Office, Hong Kong, 17 p.

3.5 Mott Connell Limited (2006). *Study on Review of Stepped Drainage Channels, Final Report*. Agreement No. CE 10/2004 (GE). Geotechnical Engineering Office, Hong Kong, 69 p.

4. DEFINITIONS

4.1 <u>Critical flow depth, d_c</u> corresponding to a given flow rate is the depth of a flow which possesses the given flow rate and a minimum specific energy.

4.2 <u>Equivalent non-aerated flow</u> of a given aerated flow is an imaginary flow in which the flow rate is equal to that of the aerated flow but air concentration is zero.

4.3 <u>Gradient of stepped channel, α</u> is the gradient of a line joining the edges of the steps.

4.4 Skimming flow is a flow regime that occurs in stepped channels, in which water flows down the channels by skimming over the channel steps with strong air entrainment. Compared to other flow regimes, skimming flow dissipates more energy, and it occurs at a higher flow rate.

4.5 Specific energy in a channel section is the energy per unit weight of water measured with respect to the channel bottom. It is equal to the sum of the depth of water and the velocity head.

4.6 Uniform aerated flow region is the downstream region of a skimming flow profile, where the air entrainment process achieves equilibrium and the flow reaches a uniform flow condition.

5. BACKGROUND

5.1 It is not uncommon to see water overflowing from stepped channels during heavy rainfall. This indicates that the capacity of stepped channels designed using the methodology given in the Geotechnical Manual for Slopes (GEO, 1984) is inadequate. A review of stepped channel design methodology has been carried out.

5.2 The recommendations contained in this TGN are based on the hydraulic design methodology proposed by Chanson (1994) and DSD (2003), in which the effect of channel steps is accounted for and the phenomenon of aeration is quantified. Discussions on the methodology are referred to Lam & Siu (2004) and Mott Connell Limited (2006).

6. TECHNICAL RECOMMENDATIONS

6.1 Standard Sized Stepped Channels

6.1.1 Standard sized stepped channels should be designed in accordance with the details and design chart provided in Figures 1 and 2 of Annex TGN 27 A1 respectively.

6.1.2 To promote the efficiency of energy dissipation, the length of stepped channels should not be less than that given in Table 1 of Annex TGN 27 A1.

6.2 Non-standard Sized Stepped Channels

6.2.1 Non-standard sized stepped channels should be designed in accordance with the procedure provided in Annex TGN 27 A2.

6.3 Drainage Provision on Steep Profile

6.3.1 For profiles steeper than 65°, the empirical correlation among the design parameters becomes invalid. Specialist advice from hydraulic expert should be sought on the design of such stepped channels. Alternatively, other drainage measures such as stepped channels with covers may be considered.

