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Irrigation and Drainage Engineering

Chapter Seven
Irrigation Canals

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Irrigation Canals

قنوات الري

A Canal is an irrigation struture constructed on or in the graund to convey (transport) the water from the source such as (river, lake, reservoir, ...etc.)

القناة الاروائية : هي أحد منشآت الري تنشأ على أو في الأرض لنقل الماء من المصدر (نهر، خزان ... إلخ) الى المزارع .

Classification of Canals تصنيف القنوات الري

1. According to shape
   - Trapezoidal Canal
   - Rectangular Canal
   - Traingular Canal
   - Prabolic Canal
   - circular (Closed conduit).
   - Semi-circular.
2. According to Construction
   - Unlined Canal قناة طبيعية (غير مبطنة)
   - Lined Canal قناة مبطنة .
3. According to discharge capacity
   - Main Canal (Mc) قناة رئيسية
   - Branch Canal (Bc) قناة فرعية $Q: 1.5 - 5 \ m^3/sec$
   - Distributary Canal (Dc) قناة موزعة / ثانوية $Q: 0.11 - 1.5 \ m^3/sec$
   - water Course (Wc) قناة المسقى الحقلية
   - Farm or field channel - (FC) الساقية الحقلية

Fig(1)

Irrigation & Drainage system نظام الري والبزل

The main function of irr. & Drain. system is to supply the water for all units of the project, and to drain all surface and subsurface water in a way that ensures not get phenomenon of salinization.

الهدف الرئيسي من شبكة الري والبزل هو تجهيز كمية وافية من المياه لإرواء كافة وحدات المشروع وتصريف المياه الزائدة السطحية وتحت السطحية بما يضمن عدم حدوث ظاهرة التملح. نظام الري المفضل في العراق هو الري السطحي.

شبكة الري — **Irrigation system**

↓

المصدر المائي — **Water Source**

↓

القناة الرئيسية (تزود المشروع بالماء) — **Main Canal MC**

↓

القناة الفرعية — **Lateral Canal LC** — Branch canal, primary canal

↓

القناة الموزعة (الثانوية) — **Distributary Canal DC** — secondary Canal

↓

القناة المغذية للوحدة المزروعة — **Water Course WC** — Tertiary

↓

السواقي الحقلية {تسقي وحدات تصل مساحتها 5-7.5 ha.} — **Farm ditch.** — field canal

(Irrigation system Layout)
مخطط شبكة الري

Outfall Drain → Drainage system

المصب العام (أكبر مبزل خارج المشروع وربما يخدم أكثر من مشروع)

↓

يصرف المياه لكامل المشروع	Main Drain MD	مبزل المشروع الرئيسي
يصرف مياه البزل لجزء من المشروع	Lateral drain LD	مبزل فرعي (مفتوح)
Secondary Drain يصرف مياه البزل لجزء من المشروع	Main Collector Drain MCD	مبزل مجمع رئيسي (مفتوح)
يجمع عند حافة المزرعة	Collector Drain CD	مبزل مجمع (مفتوح)
أنابيب لتجميع المياه المبزولة من رقعة المزرعة.	Field drain FD	

Fig(1): (Drainage system layout) مخطط شبكة البزل

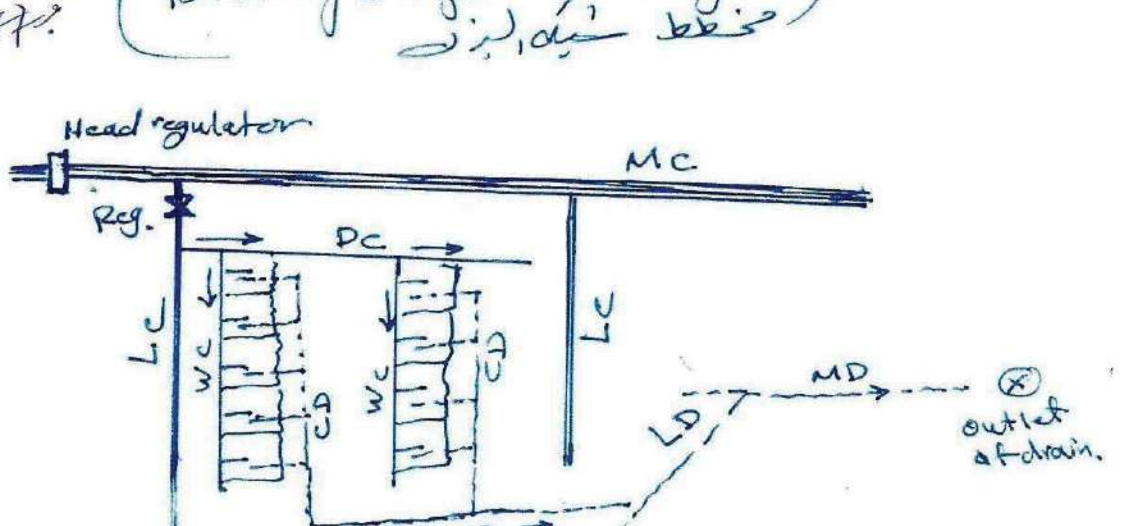
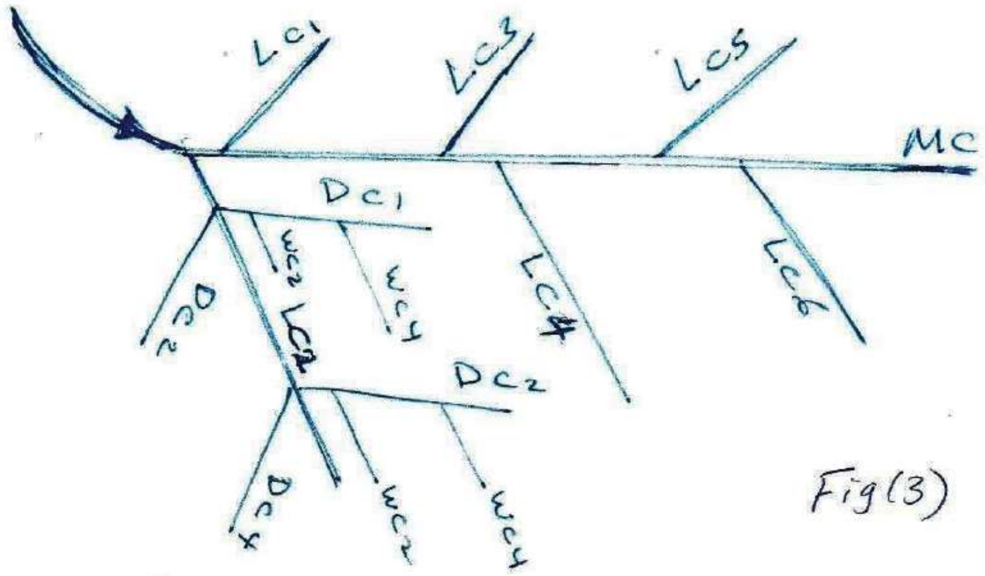


Fig.(2)

Canals and Drains Designation : تسمية القنوات والمبازل

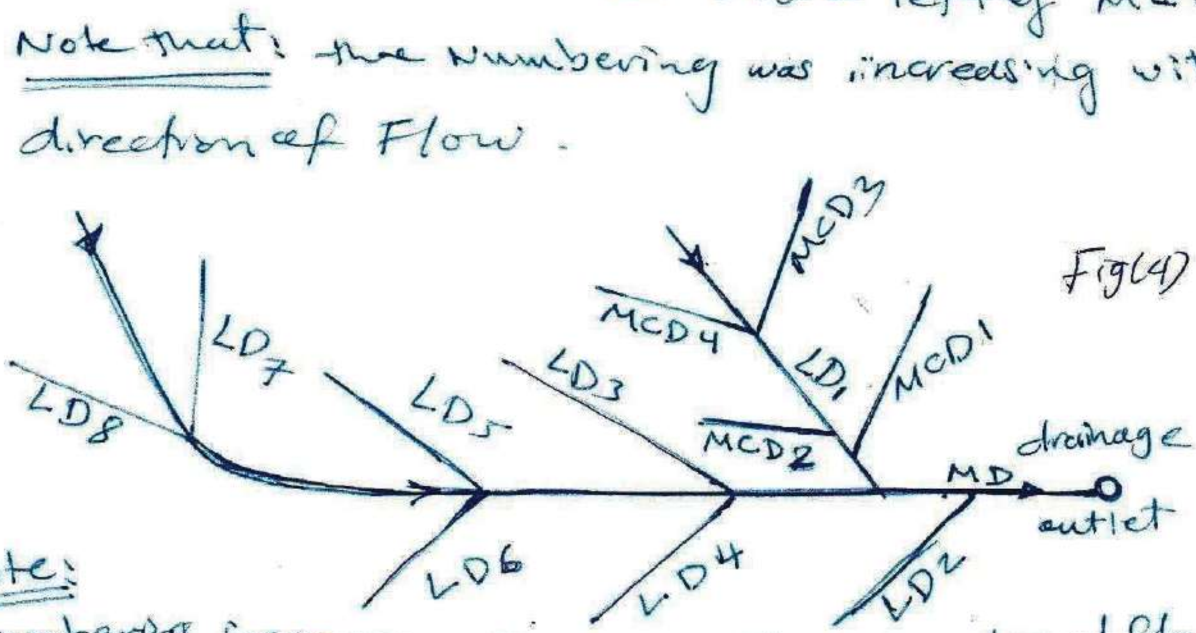
① use even No. for canals at right.
② Use odd No. for canals at left.



