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Analysis of Seepage Behavior on the Road over the Embankment Using Smoothed Particle Hydrodynamics (SPH) Modelling

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Abstract

The impact of seepage in geotechnical engineering, especially in the design of embankments and retaining structures, has a significant influence on their stability and performance. This can occur due to differences in hydrostatic pressure between water in the channel and groundwater in the surrounding area. When water seeps or permeates through the embankment, it can have a significant impact on the stability of the embankment and increase the risk of collapse. Therefore, this research is conducted to investigate the effect of seepage on road settlement over the embankment using the Smoothed Particle Hydrodynamics (SPH) method. The SPH method is enhanced in PersianSPH for more accurate and efficient fluid simulation. Darcy's law and Forchheimer's law are used to describe seepage and measure physical characteristics in the simulation. The analysis in this research indicates that low-density seepage has the potential to damage structures above it due to soil support loss. Overall, water stability and seepage movement can affect the stability and strength of soil structures such as embankments.

Keywords: Seepage impact, embankment performance, hydrostatic pressure, road settlement, SPH method, PersianSPH, Darcy law, Forchheimer law, seepage movement

1. Introduction

In geotechnical engineering, seepage is a critical factor, especially in the design of embankments or other retaining structures. Seepage refers to the flow of water within the interstitial spaces of soil, and when water seeps through an embankment, it can threaten its stability and increase the risk of failure. Therefore, the analysis of seepage behavior on the soil beneath an embankment is essential. This study pertains to the soil geometry alongside the Eastern Canal Inspection Road (IKT), which is built along the side of the eastern canal embankment, with a marsh designated for river maintenance and operations. The analysis is not primarily focused on the IKT road itself; the geometry is used merely for visualization purposes. Instead, this analysis is based on previous research by M. Gholami Korzani, involving embankment analysis using Smoothed Particle Hydrodynamics (SPH) with variations in seepage type. The analysis aims to examine the influence of seepage on the settlement of the road atop the embankment.

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Seepage effects are modeled using the SPH (Smoothed Particle Hydrodynamics) method, which represents water flow as small particles and measures their relative contributions. This method is enhanced in PersianSPH to achieve better, more accurate, and efficient fluid simulation results. Within SPH, particle interactions occur through a commonly used kernel function in simulating fluid flow dynamics to estimate physical properties around each particle. This analysis is based on Darcy's law (1856) and Forchheimer's law (1901) to describe seepage and evaluate characteristics such as density, pressure, and velocity. In the context of seepage within SPH, Darcy's law is used to model water flow through porous media, while Forchheimer's law is an extension of Darcy's law that accounts for non-linear effects in fluid flow through porous media.

The SPH method was first proposed by Lucy (1977) and further developed by Gingold and Monaghan (1977) to address problems in astrophysics. This technique employs Lagrangian moving particles to map space, with Lagrangian properties referring to the individual particle approach, where particles are considered independent entities moving in space and time.

M. Gholami Korzani (2017) also used SPH to analyze the impact of high floods on embankment strength. Generally, embankments are exposed to the atmosphere due to their geometry, resulting in precipitation and evaporation causing significant variations in water content within the embankment. The goal of their work was to provide an alternative approach using SPH to study the hydro-mechanical behavior of soil structures in geotechnics.

Therefore, this analysis will further discuss the influence of seepage on embankments using the SPH method in PersianSPH, as previously explained. While it has potential, its effectiveness varies and requires further research to understand its benefits and limitations in various simulation scenarios.

2. Research Method

2.1 SPH Method

The Smoothed Particle Hydrodynamics (SPH) method is a meshless numerical approach that is flexible and robust for simulating Lagrangian fluid dynamics, utilizing interpolation techniques to describe the continuum. The Lagrangian nature refers to the individual particle-based approach. In this approach, particles are considered entities that move independently in space and time. Each particle in the SPH method possesses physical attributes such as mass, velocity, and density.