7. **ANNEX**

7.1 TGN 27 A1 – Details, Chart and Table for Standard Sized Stepped Channel Design

7.2 TGN 27 A2 – Design Procedure for Non-standard Sized Stepped Channels

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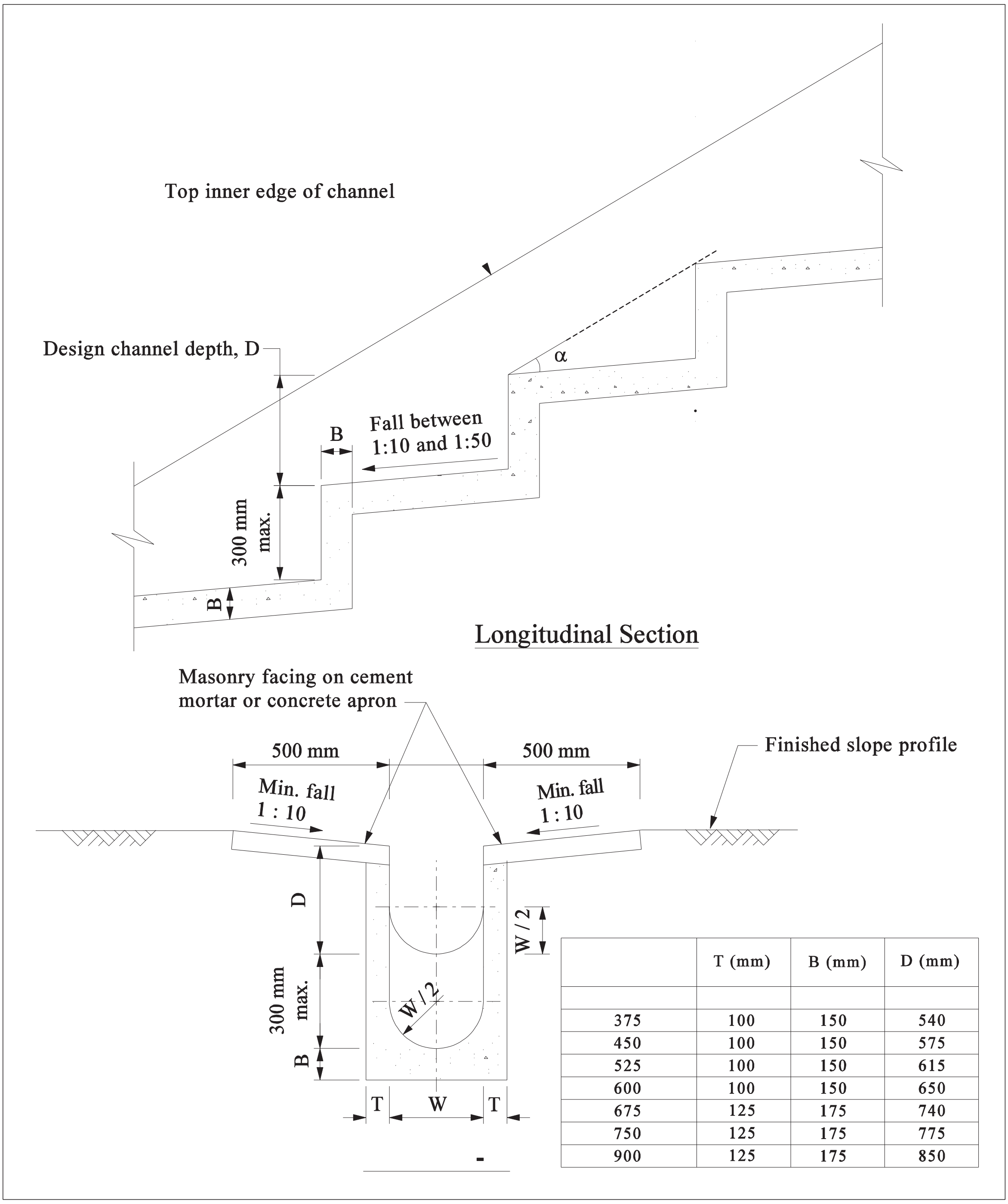
Figure 1 – Details of Standard Sized Stepped Channels



	T (mm)	B (mm)	D (mm)
375	100	150	540
450	100	150	575
525	100	150	615
600	100	150	650
675	125	175	740
750	125	175	775
900	125	175	850

