CHAPTER 16 ENGINEERED CHANNEL

16.1 INTRODUCTION

Drainage should be designed in an environmentally responsible way to minimise disruption of the natural environment of the nation's streams and channels.

Engineered channels are a preferred means of meeting the above objective by providing a drainage system that is more closely resembles natural streams. The word "engineered" in the title indicates that the channels are carefully designed to achieve this condition.

Engineered channels is one of the components for the major drainage system designed to collect and convey flows from the minor drainage system and to provide for the safe passage of larger flows up to the major design storm.

16.1.1 Advantages

In urban settings, a wide variety of options are used for lining engineered channels. Although these engineered channels are more costly than the use of vegetation, but they do offer advantages such as stability under higher velocities and can accept runoff immediately after construction.

16.1.2 Disadvantages

Engineered channels with a more natural form will convey flows less efficiently than traditional straight-lined channels. As a result, a natural-form engineered channel will require a larger cross-sectional area to convey the same flow. Grassed channels generally need suitable soils for vegetation and adequate area for installation. It is critical during the vegetative establishment period to restrict outside water from flowing through the channel. Therefore, it may be necessary to delay construction until the engineered channel is well established. Grassed waterways are also used as filters to remove sediment, but may sometimes lose their effectiveness when there is excessive sediment build up in the engineered channel.

16.1.3 Engineered Channel Types

The types of engineered channels available for urban drainage systems are almost infinite, depending only upon good hydraulic practices, environmental design, sociological impact, and basic project requirements. However, from a practical standpoint, the basic choice to be made initially is whether or not the engineered channel is to be a hard-lined one for higher velocities, a grassed channel, or a natural channel already existing. The following types shown in Table 16.1 are applicable in urban areas.

16.2 DESIGN CONSIDERATIONS AND REQUIREMENTS

16.2.1 General

The design of constructed engineered channels should, wherever practicable, mimic the natural stream forms in the immediate region. The following shall be considered for the successful management of aquatic, ephemeral and terrestrial environments along constructed channels (Melbourne Water, 2009):

- the capacity and hydraulic functions of the channel;
- an integrated approach to planting and hydraulic planning to prevent or reduce flooding;
- consideration of roughness issues and potential impacts on localised flooding where Manning's *n* values are increased due to excessive use of shrubs in revegetation;
- planting for the purpose of mitigating problems associated with increased flows resulting from greater impervious surfaces due to urban development (i.e. for erosion and bank stabilisation control); and
- revegetation design also needs to consider the impact of hydraulic roughness and potential barriers to flow. The increased resistance to flow from denser vegetation growth tends to slow the passage of flood water, thereby reducing channel conveyance and raising water levels for a given flow.

Table 16.1: Engineered Channel Types Applicable in Urban Areas in Malaysia

Types and Descriptions	Example
Natural Channels: These are engineered channels carved or shaped by nature before urbanisation occurs and are the most desirable of the various types of constructed or modified channels. They often, but not always, have mild slopes and are reasonably stable. As the tributary catchment urbanises, natural channels often experience erosion and may need grade control checks and localised bank protection for channel stabilisation.	
Grassed Channels: These are soft-lined engineered channels designed to lower flow velocities, provide channel storage, and offer various multiple use benefits. Low flow areas generally need to be concrete or rock lined to minimise erosion and maintenance problems. Generally, grassed channels should be located to conform with and use the natural drainage system. Grassed channels may also be developed along roadways and property lines but should avoid sharp changes in flow direction and longitudinal slope.	
Concrete Lined Channels: Concrete lined channels are high velocity artificial channels that are not encouraged in urban areas. However, in retrofit situations where existing flooding problems need to be solved and where a drainage reserves are limited, concrete channels may offer advantages over other types of engineered channels.	
Other Channel Liners: A variety of artificial channel liners may be used to protect the channel walls and bottom from erosion at higher velocities. These include gabions, interlocked concrete blocks, concrete revetment mats formed by injecting concrete into double layer fabric forms, and various types of synthetic fibre liners. As with rock and concrete liners, all of these types are best considered for helping to solve existing urban flooding problems, but are not recommended for new developments. Each type of liners has to be scrutinised for its merits, applicability, how it meets other community needs, its long-term integrity, maintenance needs and costs.	

16.2.2 Location

Continuous designated overland flow paths shall be provided from the top of the catchment through the entire urban area.

Engineered channels may be located within designated drainage reserves, roadways, parkland and open space areas, and pedestrian ways. All engineered channels shall be located wholly outside of privately owned lots. If circumstances arise where this arrangement cannot be provided, prior agreement to locate engineered channels within privately owned areas must be obtained from the local regulatory authority and the affected private landowners. Engineered channels are generally not recommended for construction within river floodplains. In these situations the aim is to ensure that flood flows spread across the floodplain as they would under natural conditions (NRW, 2004).

Engineered channels shall be provided along the alignment of existing watercourses and drainage depressions. Diversion of engineered channels away from their natural paths will only be permitted in exceptional circumstances and only with the approval of the local regulatory authority.

Wherever possible, landuse within engineered channel corridors should be designated as public open space. Other types of landuse may be considered, but they must be fully compatible with the primary role of the channel to convey flood flows up to and including the design storm.

