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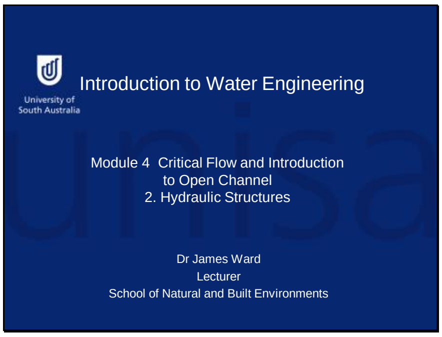

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Introduction to Water Engineering

Module 4 Critical Flow and Introduction
to Open Channel
2. Hydraulic Structures

Dr James Ward
Lecturer
School of Natural and Built Environments

Welcome to Module 4, part 2, hydraulic structures

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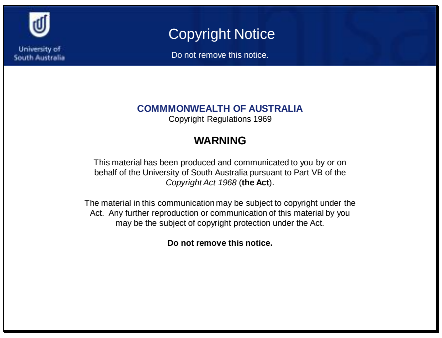

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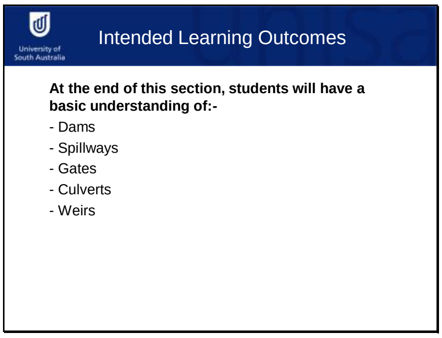

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Intended Learning Outcomes

At the end of this section, students will have a basic understanding of:-

- Dams
- Spillways
- Gates
- Culverts
- Weirs

The learning outcomes are presented here – we'll look at various types of hydraulic structures including dams, spillways, gates, culverts and broad-crested weirs. We won't go into a lot of detail with calculations here; it's more of an introduction into the nature of these structures.

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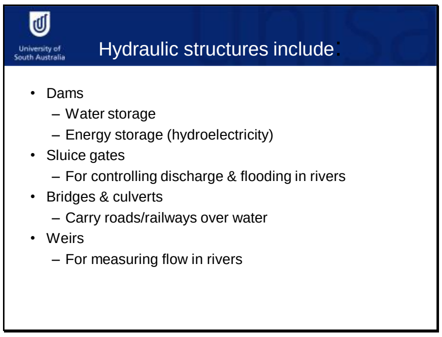

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Hydraulic structures include

- Dams
  - Water storage
  - Energy storage (hydroelectricity)
- Sluice gates
  - For controlling discharge & flooding in rivers
- Bridges & culverts
  - Carry roads/railways over water
- Weirs
  - For measuring flow in rivers

When we talk about hydraulic structures we tend to mean large structural devices that get used for either water supply or for managing water flows. Examples of hydraulic structures include

dams,

Which we use to store water for all sorts of uses

Or for storing energy for hydro power

We can also look at sluice gates,

Which are special gates for regulating water flows in rivers and channels, for instance to control flooding

Then there's bridges and culverts

which are generally transport structures used to overcome the barrier that water tends to present

and last of all, we'll look at weirs for measuring flow in rivers.

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Dams

First let's look at Dams

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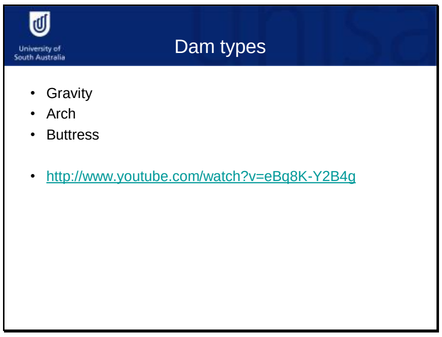

Dam types

- Gravity
- Arch
- Buttress

- http://www.youtube.com/watch?v=eBq8K-Y2B4g

The most common dam types are categorised into gravity, arch and buttress dams. Here's a fun little video involving an arch dam.

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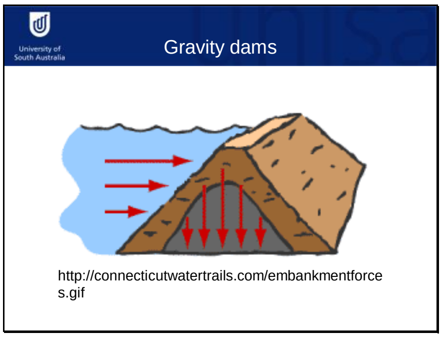

Gravity dams

http://connecticutwatertrails.com/embankmentforces.gif

It's easy to picture a dam as some sort of device that holds back the water, which in engineering terms just means it's resisting the hydrostatic force. So the simplest way to do this is plonk something heavy there, and that's called a gravity dam. It relies on the weight of the dam generating enough friction to stop it sliding away under the force of the water. So the thing you're designing in a gravity dam is basically the width of the structure, which generates the overall weight.

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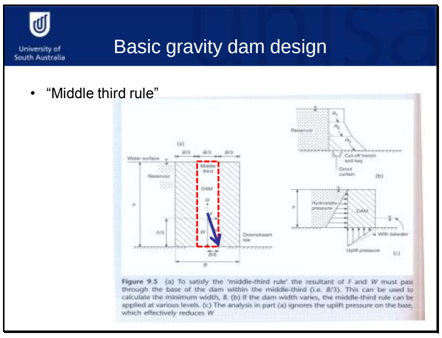

Basic gravity dam design

- "Middle third rule"

Figure 9.5 (a) To satisfy the 'middle-third rule' the resultant of F and W must pas through the base of the dam within the middle-third (i.e. B/3). This can be used to calculate the minimum width, B. (b) If the dam width varies, the middle-third rule can be applied at various levels. (c) The analysis in part (a) ignores the uplift pressure on the base, which effectively reduces W

The easiest way to understand how a gravity dam' work is to simplify it to a rectangular cross-section. The design uses what's called the "middle third rule",

which means the resultant force, which you get from the combined hydrostatic force and the dam weight, has to pass through the middle third of the dam. This translates into the dam width being the key design parameter. The wider you make the dam, the wider the middle section is, which means it's easier for the force to be passing through that section, but also the wider you make the dam the heavier it is, assuming it's made of the same material, so that makes the vertical component of the resultant force higher, making it more likely to pass through the middle third.

Image source- Les Hamill 2011, Understanding hydraulics.

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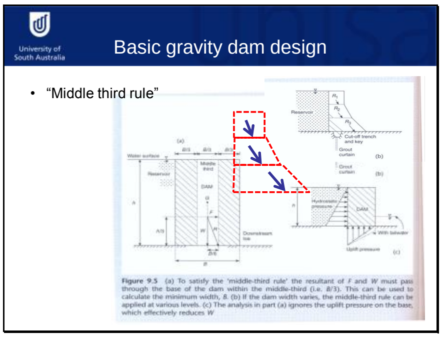

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Basic gravity dam design

- "Middle third rule"

Figure 9.5 (a) To satisfy the 'middle-third rule' the resultant of F and W must pass through the base of the dam within the middle-third (i.e. $B/3$). This can be used to calculate the minimum width, B. (b) If the dam width varies, the middle-third rule can be applied at various levels. (c) The analysis in part (a) ignores the uplift pressure on the base, which effectively reduces W

If you've got a gravity dam made of some sort of composite structure,

the same middle third rule can be applied to each component.