In this method, the material properties of each particle are then computed through interpolation processes considering other neighboring particles. This interpolation process is based on the integral representation of the field function:

$$f(x_a) = \sum_b m_b \frac{f_b}{\rho_b} W(r_{ab}, h) \tag{2.1}$$

Where:

a	: Integration point (particle) (constant)
b	: Particles within the vicinity of particle a (constant)
$\boldsymbol{r_{ab}}$	: Distance between particle a and b (m)
W	: Kernel (smoothing function) (m^{-2})
m	: Mass (kg)

ρ : Density (kg/m^3)

Here subscript *a* refers to the integration point (particle), and subscript *b* is used for particles in the neighborhood of particle *a*, with representing $\boldsymbol{r_{ab}}$ the distance between particle *a* and *b*. *W* is the kernel (smoothing function) that must satisfy various conditions, which are comprehensively explained in relevant literature. The involved field variables are *m* (mass) and ρ (density), each representing the mass and density of each particle respectively.

2.2 The Function of Kernels in Research

The cubic spline kernel is one of the types of kernel functions used in the Smoothed Particle Hydrodynamics (SPH) method. This kernel is commonly employed in simulating the dynamics of fluid flow to estimate the physical properties around each particle. The cubic spline kernel function is applied to each particle and contributes to the computation of density and pressure within the SPH simulation.

Kernels play a crucial role in the accuracy, efficiency, and stability of the SPH scheme. The kernel's behavior depends on the smoothing length, denoted as *h* and the dimensionless distance between particles, denoted as $q = r_{Ab}/h$. The most well-known kernel function (the cubic spline) used in this research is defined as follows:

$$W_{ab} = W(r_{ab}, h) = \alpha_d \begin{cases} 1 - \frac{3}{2}q^2 + \frac{3}{4}q^3, & 0 \le q \le 1 \\ \frac{1}{4}(2-q)^3, & 1 \le q \le 2 \\ 0, & q \le 2 \end{cases} \tag{2.2}$$

The meaning of this formula is as follows: *r* represents the distance between the central particle and the nearest neighboring particle, and *h* is the search radius or smoothing kernel radius. The distance *r* and smoothing radius *h* are typically expressed in distance units. Additionally, *q* is defined as *r/h*, which is the ratio of "*r*" to the smoothing kernel radius.

The cubic spline kernel function possesses several important properties. First, it ensures that the weights of particles farther away from the central particle are zero, so only the nearest particles make a significant contribution. This property is achieved by setting the kernel function to zero when q ≥ 2. Second, the cubic spline kernel is a continuous and differentiable cubic polynomial function. This property enables accurate computation of gradients of physical properties in SPH simulations.

2.3 The Darcy and Forchheimer Laws

In the SPH (Smoothed Particle Hydrodynamics) method, the Darcy and Forchheimer laws are employed to model the flow of water or seepage within porous media. The Darcy Law, in particular, serves as the fundamental principle used to describe fluid flow within porous media. This law states that the rate of fluid flow within porous media is directly proportional to the pressure gradient and the permeability of the media. In the context of seepage within the SPH method, the Darcy Law is used to model the flow of water through porous media.

On the other hand, the Forchheimer Law is an extension of the Darcy Law that takes into account

nonlinear effects in fluid flow through porous media. This law incorporates additional terms that depend on the fluid flow velocity. These additional terms represent the energy losses due to nonlinear resistance in porous media.

By incorporating the Darcy and Forchheimer laws into the SPH formulation, we can simulate fluid flow involving porous media with greater accuracy. The equations for these laws that enable fluid flow simulations are as follows:

2.3.1 Darcy's Law Equation

Darcy's Law states that the seepage rate through a saturated porous medium in the horizontal direction is proportional to the hydraulic gradient (difference in hydrostatic pressure) between two points. The mathematical formula is as follows:

$$Q = -kA\frac{dh}{dx} \tag{2.3}$$

where:
Q : seepage rate (m^3/s)
k : permeability coefficient of the porous medium (m^2)
A : cross-sectional area of the flow path (m^2)
$\frac{dh}{dx}$: hydraulic gradient (m/m).