Fig(3)

WC2/DC1/LC5/MC ; is the first water course on the right of DC1, which is the first distributary on the left of LC5, which is the third Lateral canal on the left of MC.

Note that: the Numbering was increasing with direction of Flow.

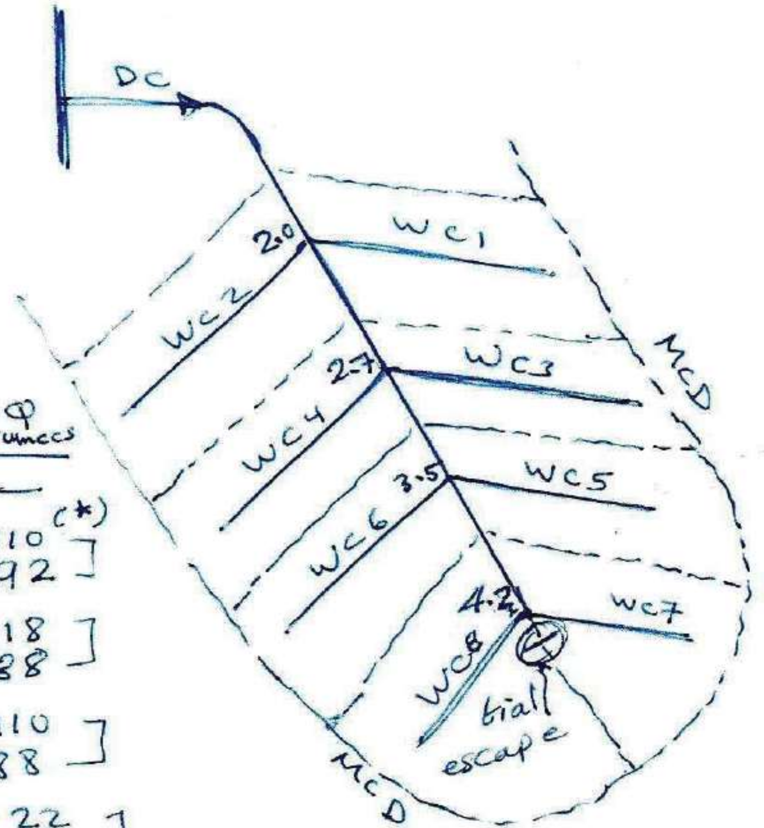


Fig(4)

Note:
Numbering increases with opposite direction of flow

Calculation sample:

Given a water duty of 3500 Donums/cumecs at the farm gate. Seepage losses in the water courses = 3 % of the discharge at inlet, and the seepage losses in the distributary = 2 lps/km



Fig(5)

Km	WC	G. Area (Donum)	Q cumecs
0	—	—	—
2	WC1	375	110 (*)
	WC2	313	92
2.7	WC3	400	118
	WC4	300	88
3.5	WC5	375	110
	WC6	300	88
4.2	WC7	413	122
	WC8	350	103
		Σ=2826	

(*) How to find Q lps

$$Q = \frac{A}{WD_u}$$

$$Q_{farm} = \frac{375}{3500} \times 1000 = 107$$

$Q_{wc} = Q_{farm} + \text{losses}$

$Q_{wc} = Q_{farm} + \frac{3}{100} Q_{wc}$

$$Q_{wc} = \frac{Q_{farm}}{0.97} = \frac{107}{0.97} = 110 \text{ lps}$$

$$q_1 = 103 + 122 + \frac{2\,lps}{km} \cdot 0.7\,km$$
$$= 226 \text{ lps}$$

$$q_2 = 226 + 110 + 88 + 0.8(2)$$
$$= 427 \text{ lps}$$

$$q_3 = 427 + 118 + 88 + 0.7(2)$$
$$= 634 \text{ lps}$$

$$q_4 = 634 + 110 + 92 + 2(2) = 840 \text{ lps}$$

WDu at distributary inlet is 2826 / 0.84 = 3364

Design of irrigation Canals

After knowing the discharge from W.Du, in which $W.Du = \frac{8.6 \times B\,(days)}{\Delta(cm)}$ (hec/cumecs)

See equation (6.16)

and consequently $Q = \frac{Area}{W.Du}$, hence, one can design the canal depend upon the type of it, i.e., whether the canal is alluvial, nonalluvial, rigid boundary.

- Determination of discharge requirements

example: Calculate the discharge for a canal from the following data:

اكثافة الري Intensity of irrigation $I = 60\%$

Gross commanded area (G.C.A) = 40 000 hec.
Culturable commanded area (C.C.A) = 80%
Present crop distribution pattern is as follow:

	Crop	%	Total
Kharif	Rice	20%	%40
	Maize	15%	
	other crops	5%	
	Sugar cane	15%	%15
Rabi	Wheat	30%	%45
	Barley	5%	
	other crops	10%	

Rainfall is 103 mm. Soil is good dumat (mud). Base period for wheat is 4 weeks and depth is 13.5 cm. Base period "kor" for rice is 2.5 weeks and depth is 19 cm.

Sol: Rice $\frac{15\%}{20\%}$ + wheat $\frac{30\%}{30\%}$ + sugar cane $\frac{15\%}{15\%}$ = 60% = I o.k.

discharge will depend on rice & wheat requirement while sugar cane will be irrigated when no water required for Rabi & Kharif.

Area under Wheat $= 40000 \times 0.8 \times 30\%$
$= 9600$ hec.

Area under rice $= 40000 \times 0.8 \times 15\%$
$= 4800$ hec

W.Du for Wheat $= \dfrac{8.64 \times B}{\Delta} = \dfrac{8.64 \times (4 \times 7)}{0.135} = 1800 \ \dfrac{\text{hec}}{\text{cumecs}}$

Discharge for Wheat $= \dfrac{A}{W.Du} = \dfrac{9600}{1800} = 5.34$ cumecs

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W.Du for rice $= \dfrac{8.64 \times (2.5 \times 7)}{0.19} = 795$ hec/cumecs

Discharge requirement for rice $= \dfrac{A}{W.Du} = \dfrac{4800}{795} = 6.05$ cumecs

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So the canal was designed for discharge of $6.05 \ m^3/s$.

Desingn parameter of a canal معالم التصميم للقناة

It included the determination of the following parameters:

1- Cross sectional area مساحة مقطع الجريان
2- depth of flow عمق الجريان
3- Bed width عرض القناة
4. Side slope & longitudinal slope ميل الجوانب والميل الطولي للقناة

Design factors: عوامل التصميم

1- Irrigated area (cultivated). الأرض المزروعة
2- Water requirements of crops. الاحتياجات المائية للمحصول
3- Existance of silt. وجود الغرين
4. Canal material type (rigid, Movable). نوع مادة القعر في القناة.

Canal Elements عناصر القناة

Consider the trapezoidal section of the canal since it is the general case for triangular, rectangular or even square section.

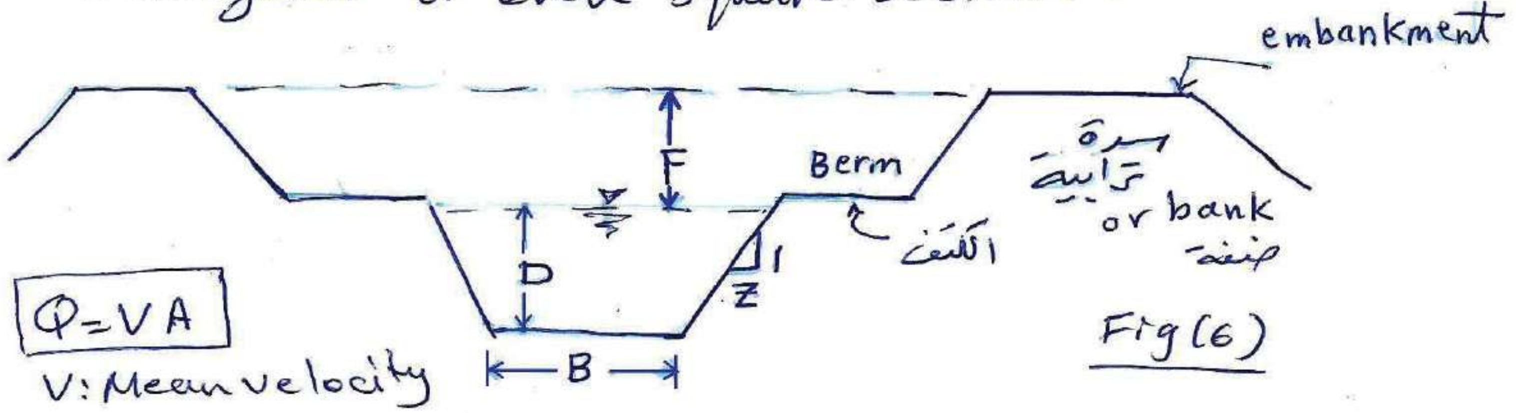


Fig (6)

$\boxed{Q = VA}$

V: Mean velocity

A: Area of Canal section. مساحة القطاع

$A = BD + ZD^2$

P: Wetted perimeter المحيط المبلل

$P = B + 2D\sqrt{1+Z^2}$

Z: is side slope 1 V : Z H ميل الجوانب

$R = \frac{A}{P}$; hydraulic radius نصف القطر الهيدروليكي

S: longitudinal slope الانحدار الطولي للقناة

F: Free board فضلة العمق
(حماية القناة من الفيضان)

For earth canals:

$F_{meter} = 0.25 + 0.15 D_{meter}$

For lined canal

$F_m = \sqrt{C D_m}$; $C = 0.45 + \frac{Q_{m^3/s}}{275}$

For small canal $\left(\frac{B}{D}\right)$ can be selected as Ce (optimum ratio).
For large canal (B/D) increases with discharge increasing.

