A SunCam online continuing education course

Culvert Design for Fish Passage

by

David E. Fantina, PE

Introduction:

Engineers that design roadway drainage systems have to account for several design parameters. Most importantly, any roadway culvert must safely pass the design storm through the structure without overtopping the roadway. However, there are other considerations besides hydraulic capacity to be considered. The velocity through the culvert must not be erosive, for example, or else appropriate energy dissipators must be placed at the downstream end to mitigate this effect. In addition, several jurisdictions require that culverts be designed to allow for passage of fish (and other aquatic organisms). This course presents an overview of culvert design and retrofitting to allow for fish passage. This is an important topic because culverts can act as fish barriers, if they are not properly designed and maintained.

When you complete this course you should have an understanding of the ways in which culverts can act as barriers to fish and should also be familiar with the wide variety of techniques that are employed to design or retro-fit culverts to allow for fish passage. The methodologies employed in this field are so varied and, in some cases, so complicated that only an overview can be presented in this course.

For this course the primary reference is the USDOT's Publication entitled "Design for Fish Passage at Roadway-Stream Crossings: Synthesis Report", dated June 2007. However, there are several other publications available which discuss this situation. As will be seen throughout this course, several states have promulgated their own guidelines for dealing with the passage of aquatic organisms through culverts.

Nature of the Problem:

River and stream corridors provide vital habitat for fish and other wildlife throughout the United States. Culverts are generally designed to safely pass the stream under a roadbed, but often little or no consideration is given to fish or other animal passage through the culvert, itself. For this reason many culverts act as effective fish barriers. This has many adverse environmental consequences, including:

1. Isolation of sub-populations of fish (or other organisms).
2. Local extinction of fish species.
3. Loss of prey species for other wildlife (mink, otters, fish-eating birds, etc.)

There are several different ways that a culvert can act as a barrier to fish. Essentially, a culvert will become a barrier when it causes conditions that exceed the fishes' biological capabilities. Some ways that a culvert are as follows:

1. Causing excessive water velocities.
2. Causing a drop at the culvert inlet or outlet.
3. Causing insufficient flow depth during low flow conditions.
4. Physical barriers, including but not limited to, weirs, baffles, or debris that is caught in the culvert barrel.
5. Behavioral barriers.
6. Excessive turbulence (which can be caused by inlet contraction).

Each of these is discussed in some detail below:

Causing excessive water velocities. There are actually several different velocity parameters that can cause barriers to fish. These are classified as follows:

1. Boundary layer velocity. Based on the properties of fluid mechanics, the water velocity at all points of contact with the culvert is zero. This is known as the boundary layer and velocity increases as the distance from the culvert surface increases. In some cases, fish have been observed to use this boundary layer to rest for periods as they traverse the culvert barrel. This phenomenon has not been sufficiently studied to be of use in the design of culverts. However, using corrugated pipe with large corrugations is a common practice because it is felt that these corrugations maximize the lower-velocity boundary layer (and maximize the areas that fish can use for resting).
2. Average velocity. This is an easy parameter to calculate. However, it may not represent conditions throughout the path of a fish traversing the culvert (see the discussion of boundary layer discussion above).
3. Maximum point velocity. Maximum velocity points occur within the culvert at locations such as obstructions and baffles. It is likely that these locations can cause significant stress on fish travelling through the culvert.
4. Inlet transition velocity. The inlet of the culvert is the last transition that a fish must traverse in traveling upstream through the structure. In some cases the velocity at this location can be higher than it is through the rest of the culvert (especially if deposits at the upstream end increase the local slope of the streambed). A skewed entrance will produce a higher entrance velocity than a standard entrance will. Providing tapered wingwalls can significantly reduce the severity (and associated velocity) of the inlet transition.

Causing a drop at a culvert inlet or outlets. One of the most obvious ways that a culvert (or other stream structure) can become a barrier is by providing a drop that the fish cannot negotiate. Different species of fish have differing jumping abilities and these should be considered when designing culverts. (For information on over 20,000 species of fish, the engineer can refer to FishBase, which is available on the web at http:// http://www.fishbase.org/search.php. This website contains data on fish swimming speeds, distribution, biology, etc. This is not a substitute for having a qualified fisheries biologist on the design team, but it is a good place to start to look for information).

The outlet of a corrugated aluminum culvert is shown below. This culvert not only has a drop at the outlet but appears to have very little flow depth in the barrel. Both of these factors can make this culvert a barrier to fish.

The spillway of a small dam in Somerset County, New Jersey is pictured below. Note that this structure effectively blocks fish passage upstream because of the significant drop.

Causing insufficient depth (during low flow conditions) for the fish to swim through the culvert. If there is insufficient depth, it impairs the fishes' ability to generate maximum thrust, increases the contact with the channel bottom, and reduces the fishes' ability to gather oxygen from the water column. Not surprisingly, the depth required depends on the fish present in the waterway. Therefore, different states have different criteria for what constitutes an acceptable flow depth for fish passage. In Maine, the minimum low-flow depth is considered to be 1.5 times the target fish thickness. California, on the other hand, provides a variety of minimum depths (depending on the fish species present). The required depth for adult anadromous salmonids is 1 foot. Other states have other criteria. (Anadromous fishes are those that spawn in freshwater, migrate to the ocean to mature, and return to freshwater to spawn and begin the cycle again. Salmonids refer to salmon and related fish such as trout, char, etc.).

The photograph below shows an elliptical culvert. This structure causes a low flow depth that is probably too shallow for the passage of most fish. In addition, this is a very long culvert and probably represents a "behavioral barrier" as described in some detail later in this course.

Physical barriers including, but not limited to, weirs, baffles, or debris that is caught in the culvert barrel. Culverts with small diameters, or with baffles, or large roughness elements are more prone to collect debris. This should be considered by the design engineer, especially in locations where anthropogenic or natural debris is likely. A monitoring or maintenance program can be instituted where debris build-up is expected. However, in many cases it is hard to ensure that maintenance will be provided on a regular basis in the long term.

