DEVELOPMENT OF THE PERMEABLE DESIGN PRO PERMEABLE INTERLOCKING CONCRETE PAVEMENT DESIGN SYSTEM

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Note: The following is the notation used in this paper: (.) for decimals and (   ) for thousands.

Summary

National, state/provincial and municipal legislation regulating stormwater runoff in the United States and Canada have provided increased incentives for using permeable pavements. In addition, regulatory frameworks for implementation of sustainable design have embraced permeable pavement solutions. These regulations are often called low impact development (LID) or sustainable urban drainage systems (SUDS). A logical and technically sound design process using design software can support design professionals and help permeable pavement achieve full potential in North America.

In 2008, the Interlocking Concrete Pavement Institute (ICPI) introduced a non-proprietary software program called Permeable Design Pro that integrates hydrological and structural design solutions for permeable interlocking concrete pavement. The hydrological analysis determines if the volume of water from user-selected rainfall events can be stored and released by the pavement structure. User defined parameters determine how much water infiltrates into the soil subgrade, enters pipe subdrains or flows from the pavement surface. The structural capacity of PICP is determined using the American Association of State Highway and Transportation Officials [AASHTO, 1993] structural design equations for base/subbase thickness to support vehicular traffic. This paper describes the development of the structural and hydrological design methodology with an example of its use.

1. INTRODUCTION

Environmental responsibility through green or sustainable design is being embraced throughout North America from grass roots community groups to federal governments. One technology in the sustainable infrastructure design tool box is permeable interlocking concrete pavement (PICP) which can help replicate natural hydrology, encourage groundwater recharge or provide water harvesting while offering other environmental and aesthetic benefits.

Sustainable design evaluation programs such as the Leadership in Energy and Environmental Design (LEED[®]) are seeing increased use by cost conscious project owners and public agencies. Such programs assign points for design decisions that favor conservation of natural resources as well as reduced air and water pollution. PICP can generate LEED[®] points for reducing stormwater runoff,

improving water quality, using recycled materials, and reducing heat island effects [Green Alberta, 2008].

2. DESIGN PROCESS

As designers use PICP, they should understand the need for traditional structural design to ensure traffic load support and the need to satisfy hydrological design requirements for accommodating expected rainfall events. Permeable Design Pro software [ICPI, 2008] was created to satisfy both needs. Like any pavement, PICP design should provide a safe driving surface for cars, commercial vehicles, and pedestrians. PICP can accommodate rainfall onto the pavement or draining from adjacent areas. The overall design process is outlined in Figure 1.
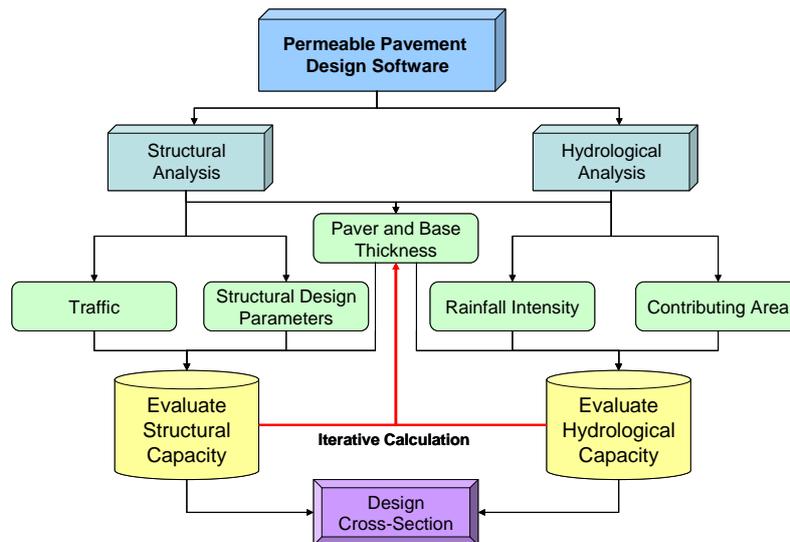

Figure 1. Flow chart of the permeable pavement design process.