16.3 DESIGN CRITERIA

16.3.1 Design Storm

Engineered channels shall be designed to cater to flows up to and including the major system design ARI. All new urban developments shall be provided with major drainage systems designed with sufficient capacity and freeboard to ensure that flood flows up to 100-year ARI do not encroach upon private leases. Extreme flood events should also be considered to allow for the investigation of the channel stability and performance under unusually large flood events. At times, it may be necessary to adjust design flows to match more realistic observed or historical flows (ACT Government, 1992).

Adjoining low-lying land may need to be acquired and/or reclaimed to ensure effective surface drainage and containment of the design ARI flow within an engineered channel.

16.3.2 Reserve

Reserves are required for all engineered channels. These must be clearly defined on all development plans to ensure that future developments do not encroach upon land inundated by flows up to and including the design storm.

The prime function of reserves is to give ready access to personnel, plant and materials, which may, from time to time, be required for channel and berm maintenance. No encroachment, especially earth fill that may inhibit such access or make such maintenance unduly difficult, shall be allowed on reserves.

Engineered channel easement shall be wide enough to contain the service and provide working space on each side of the service for future maintenance activities. The minimum channel reserve width shall be the top channel width for the major storm ARI flow plus a 300 mm freeboard requirement. Maintenance width requirements may be incorporated within this reserve width by benching. If this cannot be achieved, the reserve width must be increased to include maintenance width requirements. Minimum widths to be provided for maintenance access shall be in accordance with Table 16.2.

Table 16.2: Minimum Requirements for Maintenance Access

Top Width of Engineered Channel	Minimum Requirements for Maintenance Access
W ≤ 6m	One side 3.7 m, other side 1.0 m
W > 6m	Both sides 3.7 m

Where other hydraulic services or electrical services are located within the same reserve, the required reserve width shall be increased to provide adequate clearance between the services.

When planning development along an engineered channel for which a master plan is not yet available, a drainage reserve width shall be estimated based on the premise that the design storm flow will be catered to by a grassed channel. This premise ensures that sufficient land will be available for the design of the engineered channel when carried out in conjunction with detailed landuse planning at a later date.

16.3.3 Freeboard

The freeboard above the design storm water level for all engineered channels shall be a minimum of 300 mm, as shown in Table 16.3 unless suggested otherwise by the local regulatory authority. A higher freeboard should be considered at locations where superelevation or hydraulic jumps are anticipated.

16.3.4 Access Requirements

For engineered channels lined with concrete, stone pitching and rock mattresses, access ramps shall be provided for maintenance machinery to gain access to the channel bottom when necessary. Ramps shall be a minimum of 3.5 m wide with a longitudinal slope not steeper than 10(H):1(V) and have a non-slip surface.

16.3.5 Longitudinal Slope

Engineered channels shall be constructed with sufficient longitudinal slope to ensure that ponding and/or the accumulation of silt does not occur, particularly in locations where silt removal would be difficult.

The minimum longitudinal slope for engineered channels shall be as shown in Table 16.3. The longitudinal slope shall not produce velocities less than 0.6 m/s if low flow inverts flowing full.

16.3.6 Design Velocity

Engineered channels, either bare or lined with vegetation, should carry the design discharge at nonerosive velocities. Engineered channels also shall be designed with longitudinal grades that minimise the incidence of hydraulic jumps, dangerous conditions for the public, and erosion of surface linings and/or topsoil.

Longitudinal slopes shall be chosen such that the design storm average flow velocity will not exceed the limits shown in Table 16.3.

16.3.7 Side Slope

The recommended maximum side slopes for engineered channel is indicated in Table 16.3.

Table 16.3 Engineered Channel Types Design Criteria

Channel Type	Minimum Freeboard (mm)	Minimum Longitudinal Grade (%)	Maximum Average Flow Velocity (m/s)	Maximum Side Slope
Natural channels	300	0.1	2	1V:3H
Grassed channels	300	0.1	2	1V:3H
Soft lined channels with turf reinforcement mats (TRM)	300	0.1	4	1V:2H
Composite channels	300	0.4	4	1V:1.5H
Hard lined channels	300	0.4	4	Vertical

16.3.8 Drop Structures

Drop structures should be provided to reduce channel longitudinal slopes such that the design storm average flow velocities do not exceed the limits specified in the previous section. Drop structures shall be designed to ensure that the structures do not get 'drown out' due to high tailwater levels under the major system design flow plus freeboard. Design requirements for drop structures are provided in Chapter 20.

16.3.9 Roughness Coefficient

The Manning's roughness coefficient is dependent on a number of variables including surface roughness, channel irregularity, the presence of obstructions, channel alignment, and the likelihood of sedimentation or scour. Manning's roughness coefficients for the various types of engineered channels are provided in Table 16.4. The choice of an appropriate value for the roughness coefficient of an engineered channel is often critical in the overall design procedure and requires a considerable degree of judgment.

