Open channels are designed to carry a design discharge in a safe and economical way.

** For water distribution channels, such as those used in irrigation and water supply projects, the design discharge is determined on the basis of total delivery requirements.

Open channels are usually designed for uniform or normal flow conditions. Designing an open channel involves the selection of:-

- Channel alignment,
- Size and shape,
- Longitudinal slope, and
- The type of lining material.

Normally, the designer considered several hydraulically feasible alternatives, and compare them to determine the most cost-effective alternative. This lecture will emphasize the hydraulic considerations involved in channel design rather than economic analyses of different alternatives.

1-GENERAL DESIGN CONSIDERATIONS

**** Selection of channel alignment;**

It is the first step in designing an open channel. Generally, the topography of the area, existing and planned adjacent structures and transportation facilities control the channel alignment. The topography also controls the invert elevations and bottom slope of the channel.

**** Cross-sectional shape and size;**

Most manmade surface channels are trapezoidal in cross-section, although triangular, parabolic and rectangular channels are also used. The hydraulic capacity is a main factor to accommodate the design discharge. There are, however, other factors to be considered, these are:-

- the **depth** of the channel may be limited due to a high water table in the underlying soil.
- channel **widths** and **side slopes**, where;
* large channel width and mild side slope will result in high costs of crossing ways and structures such as bridges and regulators.
* Small channel widths, on the other hand, may create construction difficulties. Likewise, steep side slopes can cause slope stability problems as well as high erosion rates in earthen channels.

**** Flow conditions;**

Mostly open channels are designed for subcritical flow ($Fr<1$). The design discharge is only a single estimated value; the actual discharge occurring in a channel will vary possibly above and below the design discharge.

**** State of Boundary;**

Channels are often **lined** to prevent the sides and the bottom of the channel from suffering erosion due to the shear stresses caused by the flow. The types of channel linings can be categorized into two broad groups:

- Rigid
- Flexible.

* Rigid lining materials include;
- cast-in-place concrete,
- cast-in-place asphaltic concrete,
- stone masonry,
- soil cement, and
- grouted riprap.

Rigid linings can:-
- resist high shear stresses and provide a much higher conveyance capacity for the same cross-sectional size and channel slope,
- reduce losses of water from the channel due to seepage.

The disadvantage of rigid lining is it susceptible to failure from structural instability caused by freeze-thaw, swelling, and excessive soil pore pressures.

When a rigid lining deteriorates, large broken slabs may be dislodged and displaced by the channel flow, resulting in significant erosion problems and slope and structure failures.

*Flexible linings can be further classified into:

- Permanent, and
- Temporary linings.

Permanent flexible linings include;

- riprap,
- vegetation lining, and
- gravel.

* Temporary linings are used for temporary protection against erosion until vegetation is established. It include synthetic mat. Flexible linings have several **advantages** compared to rigid linings these are:

- less susceptible to structural failure, because they can conform to the changes in the channel shape.
- allow infiltration.

The **disadvantages** of flexible linings are:

- It can only sustain limited magnitudes of erosive forces.
- To accommodate the same design discharge safely, a channel section with a flexible lining would have to be considerably larger than a section lined with a rigid material. Therefore, flexible lining can lead to higher overall channel costs although the flexible lining materials are usually less expensive than the rigid lining materials in terms of construction costs.

**** Freeboard;**

Is the vertical distance between the top of the channel and the water surface that prevails under the design flow conditions. This distance should be sufficient to allow variations in the water surface due to wind-driven waves, tidal action, occurrence of flows exceeding the design discharge, and other causes. There are no universally accepted rules to determine a freeboard. In practice, freeboard selection is often a matter of judgment, or it is stipulated as part of the prevailing design standards. For preliminary estimates, the US Bureau of Reclamation (Chow, 1959) recommends that the unlined channel freeboard be computed as:

$$F = \sqrt{Cy} \qquad \text{.. (1)}$$

Where F=freeboard, y=flow depth, and C=a coefficient depends on system of units;

- C=1.5ft - 2.5ft (for channel capacity ranged between 20 - 3000 ft^3/s)
- C=0.5m - 0.76m (for channel capacity ranged between 0.6 - 85m^3/s)

Linear interpolation is acceptable to determine the intermediate values of C. For lined channels, the curves displayed in Fig.(L9-1) can be used to estimate the height of bank above water surface and the height of lining above water surface. This figure follows the US Bureau of Reclamation recommendations.