2.1   Flexible Pavement Structural Design

With Permeable Design Pro, PICP design is approached as a flexible pavement. Like asphalt pavement, PICP materials are typically placed in layers of increasing strength such that traffic loads are in contact with the strongest layers that distributing loads and reducing stresses to deeper layers. The intent is to prevent deformation of subgrade soil under the anticipated vehicle or axle loads over the pavement life. Figure 2 illustrates this familiar notion of how pavements distribute loads.
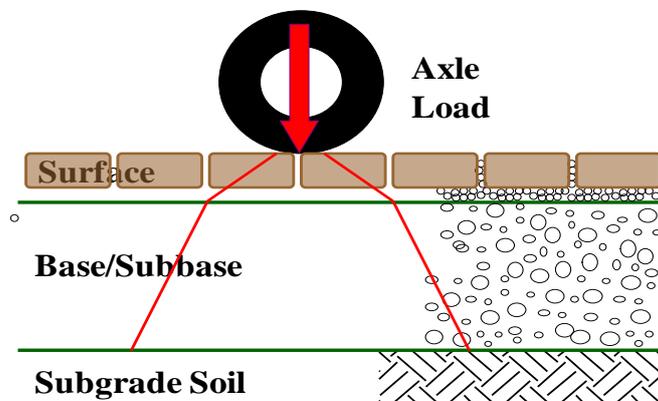

Figure 2. Distribution of traffic loads into underlying layers.

Pavement ride quality relies on structural capacity. Within Permeable Deign Pro, PICP structural capacity derived from the subbase, base and surface thicknesses is determined from the flexible pavement design methodology in the American Association of State and Highway Transportation Officials (AASHTO) 1993 *Guide for Design of Pavement Structures* [AASHTO, 1993]. The AASHTO procedure defines pavement layer strengths and calculates the thickness of each layer required to protect the underlying subgrade material from permanent deformation from traffic loads over a design life. The AASHTO methodology was selected because its underlying concepts are transferrable to PICP (using open-graded bases) and the procedure is familiar to North American pavement designers.

2.2   Traffic Requirements

In AASHTO, the anticipated traffic and load information is characterized by 80 kN equivalent single axle loads (ESALs) over the pavement's design life. To estimate the total number of ESALs expected over the pavement design life, the number and types of vehicles driving on the road need to be determined. Vehicles have different characteristics including the number and spacing of axles and vehicle weight. Examples of truck weight factors are provided in the AASHTO Guide and can be used to estimate the total number of ESALs. Since PICP typically is used for low traffic volume applications, it is common to make general assumptions for the design traffic loads rather than conduct detailed traffic surveys. Experience has shown that while traffic volumes are typically low, PICP can withstand high axle loads as shown in Figure 3. Permeable Design Pro software enables the user to characterize traffic for roadways and parking lots.

Figure 3. High axle load traffic on PICP.

2.3   Hydrological Analysis

The stormwater quantity entering the pavement surface is described as a water balance among sources and destinations. These are shown in Figure 4. Permeable Design Pro software manages the volume of water in the pavement system as:

$$Water\ Volume\ (Time) = Initial\ Water\ Level + \int_{0}^{Time} (Inflow\ (Time) - Outflow\ (Time)) \tag{1}$$

The analysis procedure uses small time steps to estimate the expected water inflow from precipitation and any surrounding areas that drain onto the PICP. The outflow from surface runoff to

groundwater recharge and subsurface drainage during each time step is also estimated. The inflow/outflow analysis enables the water level in the pavement base/subbase to be estimated during the storm and while draining afterwards. Antecedent water levels in the base/subbase can also be modeled to simulate the outflow effects from sequential storms. Water harvesting can be modeled by limiting the subgrade infiltration rate.
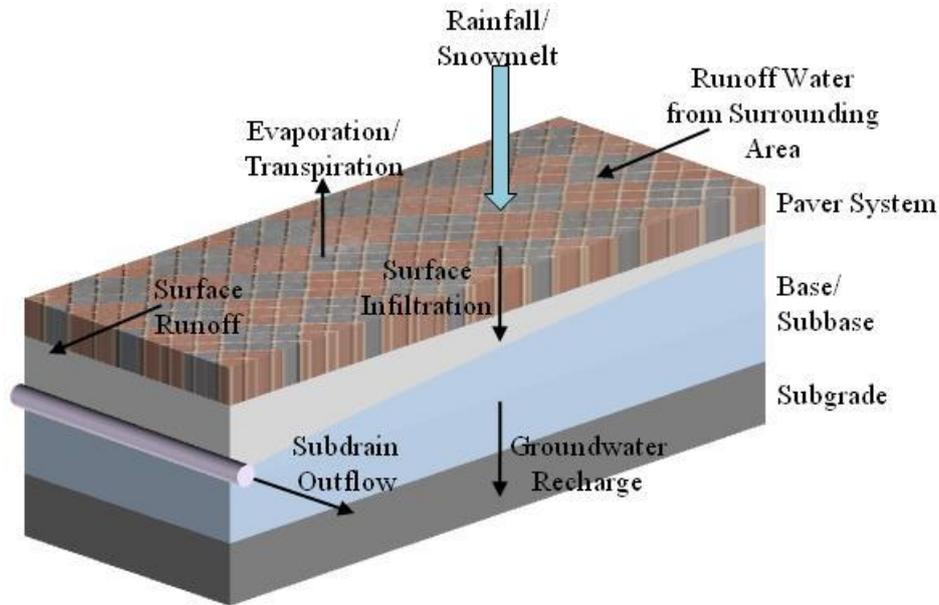

Figure 4. Inflow and outflow of water on permeable pavement.