The concrete culvert shown below is a three-sided culvert, meaning that the bottom of the culvert is actually the streambed. This type of culvert is often the best solution for allowing for fish passage. Note the following:

1. There is no drop at the outlet.
2. There appears to be sufficient depth for fish to pass through the culvert.
3. There is no indication of excess velocity or turbulence.

The twin elliptical culverts pictured below can present a barrier to fish in a variety of ways. For one thing the culverts (especially the one on the right hand side) have sediment deposited in them which can both act as a physical barrier and also increase turbidity during flood flows. (Turbidity is a measure of the degree to which water loses its transparency due to the presence of suspended solids. Generally, the more suspended solids are present, the greater is the turbidity, and the less is the actual water quality.) Replacing these two culverts with an appropriate single span could alleviate this situation.

In addition to the above, there are a series of conditions that are known as "behavioral barriers" to fish. For example, excessively long culverts can provide a barrier for a variety of reasons. For one thing these culverts can be so dark that at least some fish species are discouraged from entering them. (To address this problem the National Marine Fisheries Service Southwest Division requires that consideration be given to lighting culverts that are over 150 feet in length.) In addition, long culverts may tax fish by requiring them to swim against a fast current for longer periods of time. For this reason, maximum allowable velocity decreases with increasing culvert length.

Dam structures, like the one pictured below, often present obstacles to fish passage. “Fish ladders” are sometimes used to alleviate this problem. A fish ladder allows fish to detour around a drop such as the one in this photograph.

Fish ladders are not applicable to culvert installations but, because they are an integral part of the fish passage design on many waterways, they will be discussed in some detail here. Fish ladders and fishways provide migrating fish with an upstream passage through or around fish barriers. These devices function by attracting the fish into the ladder, and allowing them to step up the gradient until they reach a point in the stream upstream of the barrier and can resume their migration. The actual fish passage feature can employ weirs, gates, orifices, and other devices.

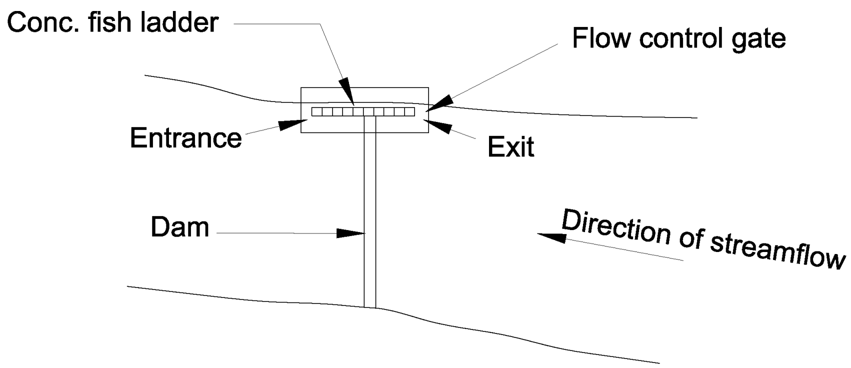
Fish ladders can be constructed of a variety of materials and can take various shapes. Some of these include the following:

1. Excavated, earthen channels roughened with large rocks.
2. Semi-natural channels equipped with stair-stepped resting pools held in place with rocks, logs, or similar heavy objects. (Note that resting pools are an essential part of fish ladders, especially if the ladders are long).
3. Concrete or metal structures that slow the water velocity sufficiently to provide upstream passage for the fish.

Note that one of the features that is required for a fish ladder to be successful is to attract the fish into the ladder in the first place. This requires that the engineer (and other design team members) understand the behavioral responses of the fish so that the correct attractors (and detractors) can be employed to lead the fish into the ladder. These stimuli can include shade, sunlight, sound, water temperature and host of other factors. For instance, shad (and some other species) are hesitant to swim through a submerged orifice. For these species, vertical slots or weirs should be used. If there is excessive turbulence at the entrance to the fish ladder, the fish may become confused or may be deterred from entering the system. Research shows that many species migrating upstream use the lower velocity that is present adjacent to the shore. On the other hand, juvenile migrants often move downstream in the fastest portion of the stream, often travelling within 1 foot of the surface.

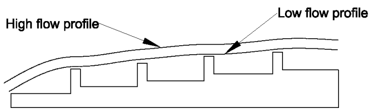
To determine that the individual weirs within a fish ladder are appropriate and that the resulting velocity within the ladder is suitable for the specific fish, the following equation can be used:
$V_{weir} = Q/L(0.67)H$, where”
V_{weir} is the velocity of the of the water over the weir in the fish ladder in ft/sec.
Q is the design flow rate in cfs
L is the length of the weir in feet
H is the head over the weir in feet
The resulting velocity can be compared with the target species’ swimming capabilities.

A schematic of a fish ladder is shown below:

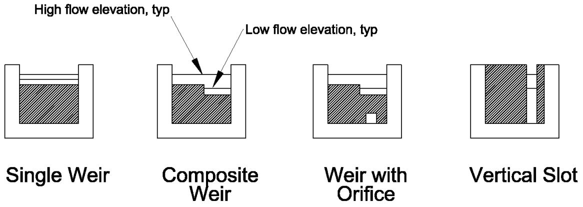


Schematic Fish Ladder Plan

A schematic of a longitudinal profile and cross sections of some typical weir configurations are shown below:



Typical Profile Through Fish Ladder



Typical Fish Ladder Weir Configurations

The photograph below shows the fish ladder that allows passage around the John Day Lock & Dam on the Columbia River in Oregon. This dam, completed in 1971, creates a reservoir known as Lake Umatilla. Note the numerous weirs that allow fish to gradually traverse the great height of the dam. Note also that there are pools with relatively calm water at the turning points. These pools allow the fish to rest on their journey upstream.