The influence of Darcy's Law on seepage is that seepage tends to follow the hydraulic gradient. The greater the difference in hydrostatic pressure between two points, the greater the seepage rate.

2.3.2 Forchheimer's Law Equation

Forchheimer's Law is an extension of Darcy's Law that considers nonlinear effects on the flow rate when fluid velocity becomes higher. This typically occurs in stronger flows or in porous media with smaller pore sizes. Forchheimer's Law can be written as follows :

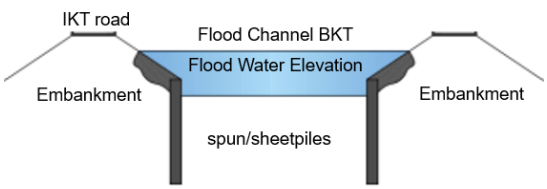
$$Q = -kA\left(\frac{dh}{dx} + \beta v + \gamma v^2\right) \tag{2.4}$$

where:
β and γ : constants related to nonlinear effects,
v : fluid flow velocity (m/s).

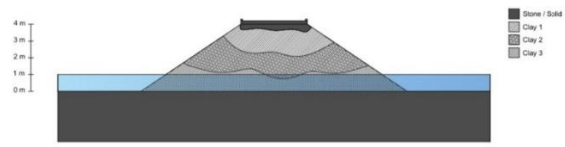
The influence of Forchheimer's Law on seepage is that it accounts for nonlinear effects in fluid flow. At higher flow velocities, nonlinear contributions can become significant, and Forchheimer's Law provides a more accurate model for predicting seepage. In the context of seepage, both Darcy's Law and Forchheimer's Law are used to describe and predict the movement of water or fluids through porous media. Forchheimer's Law is often applied when fluid flow becomes more complex and nonlinear effects occur, such as in the flow of water in very fine porous media or in applications involving high-velocity flow.

2.4 Geometry

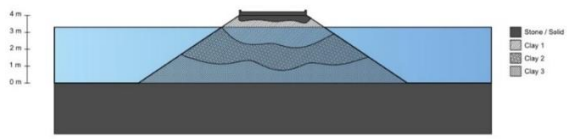
In this study, the road geometry constructed along the eastern canal embankment side is solely utilized for visualization purposes and is not constrained by the IKT Road. The author only considers the soil type used, which is clay as described in the soil type geometry illustration. This research, on the other hand, is based on previous research by M. Gholami Korzani, which involves embankment analysis using Smoothed Particle Hydrodynamics (SPH), and the author further extends it by incorporating seepage analysis.



(a) Geometry IKT road



(b) The geometry of soil embankment seepage type 1



(c) The geometry of soil embankment seepage type 2

Figure 1. The geometric characteristics of the IKT road and the soil embankment type geometry in seepage type 1 and 2

The figure 1(a) represents the actual geometric shape that is the subject of the research, but for modeling in PersianSPH, we use assumed images 1(b) and 1(c) in the PersianSPH modeling. The soil layer in the modeling assumption is only an approximation of the movement of soil particles with a homogeneous soil type.

2.5 Visualization Parameter Data

The parameters utilized in seepage modeling are as follows:

Table 1. Visualization Parameter for Seepage 1 and 2

Variable	Seepage 1	Seepage 2	Unit
Density of soil particle ρ_s	2642,21	2644	kg/m^3
Particle diameter	0,02	0,02	mm
Kernel function	Qubic Spline	Qubic Spline	
Seepage equation	2	1	

The density condition concerning the influence of seepage on an embankment, employing Smoothed Particle Hydrodynamics (SPH) modeling, entails the simulation of water flow along and through the embankment using the SPH method. In this analysis, the primary objective is to comprehend how seepage (the infiltration of water through the embankment) can affect the material density of the embankment. The selection of seepage equation types 1 and 2 is based on the inherent type of the PersianSPH formula for seepage.

