

## Supplementary Lecture 5: Drainage Design

A senior engineer once said to me (which an earlier senior engineer had said to him): “There are three secrets to building a road or railway to last: 1) Drainage, 2) Drainage, and 3) Drainage”.

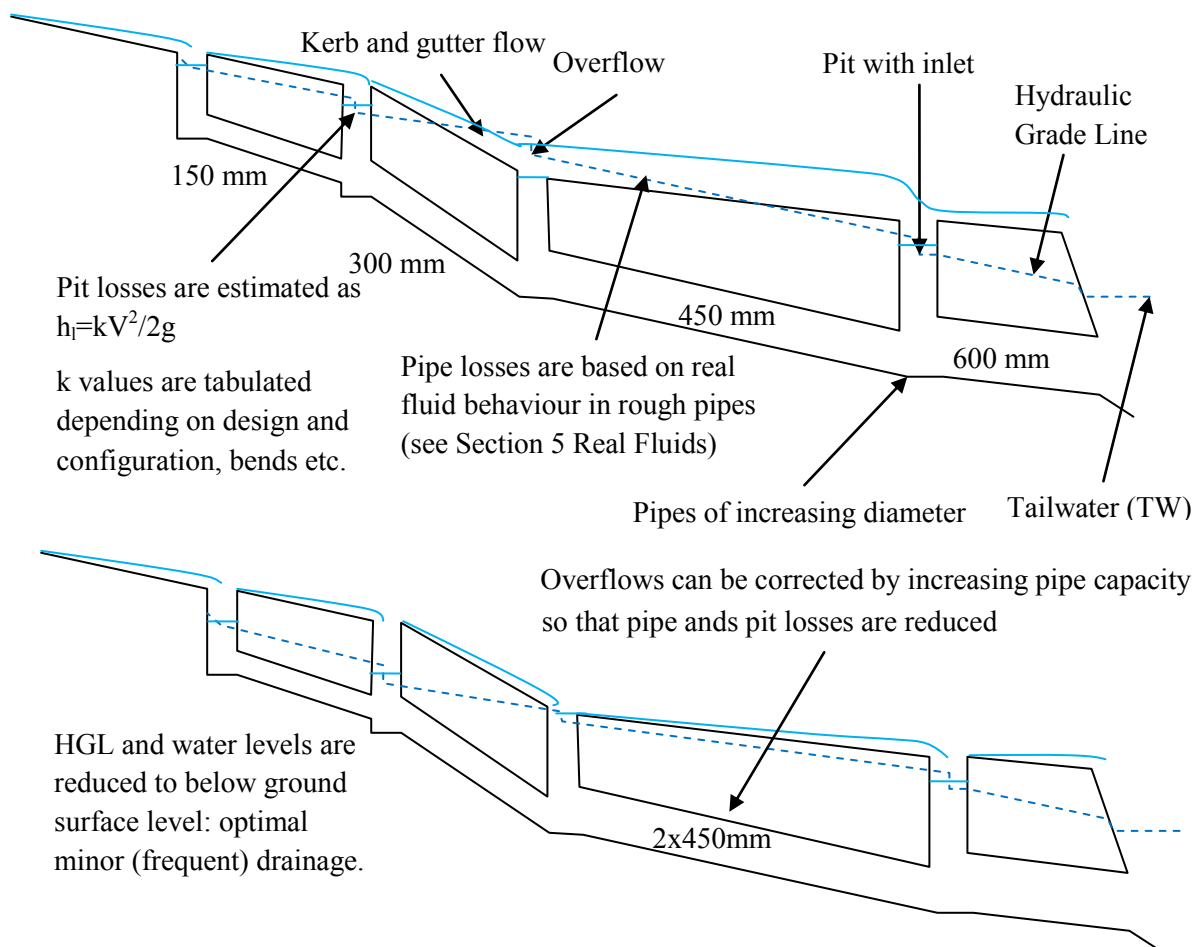
This supplementary lecture covers *some* of the broad principles of drainage design, including the essential focus on safety. In practice this will only be relevant to the Civil Major students, and even they will find that the real world is a very deep pond in comparison to this brief introduction.

### Minor System Drainage Hydraulics

Drainage design incorporates a large number of elements, including the hydrologic (flow-producing) characteristics of the landscape and the hydraulic (flow-carrying) attributes of the drainage surfaces and collectors. A minor drainage system consists of kerbs and gutters draining into pits via kerb inlets, and a system of underground pipes converging on outlets to river or tidal drainage.