Estimation of an equivalent or composite Manning's roughness coefficient in a channel of varying roughness is often required when there is a marked variation in the boundary roughness across a cross section. In the case of an engineered channel designed within a typical urban environment, examples of this situation include a grassed channel containing a concrete low flow invert, or a channel containing a low level access road along one side of the channel. Equation 16.1 may be used to estimate the overall roughness coefficient in engineered channels of composite roughness. It is important for the designer to check if the composite Manning's roughness coefficient value obtained using Equation 16.1 is reasonable. A distorted or inaccurate value will result in inaccurate predictions of channel flow conditions.

$$n^* = \frac{\sum_{i=1}^{m} \frac{n_i A_i^{5/3}}{P_i^{2/3}}}{\sum_{i=1}^{m} \frac{A_i^{5/3}}{P_i^{2/3}}} \tag{16.1}$$

where,

n^* = equivalent Manning's roughness coefficient for the whole cross section;

n_i = Manning's roughness coefficient for segment i;

A_i = flow area of segment i (m^2);

P_i = wetted perimeter of segment i (m); and

m = total number of segments.

16.3.10 Safety Requirements

Where the design storm flow depth within a lined channel exceeds 0.9 m, a 1.2 m high handrail fence shall be provided on both sides of the channel to discourage public access. Handrail fencing should be parallel to the channel as far as practicable and should be located within 1 to 3 m from the channel edge. Lockable gates shall be placed at appropriate locations to permit access for maintenance.

Where a lined channel is adjacent to a public road or sited close to carriageway and housing lots, guard railing shall be provided instead of a handrail fence. Guard rails shall be provided in accordance with the requirements of the relevant Authority and/or those for the Public Works Department (JKR) Roads. Alternatively, precast reinforced concrete covers may be also provided for the concrete lined channels. Service opening shall be provided along the channel with maximum interval spacing of 100 m.

Ladder-type steps or step irons should be provided where the channel side slope is steeper than 2(H):1(V), or where the channel depth exceeds 1.2 m. These should be installed no more than 120 m apart on alternating sides of the channel. The bottom rung of the ladder or bottom step iron shall be placed approximately 300 mm vertically above the channel invert. Steps of step irons shall be provided to the top of benching and toe holes provided in the benching.

16.4 NATURAL CHANNEL

Natural channels are either in the form of steeply banked streams, which have erodible banks and bottoms, or mild channels, which are reasonably stabilised. For either type of channel, if it is to be used for carrying storm runoff from an urbanised area, it can be assumed initially that the changed runoff regime will result in highly active erosional tendencies. In nearly all cases, some form of modification of the channel will be required to create a more stabilised condition for the channel (ACT Government, 1992).

The design guidelines for grassed channels do not necessarily apply to natural channels, but such criteria can be utilised in gauging the adequacy of a natural channel for future changes in runoff regime. Design criteria and techniques, which should be used in the design of natural channels, include the following:

- channel and overbank capacity shall be adequate for the design storm;
- channel velocity shall not exceed the lesser of 2 m/s or the critical velocity for any particular section. Manning's roughness coefficient, n , which are representative of maintained channel conditions shall be used for determining critical channel velocities;
- water surface limits shall be defined so that the floodplain can be zoned and protected. Manning's roughness coefficient, n , which represent unmaintained channel conditions shall be used for the analysis of water surface profiles; and
- drop structures or check dams should be constructed to limit flow velocities and control water surface profiles, particularly for the initial storm runoff.

Table 16.4 Suggested Values of Manning's Roughness Coefficient, n

Surface Cover	Suggested n Values
Natural Channels	
Small streams	
Straight, uniform and clean	0.033
Clean, winding with some pools and shoals	0.045
Sluggish weedy reaches with deep pools	0.080
Steep mountain streams with gravel, cobbles, and boulders	0.070
Large streams	
Regular cross-section with no boulders or brush	0.060
Irregular and rough cross-section	0.100
Overbank flow areas	
Short pasture grass, no brush	0.035
Long pasture grass, no brush	0.050
Light brush and trees	0.080
Medium to dense brush	0.160
Dense growth of trees and brush	0.200
Grassed Channels	
Grass cover only	
Short grass (< 150 mm)	0.035
Tall grass (≥ 150 mm)	0.050
Shrub cover	
Scattered	0.070
Medium to dense	0.160
Tree cover	
Scattered	0.050
Medium to dense	0.120
Lined Channels and Low Flow Inverts	
Concrete	0.015
Shotcrete	0.025
Stone Pitching	
Dressed stone in mortar	0.017
Random stones in mortar or rubble masonry	0.035
Rock Riprap	0.030

16.5 GRASSED CHANNEL

16.5.1 General

Grassed channels are engineered channels included in the soft-lined category. Engineered channels of this type are generally regarded as more aesthetically pleasing than the hard-lined channels and they can be designed to blend into the surrounding natural environment. Grassed channels can be used in situations where;

- flow velocities are insufficient to produce scour;
- the drainage reserve width is not a problem; and
- aesthetics is an important design consideration.

Whilst grassed channels generally have significant construction cost advantages over hard-lined channels, this benefit is in some cases offset by their additional land-take requirements. However, the effect of this additional land-take can be minimised by designing the channel for multi-purpose use. When a grassed channel is to be constructed in a poorly drained area, a dry period must be chosen in which to do the work. In some instances, it may be necessary to direct water away from a new channel until all the work has been completed and the vegetative cover stabilized.

