

Description

The term *Permeable Pavement System*, as used in this manual, is a general term to describe any one of several pavements that allow movement of water into the layers below the pavement surface. Depending on the design, permeable pavements can be used to promote volume reduction, provide treatment and slow release of the water quality capture volume (WQCV), and reduce effective imperviousness. Use of permeable pavements is a common Low Impact Development (LID) practice and is often used in combination with other BMPs to provide full treatment and slow release of the WQCV. A number of installations within the UDFCD



Photograph PPS-1. The reservoir layer of a permeable pavement provides storage volume for the WQCV. Photo courtesy of Muller Engineering and Jefferson County Open Space.

boundary have also been designed with an increased depth of aggregate material in order to provide storage for storm events in excess of the water quality (80th percentile) storm event. This requires some additional design considerations, which are discussed within this BMP Fact Sheet.

Site Selection

This infiltrating BMP requires consultation with a geotechnical engineer when proposed near a structure. In addition to providing the pavement design, a geotechnical engineer can assist with evaluating the suitability of soils, identifying potential impacts, and establishing minimum distances between the BMP and structures.

Permeable pavement systems provide an alternative to conventional pavement in pedestrian areas and lower-speed vehicle areas. They are not appropriate where sediment-laden runoff could clog the system (e.g., near loose material storage areas).

This BMP is not appropriate when erosive conditions such as steep slopes and/or sparse vegetation drain to the permeable pavement. The sequence of construction is also important to preserve pavement infiltration. Construction of the pavement should take place only after construction in the watershed is complete.

For sites where land uses or activities can cause infiltrating stormwater to contaminate groundwater, special design requirements are required to ensure no-infiltration from the pavement section.

Permeable Pavement	
Functions	
LID/Volume Red.	Yes
WQCV	Yes
WQCV+Flood Control	Yes
Fact Sheet Includes EURV Guidance	No
Typical Effectiveness for Targeted Pollutants³	
Sediment/Solids	Very Good ¹
Nutrients	Good
Total Metals	Good
Bacteria	Unknown
Other Considerations	
Life-cycle Costs ⁴	High ²
¹ Not recommended for watersheds with high sediment yields (unless pretreatment is provided). ² Does not consider the life cycle cost of the conventional pavement that it replaces. ³ Based primarily on data from the International Stormwater BMP Database (www.bmpdatabase.org). ⁴ Based primarily on BMP-REALCOST available at www.udfcd.org . Analysis based on a single installation (not based on the maximum recommended watershed tributary to each BMP).	

Permeable pavements and other BMPs used for infiltration that are located adjacent to buildings, hardscape or conventional pavement areas can adversely impact those structures if protection measures are not provided. Wetting of subgrade soil underlying those structures can cause the structures to settle or result in other moisture-related problems. Wetting of potentially expansive soils or bedrock can cause those materials to swell, resulting in structure movements. In general, a geotechnical engineer should evaluate the potential impact of the BMP on adjacent structures based on an evaluation of the subgrade soil, groundwater, and bedrock conditions at the site. In addition, the following minimum requirements should be met:

- In locations where subgrade soils do not allow infiltration, the pavement section should include an underdrain system.
- Where infiltration can adversely impact adjacent structures, the filter layer should be underlain by an underdrain system designed to divert water away from the structure.
- In locations where potentially expansive soils or bedrock exist, placement of permeable pavement adjacent to structures and conventional pavement should only be considered if the BMP includes an underdrain designed to divert water away from the structure and is lined with an essentially impermeable geomembrane liner designed to restrict seepage.

Designing for Maintenance

Recommended ongoing maintenance practices for all BMPs are provided in the BMP Maintenance chapter of this manual. During design and construction, the following should be considered to ensure ease of maintenance over the long-term:

- Hold a pre-construction meeting to ensure that the contractor has an understanding of how the pavement is intended to function. Discuss the contractor's proposed sequence of construction and look for activities that may require protection of the permeable pavement system.
- Ensure that the permeable pavement is protected from construction activities following pavement construction (e.g., landscaping operations). This could include covering areas of the pavement, providing alternative construction vehicle access, and providing education to all parties working on-site.
- Include an observation well to monitor the drain time of the pavement system over time. This will assist with determining the required maintenance needs. See Figure PPS-8.

Benefits

- Permeable pavement systems provide water quality treatment in an area that serves more than one purpose. The depth of the pavement system can also be increased to provide flood control.
- Permeable pavements can be used to reduce effective imperviousness or alleviate nuisance drainage problems.
- Permeable pavements benefit tree health by providing additional air and water to nearby roots.
- Permeable pavements are less likely to form ice on the surface than conventional pavements.
- Some permeable pavements can be used to achieve LEED credits.

Limitations

- Additional design and construction steps are required for placement of any ponding or infiltration area near or upgradient from a building foundation, particularly when potentially expansive soils exist. This is discussed in the design procedure section.
- In developing or otherwise erosive watersheds, high sediment loads can clog the facility.

- Call for construction fence on the plans around pervious areas where infiltration rates need to be preserved and could be reduced by compaction from construction traffic or storage of materials.

Example Construction Drawing Notes

- Excavation of subgrade shall not commence until after the pre-construction meeting.
- Subgrade shall be excavated using low ground pressure (LGP) track equipment to minimize over compaction of the subgrade.¹
- Grading and compaction equipment used in the area of the permeable pavement should be approved by the engineer prior to use.
- Loose materials shall not be stored on the permeable pavement area.
- The contractor shall, at all times during and after system installation, prevent sediment, debris, and dirt from any source from entering the permeable pavement system.
- Placement of the wearing course shall be performed after fine grading and landscaping in adjacent areas is complete. If the wearing course becomes clogged due to construction activities, clean the surface with a vacuum machine to restore the infiltration rate after construction is complete.

¹ For partial and full infiltration sections only.

Design Procedure and Criteria

Note: This manual includes a variety of specific pavements, which are discussed and distinguished in supplemental BMP Fact Sheets T-10.1, T-10.2, etc. This BMP Fact Sheet outlines the design procedure and other design components and considerations that are common to all of the systems. Review of the supplemental Fact Sheets is recommended to determine the appropriate pavement for a specific site or use.

1. **Subsurface Exploration and Determination of a No-Infiltration, Partial Infiltration, or Full Infiltration Section:** Permeable pavements can be designed with three basic types of sections. The appropriate section will depend on land use and activities, proximity to adjacent structures and soil characteristics. Sections of each installation type are shown in Figure PPS-1.
 - **No-Infiltration Section:** This section includes an underdrain and an impermeable liner that prevents infiltration of stormwater into the subgrade soils. Consider using this section when any of the following conditions exist:
 - Land use or activities could contaminate groundwater if stormwater is allowed to infiltrate.
 - Permeable pavement is located over potentially expansive soils or bedrock that could swell due to infiltration and potentially damage the permeable pavement system or adjacent structures (e.g., building foundation or conventional pavement).

- **Partial Infiltration Section:** This section does not include an impermeable liner, and allows some infiltration. Stormwater that does not infiltrate is collected and removed by an underdrain system.
- **Full Infiltration Section:** This section is designed to infiltrate the water stored in the voids of the pavement into the subgrade below. UDFCD recommends a minimum infiltration rate of 2 times the rate needed to drain the WQCV over 12 hours.