$Ce = 2\tan\theta = 2\left[\sqrt{1+Z^2} - Z\right]$

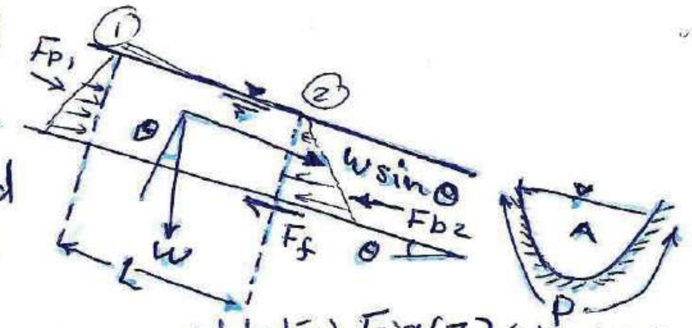
Ce derivation will shown later in page 25.

Flow Resistance Equations معادلات مقاومة الجريان

There are many equations dealed with flow in canals and rivers. Two of well-known equations are discussed below:

1. Chézy equation: (1775)

From boundary Layer theory, the Shear force F_τ, Drag force F_D, and Lift force F_L can be expressed as



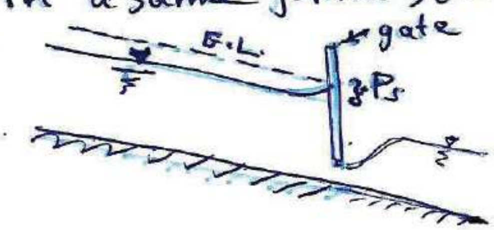
(مقطع طولي) Fig(7) (مقطع عرضي)

$F = C_f A_P \frac{\rho V^2}{2} \Rightarrow \tau_o = \frac{F_f}{A}$

$\Rightarrow \tau_o = C_f \frac{\rho V^2}{2}$, actually $C_f = \frac{f}{4}$, where f: friction factor

also stagnation pressure can be written in a same form, i.e,

$P_s = \frac{\rho V^2}{2}$



Fig(8)

Thus;

$$\tau_o = C_f \frac{\rho V^2}{2} \quad \text{-------} \quad (7.1)$$

Apply Momentum equation

$$-F_f + \cancel{F_{b1}} - \cancel{F_{b2}} + W\sin\theta = \rho Q(\cancel{V_2 - V_1})^{=0}$$

$F_f = W\sin\theta$; $\sin\theta \approx \tan\theta = S$

but $W = \gamma \forall = \gamma A L$; for small angle θ

$F_f = \tau_o (P \times L)$ قوى القص = اجهاد القص × مساحة التماس

$$\Rightarrow \tau_o = \frac{\gamma A L S}{P L} = \gamma R S$$

$$\boxed{\tau_o = \gamma R S} \quad \text{———} \quad (7.2)$$

$\sqrt{\frac{\tau_o}{\rho}} = V_*$ called shear velocity (why?)

From equation (7-2):

$$V_* = \sqrt{gRS} \qquad (7.3)$$

Now, equating eqs. (7.1) & (7.2) yields

$$C_f \frac{\rho V^2}{2} = \gamma R S$$

$$V^2 = \frac{2}{C_f} \frac{\gamma}{\rho} R S$$

$$\Rightarrow V = \sqrt{\frac{2}{C_f} g} \sqrt{RS} = \sqrt{\frac{8g}{f}} \sqrt{RS}$$

$\sqrt{\frac{8g}{f}}$ is called Chézy Coefficient and reffered as "C"

Hence,

$$V = C \sqrt{RS} \qquad (7.4)$$

The above equation is so-called Chézy equation.

Divide eq (7.3) by eq (7.2), yields;

$$\frac{V}{V_*} = \frac{C}{\sqrt{g}} = \sqrt{\frac{8}{f}} \qquad (7.5)$$

(2.) Manning equation

In 1889, Irish engineer Robert Manning presented a well-known formula which submitted to Inst. of civil Engineering in Irland, that is;

$$V = \frac{1}{n} R^{2/3} S^{1/2} \qquad (7.6)$$

S: longitudinal slope.
n: Manning Coefficient.
R: hydraulic radius.
V: mean velocity.

Equating (7.4) & (7.6) yield

$$C = \frac{R^{1/6}}{n} \qquad (7.7)$$

Design Procedure:

غير قابلة للحت أو التعرية

1. For Non-alluvial canal (non erodible canal)

It has stable section (does not change with time)

To design this type of canal by using Manning equation, the following parameters were difined:

$n = 0.02 - 0.025$, the following values of n for different cases are listed below. n for lined canal is of 0.015 as an average value.

Table -1-

Sl. No.	Surface Characteristics	Range of n
(a)	Lined channels with straight aligment	
1	Concerete (a) formed, no finish	0.013–0.017
	(b) Trowel finish	0.011–0.015
	(c) Float finish	0.013–0.015
	(d) Gunite, good section	0.016–0.019
	(e) Gunite, wavy section	0.018–0.022
2	Concrete bottom, float finish, sides as indicated	
	(a) Dressed stone in mortar	0.015–0.017
	(b) Random stone in mortar	0.017–0.020
	(c) Cement rubble masonry	0.020–0.025
	(d) Cement-rubble masonry, plastered	0.016–0.020
	(e) Dry rubble (rip-rap)	0.020–0.030
3	Tile	0.016–0.018
4	Brick	0.014–0.017
5	Sewers (concrete, A.C., vitrified-clay pipes)	0.012–0.015
6	Asphalt (i) Smooth	0.013
	(ii) Rough	0.016
7	Concrete lined, excavated rock	
	(i) good section	0.017–0.020
	(ii) irregular section	0.022–0.027
8	Laboratory flumes-smooth metal bed and glass or perspex sides	0.009–0.010
(b)	Unlined, non-erodible channels	
1	Earth, straight and uniform	
	(i) clean, recently completed	0.016–0.020
	(ii) clean, after weathering	0.018–0.025
	(iii) gravel, uniform section, clean	0.022–0.030
	(iv) with short grass, few weeds	0.022–0.033
2	Channels with weeds and brush, uncut	
	(i) dense weeds, high as flow depth	0.05–0.12
	(ii) clean bottom, brush on sides	0.04–0.08
	(iii) dense weeds or aquatic plants in deep channels	0.03–0.035
	(iv) grass, some weeds	0.025–0.033
3	Rock	0.025–0.045
(c)	Natural channels	
1	Smooth natural earth channel, free from growth, little curvature	0.020
2	Earth channels, considerably covered with small growth	0.035
3	Mountain streams in clean loose cobbles, rivers with variable section with some vegetation on the banks	0.04–0.05
4	Rivers with fairly straight aligment, obstructed by small trees, very little under brush	0.06–0.075
5	Rivers with irregular aligment and cross-section, covered with growth of virgin timber and occasional patches of bushes and small trees	0.125

The side slope Z is depended on whether the bed material is alluvial or not. The suggested side slopes reported by Fortier and Scobey in 1926 as follow:

Materal	Z: side slope
Rock	nearly vertical
stiff clay	$Z = \frac{1}{2}$ to 1
firm soil	$Z = 1.0$
loose sandy soil	$Z = 2$
Sandy loam	$Z = 3$

Some times Z is slected according to Q

if $Q > 1\ m^3/sec$ $Z = 1.5$

if $Q < 1\ m^3/sec$ $Z = 2$

and for lined canal

$Z = 1.0$ for small canal (water course)

$Z = 1.5$ for large canal

The design depend on flow resistance equation, such as Manning equation with additional condition imposed by velocity, which is called permissible velocity.
It is nonsilting nonscouring velocity, US Army Corps of Engineers recommended a values for these velocities as follow

Table -2- Recommended Permissible Velocities*

Material	V (m/s)
Fine sand	0.6
Coarse sand	1.2
Earth	
Sandy silt	0.6
Silt clay	1.1
Clay	1.8
Grass-lined earth (slopes < 5 per cent)	
Bermuda grass	
Sandy silt	1.8
Silt clay	2.4
Kentucky Blue grass	
Sandy silt	1.5
Silt clay	2.1
Poor rock (usually sedimentary)	
Soft snadstone	2.4
Soft shale	1.1
Good rock (usually igneous or hard metamorphic)	6.1

* After U.S. Army Corps of Engineers [1970]

Design Method (1) (Permissible velocity method)

given Q, S, Z, n find B, D

1- set premissible velocity according to above table

2. $A = \frac{Q}{V}$

3. $V = \frac{1}{n} R^{2/3} S^{1/2}$

4. find R ; $R = \left(\frac{nV}{\sqrt{S}}\right)^{1.5}$

5. find $P = \frac{A}{R}$

6. from A & P find B & D

where:

$A = BD + ZD^2$

$P = B + 2D\sqrt{1+Z^2}$

Two unknows with two equations solve for B & D

Design method (2) (Tractive force method)

Canals of erodible material can be designed to prevent the expected scouring induced by clear water. The method is based on the concept of tractive foorce (قوة جر او السحب)

The scour in a canal occurs when tractive force exerted by flow is adequate to cause movement of bed particle having representative diameter d_s, some time is taken as d_{50}. This method was proposed by Lane and also known as the USBR method.