Grassed channels shall conform to the following general requirements:

- channels shall be grassed with provision for low flows; and
- access road and footpath paving within a channel shall be designed to withstand the design discharge in areas of high velocity such as adjacent to bridges and underpasses.

16.5.2 Geometry

Side slopes for grassed channels areas must be adequate to ensure drainage without localised ponding occurring. Batter side slopes should not be milder than 6(H):1(V) for reasons of public safety. However, steeper side slopes up to a maximum of 3(H):1(V) may be provided in special circumstances, such as to preserve existing trees and other natural features, or in existing areas where the land available for a grassed channel is limited.

The base width of a grassed channel should be designed to accommodate the hydraulic capacity of the floodway with due consideration given to limitations on flow velocity. The width must be sufficient to allow access to the base for maintenance purposes. The channel base side slopes shall not be less than 50(H):1(V). Alternative arrangements may be provided to widen a grassed channel adjacent to public open space or recreational areas. In such cases, the minimum side slope for the channel shall be 50(H):1(V).

The preferred cross-section for grassed channels is shown in Figure 16.1.

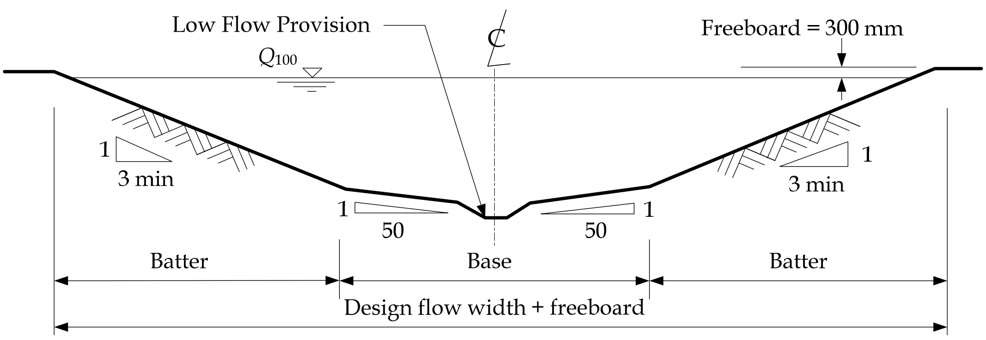

Figure 16.1: Typical Grassed Channel Cross-Section (Modified from ACT Government, 1992)

Terracing, as indicated in Figure 16.2, may be introduced across the grassed channel to contain more frequent flood flows and to localize much of the maintenance to the frequently flooded zone. Terraces may be adjacent public open space and recreational areas or dedicated right of way. This type of section provides for flood storage and to reduced downstream flood levels and lower average velocities for the major system design flow and more natural green space for wildlife and public recreation. Flooding of the adjacent open space and recreational areas should only be incorporated in such areas where flood protection less than the design storm is satisfactory. The minimum side slope for the terrace base shall be 50(H):1(V).

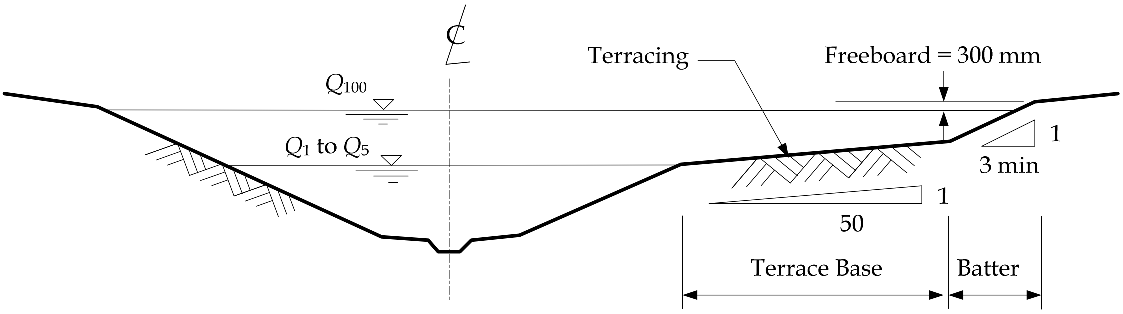

Figure 16.2: Typical Grassed Channel Terracing (Modified from ACT Government, 1992)

16.5.3 Grass Cover

The grass species chosen for lining of channels must be sturdy, drought resistant, easy to establish, and able to spread and develop a strong turf layer after establishment. A thick root structure is necessary to control weed growth and erosion.

A protective cover consisting of mulch and grass seeding is necessary to protect newly constructed engineered channels immediately after construction. If possible, disturbed areas should be seeded with a permanent grass seed mix. Permanent grassing for channels and planting plan shall be in accordance with Annex 1.

16.5.4 Low Flow Provision

The primary function of low-flow channels within open channels is to (NRW, 2007):

- allow efficient drainage of the greater channel or floodway area to minimise the risk of undesirable waterlogging of the soil;
- control erosion along the invert of large drainage channels;
- provide a hydraulic regime that allows the flushing of regular sediment;
- flows towards specified instream sediment traps; and
- provide necessary ecological features (e.g. habitat and passage) within channel habitats.