The actual design of the ladder and the height of the weirs depends on the swimming speed and jumping abilities of the target species. A partial list of swimming speeds and jumping abilities of several Salmond species is included in the table below:

Salmonid Species	**Sustained Swimming Speed**	**Burst Speed**	**Maximum Jump Height**
Steelhead	4.6 ft/sec	26.5 ft/sec	11.2 feet
Chinook	3.4 ft/sec	22.4 ft/sec	7.8 feet
Coho	3.4 ft/sec	21.5 ft/sec	7.2 feet
Cutthroat	2.0 ft/sec	13.5 ft/sec	2.8 feet
Chum	1.6 ft/sec	10.6 ft/sec	1.7 feet
Sockeye	3.2 ft/sec	20.6 ft/sec	6.9 feet

Once again, the engineer must consult with qualified experts to ensure that the fish ladder has the appropriate configurations (including water velocity and jumping height over the individual weirs) to allow the target species to negotiate the ladder. However, the overall usefulness of fish ladders remains a matter of some debate. While some fish ladders are certainly useful in allowing passage of some fish there is evidence that smaller species and young fish may not be able to negotiate the barriers involved in many fish ladders.

Excessive turbulence (which can be caused by inlet contraction). The actual effects of turbulence on fish passage are not completely understood. However, recent research indicates that fish prefer to hold or rest in low turbulence zones. The states of Washington and Maine have design guidelines that suggest allowable fish turbulence thresholds. They quantify the amount of turbulence using and Energy Dissipation Factor (EDF) which can be calculated as follows:

EDF=yQS/A, where
y is the unit weight of water in lbs/ft^3
Q is the fish-passage design flow in CFS
S is the slope of the culvert in feet/ft
A is the cross-sectional area for the fish-passage design flow in ft^2 (Note that, if baffles are present, the cross sectional area used is taken between the baffles).

Washington State has suggested the following EDF values:

1. <7.0 foor roughened channels.
2. <4 for fishways
3. Between 3.0 and 5.0 for baffled culverts

Energy Dissipation Factor Example:
An existing 4 foot diameter circular with baffles in Washington State has a slope of 2%. Would this culvert be considered to have an acceptable EDF for a design flow of 32 CFS?
Using the equation above, input the following values:

- y is 62.2 lbs/cf (specific weight of water)
- Q is 32 CFS
- S is 0.02 ft/ft
- A 12.56 SF (area of a 4' diameter culvert)

EDF = (62.2)(32)(0.02)/12.56 = 3.17
The value of EDF (3.17) is between 3.0 and 5.0. Therefore, this culvert would be considered to be acceptable for fish passage.

The New York State Department of Environmental Conservation (NYDEC) has published a brochure on culverts for fish passage. This brochure points out that the goal of a properly designed culvert is to be "invisible' to the fish. That is to say that it should mimic the natural streambed as closely as possible. The stream bed should not be fragmented or constricted in any way. The NYDEC concludes that "good crossings that create no noticeable change in the stream include bridges and open-bottom arches and culverts that sufficiently span the stream-channel bed, and box and pipe culverts that sufficiently span and are adequately sunk into the stream-channel bed."

The stream crossing pictured below appears to be nearly "invisible" to fish, at least during low flow periods. This old stone bridge is better for fish passage than a circular culvert would be.

The photograph below shows another bridge crossing that could be considered more or less invisible to fish under ordinary circumstances.

Design Approaches:
In order to properly design culverts so that they allow for fish passage it is necessary to understand the limitations of the fish that will be present in the particular waterway under consideration. For this reason the engineer may have to consult with a competent fisheries biologist in the design or retro-fitting of a culvert. There are several different design approaches or philosophies that can be used to ensure that fish passage is not impeded at a roadway crossing These can be divided into four broad categories, as outlined below:

1. No impedance approach. No impedance simply means that the crossing produces absolutely no impediment to fish passage by spanning the entire waterway. This is often not a feasible option. The only ways to achieve this are the following:
    - Remove the road crossing altogether (which is generally not an option) or

   - Construct a bridge which spans the entire waterway (which is usually a much more expensive solution that installing a culvert).
2. The geomorphic simulation approach. This is also known as the stream simulation approach. The goal of this method is to recreate or maintain the natural stream geomorphic elements (i.e. slope, channel bed width, stream bed materials, and the form of the channel bed). Generally, this will require a wide (and expensive) culvert. This approach has the following benefits:
   - It will provide passage for fish much more readily than will narrower crossings.
   - In some cases it may provide passage for other aquatic organisms and some terrestrial species. (For example, raccoons may use these types of culverts to pass safely under a roadway crossing).
   - It will not increase downstream channel velocities (at least for discharges less than bankfull values).
   - It will increase downstream channel velocities less than narrower span culverts for discharges above bankfull values.
   - Maintenance of these culverts, including removal of debris and manipulation of the channel, should be less than for narrower culvert spans.
3. The hydraulic simulation approach. This technique provides hydraulic conditions conducive to fish passage by utilizing embedded culverts, synthetic or natural bed mixes, and natural roughness elements such as oversized rocks. The underlying assumption is that providing hydraulic diversity similar to, but not identical to, that found in natural channels will create a structure that allows for fish passage without the necessity of checking for excessive velocity or turbulence. One of the main advantages of this approach, over the geomorphic simulation approach, is that it will generally result in a smaller (and less expensive) span culvert.
4. The hydraulic design approach. The goal of this approach is to create water depths and velocities that meet the swimming abilities of specific target fish populations and life stages during specific periods of fish movement. This technique is most often used for retro-fit projects and often involves flow control structures such as baffles, weirs, etc. Design considerations include the effect of culvert slope, size, material, and length. This procedure will generally result in a smaller culvert span (although the cost of installation can be variable due to the design of baffles, weirs, steps, or other features). It should be reiterated that this technique will not allow for the passage of all fish at all times of the year but is only meant to address the needs of one, or more, target species at specified times of their life cycle.

Within each of these categories there are several design methodologies that can be employed. For instance several states (e.g. Washington, Maryland, Alaska, and others) have developed methodologies to design or retro-fit culverts for fish passage. A discussion of each of these methodologies is obviously beyond the scope of this course. However, we will attempt to point to some of the principals employed by these different methodologies. (It should also be noted that all of these approaches have some overlap and there is not really a sharp boundary between one methodology and another. This is understandable because all of these guidelines have as their ultimate goal installing a culvert that will permit passage of fish and other aquatic organisms. Therefore, there will be some repetition in the pages that follow.)