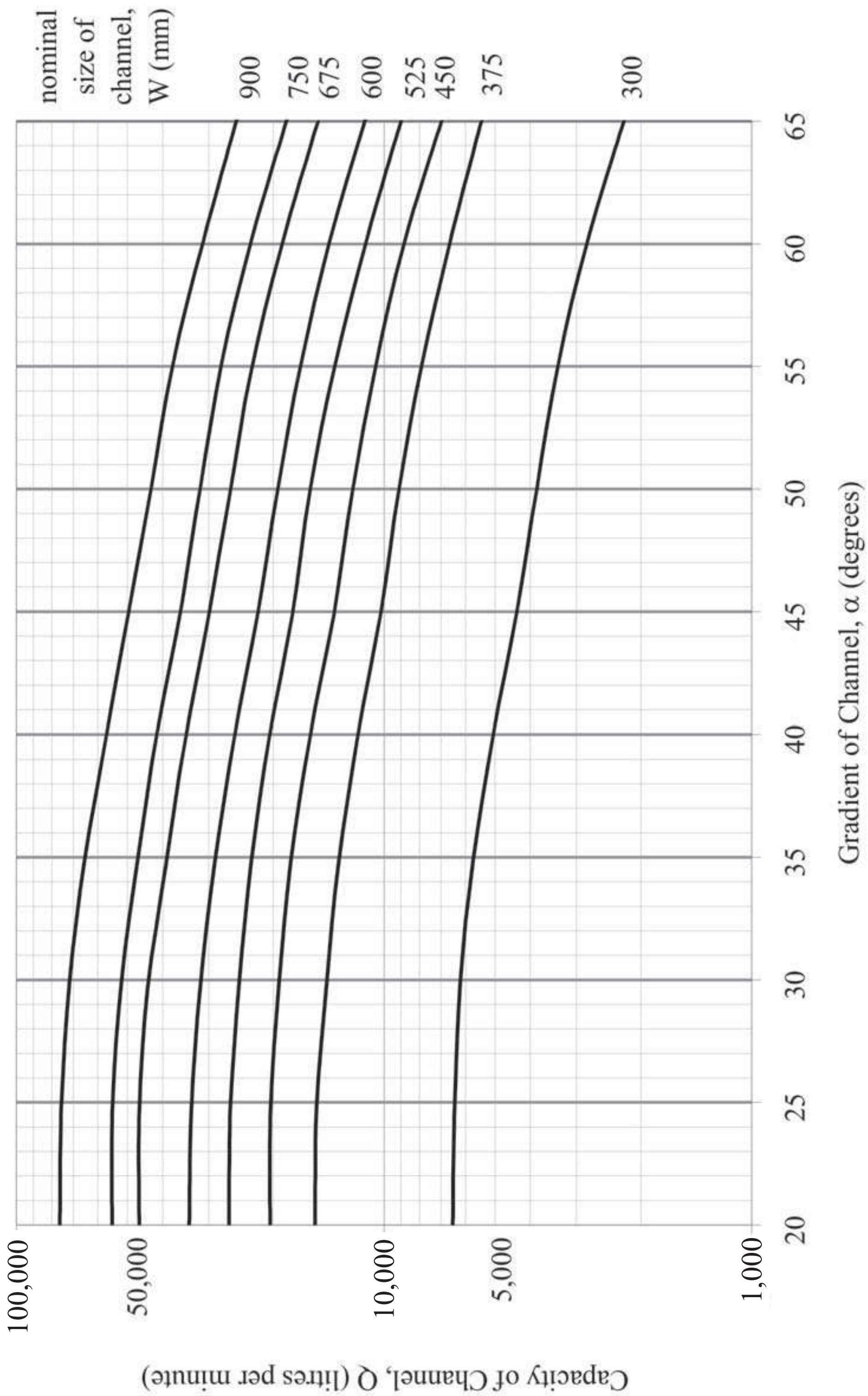


Figure 2 – Design Chart for Standard Sized Stepped Channels

Table 1 – Recommended Minimum Length of Standard Sized Stepped Channels (in metres)

Nominal size of channel, W (mm)	Channel gradient, α (degrees)									
	20	25	30	35	40	45	50	55	60	65
300	3.3	3.2	3.1	3.0	3.0	3.0	3.0	3.0	3.0	3.0
375	5.1	5.0	4.8	4.7	4.5	4.3	4.3	4.3	4.3	4.3
450	5.5	5.4	5.2	5.1	4.8	4.6	4.6	4.6	4.6	4.6
525	6.0	5.8	5.7	5.4	5.2	5.0	5.0	5.0	5.0	5.0
600	6.4	6.3	6.1	5.8	5.6	5.3	5.3	5.3	5.3	5.3
675	7.3	7.2	6.9	6.6	6.3	6.1	6.0	6.0	6.0	6.0
750	7.8	7.6	7.3	7.0	6.7	6.4	6.4	6.3	6.3	6.3
900	8.6	8.4	8.1	7.8	7.4	7.0	7.0	7.0	7.0	7.0

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DESIGN PROCEDURE FOR NON-STANDARD SIZED STEPPED CHANNELS

1. PRINCIPLES

1.1 This procedure is based on the hydraulic design methodology proposed by Chanson (1994) and DSD (2003). The design flow is assumed to be in a skimming flow regime. A typical skimming flow profile is shown in Figure 3.

1.2 The objective of design is to ensure that the design stepped channel is deep enough to retain the flow in the uniform aerated flow region, where the flow depth is the largest. The design stepped channel is first assumed to be full, i.e. the channel depth equals the flow depth, and its capacity is then back-calculated. The assumption of skimming should be verified prior to adopting the back-calculated channel capacity. Additionally, the channel length is checked to be long enough to develop a uniform aerated flow.