Subsurface Exploration and Testing for all Sections: A geotechnical engineer should scope and perform a subsurface study. Typical geotechnical investigation needed to select and design the pavement system for handling anticipated traffic loads includes:

- Prior to exploration review geologic and geotechnical information to assess near-surface soil, bedrock and groundwater conditions that may be encountered and anticipated ranges of infiltration rate for those materials. For example, if the site is located in a general area of known shallow, potentially expansive bedrock, a no-infiltration section will likely be required. It is also possible that this BMP may be infeasible, even with a liner, if there is a significant potential for damage to the pavement system or adjacent structures (e.g., areas of dipping bedrock).
- Drill exploratory borings or exploratory pits to characterize subsurface conditions beneath the subgrade and develop requirements for subgrade preparation. Drill at least one boring or pit for every 40,000 ft², and at least two borings or pits for sites between 10,000 ft² and 40,000 ft². The boring or pit should extend at least 5 feet below the bottom of the base, and at least 20 feet in areas where there is a potential of encountering potentially expansive soils or bedrock. More borings or pits at various depths may be required by the geotechnical engineer in areas where soil types may change, in low-lying areas where subsurface drainage may collect, or where the water table is likely within 8 feet below the planned bottom of the base or top of subgrade. Installation of temporary monitoring wells in selected borings or pits for monitoring groundwater levels over time should be considered where shallow groundwater that could impact the pavement system area is encountered.
- Perform laboratory tests on samples obtained from the borings or pits to initially characterize the subgrade, evaluate the possible section type, and to assess subgrade conditions for supporting traffic loads. Consider the following tests: moisture content (ASTM D 2216); dry density (ASTM D 2936); Atterberg limits (ASTM D 4318); gradation (ASTM D 6913); swell-consolidation (ASTM D 4546); subgrade support testing (R-value, CBR or unconfined compressive strength); and hydraulic conductivity. A geotechnical engineer should determine the appropriate test method based on the soil type.
- For sites where a full infiltration section may be feasible, perform on-site infiltration tests using a double-ring infiltrometer (ASTM D 3385). Perform at least one test for every 160,000 ft² and at least two tests for sites between 40,000 ft² and 160,000 ft². The tests should be located near completed borings or pits so the test results and subsurface conditions encountered in the borings can be compared, and at least one test should be located near the boring or pit showing the most unfavorable infiltration condition. The test should be performed at the planned top of subgrade underlying the permeable pavement system, and that subgrade should be prepared similar to that required for support of the permeable pavement system.
- Be aware that actual infiltration rates are highly variable dependent on soil type, density and moisture content and degree of compaction as well as other environmental and construction influences. Actual rates can differ an order of magnitude or more from those indicated by

infiltration or permeability testing. Selection of the section type should be based on careful assessment of the subsurface exploration and testing data.

2. **Required Storage Volume:** Provide the WQCV based on a 12-hour drain time.

- Find the required WQCV (watershed inches of runoff). Using the effective impervious area of the watershed area, use Figure 3-2 located in Chapter 3 to determine the WQCV based on a 12-hour drain time. The maximum recommended ratio for tributary impervious area to permeable pavement area is 2.0. Higher loading is not recommended, as it may increase the required maintenance interval.
- Calculate the design volume as follows:

$$V = \left[\frac{\text{WQCV}}{12} \right] A \quad \text{Equation PPS-1}$$

Where:

A = watershed area tributary to the permeable pavement (ft²)

V = design volume (ft³)

- Add flood control volume if desired. When designing for flood control volumes, provide an overflow that will convey runoff in excess of the WQCV directly into the reservoir. A gravel strip or inlet that is connected to the reservoir can provide this overflow.