A grassed channel or floodway must be provided with a low flow system to facilitate drainage, pest control, and maintenance. Urban engineered channels normally have a continuous dry-weather base flow mainly due to runoff from domestic water usage. Continuous flow over the grass lining in the waterway invert will destroy the grass stand and promote weed growth. The invert may also become eroded and form pools of water, which may cause soggy ground conditions, a breeding ground for mosquitoes.

(a) Design Capacity

Low flow inverts shall be sized for a minimum capacity of the 3-month ARI flow.

(b) Invert

Careful consideration shall be given to minimising the possibility of scour at the interface between the invert edge and the grassed surface of the channel. It may be necessary to provide a transition zone using a stabilisation system such as reinforced grass.

16.6 LINED AND COMPOSITE CHANNEL

16.6.1 General

Engineered channel lined with concrete, stone pitching, and rock mattresses are typical of the type of channel included in this category. Lined channels of this type should only be used for upgrading works in existing areas where:

- the flow velocity would cause scour in a grassed channel;
- the drainage reserve width is restricted;
- continual maintenance of the channel is a problem; and
- other factors dictate that a grassed channel is not practicable.

16.6.2 Geometry

The slope of the composite channel sides shall be no steeper than 1.5(H):1(V) unless designed to act as a structurally reinforced wall to withstand soil and groundwater forces.

The inverts of lined channels should have a nominal invert 'vee' of at least 10(H):1(V) or a precast 'pudu-cut' section, such that low flows remain concentrated along a single location within the channel invert (Figure 16.3). The low flow invert may be either centrally located or offset to one side of the channel. Channels lined with rock mattresses should be provided with a cast-in-situ or precast concrete low flow drain located within the channel invert. The requirements for this low flow drain are the same as those for grassed channels.

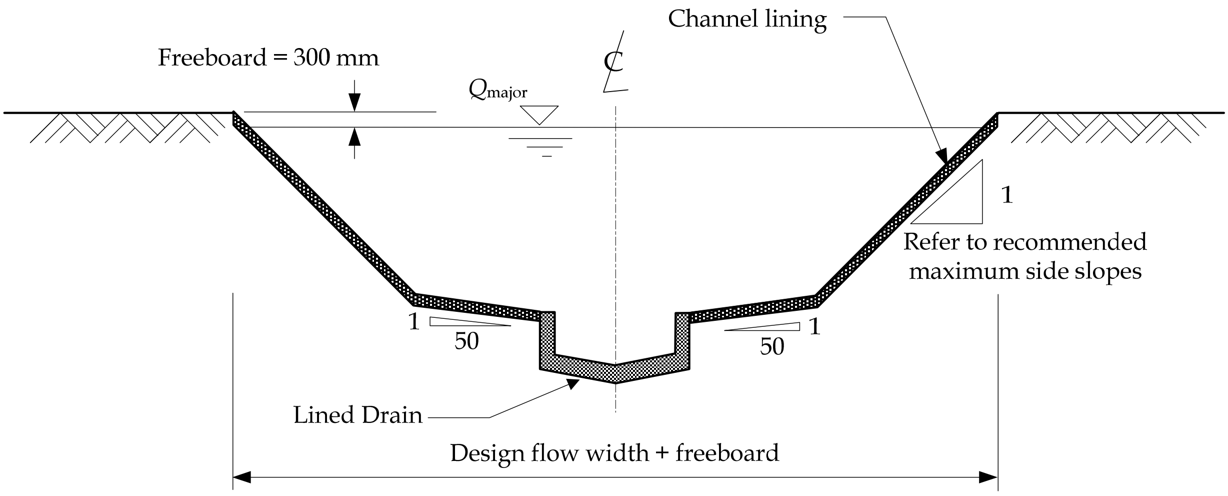

Figure 16.3: Typical Composite Channel

16.6.3 Superelevation

When flow moves around a channel bend, a rise in the water surface elevation occurs along the outer radius of the bend, whilst a corresponding lowering in the water surface elevation occurs along the inner radius of the bend. This difference in water levels is known as the superelevation, and in some cases may be an important factor in channel design (NRW, 2007).

Superelevation of the water surface must be determined at horizontal curves and the design of the channel cross-section adjusted accordingly. An approximation of the superelevation can be obtained from the following equation:

$$h = \frac{V^2 W_T}{g r_c} \tag{16.2}$$

where,

h = required superelevation (m);
V = velocity (m/s);
r_c = centreline radius of curvature (m);
WT = top width of channel (m); and
g = acceleration due to gravity (9.81 m/s^2).

16.7 EROSION AND SCOUR PROTECTION

16.7.1 General

The design average flow velocity limits specified in Section 16.3.5.2 have been selected to prevent erosion and scour of channel surfaces under normal conditions. However, engineered channels may be subject to intense local erosion or scour at obstructions (e.g. bridge piers, pipe headwalls), sudden changes in engineered channel cross-sections, drops, regions of changes in engineered channel bed materials, and other similar conditions (ACT Government, 1992). The following factors should be considered wherever significant changes in flow regime occur and appropriate measures provided to protect the engineered channel surface from local scour.

The main factors that provide favourable conditions for erosion and scour in a engineered channel are high flow velocities, particularly at shallow depths, and soft and/or fine bed materials. Velocities are higher in steep waterways, at changes in engineered channel configuration, in smooth waterways, and at higher discharges. Soil type largely determines the erosion potential of bed materials.