So you'd work out the resultant of the hydrostatic force acting on each individual section

And the weight force from that section

And try design the structure so the resultant passes through the middle third of each component part.

Image source- Les Hamill 2011, Understanding hydraulics.

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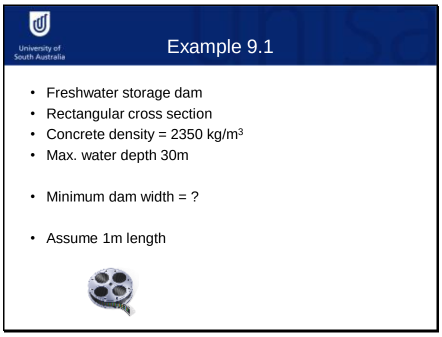

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Example 9.1

- Freshwater storage dam
- Rectangular cross section
- Concrete density = 2350 kg/m^3
- Max. water depth 30m
- Minimum dam width = ?
- Assume 1m length

So here's an example – we've got a simple rectangular dam that we're going to make out of concrete with a density of just under 2.4 tonnes per cubic metre. We're dealing with a maximum water depth of 30 metres so we'll use that as our design state for working out the hydrostatic force. We just need to work out the dam width that'd give us enough weight to push the resultant force through the middle third. To work out the hydrostatic force and the weight you need a length so just assume 1 metre. As usual you can consult the textbook if you've got any dramas.

http://www.youtube.com/watch?v=w2Q_x89GCKA

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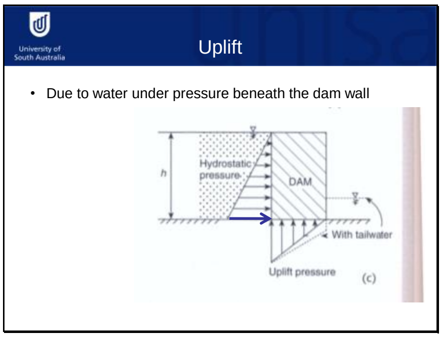

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Uplift

- Due to water under pressure beneath the dam wall

One of the problems with gravity dams is that the soil under the dam can get saturated,

Which means the hydrostatic pressure at the bottom of the dam in the water ends up underneath the dam as well. The distribution of pressure along the dam base depends on whether the other side of the dam's open to atmospheric pressure or whether there's water there at a different level, but in any case the net result is some degree of uplift due to buoyancy, which effectively takes away some of the weight force you're relying on in your gravity dam design.

Image source- Les Hamill 2011, Understanding hydraulics.

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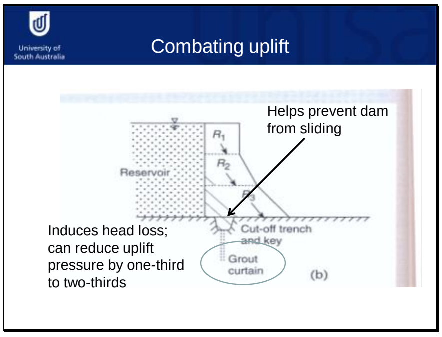

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Combating uplift

Helps prevent dam from sliding

Induces head loss; can reduce uplift pressure by one-third to two-thirds

You can do a couple of things in the dam design to combat uplift;

one is to factor in a grout curtain, which is basically a deep trench under the dam filled with really low-permeability grout;

This induces a head loss from one side to the other as water seeps through, in other words it means that while there's still water under the dam, the stuff on the other side of the grout curtain's at a lower pressure than it would be otherwise, and because of the reduced pressure there's less uplift.

Another common design is to key the dam into the soil, which increases the resistance of the dam against the hydrostatic force of the water. Obviously water isn’t necessarily the only force the dam has to contend with and in some cases the design loads due to earthquakes, or even forces due to ice or waves could be dominant.

Image source- Les Hamill 2011, Understanding hydraulics.

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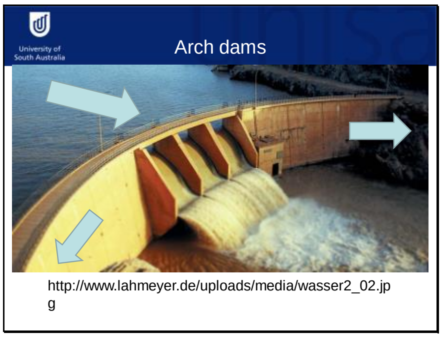

Arch dams

http://www.lahmeyer.de/uploads/media/wasser2_02.jpg

Gravity dams are a simple idea, and aren’t necessarily efficient in terms of materials. Arch dams are more elegant than gravity dams for engineering solutions. Whereas the gravity dam relies on absolute weight for holding water back, the arch dam relies on deflecting that force out to the sides, so it’s got the advantage of any arch structure. Arch dams can be concave in one or both directions.

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Spillways

Now for Spill ways and Drawoffs

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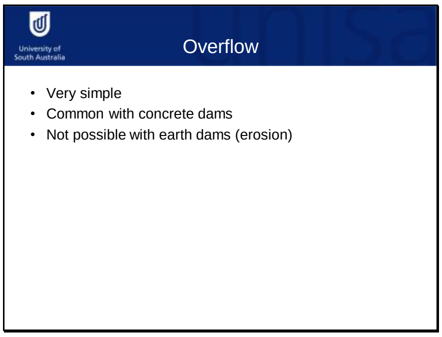

Overflow

- Very simple
- Common with concrete dams
- Not possible with earth dams (erosion)

In general, dams need to be designed with some way of safely dealing with surplus water where there's more water than you can store. A simple overflow's a common approach in concrete dams, where a channel or chute can be built into the concrete structure quite easily. But this isn't really possible on an earth or agricultural dam due to erosion problems with the overflowing water.

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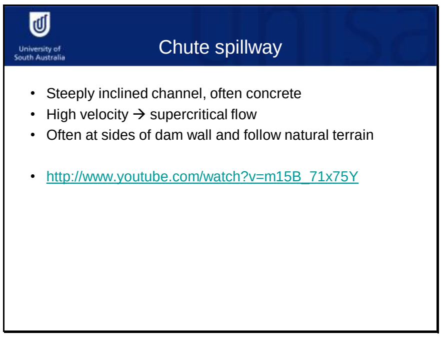

Chute spillway

- Steeply inclined channel, often concrete
- High velocity → supercritical flow
- Often at sides of dam wall and follow natural terrain

- http://www.youtube.com/watch?v=m15B_71x75Y

Chute spillways are typically very steep, which causes high velocity and supercritical flow conditions. It's typical to construct the chute at the edge of the dam, so it can follow the natural terrain. Here's a silly video of a chute spillway.

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Shaft spillway

This picture shows a shaft spillway.