2.6 Phase of Movement Flow

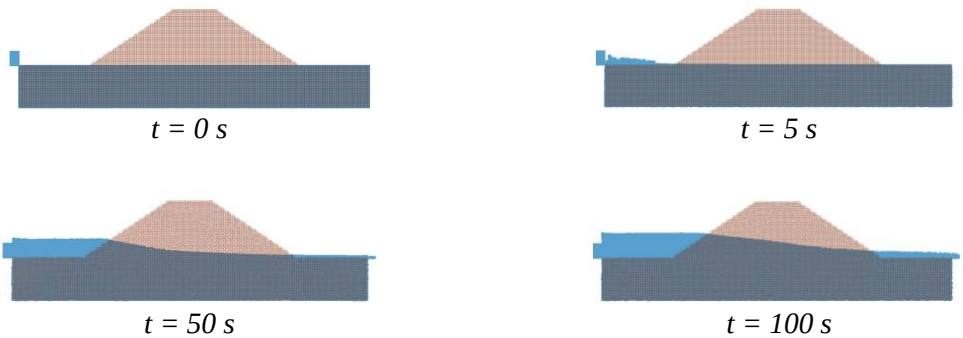


Figure 2. The Illustrates the water flow in the embankment at various time steps with a discharge of Q = 0.25 m3/s. Source: Golami Korzani & Galindo, Case Embankment PersianSPH.

In Figure 2, it is shown how the phreatic surface within the embankment evolves over time before reaching a constant state, eventually leading to the water levels generated upstream and downstream of the embankment, as well as the stabilized phreatic surface within the embankment.

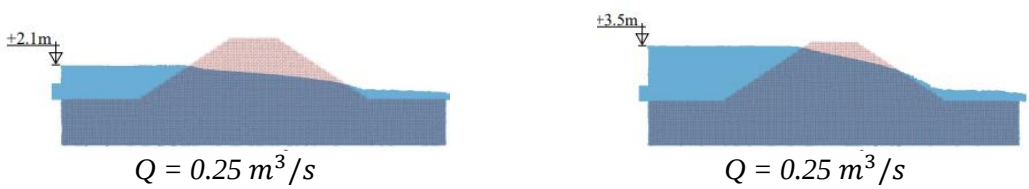


Figure 3. The Shows the water level on the embankment under stable conditions. Source: Golami Korzani & Galindo, Case Embankment PersianSPH.

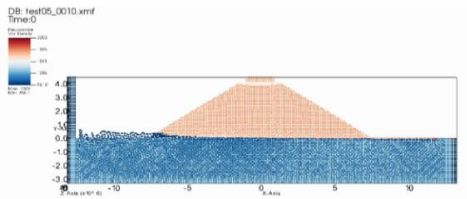
For both flood scenarios (2) and (3), they are illustrated in Figure 3 (hydraulic equilibrium condition). Deformation simulations are observed on the embankment due to the flow of water, until the water level on the embankment reaches a stable condition.

In figure 3, it is an example depicting the application of the SPH method in the analysis of seepage equations based on research published by Golami Korzani & Galindo, which serves as a benchmark for the success of simulating seepage behavior on a drop of road over the embankment using Smoothed Particle Hydrodynamics (SPH) modeling.

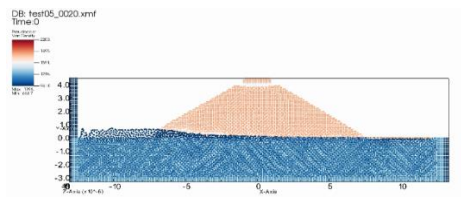
3. Results and Discussion

3.1 Analysis of Density Visualization in Type 1 Seepage

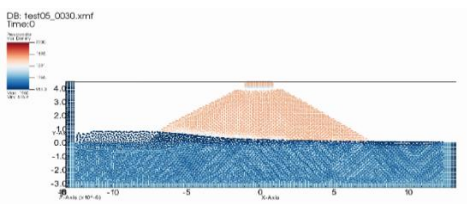
In this analysis, the author models the visualization of conditions for seepage 1 and 2, where seepage 1 represents the initial modeling with a relatively high geometric seepage condition. This serves as a reference for the seepage condition in type 2. To map the flow, Forchheimer's law is employed.