2.3.1 Water Inflow
Water entering the PICP surface including surrounding areas is estimated using rainfall, soil type, land use and runoff characterizations based on Natural Resource Conservation Service Technical Release 55, *Urban Hydrology for Small Watersheds* [NRCS 1986]. All inflow from adjacent areas is assumed to be sheet flow. PICP surface infiltration rates can be input by the user based on test results data and/or experience. Rainfall events can be selected from 2 year to 100 year storm events. Figure 5 illustrates the rainfall events screen with rainfall events selected for Buffalo, New York, USA. The software contains a library of storm events for Canada and the United States, and allows for additional rainfall events sites to be manually entered.

Rainfall timing can be important when evaluating PICP potential to infiltrate water from surrounding areas. The time delay between the rainfall on these areas (with some infiltration) and the time the water enters the PICP surface during the peak rainfall intensity can also reduce the peak outflow, thereby conserving the need for larger storm sewer pipes and reducing potential downstream erosion.

2.3.2 Water Outflow
Stormwater exits PICP via groundwater recharge (soil subgrade infiltration), subdrains (generally perforated pipes) and through evaporation/transpiration. Permeable Design Pro estimates the water infiltrating into the soil subgrade and into pipe subdrains. The drains are typically used with low infiltration soils and the user can specify the pipe size, slope, horizontal spacing, and height above the soil subgrade. The latter can be important to creating some water detention in the base for infiltration and nutrient reduction. Besides modeling complexities, evaporation and transpiration are considered insignificant and are not part of the program.

2.3.3 Groundwater Recharge

Based on the user selected soil subgrade permeability, the program assumes saturated conductivity and calculates infiltration over time using Darcy's Law [Cedegren, 1989]. Since the water table is typically some distance below the base/subbase layer, the hydraulic gradient can be assumed to be 1.0 as the drop in elevation causes downward flow. The program assumes that drainage occurs uniformly across the bottom of the pavement as the base/subbase becomes saturated.
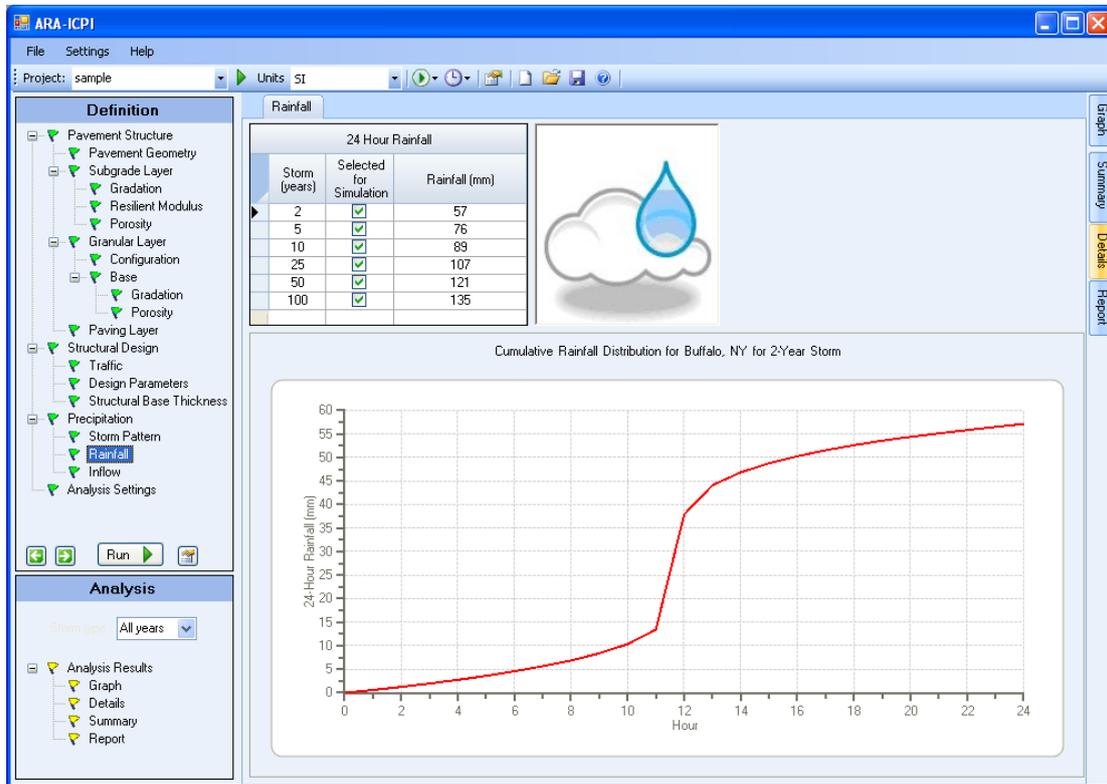