Image source: http://s0.geograph.org.uk/photos/89/40/894058_fe70637d.jpg

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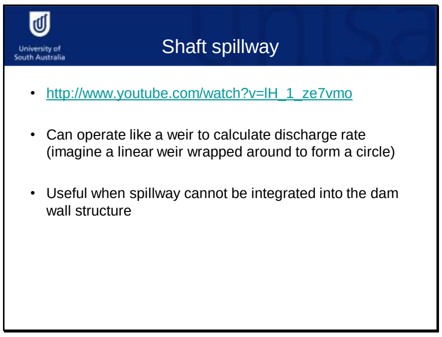

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Shaft spillway

- http://www.youtube.com/watch?v=IH_1_ze7vmo
- Can operate like a weir to calculate discharge rate (imagine a linear weir wrapped around to form a circle)
- Useful when spillway cannot be integrated into the dam wall structure

A shaft spillway basically operates like a weir as a flow measurement device – we've only looked at weirs that are straight but there's no real reason why they can't be wrapped round into a circle. It could also be useful to use a shaft as a spillway, when for some reason a conventional chute can't be integrated into the dam wall structure.

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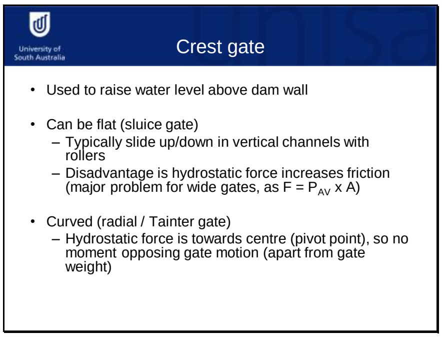
Gates

Now for Gates

Slide 20



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Crest gate

- Used to raise water level above dam wall
- Can be flat (sluice gate)
  - Typically slide up/down in vertical channels with rollers
  - Disadvantage is hydrostatic force increases friction (major problem for wide gates, as $F = P_{AV} \times A$)
- Curved (radial / Tainter gate)
  - Hydrostatic force is towards centre (pivot point), so no moment opposing gate motion (apart from gate weight)

So we we've got a need to deal with overflowing water, and we just had a brief look at some of the spillway devices that we can incorporate into the dam structure one way or another. But if we've got potentially large flows that could cause flooding downstream, we need to be able to regulate the flow at the top of the dam wall, to release it at a safe rate. This means we need adjustable structures that either raise a wall to hold back extra water, or else they open up a given amount and let the water out at an appropriate rate. There are a variety of gates used at the crest of dams; one simple design is called a sluice gate, which is a flat, typically rectangular gate that can also be used in a channel. The problem with the flat gate is that it can't be made very wide because force is equal to pressure times area, and this increases the friction on the rollers at the edge of the gate. So, often the preference is what's called either a radial or "Tainter" gate, which directs the force to a central axle that's easier to manage.

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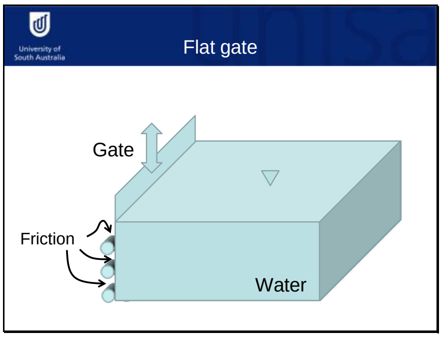

Flat gate

Flat gates are nice and simple,

but the problem is that the overall hydrostatic force

Is proportional to the gate width, which could be pretty big for a decent sized dam. This all gets translated into friction on the rollers at the edges of the gate , which can get hard to manage.

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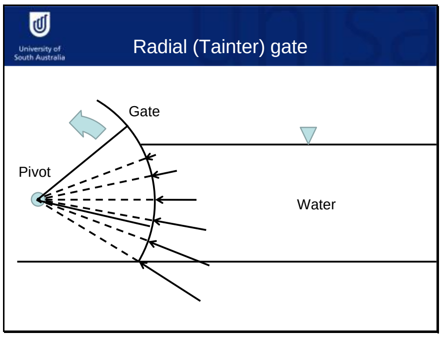

Radial (Tainter) gate

In radial gates, the shape of the gate's always a part-circle

And as we know in hydrostatics the pressure always acts perpendicular to the surface

So the forces distributed over the curved surface all end up going through the centre of curvature, and the operation's basically like an axle.

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Radial gates can be used to regulate channel flow, too.
Image source - http://upload.wikimedia.org/wikipedia/commons/3/30/Carlyle_Lake_Dam_gates_open.jpg

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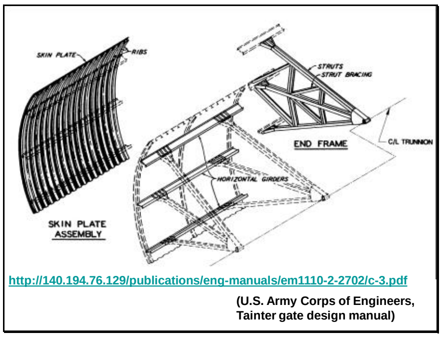

http://140.194.76.129/publications/eng-manuals/em1110-2-2702/c-3.pdf

(U.S. Army Corps of Engineers, Tainter gate design manual)

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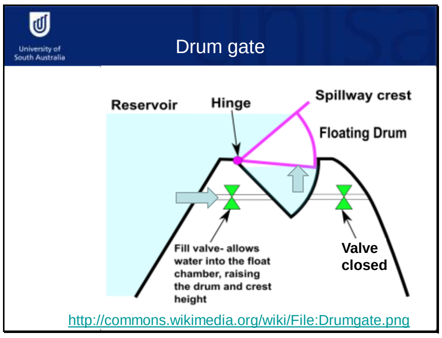

Drum gate

http://commons.wikimedia.org/wiki/File:Drumgate.png

A really nifty gate is a thing called a drum gate; it sits inside a little receptacle at the top of the dam wall. The chamber's got an inflow and outflow pipe, each one with a valve on it.

When the inflow valve's open and the outflow's closed, water from the dam fills the chamber

and the drum gate floats up. This is a way to artificially raise the height of the dam.

Image source – Wikimedia.

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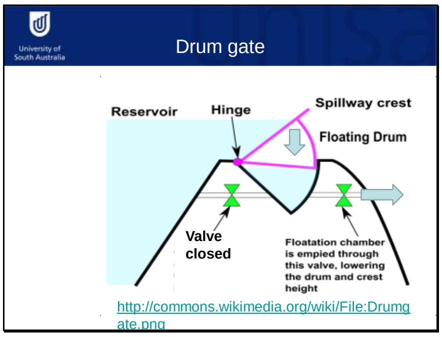

Drum gate

http://commons.wikimedia.org/wiki/File:Drumgate.png

When you want to lower the water level, you close the inflow valve and open the outflow.

This drains the chamber

and the floating gate can come down.

Image source – Wikimedia.

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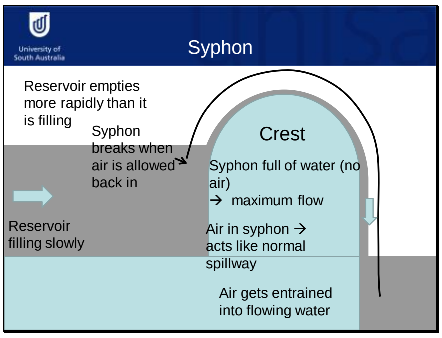

Syphon

An automatic syphon's another way of emptying a reservoir.