The minor system carries only minor storms, up to expected magnitudes recurring on average every two to five years. Larger flows cause road flooding, ideally designed for pedestrian safety (ie no deep or rapid flow concentrations in kerb or footpath) and approach the capacity of the trunk drainage (major) system of open channel and floodplain flows.

A minor drainage system can be visualised in operation as a hydraulic grade line:

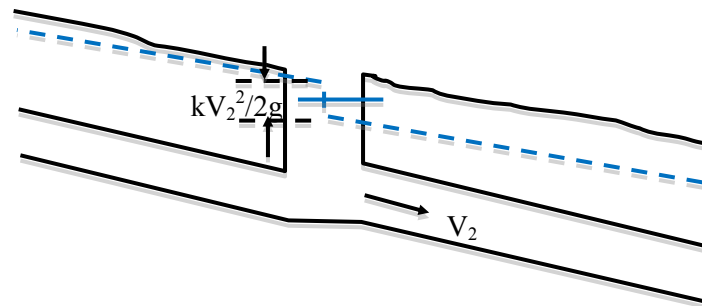


Starting at the tailwater, which is a water level based on a river or tidal model, a designer works upstream and calculates the HGL by adding head losses due to pipe friction and pit losses. The friction slope increases with increasing flow rate or decreasing pipe capacity (diameter and/or condition of inside surface).

For containment of overflows, the designer usually has some limited options for increasing pipe, pit and channel capacities, or of raising the ground surface to contain local flooding. Lowering the tailwater through major downstream hydraulic engineering is another option.

### *Pit Losses in Urban Drainage*

Drainage systems are designed using standard pit loss factors at the major junctions between pipes. Pipe junctions are usually constructed as pit inlets where kerb and gutter flow enters the pipe system. Pits overflow or *surcharge* if the hydraulic grade line at the pit is higher than the street level, hence design allowances are made for losses through the pit.



| <b>Pit-Pipe Configuration</b>          | <b>Approximate Loss Factor k</b>              |
|----------------------------------------|-----------------------------------------------|
| Straight through line                  | 0.5                                           |
| Bend 0° to 45°                         | 0.75                                          |
| Bend 46° to 90°                        | 1.0                                           |
| Junction Pit (Multiple Pipe Inflow)    | 1.5                                           |
| Top Inlet Structures: (No Pipe Inflow) | 2.0 – 8.0 depending on depth of water in pit: |

$$k = 7.5 \left( \frac{d}{D_o} \right)^{-0.76} \quad \text{Top inlet kerb flow in same direction as pipe}$$

$$k = 13.4 \left( \frac{d}{D_o} \right)^{-1.06} \quad \text{Top inlet kerb flow at right angles to pipe}$$

where  $d$  is the depth of water in the pit and  $D_o$  is the outlet pipe diameter (formulae obtained by analysis of design graph 10-2200B Queensland Urban Drainage Manual 1992)

Urban drainage manuals provide standard design graphs of pit losses for various configurations, enabling more economical design. It is often convenient to fit equations to these graphs using curve-fitting methods. Drainage design programs usually include a range of automated calculations based on slope and pipe configurations in GIS and CAD data.

### *Gutter and Kerb Inlet Flows*

Having covered the theory on normal and critical depth, in principal it would now be possible to perform accurate calculations of flow depth in kerb and gutter flow systems, assuming normal depth of flow in the gutter and critical depth occurring at the inlets to kerb drains.

In practice this is very rarely done to any degree of accuracy, for the simple reason that the hydrologic calculation of gutter flowrates is approximate, based on average rainfall conditions over 2- to 5-year recurrence intervals. Hydraulic calculations at this level of approximation aim for acceptable standards of safety and serviceability rather than any degree of precision.

A simplified form of Manning's equation for a general road cross section is Izzard's equation:

$$Q = \frac{0.375Zd^{8/3}S^{1/2}}{n} \quad \text{Izzard's gutter flow rate (m}^3\text{/s)}$$

Where  $Z = 1/\text{road crossfall (slope from crown to gutter)}$ , typically 1 in 30 or  $Z = 30$

$d = \text{flow depth in m}$

$S = \text{road gradient in m/m and } n = 0.015 \text{ (bitumen)}$

Thus given a hydrologic estimate of  $Q$  we can solve for the gutter flow depth:

$$d = \left( \frac{nQ}{0.375ZS^{1/2}} \right)^{3/8} \quad \text{Izzard's gutter flow depth (m)}$$

A very simple triangular flow area gives  $A = Zd^2/2$ . With  $V = Q/A$  we can estimate the flow velocity:

$$V = \frac{Q}{A} = \frac{0.75d^{2/3}S^{1/2}}{n} \quad \text{Izzard's gutter flow velocity (m/s)}$$