استدعى
Invoking eq (7.2):

$$T_o = \gamma R S \qquad (\gamma = \rho . g)$$

The shear stress is not uniformly distributed over the canal perimeter. It has some variation as shown in the below figures.

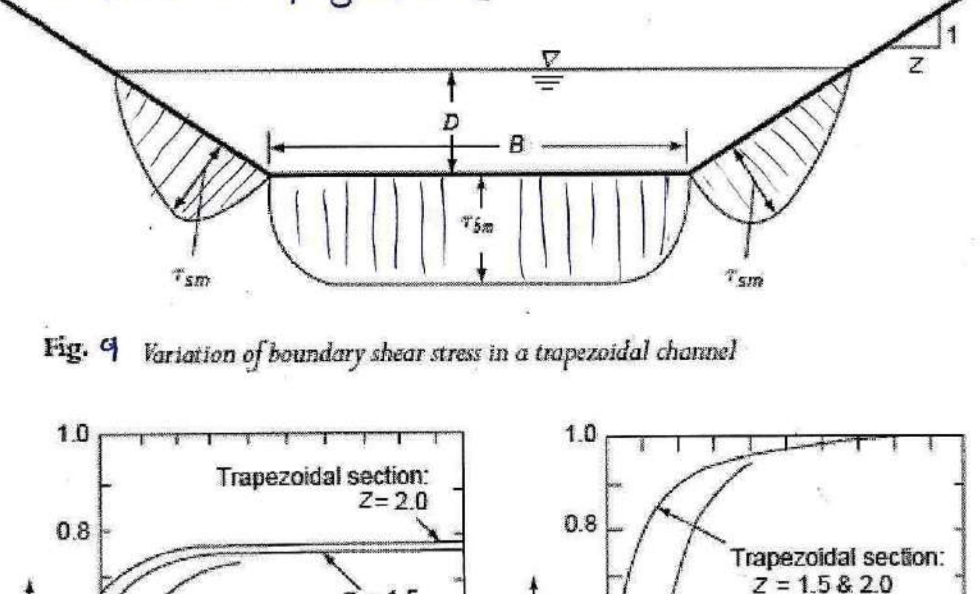


Fig. 9 *Variation of boundary shear stress in a trapezoidal channel*

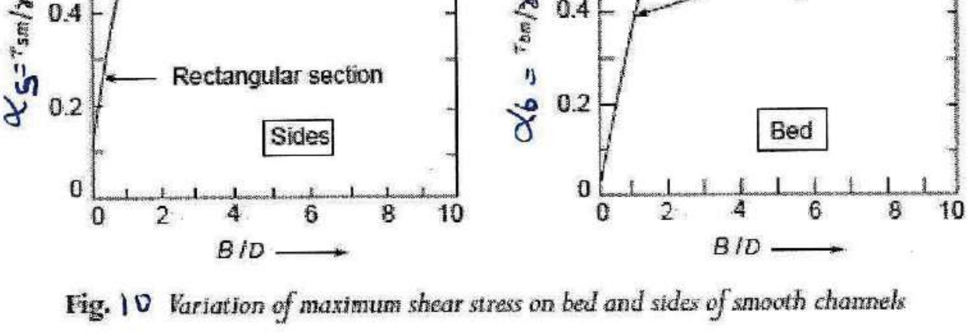


Fig. 10 *Variation of maximum shear stress on bed and sides of smooth channels*

τ_{bl} = Shear Stress at Level of bed.
τ_{sl} = shear stress at sideslope.
τ_{bm} = max. shear act on bed
τ_{sm} = max. shear act on sides

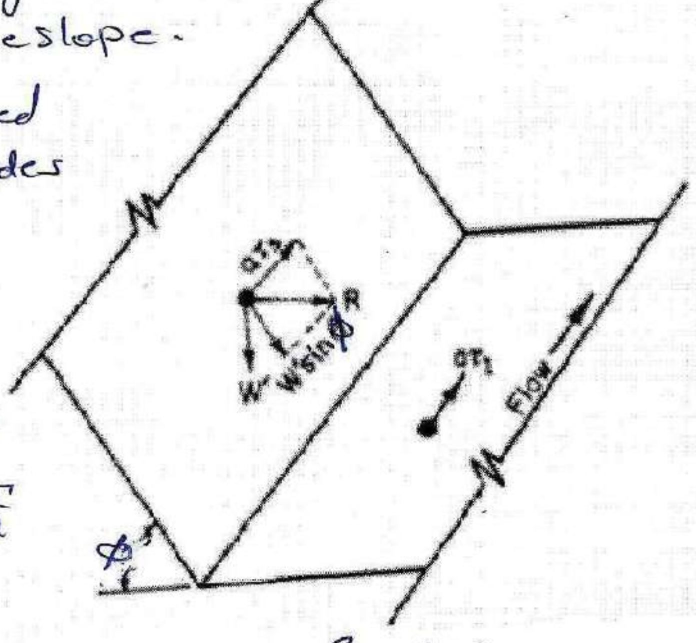
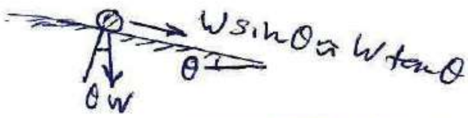


fig (11)

$a\tau_{bL} = W \tan\theta$



$$W\cos\phi\tan\theta = \sqrt{W^2\sin^2\phi + a^2\tau_{sl}^2}$$

$$\tau_{sl} = \frac{w_s}{a}\cos\phi\tan\theta\sqrt{1-\frac{\tan^2\phi}{\tan\theta}}$$

$\because$ $\tau_{bl} = \frac{w_s}{a}\tan\theta$

$$K = \frac{\tau_{sl}}{\tau_L} = \cos\phi\sqrt{1-\frac{\tan^2\phi}{\tan^2\theta}}$$

or $\boxed{K = \sqrt{1-\frac{\sin^2\phi}{\sin^2\theta}}}$ ———— (7.8)

or $\tau_{sl} = K\,\tau_{bl}$ ———— (7.9)

Conditions: $\tau_{bl} < \tau_c$

Say $\tau_{bl} = 0.9\,\tau_c$ ———— (7.10)

τ_c is critical shear stress.

The critical shear stress in straight canal differs slightly for other curved canal, as shown below

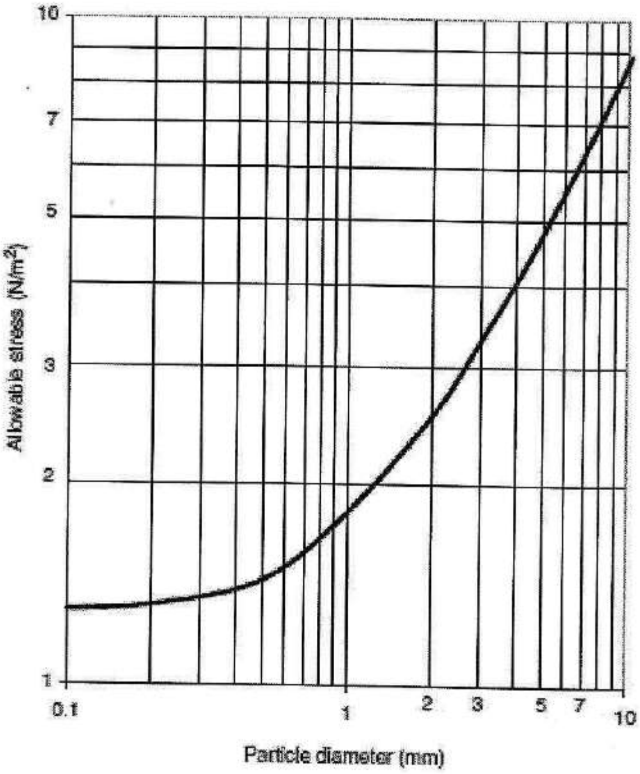
Type of canal	Critical shear stress
1. straight canal	τ_c (as it is.)
2. Slightly curved	$0.9\,\tau_c$
3. Moderately curved	$0.75\,\tau_c$
4. very curved canal	$0.6\,\tau_c$

Thus eq. (7.10) is modified to include the above factors. for example type(2) $\tau_{bl} < 0.9(0.9\tau_c) \Rightarrow \tau_{bl} < 0.81\tau_c$.

τ_c can be calculated from different approximated methods. τ_c is strongly related to particle size, d. as shown in fig (12).

But the more factual values of τ_c can be obtained from Shield's diagram show in Fig (13).

Although shields diagram is not straightforward to find τ_c, It is of an plicit slouti , Sometimes the complex procedure causes an alteration to an explicit form of Shields diagram, as show in figure (14).