Imagine the water level rising like this. When it reaches the height of the crest, it starts to spill over, just like a normal spillway which operates under atmospheric conditions

But because the syphon takes place in a closed conduit, air gradually get entrained by water and creates a suction effect;

once the syphon's full of water, it basically operates as a full pipe, so the water's being driven by the head difference between the upstream and downstream levels. This tends to be faster than the open channel flow generated by atmospheric conditions. As a result the reservoir empties more quickly than the filling rate,

and the level goes back down until it breaks the syphon, letting air back into the line. These systems can be used to maintain a reservoir level within a fairly narrow range, or in small-scale applications like hydroponic plant production, these auto-syphons can be useful to create a reciprocating cycle of filling and draining.

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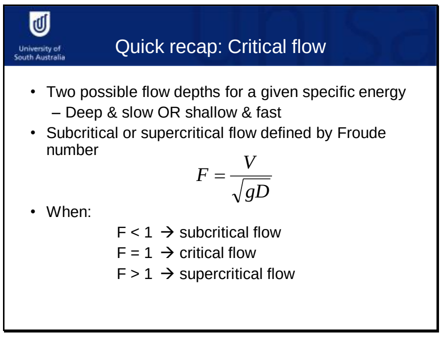

Quick recap: Critical flow

- Two possible flow depths for a given specific energy
  - Deep & slow OR shallow & fast
- Subcritical or supercritical flow defined by Froude number

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

- When:

F < 1 → subcritical flow
F = 1 → critical flow
F > 1 → supercritical flow

Just to jog your memory.

There are two flow depths for open channel flow of a particular specific energy

The subcritical flow condition is deep and slow ,and supercritical flow is shallow and faster. The exception is the critical flow condition, which only has the one flow depth.

We use the Froude number to work out whether we're at supercritical or subcritical flow, and that's velocity over the square root of gravity times the water depth.

When F's less than one, we've got relatively low velocity combined with relatively large water depth, so that's subcritical flow with slow, deep water. When it's greater than one we've got relatively high velocity and relatively low water depth, so that's the fast and shallow, or supercritical condition. Obviously if F equals 1 then it's critical flow.

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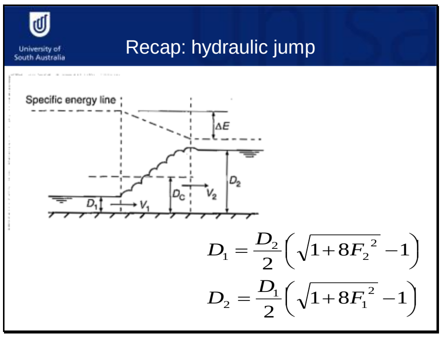

Recap: hydraulic jump

$$D_1 = \frac{D_2}{2}\left(\sqrt{1+8F_2^2}-1\right)$$

$$D_2 = \frac{D_1}{2}\left(\sqrt{1+8F_1^2}-1\right)$$

The other thing we need to quickly recap is the hydraulic jump, where you had this sort of relationship between the upstream and downstream flow depths and the Froude number. You can use these equations to work out whether you've got the right combination of conditions for a hydraulic jump to form, which basically means you can work out how deep the water needs to be on one side given a known depth and Froude number on the other side of the jump.

Image source- Les Hamill 2011, Understanding hydraulics.

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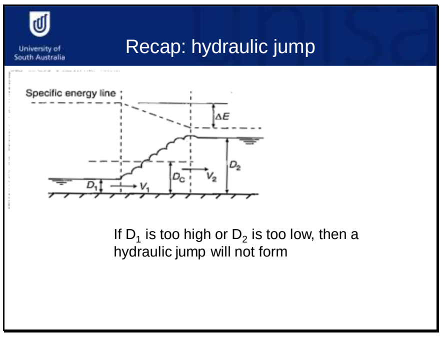

Recap: hydraulic jump

If D_1 is too high or D_2 is too low, then a hydraulic jump will not form

Essentially, if there's a situation where the upstream flow's too deep or the downstream flow's too shallow, a hydraulic jump can't form. It's important to know this, because our hydraulic designs are based on water flowing under particular conditions. For instance sluice gates might be designed to discharge water under supercritical conditions, on the expectation that downstream that water'll transition back to subcritical via a hydraulic jump. If we find out that we haven't got the right conditions for a hydraulic jump, it could mean the whole design is incorrect and it won't discharge the way we expect it to.

Image source- Les Hamill 2011, Understanding hydraulics.

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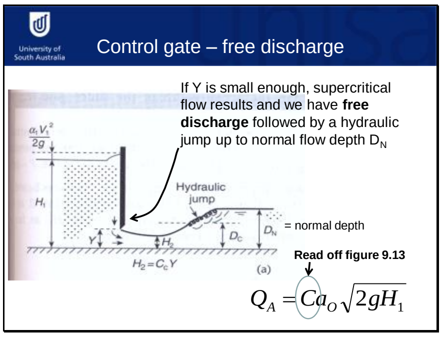

Control gate – free discharge

If Y is small enough, supercritical flow results and we have **free discharge** followed by a hydraulic jump up to normal flow depth D_N

= normal depth

Read off figure 9.13

$$Q_A = C a_O \sqrt{2gH_1}$$

Let's look at that a bit more here. We've got a sluice gate forcing water from a channel through a smaller space; it's important to know whether it is going to discharge freely or not.

In order to get freely discharge, supercritical flow needs to be coming out of the gate, which really means the height Y should be set low enough to force fast-moving, supercritical conditions. If we've got the right conditions then there'll be a hydraulic jump downstream and flow should transition to some normal flow depth later. The discharge equation at the bottom here's very similar to other discharge equations like orifice flow.

The co-efficient of discharge (C) comes from Figure 9.13 of the text book.

Image source- Les Hamill 2011, Understanding hydraulics.

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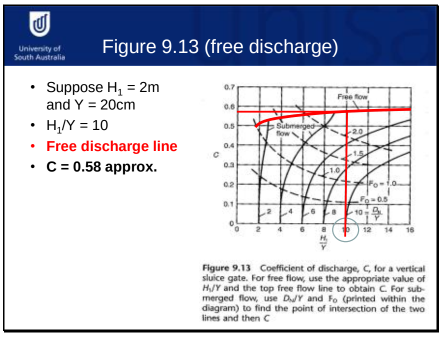

Figure 9.13 (free discharge)

- Suppose H_1 = 2m and Y = 20cm
- $H_1/Y = 10$
- **Free discharge line**
- **C = 0.58 approx.**

Figure 9.13 Coefficient of discharge, C, for a vertical sluice gate. For free flow, use the appropriate value of H_1/Y and the top free flow line to obtain C. For submerged flow, use D_N/Y and F_O (printed within the diagram) to find the point of intersection of the two lines and then C

Here's how we use that figure to work out the coefficient of discharge.

Let's pick an example where the upstream flow depth is 2 metres and we've got a gate lifted 20 centimetres off the channel bed

So H1/Y is 10 in this case.

Under free discharge conditions, which means supercritical flow ,

we find the coefficient of discharge is about 0.58 by looking for the intercept on the graph. Hopefully you can see how if we didn't have the conditions to sustain supercritical flow under the gate, we'd be looking at one of the submerged flow lines which depend on several other factors and the calculation ends up being quite different.