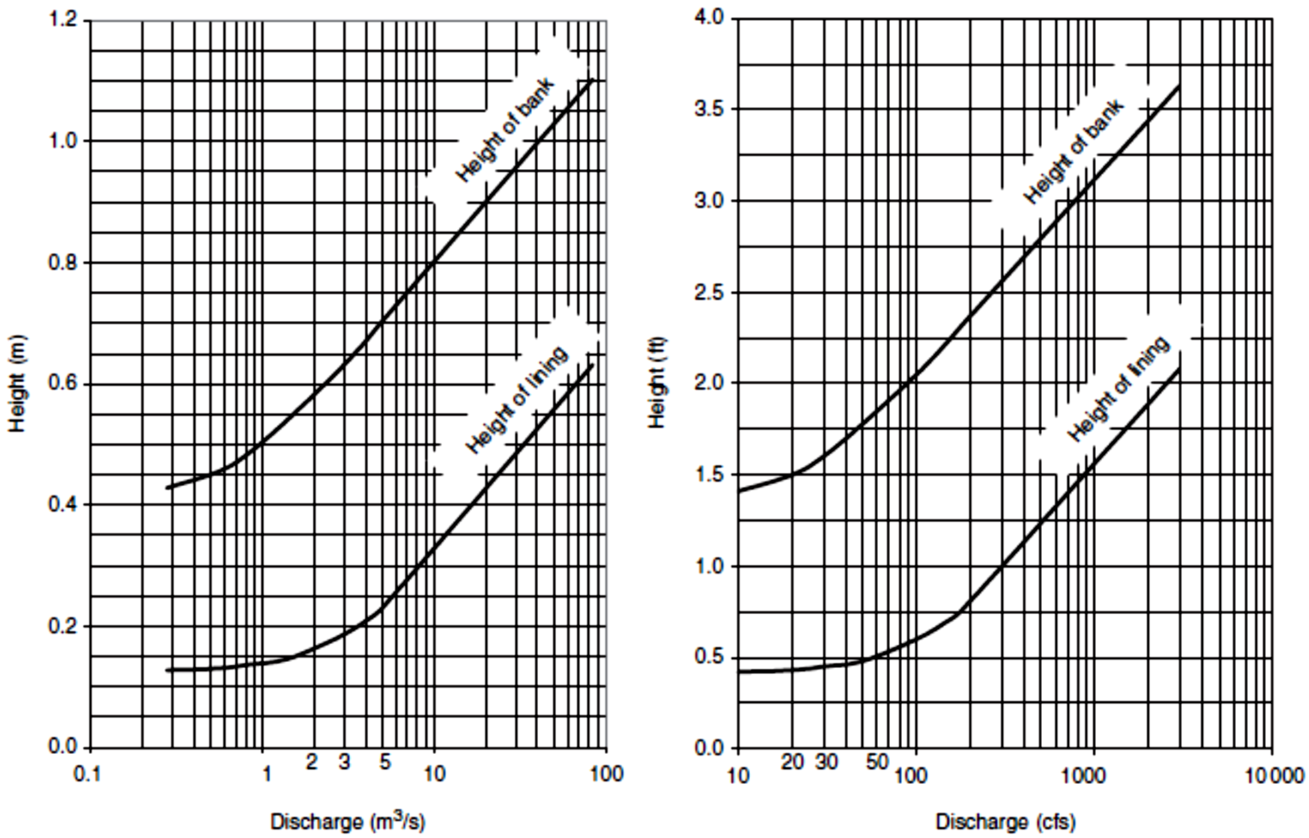


Fig.(L9-1): Suggested heights of lining and bank above water surface

2-DESIGN OF UNLINED CHANNELS

The sides and bottoms of earthen channels are both erodible. The main criterion for earthen channel design is that the channel is not eroded under the design flow conditions. There are two approaches to erodible channel design;

- The maximum permissible velocity method and
- The tractive force method.

