Pit run sand and 2- to 4-inch cobbles were used to harden this forest road segment with an approximately 10% grade. Although ATVs displace some of the smaller cobbles and gravels, larger particles – imbedded in sand and compacted – remain in place.

Adequately Graded Aggregate

Moderate and high displacement uses need larger aggregate particles to reduce the propensity for surface displacement. Large particles in the surface form a rocky bearing surface that resists tread abrasion from visitor use. Surface displacement is a serious problem because it can remove the top from hardened tread, which in turn changes its drainage, reduces its effective hardening, and results in increased erosion – which is the exact opposite of what was intended in the first place.

The largest particles need to be large enough to be firmly bedded in the aggregate layer with only their tops exposed. Rounded particles, such as glacially or water-rounded stones, are most suitable – although a full range of aggregate particle sizes need to be present to enable firm bedding and compaction. The following graphics on this and the next page define the function of rock and soil materials in greater detail.

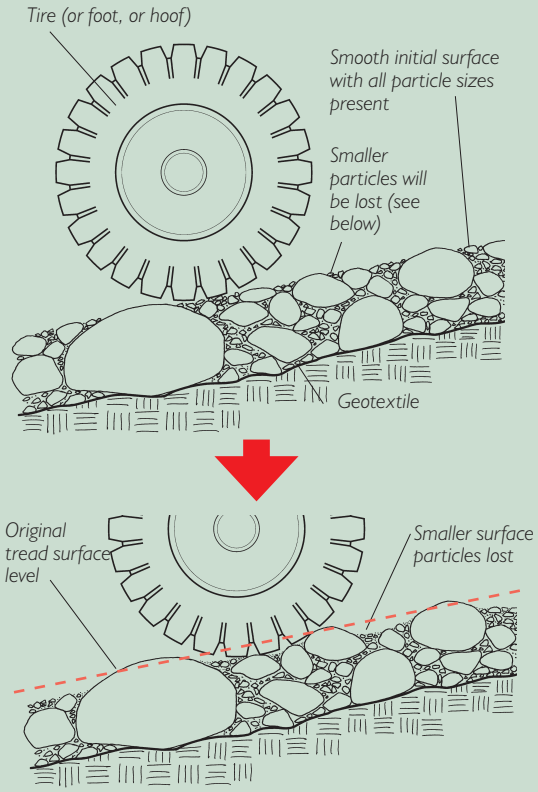
Aggregate Loss on Tread Climbs

With any aggregate hardening on a nonlevel tread, some of the surface aggregate is lost through displacement and erosion. At installation, the tread surface is smooth with all sizes of particles from dust to the maximum size in the aggregate layer. The top illustration shows tread hardening with pit run (rounded river rocks and sand).

After trail use, however, smaller surface particles – and some larger ones – are lost to displacement and/or erosion, as shown in the bottom illustration.

The depth and amount of surface loss increases with:

- Steeper tread grades
- Higher displacement uses
- Larger tread watersheds
- Smaller maximum size of aggregate particles (i.e., where the largest particles are not large enough to be buried deeply enough to withstand surface displacement)



The larger cobbles of this pit run and Class 5 material resist surface displacement on this on-road ATV trail. Note how centrifugal displacement has migrated the thin cap of Class 5 to the outside edge of the curve while the cobbles remain firmly embedded in sand and fines. For high-displacement uses, cobbles should be the final tread-bearing surface. Cobbles also prevent the curve from becoming superelevated.

Although crushed limestone can work well for low displacement uses, it is too lightweight and does not contain enough natural lime binders to resist surface displacement by high-displacement uses. Performance in this case could have been improved somewhat by superelevating this curve. (Note that use is already forming superelevation.)

Rock and Soil Materials

Avoid Graded Rock Products

"Grading" is sorting by particle size to eliminate certain sizes as too large and/or too small. Grading often eliminates dust and fines essential for bedding and compaction. For tread hardening, avoid graded products for tread surfaces (e.g., railroad ballast, washed rock, and pit run cobbles without fines).

Aggregate Screening

Screening limits the maximum size of particles. For instance, a "3/4 minus" screen limits the aggregate to particles that can fit through 3/4-inch openings in a screen. Screened material should contain the full range of smaller particles, fines and dust.

Crushed Stone

Pure crushed stone (100 percent from crushing quarried, solid rock including all fines and dust) can form a dense, stable aggregate layer. Nearly all of the particle faces are angular, contributing to mechanical interlock and strength.

Pit Run

Glacially or river-rounded rock and sand found in deposits make excellent hardening materials. Larger stones are rounded, making them smooth when exposed in trail tread, and sands and gravels act as bedding fines. Material should include sand and fines as well as the full range of particle sizes.

Sand and Mineral Soil

In a geocell application, if rocky products are not readily available to pack geocells, sand and well-drained, compactable, nonexpansive mineral soils can be used. The resulting geocell layer will not be as strong as rock aggregate, but it may be adequate for trail use. Geocell layers can be stacked for extra load-bearing strength if needed.

Rocky aggregate is highly recommended as a cap layer and tread-wearing surface. If aggregate is not available, locally gathered stones and gravels can be added to the top tread layer. Even a few stones are better than none.

Favor Heavyweight Aggregates for Tread Surface

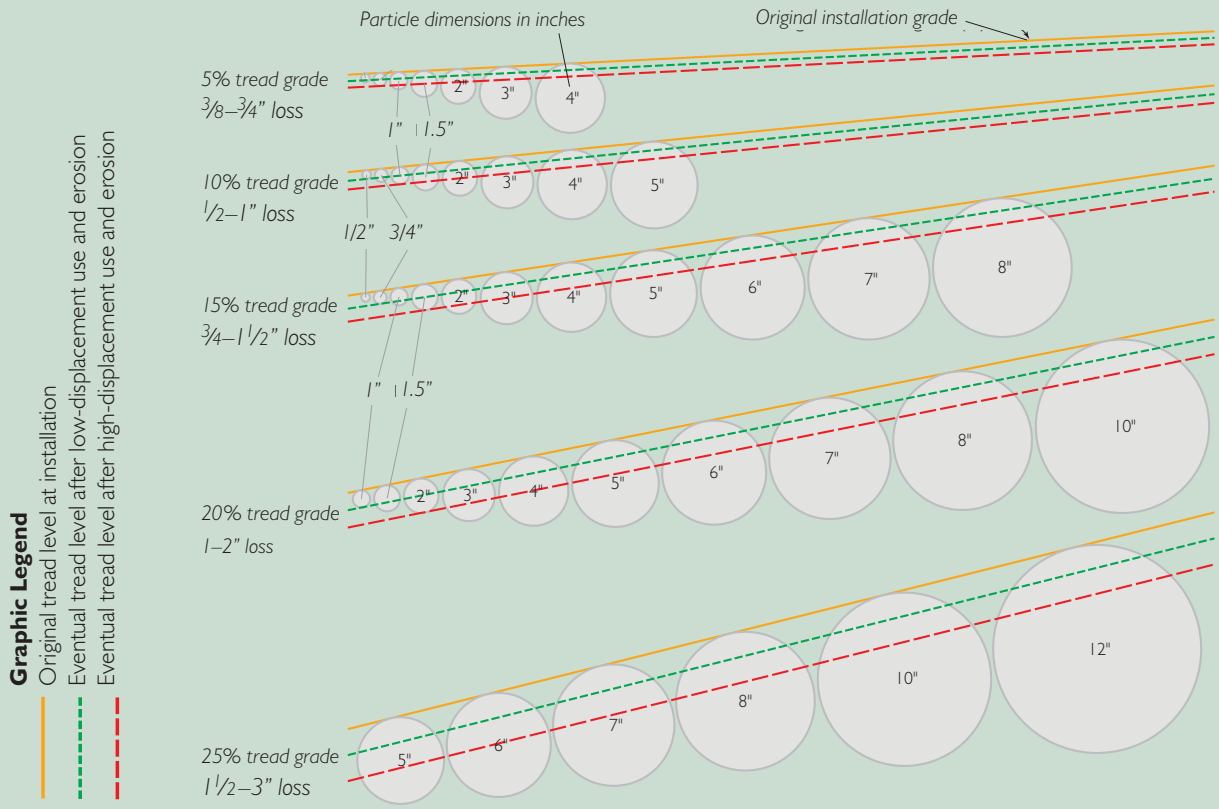
Where there is a choice, use the heaviest available aggregate material for the tread wearing surface or any place exposed to moving water. In particular, granite is preferred over limestone because of its greater weight and density. The weight of individual particles, including dust, helps reduce displacement and erosion.