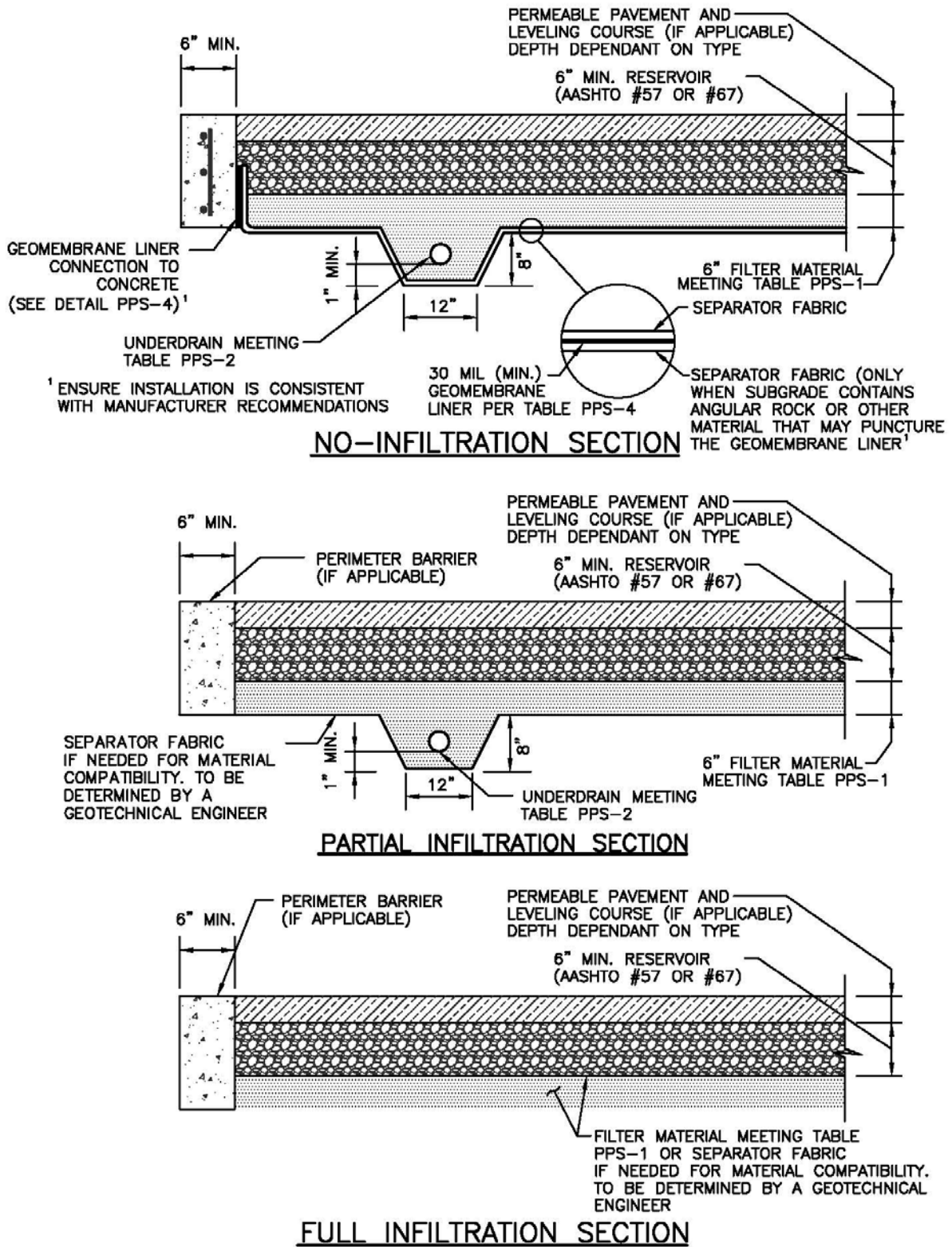


Figure PPS-1. Permeable Pavement Sections

3. **Depth of Reservoir:** The minimum recommended depth of AASHTO No. 57 or No. 67 coarse aggregate is 6 inches. Additional depth may be required to support anticipated loads or to provide additional storage, (i.e., for flood control). This material should have all fractured faces. UDFCD recommends that void storage be calculated only for the reservoir, assuming the aggregate filter layer is saturated. With the exception of porous gravel pavement, use a porosity of 40% or less for both No. 57 and No. 67 coarse aggregate. For porous gravel pavement use a porosity of 30% or less to account for reduced volume due to sediment. Porous gravel pavements typically allow greater sediment volumes to enter the pavement. See Figures PPS-2 and PPS-3 for alternative pavement profiles. Calculate available storage using equation PPS-2 for a flat subgrade installation, and PPS-3 for a sloped subgrade installation. These equations allow for one inch of freeboard. Flat installations are preferred as the design spreads infiltration evenly over the subgrade. For sloped subgrade installations, the increased storage depth located upstream of the lateral barrier (see step 7) can increase lateral movement (parallel to the flow barrier) of water into areas adjacent to the pavement section.

When used for vehicular traffic, a pavement design should be performed by a qualified engineer experienced in the design of permeable pavements and conventional asphalt and concrete pavements. The permeable pavement should be adequately supported by a properly prepared subgrade, properly compacted filter material and reservoir material.

Reservoir aggregate should have all fractured faces. Place the aggregate in 6-inch (maximum) lifts, compacting each lift by using a 10-ton, or heavier, vibrating steel drum roller. Make at least four passes with the roller, with the initial passes made while vibrating the roller and the final one to two passes without vibration.

- For flat or stepped installations (0% slope at the reservoir/subgrade interface):

$$V = P \left[\frac{D - 1}{12} \right] A \quad \text{Equation PPS-2}$$

Where:

V = volume available in the reservoir (ft³)

P = porosity, ≤0.30 for porous gravel, ≤0.4 for all other pavements
using AASHTO No. 57 or No. 67 coarse aggregate in the reservoir

D = depth of reservoir (in)

A = area of the permeable pavement (ft²)

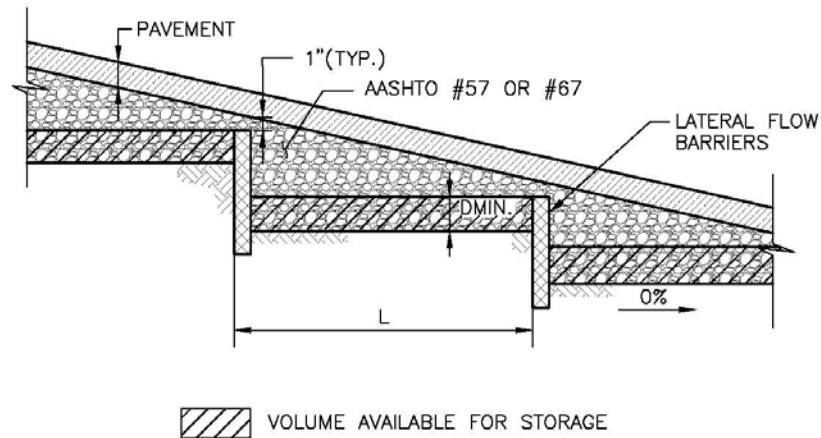


Figure PPS-2. Permeable Pavement Profile, Stepped Installation

- For sloped installations (slope of the reservoir/subgrade interface > 0%):

$$V = P \left[\frac{D - 6sL - 1}{12} \right] A \quad \text{Equation PPS-3a}$$

While:

$$L < \frac{2 \text{ WQCV}}{sAP} \quad \text{Equation PPS-3b}$$

Where:

- V = volume available in the reservoir (ft³)
- P = porosity, ≤0.30 for porous gravel, ≤0.4 for all other pavements using AASHTO No. 57 or No. 67 coarse aggregate in the reservoir
- s = slope of the reservoir/subgrade interface (ft/ft)
- D = depth of the reservoir (in)
- L = length between lateral flow barriers (see step 4) (ft)
- A = area of the permeable pavement (ft²)
- WQCV = water quality capture volume (ft³)

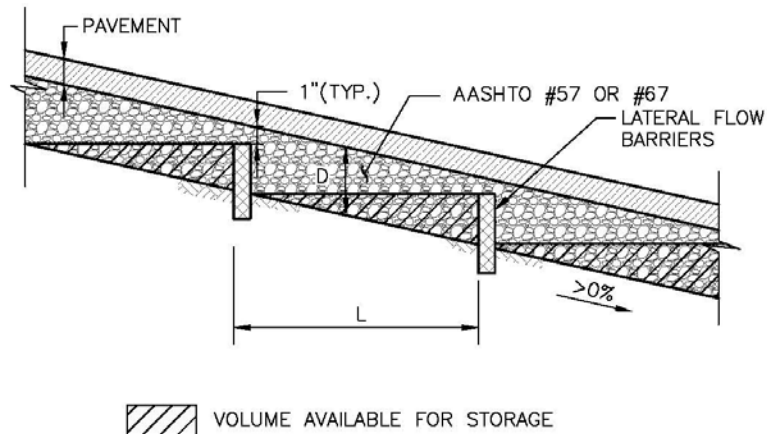


Figure PPS-3. Permeable Pavement Profile, Sloped Installation.

4. **Lateral Flow Barriers:** Construct lateral flow cutoff barriers using concrete walls or a 30 mil (minimum) PVC geomembrane. Lateral flow barriers should be placed parallel to contours (normal to flow). This will preserve the volume available for storage and ensure that stormwater will not resurface, washing out infill material. See Figure PPS-6 and Table PPS-4 when using a PVC geomembrane for this purpose. Also include a separator fabric, per Table PPS-3, between the geomembrane and all aggregate materials. Lateral flow barriers should be installed in all permeable pavement installations that have a reservoir/subgrade interface greater than 0%. Lateral flow barriers should be spaced, as necessary, to satisfy equations PPS-3a and PPS-3b. One exception is reinforced grass pavement. Infill washout is not a concern with reinforced grass pavement.

5. **Perimeter Barrier:** For all no-infiltration sections, provide a reinforced concrete barrier on all sides of the pavement system. Perimeter barriers may also be recommended for other permeable pavement installations depending on the type or use of the pavement. For PICP and concrete grid pavement, a barrier is required to restrain movement of the pavers or grids. Precast, cast-in-place concrete or cut stone barriers are required for commercial vehicular areas. For residential use and commercial pedestrian use, a metal or plastic edge spiked with 3/8-inch-diameter, 10-inch-long nails provides a less expensive alternative for edge restraint.

For all pavements, consider the section beyond the permeable pavement when evaluating the perimeter design. The perimeter barrier helps force water into the underdrain and reduces lateral flow of water. Lateral flow can negatively impact the adjacent conventional pavement section, structure, or embankment (especially when the subgrade is sloped). Also consider material separation. Consider construction of the interface between the permeable pavement and the adjacent materials and how the design will prevent adjacent materials from entering the permeable pavement section. Depending on the soils, depth of pavement, and other factors, this may be achieved with fabric or may require a more formalized barrier.

