Chapter

Prediction of Internal Soil Erosion in Hydraulic Works

Benaissa Kissi, Chafik Guemimi, Miguel Angel Parron Vera, Maria Dolores Rubio Cintas and Rachid Elkhayma

Abstract

Hydraulic structures built on land, such as dams, are numerous and essential as their purpose is to protect people and property (dikes and levees), generate electricity, or create water reserves (dams). Soil erosion, known as hydraulic foxing, is a complex phenomenon which, in its ultimate stage, produces insidious leakage of fluids beneath hydraulic infrastructures known as pipes, and is the main cause of their failure. The HET pipe erosion test is commonly used to quantify the rate of pipe erosion. In this work, the hole erosion test is modeled using ANSYS Fluent software. The aim is to predict the soil erosion rate during the hole erosion test in order to predict the phenomenon of hydraulic foxing within hydraulic structures. The renormalization group theory-based $k - \varepsilon$ turbulence model equations are used. This modeling makes it possible to describe the effect of the clay concentration in flowing water on erosion. Contrary to the usual one-dimensional models, the modeling proposed in this study shows that erosion is not uniform along the entire length of the hole. In particular, clay concentration was found to significantly increase the erosion rate.

Keywords: erosion, piping, hole erosion test, computational fluid dynamics, numerical modeling, embankment dam, risk analysis

1. Introduction

Internal erosion is one of the main causes of instability of earthen hydraulic structures (dike, levee, dam, etc.). The disorders observed on recent structures underline the need for a better understanding and quantification of the phenomena that govern internal erosion. The entrainment and transport of grains by the internal flows affect the granulometric distribution and modify the porosity, as well as the mechanical and hydraulic characteristics.

Dike failures are much more numerous than those of dams due, on the one hand, to the variability of hydraulic solicitations and, on the other hand, to the length and heterogeneity and sometimes the age of dykes and levees, which make monitoring and maintenance difficult.

Numerous dam failures have occurred worldwide, some of them reported by Foster et al. [1]. The main cause of these failures has been identified as being linked to a channeling phenomenon that occurred in the foundation soil or in the dam structure. To ensure the viability of hydraulic infrastructures, it is essential to take into account the vulnerability of the soil to infiltration [2, 3]. Normally, in the case of unconsolidated soils, which are generally made up of slightly cohesive sand particles, we find that water flow velocity plays a very important role in the erosion phenomenon that can occur. Interpreting and understanding the underlying mechanisms and quantifying the effects of relevant variables on this erosion phenomenon is of great practical importance. Soil erosion due to liquid flow can be modeled using a variety of approaches. These include continuum-based models and discrete models, which use certain parameters that are calibrated using laboratory tests or field observations to predict when internal soil erosion begins to occur and the expected erosion rate. Several models for predicting soil erosion rates at the solid/fluid interface have been developed in the literature [3, 4]. One of the most important tests used to predict erosion is the tube erosion test (HET). A model for interpreting the HET with a constant pressure drop has been developed by Bonelli and Brivois [5]. This model provides a characteristic erosion time that depends on the initial hydraulic gradient and the soil erosion rate.

One of the aims of this work is to describe the turbulent two-phase fluid flow that causes erosion inside the porous soil sample, taking into account the influence of the variable clay concentration in the flow fluid. A computational fluid dynamics (CFD) approach will be used to study the shear stress developing at the water/soil interface, which represents the main mechanical action at the origin of surface erosion.

2. Internal erosion processes

It has been found that the soil fractions considered most susceptible to erosion are coarse silts and relatively uniform fine sands.

Cohesive soils, such as clays, are more resistant to erosion as long as chemical bonds are not destroyed [11]. It also seems that certain central materials of glacial origin are particularly sensitive to internal erosion.

According to [12], four conditions must be met for internal erosion and channeling to occur. These conditions are as follows:

There must be a seepage path and a water source.

There must be erodible material within the flow path, and this material must be transported by an infiltration flow.

There must be an unprotected outlet from which the eroded material can escape.

For a channel to form, the transported material, or the material directly above it, must be capable of forming and supporting the channel's "roof."