Minimum Aggregate Particle Sizes Likely to Remain Bedded in Tread Grades

After trail displacement and erosion remove smaller particles from the surface, only those that are still more than half buried will be able to resist displacement. The table and diagram below define the minimum particle size that can be expected to resist displacement. For example, on a 20 percent tread grade with a high-displacement use, the minimum particle size likely to remain embedded is 5 inches. Particles smaller than 5 inches will be largely displaced from the tread surface, leaving a bearing surface of particles 5 inches and larger. Yet those smaller particles – all the way down to dust – must be present in order to bed the larger particles.

Tread Grade	5%	10%	15%	20%	25%
Low-displacement trail use	1"	1.25"	1.5"	2.5"	3.25"
Moderate-displacement trail use	1.25"	1.75"	3"	4"	6"
High-displacement trail use or high traffic level	1.75"	2.5"	3.5"	5"	8"

Note that the listed sizes are minimum sizes. Within the parameters of the trail type and desired experience, larger particles than those listed will increase stability and tread roughness. Important note: The extent of displacement is the total effect of type and level of use.

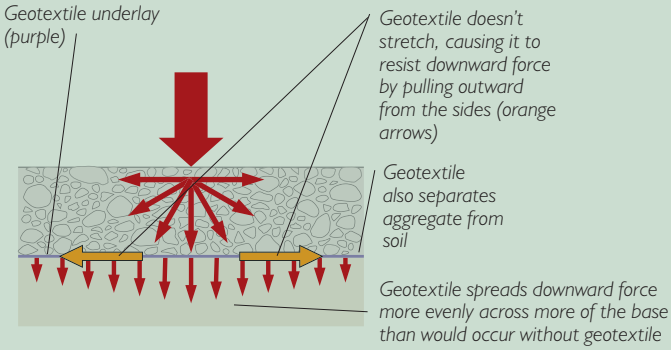


Geotextile, Geocells, and Edge Containment

Geotextile, also known as construction fabric, is a strong, synthetic (polyester), porous, permanent ground fabric that resists stretching. Buried under an aggregate layer, it adds lateral strength by using the weight and compaction of the aggregate itself to prevent aggregate spread under load. Geotextile works even when the soil below it is somewhat unstable. Geotextile also separates aggregate from the soil below, preventing it from mixing with soil and losing effectiveness. Geotextile should always be used between aggregate and underlying soil, as illustrated in the following box.

Aggregate Load Bearing Structure With Geotextile Underlayment

Geotextile laid before fill material is placed to create a stable trail tread through a stretch of unstable soil. Geotextile strengthens the tread and prevents the fill material from mixing with the soil below.



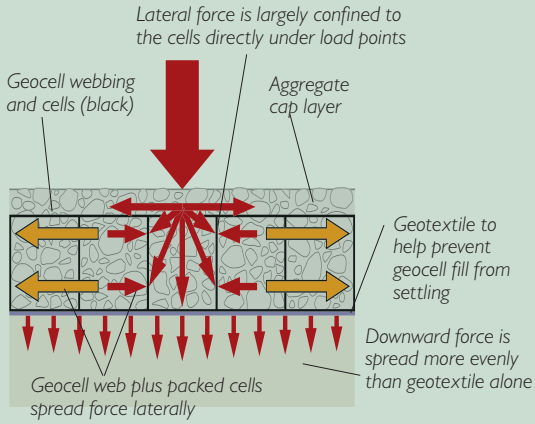
Geotextiles are available in woven and nonwoven forms. Nonwoven forms are preferred because they are easier to handle and spread forces in more directions. Geotextiles will last indefinitely when buried, but are photodegradable and should not be used where they would be exposed to light –including in situations where tread displacement would expose them.

Geocell, also know as cellular confinement system and by trade name such as Geoweb, is a synthetic webbing of cells with open tops and bottoms. Aggregate is compacted into each cell. The tighter the compaction, the better it works. When each cell is tightly packed, horizontal spreading under load is resisted by the entire cell wall vertically through the web. The entire geocell layer becomes stiff like a slab, spreading loads over a larger area and enabling a relatively thin layer of aggregate to carry more than geotextile can with the same thickness of aggregate, as illustrated in the following box.

Aggregate Load-Bearing Structure With Geocell

Geocell over wet organic soils. Behind the staked board, the cells have already been filled with crusher fines and compacted. This is 4" thick geocell installed in a turnpike, but the wood sides serve mostly to hide the edges of the raised geocell webbing. Although not used here, geotextile should be used under the geocell to help prevent cell fill from mixing with unstable soil below.

On this ATV trail, the crushed limestone cap layer used is too lightweight and too small in particle size to withstand displacement. While the stiff geocell webbing will prevent further deepening, it will need to be top dressed with replacement limestone every year.



Given the expense, geocell is best used over unstable soils. It can also help prevent erosion on steeper tread grades and in flood-prone drainage crossings. It is currently manufactured in 4-, 6- and 8-inch vertical cell heights. Geocell is also available with perforated cell walls to facilitate horizontal water movement. Although geocell is not photosensitive, cell walls should not be exposed in the tread. Exposed cell edges are unsightly and can cause less traction or a tripping hazard. Therefore, geocell should always be used with an aggregate cap layer with sufficiently large aggregate particles to withstand displacement by trail uses.

Timber edge containment is discouraged because of few benefits, high cost, and drainage problems.

Edge containment helps prevent horizontal aggregate from spreading at the edges of the tread. It can be achieved with stones or timber, or burying the aggregate in a trench in stable native soil. The benefit is most apparent in narrow treads where visitors have to travel near the edges. An extra width of hardened tread also provides edge containment for the heavily used center portion of the tread. Hence no added edge containment may be necessary for many hardened treads. The use of wood or timber edging for hardened tread is discouraged in most cases. Wood is not that effective as containment, tends to trap water on the tread, and decomposes too quickly to make it worthwhile unless there is a clear need in a certain spot.

Additional Considerations for Mechanically Stabilized Rock and Soil

The following provides additional information on mechanically stabilized aggregate techniques.

Mechanically Stabilized Aggregate Techniques For Near-Level Tread

Suggested Aggregate Hardening Specifications For Level And Near-level Treads

Letters A, B, and C in the table refer to layers in the drawings below. For each layer, the first number is the thickness of that layer. The second number is the maximum screen size in inches for aggregate particles. For example, "(A) 6", 1" means that Layer A should be 6 inches thick of particles passing a 1-inch screen (i.e. particles from dust to approximately 1-inch in diameter). "(B) 4" geocell, 3" means that Layer B should be 4-inch geocell filled with particles passing a 3-inch screen. Some situations only need Layer A or A+B. All techniques assume geotextile under the bottom layer. If Layer C is used, geotextile between B and C is recommended.

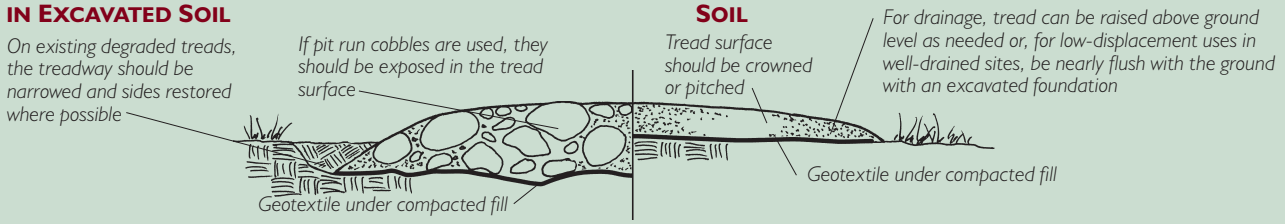
For particles 2 inches and larger in layer A, glacially rounded pit run particles are preferred since they will be exposed in the tread surface. For Layer C, "aggregate" can be any particle screen from 1-inch minus upward. For wheeled uses, curves should be superelevated and/or additionally hardened to better withstand centrifugal surface displacement. Note that 1-inch minus aggregate is equivalent to Mn/DOT Class 5, a common crushed stone road base in Minnesota. Aggregate in screens smaller than 1-inch should be from crushed rock and contain a high percentage of fines and rock dust as physical binders.