2. INPUT PARAMETERS

2.1 The required input parameters are as follows:

Q_{req}	required channel capacity
α	channel gradient
L	channel length
D	design channel depth
W	design channel width
h	design channel step height
l	design channel step length

2.2 The channel dimensions are denoted as shown in Figure 4.

3. DETERMINATION OF CHANNEL CAPACITY

3.1 **Determining the Average Air Concentration, C_e**

3.1.1 Average air concentration is correlated with channel gradient as follows:

$C_e = 0.9 \sin \alpha$ for $20° \leq \alpha \leq 45°$

or $C_e = 0.3265 \sin \alpha + 0.4055$ for $45° < \alpha \leq 65°$

3.2 Determining the Darcy's Friction Factor of Aerated Flow, f_e

3.2.1 Darcy's friction factor is correlated with average air concentration as follows:

$$f_e = 0.5\,f \left\{ 1 + \tanh\left[0.628 \frac{0.51 - C_e}{C_e (1 - C_e)} \right] \right\}$$

where tanh(x) is the hyperbolic tangent function, i.e. $\tanh(x) = (e^x - e^{-x}) / (e^x + e^{-x})$; and f is the Darcy's friction factor of non-aerated flow. It is recommended to use f = 1.0 as an order of magnitude of the friction factor.

3.3 Determining the Characteristic Aerated Flow Depth, Y_{90}

3.3.1 Assume the design channel is full, i.e.

$$Y_{90} = D \cos \alpha$$

where Y_{90} is the flow depth corresponds to the local air concentration of 90%

3.4 Determining the Equivalent Non-aerated Flow Depth, d_o

3.4.1 $d_o = Y_{90} (1 - C_e)$

3.5 Determining the Hydraulic Diameter of Equivalent Non-aerated Flow, D_H

3.5.1 $$D_H = 4\,A_W / P_W = 4 \times \left(\frac{d_o \times W}{2\,d_o + W} \right)$$

where A_W is the cross-sectional area of the equivalent non-aerated flow; and P_W is the wetted perimeter of the equivalent non-aerated flow.

3.6 Determining the Equivalent Non-aerated Flow Velocity, V_o

3.6.1 By momentum equation,

$$V_o = \sqrt{\frac{8\,g \sin \alpha}{f_e} \times \frac{D_H}{4}}$$

where g is the acceleration of gravity.

3.7 Determining the Channel Capacity, Q

3.7.1 $Q = V_o \times d_o \times W$

3.7.2 The calculated channel capacity Q should be equal to or larger than the required capacity Q_{req}. Otherwise, the size of the design channel should be increased.

4. VERIFICATION OF FLOW REGIME

4.1 Determining the Discharge per Unit Channel Width, q_w

4.1.1 $q_w = Q / W$

4.1.2 The discharge per unit width q_w should not be larger than 2 m^2/s, or else the downstream catchpit may be overshot.

4.2 Determining the Critical Flow Depth for the Given Discharge per Unit Width, d_c

4.2.1 $d_c = (q_w^2 / g)^{1/3}$

4.3 Determining the Critical Flow Depth for Onset of Skimming Flow, $(d_c)_{onset}$

4.3.1 $(d_c)_{onset} = (1.057 - 0.465\, h / l)\, h$

4.4 Verifying the Skimming Flow Assumption

4.4.1 If d_c is equal to or larger than $(d_c)_{onset}$ the skimming flow assumption is valid and the calculated channel capacity Q can be adopted.

4.4.2 If d_c is less than $(d_c)_{onset}$, it indicates that the design channel is not deep enough to onset a skimming flow, i.e. the flow will not achieve skimming even if the channel is full. To achieve a skimming flow, the geometry of the channel should be amended, e.g. increasing the design channel depth.

5. CHECK FOR MINIMUM CHANNEL LENGTH

5.1 Determining the Minimum L/*h* Ratio to Develop Uniform Aerated Flow

5.1.1 To develop uniform aerated flow, the flow has to travel a certain distance until the air entrainment process achieves equilibrium. If the channel is not long enough to provide this distance, uniform aerated flow would not develop and the energy dissipation ability of the channel would be reduced.

5.1.2 The minimum L/*h* ratio to develop uniform aerated flow can be read from Table 2 by entering the α and d_c/h values.

5.2 **Checking for the Minimum L/*h* Ratio**

5.2.1 It is preferable to have the design L/*h* ratio equal to or larger than the minimum L/*h* ratio such that uniform aerated flow would develop.

5.2.2 If the minimum L/*h* ratio cannot be achieved, the design channel is still acceptable. However, to enhance the energy dissipation ability, it is preferable to reduce the channel step height in order to fulfil the minimum L/*h* ratio. Alternatively, the channel layout can be amended so as to increase the channel length if the field conditions allow.