Image source- Les Hamill 2011, Understanding hydraulics.

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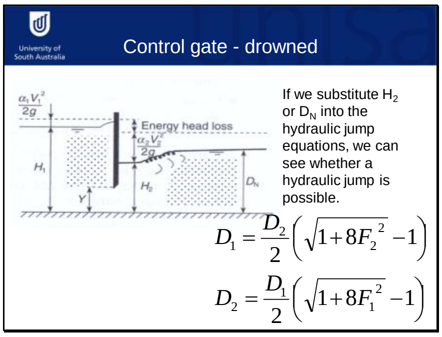

Control gate - drowned

If we substitute H_2 or D_N into the hydraulic jump equations, we can see whether a hydraulic jump is possible.

$$D_1 = \frac{D_2}{2}\left(\sqrt{1+8F_2^{\ 2}} - 1\right)$$

$$D_2 = \frac{D_1}{2}\left(\sqrt{1+8F_1^{\ 2}} - 1\right)$$

Drowned conditions are what we refer to when there's no supercritical flow and a hydraulic jump can't form. It means that the deeper flow conditions downstream migrate back up until they reach the gate, and now the height H2 is greater than the height of the gap under the gate (Y).

To work out whether a hydraulic jump is going to occur, and therefore to figure out whether you've got free discharge or submerged flow, you need to use those hydraulic jump formulae again; typically you'd use the top formula, substituting DN for D2 and the corresponding Froude number at that flow. Then, you'd get a value for the required upstream depth D1 and compare it to your value of H2 – if H2 is less than this value, then it means you've got supercritical conditions, so you get a hydraulic jump.

Image source- Les Hamill 2011, Understanding hydraulics.

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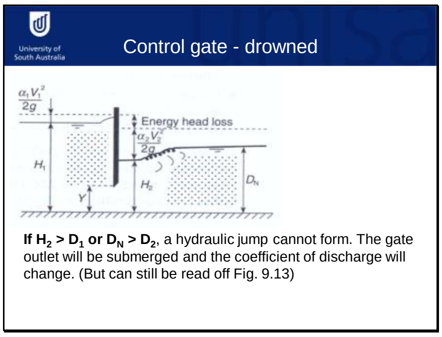

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Control gate - drowned

If $H_2 > D_1$ or $D_N > D_2$, a hydraulic jump cannot form. The gate outlet will be submerged and the coefficient of discharge will change. (But can still be read off Fig. 9.13)

If H2 is greater than D1 or DN is greater than D2, a hydraulic jump won't be able to form so you can expect the outlet to be submerged.

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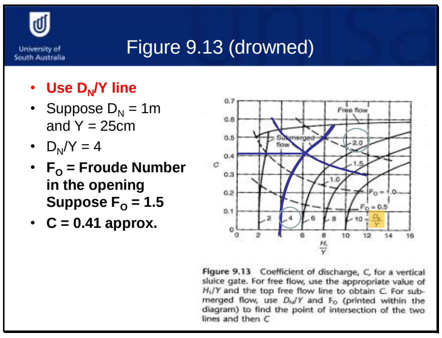

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Figure 9.13 (drowned)

- **Use D_N/Y line**
- Suppose D_N = 1m and Y = 25cm
- D_N/Y = 4
- **F_O = Froude Number in the opening Suppose F_O = 1.5**
- **C = 0.41 approx.**

Figure 9.13 Coefficient of discharge, C, for a vertical sluice gate. For free flow, use the appropriate value of H_1/Y and the top free flow line to obtain C. For submerged flow, use D_N/Y and F_O (printed within the diagram) to find the point of intersection of the two lines and then C

Let's look at an example of that now.

The crucial thing here is we're looking at the downstream flow depth DN dominating the discharge conditions, so we use the DN/Y line.

Let's say the downstream flow depth DN is 1 m and Y is 25 cm

So, DN/Y is 4. Then we follow the DN/Y line at 4, and look for the intercept with the appropriate Froude number taken in the gate opening.

If we say for argument's sake that the Froude number's 1.5,

then joining it up we can get the approximate value of coefficient of discharge C as 0.41.

Image source- Les Hamill 2011, Understanding hydraulics.

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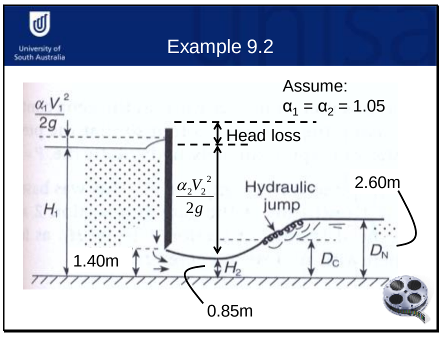

Example 9.2

Assume:
$\alpha_1 = \alpha_2 = 1.05$

Let's put it together in an example.

We've got channel flow and a sluice gate that's been lifted up by 1.4 metres

The water shoots out and there's a vena contracta with depth 0.85 metres, which is what we'll use for our depth H2.

Downstream normal flow depth is 2.6 metres, so we'll need to figure out whether we've got the right conditions for a hydraulic jump or whether that's going to migrate back to force it to be a submerged outlet.

You'll notice the velocity head terms for the energy equation have an "alpha" attached to them – these are energy coefficients and we'll assume they're both equal to 1.05. See how you go - if there's a problem, always consult the textbook.

http://www.youtube.com/watch?v=_v6h4VEPRGo
Image source- Les Hamill 2011, Understanding hydraulics.

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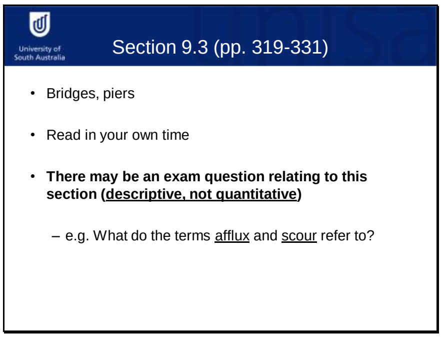

Section 9.3 (pp. 319-331)

- Bridges, piers
- Read in your own time
- **There may be an exam question relating to this section (descriptive, not quantitative)**
  - e.g. What do the terms afflux and scour refer to?

There's a whole lot of interesting stuff in the textbook on bridges and piers. Any exam questions on this material will be qualitative, not quantitative, and quantitative aspects of design for these types of structures is left to later studies. But it's useful if you have a read of this section, 9.3 in your own time.

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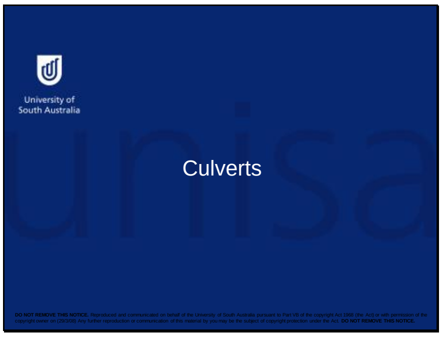

Culverts

Alright, now on to Culverts

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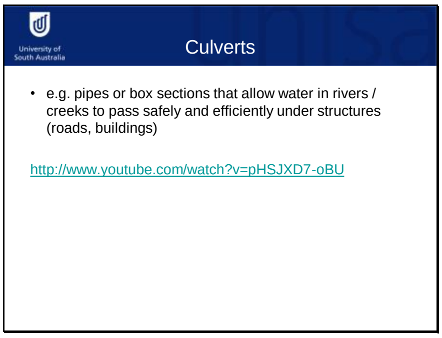

Culverts

- e.g. pipes or box sections that allow water in rivers / creeks to pass safely and efficiently under structures (roads, buildings)

http://www.youtube.com/watch?v=pHSJXD7-oBU

Here’s a nice little YouTube video showing the construction of a culvert. Culverts are pipes or box sections that allow water in rivers and creeks to pass safely and efficiently under structures. They’re a simple alternative to a bridge, and they tend to be cost-effective for relatively small flows such as those you typically find in urban catchments and small natural streams or creeks.

