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Numerical Simulation of Infiltration and Runoff in Permeable Pavement under Torrential Rain

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Abstract
Rapid urban industrial development has expanded impervious land areas, intensifying surface runoff post-rainfall and contributing to global flooding trends. Enhancing land permeability is crucial, with permeable pavements serving as an effective mitigation strategy. However, assessing their water retention and permeability faces challenges due to variable rainfall and soil conditions. This study addresses these issues by developing a numerical infiltration model to evaluate water infiltration in permeable pavements. Key findings reveal that impervious pavements prevent rainfall infiltration entirely regardless of soil type (sand, silt, clay), resulting in 100% runoff. In contrast, permeable pavements exhibit infiltration rates ranging from 24% to 76%, varying with soil type. Porous asphalt or concrete pavements demonstrate superior infiltration performance, promoting groundwater recharge. Moreover, subgrade soil permeability significantly influences water infiltration; lower permeability restricts infiltration, increasing the risk of surface runoff from saturated soils. This study's numerical model enhances our understanding of how pavement types and hydrological factors impact the effectiveness of permeable pavements, crucial for improving urban flood management strategies.

Keywords: *Land Development, Permeability, Numerical Infiltration Model.*

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I. INTRODUCTION

Due to excessive impermeabilization, land has lost its water retention capacity, resulting in a significant increase in surface runoff and causing floods. This situation has become more severe in the past decade with extensive development of hillsides and agricultural land into recreational or commercial areas. However, these disasters are not inevitable; they can be mitigated by enhancing the water retention and permeability of development sites. Implementing permeable pavements such as permeable asphalt, permeable concrete, non-continuous pavers, and perforated pavements in pathways, squares, and other areas within development zones can increase land permeability. This proactive approach can greatly reduce the environmental impact of land development activities [1-6].

Against this backdrop, this study uses numerical models to establish and simulate the water infiltration efficiency and runoff suppression of various pavements, including impermeable pavements, porous asphalt, permeable concrete, non-continuous pavers, and perforated pavements. The research findings aim to provide valuable insights for promoting improved land permeability enhancements.

II. LITERATURE REVIEW

2.1 Road Pavement

The structure of road pavement generally comprises two main layers: the surface layer and the base layer [7-10].

- **Surface Layer:** The surface layer, positioned atop the road pavement, is designed to provide a smooth, durable surface with high friction for pedestrians and vehicles. It consists of wear-resistant materials such as special asphalt mixes, asphalt concrete, or paving bricks. This layer supports the loads from vehicles and pedestrians and distributes these loads evenly to the underlying base layer.
- **Base Layer:** Also known as the bearing layer, the base layer consists of materials like gravel, graded aggregates, or concrete. Its primary function is to evenly distribute the loads from the surface layer to the subgrade soil layer, providing support and stability to the entire pavement structure. The selection and design of materials for the base layer consider the magnitude and frequency of loads to ensure the pavement remains stable and functional throughout its design life.

The design and materials of road pavement structures impact the safety, comfort, and longevity of roads.

Different types of roads (e.g., highways, urban streets, sidewalks) typically have pavement structures tailored to their specific usage and load requirements, ensuring they meet both traffic needs and user comfort standards.

2.2 Impervious Pavement [1-4]

Impervious pavement refers to hard surface coverings such as roads or pavements that do not allow water to infiltrate into the ground. Widely used in urban areas, these pavements introduce several environmental and societal issues, including primary hazards:

- **Increased Surface Runoff:** Impervious pavements hinder rainwater infiltration, leading to elevated surface runoff post-rainfall. This strains urban drainage systems and heightens the risk of flooding.
- **Disruption of the Hydrological Cycle:** Impervious pavements disrupt the natural interaction between surface water and groundwater. Surface water cannot permeate the soil, reducing groundwater recharge and affecting groundwater levels and hydrological cycles.
- **Urban Heat Island Effect:** Impervious pavements absorb and store more solar energy, exacerbating the urban heat island effect. This phenomenon raises temperatures within cities compared to surrounding areas, impacting climate comfort and energy consumption.
- **Ecological Degradation:** Impervious pavements disrupt the continuity of natural ecosystems. They impede soil biodiversity, affecting plant growth and animal habitats.
- **Water Quality Issues:** Impervious pavements prevent rapid natural filtration of accumulated pollutants, increasing the risk of water pollution. During rainfall, pollutants on surfaces are washed into water bodies.