(A): Maximum Permissible Velocity Method

This method is based on the assumption that a channel will not be eroded if the average cross-sectional velocity in the channel does not exceed the maximum permissible velocity. The magnitude of the maximum permissible velocity depends on the type of channel boundary material as well as the channel alignment. The maximum permissible velocities presented in Table (L9-2). These values are usually considered to be valid for straight channels having a flow depth of up to 3 ft or 1 m. The values given in Table 5.2 can be reduced by:

* 13% for moderately sinuous channels and

* 22% for very sinuous channels.

Also, for flow depths exceeding 3 ft or 1 m, the maximum permissible velocities can be increased by about 0.50 fps or 0.15 m/s.

The design guide for cross-section side slope can be taken from Table (L9-1)

Table (L9-1): Steepest recommended side slopes for channels

Material	Side slope, m (run to rise ratio)
Rock	0–0.25
Earth with concrete lining	0.50
Stiff clay or earth	1.0
Soft clay	1.5
Loose sandy soil	2.0
Light sand, sandy loam	3.0

Table (L9-2): Suggested maximum permissible channel velocities

Channel material	V_{MAX} (fps)	V_{MAX} (m/s)
Fine sand	2.0	0.6
Coarse sand	4.0	1.2
Fine gravel*	6.0	1.8
Sandy silt	2.0	0.6
Silt clay	3.5	1.0
Clay	6.0	1.8
Bermuda grass on sandy silt**	6.0	1.8
Bermuda grass on silt clay**	8.0	2.4
Kentucky bluegrass on sandy silt**	5.0	1.5
Kentucky bluegrass on silt clay**	7.0	2.1
Sedimentary rock	10.0	3.0
Soft sandstone	8.0	2.4
Soft shale	3.5	1.0
Igneous or hard metamorphic rock	20.0	6.0

*Applies to particles with d_{50} less than 0.75 in (20 mm).
**Velocities should be kept less than 5.0 fps (1.5 m/s) unless good cover and proper maintenance can be obtained. Slopes should be less than 5%.

In a typical problem, the solution regarding sizing a channel section, it should know firstly;
- the channel bottom slope, S_0,
- the design discharge, Q, and
- the type of the channel material. The procedure to design the size the channel section according to max. permissible velocity method consists of the following steps:

1. For the specified channel material, determine the Manning roughness factor "n", the side slope m from Table (L9-1), and the maximum permissible velocity "V_{MAX}" from Table (L9-2).
2. Compute the corresponding hydraulic radius, R, from the Manning formula.
3. Compute the required flow area as $A=Q/V_{MAX}$.
4. Compute the wetted perimeter as $P=A/R$.

5. Knowing the magnitudes of “A” and “P” and using the geometrical expressions for A and P, solve for the flow depth “y” and the bottom width “b” simultaneously.
6. Check the Froude number to ensure that it is not close to the critical value of 1.0.
7. Add a freeboard and modify the section for practical purposes.

Step (5) of this procedure requires the solution of two simultaneous equations. This can be facilitated for trapezoidal channels by using the following equations:

$$W = \frac{Q}{R^2 V_{MAX}\left(2\sqrt{1+m^2}-m\right)} \quad \text{.................................... (2)}$$

$$y = \frac{RW}{2}\left(1-\sqrt{1-\frac{4}{W}}\right) \quad \text{.. (3)}$$

$$b = \frac{Q}{RV_{MAX}} - 2y\sqrt{1+m^2} \quad \text{....................................... (4)}$$

Where W is an intermediate dimensionless parameter.

(B): Tractive Force Method

The forces acting on the soil particles comprising the channel bottom and sides are considered in this method. Flow in a channel exerts tractive forces (or shear forces) on the channel bed that are equal in magnitude but opposite in direction to the friction forces exerted by the channel bed on the flow.
** The tractive forces tend to move the particles on the channel bed in the flow direction.
** Erosion will occur if the tractive forces exceed the resistive forces preventing the movement of these particles.

The design of an earthen channel, must proportion the channel section so that the particles will not move under the design flow conditions.