In an earth and rockfill dam with a central core, there are mainly three processes [12] that can initiate channelization: backward erosion, concentrated leakage, and suffusion. Backward erosion is initiated at the point where the seepage exits, and erosion progresses progressively backward to form a channel. Concentrated seepage begins with a crack or soft zone emanating from the water source to an exit point (downstream). Erosion continues progressively along the walls of the erosion hole, intensifying the concentrated leak. Suffusion is the process by which fine soil particles are carried away or eroded by the voids formed by coarser particles. This phenomenon can be avoided if the soil has a well-spaced granulometric distribution and sufficiently small voids. Soils are said to be internally unstable if suffusion occurs, and internally stable if the particles are not eroded by the infiltration flow.

Piping can occur in the backfill through the foundation and from the backfill into the foundation. Conceptual piping failure development models for these three cases are shown in **Figure 1**. In addition, a failure path diagram for piping failure through backfill is shown in **Figure 1**. Similar failure diagrams for failure by piping through the foundation and backfill in the foundation can be found in [13] or [14].

3. CFD modeling approach of erosion in the HET

The turbulence of the water flowing inside the HET sample hole is modeled using Fluent software. Fluent is a general-purpose CFD code that has been applied to various problems in the fields of fluid mechanics and heat transfer. The code has been validated in numerous studies. Fluent is, especially, appropriate for the complex physics involved in heat and mass transfer and considers mixtures by modeling each fluid phase independently or as a homogenized medium [6].

Flow taking place inside the hole is turbulent. To perform realistic simulation of turbulence, the exact instantaneous Navier-Stokes governing equations are habitually time-averaged or ensemble-averaged. The obtained averaged equations contain further unknown variables, and turbulence models are introduced in order to determine them in terms of known quantities. Various turbulence models have been proposed in the literature; however, there is no single turbulence model, which could be applied for all classes of problems. The choice of a pertinent model for a given problem will depend on the actual physics of the flow, the degree of accuracy required, and the computational cost tolerated. Fieldview Reference Manual [7] gives a detailed discussion on how to perform at best the appropriate choice of a turbulence model. Among the various models, the standard $k - \varepsilon$ model, which was proposed first by Launder and Spalding [8], has become the most popular one when dealing with practical engineering flow calculations. This model relies on phenomenological considerations and integrates empiricism to perform closure of turbulence equations.

Improvements of the standard $k - \varepsilon$ model, such as the RNG $k - \varepsilon$ model, have been made by [9]. This model was derived by using a rigorous statistical technique called renormalization group theory (RNG).

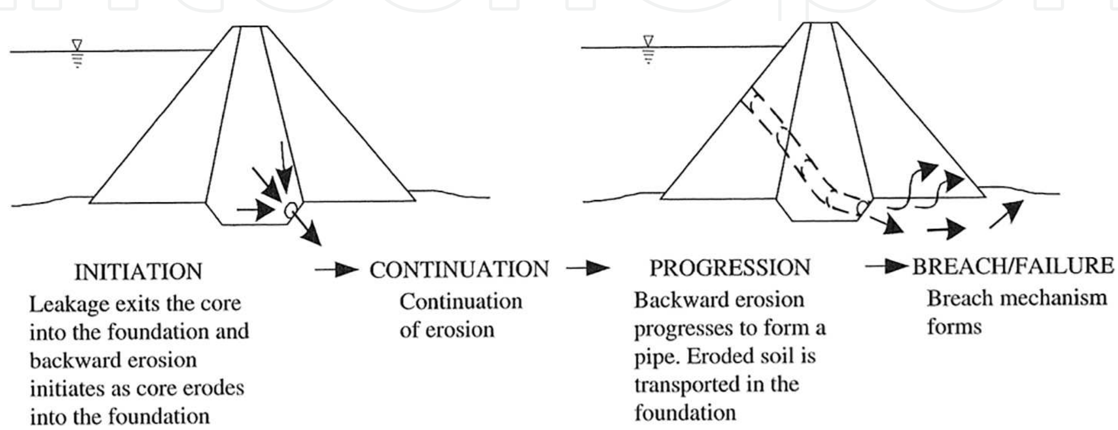

Figure 1.
Conceptual model for development of failure by piping from the embankment into the foundation [13].