Similarly kerb inlet flow rates can be estimated from simplified weir and orifice formulae:

$$Q = 1.8Ld^{3/2} \quad \text{Kerb inlet low-level flowrate (m}^3\text{/s)}$$

Where  $L$  is the length of the edge of the inlet. This would apply for low flowrates, say to a depth 10% of the length of the inlet, above which the flow transitions (drowns) to orifice flow:

$$Q = 0.5A\sqrt{2gd} \quad \text{Kerb inlet high-level flowrate (m}^3\text{/s)}$$

In practice additional complicating factors such as gratings, formed soffits and the effect of approach velocity make these calculations very approximate. Inlet manufacturers typically publish design flow charts which can be applied directly or analysed for correlation formulae.

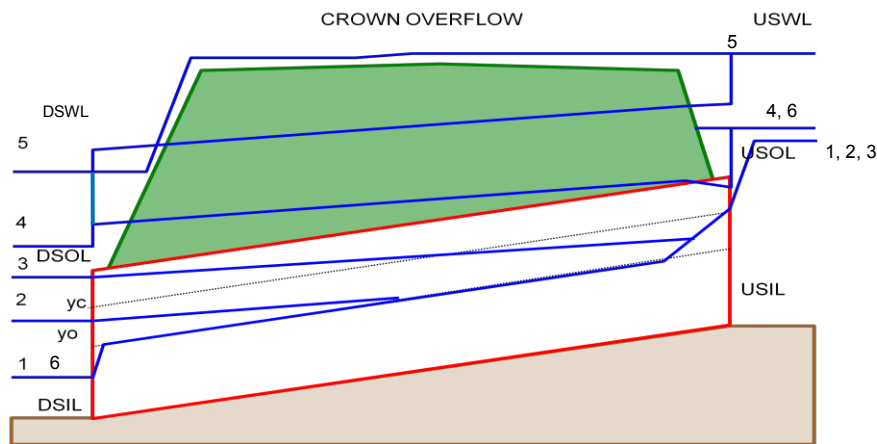
**Road drainage design is the responsibility of local and to some extent State jurisdictions, who will require their design guidelines, formulae and charts to be applied to local conditions. *You must use the standards provided.* These formulae apply only as a very broad brush reality check (although Izzard's equation is often used as a standard).**

### *Culvert Design*

Culverts are at first glance a very simple type of pipe system, consisting of straight lengths of concrete pipe or box section, arranged in single or multiple arrays to convey flows under a roadway.

In fact culvert behaviour is highly complex, combining open channel flow with part-full or full pipe flow and subject to a very wide range of upstream and downstream controls.

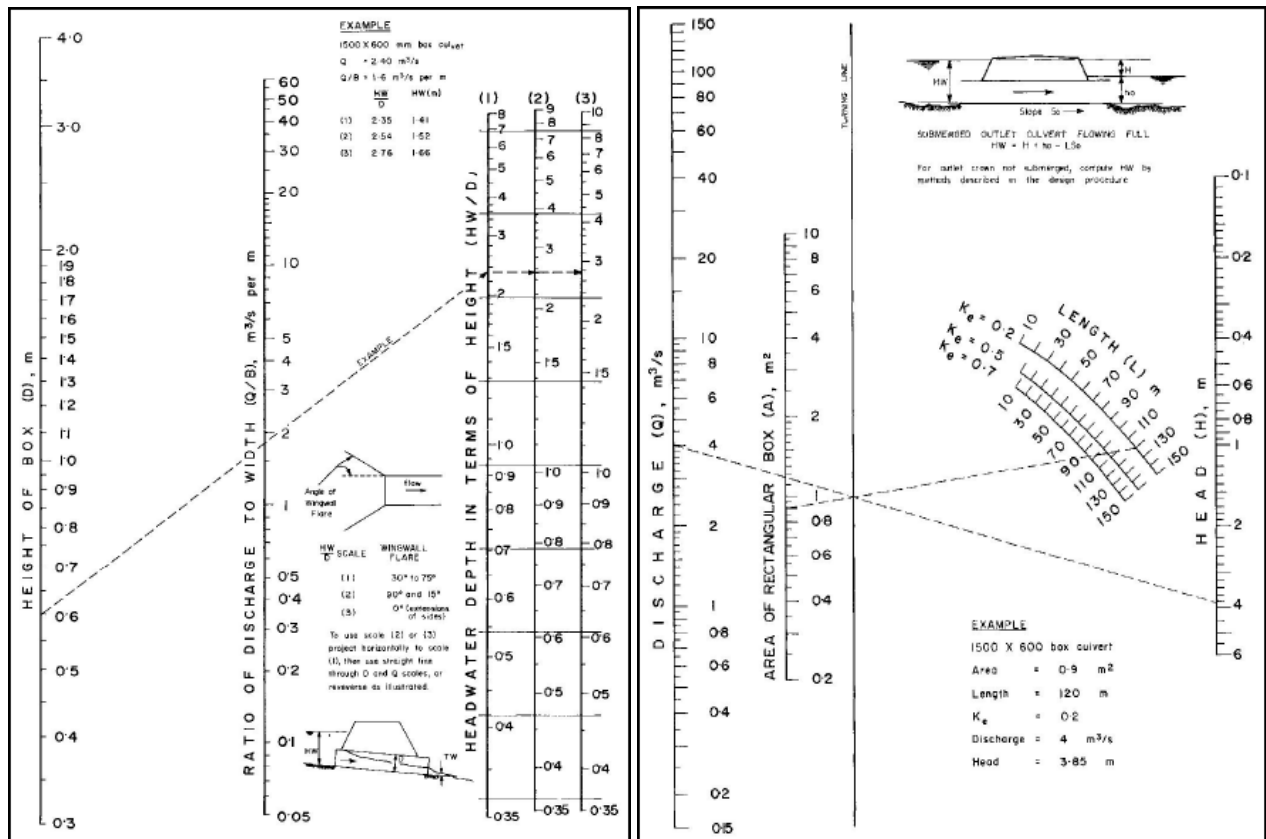
The diagram illustrates the variability of upstream water level (USWL) as a function of downstream water level (DSWL) and design invert (IL) and obvert levels (OL). Culverts are hydraulically smooth and steep, with the result that normal depth is less than critical depth and unconfined flows will be supercritical.