In conclusion, while impervious pavements offer advantages in enhancing transportation efficiency and urban aesthetics, their detrimental impacts on the environment and ecology necessitate careful consideration. Strategies such as replacing impervious pavements with permeable alternatives should be explored to effectively mitigate these negative effects.

2.3 Permeable Pavement [7-9]

Permeable pavement is a specially designed surface that allows rainwater to penetrate directly into the underlying soil. This design helps reduce surface runoff caused by extensive impervious surfaces in urban areas, thereby decreasing flood risks and enhancing groundwater recharge. Permeable pavements are typically made from materials with high permeability and porosity, including:

- **Porous Asphalt Pavement:** Made from fine aggregates and special asphalt mixtures, it effectively allows rainwater to pass through the pavement into the underlying soil.
- **Permeable Concrete Pavement:** Concrete with arranged particles that allow water to penetrate through into the ground.
- **Paver Blocks or Perforated Pavement:** These surfaces use interlocking blocks or designs with perforations that enable rainwater to pass through the gaps or holes into the soil.

Permeable pavements find wide application in pedestrian walkways, bicycle lanes, parking lots, and residential roads with light traffic. They not only assist in stormwater management but also improve urban microclimates and maintain stable groundwater levels. The design of permeable pavements considers the connection between surface and groundwater, effectively reducing environmental impacts associated with urbanization while enhancing the efficiency and comfort of public spaces.

III. NUMERICAL MODEL

To analyze water infiltration through permeable pavement, this study establishes a numerical model using the finite element method. The constructed model incorporates pavement types and soil characteristics gathered from literature, along with geometric boundaries, boundary conditions, and initial conditions. The analysis aims to evaluate the effectiveness of rainfall infiltration and runoff suppression for different pavements.

3.1 Numerical Model

The finite element method discretizes soil water infiltration control equations to establish a numerical model, creating a multidimensional saturated and unsaturated water infiltration transport model. The Weighted Residual and Galerkin Methods solve finite differences in the time domain. The fluid control equation used in the model is a modified Richards equation [21-23]:

$$\mathrm{F}\frac{\partial \Psi}{\partial \mathrm{t}} = \nabla * [\mathrm{K} * (\nabla \Psi + \nabla \mathrm{Z})] + \mathrm{q}$$

where F is the storage coefficient, Ψ is the pressure head, t is time, K is the hydraulic conductivity tensor, Z is the elevation head, and q is the internal point source or point sink.

The Darcy velocity calculation is:

$$V = -K * (\nabla\Psi + \nabla Z)$$

This study uses the van Genuchten [24] soil-water retention curve model and the Mualem [25] unsaturated hydraulic conductivity model to describe soil hydraulic properties.

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = (1 + |\alpha\Psi|^n)^{-m} \quad when\ \Psi < 0$$

$$\theta = \theta_s \quad when\ \Psi \geq 0$$

where θ is the soil volumetric water content, θ_s is the soil saturated volumetric water content, θ_r is the soil residual volumetric water content, α is the air entry potential factor, n is the pore index, and m is the curve fitting parameter, with $m = 1 - (1/n)$.

The relative permeability function $k_r(\theta)$ is given by:

$$k_r(\theta) = (\frac{\theta - \theta_r}{\theta_s - \theta_r})^{0.5}\{1 - \left[1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{\frac{1}{m}}\right]^m\}^2 \quad when\ \Psi < 0$$