When a permeable pavement section is adjacent to conventional pavement, a vertical liner may be required to separate the reservoir of the permeable pavement system from dense-graded aggregates and soils within the conventional pavement. An impermeable liner can be used to provide this vertical barrier and separate these two pavement systems.

No-Infiltration Section: For this type of section, the perimeter barrier also serves to attach the impermeable membrane. The membrane should extend up to the top of the filter layer and be firmly

attached to the concrete perimeter barrier using batten bars to provide a leak-proof seal. A nitrile-based vinyl adhesive can be used when the need for an impermeable liner is less critical. See Figures PPS-4 and PPS-5 for installation details. For ease of construction, including the placement of geotextiles, it is suggested that the barrier extend to the bottom of the filter layer.

Partial and Full Infiltration Section: The perimeter barrier for these sections also restricts lateral flow to adjacent areas of conventional pavement or other structures where excessive moisture and/or hydrostatic pressure can cause damage. When this is of particular concern, the perimeter barrier should be extended to a depth 12 inches or more below the underdrain. Otherwise, extend the barrier to the bottom of the filter layer.

- 6. Filter Material and Underdrain System:** An aggregate filter layer and underdrain are required for all partial and no-infiltration sections. Without this filter layer, the section will not provide adequate pollutant removal. This is based on research performed by UDFCD monitoring sites with and without this component. A filter or separator fabric may also be necessary under the reservoir in a full infiltration section if the subgrade is not filter compatible with the reservoir material such that finer subgrade soils could enter into the voids of the reservoir.

In previous versions of the USDCM, UDFCD recommended that the underdrain be placed in an aggregate drainage layer and that a geotextile separator fabric be placed between this drainage and the filter layer. This version of the USDCM replaces that fabric, which could more easily plug or be damaged during construction, with aggregate filter material that is filter-compatible with the reservoir, and a drainpipe with perforations that are filter-compatible with the filter material. This eliminates the need for a separator fabric between the reservoir and the underdrain layer. The filter material provided below should only be used with the underdrain pipe specified within this section.

The underdrain should be placed below a 6-inch-thick layer of CDOT Class C filter material meeting the gradation in Table PPS-1. Extend the filter material around and below the underdrain as shown in Figure PPS-1.

Provide clean-outs to allow inspection (by camera) of the drainpipe system during and after construction to ensure that the pipe was not crushed or disconnected during construction and to allow for maintenance of the underdrain.

Use of Class C Filter material with a slotted PVC pipe that meets the slot dimensions provided in Table PPS-2 will eliminate the need for an aggregate layer wrapped geotextile fabric.

Design Opportunity

Pollutant removal occurs in the filter material layer of the section. The basic permeable pavement section may be considered with other wearing courses to provide water quality as long as:

- the filter layer is included in the section,
- the wearing course provides adequate permeability, and
- the new section does not introduce new pollutants to the runoff.

Table PPS-1. Gradation Specifications for Class C Filter Material (Source: CDOT Table 703-7)

Sieve Size	Mass Percent Passing Square Mesh Sieves
19.0 mm (3/4")	100
4.75 mm (No. 4)	60 – 100
300 μm (No. 50)	10 – 30
150 μm (No. 100)	0 – 10
75 μm (No. 200)	0 - 3

Table PPS-2. Dimensions for Slotted Pipe

Pipe Diameter	Slot Length ¹	Maximum Slot Width	Slot Centers ¹	Open Area ¹ (per foot)
4"	1-1/16"	0.032"	0.413"	1.90 in ²
6"	1-3/8"	0.032"	0.516"	1.98 in ²

¹ Some variation in these values is acceptable and is expected from various pipe manufacturers. Be aware that both increased slot length and decreased slot centers will be beneficial to hydraulics but detrimental to the structure of the pipe.

Compact the filter layer using a vibratory drum roller or plate. The top of each layer below the leveling course must be uniform and should not deviate more than a 1/2 inch when a 10-foot straight edge is laid on its surface. The top of the leveling course should not deviate more than 3/8 inch in 10 feet.

- Impermeable Geomembrane Liner and Geotextile Separator Fabric:** For no-infiltration sections, install a 30 mil (minimum) PVC geomembrane liner, per Table PPS-4, on the bottom and sides of the basin, extending up at least to the top of the filter layer. Provide at least 9 inches (12 inches if possible) of cover over the membrane where it is attached to the wall to protect the membrane from UV deterioration. The geomembrane should be field-seamed using a dual track welder, which allows for non-destructive testing of almost all field seams. A small amount of single track and/or adhesive seaming should be allowed in limited areas to seam around pipe perforations, to patch seams removed for destructive seam testing, and for limited repairs. The liner should be installed with slack to prevent tearing due to backfill, compaction, and settling. Place CDOT Class B geotextile separator fabric, per Table PPS-3, above the geomembrane to protect it from being punctured during the placement of the filter material above the liner. If the subgrade contains angular rocks or other material that could puncture the geomembrane, smooth-roll the surface to create a suitable surface. If smooth-rolling the surface does not provide a suitable surface, also place the separator fabric between the geomembrane and the underlying subgrade. This should only be done when necessary because fabric placed under the geomembrane can increase seepage losses through pinholes or other geomembrane defects. Connect the geomembrane to perimeter concrete walls around the basin perimeter, creating a watertight seal between the geomembrane and the walls using a continuous batten bar and anchor connection (see Figure PPS-5). Where the need for the impermeable

membrane is not as critical, the membrane can be attached with a nitrile-based vinyl adhesive. Use watertight PVC boots for underdrain pipe penetrations through the liner (see Figure PPS-4).

Table PPS-3. Physical Requirements for Separator Fabric¹

Property	Class B		Test Method
	Elongation < 50% ²	Elongation > 50% ²	
Grab Strength, N (lbs)	800 (180)	510 (115)	ASTM D 4632
Puncture Resistance, N (lbs)	310 (70)	180 (40)	ASTM D 4833
Trapezoidal Tear Strength, N (lbs)	310 (70)	180 (40)	ASTM D 4533
Apparent Opening Size, mm (US Sieve Size)	AOS < 0.3mm (US Sieve Size No. 50)		ASTM D 4751
Permittivity, sec ⁻¹	0.02 default value, must also be greater than that of soil		ASTM D 4491
Permeability, cm/sec	k fabric > k soil for all classes		ASTM D 4491
Ultraviolet Degradation at 500 hours	50% strength retained for all classes		ASTM D 4355

¹ Strength values are in the weaker principle direction

² As measured in accordance with ASTM D 4632

Table PPS-4. Physical Requirements for Geomembrane

Property	Thickness 0.76 mm (30 mil)	Test Method
Thickness, % Tolerance	±5	ASTM D 1593
Tensile Strength, kN/m (lbs/in) width	12.25 (70)	ASTM D 882, Method B
Modulus at 100% Elongation, kN/m (lbs/in)	5.25 (30)	ASTM D 882, Method B
Ultimate Elongation, %	350	ASTM D 882, Method A
Tear Resistance, N (lbs)	38 (8.5)	ASTM D 1004
Low Temperature Impact, °C (°F)	-29 (-20)	ASTM D 1790
Volatile loss, % max.	0.7	ASTM D 1203, Method A
Pinholes, No. Per 8 m ² (No. per 10 sq. yds.) max.	1	N/A
Bonded Seam Strength, % of tensile strength	80	N/A