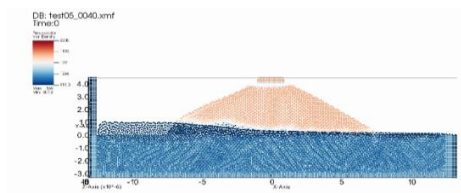
(a) Duration of 10 seconds



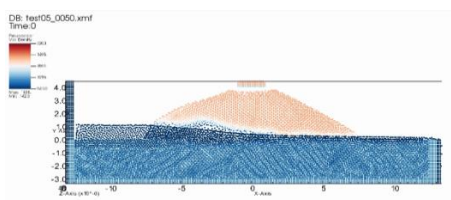
(c) Duration of 20 seconds



(b) Duration of 30 seconds



(d) Duration of 40 seconds



(e) Duration of 50 seconds

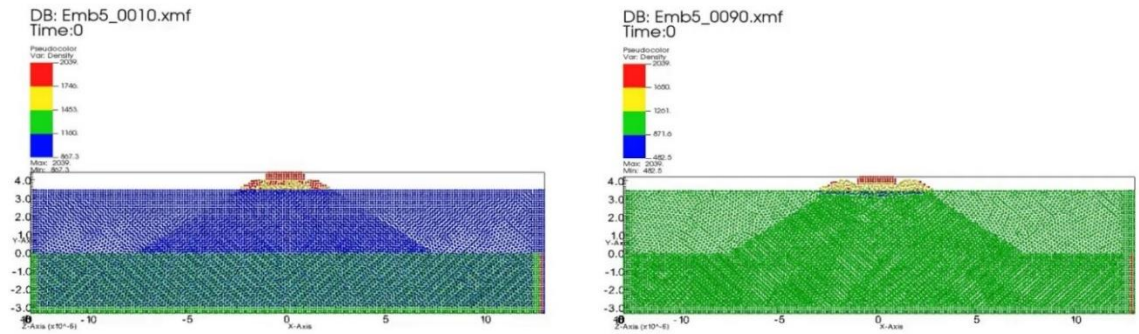
Figure 4. Analysis of Density Visualization in Type 1 Seepage

As shown in Figure 4, In Figure 4(a) the initial water height condition is 0.2 meters (increased) at a duration of 0.01 seconds, with the onset of seepage becoming apparent. Figure 4(b) depicts the initial water height condition at 0.5 meters (increased) at a duration of 0.02 seconds, where seepage becomes visible, and some signs of instability are observed. Figure 4(c) illustrates the initial water height condition at 1 meter (increased) at a duration of 0.03 seconds, with significant signs of seepage-induced instability becoming evident. Figure 4(d) shows the initial water height condition at 1 meter (increased) at a duration of 0.04 seconds, with highly significant seepage-induced instability leading to overtopping of the embankment. Finally, in Figure 4(e), the initial water height condition ranges from 1 to 1.2 meters (increased) at a duration of 0.05 seconds, with seepage causing very significant instability and a substantial volume breach of the embankment. During a 10 second duration, the water level rises with a maximum seepage discharge of 2039 m^3/s, and the soil particle density is 886.1 kg/m^3. In subsequent conditions, the water level remains at its maximum position, while the density is at its minimum. Therefore, in this condition, it is noted that low soil density can facilitate

the formation and expansion of water seepage paths. High velocities of water seepage in low-density soil can also influence the behavior of structures built on it, resulting in damage to foundation support capacity due to the loss of effective soil bearing capacity due to high seepage.

3.2 Analysis of Density Visualization in Type 2 Seepage

In this analysis, the simulation results are intended to examine the comparison with previous seepage. To map the flow, Darcy's law is employed.