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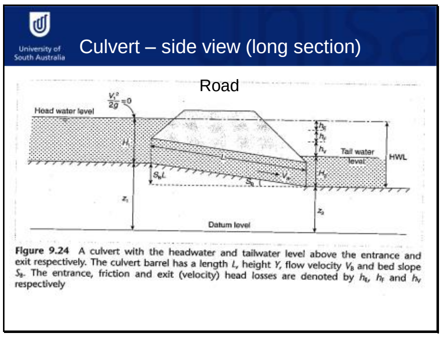

Culvert – side view (long section)

Figure 9.24 A culvert with the headwater and tailwater level above the entrance and exit respectively. The culvert barrel has a length L, height Y, flow velocity V_B and bed slope S_B. The entrance, friction and exit (velocity) head losses are denoted by h_E, h_F and h_V respectively

This drawing might take a moment or two to understand – we’re looking at a cross section where the road’s running into the page, and it’s crossing over a stream that runs from left to right. The culvert’s the bit under the road, labelled here with a length, L. In this case both the entrance and the exit of the culvert are submerged so you’d analyse this situation like any full pipe. But depending on the conditions, the inlet and/or outlet might not be submerged. If the culvert’s not flowing full, it needs to be analysed as an open channel and then you might encounter subcritical or supercritical conditions that depend on the flow rate, size of the culvert and the bed slope.

Image source- Les Hamill 2011, Understanding hydraulics.

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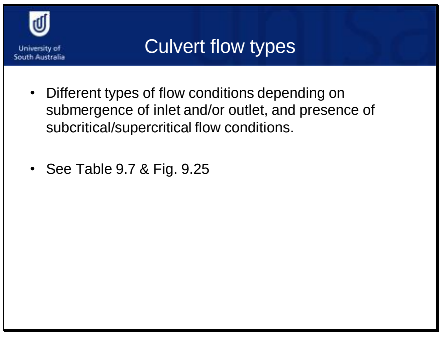

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Culvert flow types

- Different types of flow conditions depending on submergence of inlet and/or outlet, and presence of subcritical/supercritical flow conditions.
- See Table 9.7 & Fig. 9.25

Table 9.7 and Figure 9.25 in the textbook give the description of different culvert flow types. We'll go through them one by one.

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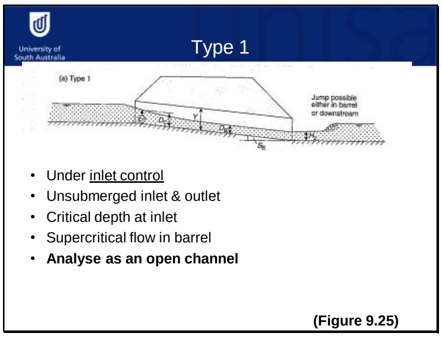

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Type 1

- Under inlet control
- Unsubmerged inlet & outlet
- Critical depth at inlet
- Supercritical flow in barrel
- **Analyse as an open channel**

(Figure 9.25)

So we're looking at the same basic cross-section as before, but we've got an open inlet and outlet so it's an open channel type of analysis. The Type 1 culvert is under what we refer to as "inlet control". This means that the inlet is the point with the lowest discharge capacity so it dictates the overall capacity of the culvert. The critical point here happens to be where there's critical flow, that is, where the depth changes to critical depth. The slope of the culvert is steep enough that the rest of the flow's supercritical which is why the limiting discharge was at the inlet.

Image source- Les Hamill 2011, Understanding hydraulics.

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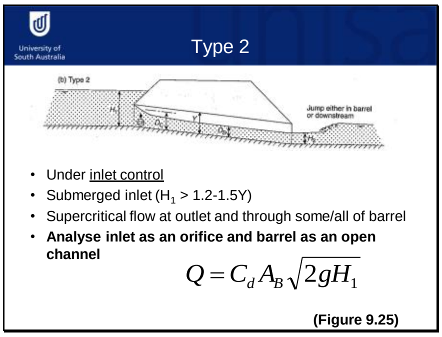

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Type 2

- Under inlet control
- Submerged inlet (H_1 > 1.2-1.5Y)
- Supercritical flow at outlet and through some/all of barrel
- **Analyse inlet as an orifice and barrel as an open channel**

$$Q = C_d A_B \sqrt{2gH_1}$$

(Figure 9.25)

Moving on, now we've got the Type 2 culvert, where the combination of flow and culvert size leads to a submerged inlet. But, the slope of the culvert's enough to let the flow go through critical and down to supercritical for most of the length, which means it's still atmospheric pressure inside the culvert so we still analyse it as an open channel. However, in this case we need to analyse the flow through the inlet as discharge through an orifice, using something like the equation here with AB being the cross-sectional area of the barrel. Like the Type 1 culvert, the control point's near the inlet so this is under "inlet control". Depending on the specific design, it might be that the limiting discharge comes from the flow capacity of the inlet orifice, or maybe it's the subcritical flow that happens before it transitions to supercritical. Either way the control point's up near the inlet.

Image source- Les Hamill 2011, Understanding hydraulics.

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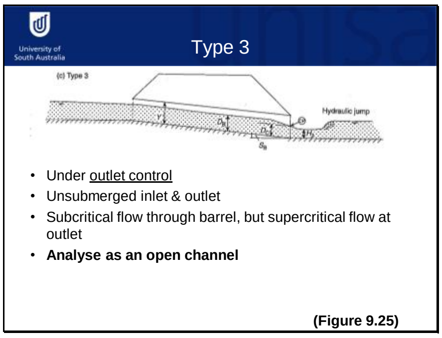

Type 3

- Under outlet control
- Unsubmerged inlet & outlet
- Subcritical flow through barrel, but supercritical flow at outlet
- **Analyse as an open channel**

(Figure 9.25)

In type 3 culverts, both ends are open and at first glance it looks just like a Type 1. The difference is that there's subcritical flow through the whole culvert with critical flow reached just at the outlet, whereas the Type 1 had supercritical flow throughout most of the culvert. So this one's a slower-flow situation and the limiting flow occurs at the critical depth, so the control point's actually at the outlet. You'd still analyse the whole thing as an open channel, same as Type 1.

Image source- Les Hamill 2011, Understanding hydraulics.