Local scour occurs in non-uniform flow regions where pressure forces, lift forces, and shear forces fluctuate. For example, local scour around bridge piers is caused by the vortex resulting from water piling up on the upstream edge and subsequent acceleration of flow around the nose of the pier. Local scour is a function of a combination of several of the following factors:

- slope of the engineered channel;
- characteristics of the bed materials;
- characteristics of the flood hydrograph;
- direction of the flow in relation to its depth;
- direction of the flow in relation to its structures; and
- characteristics of the transported materials.

The following locations are the most common areas where localised erosion can occur and will require careful consideration of the need for erosion protection measures (ACT Government, 1992):

- Transitions: Any changes in cross-section or changes in engineered channel lining material. Particular attention should be paid to the region immediately alongside low flow inverts;
- Bends: The outside bank of bends will be subject to higher flow velocities;
- Drain tributaries: Engineered channels usually have many small capacity tributary drain and pipe connections. Flows from these tributary connections will normally be of relatively high velocity and the angle of entry will cause turbulence in the engineered channel;
- Engineered channel tributaries: Other engineered channels entering the main channel system may cause turbulence and erosion of the engineered channel bottom and opposing bank;
- Energy dissipater structures: Changes in the flow regime will usually occur immediately upstream and downstream of drop structures and energy dissipation basins;
- Culverts: Exit velocities from culvert crossings will normally be supercritical;

- Bridges: Flow velocities around bridge piers and abutments may be higher than the engineered channel limit; and
- Localised scour or general degradation can quickly lower the bottom of a channel. Erosion protection facilities must have deep toe protection or they can fail by being undermined.

16.7.2 The Froude Number

The Froude Number (Fr) characterises the conditions in flowing water in terms of its velocity and depth. An understanding of critical flow conditions and the appreciation of Froude Numbers can assist in the design of channels to prevent erosive damage to the channel does not occur. The Froude Number provides a means for determining whether a given flow is subcritical, critical or supercritical.

In natural and grassed channels, channels become unstable when a Froude Number of 1.0 is approached. Flows at Froude numbers between 0.8 and 1.2 are unstable and unpredictable and should be avoided (UDFCD, 2008). For safe design of vegetated channels, the Froude Number of the design flow should be less than 0.8 (subcritical flow) depending on the degree of erosion resistance provided by the vegetation. Where values exceed unity it would be necessary to ensure that the channel lining had a very high degree of erosion resistance (refer to Chapter 20).

16.7.3 Protection Measures

Engineered channel protection must be provided to suit the local physical and scour characteristics. Erosion protection is required for waterway linings in reaches where the maximum permissible flow velocities or critical tractive forces are exceeded under the design storm flow conditions.

Waterway vegetation is perhaps the simplest erosion and scour control measure. However, where the flow velocities will exceed the velocities at which the vegetation is effective, other erosion protection measures will need to be considered (see Chapters 17 and 20).

16.8 DESIGN PROCEDURE

After an engineered channel type has been selected, the general procedure outlined in Figure 16.4 may be used for locating and sizing the engineered channel.