The range of design conditions in a typical culvert is surprisingly complex.

- Case 1: DSWL less than normal depth in the pipe. Flow is *inlet controlled* as the inlet must pass through critical depth ie it behaves as a weir. Outlet gushes at supercritical normal depth. Energy dissipation must be provided at the outlet to prevent erosion of the outlet channel.
- Case 2: DSWL greater than normal depth in the pipe. A minor backwater occurs in the pipe. Flow is inlet controlled as per case 1. Energy dissipation at outlet not so severe.
- Case 3: DSWL greater than critical depth in the pipe. A major backwater occurs in the pipe, possibly drowning the inlet, in which case the water level may step up to case 4, 6. Flow is inlet controlled, varying from weir to orifice inlet behaviour. Inlet vortices may appear.
- Case 4: DSWL greater than DSOL. Flow shifts from inlet control to *outlet control* as the pipe flows full for most or all of its length. Inlet is drowned. USWL determined by adding pipe friction loss to DSWL.
- Case 5: DSWL greater than DSOL and pipe friction slope  $S_f$  greater than bed slope  $S_o$ . Flow is outlet controlled as pipe flows full. Inlet is drowned. USWL determined by adding pipe friction loss to DSWL. Crown overflow (road flooding) may occur.
- Case 6: DSWL less than normal or critical depths but friction slope greater than bed slope. Pipe flows full as water level steps up to DSOL and then determined by outlet control of friction slope. USWL determined by adding pipe friction loss to DSOL.

It would in principle be possible to calculate pipe normal depth, critical depth, and friction slope, and then apply a decision process as to which of case 1 to 6 you are dealing with, but this is seldom done in practice. Culvert nomographs are a common alternative design method requiring only an assessment of whether the culvert is inlet controlled or outlet controlled:



Culvert nomographs: a) Inlet control and b) outlet control (see Reading 16)

Culverts have very significant safety issues, including the risk of children drowning. *Do not underestimate culvert design.*

### Velocity Limits and other safety factors

Despite the intensely theoretical treatment offered so far, the management of urban drainage is a highly practical *art* best based on experience and critical judgement. It is standard practice to base an entire design on uniform flow considerations, avoiding critical and supercritical flow, and in particular keeping well within certain limits based on flood depth and flow speed for safety and erosion control.

Essentially we acknowledge the many uncertainties associated with open channel flow by working with simplified models that are unlikely to lead to serious errors. Significant safety factors are allowed for to ensure that the (unknown) reality does not collide with the simplified models.

### Velocity limits

Flow velocities are limited to avoid erosive accumulations of stream power and in particular to avoid risks to pedestrians particularly children.