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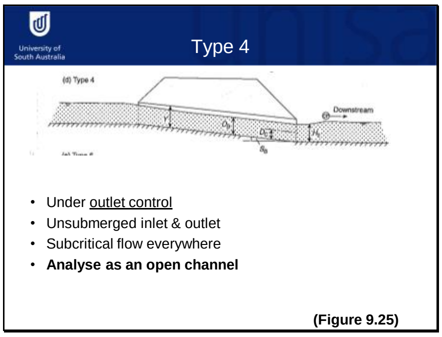

Type 4

- Under outlet control
- Unsubmerged inlet & outlet
- Subcritical flow everywhere
- **Analyse as an open channel**

(Figure 9.25)

Type 4 has a subtle difference from type 3; again we've got subcritical flow everywhere in the culvert and we analyse it as an open channel, but in this case there's no transition to critical and supercritical flow at the end. Hopefully you might remember that one of the fundamental things about subcritical and supercritical flow was that in subcritical flow, things downstream can propagate upstream whereas in supercritical flow they can't. So the transition point where it went through critical flow to supercritical in the Type 1 and Type 3 culverts was really important because it meant that whatever happened downstream from there wasn't going to affect the flow in the culvert. But in this case, we don't have that sort of "break point" and there could be some interruption to the flow downstream that's causing water to back up. So the control point that influences the design flow's actually located somewhere downstream of the outlet – but we still call it "outlet control" as distinct from “inlet control”.

Image source- Les Hamill 2011, Understanding hydraulics.

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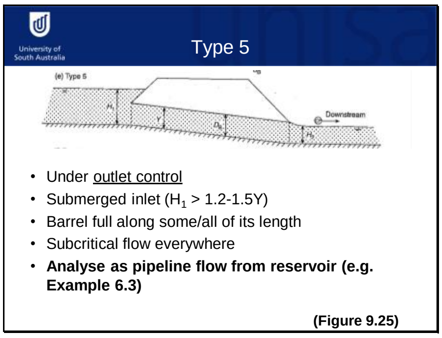

Type 5

- Under <u>outlet control</u>
- Submerged inlet (H_1 > 1.2-1.5Y)
- Barrel full along some/all of its length
- Subcritical flow everywhere
- **Analyse as pipeline flow from reservoir (e.g. Example 6.3)**

(Figure 9.25)

The last two culvert types involve water flowing full through the barrel for at least part of the distance, so they’re analysed as flow through a pipeline where the upstream part is considered to be the reservoir. Both types 5 and 6 are under outlet control but for both types the control point’s located some distance downstream. Type 5 has a downstream water level roughly at the level of the outlet, which might mean the barrel doesn’t end up flowing full for its whole length but reverts to open channel some way along.

Image source- Les Hamill 2011, Understanding hydraulics.

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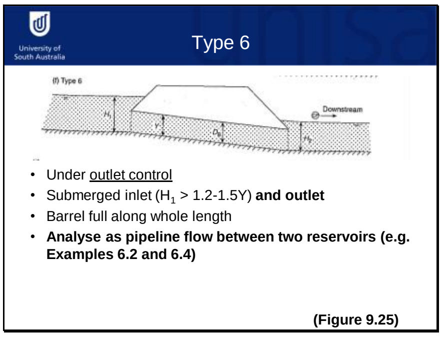

Type 6

- Under <u>outlet control</u>
- Submerged inlet (H_1 > 1.2-1.5Y) **and outlet**
- Barrel full along whole length
- **Analyse as pipeline flow between two reservoirs (e.g. Examples 6.2 and 6.4)**

(Figure 9.25)

The main difference between Type 5 and Type 6 is that this one has a head downstream, called the “tailwater”, above the level of the outflow so it operates like a full pipe flowing between two reservoirs.

Image source- Les Hamill 2011, Understanding hydraulics.

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Weirs

Our last topic in this presentation is about Weirs

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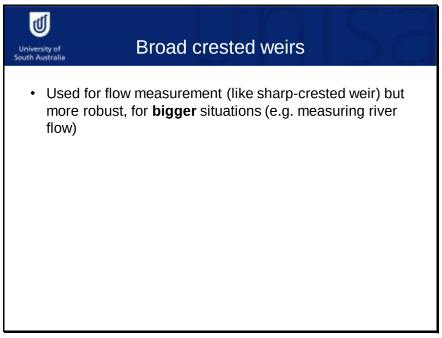

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Broad crested weirs

- Used for flow measurement (like sharp-crested weir) but more robust, for **bigger** situations (e.g. measuring river flow)

When we looked at flow measurement devices, we included sharp-crested weirs like the V-notch weir. Those were fine for laboratory-scale flow measurement and experimental work. But a sharp-crested weir won't be any use for measuring flows in, say, the middle of a river. We need serious structures if they're going to stand up to real-world conditions. So broad crested weirs are more robust and used for bigger situations, like measuring river flow. These are built kind of like dams that are designed to spill water basically all the time, and they're designed to be broad enough to induce critical flow conditions. That means if we can measure the water depth, we're automatically getting the critical flow depth and we can relate that back to velocity.

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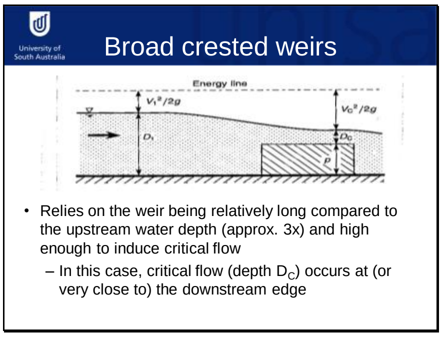

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Broad crested weirs

- Relies on the weir being relatively long compared to the upstream water depth (approx. 3x) and high enough to induce critical flow
  - In this case, critical flow (depth D_C) occurs at (or very close to) the downstream edge

The critical thing – if you'll pardon the pun – of the broad crested weirs is that they need to be designed wide compared to upstream water depth. The width of the weir should be long enough to induce critical flow,

which typically means about 3 times the upstream head.

Then the critical flow should generally occur at around about the downstream edge.

Image source- Les Hamill 2011, Understanding hydraulics.

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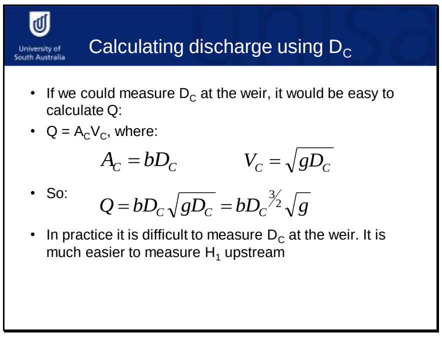

Calculating discharge using D_C

- If we could measure D_C at the weir, it would be easy to calculate Q:
- $Q = A_C V_C$, where:

$$A_C = bD_C \qquad V_C = \sqrt{gD_C}$$

- So:

$$Q = bD_C\sqrt{gD_C} = bD_C^{3/2}\sqrt{g}$$

- In practice it is difficult to measure D_C at the weir. It is much easier to measure H_1 upstream

If we could measure the critical depth DC, it'd be really easy to calculate the flow rate Q

By using Q equals V A

Assuming we know the length of the weir across the channel, B, then the area of flow's just that times the critical depth DC and we know VC by rearranging the Froude number, remembering it's equal to 1 for critical flow.

So that'd all come together neatly if we could measure the depth at the downstream edge.

Unfortunately in practice, it can be difficult to measure this, and it's much easier to measure the upstream depth.