Frg(12)Permissible unit tractive force for non-cohesive material

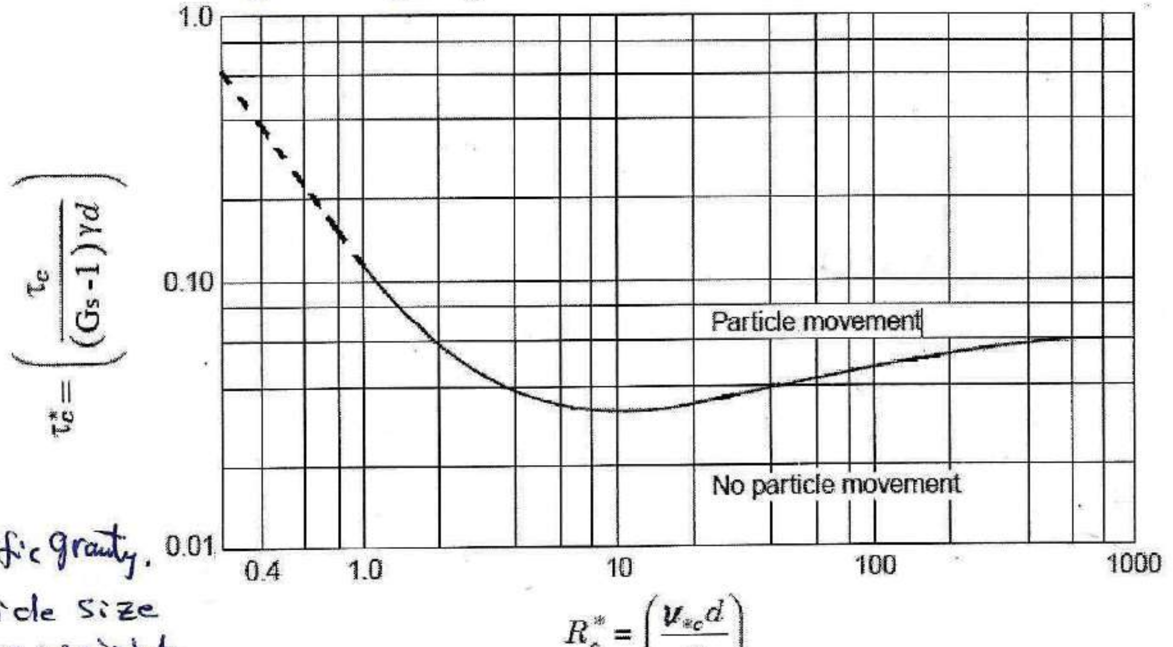


Fig (13). Shields curve for incipient motion

Gs : specific gravity.

d : particle size

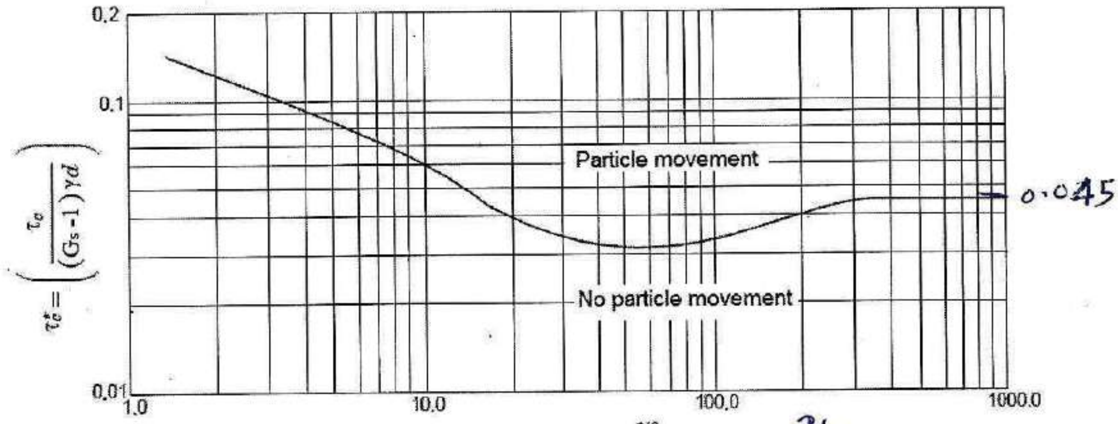
γ : water weight density, N/m^3

Note that $V_* = \sqrt{\frac{\tau_o}{\rho}} \Rightarrow V_{*c} = \sqrt{\frac{\tau_c}{\rho}}$

R_c^* : dimensionless boundary Reynolds Number, or Some times called (particle Reynolds No.)

Sheild's relation can be approximated as:

$$\tau_c^* = \frac{0.243}{d_*} + \frac{0.06\, d_*}{[3600 + d_*^2]^{1/2}} \quad \text{where } d_* = d\left[\frac{(G_s-1)g}{\nu^2}\right]^{1/3}$$



$$R_o^* = \left(\frac{(G_s-1)gd^3}{\nu^2}\right)^{1/2} = d_*^{3/2}$$

Fig (14) *Yalin and Karahan curve Adapted from Shields curve for incipient motion*

R_o^* : boundary Reynolds No.

how to find τ_c :

① $G_s = \frac{\gamma_s}{\gamma}$

② for given kinematic viscosity of water $\approx 1\times10^{-6}\ \frac{m^2}{s}$ and particle size d ($\approx d_{50}$), one can compute R_o^* (it do not include τ_c).

③ from fig (14) find dimensionless critical shear stress τ_c^*.

④ $\tau_c = \tau_c^* (G_s-1)\gamma d$

The design

① For given $d, \gamma_s, \gamma, \nu \Rightarrow$ find τ_c

② $\tau_{bl} = (1)(0.9)(\tau_c) = \tau_{bm}$; for straight canal $C = 1.0$

③ $\phi = \tan^{-1}\left(\frac{1}{z}\right)$

④ θ = coefficient of friction (angle of repose) زاوية الاحتكاك للمادة
من جداول أو مرتسمات .

⑤ Calculate $K = \sqrt{1 - \frac{\sin^2\phi}{\sin^2\theta}}$

⑥ $\tau_{sl} = K \cdot \tau_{bl} = \tau_{sm}$

repeat

⑦ assume $\left(\frac{B}{D}\right)$ ratio

⑧ From Fig (10) find $\left(\frac{\tau_{sm}}{\gamma D S}\right) \Rightarrow$ Find D

⑨ Find B

⑩ For given Q using Manning equation to check D&B.

Hint:

If Manning Roughness coefficient is not given, one can use Strickler formula:

From eq. (7.7)

$$C = \frac{R^{1/6}}{n}$$; subs. into equation (7.4) i.e, chezy eq.

$$V = \frac{1}{n} * \frac{1}{\sqrt{g}} * R^{1/6} \sqrt{gRs}$$

$$V = \frac{1}{n} \frac{1}{\sqrt{g}} R^{1/6} V_* \quad \text{(From definition followed in eq. (7.3))}$$

$$\Rightarrow \frac{V}{V_*} = \frac{R^{1/6}}{n\sqrt{g}}$$

From Keulegan logarithmic equation for rough canals:

$$\frac{V}{V_*} = 5.5 \log \frac{R}{ks} + 6.25 \qquad \text{— (a)}$$

equating both expression, yields:

$$\frac{R^{1/6}}{n\sqrt{g}} = 5.5 \log \frac{R}{ks} + 6.25 \qquad \text{— (b)}$$

The above expression can be approximated as:

$$\frac{R^{1/6}}{n\sqrt{g}} = 8.16 \left(\frac{R}{ks}\right)^{1/6} \text{— (c) for} \quad 5 < \frac{R}{ks} < 700$$

$\boxed{\text{for smooth boundary } \frac{R}{ks} < 1500}$.

equation (c) can be reduced to:

$$\frac{(ks)^{1/6}}{n\sqrt{g}} = 8.16 \qquad \text{— (d)}$$

$$\text{or} \quad n = \frac{ks^{1/6}}{8.16\sqrt{g}}$$

For metric units (SI unit) $g = 9.81$, and $ks = d$ mm

$$n = \frac{d_{mm}^{1/6}}{25.6} \qquad \text{———— (7.11)}$$

which called Strickler-Manning equation.

Example:

Design of non-erodible canal carried 15 m^3/sec when the permissible velocity is 0.8 m/s. The longitudinal slope is 1:4000 and side slope 1:1. Assuming $n = 0.025$.

Solution by method (1)

$$Q = VA \Rightarrow A = \frac{15}{0.8} = 18.75\ m^2$$

$$R = \left(\frac{nV}{\sqrt{S}}\right)^{1.5} = \left[\frac{0.025 * 0.8}{(1/4000)^{1/2}}\right]^{3/2} = 1.42\,m$$

$$P = \frac{A}{R} = \frac{18.75}{1.42} = 13.2\,m$$

Now

$$\left.\begin{aligned}(B + ZD)D &= A \\ B + 2D\sqrt{1+Z^2} &= P\end{aligned}\right\} Z = 1.0$$

or $(B + D)D = 18.75$ —— (1)

$B + 2.828\,D = 13.2$

or $B = 13.2 - 2.828\,D$ —— (2)

subs. (2) into (1) to get

$$13.2D - 2.828D^2 + D^2 = 18.75$$

$$\Rightarrow D^2 - 7.22D + 10.25 = 0$$

$$D = \frac{+7.22 \mp \sqrt{(7.22)^2 - 4(10.25)}}{2}$$

$\longrightarrow D = 1.95\,m \Rightarrow B = 7.7\,m$

$\times\ D = 5.28\,m \Rightarrow B = -1.73\,m\ \times$

$D = 5.28\,m$ is neglected since it gives a negative value for B

Example 2

Design a trapezoidal canal $(z=2)$ to carry 25 cumecs of clear water. The slope $S = 1\times10^{-4}$. The bed and banks comprise gravel (angle of repose $\theta = 31^\circ$) and the size is 3 mm. Use kinematic viscosity equals to 10^{-6} m²/s.