Flow Mechanism

- The flow-induced tractive forces are tending to move the soil particles lying on the channel bottom and on the sides of the channel as well.
- The particles on the sides of the channel tend to roll down the slope due to the effect of gravity. Therefore, the forces tending to move the particles on the sides of a channel are the resultant of the flow-induced tractive forces and the gravitational forces acting on the soil particles.
- For cohesive soils, the gravitational forces are much smaller than the cohesive forces keeping the soil particles together.
- For design purposes, the forces acting on unit areas on the channel bottom and sides are considered rather than individual soil particles.
- For normal flow, the flow-induced average unit tractive force, or the average tractive force per unit area over the channel perimeter, is equal to γRS_0 where γ =specific weight of water, R=hydraulic radius, and S_0=bottom slope of the channel.
- The distribution of the unit tractive force over the channel perimeter is non-uniform, as shown in Figure (L9-2).

Defining τ_b=maximum unit tractive force on the channel bottom, and, τs_0=maximum unit tractive force on the sides, Lane (1955), has been express τ_b and τ_{s0} in terms of the flow depth as;

$$\tau_b = K_b \gamma y S_0 \quad \text{.......................................} \quad (5)$$

$$\tau_{s0} = K_s \gamma y S_0 \quad \text{.......................................} \quad (6)$$

The dimensionless coefficients K_b and K_s depend on the side slope, "m" and the bottom width to depth ratio "b/y". The largest values of K_b are near but below unity. Therefore, in design using (K_b=1.0) for simplicity. Figure (L9-2) presents the suggested values of "Ks" for (1<(b/y)<6) as a function of the side slope, "m".

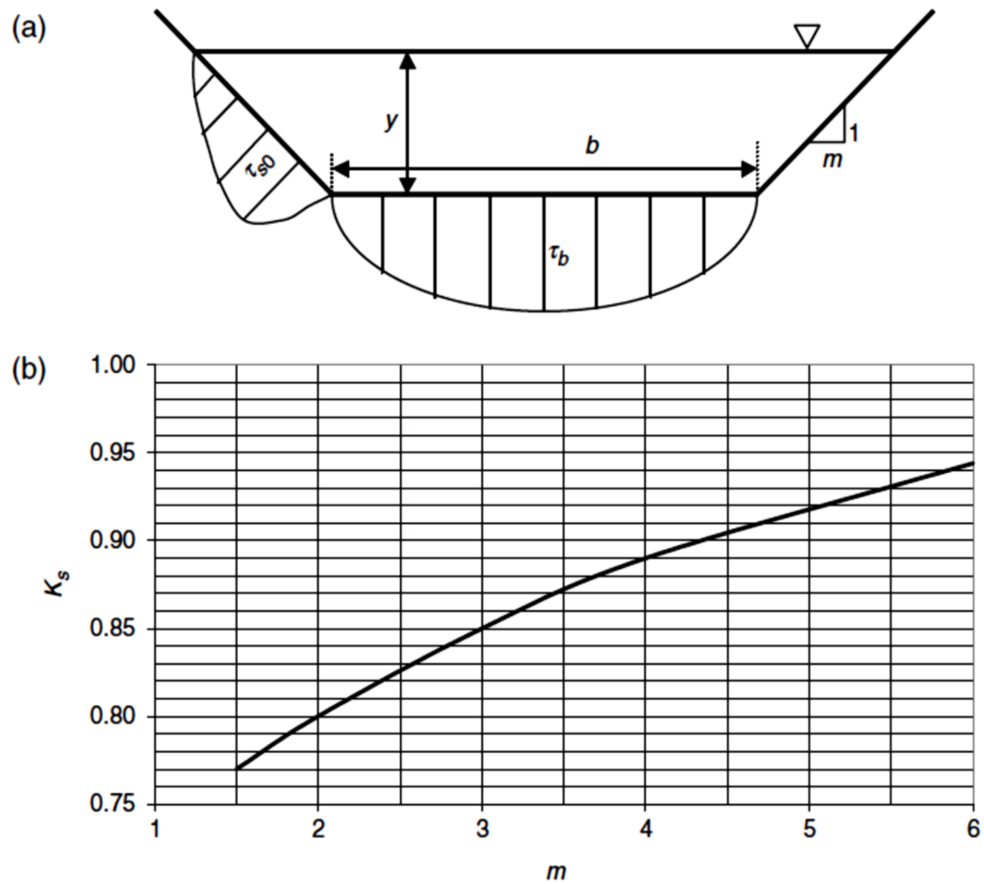


Fig.(L9-2): Shear stress distribution on channel bottom and sides

The maximum unit force (force per unit area) tending to move the particles due to the flow-induced tractive force and the gravitational forces combined can be expressed $\tau_s=\tau_{s0}/K$, or;