4. RNG based k-ε erosion model equations for the HET

The RNG $k - \varepsilon$ model differs from the standard model by the special form of the transport equations, which contain the additional term R_ε. These equations write

$$\frac{\partial k}{\partial t} + \frac{1}{r}\frac{\partial (rku)}{\partial r} + \frac{\partial (kv)}{\partial z} = \frac{1}{r}\frac{\partial}{\partial r}\left(\alpha\mu_t r\frac{\partial k}{\partial r}\right) + \frac{\partial}{\partial z}\left(\alpha\mu_t\frac{\partial k}{\partial z}\right) + \alpha\mu_t\frac{k}{r^2} + \mu_t S^2 - \varepsilon \qquad (1)$$

$$\frac{\partial \varepsilon}{\partial t} + \frac{1}{r}\frac{\partial (r\varepsilon u)}{\partial r} + \frac{\partial (\varepsilon v)}{\partial z} = \frac{1}{r}\frac{\partial}{\partial r}\left(\alpha\mu_t r\frac{\partial \varepsilon}{\partial r}\right) + \frac{\partial}{\partial z}\left(\alpha\mu_t\frac{\partial \varepsilon}{\partial z}\right) + \alpha\mu_t\frac{k}{r^2} + C_{1\varepsilon}\frac{\varepsilon}{\rho k} - C_{2\varepsilon}\frac{\varepsilon^2}{\rho k} - \frac{1}{\rho}R_\varepsilon \qquad (2)$$

With

$$R_\varepsilon = \frac{C_\mu \rho S^3 k^2 \varepsilon(\eta_0\varepsilon - Sk)}{\eta_0(\varepsilon^3 + \beta S^2 k^3)} \qquad (3)$$

$$S^2 = 2\left(\frac{\partial u}{\partial r}\right)^2 + 2\left(\frac{\partial v}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial r} + \frac{\partial u}{\partial z}\right)^2 \qquad (4)$$

where u and v are average radial and axial flow velocities, r and z are axial and radial coordinates, t is time, ε the rate of dissipation of turbulent kinetic energy, k is the turbulent kinetic energy, ρ is the fluid density, μ_t the total kinematics viscosity, α is the inverse effective Prandtl number for both k and ε, and $C_{1\varepsilon}$, $C_{2\varepsilon}$, C_μ, η_0 and β are constants.

To calculate the tangential shear stress distribution on the cylinder inner wall, boundary conditions must be introduced. When the shear stress is calculated using ANSYS Fluent software, the classical linear erosion law is used to estimate the erosion rate. This law states the estimated erosion rate, defined as the mass departure of particles due to erosion per unit time and per unit area, is expressed by the following formula: $\dot{\varepsilon}_{er} = c_{er}(\tau - \tau_{cr})$ where c_{er} and τ_{cr} are constant depending on the considering soil material. The rate $\dot{\varepsilon}_{er}$ can be related to time variation of local radius by $\dot{\varepsilon}_{er} = \rho_d dR/dt$ where ρ_d represents the dry density of the soil and R the inner radius of the hole. The law of erosion states that the rate of erosion ε_{er} is proportional to the shear stress, exceeding the critical shear τ_{cr} for which erosion begins [10].

5. Interpretation and analysis of results

The fluid is assumed to be axisymmetric, extending over a length of 0.117 m in the axial direction z and 0.03 mm in the radial direction r. The model is designed so that inlet pressure is on the left and outlet pressure is on the right (**Figure 2**).

Figures 3–6 shows shear stress that develops at the soil sample interface with flowing flow for pressure P = 3726 (Pa).

Figure 7 shows that for two clay concentrations, the calculated erosion rate value is 10^{-6} kg/s. This erosion rate value is obtained by integrating the erosion law over the entire length of the sample hole and multiplying the result by the initial hole circumference. The erosion constants used are: $c_{er} = 5.6 \times 10^{-4} s/m$ and $\tau_{cr} = 7,1Pa$. These correspond to a specific soil sample containing 50% kaolinit clay and 50% sand that was tested as reported in Pham [10].

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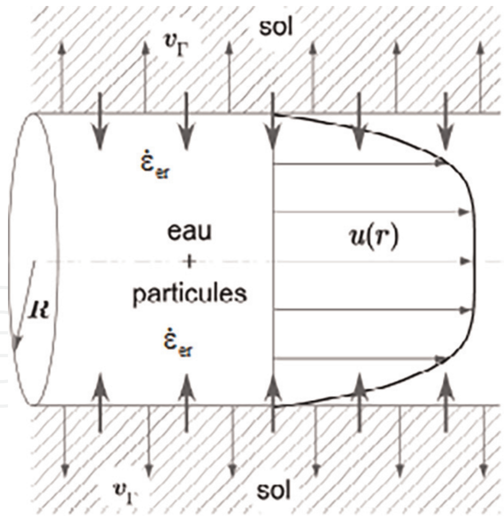

Figure 2.
Geometry of the HET tube.