- Outlet:** The portion of the WQCV in each cell should be slowly released to drain in approximately 12 hours. An orifice at the outlet of the underdrain can be used for each cell to provide detention and slow release of the WQCV to offset hydromodification. Use a minimum orifice size of 3/8 inch to avoid clogging. If lateral walls are required, each cell should be considered a separate system and be

controlled independently. See Figure PPS-6 for underdrain system layout and outlet details showing a multi-cell configuration. Equations PPS-4 and PPS-5 can be used to determine the depth of the WQCV within the pavement section (based either on the stepped/flat installation shown in Figure PPS-2 or the sloped installation shown in Figure PPS-3) and Equation PPS-6 can be used to size the WQCV orifice. If the design includes multiple cells, these calculations should be performed for each cell substituting WQCV and V_{Total} with the volumes provided in each cell. The UD-BMP workbook available at www.udfcd.org can be used when multiple cells are similar in area. The workbook assumes that the WQCV is distributed evenly between each cell.

For calculating depth of the WQCV using a flat/stepped installation, see Figure PPS-2:

$$d = \frac{12 \text{ WQCV}}{PA} \quad \text{Equation PPS-4}$$

Where:

d = depth of WQCV storage in the reservoir (in)

P = porosity, ≤ 0.30 for porous gravel, ≤ 0.4 for all other pavements using AASHTO No. 57 or No. 67 coarse aggregate in the reservoir

A = area of permeable pavement system (ft^2)

WQCV = water quality capture volume (ft^3)

For calculating depth of the WQCV using a sloped installation, see Figure PPS-3:

$$d = 6 \left[\frac{2 \text{ WQCV}}{PA} \right] + sL \quad \text{Equation PPS-5}$$

Where:

d = depth of WQCV storage in the reservoir (in)

A = area of permeable pavement system (ft^2)

s = slope of the reservoir/subgrade interface (ft/ft)

L = length between lateral flow barriers (see step 4) (ft)

For calculating the diameter of the orifice for a 12-hour drain time (Use a minimum orifice size of 3/8 inch to avoid clogging.):

$$D_{12 \text{ hour drain time}} = \sqrt{\frac{V}{1414 y^{0.41}}} \quad \text{Equation PPS-6}$$

Where:

D = diameter of the orifice to drain a volume in 12 hours (in)

Y = distance from the lowest elevation of the storage volume (i.e. the bottom of the reservoir) to the center of the orifice (ft)

V = volume (WQCV or the portion of the WQCV in the cell) to drain in 12 hours (ft³)

Additional Design Considerations

Subgrade Preparation

Partial Infiltration and Full Infiltration Installations: The subgrade should be stripped of topsoil or other organics and either excavated or filled to the final subgrade level. Unnecessary compaction or over-compaction will reduce the subgrade infiltration rate. However, a soft or loosely compacted subgrade will settle, adversely impacting the performance of the entire permeable pavement system. The following recommendations for subgrade preparation are intended to strike a balance between those competing objectives:

- For sites, or portions thereof, requiring excavation to the final subgrade level, compaction of the subgrade may not be needed, provided that loose materials are removed from the excavation, and a firm subgrade is provided for the support of the pavement system. A geotechnical engineer should observe the prepared subgrade. Local soft areas should be excavated and replaced with properly compacted fill. As an alternative to excavating and replacing material, stabilization consisting of geogrid and compacted granular fill material can be used to bridge over the soft area. Fill material should be free draining and have a hydraulic conductivity significantly higher than the subgrade soil. Fill is typically compacted to a level equivalent to 95% Standard Proctor compaction (ASTM D 698). The designer should specify the level of compaction required to support the pavement system.
- For sites (or portions thereof), requiring placement of fill above the existing subgrade to reach the final subgrade level, the fill should be properly compacted. Specify the hydraulic conductivity for the material that is to be placed. This should be at least one order of magnitude higher than the native material. If the type or level of compaction of fill material available for construction is different than that considered in design, additional testing should be performed to substantiate that the design infiltration rate can be met. However, additional infiltrometer testing may not be necessary, provided that it can be demonstrated by other means that the compacted fill material is more permeable than that considered for design.
- Low ground pressure (LGP) track equipment should be used within the pavement area to limit over-compacting the subgrade. Wheel loads should not be allowed.

No-Infiltration Sections: Unless otherwise indicated by the geotechnical engineer, the subgrade for this section should be scarified and properly compacted to support the liner and pavement system. A level of compaction equivalent to 95% of the Standard Proctor density (ASTM D 698) is typically used. The designer should specify the level of compaction. No-infiltration sections should be smooth rolled with a roller compactor, and the prepared subgrade surface should be free of sharp objects that could puncture the liner. Both the designer and the liner installer should inspect the subgrade for acceptance prior to liner placement.

Filter and Reservoir Layer Compaction

Filter material placed above the prepared subgrade should be compacted to a relative density between 70% and 75% (ASTM D4253 and ASTM D4254) using a walk-behind vibratory roller, vibratory plate compactor or other light compaction equipment. Do not over-compact; this will limit unnecessary infiltration into the underlying subgrade. The reservoir layer may not be testable for compaction using a method based on specified density (e.g., nuclear density testing). The designer should consider a method specification (e.g., number of passes of a specified vibratory compactor) for those materials. The number of passes appropriate is dependent on the type of equipment and depth of the layer.