These approaches are summarized in the table below:

Category	**Description**	**Relative Width**	**Biological Characteristics**	**Geomorphic Characteristics**	**Hydraulic Characteristics**
NA	No Impedance	>100 year floodplain	Pass all fish & other aquatic organisms	Unchanged	Q_{100} Unrestricted
1	Geomorphic Simulation	>bankfull	Pass all fish & other aquatic organisms	Natural substrate, mobile bed, stability of substrate is generally not checked.	Unaltered for Q slightly above bankfull; check Q_{100}
2	Hydraulic Simulation	<bankfull	Reported to pass all fish & other aquatic organisms	Oversized substrate; stationary bed; stability of bed usually checked	Similar for Q slightly less than bankfull; check Q_{100}
3	Hydraulic Design	Variable but usually <bankfull	Pass target species at target life stage.	Artificial channel	Must meet target species & life stage requirements; check for Q_{100}

In the table above Q_{100} refers to the maximum 100 year flow in the stream.

No matter which methodology is chosen for design there are several factors that need to be considered. These include the following:

Channel Geometry:

Several parameters are involved in the determination of channel geometry including width, profile, condition, evolution and others.

Channel width can be divided into "active width" and "bankfull width". Active width refers to the stream width at its current or recent discharges. Generally, this width can be easily determined because at this point terrestrial vegetation and other "permanent" features will dominate the channel. (Erosion, shelving and terracing, a change in soil characteristics, and moss growth can all be used to determine the active channel width). Bankfull width, on the other hand, is sometimes obvious in the field and sometimes very difficult to determine. In the

absence of a well defined "bank" the engineer can approximate the bankfull width by determining the peak 1 year or 2 year elevation in the channel.
The channel profile is often a dynamic parameter due to structural changes with time including incision, headcutting, scour, and regrading. (A headcut refers to an abrupt step in the channel profile upstream which often exposes the subsoil and leads to accelerated erosion. Incision is similar but is a step in the downstream direction and can be caused by a reduction in sediment deposition and an increase in sediment transportation).

Stream Classification:

Stream classification is often an important first step in determining what type of methodology to use. The classification can tell the engineer a lot of information about the stream characteristics and can provide information on the stream habitat as well.

There are a surprisingly large number of schemes for classifying streams. The one summarized in the table below (developed by Montgomery and Buffington) was initially designed to classify streams in the Pacific northwest but it can be used, with modifications, in other areas as well.

Stream Gradient	**Stream Type**	**Typical Bed Material**	**Dominant Sediment Source**	**Dominant Sediment Storage**	**Typical pool Spacing (In terms of channel width)**
8%-20%	Cascades	Cobbles & boulders	Fluvial, hill slopes, debris flows	Around flow obstructions	<1
4%-8%	Step-pool	Cobbles & boulders	Fluvial, hill slopes, debris flows	Bedforms	1-4
2%-4%	Plane-bed, forced pools	Gravel & cobbles	Fluvial, bank failure, debris flows	Overbank	None
0.1%-2%	Pool-riffle	Gravel	Fluvial, bank failure	Overbank, bedforms	5-7
<0.1%	Dune-riffle	Sand	Fluvial, bank failure, bedforms	Overbank	5-7

An alternate methodology which is commonly used is known as the Rosgen Stream Classification System. A simplified Rosgen Classification for major stream is shown below:

Stream Type	**Stream Name**	**Characteristics**
A	Step-pool or cascading	Plunge & scour pools, high energy, low sediment storage, stable.
B	Riffles & rapids	Some scour pools, sand bars rare, stable.
C	Pool-riffle sequence	Meandering, point bars, well developed floodplain, banks stable or unstable.
D	Braided	Multiple channels, shifting bars, deposition, high sediment supply, eroding banks.
DA	Anastomising	Multiple channels, pool-riffle, vegetated floodplains, adjacent wetlands, stable banks.
E	Meadow meanders	Well developed floodplains, riffle-pool, relatively high sediment conveyance.
F	Valley meanders	Incised into valleys, poor floodplain development, pool-riffle, banks stable or unstable.
G	Gullies	Incised into hill slopes and meadows, high sediment supply, unstable banks, step-pool.

Stream morphology:

Streams are constantly evolving and any successful culvert project has to take into account not only the present conditions in the stream but future potentialities as well. For instance, a culvert placed in a highly erodible channel must be placed deep enough so that it does not become a barrier to fish passage. Stream morphology refers to the following channel characteristics:

1. Gradient.
2. Bed material.
3. Roughness. (See below).
4. Subsurface flows. (These are not present in all stream types but they represent a large portion of the total flow in cobbly and gravelly channels).
5. Bed mobility. (This refers to the degree to which the bed material is moved downstream by the streamflow).

Some of these are discussed in more detail below.

Streambed Roughness:

The stream morphology term, "roughness" is, of itself, a significant characteristic of the stream channel that affects the conveyance of the stream. The roughness is a component of the well-known Manning's Equation, which can be used to determine the capacity of a stream channel. The Manning's Equation can be written as :$Q=1.486/nAR^{2/3}S^{1/2}$, where

Q is the flow in CFS

A is the cross-sectional area, in SF.
R is the hydraulic radius in FT. (This is defined as the area divided by the wetted perimeter. The wetted perimeter is simply the area the length of the channel wetted during the design flow).
S is the channel slope in ft/ft.
n is the roughness coefficient.

The roughness coefficient is a factor of the physical characteristics of the channel. The appropriate assignment of an n value to a particular channel requires a significant amount of engineering judgement. However, some typical values of natural channels are included in the table below:

Description of Channel	**Range of n values**
Concrete	0.015 to 0.020
Natural channel on plain, straight, clean & without rifts or deep pools.	0.025 to 0.033
Same as above but with some pools, weeds, & stones.	0.030 to 0.045
Natural channel, with very weedy channel or floodways with heavy stands of timber.	0.075 to 0.15
Mountain streams with a bottom of cobbles.	0.040 to 0.070

Based on the table above, the stream shown on the photograph below would probably be assigned a roughness coefficient of between 0.040 and 0.070 (mountain stream with cobble bottom). The cobbles do not appear to be sufficiently large or numerous enough to materially affect the flow. Therefore, the lower end of this range (maybe 0.040 or 0.045) would be appropriate.