	Soil with good to fair weight-bearing ability	Soil with moderate to low weight-bearing ability *	Highly and deeply unstable soil with poor weight-bearing ability *
ORV	(A) 6", 1	(A) 16", 1 or (A) 4", 3 (B) 8" geocell, 3	(A) 24-36", 10 or (A) 4", 3 (B) 8" geocell, 3 (C) 12" agg
ATV	(A) 5", 2.5 preferred or 6", 1	(A) 10", 3 or (A) 3", 3 (B) 4" geocell, 3	(A) 4", 3 (B) 6" geocell, 4 (C) 6" agg
OHM	(A) 5", 2	(A) 8", 2 or (A) 3", 3 (B) 4" geocell, 3	(A) 3", 3 (B) 6" geocell, 3 (C) 6" agg
Horse	(A) 6", 1 with mod. % fines	(A) 10", 1.5 or (A) 3", 2.5 (B) 6" geocell, 2.5	(A) 3", 2.5 (B) 8" geocell, 2.5 (C) 6" agg
Mountain bike	(A) 4", 5/8 with high % fines	(A) 8", 1.5 or (A) 2.5", 1.5 (B) 4" geocell, 1.5	(A) 2.5", 1.5 (B) 4" geocell, 1.5 (C) 6" agg
Hiking	(A) 4", 5/8 with high % fines	(A) 6-8", 1 or (A) 2", 5/8 (B) 4" geocell, 1	(A) 2", 5/8 (B) 4" geocell, 1 (C) 6" agg
Wheelchair	(A) 4", 1/4 with high % fines	(A) 8", 1/4 or (A) 2", 1/4 (B) 4" geocell, 1	(A) 2", 1/4 (B) 4" geocell, 1 (C) 6" agg

* Suggested starting points. Site conditions vary widely, professional advice is advised.

Layer A – on Top of Existing Sunken Tread or in Excavated Soil

Layer A – New Trail on Well-Drained Mineral Soil

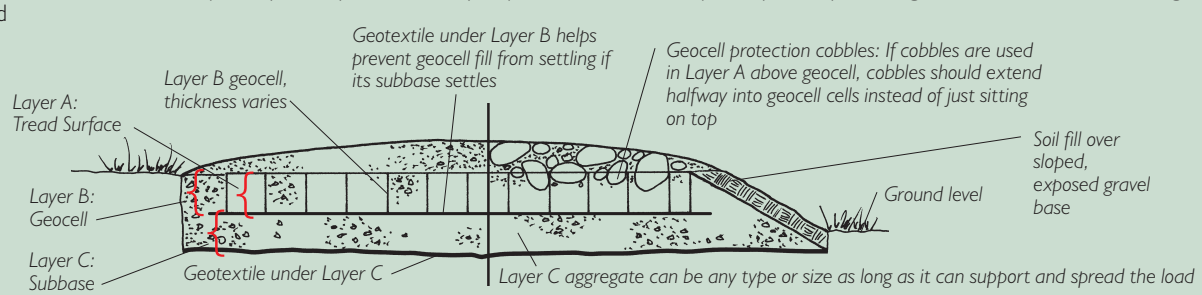


Layers A, B, and C – Mostly Below Ground

In a well-drained site, can be partially or fully buried to any depth needed

Layers A, B, and C – Mostly Above Ground

Can be partially or fully above ground as needed for drainage



The following photos illustrate a variety of mechanically stabilized rock and soil-hardening techniques used for trail treads.

Hardening material found near the site. *In many cases, well-graded pit run gravels can be used for tread hardening to create a stable trail at reasonable cost (left). For some uses, hardening also serves as a trail challenge, as is the case with this OHV trail in an OHV recreation site (right). Both of these will likely prove to be very stable over an extended period of time.*

Crushed stone. *In this nearly level site for a multiuse trail, native soil was replaced with crushed stone. The tread surface is only slightly raised above the surrounding ground.*

Firming. *This is done by compressing stony material into the top layer of native soil rather than modifying the entire tread. Firming may sometimes be sufficient for lightweight, low-displacement uses.*

Mechanically stabilized rock and soil-hardening techniques are often used for drainage crossings.

Unitized Wear Surfaces

Unitized wear surfaces provide a nonaggregate-based load-bearing hardened surface with high lateral strength. There are a variety of materials or products that may be suitable for unstable soils, underwater applications, steep tread grades, and wet applications. The following considers the most common.

Concrete Block, Concrete Planks, and Poured Concrete Slabs

Concrete blocks, planks, and slabs are very artificial but highly effective means of hardening OHV trails, especially where weaker soils are prevalent. These materials are only used where other less-obtrusive options are not suitable or resilient enough for the intended use. This type of material is used less often for hiking, mountain biking, or horse trails, where other techniques are more suitable and visually appealing. Concrete blocks can be used for drainage crossings, trail approaches, and steep trail sections that need additional protection from erosion. Concrete planks and poured concrete are generally used for low-speed water crossings.

Advantages: Concrete planks and blocks and poured concrete are very effective hardening techniques that can stabilize challenging trail sections and crossings that cannot be remedied any other way. They also tend to be relatively low maintenance.

Disadvantages: These materials are not very natural looking, and it can be a challenge to get materials to remote sites. Paving material may be slippery when wet. Also, concrete block installation requires excavation in a drainageway, which can be challenging to restore.

Installation: Generally, topsoil is removed and stockpiled along the edges for reuse. In some cases, compacted aggregate material is needed to provide a solid base under planks, blocks, and poured concrete. Occasionally, geotextile is used in combination with aggregate to form a stable base for planks. Installation requirements are site-specific and often require technical evaluation by an engineer. Poured concrete also requires reinforcement, such as wire mesh and or fiber mesh.

Interlocking concrete block *(left) was used to harden both the approach and the drainage crossing. While not natural, it effectively controls displacement and erosion. Extensive use of concrete block is recommended only where more natural hardening methods are not feasible. Note that one of the main advantageous of blocks over stones is that they interlock, creating a stronger bond.*

Porous concrete block *(right) hardens only the bottom of this drainage crossing on a popular mountain bike trail. The block extends well under the soil tread to eliminate any lip.*

Concrete boat ramp planks. *Planks laid on aggregate fill can provide lateral stability for slow water crossings. Planks are laid perpendicular to the trail.*

Water flow undermined small diameter aggregate under some of the planks*. Larger diameter cobbles are needed as a foundation in channels with higher flow speeds.*

Paved dip for ATVs. *Small concrete planks have diagonally scored faces for traction. Since this is a low flow, seasonally flowing drainage, planks are set directly in native soil tread.*

These crushed stone treads use poured concrete swales to prevent tread erosion by concentrated surface flows. *Both trails are accessible. At left, loose stone particles have collected in the dip, partly clogging it and possibly forming a slipping hazard. At right, the concrete dip is barely visible – crushed stone from the tread itself was used as concrete aggregate and exposed during curing. As a result, concrete color and texture exactly matches the tread.*

Porous Panels

Porous panels are one of the most promising emerging OHV trail-hardening systems for wetlands and sensitive areas. The panels are long lasting, low maintenance, and good at transferring lateral loads. The panels are suitable for OHV use, but a poor choice for horses and only fair for foot traffic.

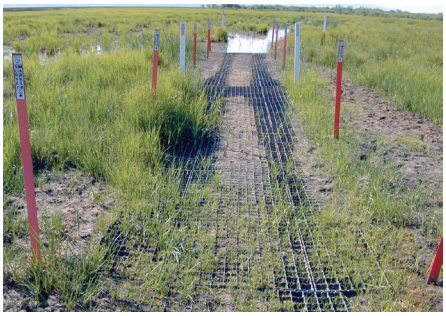
The grid-like plastic panels are designed to lay on the ground surface. The bottoms of the panels have many holes to allow plants to grow through and enough strength and stiffness to be able to spread a load across the panel (or several connected panels). The top edge of the panel cells are designed to directly support traffic, but can also be ballasted or capped with soil or gravel to completely hide them.