$$\tau_s = \frac{K_s \gamma y S_0}{K} \quad \text{...} (7)$$

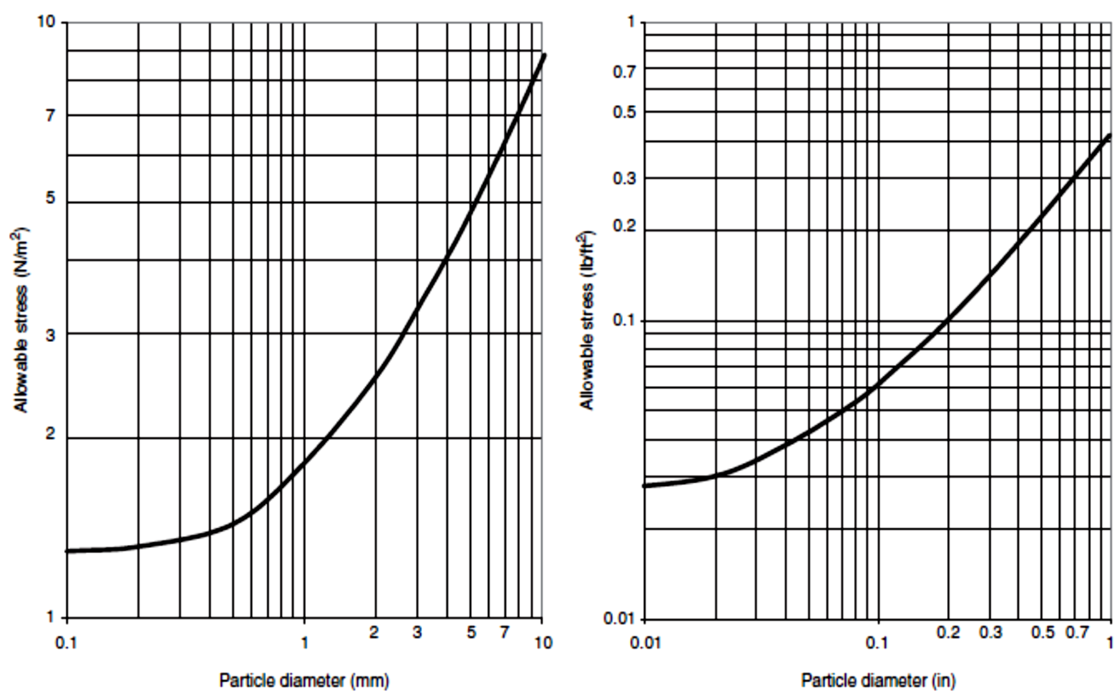
τ_s=maximum unit force tending to move the particles, and K=tractive force ratio; it is a dimensionless parameter reflecting the tendency of soil particles to roll down the side slopes due to gravity.

- For cohesive soils, K=1.0 (that is refer the effect of the gravitational forces is negligible).
- For cohesionless soils;

$$K = \sqrt{1 - \frac{1}{(1+m^2)\sin^2\alpha_R}} \quad \text{.................................. (8)}$$

α_R= angle of repose of the cohesionless channel material.

The permissible unit tractive force, τ_p, is the maximum unit tractive force (combining the flow-induced shear force and gravitational forces acting on soil particles) that will not cause erosion. This can also be interpreted as the resistive force per unit area opposing the movement of soil particles. If τ_b exceeds the permissible tractive force, τ_p, the channel bottom will be eroded. For non-cohesive soils, as suggested by (Chen and Cotton, 1988), the permissible tractive force is a function of the mean diameter of the channel material as shown in Figure L9-3.