Determining an appropriate roughness coefficient is important in designing a culvert for fish passage because the roughness is directly proportional to the velocity. The Manning's Equation can be re-written to determine the velocity, as follows:
Velocity (V)=$1.486/nR^{2/3}S^{1/2}$
Note that this is the same equation as the above Manning's Equation except that the area term has been removed from both sides. (Recall that the flow (Q) equals the velocity times the cross-sectional area.)

Bed mobility:
This is a function of the particle sizing and sediment mixture. It is generally a good policy to utilize existing bed material when retro-fitting a culvert for fish passage (assuming that the existing bed is stable). However, if the engineer must import material there are a number of ways to determine what size particles to use. The method described below is called the Critical Unit Discharge Approach. (Note that the USDOT describes at least eight other design methodologies, each suited to a particular set of stream gradients and conditions).

Critical Unit Discharge Approach: For use where:

- The channel slope is very steep (>10%).
- Flow depth is shallow compared to channel bed particle bed diameter. (Generally, this means that the depth is fairly shallow and the channel bed consists of boulders and other very coarse material).

This approach is based on unit discharge and a value of critical unit discharge is compared to the channel unit discharge to determine particle entrainment. (Particle entrainment simply means the particles are lifted into the flow).

The following equation (Equation A) is used to determine the channel unit discharge:

$q=Q/w$, where
q is the unit discharge in CFS/ft
Q is the total discharge in the channel in feet
w is the channel width in feet

Then the following equation (Equation B) can be used to predict the entrainment of the particle size of interest:

$q_{cD50}=(0.15)g(0.5D_{50}^{1.5})/S^{1.12}$, where
q_{cD50} is the critical unit discharge to entrain the D_{50} particle size in CFS
g is acceleration due to gravity: (32.2 ft/sec^2)
D_{50} is median particle size in feet
S is the channel slope in ft/ft

Other equations that need to be employed are as follows:

Equation D: (For use in finding the critical unit discharge to entrain the *i*th particle size):

$q_{ci}=q_{cD50}\,(D_i/D_{50}{}^{b})$, where
D_i is the particle size of interest in feet and
b is a measure of the range of particle sizes that make up the channel beds. This quantifies the effects on particle entrainment of smaller particles being hidden and larger particles being exposed to flow. b can be calculated as follows:
(Equation C): $b= 1.5\,(D_{84}/D_{16})^{-1}$, where D_{84} and D_{16} are the 84th percentile and 16th percentile particle sizes, respectively, measured in feet

The overall process consists of the following steps:

1. Calculate the unit discharge for bankfull flow using Equation A.
2. Calculate the critical unit discharge needed to entrain the D_{50} particle size at a given cross section, using Equation B.
3. Calculate the sorting of the channel bed using Equation C.
4. Calculate the critical discharge needed to entrain the particle size of interest at any given cross section using Equation D.
5. Compare the critical unit discharge to the unit discharge in the channel at the specified flow. If the unit discharge is less than the critical unit discharge, then the

particle size being investigated will not be entrained. (Or, in other words, the particle will remain immobile on the channel bed). Conversely, if the unit discharge is greater than the critical unit discharge, then the particle size under investigation will become entrained.

The photograph below shows the gradation of materials present in a typical stream channel in New Jersey. Note that much of the material is sandy but that there are some pebbles present.

Geomorphic Simulation Design:

There are several different variants of this method and the one that will be described briefly below is taken from The USDA's "Stream Simulation: An Ecological Approach to Providing Passage for Aquatic Organisms at Road-Stream Crossings". This publication points out the need for extensive on-site data retrieval including obtaining characteristics of the upstream and downstream channel reaches so the at the stream simulation will be appropriate to the particular circumstances encountered.

As far as the actual design is concerned, the following steps are required:

1. Determine the project alignment and slope. In most cases, this is obvious because a new or replacement culvert needs to be placed at a certain location in the stream. However, if there is flexibility in the location, the engineer should consider revising the alignment, slope, or location of the culvert. On problem that is sometimes encountered is when the stream intersects the road at a skew. This is illustrated in the photograph below which shows a small brook flowing under a major county road in New Jersey. Bends like the one shown immediately upstream of the culvert in this photograph should be avoided whenever possible.

A skewed alignment between a stream and a culvert crossing (like the one pictured above) can create a variety of problems. In flood flows, the culvert entrance is more likely to become clogged with sediment and debris and can even cause severe bank erosion. (Note that there is no general rule as to which is better for fish passage; a long straight culvert or a short, skewed culvert. The design engineer should check with a qualified fisheries biologist to determine which is best for the particular target species involved). In designing a culvert alignment for fish passage there are a number of parameters to consider including the following:

- Generally, the flatter and straighter the crossing, the better.
- Short crossings are preferable to longer crossings (all other considerations being equal). The length of the crossing can be minimized by adding retaining walls and/or wingwalls at the upstream and/or downstream faces, by making the road embankment steeper, or by lowering the road elevation relative to the stream bed. Note that the long wingwalls shown in the photograph below greatly shorten the actual length of the culvert that fishes in this river have to traverse.

- The stream through the culvert barrel should simulate the existing channel (in slope, geometry, and bed material) to the greatest extent possible.
- The transitions into and out of the culvert are of particular importance. These areas are often of critical importance in fish passage because of the potential for increased velocities in these areas.

2. Verify the reference reach and stream simulation feasibility. This step includes a visual inspection of the reference reach (generally a reach on the same stream in the vicinity of the culvert which is functioning properly). Determining the bed material

of the reference reach either by a sieve analysis or by a pebble count (or both) is critical so that the culvert and its transitions can mimic this material.