The panels allow for wetland crossings with minimal disturbance to vegetation and the ground. They are less disruptive to vegetation than a boardwalk, which largely kills all vegetation beneath it. The panels can also be used to carry a trail over a cultural site without damaging the site.

Advantages: Panels are quite rigid, strong, and durable, yet lightweight. They can be completely removed with no remnants and no soil disturbance and can be reused elsewhere. Panels are hidden by wetland vegetation until one is near it on the trail (unlike a raised boardwalk, which can be seen from a distance).

Disadvantages: Panels are more expensive than some other surfaces. Uncapped plastic material does not look as natural as do some other hardening materials. Panels are not suitable for wheelchairs, foot traffic, or horse unless they are filled with soil or aggregate.

Installation: There are two major brands of porous panels available on the market as of this publication: GeoBlock (Presto Products, Appleton, WI) and SolGrid (SolPlastics, Montreal, Quebec, Canada). Installation of these or other suitable products should be in accordance with manufacturer specifications and instructions. In general, GeoBlock does a good job of transferring weight between rigid panels, whereas SolGrid has connectors between panel subsections that makes it more flexible. For both products, panels are screwed together to make long continuous surfaces. GeoBlock can be laid directly on top of existing soils and vegetation even in wetland areas, with vegetation growing up through holes in the panels to both anchor and hide the product. If used underwater, panels must be anchored since they will float just below the water surface if submerged. The easiest anchoring method is to fill the cells with aggregate as ballast. The panels can also be diagonally pinned into the ground with custom bent rebar or commercially available L-angled spikes. The panels tend to expand in direct sun so expansion joints are needed for continuous runs. Note that the current panels on the market can support OHMs and ATVs, but ORVs might break the joints or the screws at the joints unless they are on load-bearing soil.



Green hardening. *A major advantage of plastic porous pavement panels (top) is their ability to support vegetation. Each cell has a relatively large hole in the bottom through which vegetation can grow. This enables a drainage crossing to support plants even while serving as part of the trail.*

Porous pavement panels work underwater. *Ballasted with small rock, filled with soil and planted, or otherwise anchored, panels function well underwater, making them highly suitable for drainage crossings. They spread the load enough to carry vehicles, including ATVs, without sinking into the wet soil below. Unlike currently available geocell, porous pavement panels do not need to be protected from sunlight.*

Hidden paneled drainage crossing. *Ballasted with soil, panels can almost disappear. The top edges of the plastic cells will reappear with trail use when the top layer of soil displaces, but the tread will be laterally unified. Ruts cannot form, displacement and erosion are limited, and plants can potentially grow in the drainage channel and tread for further stabilization.*

Paneled drainage crossing installation. *Some panels (left) have flexible joints built in to enable them to contour to irregular treads. This photo illustrates a drainage crossing in an early stage. Grids can be left exposed or ballasted with soil or rock.*

Stone Paving

Stone paving can be used for drainage crossings, trail approaches, and steep trail sections that need additional protection from erosion. Because they do not interlock, stone paving is more susceptible than concrete blocks to displacement on steep approaches.

Advantages: Stone paving is a relatively effective hardening when care is taken to fit stones together. Flat stones can be used to stabilize challenging trail sections and crossings. Stone paving also tends to be relatively low maintenance if well constructed. Stones are more visually appealing than concrete-based products.

Disadvantages: If not readily available on the site, the cost to import material is high. Stone paving is labor intensive to install and it can be a challenge to get materials to remote sites. Smooth stones may be slippery when wet. Also, stone paving installation requires excavation in a drainageway, which can be challenging to restore.

Installation: Generally, topsoil is removed and stockpiled along the edges for reuse. In some cases, compacted aggregate material is needed to provide a solid base under stones. Occasionally, geotextile is also used with aggregate to form a stable base for the stones. Stones have to be sized relative to the intended use, with smaller stones being adequate for hiking trails and much larger and heavier ones being necessary for OHVs.

Hand-fitted stones carry relatively constant spring outflow across the trail. The shallow, ramped dip enables mountain bikes to pass through without muddying the water. This technique is recommended primarily for relatively constant yet low volume flows where water quality is to be protected. Although installation is labor intensive and requires a supply of stones with flat faces, the result can be an attractive trail feature that accentuates the water passing through it.

Where there is little sideslope, the stone paving should extend beyond the tread on both sides to ensure full coverage. Attractive stone paving is considered a desirable feature on nonmotorized trails, especially hiking trails. Using a variety of stone shapes adds natural shape and enhances rustic appearance.

Chemical Binding

Chemical binding is generally used to form smooth, firm treads from small soil particles on level or low tread grades in reasonably well-drained sites for low- and medium-displacement uses. Chemical binding tends to be a very specialized approach to trail hardening requiring specific products and installation techniques. The following provides an overview of the common choices. However, the use of any of these approaches requires independent evaluation to ensure that the product is suitable for the application. Generally, chemical binding is not used when other, more standard techniques are sufficient.

Crusher Fines

100% finely crushed stone with all fines and dust can sometimes bond to itself with its original natural cementing agents. How much this occurs is specific to each mix, but the best mixes can bond quite tightly when dry.

Recycled Asphalt

Recycled asphalt forms a durable tread on grades up to 8 percent when laid 6 inches thick and thoroughly compacted. It has to be located in sun because it does not bond to itself unless it is heated. The surface may partially unravel under ATV use, especially on curves. Although the surface can be seal coated with slurry seal to bond the surface, this would make it look like regular asphalt.

The asphalt can be strengthened with copolymers or other treatments. It can also work well in geocell, especially on steeper grades.

Copolymer Soil-Bonding Agents

New copolymer soil bonding agents are being introduced by several companies, although their application in Minnesota has yet to be fully tested in many cases. Light application of these agents can lightly bond soil particles. Heavier applications create very hard polyurethanelike waterproof bonding, essentially turning compacted soil into a bricklike surface.

The one advantage of some of these products is that the trail tread maintains a near-natural appearance. If these products perform as promoted, they do hold some promise as a nontoxic, durable soil hardener that may be easier to apply and more natural looking than other hardening methods. Given the limited field testing of most of these products, none are listed here. Contact manufacturers of these products for technical information.

Hardening Techniques To Avoid

There are a number of hardening techniques that should generally be avoided. These include:

- **Wood chips** – in a thick layer, chips are temporarily effective but quickly decompose into organic soil that is most often unsuitable as tread. Wood chips also float, readily wash away, and form an excessively spongy tread. Avoid wood chips as a permanent solution.
- **Gabions** – these have been used as tread in some cases, but the exposed wire mesh eventually breaks and becomes hazardous.
- **Soil cement** – adding bagged cement mix to native or amended soil simply does not work.
- **Flexible surface mattings** – when laid on unstable surfaces, these mats lack load-bearing characteristics and typically fail. They also tend to be very expensive.
- **Metal grids and platings** – these are unsightly and tend to rust and bend.
- **Shredded tires and other recycled aggregate products** – these tend to have little hardening ability while adding difficult-to-remove synthetic materials to the natural environment.

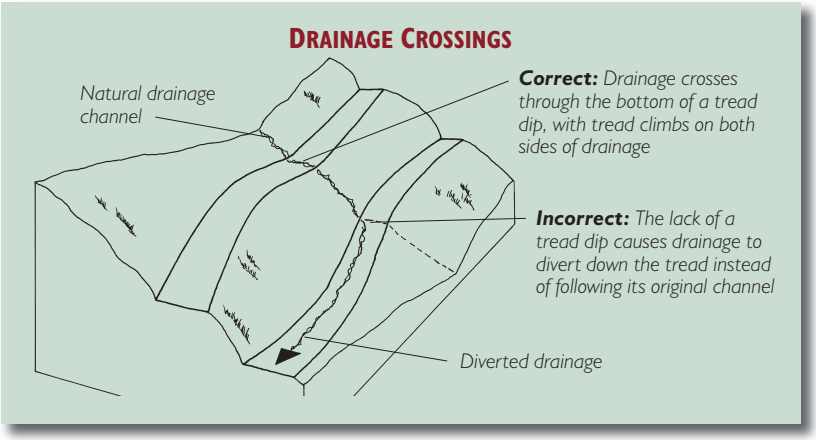
Drainage Crossings

Drainage crossings occur wherever the tread crosses a concentrated site drainage channel, including runoff swales that are typically dry except after rainfall. In all cases, drainage flow *must* continue on its original course and in its original channel. In no instances should water be intercepted and redirected down the tread itself. This is especially the case when trails traverse significant sideslopes, where intercepted storm runoff channels and even small streams can cause serious tread erosion and alter site hydrology.