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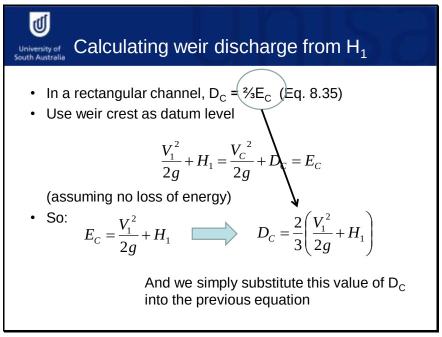

Calculating weir discharge from H_1

- In a rectangular channel, $D_C = ⅔E_C$ (Eq. 8.35)
- Use weir crest as datum level

$$\frac{V_1^2}{2g} + H_1 = \frac{V_C^{\,2}}{2g} + D_C = E_C$$

(assuming no loss of energy)

- So:

$$E_C = \frac{V_1^2}{2g} + H_1 \quad \Rightarrow \quad D_C = \frac{2}{3}\left(\frac{V_1^2}{2g} + H_1\right)$$

And we simply substitute this value of D_C into the previous equation

In order to calculate the flow rate by measuring upstream water depth, we use a nifty relationship buried in the open channel stuff in Chapter 8, which says the critical flow in a rectangular channel's two-thirds of the critical specific energy, EC.

Now we're going to hit it with the energy equation using the weir crest as a datum, to work out an expression for critical specific energy EC

So that'll look like this, assuming no loss of energy

So

Our EC's equal to the upstream velocity head plus depth,

and assuming no energy losses this'll be equal to the downstream energy where we know we've got critical flow, so we can use that two-thirds relationship from before. And that gives us a way to calculate DC from the upstream velocity

And solve the previous equation. You could be forgiven for thinking that it would be easier to simply measure DC on the downstream edge!

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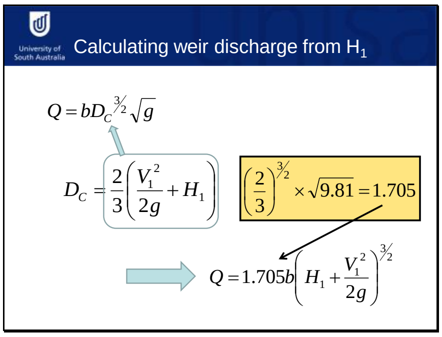

Calculating weir discharge from H_1

$$Q = bD_C^{3/2}\sqrt{g}$$

$$D_C = \frac{2}{3}\left(\frac{V_1^2}{2g} + H_1\right)$$

$$\left(\frac{2}{3}\right)^{3/2} \times \sqrt{9.81} = 1.705$$

$$Q = 1.705b\left(H_1 + \frac{V_1^2}{2g}\right)^{3/2}$$

So that was just this equation

And we're subb-ing in our new expression for DC

Which lets us solve it using the upstream height H1

Giving us the overall equation for flow here

With 1.705 just being these constants multiplied together.

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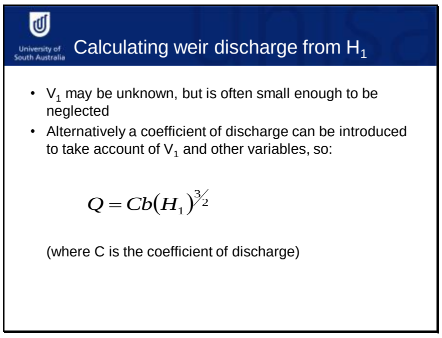

Calculating weir discharge from H_1

- V_1 may be unknown, but is often small enough to be neglected
- Alternatively a coefficient of discharge can be introduced to take account of V_1 and other variables, so:

$$Q = Cb(H_1)^{3/2}$$

(where C is the coefficient of discharge)

If you're really switched on, you might have twigged to the fact that the equation for flow's got a big V1 term stuck in it, which isn't much use given that this is supposed to help us work out the flow rate. Luckily in a lot of real-world streams, the velocity's small enough that the velocity head is negligible compared to H1 and it won't affect the calculation too much if you actually just ignore it.

An alternate way is to throw in a coefficient of discharge that more-or-less captures the approximate value of velocity head, the advantage being that you can encompass a few other things like energy head losses into the coefficient of discharge too.

So you'd wind up with an expression for discharge looking, not surprisingly, very much like the equations we've used in all the other flow-measuring devices we've studied before.

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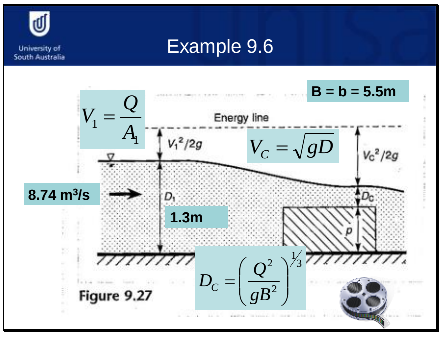

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Example 9.6

B = b = 5.5m

$V_1 = \frac{Q}{A_1}$

$V_C = \sqrt{gD}$

8.74 m³/s

1.3m

$D_C = \left(\frac{Q^2}{gB^2}\right)^{1/3}$

Figure 9.27

Let’s look at an example. Here we want to know what height we can feasibly make the broad-crested weir to get it to function properly. We know it should be about 3 times wider than the upstream head but obviously the height is fairly key to the operation too.

We’ve been told the upstream depth is 1.3 metres with a flow of 8.74 cubic metres a second and the width of the channel’s the same as the weir length, at 5.5 metres. The trick with this question is that the upstream energy equation terms, basically just D1 plus the velocity head, equals the downstream terms, DC plus velocity head, plus the extra elevation P.

So you can get V1 from the information given

And hopefully you know how to work out DC from the flow rate and width

And VC’s obviously root G D. Throw all this into the energy equation with P as the downstream elevation head and you should get an answer for the operating height of the weir. As usual consult the textbook if you need to.

http://www.youtube.com/watch?v=M1ej6jXdX1U

Image source- Les Hamill 2011, Understanding hydraulics.

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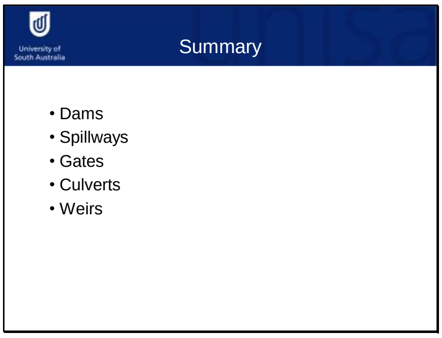

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Summary

- Dams
- Spillways
- Gates
- Culverts
- Weirs

So in summary, we’ve looked at dams, spillways, gates, culverts and weirs with a few calculations thrown in along the way.

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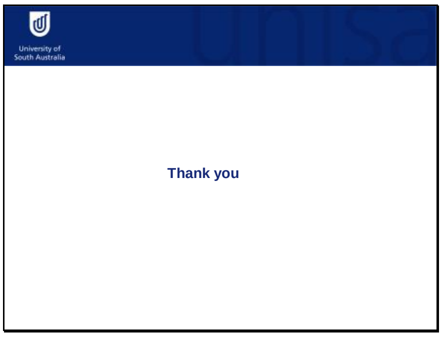

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Thank you

If you’ve got any questions or need further clarification, please post a question or comment on the Discussion Forum.