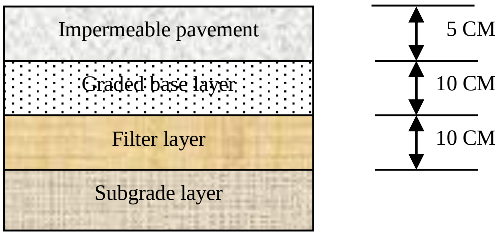
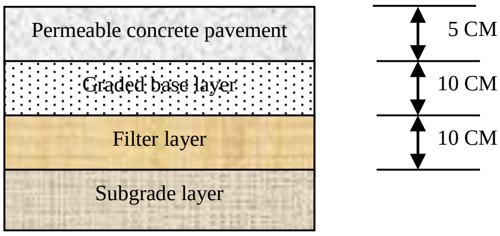
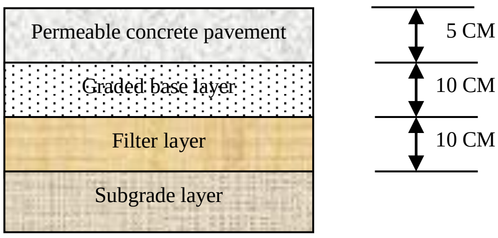
$$k_r(\theta) = 1 \quad when\ \Psi \geq 0$$

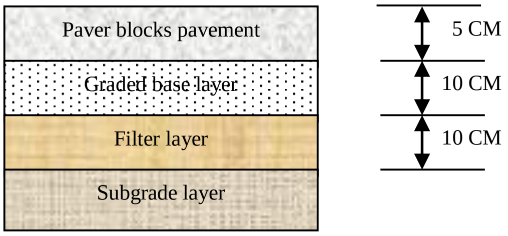
where $k_r(\theta) = \frac{k(\theta)}{k_s}$, k_s is the saturated hydraulic conductivity。

3.2 Geometric Conditions, Boundary Conditions, Initial Conditions, and Soil Characteristics Parameters

This study includes four types of pavements in the simulation analysis: general impervious pavement, porous asphalt or permeable concrete pavement, block paver pavement, and perforated (grass paver) pavement. The constructed numerical model framework is three-dimensional. Details on the setup for permeable pavements are provided in Table 1, based on research findings and academic studies [1-4, 13-14].

Table 1: Parameters Related to Numerical Simulation

Numerical Model	Simulated Cross-section	Boundary and Initial Conditions
Impermeable pavement		
Permeable asphalt pavement		● Upper boundary condition: Rainfall boundary for torrential rain (100mm/3hr) or no standing water depth ● Lower boundary condition: Water infiltration boundary at -600 cm ● Lateral boundary condition: No flow boundary condition ● Initial condition: Starting from the water infiltration level (P = 0 cm), pressure head decreases linearly with depth to P = -600 cm
Permeable concrete pavement		

Paver blocks or porous (grass-crete) pavement		

Based on references [4, 13, 21-26], geometric boundary conditions and soil hydraulic parameters required for the numerical model are detailed in Table 2.

Table 2: Hydraulic Parameters [4, 13, 21-26]

Material	Saturation Water Content	Residual Water Content	Air Entry Value Factor	Porosity Index
Porous Asphalt or Permeable Concrete Pavement	0.20	0.050	0.145	2.68
Paver Blocks Pavement	0.15	0.030	0.060	2.64
Graded Base Layer (Gravel)	0.35	0.040	0.175	3.00
Filter Layer (Sand)	0.43	0.045	0.145	2.68
Subgrade Layer (Sand)	0.41	0.045	0.140	2.50
Subgrade Layer (Silty Soil)	0.46	0.034	0.106	1.37
Subgrade Layer (Clay)	0.38	0.068	0.008	1.09
Note: Permeable block pavements are typically made of concrete with very low permeability, considered impermeable.				

IV. NUMERICAL SIMULATION AND DISCUSSION OF RESULTS

A The numerical model framework is depicted in Figures 1 and 2. Each simulation scenario employed variable boundary conditions at the upper boundary. Initially, a rainfall boundary condition was applied with a rate of 300 millimeters per 3 hours. Throughout the simulation period, this boundary condition adjusted according to the saturation state of the upper soil layer. Upon saturation of the upper soil, the boundary condition transitioned to a standing water condition, maintaining a water depth of 0 cm.

The initial conditions for each simulation state assumed a groundwater level 600 cm below the ground surface, treated as a gravity drainage boundary. Therefore, the pressure head for the water infiltration boundary at P(x, y, z = −600 cm) =0 cm decreased linearly upwards to P(x, y, z = 0 cm)= −600 cm at the ground surface.