A drainage crossing is designed to prevent treads from intercepting drainages. In all cases, drainage crossings are a form of tread dip with water crossing the tread at its bottom. This ensures that the tread will climb up from the drainage on both sides of the crossing even when the tread is climbing and traversing. The following graphic illustrates correct and incorrect drainage crossings.

Incorrect drainage crossing. *Runoff from an intercepted stream runs down this tread and creates extensive and unsustainable erosion.*

Correct drainage crossing. *This ORV trail properly crosses a drainage swale by dipping through it and climbing on both sides. After climbing out of the crossing (background), the trail continues dropping while traversing the slope.*



Types of Drainage Crossings

Any concentrated site runoff or other side drainage intersected by the tread is considered a drainage crossing. There are basically three types of drainage crossings that need to be considered:

- Defined flow or stream channels that intermittently or continuously carry water
- Swales that collect and concentrate intermittent runoff (swales are depressions in the side of a slope, vary greatly in size, and lack a defined channel)
- Seeping or chronically wet slopes

Whether a seep, swale, or flowing stream, all drainage crossings must be at low spots in the trail and be formed to continue the natural flow of water across the landscape that is being traversed.

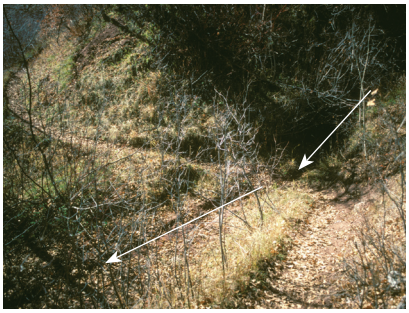
Suitable technique. *On this steep sideslope, the trail is aligned relatively level and curved around the inside of the drainage to minimize tread erosion and improve safety. Enough of a dip must be provided to keep water in the drainage. In this case, the limited drainage requires only a small dip at each crossing.*

Correct drainage crossing. *Most drainages crossed are very small and shallow but long enough to not clog.*

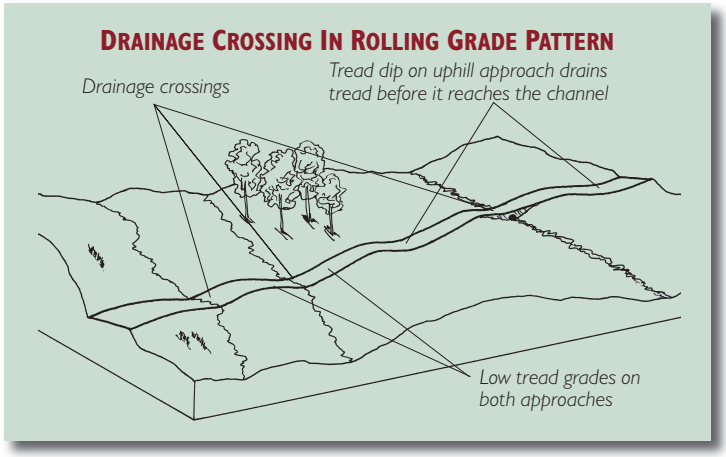
Correct drainage crossing. *The tread directly crosses a small yet defined runoff channel (the light-colored soil in the immediate foreground). Well-drained soil prevents muddiness on this ATV trail.*

Drainage Crossings in Rolling Grade Pattern

In a rolling grade pattern, drainage crossings are a special form of tread dip. In practice, rolling grade is commonly planned and aligned as a series of dips and drainage crossings that divide longer tread watersheds, as illustrated in the following graphic.



Correct rolling grade drainage crossing. *The trail crosses this channel in a tread dip. Since this drainage is usually dry and the soil is sandy, water can cross directly on native tread without extensive erosion. The tread climb out of the drainage is visible in both directions.*



Incorrect rolling grade drainage crossing. *This trail is intercepting and diverting water from a site drainage crossing behind the photographer, sending it down the tread. If the tread had a rolling grade on the slope at left, this diversion could be prevented.*

ECOLOGICALLY SUSTAINABLE DRAINAGE CROSSINGS

Crossing any drainage inherently brings up concerns about ecological sustainability given the potential for the trail to disrupt natural water flows, erosion, and sediment transfer downstream. Drainage crossings can also introduce nonnative plants, causing impacts to native aquatic plants or ecosystems. Drainage crossings also tend to be richer ecotonal areas with a very delicate balance of native plant species.

To be sustainable, drainage crossings must respect and protect five components of river systems: 1) the flow (hydrology); 2) the shape (geomorphology); 3) the connections (connectivity); 4) the quality (water quality); and 5) the life (biology). For this reason, all drainage crossings should be consistent with the guiding principles for sustainable trails as defined in Section 3 - Principles of Ecological Sustainability. The most important of these is avoiding sensitive ecological areas and critical habitats wherever possible.

If a drainage crossing is necessary, preventing erosion and minimizing sediment transfer into drainages is the most important consideration in determining which crossing approach is the most appropriate. Inevitably, drainage off the tread flows into the drainage being crossed. The box on the next page considers approaches to drainage crossings to ensure that in the process erosion and sediment transfer are prevented or kept to a minimum.

Approaches to Various Types of Drainage Crossings

The following describes approaches to crossing various types of drainage. A conservative approach to selecting a crossing approach is recommended to avoid having to do expensive and often difficult remedial work to resolve problems caused by erosion and sediment transfer.

Low Flow Intermittent Storm Runoff Channels

There are no limitations on draining the tread into low-flow or intermittent channels as long as water flowing off the tread does not significantly contribute to sedimentation of the channel or any nearby water body. If it would, manage the drainage crossing as defined below for seasonal flow or natural open water channels.

Seasonal Flow Channel

This refers to channels with a continuous flow for days or weeks at a time. The amount of trail use, soil type, likelihood of tread erosion, and other relevant factors all need to be considered in determining the potential for sedimentation. General suggestions for reducing sedimentation include:

- Minimize trail grades on final approaches to the channel
- Use tread dips some distance from the channel to drain tread water before it can reach the channel
- Consider using hardened tread on approaches where natural soils are insufficient to prevent sedimentation from occurring
- Consider using a culvert or built structure to span the drainage entirely

Natural Open Water Channel – Flowing and Standing on a Perennial Basis

The tread should be designed to minimize or completely eliminate direct sedimentation into a natural open water channel with flowing or standing water.

Potential sedimentation control measures include, but are not limited to:

- Use same measures suggested for seasonal flows, especially culverts or built structures.
- Use "green" hardening techniques for relatively steep approach grades, high displacement uses, highly erosive tread, or other factors that cause sedimentation despite other countermeasures.
- Plant appropriate native vegetation in all nontread areas disturbed by trail construction and maintenance, including all surfaces of drainage channels.

Channels in Primitive Areas or Along Challenging Trails

Crossing natural water channels, including fording streams, can be an enjoyable part of the experience of primitive trails. Although direct contact of visitors with water is discouraged even on these trails, it can be considered where impacts can be kept to a minimum. Any crossing also requires careful evaluation and surveying of in-stream habitat in order to maintain the integrity of the riparian corridor to avoid degradation of the stream banks and water quality.

If a ford is acceptable, natural rock bottomed in-channel crossings are preferred. Hardening channel bottoms with boulders, rock, cellular confinement systems, concrete or other heavy, stable materials can also be considered as long as its appearance is consistent with the setting.

Reducing or eliminating sedimentation from water flowing off the trail may be difficult. This is especially the case with wheeled uses, which push and lift water from the channel that then flows back into the channel. In many cases, approaches will likely need to be hardened, preferably with naturalistic methods such as larger native rock. (Do not use gravel and aggregate for hardening approaches and channel bottoms.)

In primitive areas and along challenging trails, ensuring that the crossing will not widen or move through trail use is also very important to managing sedimentation and maintaining the desirable trail character. Careful use of anchors in these instances is typically the most successful approach.