Solution use method ② (Tractive force)

$$R_o^* = \left[\frac{(G_s-1)\,g\,d^3}{\nu^2}\right]^{1/2} = \left[\frac{(2.65-1)\,9.81\,(0.003)^3}{1\times10^{-12}}\right]^{1/2}$$

$$R_o^* = 661.1 \Rightarrow \text{from fig (14)}$$

$$\tau_c^* = 0.045$$

$$\tau_c = 0.045\,(2.65-1)\,9810\,(0.003) = 2.185\ N/m^2$$

τ_{bl} for stright canal is:

$$\tau_{bl} = 0.9\,\tau_c = 1.97\ N/m^2 \qquad \phi = \tan^{-1}\frac{1}{2} = 26.56^\circ$$

$$\tau_{bm} = 1.97\ N/m^2$$

$$K = \sqrt{1-\frac{\sin^2\phi}{\sin^2\theta}} = \sqrt{1-\frac{\sin 26.56^\circ}{\sin^2 31^\circ}} = 0.496$$

$$\tau_{sl} = K\,\tau_{bl} = 0.496\,(1.97) = 0.977\ N/m^2 = \tau_{sm}$$

Assume $\frac{B}{D} = 10$ — نحن نصمم على τ_{sm} وليس τ_{sl} لأنه الأقل ويعطي Q أكبر

from Fig (10)

$$\frac{\tau_{sm}}{\gamma DS} = 0.78 \Rightarrow D = \frac{0.977}{9810\times1\times10^{-4}\,(0.78)} = 1.27\ m$$

$$\Rightarrow B = 10D = 12.7\ m$$

$$A = BD + 2D^2 = 19.355\ m^2$$

$$P = B + 2\sqrt{5}\,D = 18.38$$

$$R = 1.053\ m$$

$$n = \frac{d^{1/6}}{25.6} = \frac{3^{1/6}}{25.6} = 0.0148$$

$$Q = \frac{1}{n} A R^{2/3} S^{1/2} = \frac{1}{0.0148}(19.355)(1.053)^{2/3}(10^{-4})^{1/2}$$

$$= 13.5\ m^3/sec < 25 \Rightarrow \text{Choose } \frac{B}{D} = 20$$

B/D	$\frac{\tau_{sm}}{\gamma DS}$	D	B	A	P	R	Q
10	0.78	1.27	12.7	19.355	18.38	1.053	13.50
20	0.78	1.27	25.4	35.484	32.08	1.142	26.195

2- for rigid boundary Canal (Lined canal)

Canals have boundaries like rock or artificial lining. It can carry discharge greater than nonerodible canals of same dimensions. The design procedure depend on permissible velocity or using best hydraulic section - [illegible]

Table(3) Maximum permissible velocity

Type of lining	max. Velocity (m/s)
Boulder lining	1.5
Brick tile lining	1.8
Cement concrete lining	2.7

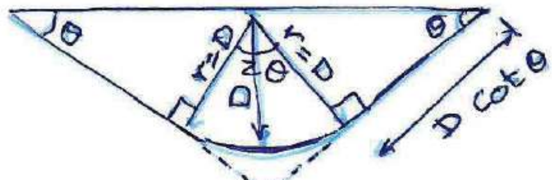
Table(4) Maning's coefficient "n"

Material of lining	Manning's n
cement concrete	0.013 - 0.022
Bricks lining	0.014 - 0.017
Asphalt	0.013 - 0.016
Wood planed clean	0.011 - 0.013
Concrete lined, excavated rock	0.017 - 0.027

cross-section of lined canal

For practicle design, semi-circular section is not used, thus the trapezoidal & traingular with rounded edges are used to increase the hydraulic radius R.

1. Traingular section:



$A_s = \frac{1}{2} r^2 \theta_s$ (angle of sector)

$A_s = \frac{1}{2} D^2 (2\theta)$

$A_s = \theta D^2$ θ : in radian

if θ in degree $\Rightarrow \theta_{rd} = \theta^\circ * \frac{\pi}{180}$

$A = A_s + D^2 \cot\theta$

$A = D^2 (\theta + \cot\theta)$ ——— (7.12)

$P = 2D\theta + 2D\cot\theta$

$P = 2D(\theta + \cot\theta)$ ——— (7.13)

Example

Design a lined canal to carry 50 cumecs, Assuming $S = \frac{1}{8100}$, $n = 0.015$, $Z = 1$.

solution: $\theta = \tan^{-1}\frac{1}{1} = 45^\circ = \frac{\pi}{4}$

$$\left.\begin{array}{l} A = 1.785 D^2 \\ P = 3.57 D \end{array}\right]$$

From Manning formula

$V = \frac{Q}{A}$ or $Q = \frac{1}{n} A R^{2/3} S^{1/2}$

$$50 = \frac{1.785 D^2}{0.015} \left(\frac{1.785 D^2}{3.570 D}\right)^{2/3} \left(\frac{1}{8100}\right)^{1/2}$$

$50 = 0.833 D^{8/3}$

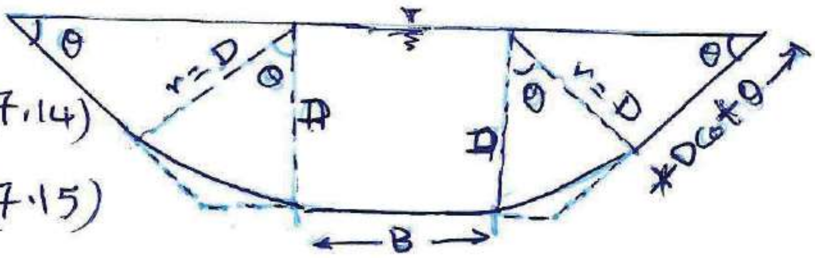
$D = 4.64$ m.

2. Trapezoidal section

$$A = BD + \theta D^2 + D^2 \cot\theta$$

$$A = BD + D^2(\theta + \cot\theta) \quad \text{---(7.14)}$$

$$P = B + 2D(\theta + \cot\theta) \quad \text{---(7.15)}$$



Example:

Design a lined canal of discharge 120 m^3/sec. The permissible velocity of flow is taken as 2 m/sec. Assume side slope 1:1 and n = 0.018 whereas the slope of canal is 1/3000.

Solution

$$A = \frac{Q}{V} = \frac{120}{2} = 60\,m^2$$

$$R = \left(\frac{nV}{\sqrt{S}}\right)^{1.5} = \left(\frac{0.018\,(2)}{\sqrt{1/3000}}\right)^{3/2} = 2.77\,m$$

$$P = \frac{A}{R} = \frac{60}{2.77} = 21.66\ m$$

Now:

$$A = BD + D^2(\theta + \cot\theta)$$

$$60 = BD + 1.785\,D^2 \quad \text{--- (a)} \qquad \text{where } \theta = \frac{\pi}{4}$$

$$21.66 = B + 2.57D$$

$$\text{or} \quad B = 21.66 - 2.57D \quad \text{--- (b)}$$

Subs. (b) into (a) to get:

$$60 = (21.66 - 2.57D)D + 1.785\,D^2$$

$$\Rightarrow D^2 - 12.13D + 33.61 = 0$$

D = 4.28 m	D = 7.85 m
B = 6.38 m	B = 1.50 m
	it is too small similar to triangular section

Sundries: متنوعات

for main canal, lateral & distributary canal

① $S_{min} = 0.00015\, Q_{m^3/sec}^{-0.2}$ m/m ——— (7.16)

Q is full supply discharge + 10% operation losses.

Slope for water courses 20 – 60 cm/km.

If slope is steep the velocity may increase rapidly and F must not exceed 0.6

② $F = \frac{V}{\sqrt{gD}} \leq 0.6$ ——— (7.17)

③ S_{max} for main, lateral and distributary canal is:

$S_{max} = 0.00025\, Q^{-0.2}$ ——— (7.18)

④ (B/D) increasing causes cost increasing.

(B/D) = 1 to 2 for 10 m^3/sec.

⑤ min. velocity in canal

$V_{min} = 0.33\, Q_{m^3/sec}^{0.2}$ (m/s) ——— (7.19)

Ex. :- prove that the prameter R_o^* which equals to $\frac{R_c^*}{\sqrt{\tau_c^*}}$ is equavelent to dimensionless particle size $d_*^{1.5}$, where d_* is equal to $\left[\frac{(G_s-1)gd^3}{\nu^2}\right]^{1/3}$.

Solution

$$\frac{R_c^*}{\sqrt{\tau_c^*}} = \frac{V_{*c}\cdot d/\nu}{\sqrt{\frac{\tau_c}{(\gamma_s-\gamma)d}}} = \frac{\sqrt{\frac{\tau_c}{\rho}}\cdot d/\nu}{\sqrt{\frac{\tau_c}{g\rho(\frac{\gamma_s}{\gamma}-1)d}}}$$

$$= \frac{\cancel{\sqrt{\frac{\tau_c}{\rho}}}\cdot d/\nu}{\cancel{\sqrt{\frac{\tau_c}{\rho}}}\cdot\sqrt{\frac{1}{g(G_s-1)d}}}$$

$$= \frac{d}{\nu}\cdot\left((G_s-1)gd\right)^{1/2}$$

$$= \left[\frac{(G_s-1)gd^3}{\nu^2}\right]^{1/2}$$

$$= \left[(d_*)^3\right]^{1/2}$$

$$\Rightarrow R_o^* = d_*^{3/2} \qquad \underline{\underline{\text{o.k}}}$$

(2) The Best hydraulic section:

is the channel section having least wetted perimeter for a given area has the maximum conveyance, According to this definition, the semi-circle section has the least wetted perimeter for all section having same area.