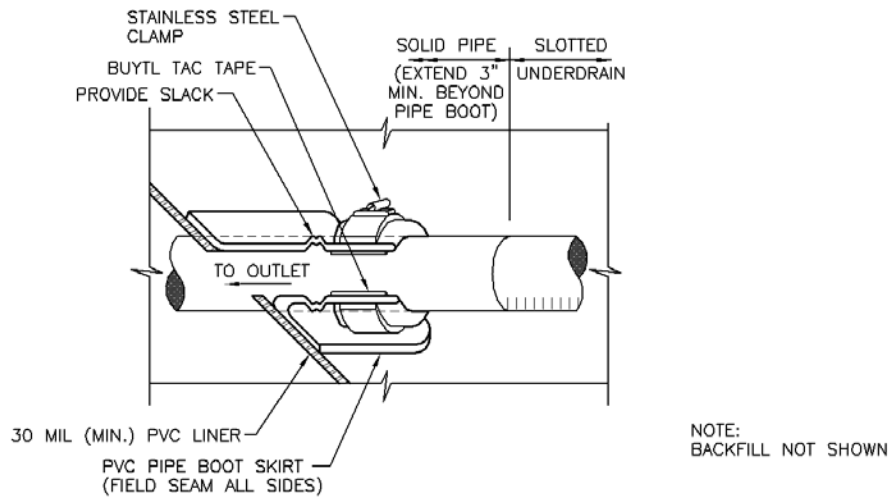


Figure PPS-4. Geomembrane Liner/Underdrain Penetration Detail

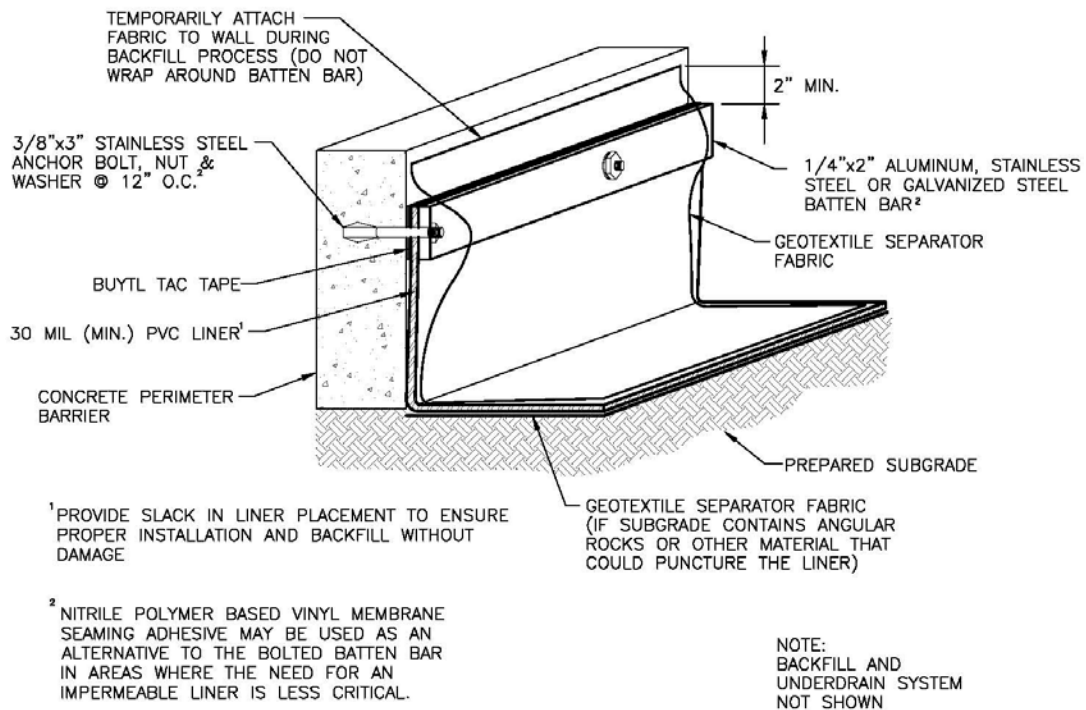


Figure PPS-5. Geomembrane Liner/Concrete Connection Detail

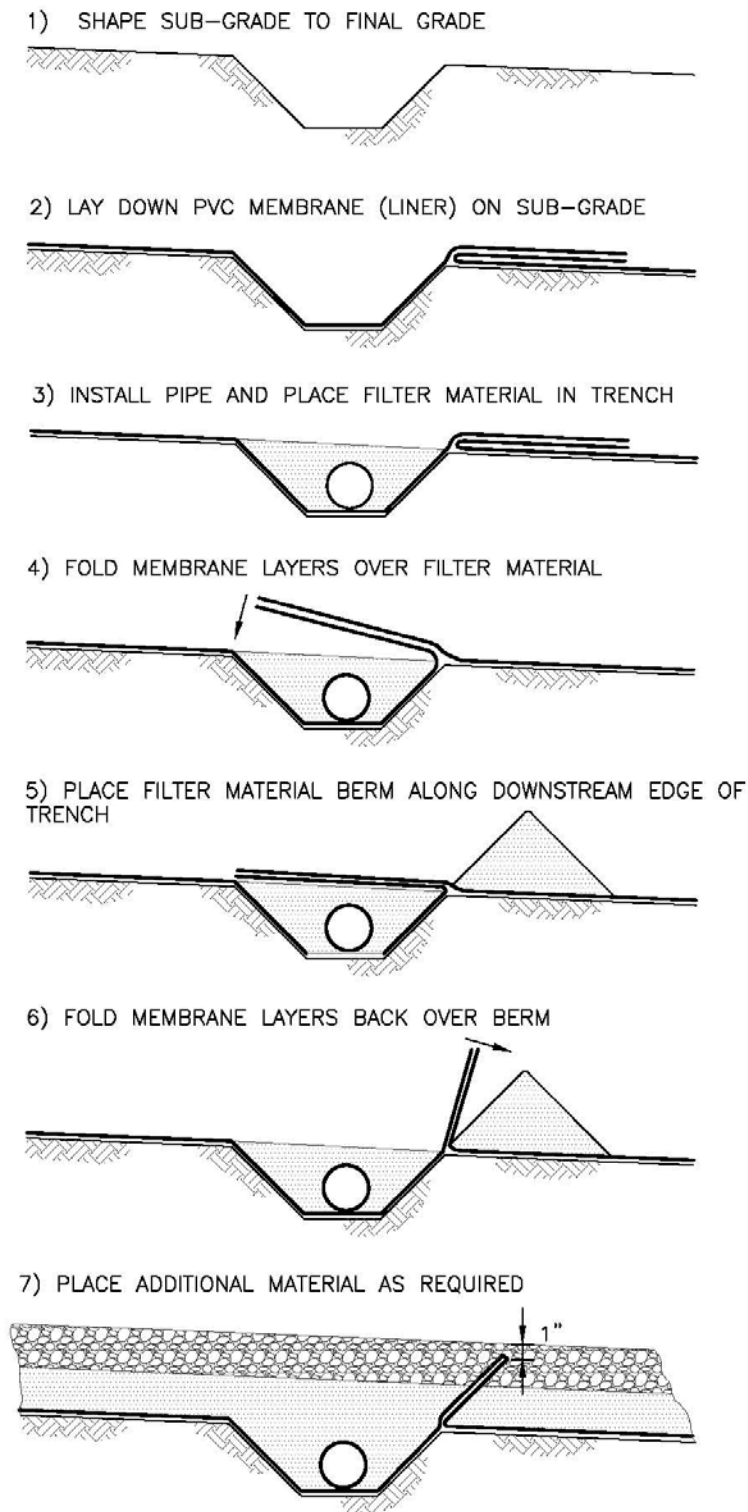


Figure PPS-6. Lateral Barrier Installation

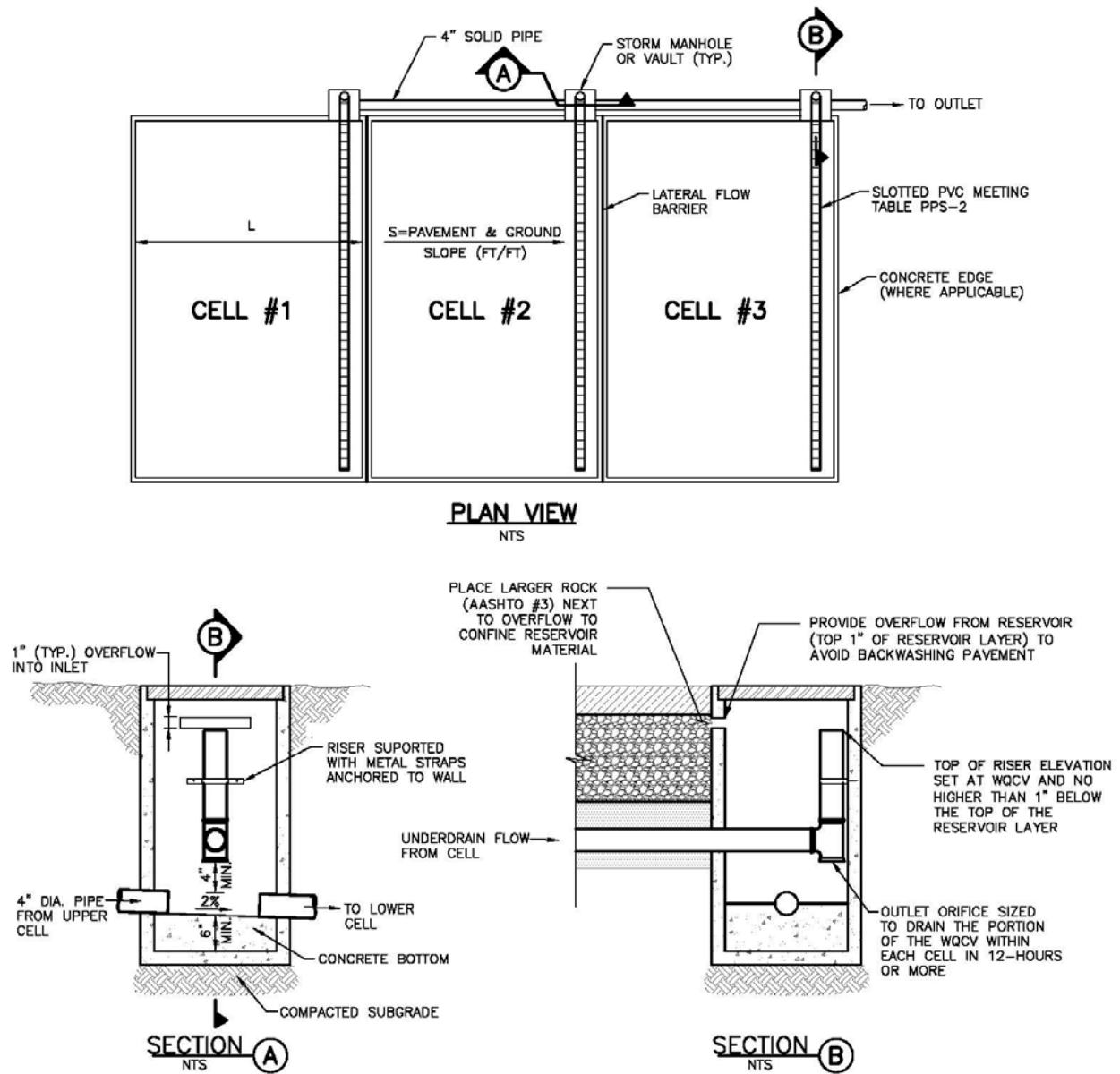


Figure PPS-7. Underdrain System Layout and Outlet Details

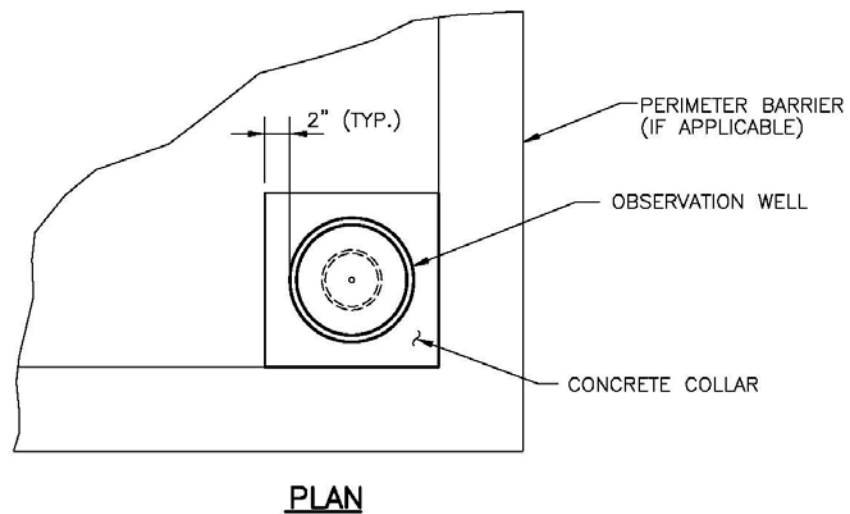
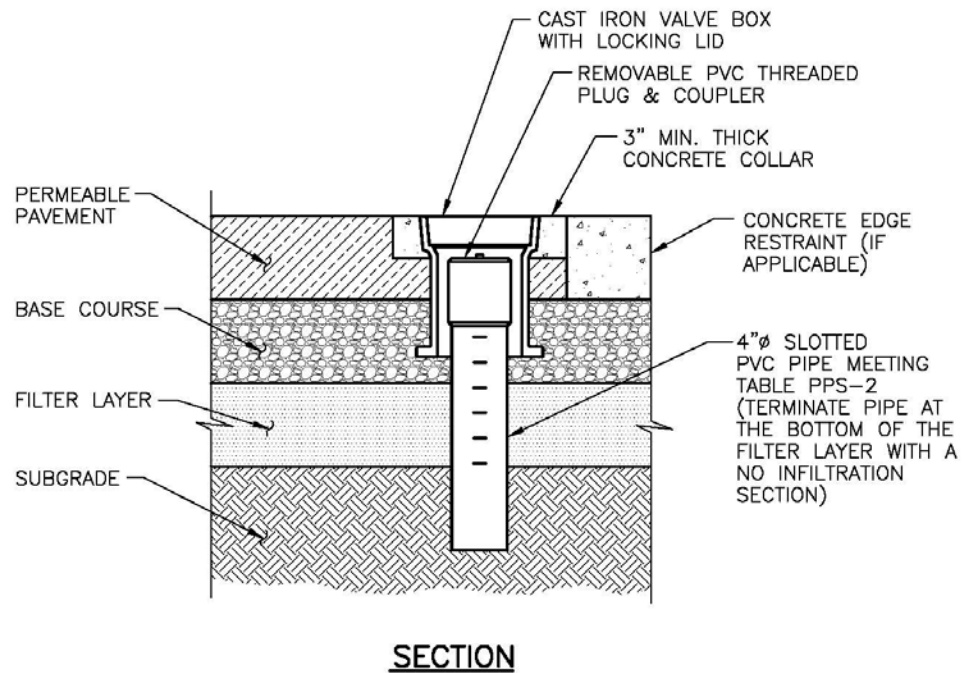


Figure PPS-8. Observation Well

Construction Considerations

Proper construction of permeable pavement systems requires measures to preserve natural infiltration rates (for full and partial infiltration sections) prior to placement of the pavement, as well as measures to protect the system from the time that pavement construction is complete to the end of site construction. Supplemental Fact Sheets on the specific pavements provide additional construction considerations. The following recommendations apply to all permeable pavement systems:

- When using an impermeable liner, ensure enough slack in the liner to allow for backfill, compaction, and settling without tearing the liner.
- Provide necessary quality assurance and quality control (QA/QC) when constructing an impermeable geomembrane liner system, including, but not limited to fabrication testing, destructive and non-destructive testing of field seams, observation of geomembrane material for tears or other defects, and air lace testing for leaks in all field seams and penetrations. QA/QC should be overseen by a professional engineer. Consider requiring field reports or other documentation from the engineer.
- Keep mud and sediment-laden runoff away from the pavement area.
- Temporarily divert runoff or install sediment control measures as necessary to reduce the amount of sediment run-on to the pavement.
- Cover surfaces with a heavy impermeable membrane when construction activities threaten to deposit sediment onto the pavement area.