Drainage Crossing Options

There are four primary options for crossing drainages:

- **Direct crossing** – suitable where intermittent and low-flow runoff from a storm does not pose any significant crossing challenges and is sustainable.
- **Hardened tread crossing** – used where needed to reinforce a channel crossing to handle more intense storm runoff or to harden mud-prone areas.
- **Culverts** – used for deeper channels and those that carry water for extended periods.
- **Built structures** – bridges, boardwalks and other such structures are favored over culverts for open and/or flowing water that can support fish.

Important consideration!

As a general rule, avoid direct user contact with water unless the water flow is transient (such as storm runoff) and minimal and trail use does not produce excessive mud or sedimentation. The following provides examples of each of these options.

Direct Crossing

If flows are spread out and clearly intermittent, a direct crossing can be used. However, all direct crossings should be designed to allow a more aggressive approach (in most areas, hardening the crossing) should the trail change the flow enough to require it.

Sustainable crossing across a low-flow drainage. *This should be sustainable for many years with little maintenance.*

Low- flow crossing. *This crossing only occasionally flows during heavy rains and dries up quickly thereafter, requiring no hardening to keep it sustainable.*

Hardened Tread Crossing

Hardening is used to reinforce a crossing to handle intense storm runoff or to stabilize mud-prone areas. The following considers a variety of common techniques where the water is not too deep or too fast, and where trail traffic is relatively low and/or water quality disturbance in the crossing is expected to be minimal. These techniques are most commonly used in storm runoff channels that may otherwise scour through native tread, or in normally shallow, slow-moving, low-flow, seasonal channels.

Road Base

Road base provides a simple drainage crossing solution and can be used where crossings are usually dry and water speed and volume is periodic and low.

Advantages: Smooth surface and easy to construct.

Disadvantages: Displacement increases under wet conditions, and can lead to formation of a puddle or mudpit. Rock dust washes away, leaving unconsolidated aggregate. Aggregate can wash away with higher water speed. Displacement rapidly increases with visitor speed. A berm can form on the lower edge, causing ponding on the tread. Road base is not very natural in appearance.

Installation: Larger cobbles of varying sizes are highly recommended. Use geotextile and/or geocell underneath if the soil is unstable or if the aggregate is at risk of sinking into the underlying soil. Otherwise, simply use a sufficiently thick layer of aggregate (at least 6 inches) to spread traffic load over the underlying soil.

Typically dry equalizer drainage crossing. *Class 5 plus larger cobbles stabilize this dip on a former railroad grade across wetlands.*

Low-speed, low-flow crossing. *Class 5 plus larger cobbles cross this drainage on a forest road and on-road trail. With a seasonal flow that washes away small particles, the cobbles help reduce displacement and provide the tread surface.*

Ponding caused by displacement. *Class 5 by itself does not withstand displacement with higher water flow rates – the particles are too lightweight. The higher the flow and the longer the period of flow, the more large cobbles are needed.*

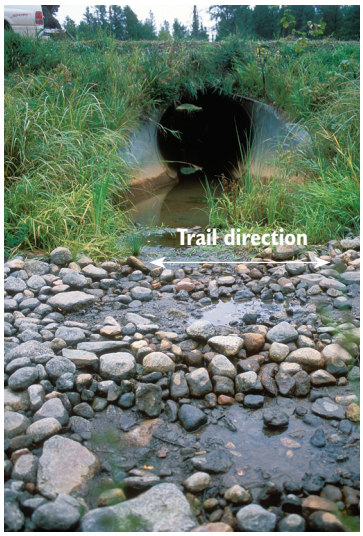
Stone Cobbles

Cobbles are used for OHV trails with low to medium water speed and volume. They are preferred over road base for any crossing with regular water flow.

Advantages: Cobble crossings are easy to construct. They do not contribute to sedimentation. They are more difficult to displace or erode and more natural than road base.

Disadvantages: Stones can become loose and roll around. Stones can be rough and uncomfortable for any use without wide tires. Stones may become slippery if continually wet.

Installation: Rounded stones should be used. In unstable soils, a base layer of stones 14 to 24 inches and up may stabilize the crossing, even for ORVs. For ATVs and OHMs, smaller rocks can provide sufficient stability. Use a variety of stone sizes to improve stability. Use a sufficiently thick layer of cobbles to spread the load over the underlying soil. Geotextile under stones greatly improves stability.



Cobbled crossing of a wetland drain. *On this ditch trail, cobbles were used below the road culvert to provide a stable, nonmuddy crossing for ATVs. The usual ATV displacement is not a problem because water flows between and over the stones.*

Cobbled overflow drainage crossing. *This crossing handles wetland overflow when necessary. Because it is a floodway, geotextile beneath the cobbles adds resistance to scouring. Note the dip in this forest road.*

Geocell and Aggregate

Geocell under aggregate supports heavier traffic – even in flood conditions – and resists erosive flood flows.

Advantages: Geocell and aggregate reduce displacement under heavy traffic and flood conditions. It has a natural appearance and requires little maintenance.

Disadvantages: Installation may require excavation.

Installation: The base layer is geotextile and a geocell product of appropriate thickness for the traffic, filled with compacted cobbles and rock particles of all sizes. This is topped with more cobbles to protect the geocell from sunlight. The final tread can be smaller cobbles and/or Class 5, although larger cobbles are less susceptible to washing away during higher flows.

Forest road wetland crossing with laterally stabilized aggregate. *This entire crossing (viewed from two directions) was stabilized and a dip was formed to channel low flows. Geotextile and 8-inch-thick geocell is under grapefruit-sized and smaller stones with a layer of smaller cobbles and soil on top. Cobbles are exposed in the dip where they form relatively more of the wearing surface. Driving through produces very little water clouding.*

Overflow crossing with laterally stabilized aggregate. *Geotextile and geocell were used on both the top and sides of this causeway to stabilize for flood flows in case culverts fail. The tread was capped with Class 5, but cobbles and soil were left exposed on both flanks. Note the dip, right, which concentrates low flows.*

Causeway

When large stones are available and soil is stable enough to bear weight, a causeway can be used to raise the tread across low-lying areas and seeping hillsides.

Advantages: A causeway is a rustic, attractive structure that adds a strong anchor and natural shape to the tread. It is permanent, since the main structure cannot decompose. Causeway walls serve as a headwall for pipe culverts beneath the structure.

Disadvantages: Construction is labor intensive. It requires relatively large stones, plus rocky material for backfill. Causeways can only be used where soils can support the weight of stones. Fill can leak out between stones.

Installation: A base layer of geotextile may be needed over unstable soils. Rocks are placed on the edges and the tread is filled with compacted material.

Channelization and Stepping Stones

Use channelization and stepping stones only for hiking and equestrian trails to cross drainages not likely to flood beyond a defined channel. Water can be seasonal or perennial.

Advantages: This approach can be used for drainages in very shallow channels. It is a relatively clog-proof and easy to clean. It can be an attractive feature on a trail.

Disadvantages: It requires carefully fitted stones and a shallow channel with a flat, naturally rocky or stone-hardened bottom. It is not suited for motorized uses.

Some users find stepping stones difficult to use.

Installation: Stones are embedded on side of the channel to keep them in place. They must be tightly fitted to prevent erosion.

Turnpike

Turnpike can be used to form a raised approach in areas of unstable soils. A timber or conventional culvert can convey water under the structure, or a paved dip can carry water through it. In a near-level drainage crossing with boggy soils, ditches may need to be dug on both sides to lower the local water table below the level of the logs.

Advantages: Turnpike provides strong tread delineation, with logs minimizing tread width. It has a rustic appearance. It can be built from locally obtained materials, making it suitable for remote locations.

Disadvantages: Logs have high degree of soil contact, accelerating decomposition. Displacement from trail use can cause a sunken center that holds water.

Installation: Logs are set on each side with wooden stakes to keep them in place. Rocky fill under the surface material helps prevent sunken centers. Geotextiles should be used to contain the fill between the logs and make it easier to replace the logs over time.

Culverts

Elevated crossings (bridges) are preferred over culverts for crossing any amount of perennially flowing or standing water. Culverts can be used and are best suited for drainages with periodic flows that run in a deep, narrow, and defined channel that enables the tread to span the drainageway without building up the approaches. The major advantage of culverts is total separation between tread and water, keeping trails users dry and preventing flow disturbance.