القطع الأمثل للقناة هو القطع الذي يمتلك أقل محيط مبلل لمساحة محددة. مقطع نصف الدائرة هو الأفضل بالمقارنة مع بقية المقاطع ولنفس المساحة.

Cross section	Area A	Wetted perimeter P	Hydraulic radius R	Top width T	Hydraulic depth D_h
Trapezoid, half of a hexagon	$\sqrt{3}\,D^2$	$2\sqrt{3}\,D$	$\frac{1}{2}D$	$\frac{4}{3}\sqrt{3}\,D$	$\frac{3}{4}D$
Rectangle, half of a square	$2D^2$	$4D$	$\frac{1}{2}D$	$2D$	D
Triangle, half of a square	D^2	$2\sqrt{2}\,D$	$\frac{1}{4}\sqrt{2}\,D$	$2D$	$\frac{1}{2}D$
Semicircle	$\frac{\pi}{2}D^2$	πD	$\frac{1}{2}D$	$2D$	$\frac{\pi}{4}D$
Parabola	$\frac{4}{3}\sqrt{2}\,D^2$	$\frac{8}{3}\sqrt{2}\,D$	$\frac{1}{2}D$	$2\sqrt{2}D$	$\frac{2}{3}D$

الجدول يمثل أبعاد المقطع الأمثل.

A: cross-sectional area.
P: wetted-perimeter.
R: hydraulic radius
T: Top width
D_h: Hydraulic depth $= \frac{A}{T}$

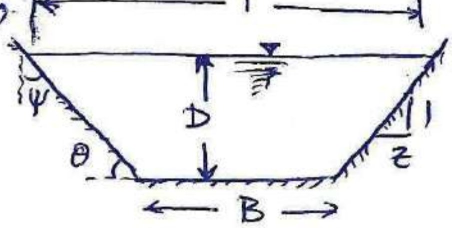
How to find the best Hydraulic section:

From Definition of B.H.S., there is easy to defind the section dimension by:

$\frac{dP}{dD} = 0$ (P min) for given area.

or even $\frac{dA}{dD} = 0$ (A max) for given P.

for example, consider the trapezoidal section, and from geometry shown in figure;



$$A = BD + ZD^2$$
$$P = B + 2D\sqrt{1+Z^2}$$

Method ①: Assuming constant A and use $\frac{dP}{dD} = 0$ (P is minimum)

Subs. one of above equation into other yields;

$$B = \frac{A - ZD^2}{D} \quad \text{---------} (7\text{-}20)$$

and thus;

$$P = \frac{A}{D} - ZD + 2D\sqrt{1+Z^2} \quad \text{-----} (7.21)$$

$$\frac{dP}{dD} = 0 \Rightarrow -\frac{A}{D^2} - Z + 2\sqrt{1+Z^2} = 0$$

$$\text{or} \quad A = D^2\left(2\sqrt{1+Z^2} - Z\right) \quad \text{-----} (7\text{-}22)$$

subs. eq. (7-22) into eq. (7-20) to get:

$$B = 2D\left[\sqrt{1+Z^2} - Z\right] \quad \text{-----} (7\text{-}23)$$

or $\frac{B}{D} = 2\left[\sqrt{1+Z^2} - Z\right]$ which is previously mentioned in page (8) and assigned as $Ce = 2\tan\theta = B/D$, and called the optimum ration of B/D.

Subs. eq. (7-23) into equations of A & P above yields;

$$A = 2D^2\sqrt{1+Z^2} - ZD^2 \quad \text{------} (7\text{-}24)$$
$$P = 4D\sqrt{1+Z^2} - 2DZ \quad \text{------} (7\text{-}25)$$

Now solve for $\sqrt{1+Z^2}$;

$$\sqrt{1+z^2} = \frac{P+2DZ}{4D} = \frac{A+ZD^2}{2D^2}$$

$$\Rightarrow P = \frac{2A}{D}$$

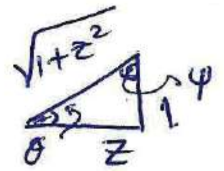
but from equation (7.25) ; $D = \dfrac{P}{4\sqrt{1+z^2}-2z}$

$$\Rightarrow P = \frac{2A}{4\sqrt{1+z^2}-2z} = \frac{4A\left[2\sqrt{1+z^2}-z\right]}{P}$$

$$\Rightarrow P = 2\sqrt{A\left[2\sqrt{1+z^2}-z\right]} \text{ ------- } (7.26)$$

Now $\dfrac{dP}{dz} = 0 \Rightarrow 0 = \dfrac{A\left(\frac{2z}{\sqrt{1+z^2}}-1\right)}{2\sqrt{A\left(2\sqrt{1+z^2}-z\right)}}$

$$\Rightarrow \frac{2z}{\sqrt{1+z^2}} = 1 \quad \text{or} \quad \frac{z}{\sqrt{1+z^2}} = \frac{1}{2}$$



$\sin\varphi = 1/2 = \cos\theta \Rightarrow \theta = 60°$, $\frac{1}{z} = \tan 60$

or $\boxed{z = \frac{1}{\sqrt{3}}}$

Now the dimensions of best hydraulic section are:

$z = \frac{1}{\sqrt{3}} = 0.57735$

From eq. (7.23) associated with $z = \frac{1}{\sqrt{3}}$

$\frac{B}{D} = \frac{2}{\sqrt{3}}$ or $\boxed{B = \frac{2}{\sqrt{3}} D}$; $P = 2\sqrt{3}\,D$, $A = \sqrt{3}\,D^2$

$\boxed{R = \frac{\sqrt{3}\,D^2}{2\sqrt{3}\,D} = \frac{D}{2}}$ $\quad 2a = P - B = \left(2\sqrt{3} - \frac{2}{\sqrt{3}}\right)D = 2D\sqrt{4/3}$

or $a = \frac{2}{\sqrt{3}} D = B$ thus the shape is a half hexagon

Method ②: Assuing constant P and use $\frac{dA}{dD}=0$ (max. A)

Invoking $A = BD + ZD^2$ & $B = P - 2D\sqrt{1+Z^2}$ to find the:

$$A = PD - 2D^2\sqrt{1+Z^2} + ZD^2 \quad \text{------} \quad (7.27)$$

Now $\frac{dA}{dD} = 0$ (max. Area) $\Rightarrow P - 4D\sqrt{1+Z^2} - 2DZ = 0$

or $P = 4D\sqrt{1+Z^2} - 2DZ$ ---------- (7.28)

but $P = B + 2D\sqrt{1+Z^2}$, thus;

$B = 2D\left[\sqrt{1+Z^2} - Z\right]$ which same as equation (7-23) that called ce. . النسبة المثلى

By same approach of eq. (7.26); eq. 7.24 and eq. 7.25 are used to find;

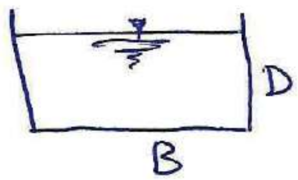
$$A = \frac{P^2}{4\left[2\sqrt{1+Z^2} - Z\right]} \quad \text{---------} \quad (7.29)$$

$\frac{dA}{dZ} = 0 \Rightarrow \frac{2Z}{\sqrt{1+Z^2}} = 1 \Rightarrow \frac{Z}{\sqrt{1+Z^2}} = \frac{1}{2} \Rightarrow \theta = 60^\circ$

same as the previous value. and so on to find dimensions

H.W

Derive the dimensions of B.H.S. for rectangular section.



Solution:

$A = BD$

$P = 2D + B$

⋮

example:

Design a lined canal of trapezoidal section by sizing it using Best Hydraulic Section approach. The canal slope 0.0016, the side slope is 1:2, discharge is 15 m³/sec. The lining material is asphalt.