Figure 3 – Typical Skimming Flow Profile

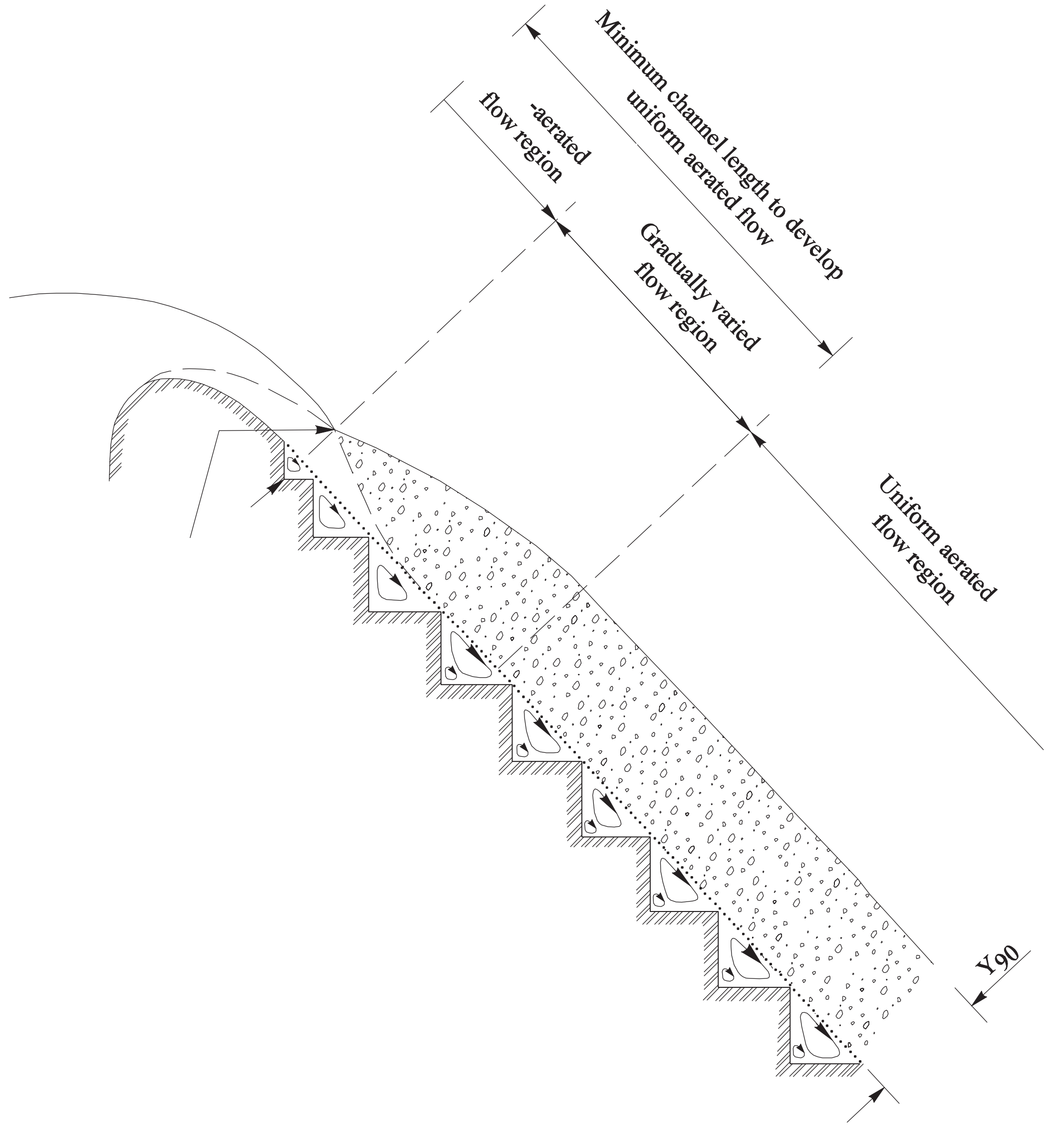

Figure 4 – Denotation of Channel Dimensions

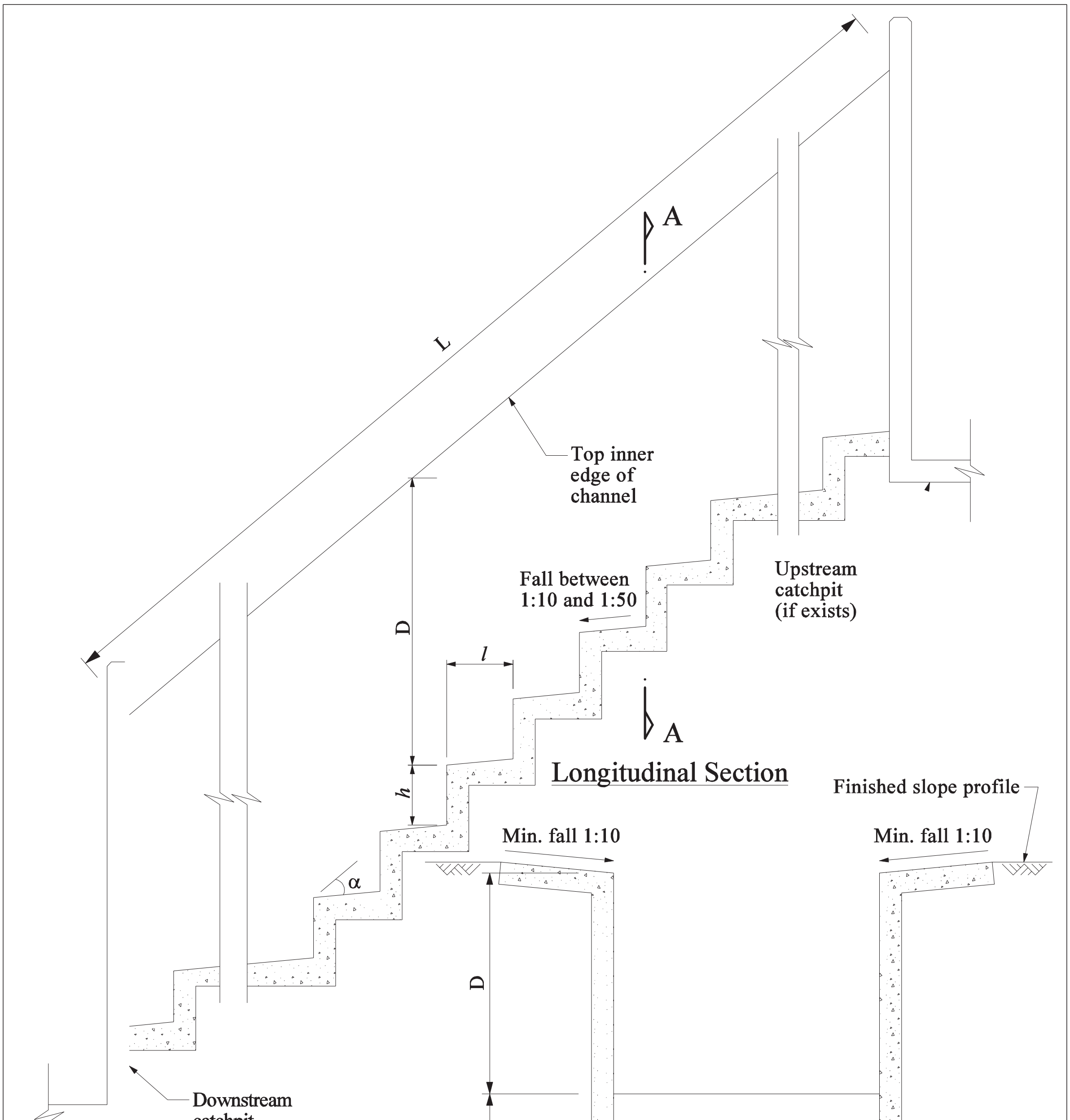

Table 2 – Minimum L/*h* Ratio to Develop Uniform Aerated Flow

L/*h*		Channel gradient, α (degrees)									
		20	25	30	35	40	45	50	55	60	65
10	d_c/h	0.731	0.745	0.743	0.729	0.702	0.664	0.616	0.559	0.495	0.423
20		1.398	1.424	1.421	1.393	1.342	1.269	1.178	1.070	0.946	0.809
30		2.042	2.080	2.076	2.035	1.960	1.855	1.721	1.563	1.382	1.182
50		3.292	3.354	3.348	3.281	3.160	2.990	2.775	2.520	2.228	1.906
75		4.810	4.900	4.891	4.794	4.617	4.368	4.054	3.681	3.255	2.784
100		6.294	6.413	6.400	6.273	6.042	5.717	5.306	4.817	4.260	3.644

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