3. Design bed material size & arrangement:
   Smaller particle sizes can be determined using the Fuller-Thompson Equation:
   $P=100(d/D_{100})^n$, where
   d is the particle size of interest in inches or mm,
   P is the percentage of the mixture smaller than d,
   D_{100} is the largest material size in the mixture in inches or mm,
   n is a parameter that determines how fine the resulting mix will be. (A value of 0.5 is generally used when the majority of the particles are rounded. For other particle shapes, the value of n can range between 0.45 and 0.71).
   There are versions of this equation that can be used to determine the proper size of different materials within the bed mixture.
4. Select structure size and elevation. This is based, of course, on a variety of factors including the design flow through the culvert, the existing channel geometry and slope, etc.
5. Verify the stability of the simulated streambed inside structure. The methodology described earlier in this course to determine particle entrainment can be used.

Hydraulic Simulation Design:

The methodology described herein is taken from the Oregon Forest Technical Note Number 4. Note, however, that this is only one set of guidelines to hydraulic simulation design of culverts for fish passage. Other states, from Alaska to Maryland, have their own set of regulations. The Oregon Department of Fish and Wildlife (ODFW) points out the need to begin with a detailed inventory of the stream characteristics in and around the proposed new or replacement culvert. These include determining the following:

1. Streambed gradient. In determining the gradient, the engineer should collect data from far enough upstream and downstream of the culvert that the structure, itself, is not affecting the results.
2. Streambed material. Because a stable stream generally needs an ample supply and diversity of sediment, the engineer should determine what is the actual content of the existing streambed mixture. The ODFW uses a different terminology for sediment size than is generally employed elsewhere as outlined below:
   - Bedrock: particle size > 13 feet.
   - Boulders: particle size between 10 inches and 13 feet.
   - Cobbles: particle size between 2.5 and 10 inches.
   - Gravel: particle size between 0.1 and 2.5 inches.
   - Fines/sand: particle size below 0.1 inches.

The photograph below shows a close-up of a stream bed. In this view some of the gradation of particle sizes that make up the stream channel is visible. This channel is obviously more rocky than the streambed pictured on page 23 of this course.

3. Depth of the streambed material. It is important to know the depth of the material and, particularly, to determine the depth to bedrock. On strategy for providing fish passage is to "sink" the culvert into the streambed. The ODFW points out that the replacement culvert sometimes fail to provide for fish passage because the presence of shallow bedrock below the channel does not allow for the culvert to be sunk to the proper depth. (In determining the depth of the streambed material it is also essential

to determine if there are any gas lines, water lines, or other utilities under the stream at the location of the proposed culvert).

4. Active channel width. In order for the culvert not to impede the passage of fish the structure should be at least as wide as the active channel. As mentioned earlier, the active channel can ordinarily be determined in the field by looking for abrupt changes in streamside vegetation, etc. In cases where this is not obvious, the engineer can approximate the active channel width by calculating the "normal" depth in the channel using the Manning's Equation with a 1 year or 2 year design storm.

Once the initial data is accumulated, the ODFW provides the following six design strategies to provide for fish passage through culverts:

1. Remove or abandon the stream crossing.
2. Provide a channel-spanning structure.
3. Provide a ford in lieu of a culvert or bridge.
4. Use streambed simulation to design a sunken or embedded culvert.
5. Provide a culvert placed at a zero grade.
6. Use a hydraulic design with weirs and baffles within the culvert. (Hydraulic design is discussed briefly in the following section of this course).

Each of these strategies is discussed briefly below:

Remove or abandon the stream crossing: Obviously this is not an option in the great majority of situations.

Channel-spanning structures: Channel spanning structures (generally bridges) are not ordinarily the most cost-effective solution to a stream crossing. However, they are very valuable in allowing for fish passage because the entire channel can remain in an undisturbed condition.

A simple channel-spanning structure is pictured below. This is a walking bridge on a nature trail in a wildlife preserve in Bernardsville, New Jersey. It is far superior to a standard culvert as far as fish passage is concerned. This bridge may look somewhat flimsy but it has actually experienced at least one 100 year storm without sustaining any damage.

Fords: Generally speaking fords are only advisable when the traffic on the roadway is infrequent. One way to determine if the traffic is sufficiently infrequent to allow for a ford to be used is that it does not cause a noticeable (visible) increase in turbidity downstream of the crossing. In addition fords are best suited to streams that have cobble or bedrock beds. The roadway approaching the ford should have a relatively gentle slope (in no case should the slope exceed 10%) and a hardened coarse material, such as cobbles, or coarse gravel should be used in the approaches to remove sediment from vehicles. Fords do have some significant advantages over culverts and bridges since they reduce the amount of fill required and result in less disturbance to the stream during construction. If the ford needs to be hardened using cobbles an impermeable Geotech fabric should be used below the cobbles. The photograph below shows a ford on the entrance roadway to a park in Somerset County, New Jersey. This ford is in somewhat of a condition of disrepair and is really only passable by very small fish under low flow conditions.

Some of the cobbles used to armor the ford have become dislodged and the resulting depth of flow within the ford is too shallow to provide adequate passage for most species of fish.

Streambed simulation: This methodology, as the name implies, calls for the structure to simulate the stream channel upstream and downstream of the structure. This is not always easy to do and requires significant attention to detail. The ODFW makes the following recommendations for this type of installation:

1. The existing stream bed should not exceed 8%.
2. This type of structure requires countersinking so it is generally not applicable in bedrock channels or in channels with large boulders (unless additional measures are taken to deal with these situations). (The ODFW defines the following terms, which are used often in this section):
   - "Sinking a Culvert refers to putting the bottom of the culvert in at a lower elevation than the existing streambed. It is measured from the estimated streambed elevation after the old crossing (if there is one) will be removed. One

method for determining the degree of sinking is to use the elevation of the first downstream riffle below the crossing and the elevation of the first pool below this riffle, and calculate the average of the two. This elevation is a rough estimate of the average streambed elevation at the culvert outlet. Using the measured stream grade and this elevation will allow for an estimate to be made of the streambed elevation at the inlet". The reader will note that this method is obviously not applicable to all stream types.

- "Countersinking a culvert refers to when the inlet is sunk into the streambed to a greater degree than the outlet. This results in a culvert gradient that is less than the channel gradient".

3. The culvert width should be equal to or greater than the active channel width of the stream.
4. For stream reaches with gradients between 4% and 8% the culvert should be sunk into the bed so that the slope through the culvert is approximately 1.5% less than the stream gradient.