Solution:

The optimum ratio ce is consider herein using equations (7-23)

$$\frac{B}{D} = 2\left(\sqrt{1+z^2} - z\right) = 2\tan\theta$$

$$= 2\left(\sqrt{5} - 2\right) = 0.47$$

$$A = 0.47D^2 + 2D^2 = 2.47D^2 \quad \text{—— (a)}$$

$$P = 0.47D + 2D\sqrt{5} = 4.942D \quad \text{—— (b)}$$

$$R = 0.5D$$

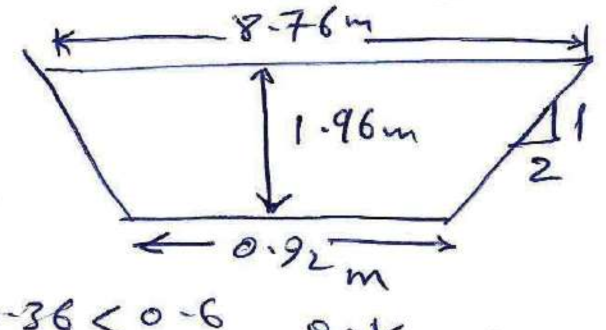
$$Q = \frac{1}{n}(A)(R^{2/3})(S^{1/2})$$

Use an average value for $n = 0.016$

$$15 = \frac{1}{0.016}\, 2.47D^2\, (0.5D)^{2/3}\, (0.0016)^{1/2}$$

$$15 = 3.89\,D^2 \Rightarrow D = 1.96\,m$$

$$B = 0.47\,(1.96) = 0.92\,m$$



$$Fr = \frac{V}{\sqrt{gD}}$$

$$Fr = \frac{15/9.488}{\sqrt{9.81\,(1.96)}}$$

$$Fr = \frac{1.58}{4.38} = 0.36 < 0.6 \quad \text{o.k}$$

3. For stable alluvial canal القنوات الطموية

After some information about the canal are avialable, one can consider the Lacey's method to design the alluvial canals according to following equations:

1. Silt factor $f = 1.76\sqrt{d_{mm}}$ ——— (7.30)

معامل الغرين

d is median size of sediment in mm.

2. $V = 10.8\ R^{2/3}\ S^{1/3}$ ——— (7-31)

V : velocity in m/sec, R hydraulic radius in m.

3. $P = 4.75\sqrt{Q}$ ——— (7-32)

P is wetted perimeter in (m), Q is discharge m^3/sec.

4. $R = 0.48\left(\frac{Q}{f}\right)^{1/3}$ ——— (7-33)

5. $S = 0.0003\ \frac{f^{5/3}}{Q^{1/6}}$ ——— (7,34)

Lacey also obtained that:

$V = \frac{1}{Na} R^{3/4}\ S^{1/2}$ ——— (7.35)

Na: is rugosity coefficient; and

$Na = 0.0225 f^{1/4}$ ——— (7.36)

Example 1

Desig a stable canal that carrying discharge of $30 m^3/sec$ by Lacey's method, assuming $f = 1.0$.

from eq. (7.32):

$P = 4.75\sqrt{Q} = 4.75(30)^{1/2} = 26.02 m$

from (7.33):

$R = 0.48\left(\frac{Q}{f}\right)^{1/3} = 0.48(30)^{1/3} = 1.49 m$

from (7.34):

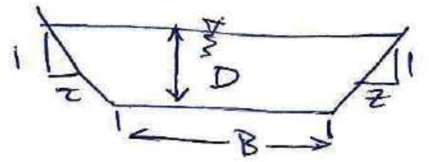
$S = 3\times10^{-4}(1)^{5/3}/(Q)^{1/6} = 1.702\times10^{-4}$

From (7.31)

$V = 10.8 R^{2/3} S^{1/3} = 10.8(1.49)^{2/3}(1.702\times10^{-4})^{1/3}$

$= 0.781 m/sec$ [Try with eq. 7.36]

choose the shape of canal, say it is trapezoidal in shape, thus, the side slope z can be selected as 0.5 (generally observed in alluvial canal).



$P = B + 2D\sqrt{1+z^2}$

$P = B + \sqrt{5}D = 26.02$

or $B = 26.02 - 2.24D$ —— (a)

$A = BD + zD^2 = BD + \frac{D^2}{2}$

since $R = \frac{A}{P} \Rightarrow A = PR = 26.02\times1.49 = 38.77 m^2$

$\Rightarrow BD + \frac{D^2}{2} = 38.77 m^3$ —— (b)

solve the two equations a & b; yields;

$1.74D^2 - 26.02D + 38.77 = 0$

by Quadratic formula الحل بالدستور :

$$D = \frac{26.02 \mp \sqrt{(26.02)^2 - 4(1.74)38.77}}{2(1.74)}$$

$D = 13.28 m$ and $1.68 m$

$D = 13.28 m$ gives by eq.(a) negative value for $B = -3.72 m$ thus, $D = 13.28$ is neglected.

$D = 1.68 \Rightarrow B = 22.23$

example 2

An irrigation canal is to be designed for discharge 50 m^3/sec adopting the available ground slope of 1.5×10^{-4}. The river bed material has median size of 2mm. Design the canal and recommend the size of coarser material to be excluded or ejected from the canal for efficient functioning.

$$f = 1.76\sqrt{d_{s}} = 1.76\sqrt{2} = 2.49$$

$$S = 0.0003\,(2.49)^{5/3}/(50)^{1/6} = 7.15 \times 10^{-4}$$

this slope is much large than ground slope.

⇒ the median size of sediment that the canal would be able to carry can be determined by computing New value of f for $S = 1.5 \times 10^{-4}$

$$S = 1.5 \times 10^{-4} = 0.0003\, f^{5/3} / Q^{1/6}$$

$$= 0.003\, f^{5/3} / (50)^{1/6}$$

$$\Rightarrow f = 0.976$$

$$d = \left(\frac{0.976}{1.76}\right)^2 = 0.3 \text{ mm}$$

Therefore material > 0.3 mm will have to be removed for the efficient functioning of the canal.

$$R = 0.48\left(\frac{Q}{f}\right)^{1/3} = 0.48\left(\frac{50}{0.976}\right)^{1/3}$$

$$= 1.78 \text{ m}$$

$$P = 4.75\sqrt{50} = 33.59 \text{ m}$$

but $P = B + \sqrt{5}\,D = 33.59$ —— (a)

$$A = BD + \frac{D^2}{2} = PR = 33.59\,(1.78)$$

$BD + \frac{D^2}{2} = 59.89$ —— (b)

Solve a & b to get B & D

$B = 29.13$ & $D = 1.99$ m.

ملحق لاشتقاق معادلات ليسي للقنوات المتوازنة

Derivation of Lacey equations for regime canals

essential equations are:

$$\boxed{V = \sqrt{\frac{2}{5}}\ \sqrt{fR}} \quad \text{——— (1)}$$

$$\boxed{Af^2 = 140\ V^5} \quad \text{——— (2)}$$

$$\boxed{V = 10.8\ R^{2/3}\ S^{1/3}} \quad \text{——— (3)}$$

هذه هي المعادلات الاساسية

Supplementary equation are: أما المعادلات التكميلية فهي

From eq. (1) : $f = \frac{5V^2}{2R}$ ——— (a)

subs. (a) into eq(2); yields

$$A\left(\frac{5V^2}{2R}\right)^2 = 140\ V^5 \quad \left[\text{multiply both side by } V\right]$$

$$Q\left(\frac{5V^2}{2R}\right)^2 = 140\ V^6$$

$$\frac{25}{4}\ \frac{Q}{R^2} = 140\ V^2$$

$$\frac{25}{4}\ \frac{Q}{(A/P)^2} = 140\ V^2$$

$$P^2 = \frac{560}{25}\ Q \quad \text{——— (b)}$$

$$\boxed{P = 4.75\sqrt{Q}} \quad \text{——— (4)}$$

From eq. (b)

$$P^2 = \frac{560}{25}\ VA$$

$$\left[\frac{P^2}{A^2} = \frac{560}{25}\ \frac{V}{A} = \frac{1}{R^2}\right] \text{multiply by } AR$$

$$\frac{A}{R} = \frac{560}{25}\ VR$$

$$P = \frac{560}{25}\ VR$$

$$4.75\sqrt{Q} = \frac{560}{25}\ VR \quad \text{——— (c)}$$

Subs. eq(1) into eq(c) to get; -

$$4.75\, Q^{1/2} = \frac{560}{25}\sqrt{\frac{2}{5}}\; f^{1/2} R^{3/2}$$

$$\boxed{R = 0.48\left(\frac{Q}{f}\right)^{1/3}} \text{———} (5)$$

For wide rectangular Canal $q = VD \approx VR$

From eq. (c) $\quad VR = 0.212\, Q^{1/2}$

and since $VR \approx VD = q$

$\Rightarrow q = 0.212\, Q^{1/2}$

subs. this equation into eq. (5) to get

$$R = 0.48\left(\frac{q}{0.212 f}\right)^{1/3}$$

$$R = 1.35\left[\frac{q^2}{f}\right]^{1/3} \text{———} (d)$$

يستفاد بمعادلة (d) في حساب عمق القطاع في القنوات.

by eliminating V from both eq. (1) and eq. (2) and equating them, one can get:

$$\sqrt{\frac{2}{5}}\sqrt{fR} = 10.8\, R^{2/3}\, S^{1/2}$$

or $\quad S = \left(\frac{\sqrt{0.4}}{10.8}\right)^3 f^{3/2} / R^{1/2}$

Recalling R from eq. (5) to obtain:

$$S = \frac{0.0002\, f^{3/2}}{R^{1/2}} \text{———} (e)$$

$$S = 0.0003\, \frac{f^{5/3}}{Q^{1/6}} \text{———} (6)$$

H.W
Prove that for regime Canal $\frac{V^2}{R}$ = Constant

From eq (3):

$$V = \frac{10.8\, R^{2/3}\, S^{1/2}}{S^{1/6}}$$

but from eq. (e): $\quad S^{1/6} = \frac{0.242\, f^{1/4}}{R^{1/12}}$

$$V = \frac{44.6\, R^{3/4}\, S^{1/2}}{f^{1/4}}$$

$Na = 0.0225\, f^{1/4}$

or $\quad \boxed{V = \frac{1}{Na} R^{3/4} S^{1/2}} \text{———} (7)$