Design Example

The *UD-BMP* workbook, designed as a tool for both designer and reviewing agency is available at www.udfcd.org. This section provides a completed design form from this workbook as an example.

Permeable Pavement Systems

T-10

Design Procedure Form: Permeable Pavement Systems (PPS)

Sheet 1 of 2

Designer: G. Frazer
Company: BMP Inc.
Date: November 29, 2010
Project: Shops at 56th Ave.
Location: SE corner of 56th Ave. and 83rd St.

<p>1. Type of Permeable Pavement Section</p> <p>A) What type of section of permeable pavement is used? (Based on the land use and activities, proximity to adjacent structures and soil characteristics.)</p> <p>B) What type of wearing course?</p>	<div style="border: 1px solid black; padding: 5px; margin-bottom: 5px;"> <p>Choose One</p> <p><input type="radio"/> No Infiltration</p> <p><input checked="" type="radio"/> Partial Infiltration Section</p> <p><input type="radio"/> Full Infiltration Section</p> </div> <div style="border: 1px solid black; padding: 5px;"> <p>Choose One</p> <p><input checked="" type="radio"/> PICP</p> <p><input type="radio"/> Concrete Grid Pavement</p> <p><input type="radio"/> Pervious Concrete</p> <p><input type="radio"/> Porous Gravel</p> </div>
<p>2. Required Storage Volume</p> <p>A) Effective Imperviousness of Area Tributary to Permeable Pavement, I_a</p> <p>B) Tributary Area's Imperviousness Ratio ($I = I_a / 100$)</p> <p>C) Tributary Watershed Area (including area of permeable pavement system)</p> <p>D) Area of Permeable Pavement System (Minimum recommended permeable pavement area = 13491 sq ft)</p> <p>E) Impervious Tributary Ratio (Contributing Impervious Area / Permeable Pavement Ratio)</p> <p>F) Water Quality Capture Volume (WQCV) Based on 12-hour Drain Time ($WQCV = (0.8 * (0.91 * i^3 - 1.19 * i^2 + 0.78 * i) / 12) * Area$)</p> <p>G) Is flood control volume being added?</p> <p>H) Total Volume Needed</p>	<p>$I_a =$ <u>65.0</u> %</p> <p>$i =$ <u>0.650</u></p> <p>$A_{Total} =$ <u>55,000</u> sq ft</p> <p>$A_{PPS} =$ <u>15,000</u> sq ft</p> <p>$R_T =$ <u>1.7</u></p> <p>$WQCV =$ <u>932</u> cu ft</p> <div style="border: 1px solid black; padding: 5px; margin-bottom: 5px;"> <p>Choose One</p> <p><input checked="" type="radio"/> YES</p> <p><input type="radio"/> NO</p> </div> <p>$V_{Total} =$ <u>6,340</u> cu ft</p> <p style="color: blue; font-size: small;">Provide overflow to carry runoff directly into the reservoir layer to ensure use of flood control volume regardless of infiltration rates.</p>
<p>3. Depth of Reservoir</p> <p>A) Minimum Depth of Reservoir (Minimum recommended depth is 6 inches)</p> <p>B) Is the slope of the reservoir/subgrade interface equal to 0%?</p> <p>C) Porosity (Porous Gravel Pavement ≤ 0.3, Others ≤ 0.40)</p> <p>D) Slope of the Base Course/Subgrade Interface</p> <p>E) Length Between Lateral Flow Barriers</p> <p>F) Volume Provided Based on Depth of Base Course Flat or Stepped: $V = P * ((D_{min.})/12) * Area$ Sloped: $V = P * [(D_{min.} - (D_{min.} - 6 * SL - 1)) / 12] * Area$</p>	<p>$D_{min} =$ <u>18.0</u> inches</p> <div style="border: 1px solid black; padding: 5px; margin-bottom: 5px;"> <p>Choose One</p> <p><input checked="" type="radio"/> YES- Flat or Stepped Installation</p> <p><input type="radio"/> NO- Sloped Installation</p> </div> <p>$P =$ <u>0.40</u></p> <p>$S =$ _____ ft / ft</p> <p>$L =$ _____ ft</p> <p>$V =$ <u>8,500</u> cu ft</p>
<p>4. Lateral Flow Barriers</p> <p>A) Type of Lateral Flow Barriers</p> <p>B) Number of Permeable Pavement Cells</p>	<div style="border: 1px solid black; padding: 5px; margin-bottom: 5px;"> <p>Choose One</p> <p><input type="radio"/> Concrete Walls</p> <p><input type="radio"/> PVC geomembrane installed normal to flow</p> <p><input checked="" type="radio"/> N/A- Flat installation</p> <p><input type="radio"/> Other (Describe): _____</p> </div> <p>Cells = <u>1</u></p>
<p>5. Perimeter Barrier</p> <p>A) Is a perimeter barrier provided on all sides of the pavement system? (Recommended for PICP, concrete grid pavement, or for any no-infiltration section.)</p>	<div style="border: 1px solid black; padding: 5px;"> <p>Choose One</p> <p><input checked="" type="radio"/> YES</p> <p><input type="radio"/> NO</p> </div>

Design Procedure Form: Permeable Pavement Systems (PPS)

Sheet 2 of 2

Designer: G. Frazer
Company: BMP Inc.
Date: November 29, 2010
Project: Shops at 56th Ave.
Location: SE corner of 56th Ave. and 83rd St.

<p>6. Filter Material and Underdrain System</p> <p>A) Is the underdrain placed below a 6-inch thick layer of CDOT Class C filter material?</p> <p>B) Diameter of Slotted Pipe (slot dimensions per Table PPs-2)</p> <p>C) Distance from the Lowest Elevation of the Storage Volume (i.e. the bottom of the base course to the center of the orifice)</p>	<p>Choose One</p> <p><input checked="" type="radio"/> YES <input type="radio"/> NO <input type="radio"/> N/A</p> <p>Choose One</p> <p><input checked="" type="radio"/> 4-inch <input type="radio"/> 6-inch</p> <p>y = <u>3.8</u> ft</p>
<p>7. Impermeable Geomembrane Liner and Geotextile Separator Fabric</p> <p>A) Is there a minimum 30 mil thick impermeable PVC geomembrane liner on the bottom and sides of the basin, extending up to the top of the base course?</p> <p>B) CDOT Class B Separator Fabric</p>	<p>Choose One</p> <p><input type="radio"/> YES <input checked="" type="radio"/> NO</p> <p>Choose One</p> <p><input type="radio"/> Placed above the liner <input type="radio"/> Placed above and below the liner</p>
<p>8. Outlet (Assumes each cell has similar area, subgrade slope, and length between lateral barriers (unless subgrade is flat). Calculate cells individually where this varies.)</p> <p>A) Depth of WQCV in the Reservoir (Elevation of the Flood Control Outlet)</p> <p>B) Diameter of Orifice for 12-hour Drain Time (Use a minimum orifice diameter of 3/8-inches)</p>	<p>D_{WQCV} = <u>1.86</u> inches</p> <p>D_{Orifice} = <u>0.62</u> inches</p>
<p>Notes: _____</p> <p>_____</p> <p>_____</p> <p>_____</p>	