Culvert placed at zero grade: This option is not for general use and is only to be used on streams that have the following characteristics:

i. A gradient of not more than 2.5%.
ii. A moderate to deep valley fill.

The downstream end of the culvert should be sunk to a depth of 6" and the upstream end should be sunk so that the entire structure has a flat grade. The ODFW considers it critical to place the culvert at a zero grade because it is felt that even a grade of 0.5% could cause a velocity that would be difficult for juvenile fish to negotiate. Also, if the culvert is not sunk to the proper depth it can be undermined on the downstream side causing a jump that fish would not be able to negotiate. If the entire structure is sunk to a depth of at least 6" then there should be adequate depth under ordinary flow conditions for most fish.

The culvert width should be similar to the active channel width in order to prevent channel constriction at the structure.

The culvert pictured below carries a stream with a fairly significant gradient, so it cannot have been placed at zero grade. However, this circular culvert does approximate, to some extent, the active width of the channel.

The double-barrel culvert shown below does not appear to present a significant barrier to fish. However, the crossing is not quite as wide as the active channel and its fish-passage capabilities could be improved by making a single, wider channel.

Hydraulic Design:
This design approach is generally recommended as a last alternative and is sometimes limited to retro-fitting of culverts. This type of design requires specific information on fish swimming speeds and migration timing. It often requires roughness elements (weirs, baffles, etc.). Because these elements are natural traps for debris, culverts designed using this approach often require enhanced monitoring and maintenance. As stated above, this approach is suited to one or more specific species and specific times in the life cycle of the fish.
This approach is called “Hydraulic Design” because of the following two issues:

1. The engineer must determine the hydrographs that would be expected during the species peak migration times in the river reach under consideration.
2. The engineer must determine the hydraulics of the culvert and compare these with the published information on the fishes swimming abilities. If the culvert hydraulics fall within the fishes capabilities, then the resulting design is considered acceptable.

The upstream face of a culvert in New Jersey is pictured below. This culvert offers several obstacles to fish passage. For one thing, there is a large drop above the culvert (see the grass ledge). In addition, the culvert is very long and may also, under high flows, reach very high velocities.

Monitoring & Maintenance:

After the installation or retro-fit of a culvert to allow for fish passage it is important that a continuing monitoring and maintenance plan be implemented. This will ensure that any benefits obtained will continue to apply in the long-term. It can also provide data for future projects, including elucidating what may have gone wrong in the design or installation.

The first step in a monitoring program is to determine the frequency of inspections. Generally once or twice a year will be adequate, but in cases where excessive sedimentation (or other problems) are anticipated, more frequent inspections may be warranted. Generally, the installation should be inspected fairly frequently immediately after completion and the inspections can become less frequent after it has been determined that the culvert is functioning properly. In designing a monitoring program the following list of potential questions may be helpful. Obviously, the engineer should consult with a qualified fisheries biologist in evaluating some of these issues.

Monitoring Question	**Effectiveness Criteria**	**Parameters to be Evaluated**	**Field Methodology**
Has the jump pool depth remained sufficient for the targeted species and life stages?	Residual pool depth at outlet of culvert.	If there is a jump, pool depth is appropriate for leap height. (Obviously this is not applicable to culverts that do not have an entry leap.)	Thalweg* profile through culvert plus water depth.
Are leap heights still within jumping ability of targeted species & life stages?	Leap height. (i.e. residual pool water surface below the culvert outlet to the outlet elevation.)	Leap height is below critical height for targeted species and life stages. (Obviously this is not applicable to culverts that do not have an entry leap.)	Thalweg profile through culver.
Is stream velocity in critical flow areas still within the swimming ability of the target species and life stages?	Stream velocity in critical areas.	Stream velocity is equal to or less than swimming ability of target species and life stages.	Stream velocity and discharge measurements.
Is upstream inlet of the culvert still at grade or below the channel bed?	Bed elevation at inlet of culvert.	Culvert inlet matches the grade of the natural channel bed.	Thalweg profile through culvert.
Is the culvert still at grade?	Slope.	Culvert is at specified designed slope or the	Thalweg profile through culvert.

		slope relative to the natural channel.	
Can sediment bed load still pass through the restored culvert?	Slope (top of riffle to opening), active channel width, and hydraulic capacity.	Culver inlet shows no signs of clogging or sediment deposition.	Thalweg profile through culvert and channel cross section surveys.
Can the culvert pass the design flood discharge and meet headwater policies?	Hydraulic capacity of culvert.	Culvert passes 100 year flows (or alternate design flow, as applicable).	Channel & overbank cross section surveys.
Does the culvert show any signs of failure?	Structural integrity.	Structure shows no signs of collapsing.	Inspection of all structural elements of the culvert.
Have channel or bank adjustments impaired the function of the culvert?	Slope, head-cutting, sediment deposition, etc.	Channel adjustments have not impaired culvert or habitat values.	Thalweg profile through culvert.
Did the project have adverse effects on upstream or downstream habitat?	Bank erosion, channel incision/head-cutting, debris accumulation or sediment deposition.	Culvert project has not adversely affected the habitat upstream or downstream of the culvert.	Thalweg profile through the culvert and channel cross section surveys.
Is the habitat upstream of the culvert still suitable for the targeted fish species & life stages?	Habitat types and quality instream reaches upstream of the culvert.	Area is suitable for targeted species and life stages.	Habitat monitoring.

*The thalweg is defined as the line of lowest elevation along a watercourse.

Case Studies:

Designing new culverts or retrofitting existing structures to allow for fish passage has commonly been accomplished over many areas of the country in recent years.
A few case studies are discussed briefly below:

West Weaver Creek, Trinity County, California:

This project involved the replacement of a circular 8 foot diameter pipe culvert with a channel spanning concrete structure that allowed for adequate fish passage and could also better handle large flood events. The circular channel presented a significant obstacle to fish passage, which was especially troubling, because the West Weaver Creek is prime salmonid habit.

The methodology utilized was the Geomorphic Simulation. Recall that this methodology utilizes a design that can pass all aquatic organisms and the design is for a flow greater than bankfull. These objectives were met by oversizing the culvert to span the entire channel.