Figure 5. Permeable Design Pro can simulate 2, 5, 10, 25, 50 and 100 year, 24-hour rainfall events in cities throughout the United States and Canada.

$$Q_{Groundwater} = k_{Subgrade} \cdot \frac{Depth\ of\ Water\ in\ Pavement}{Thickness\ of\ Pavement} \cdot Subgrade\ Infiltration\ Factor$$

(2)

Where

$Q_{Groundwater}$: Flow rate of water into groundwater recharge (m/day, ft/day).

$k_{Subgrade}$: Hydraulic conductivity of the subgrade material (m/day, ft/day).

Subgrade Infiltration Factor: Expected reduction in subgrade permeability due to clogging.

Since predicting sediment loading within the base/subbase is practically impossible, a subgrade infiltration reduction factor can be applied to conservatively account for potential clogging and reduction of the soil subgrade infiltration rate. The base/subbase water depth changes and as this factor increases, and the static pressure increases affecting the drainage rate.

2.3.4 Material Selection

PICP typically uses highly permeable, open-graded crushed stone (granular) materials between the paving units and for bedding under them. The open-graded base/subbase materials maximize water storage. Dense-graded bases are not recommended in PICP because they lack the storage capacity

typically required. The paving units are typically 80 mm thick for vehicular applications and the bedding layer is no greater than 50 mm thick. Aggregates should be crushed, angular materials to ensure high interlock. PICP typically uses ASTM No. 8, 89 or 9 stone (10 to 1 mm) for the joints and bedding, an ASTM No. 57 (25 to 2 mm) for the base and ASTM No. 2 for the subbase (65 to 20 mm).

2.3.5   Subdrain Use

In most traditional pavements, perforated drain pipes are placed at the bottom of the subbase layer so that water entering the system can be drained quickly. However, in permeable pavement sub-drains prevent over-saturation of the pavement during high depth rain events. To accomplish this, subdrain pipes are typically placed above the soil subgrade, filling when a substantial portion of the base material under them has become saturated. This allows the water from the majority of storm events to infiltrate into the subgrade. Subdrain pipes can exit to drainage ditches, storm sewers and natural drainage features such as ponds or streams. By adjusting subdrains height above the soil subgrade, discharge rates can be controlled to prevent flooding. Furthermore, the pavement base/subbase can drain within 48 h to 72 h to aid in maintaining a stable structure under vehicle loads.

2.4   **Other Design Considerations**

Other design factors include:

- Adjacent land uses.
- Available stormwater systems.
- Aggregate filter requirements.
- Geotextile.
- Winter maintenance.
- Edge restraint design.
- Constructability.
- Paver type and configuration.

Many of these factors depend on the site specific conditions and layout. These factors are not directly considered in the Permeable Design Pro software, but must be carefully considered in the overall PICP design. The Interlocking Concrete Pavement Institute provides guidance on these factors in *Permeable Interlocking Concrete Pavements – Selection Design Construction Maintenance* [Smith, 2006].

3. EXAMPLE DESIGN

The following example illustrates how PICP reduces runoff and peak flows. The project is a parking lot near Omaha, Nebraska USA. The parking is 580 m^2 of PICP set within a 2 600 m^2 traditional impermeable pavement parking lot. This site is bordered by an upslope grassed area that allows stormwater runoff onto the pavement. Drainage ditches are adjacent to the PICP to handle water volumes that exceed the PICP storage and the soil subgrade infiltration capacities.

For structural capacity, the design traffic was estimated at 91 000 ESALs over the life of the pavement (typically 20 years). The local subgrade material is low plasticity clay with low permeability and California Bearing Ratio (CBR) of 3.0. This requires a pavement structure consisting of the paving units and bedding material over 100 mm of ASTM No. 57 stone and 450 mm of ASTM No. 2 stone.