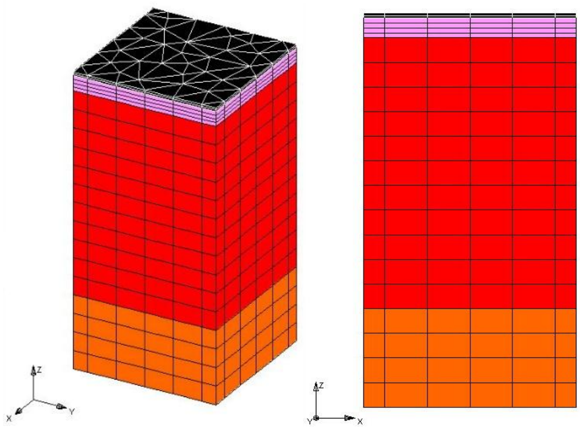


Figure 1: Numerical model grids for impermeable pavement, porous asphalt pavement, permeable concrete, and paver block pavement.

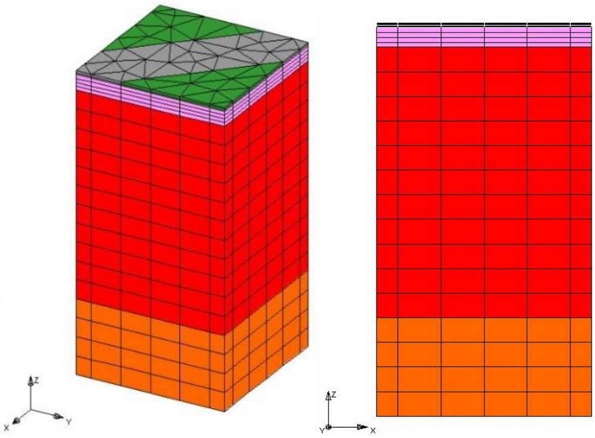


Figure 2: Grids for porous (grass-crete) pavement (the slanted striped area represents concrete on the XY plane).

Simulations were conducted over a 3-hour period of rainfall for impermeable pavement, porous asphalt, permeable concrete, paver block pavement, and porous (grass-crete) pavement. The runoff rates obtained from each numerical simulation and the water infiltration rates are presented in Tables 3 and 4, and depicted in Figures 3 and 4.

Table 3: Runoff Rates Obtained from Each Model Simulation (Rainfall Intensity 100 mm/ 3hr)

Road Base Material	Impermeable Pavement	Porous Asphalt or Concrete Pavement	Paver Block Pavement	Porous (Grass-Crete) Pavement
Sand Subgrade	100%	24%	37%	50%
Silty Soil Subgrade	100%	39%	51%	61%
Clay Subgrade	100%	64%	71%	76%

Table 4: Infiltration Rates Obtained from Each Model Simulation (Rainfall Intensity 100 mm/ 3hr)

Road Base Material	Impermeable Pavement	Porous Asphalt or Concrete Pavement	Paver Block Pavement	Porous (Grass-Crete) Pavement
Sand Subgrade	0%	76%	63%	50%
Silty Soil Subgrade	0%	61%	49%	39%
Clay Subgrade	0%	36%	29%	24%