In the tractive force method, a channel cross-section is dimensioned so that neither the channel bottom nor the sides will be eroded under the design conditions. For cohesive soils the channel bottom is usually critical, whereas for non-cohesive soils the sides usually govern the design.

Note: The values of the permissible unit tractive force obtained are for straight channels. For sinuous channels, these values should be multiplied by a reduction factor, Cp, taken from Table (L9-3).

Table (L9-3): Reduction factors for sinuous channels

Degree of sinuousness	C_p
Straight	1.0
Slightly sinuous	0.90
Moderately sinuous	0.75
Very sinuous	0.60

** Channels in cohesive soils will be designed using:-

$\tau_b \le C_p \tau_p$, or $K_b \gamma y S_0 \le C_p \tau_p$

Therefore, the limiting flow depth becomes;

$$y_{LIM} = \frac{C_p \tau_p}{K_b \gamma S_0} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Determine the channel bottom width, b, by using Eq.(10) below or Figure (L9-4);

$$b = 1.186y\left[\frac{nQ}{k_n S_0^{1/2} y^{8/3}} - \frac{m^{5/3}}{(2\sqrt{1+m^2})^{2/3}}\right]^{0.955} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

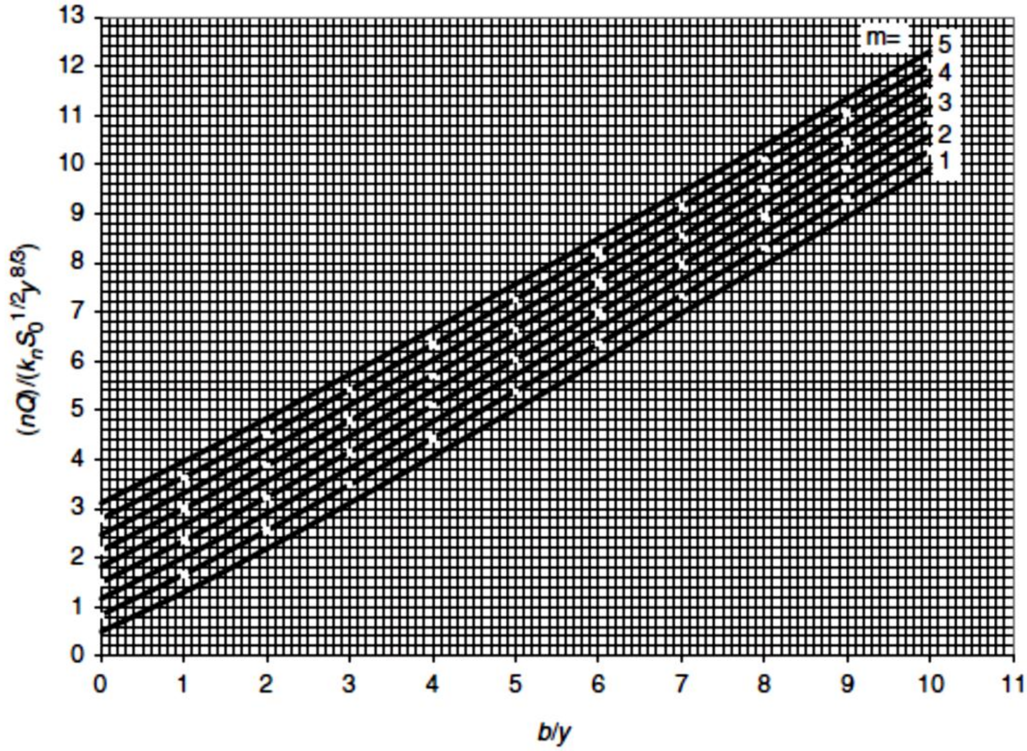


Fig.(L9-4): Graphical representation of Eq.10 (after Akan, 2001)

** Channels in cohesionless soils will be designed using:-

$$\tau_s \leq C_p \tau_p \quad \text{or} \quad \frac{K_s \gamma y S_0}{K} \leq C_p \tau_p$$

In this case, the limiting depth is;

$$y_{LIM} = \frac{K C_p \tau_p}{K_s \gamma S_0} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

Note that; Eq.10 and Fig.L9-4 also used with cohesionless boundary channel soil to calculate the approximate channel bottom width and then increase it to practical value.