Interestingly, this project was funded partly by an organization known as Northwest California Resource Conservation & Development Council, Inc., Five Counties Salmonid Conservation Program or 5C for short. Since the completion of this project in November of 2000, 5C has funded several other projects of this nature. In addition, they work with local officials and volunteers to monitor and clean up degraded stream reaches. Organizations like this can not only provide funding for these types of environmental projects but can also create jobs during and after the culvert rehabilitation.

20 Mile Creek culvert replacement over the Kootenai River, Idaho:

This project had both similarities and differences as compared with the West Weaver Creek project mentioned above. The pre-construction crossing consisted of another circular culvert. In this case it was a 6 foot diameter corrugated metal pipe. The Kootenai River in this area is home to Bull Trout. However, the trout (and other fish) were not able to traverse the crossing due to (i) a cascade over the riprap at the culvert outlet and (ii) insufficient water depth and excessive velocity within the culvert barrel, itself.

In order to accommodate the fish, the culvert was replaced with a 40 foot wide prefabricated bridge that spanned the entire channel. This is similar to the solution described above. However, this design also included the installation of 13 weirs within the stream channel, itself. Each of these weirs had a drop of 9” (which can be negotiated by adult Bull Trout) spaced 11 feet apart. The weirs were constructed of boulders and gravel and fine materials were pressure washed into the weirs to seal them and maintain surface flow. (Without the fine material, the water would have traveled through the boulder/gravel matrix and not over it).

This design utilized a version of the Hydraulic Design approach. Note that it was designed to pass not all fish and other aquatic species that might encounter the crossing but was targeted at a specific species (Bull Trout) at a specific period of their life cycle (adult).

This project provided a few design challenges that show how real-life examples are often more complex than text-book examples. For one thing, 20 Mile Creek Road provides the only access to many residences. Therefore, a temporary bypass had to be constructed to keep access to these homes during the construction. In addition, during excavation, a concrete water line was discovered in the area slated for the weirs. To accommodate this, the weirs were moved slightly downstream as a field change. These types of unforeseen problems can and do occur on almost any project of this type.

Brad’s Corner Road Culvert Replacement, Maine:

The Sandy River in Maine is a very sensitive environmental feature as it is home to both native Brook Trout and Atlantic Salmon. Some years ago a 6 foot circular culvert on this stream had to be replaced because flooding had overtopped the roadway (known as Brad's Crossing) and caused a partial failure of the road embankment. In designing the replacement culvert, engineers and biologists decided to make the culvert more accessible for fish passage. For one thing the 6 foot culvert caused a significant restriction because the river immediately upstream and downstream of the crossing is approximately 20 feet wide. The engineers considered the following three options:

- A bridge spanning the river.
- An open-bottom box culvert.
- An embedded culvert.

After a cost-benefit analysis was conducted it was decided to use an embedded concrete culvert. The design had to be approved by the US Army Corps of Engineers, which has jurisdiction over this waterway. Before a final design could be decided on however, geotechnical studies were conducted to confirm that bedrock would not be encountered in excavating for the culvert. During the actual culvert excavation, a side channel was constructed to de-water the construction zone. This channel consisted of a synthetic impermeable liner and large rocks and was of sufficient size to pass a fairly large storm event. Perhaps most impressive about the construction stage is that fish nets were installed and the native fish were caught and relocated to a safe habitat in a downstream reach of the stream during the disturbance. (This step again shows the need to include qualified experts in a variety of fields in a project of this nature).

The dimensions of the replacement culvert were 21' wide X 12' high, which simulated the natural channel. The base of the channel was placed about 3 feet below the bottom of the stream bed. The culvert bottom was 12" thick and the remaining 2 feet was covered with stream substrate material, which was carefully selected to remain stable and to simulate the remainder of the channel. Obviously, for this design to be effective in the long term a comprehensive monitoring and maintenance program would need to be employed. This is to ensure that (among other things) the bed material does not migrate downstream, leaving the bare culvert floor exposed to the fish. This would destroy the integrity of the channel geometry, flow characteristics, etc.

The final result has produced a stream crossing that can pass a 100 year storm flood without overtopping the road and also provides for adequate fish passage even during low flow periods. This design could be said to have employed the Hydraulic Simulation Method, which in some respects, is intermediate between the Geomorphic Simulation and the Hydraulic Design approaches used in the above two cases.

Final Thoughts:

When designing a stream crossing, the engineer must keep several factors in mind. One which has not been discussed in this course is the location of the culvert within the overall watershed. For instance, if the culvert is bounded by several other structures that impede fish passage in both the upstream and downstream directions, then spending a significant amount of money making this particular structural adequate for fish passage is probably not justified. If, on the other hand, fish and other aquatic organisms have a clear path for several miles both upstream and downstream, then spending the additional time and money to make a particular culvert suitable for them is a good idea.

It is worth restating that for any culvert designed to accommodate fish passage there are a great number of factors to consider. These will vary from crossing to crossing but may include some or all of the following:

1. The applicable local, state, and federal regulations pertaining to the particular project. (This is vitally important and will be applicable to <u>all</u> culvert projects).
2. The type of fish (or other organisms) that need to pass through the crossing.
3. The project budget.
4. The stream characteristics, notably:
    a. The channel geometry and, particularly, the active channel width.
    b. The channel substrate (sand, gravel, boulders, etc.).
    c. The sinuosity of the channel. (This is a measure of the extent of bends in the channel from a planimetric viewpoint). A new (or replacement) culvert should preferably be placed away from bends in a straighter portion of the stream.
    d. The channel gradient.
    e. The degree to which the channel has, or can become, eroded.
5. The design flow expected through the culvert.

The walking bridge pictured below spans the entire watercourse and obviously does not interfere with fish passage. In this way, it achieves the ultimate goal of being “invisible” to fish. However, the channel itself has been lined with concrete and it should be evaluated to see if there is sufficient depth during low flow conditions to allow for fish to traverse the stream.

As described in this course, this design was one of many options that could have been used to provide fish passage through this crossing.