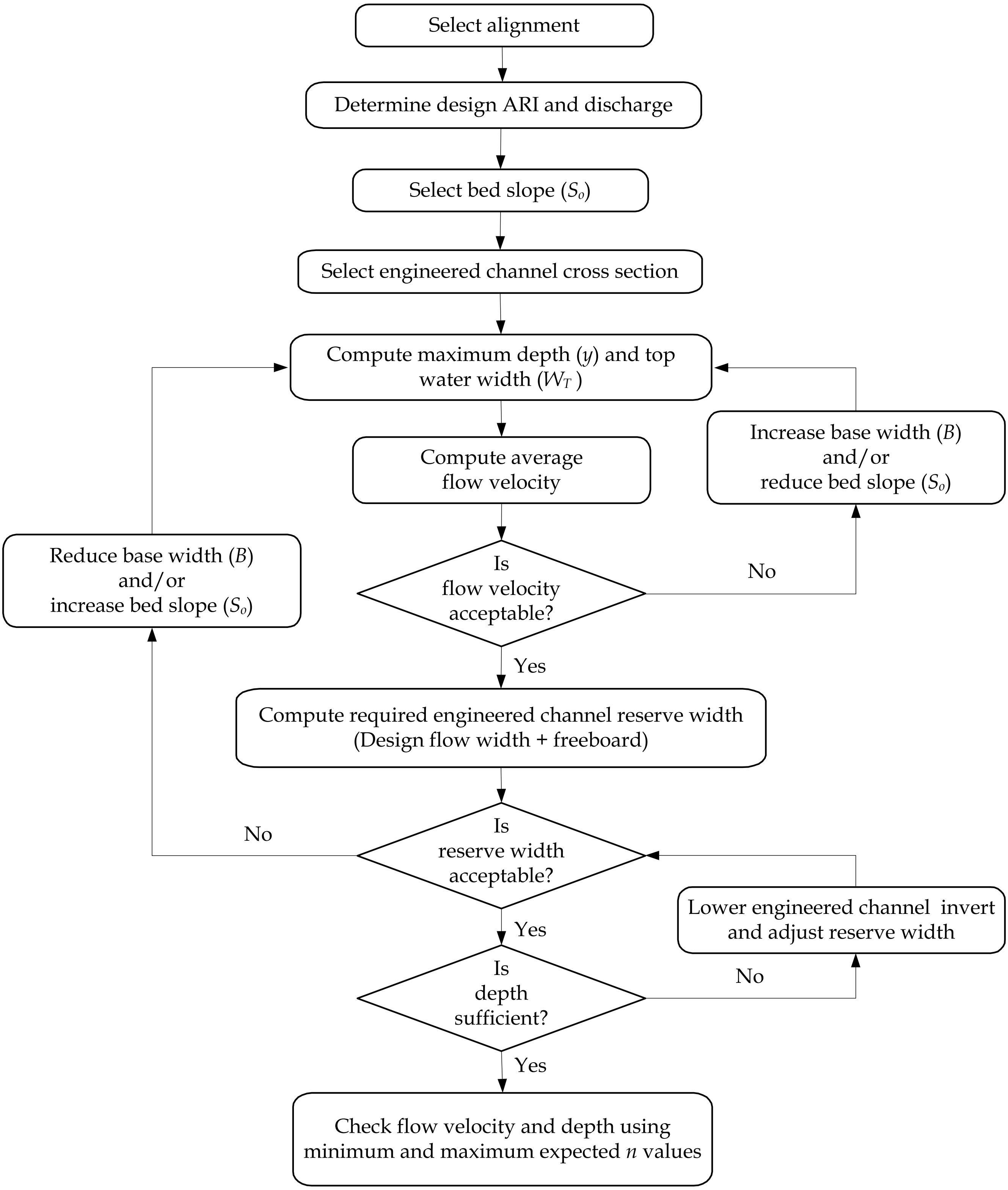

Figure 16.4: General Design Procedure for Engineered Channels

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APPENDIX 16.A EXAMPLE – GRASSED CHANNEL

Problem:

Determine the size of a grassed channel at the downstream end of a proposed 150 hectare residential area (link and terrace house) in Ipoh, Perak based on the following assumptions:

- the engineered channel is to be designed to carry the 100-year ARI flow with no freeboard;
- the post-development time of concentration t_c is estimated to be 100 minutes; and
- the engineered channel will be well maintained with an estimated design Manning's roughness coefficient of 0.035.

Solution:

Reference	Calculation	Output
	Determine design flows for the engineered channel:	
Equation 2.2	$i = \frac{\lambda T^{\kappa}}{(d+\theta)^{\eta}}$	
	where:	
	i = the average rainfall intensity (mm/hr) for selected ARI (T) and storm duration (d);	
Table 1.1	T = average recurrence interval, ARI (years);	= 100-year ARI
	d = storm duration (hours); $0.20 \le d \le 72$; and	= 100 minutes
	λ, κ, θ and η = fitting constants dependent on the raingauge location	

Appendix 2.B Table 2.B2

Location & Station ID	ARI, T (years)	Storm duration d	Derived Parameters λ	κ	θ	η
Politeknik Ungku Omar (4409091)	100	100	70.238	0.164	0.288	0.872

$$i = \frac{\lambda T^{\kappa}}{(d+\theta)^{\eta}} = \frac{70.238(100)^{0.164}}{\left(\left(\frac{100}{60}\right)+0.288\right)^{0.872}}$$ = 83.32 mm/h

Equation 2.3

$$Q = \frac{C.I.A}{360}$$

Reference	Calculation	Output
	where: Q = peak flow (m^3/s)	
Table 2.6	C = dimensionless runoff coefficient	= 0.90
	I = average rainfall intensity over time of concentration, t_c (mm/hr); and	= 83.32 mm/h
	A = drainage area (ha)	= 150 ha

$$Q_{100} = \frac{0.90 \times 83.32 \times 150}{360}$$ = 31.25 m^3/s

Appendix 2.B Table 2.B2

Location & Station ID	ARI, T (years)	Storm duration d	Derived Parameters λ	κ	θ	η
Politeknik Ungku Omar (4409091)	0.25	100	62.9315	0.3439	0.1703	0.8229

Reference	Calculation	Output

$$i = \frac{\lambda T^{\kappa}}{(d+\theta)^{\eta}} = \frac{62.9315(100)^{0.3439}}{\left(\left(\frac{100}{60}\right)+0.1703\right)^{0.8229}}$$ = 23.69 mm/h

Hence, the design flows are:

$$Q_{low\ flow} = \frac{0.90 x 23.69 x 150}{360}$$ = 8.88 m^3/s

Select grassed channel cross section:

Table 16.6

The low flow invert cross section = Trapezoidal

Manning's roughness coefficient, *n* = 0.035

Calculate size of low flow invert:

Assuming:

- Channel longitudinal slope = 0.8% (1 in 125)
- Width, B = 2.20 m
- Side slope, Z = 3