(a) Duration of 10 seconds *(b) Duration of 90 seconds*

Figure 5. Analysis of Density Visualization in Type 2 Seepage

In Figure 5(a), at a duration of 10 seconds, it begins to demonstrate the influence of seepage on particle density in both the right and left directions of the embankment. Red particles represent conditions of maximum density (2039 kg/m^3) and minimum density (867.3 kg/m^3) that will occur in subsequent conditions. This is due to the infiltration and rise of water flow within the soil particles. In Figure 5(b), at a duration of 90 seconds, the water condition remains stable. The density of the loose material is slightly less than before. The maximum density remains the same throughout, at 2039 kg/m^3, with a minimum of 482.5 kg/m^3.

In Figure 5, the water condition remains stable from start to finish at varying densities, and the influence of overflowing groundwater mixed with the soil material is observed. The maximum density of the embankment material remains consistent from start to finish, while the minimum value decreases.

3.3 The Analysis of Time History Graphs

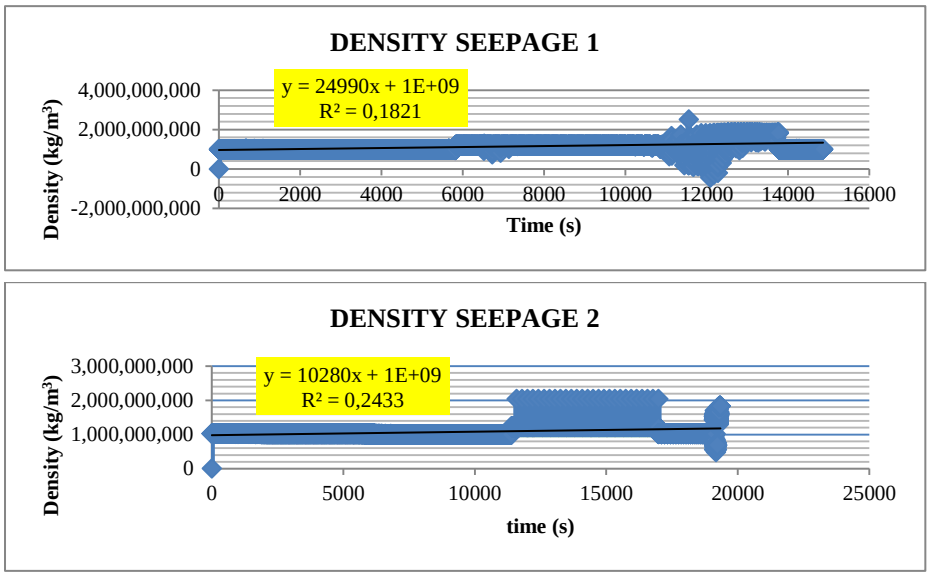


Figure 6. The density graph of seepage conditions for types 1 and 2

From the visualization results in the table using VisIt, data on movement in the x and y directions can be extracted. This data is obtained from the spreadsheet in VisIt. The analysis is conducted based on the graph. In the density graph, the values of the x-direction (density) and y-direction (time) indicate the influence of the relaxation coefficient on the density evaluation errors in particles. The graph illustrates how particle density changes over time. From the second seepage graph, it can be observed that when the relaxation coefficient value is small, specifically at 0.01, the distance between particles represented as d_0 is also 0.01. The relaxation coefficient α ranges from 0.1 to 0.20. In this case, the fluctuations in density errors are not significant. These smaller values can indicate that when saturation levels are high, the density tends to be more stable and has a better ability to resist water movement. On the other hand, seepage 1 has low soil density, and when saturation is low, a significant number of voids are still filled with air rather than water.

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Declaration of Conflicting Interests

The authors declare that they have no conflicts of interest.

Declaration of Generative AI and AI-Assisted Technologies in the Manuscript Preparation Process

ChatGPT was used to assist with manuscript formatting and language editing. It was not used to generate scientific content, perform data analysis, or draw scientific conclusions. The authors are responsible for reviewing and approving the final manuscript.

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