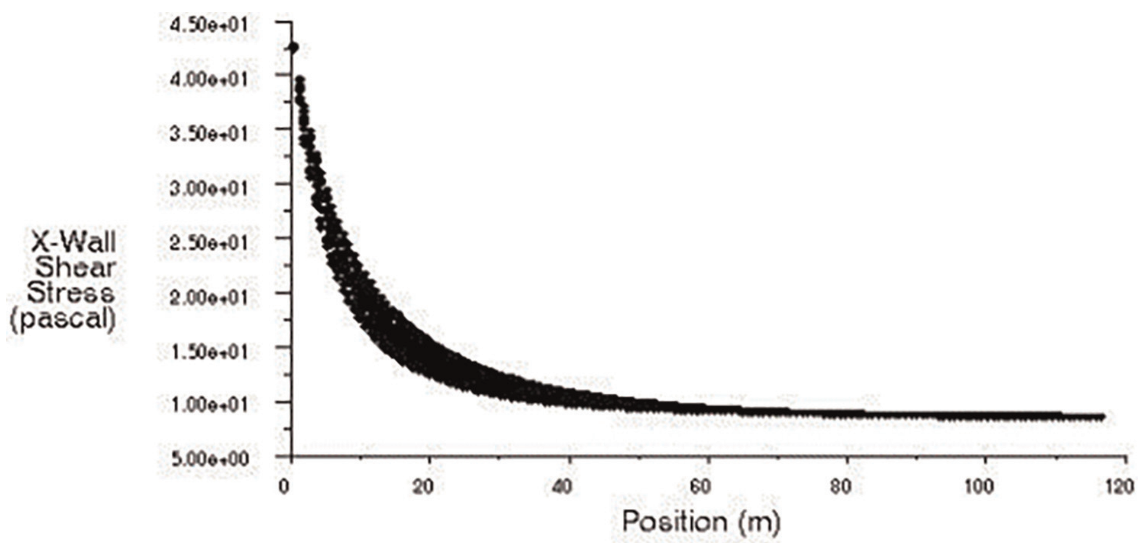

Figure 3.
X-Wall shear stress in pascal.

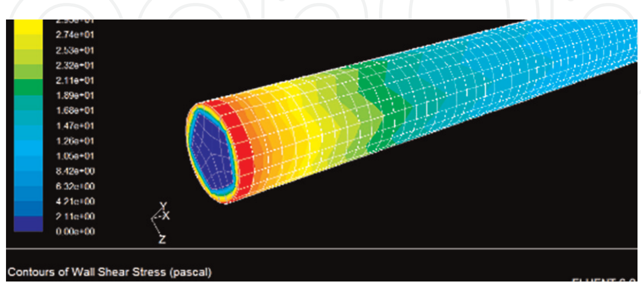

Figure 4.
X-wall shear stress mapping in the solid/fluid interface.

Figure 8 gives the y + value for the applied pressure pinlet = 3726 Pa and the four concentrations as function of the axial coordinate.

Figure 9 gives, for the three applied hydraulic gradients and the four concentrations, curves of the axial velocity at the axis of symmetry as function of the axial coordinate.

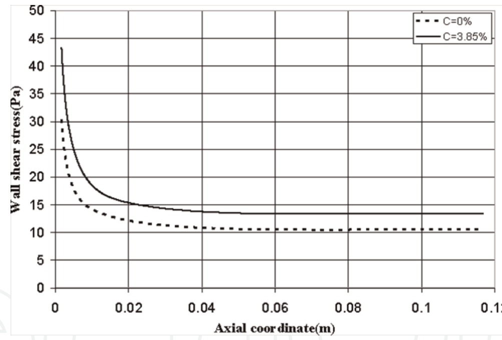

Figure 5.
Wall-shear stress obtained for P = 3726 Pa as function of clay concentration.