A useful rule of thumb often used in kerb and gutter design is to limit the product of flow depth and mean flow velocity to less than a value of  $0.4 \text{ m}^2/\text{s}$ . This ensures that children will not be swept away by gutter flows:

**SAFETY LIMIT ON GUTTER FLOW DEPTH AND VELOCITY:  $V \times d < 0.4 \text{ m}^2/\text{s}$**

It is usually impractical to place depth-velocity limits on major open channel flows other than kerb and gutter flow, nevertheless safety issues should always be kept in mind. There are few suburban scenes more dangerously attractive to a child than an open channel in full flood. *Fencing will not keep a child out.*

Fail-safe escape points such as shallow gratings that will allow a child to climb out before entering drains should be provided. Gratings should be designed so as not to trap a child with the force of water. Channel banks should have gentle slopes (max 1:4) that allow a child a chance to climb out.



*Inclined safety grating on pipe inlet. A child could escape a flood by climbing up the inclined grating.*  
[http://safety.fhwa.dot.gov/local\\_rural/training/fhwasa09024/images/drainage24.jpg](http://safety.fhwa.dot.gov/local_rural/training/fhwasa09024/images/drainage24.jpg)

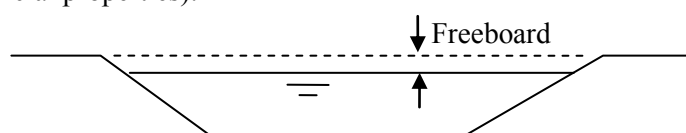
#### *Erosion Control*

Flow velocities should be limited to prevent erosion. The following table provides some suggested limits:

| Maximum Safe Flow Velocities<br>Soil / Cover | m/s        |                           |                       |
|----------------------------------------------|------------|---------------------------|-----------------------|
|                                              | Bare Earth | Moderate Vegetation Cover | Good Vegetation Cover |
| Easily Erodible Soils (Black Earth, Sand)    | 0.5        | 1                         | 1.5                   |
| Susceptible Soils (Solodics, Sandy Loam)     | 0.6        | 1.5                       | 2                     |
| Erosion-Resistant Soils (Silty Loam, Gravel) | 1          | 2                         | 2.5                   |

#### *Depth limits*

In practice there is no limit to how deep a channel can be. To prevent flooding a *design freeboard*, or free depth above the water surface, should be adopted. Freeboard may be between 100 mm (no significant safety issues or economic risks) and 300 mm (adjacent residential or high-value commercial properties):

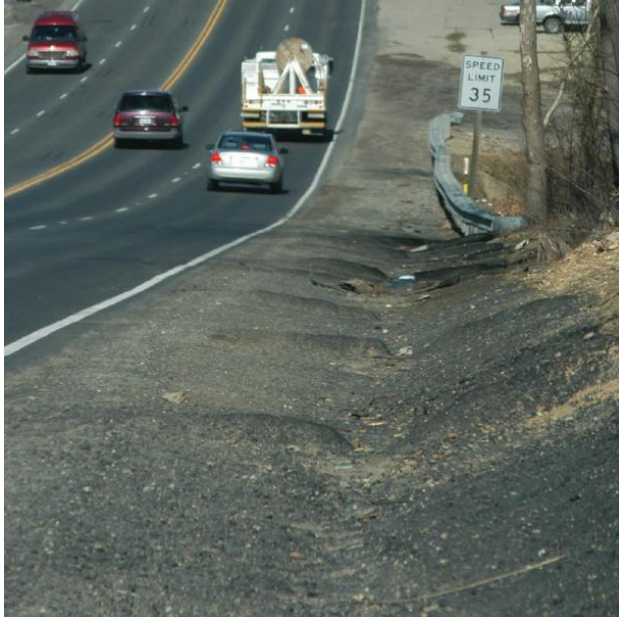


*Freeboard: 100 – 300 mm depending on adjacent property and safety values*

### *Traffic and Channel Design*

There is an entire branch of transport design dedicated to integrating traffic safety issues with drainage design. Clearly there is no space to go into that here. See Reading 15 for more detail.

In general, open drains should be *traversable*, that is it should be possible to drive over, or in a worst case scenario even spin out of control over, an open drain. Constructed elements (concrete soffits and margins) should not become collision hazards, and failed drainage elements should not threaten the stability of the roadway structure.



*a) Traversable open drain*



*b) Hazardous non-traversable ditch*

One of the most terrifying accidents of the 2007 NSW Easter holiday season was caused by the failure of a culvert which flooded and undermined the roadway. The roadway collapsed suddenly, creating a torrential outflow into which the first car of the traffic stream plunged. Witnesses told of the driver desperately trying to rescue the passengers, but all were swept to their deaths.

### **Reading**

**US Department of Transport (Reading 15)**

**QLD Department of Transport and Main Roads (Reading 16)**