Depth, *y*	Bottom width, *BW*	Side slope, *Z*	Top Width, *TW*	Area, *A*	Wet. perimeter, *P*	Hydraulic radius, *R*	Velocity, *v*	Discharge, *Q*
(m)	(m)	(m)	(m)	(m^2)	(m)	(m)	(m/s)	(m^3/s)
0.80	2.5	3	7.30	3.92	7.56	0.52	1.65	6.466
0.85	2.5	3	7.60	4.29	7.88	0.55	1.70	7.319
0.90	2.5	3	7.90	4.68	8.19	0.57	1.76	8.234
0.95	**2.5**	**3**	**8.20**	**5.08**	**8.51**	**0.60**	**1.81**	**9.212**

$>Q_{low\ flow}$ (=9.05 m^3/s)

$Q = v \, x \, A$

where : $v = \frac{1}{n} S_o^{1/2} R^{2/3}$;

$$A = (B + Zy)y = 2.50y + 3y^2$$

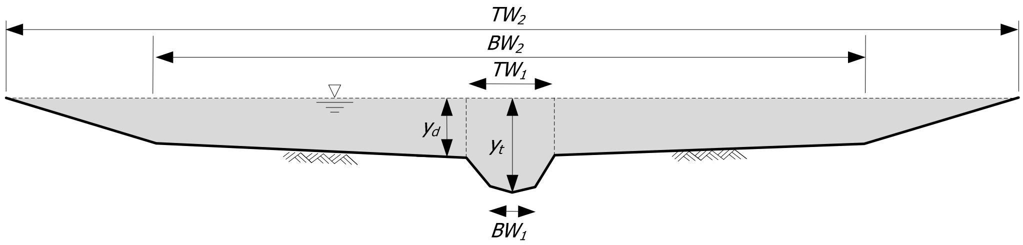
$$P = B + 2y\sqrt{1+Z^2} = 2.50 + 2y\sqrt{10}$$

Provided dimension of low flow invert:

- Bottom width, *BW* = 2.50 m
- Depth, *y* = 0.95 m
- Top width, *TW* = 8.20m
- Velocity, *v* = 1.81 m/s
- Discharge, *Q* = 9.212 m^3/s

Check flow velocity for lined drain. (0.6<v<2 m/s); ...OK

Reference	Calculation	Output



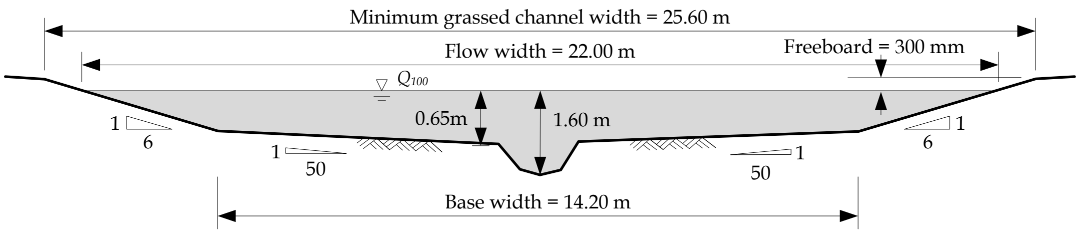
Flow Segments

Reference	Calculation		Output
	Calculate size of grassed channel section:		
Table 16.6	Manning's roughness coefficient, n	=	0.035

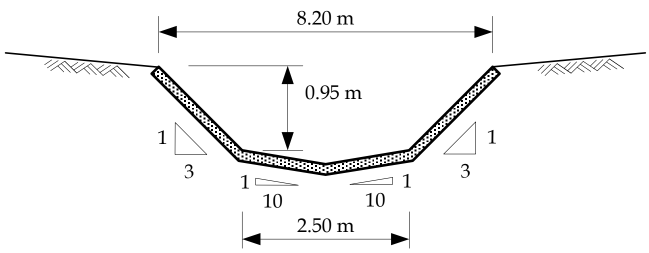
y_t (m)	y_t-y_d (m)	TW_1 (m)	BW_2 (m)	Side slope, Z	y_d (m)	TW_2 (m)	A (m²)	P (m)	R (m)	v (m/s)	Q (m³/s)
1.40	0.95	8.20	14.20	6	0.45	19.60	12.69	19.98	0.63	1.89	23.95
1.50	0.95	8.20	14.20	6	0.55	20.80	14.71	21.20	0.69	2.00	29.46
1.60	**0.95**	**8.20**	**14.20**	**6**	**0.65**	**22.00**	**16.85**	**22.42**	**0.75**	**2.11**	**35.59**
1.90	0.95	8.20	14.20	6	0.95	25.60	23.99	26.07	0.92	2.42	57.99

Output: $>Q_{100}$ (= 31.25 m³/s); …OK

Reference	Calculation		Output
Section 16.3.2	Allowing a minimum freeboard	=	300 mm
	Provided dimension of grassed channel:		
	Top width, TW_2	=	25.60
	Depth, y_t	=	1.90
	Discharge, Q	=	57.99 m³/s
Section 16.8.2	Check Froude Number for grassed channel:		
	$Fr = \sqrt{\frac{Q^2 B}{g A^3}} = \sqrt{\frac{35.59^2 (22.00)}{9.81 (16.85)^3}}$	=	0.77 (< 0.8; …OK) (Subcritical Flow)



(a) Grassed Channel



(b) Low Flow Invert

Grassed Channel and Low Flow Invert Dimensions

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