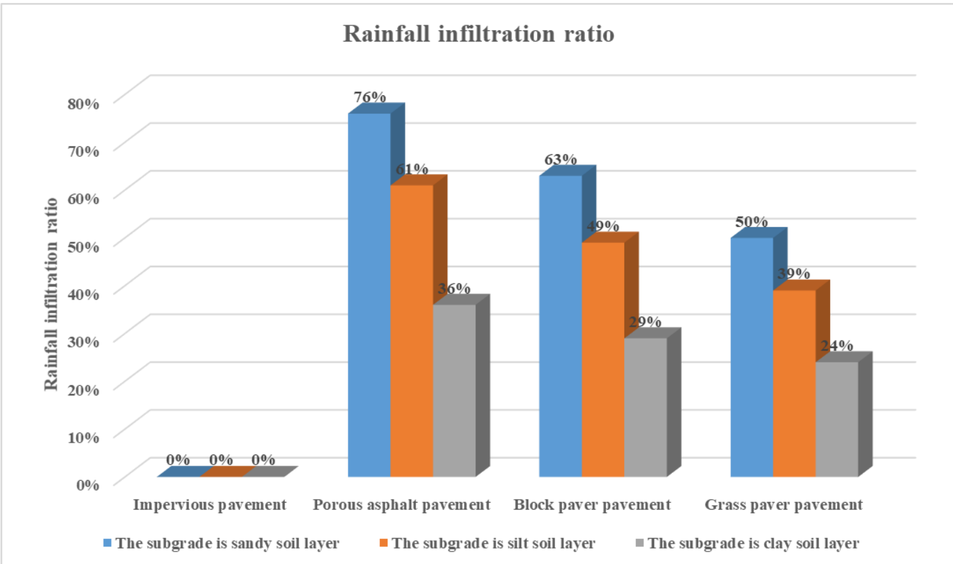


Figure 3: Rainfall Infiltration Rates Obtained from Each Model Simulation

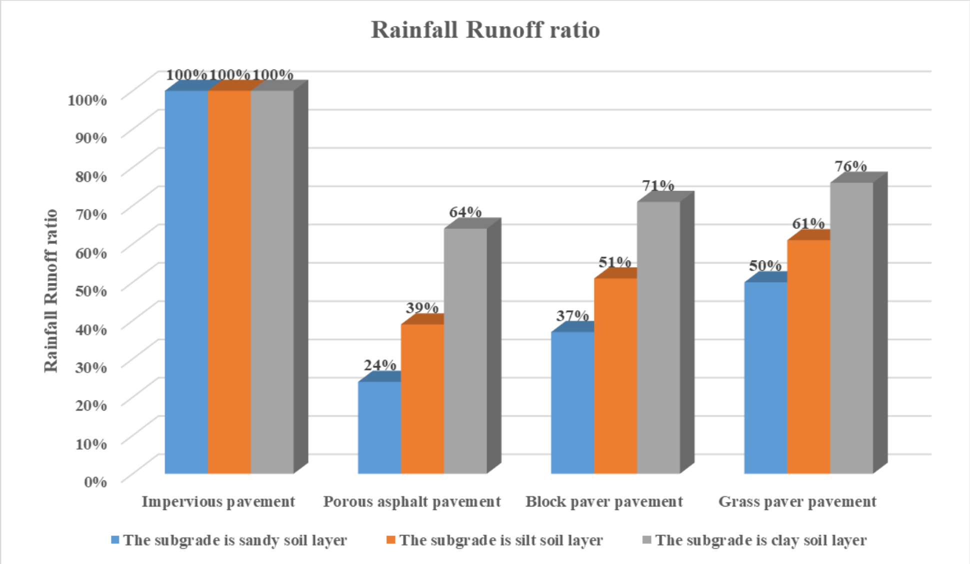


Figure 4: Rainfall Runoff Rates Obtained from Each Model Simulation

V. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

- **Impervious Pavement**: Impervious pavements, regardless of underlying soil type (sand, silty soil, or clay), prevent any infiltration of rainfall into the ground, resulting in a 100% runoff rate. This complete interception of rainfall contributes significantly to surface runoff issues.
- **Permeable Pavement**: Permeable pavements exhibit infiltration rates varying between 24% and 76%, depending on the underlying soil type. They facilitate groundwater recharge and mitigate surface runoff. Porous asphalt or concrete pavements demonstrate superior infiltration performance compared to other types.
- **Impact of Subgrade Soil Permeability**: The permeability of subgrade soil critically influences water infiltration through permeable pavements. Lower subgrade permeability reduces infiltration capacity, leading to increased surface runoff as upper layers become saturated.

5.2 Recommendations

Based on the findings:

- **Urban Planning**: Integrate more permeable pavements, particularly porous asphalt or concrete, in urban areas to reduce surface runoff and enhance groundwater recharge.
- **Maintenance**: Regularly maintain and monitor permeable pavements to ensure optimal infiltration rates. Address issues such as sedimentation and clogging, which can affect effectiveness over time.
- **Research and Development**: Invest in further research to optimize the design and materials of permeable pavements tailored to diverse soil conditions and varying rainfall intensities. This effort aims to maximize water infiltration efficiency and minimize runoff.

These conclusions underscore the pivotal role of pavement type and subgrade characteristics in effective stormwater management within urban environments.

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