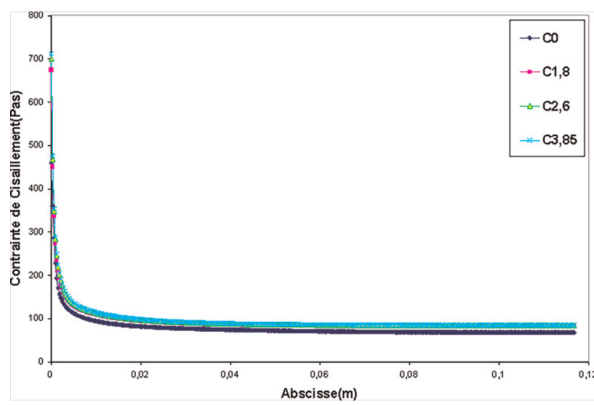

Figure 6.
Shear stress at the interface for the case of $p_{inlet} = 3726$ *Pa as a function of clay concentration.*

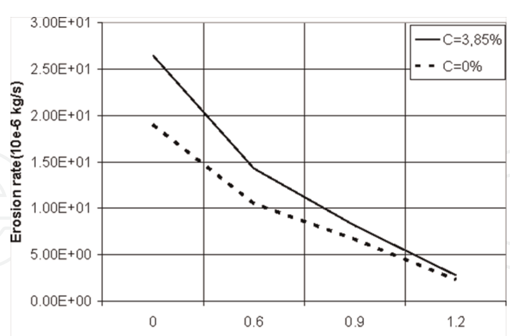

Figure 7.
Erosion rate as function of the clay concentration.

Figure 10 shows the erosion rate as a function of clay concentration for the three pressure gradients. (10^{-6} kg/s).

The results obtained, as shown in **Figure 10**, indicate that the erosion rate increases with clay concentration and with axial coordinate. This contrasts with the one-dimensional EHF model, for which the erosion rate does not depend on the axial coordinate.

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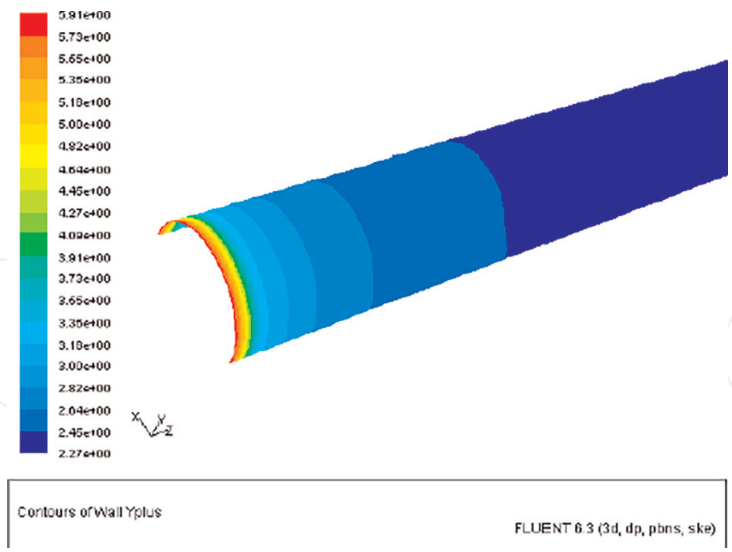

Figure 8.
Contours of wall Yplus on wall.

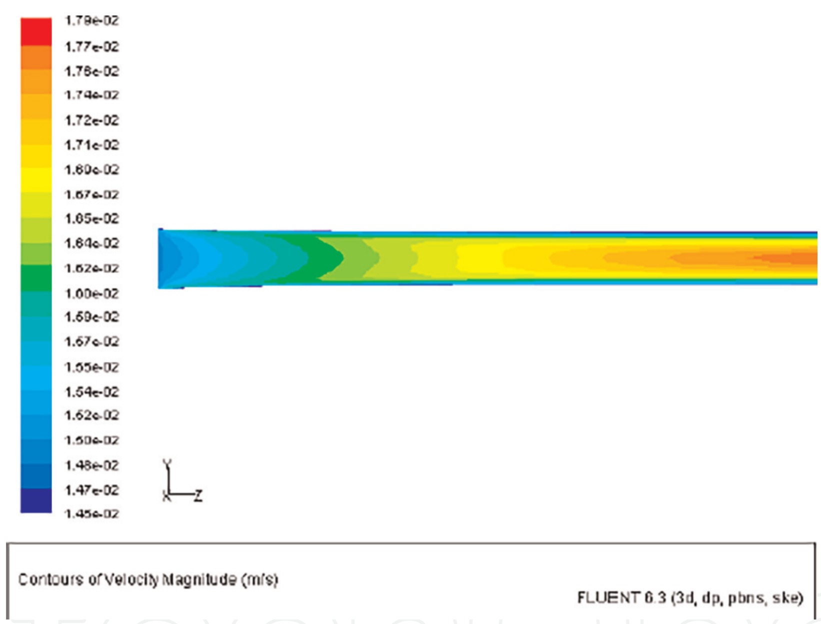

Figure 9.
Contours of velocity magnitude on $x = 0$.