Advantages: Culverts are relatively easy to construct. Little or none of the culvert is visible from the trail if properly installed. Stone headwalls and tailwalls help visually anchor culverts and better integrate them into the trail.

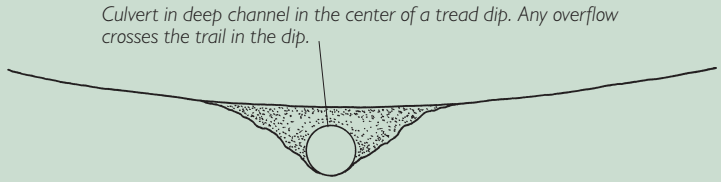
Disadvantages: Small-diameter culverts tend to clog easily and are difficult or impossible to clean out. Culverts require several inches of fill over the top to avoid revealing the pipe. Incorrect installation can lead to blowout, especially if pipes are spliced. Plastic culverts can also collapse if not buried under several inches of tread. Any visible part of the culvert pipe looks utilitarian. If the culvert is washed out, it adds sediment to the waterway.

Installation: Culverts are typically set on solid ground and installed according to manufacturers specifications, especially those relating to ground cover to prevent collapsing. Generally, the greater of half the pipe diameter or 12 inches is the minimum cover to ensure that a culvert will not collapse under load or float up over time and become exposed. The following illustrations highlight some installation techniques.

Culvert Installation Techniques

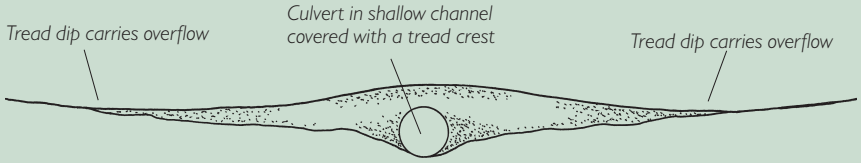
Optimal Culvert Installation

Culvert is in a relatively deep channel in the bottom of a Tread Dip. The channel is deep enough to cover the culvert with sufficient fill, making a smooth tread.



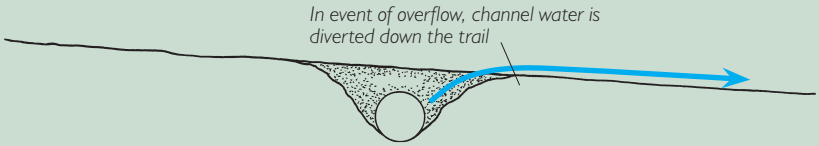
Acceptable Culvert Installation

Culvert is in the bottom of a wide, shallow Tread Dip. But the channel is too shallow to hold the culvert below the tread, making it necessary to embed the culvert in a crest with a dip on both sides. Ensure that the crest won't be displaced away with trail use.



Undesirable Culvert Installation

Tread crosses the culvert on a grade without a Tread Dip. If the culvert fails, water will follow the trail downhill, diverting the channel down the trail. Use only where the culvert is unlikely to clog and is oversized for expected maximum water flow.



Important best practice consideration!

Reference DNR Division of Waters' *Best Practices for Meeting DNR General Public Waters Work Permit GP 2004-0001* for proper siting of culverts, especially as it relates to the free movement of aquatic life through a culvert structure (www.dnr.state.mn.us/waters/index.html).

To prevent washouts and overflows, culverts must be large enough to handle the anticipated greatest water flow. In general, culverts are sized to accommodate the maximum water level of a 25- to 50-year flood. Culverts should also be placed with a slope to ensure drainage through the pipe.

Optimal. *The tread dips through a relatively deep channel, so the overflow flows over the tread above the culvert. Note the tread climbing on both sides.*

Acceptable. *Culverts are embedded in a crest to cross a shallow channel. Note the thick tread fill with larger cobbles above the pair of culverts. Ideally, however, a substantial stream crossing would use a bridge rather than culverts.*

AVOID where possible. *Although very nicely formed with stone headwalls and tailwalls, if this deep-channeled culvert were to clog, water would be diverted down the tread because there is no tread dip. Also note how tread wear has depressed the center of the tread, allowing tread water to follow the tread over the culvert.*

Built Structures

Built structures include bridges, boardwalks, and other structures. These structures are favored over culverts for open and/or flowing water that can support fish.

Structural Integrity of Structures Used for Natural Trails

Important consideration!

Structures come in many forms and styles consistent with the need and setting. *In all situations in Minnesota, structures must be structurally sound and designed to accommodate the anticipated uses and loads.* Although this does not preclude the use of rustic materials, it does require that those materials be fabricated in a way that duly considers user safety. For example, a round felled tree or log may appeal to some users, but is often slippery and too unstable for many other users to negotiate. This results in either bypassing or a greater likelihood of falls, neither of which is acceptable. Agencies and trail advocacy groups are highly encouraged to develop a design standard for all structures used on a particular type or system of trails that is professionally evaluated for structural integrity. Materials should be selected based on durability as well as appearance. Most often, this means using wood (using nontoxic, ecologically appropriate treatments) that come in certain dimensional form with predictable structural capabilities.

Examples of Built Structures

Built structures for use with natural trails come in many shapes and forms, as the following photos illustrate.

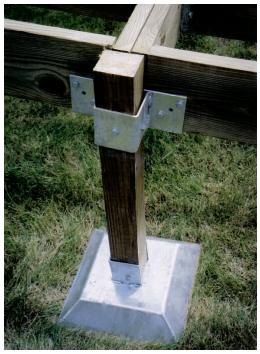
This simple drainage crossing was made from treated dimension lumber. The 24-inch width is appropriate for its level of use, where the likelihood of meeting someone at this spot is minimal. No handrail is needed since it is less than 30 inches above the ground.

This simple, low-profile crossing is located along a more popular trail. A 60-inch width is justified so people can pass each other while crossing the drainage.

Even simple, low-profile crossings must be structurally sound to handle all anticipated loads.

These photos highlight simple solutions to crossing drainages. Select materials based on structural integrity and site appropriateness. This is especially important on nature trails, where all built structures – even simple ones – are inherently part of the experience.

These boardwalks illustrate the range of possibilities and character. The two photos at left are associated with more remote trails where the idea is to simply get through an area without getting wet feet. This simple approach meets user expectations and there is no reason to do more. The two photos at right are associated with popular nature trails in state and regional parks, where the trail will appeal to a wider cross section of users, including those who are less ambulatory. Although more accommodating, these boardwalks still fit well into the settings.



A growing number of premanufactured products are available for boardwalks and bridges. The main advantage to these products is cost and durability. As the photos illustrate, products include treated wood on steel frame (left), patented footings that require no excavation (middle), and various forms of plastic material that can be laid directly on the ground (right). Although these products have some advantages, their aesthetic qualities have to be carefully considered relative to the setting. On more remote or rustic trails, some products may be incongruent with the sense of place.

Bridges associated with natural trails also come in many shapes and forms, as these photos illustrate. With appropriate structural integrity and aesthetic quality, bridges can add to the trail experience by making drainage crossings easier and providing a viewing platform to look up and down the flowage, which can offer some of the most diverse ecological and wildlife views along a trail.

Premanufactured bridges are becoming more popular due to improved materials, aesthetic qualities, and ease of installation. Improvements in design techniques for bridge abutments and foundation systems have also made these appealing.

Taking advantage of abandoned rail bridges is common with natural and paved trails. Built decades ago, these bridges are often key destinations along trails, often offering expansive views.

On this ATV trail, bollards are used to make sure that riders are aligned to cross this low bridge. The bollards also help protect the bridge abutment.

The timber sill on this stone foundation has a mortared cap. The end cap extends behind the sill to protect it from soil contact. The wide endcap and stones harden the edge and help retain the trailbed.

Bridge Foundation and Abutments

The selection of a bridge type and design is often driven by the type of foundation best suited to the site given local soils, the span of the bridge, and load-bearing requirements. In all cases, bridge foundations and abutments must be carefully considered and designed by a trained professional. The following provides an overview of common forms of bridge foundations.