For this area of Nebraska, rainfall intensities typically start low, have short periods of high intensity and then slow near the end of the storm. This rapid water inflow from intense rainfall onto impervious surfaces tends to deliver water quickly into the PICP. Although this site has a low permeability soil subgrade, stormwater management can be greatly improved by storing the water in the PICP base, allowing for a modest amount of infiltration, and slowly draining the remainder over two days. This is a substantial improvement over two hours required to drain the water from a completely impervious pavement.

For this project, water released from PICP base/subbase when full will enter drainage ditches using subdrain pipes to control the flow. Using the software program, three 100 mm diameter perforated pipe subdrains placed at the bottom of the pavement subbase at equal spacing enables water to slowly drain out within two days. The difference in inflow and outflow illustrated in Figure 6 indicates that there is some infiltration and a delay in peak flow.
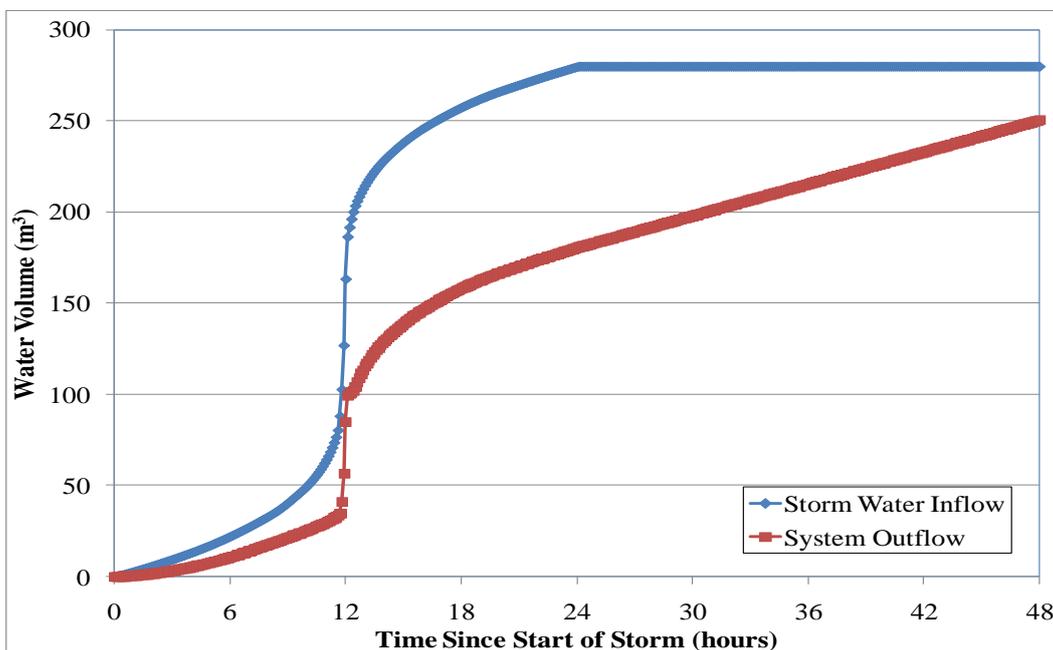

Figure 6. Comparison of PICP inflow vs. outflow.

As shown in Figure 6, the rate of water inflow is very rapid with most occurring at the 12 hour mark. With the planned design layout, the entire pavement structure is sloped towards the drainage ditches. The design forces the runoff to flow into the PICP surface and slowly release the water over time. This causes the peak inflow to be reduced by about 50% and for the remaining water to be drained over an additional 24 h to 48 h, depending on the storm intensity.

4. CONCLUSIONS

The Permeable Design Pro software tool can develop appropriate PICP designs having sufficient structural capacity to accommodate vehicular traffic and hydrological properties to accommodate and slowly release stormwater. The software uses an iterative procedure to estimate the water balance during rainfall and for up to six days afterwards to determine if the system will drain in a reasonable length of time. This allows designers to quickly determine if a site can be used for PICP and if appropriate, help assess the base/subbase thickness required for structural and hydrologic capacity for a wide range of site conditions and features.

Other detailed program outputs that support hydrological design includes hydrographs for the rainfall, inflow from contributing areas, infiltration and outflow through subdrain pipes if required. The program also calculates the NRCS curve number and runoff coefficient. On the structural side, the program calculates the required AASHTO structural number given input properties for each pavement layer. The program selects the thicker of the base/subbase required from either the structural or hydrological calculations for use as the PICP design cross section. The user can select conservative design values and program default values for input variables, especially when little or no design information is available. This enables the user to conduct sensitivity analyses and select the optimal base thickness design.

5. REFERENCES

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