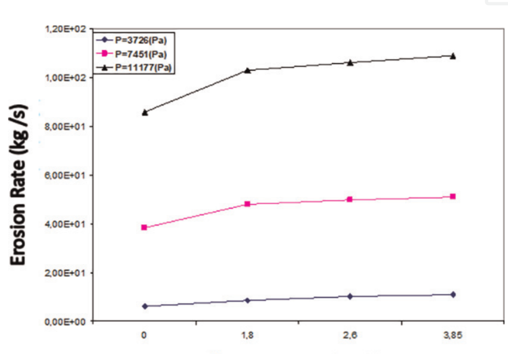

Figure 10.
Erosion rate as a function of clay concentration for the three pressure gradients $(10^{-6} kg/s)$.

6. Artificial intelligence (AI) in civil engineering

The application of artificial intelligence (AI) to civil engineering refers to the use of computer systems to simplify and automate the design and construction processes of civil engineering hydraulic structures.

In its broadest sense, artificial intelligence (AI) represents the scientific discipline concerned with the study, design, and implementation of technologies capable of imitating the cognitive abilities of a human being.

Voice assistants, home automation systems, search engines, satellite navigators, etc. are common examples of intelligent systems, capable of understanding the interests and demands of users and providing responses tailored to their needs.

AI has long been used successfully in many fields: from manufacturing to medical diagnostics, from e-commerce to video games, and more. Today, more than ever, we are witnessing the development and deployment of intelligent systems in the field of civil engineering.

Thanks to these systems, which are able to learn from their mistakes and carry out activities similar to those of humans, it is now possible to solve many of the problems associated with the construction of buildings and infrastructures.

Before analyzing the various applications of AI in civil engineering, let us find out what learning techniques this technology is based on.

Unlike conventional simulation software, machines equipped with artificial intelligence have the ability to:

- perceive the world around them and collect useful data and information.
- understand perceived reality, by logically linking collected information.
- perform autonomous operations (computerized or mechanical), deciding to act without any command from a human being.
- learn from the results of its actions, continuously improving, and learning from its mistakes.

Machine learning is one of the fundamental characteristics of intelligent systems used in civil engineering. This capability can be developed using the following techniques:

- Evolutionary computation: This is a learning technique based on the concepts of evolutionary biology. This technique is implemented on computer systems to solve complex problems characterized by too many variables to be handled by traditional algorithms. Evolutionary computation is widely used in civil engineering to solve optimization problems and automate the production of civil engineering projects.
- Artificial neural networks: Mathematical models composed of artificial neurons that reproduce the behavior of the human brain. Neural networks enable computer programs to recognize patterns and solve common problems. In engineering, they are used to improve decision-making processes, make predictions, perform data analysis, monitor structures, control the movement of robots, etc.

- Fuzzy systems: The term "fuzzy" refers to the ability of these systems to process imprecise or vague data, using a mode of reasoning close to that of humans (who do not always adopt rigorous and well-defined logic). Fuzzy logic helps computer systems used in civil engineering to deal with incorrect inputs and outputs and to model construction deadlines, costs, and risks. Fuzzy systems are also used to assess the quality of infrastructure projects.

- Expert systems: These are technological applications capable of solving problems in a very specific field, and which can reach, or even exceed, the human performance of an expert operating in that specific sector. Expert systems are mainly used in the construction and geotechnical sectors to analyze the energy consumption of buildings or to carry out geological surveys.

7. Conclusion

In this work, a two-dimensional modeling of the tube erosion test was carried out to predict the erosion phenomenon within hydraulic structures. Unlike, the first models produced by several authors, which are essentially one-dimensional and the two-dimensional modeling of this phenomenon showed that the tangential shear stress along the interface wall between the water and the body of the structure is not uniform. By applying a linear erosion law, we were able to predict nonuniform erosion along the entire length of the interface.

The study of the effect of clay concentration showed that it has a very significant effect on the evolution of wall shear stress, and therefore, in turn, affects the surface erosion that develops at the soil sample fluid interface, particularly at the end of the hole outlet where it is at its maximum. The results obtained have enabled us to understand qualitatively why the eroded profile of the hole wall, as observed during the HET experiment, is not uniform.

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