Sills – require little excavation and are only used for small bridges that can move with frost heave. Thick, treated wood sills are often installed on a rocky base or gabions to provide drainage. Bridge stringers rest on top of sills and are protected from soil by a replaceable timber end cap. If a sill rots, the end of the bridge can be jacked up and the sill replaced without dismantling or replacing the entire bridge. Sills can also be used to create a level base for stringers on a bedrock or rock foundation.

Four helical screw piles support the center of this bridge. The piles are under a widened deck section that encourages visitors to pause on the bridge. Cross-bracing prevents side-to-side swaying.

Piles – are weight-bearing columns driven or installed in holes. Friction piles are driven into soft ground until "fetched up" (cannot be driven in further). Piles such as railroad trestles are installed in holes excavated to below frost depth. Helical screw piles made of rustproof, zinc-plated steel can support trail bridges with zero excavation, making them excellent for use in firm-bottomed wetlands and riparian areas. On iced-over waters and wetlands, screw piles are driven directly through ice and frozen soil without a pilot hole. Piles are typically cross-braced to prevent side-to-side sway.

Cribbing – is usually made of squared timber or logs. It is generally not recommended as a bridge foundation (stone is preferred) because wood will eventually decay. Cribbing can be used in a remote or relatively remote area where a rustic trail experience is desired; where shorter, small and/or lightweight bridges are used and water scouring is expected and suitable stone or concrete is not available or not desired; and/or ground is firm enough to support the bridge over the broader bearing surface formed by cribbing but not firm enough to support the bridge on piles.

This small cribbed foundation is designed to be rustic and low impact. Logs are nailed together and rest directly on undisturbed ground.

Native log cribbing filled with rock forms a free-standing elevated abutment for this rustic log stringer footbridge in Oregon.

Stone – where stone is available and the ground is firm and well-drained enough to support them, stone walls can be used as a supporting foundation, or at least slope retention below bridges (especially small bridges on unpaved trails, which can move with frost). Stone can be mortared or unmortared; unmortared is recommended for both naturalism and ease of construction and maintenance. Stone retaining walls can also reduce the footprint of a raised abutment while discouraging users from leaving the trail.

Seen under construction, the ends of three steel stringers (topped by wood nailing strips) are embedded in this unmortared stone abutment. Stone minimizes the footprint of the raised abutment while visually anchoring it. Rock fill provides excellent drainage and reduces settling and tread displacement.

Concrete headwalls, wingwalls, and piers – abutment headwalls and piers transfer the weight of the bridge to bedrock or, more commonly, to a wider footer that distributes the load on suitably firm ground. Headwalls and wingwalls may also retain soil or fill on bridge approaches and protect the foundation from scouring from water flows. Footers are usually installed below frost depth, but can be a concrete pad on grade for some smaller bridges. While usually poured in place, concrete footers and abutments can be prefabricated. Typically, concrete is used for heavier load-bearing bridges requiring a strong foundation.

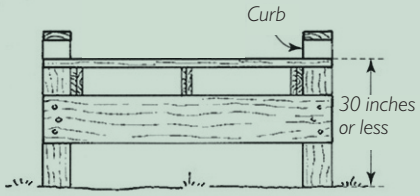
When a bridge can begin at the top of a slope, the visible portion of the headwall will be very small and pose minimal impediment to flooding. Note how the abutment is widened and the top sloped to serve as a retaining wall for the trailbed.

Other Built Structures

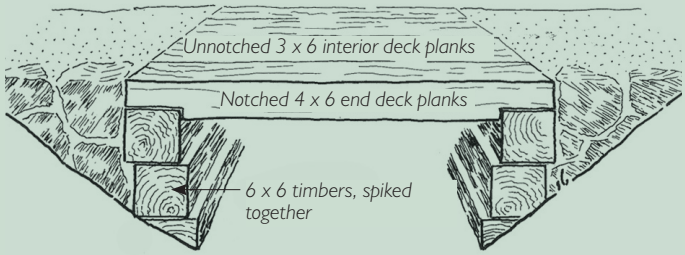
There are a number of established practices that continue have merit for crossing unstable soils, wet areas, drainages, and fences. The following graphic highlights more common structures and techniques.

Wetland Crossing Techniques

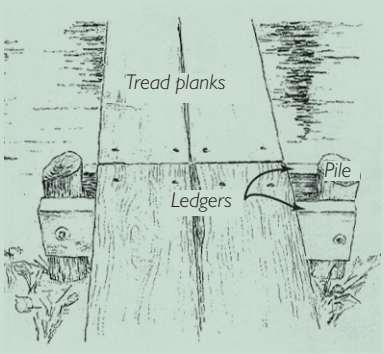
The following images are from *Wetland Trail Design and Construction,* part of the *Forest Service Trails Reports 2004* collection of reports (www.fhwa.dot.gov/environment/rectrails/trailpub.htm). Refer to this publication for additional information related to each the techniques shown, as well as information on a variety of other techniques and common tools.

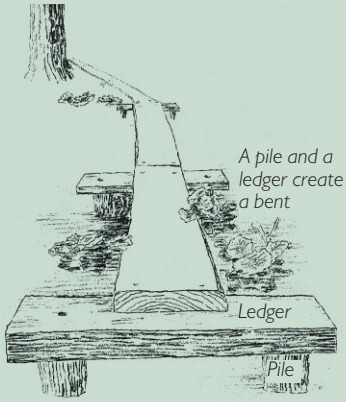


As a general rule, a handrail is required whenever the deck height of a boardwalk or footbridge exceeds 30". A curb can also be added to alert users of the edge of the deck and add character.

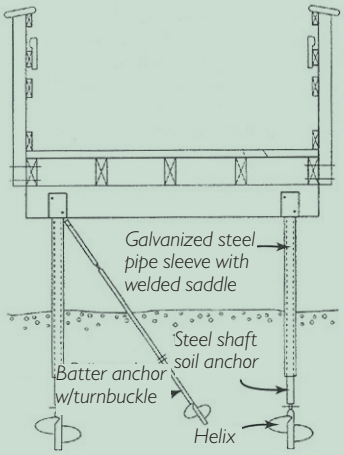


Treated timbers are occasionally used for culverts along natural surfaced trails. Notching the deck planks on both ends helps to brace the walls. Two planks with notches are adequate for a wall up to 24 inches high.

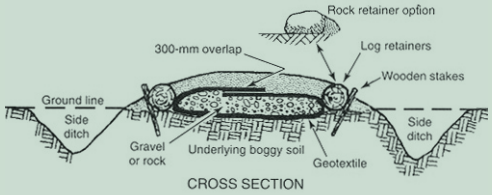


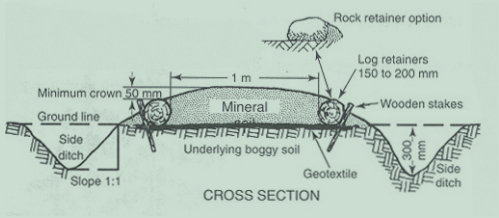


Treated timbers used as piles with either a double ledger (left) or single flat ledger (right) to support a plank tread are commonly used on rustic or remote trails where simplicity is a necessary for ease of construction.

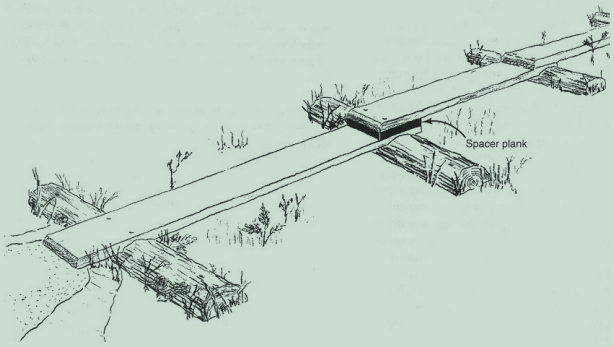


Helical piles (screw piles) are most commonly used where soil conditions make post-hole digging difficult or where minimal grade disruption is desired. Mechanized hand tools can often be used in these instances.





Turnpikes have also been used over the years for crossing wet areas. If this approach is used, caution must be taken to avoid blocking surface water flows or otherwise changing hydrology. If that is likely to occur, a boardwalk is recommended instead.



A simple bog bridge with sleepers is a historically common approach to crossing bogs in remote areas with readily available materials. The limitations of this approach is the sleepers will rot out over a period of years and have to be replaced, requiring more maintenance than other techniques.