PREDICTING EROSION RATE DURING THE HOLE EROSION TEST AS AFFECTED BY CLAY CONCENTRATION AND WALL ROUGHNESS

(GT-016)

Kissi Benaissa[1], Khamlichi Abdellatif[1*], Bezzaxi Mohammed[1],
Parron Vera Miguel angel[2], Rubio Cintas Maria Dolores[2]

[1] Modelling and Analysis of systems Laboratory, Department of Physics, Faculty of Sciences at Tetouan, Tetouan, Morocco
[2] Industrial and Civil Engineering Department, High Polytechnic School of Algeciras, Algeciras, Spain
**e-mail of corresponding author: khamlichi7@yahoo.es*

ABSTRACT

Internal soil erosion constitutes a major safety problem for dams and levees. This phenomenon yields at its final stage dangerous fluid leakage under the hydraulic infrastructures known as piping which could provoke their rupture. Such catastrophic accidents can generate material losses and result in human casualties with dramatic consequences at the social and economic levels. Many dam ruptures events have occurred throughout the world.

To characterize erodability of foundation soils under hydraulic infrastructures a lot of tests have been introduced. Among them, the hole erosion test was known to be well appropriated to get quantitative information about the erosion phenomenon that could happen. The objective of this work is to model the hole erosion test. For that purpose, we give description of the homogenized biphasic turbulent flow provoking erosion at the hole wall as it could be affected by the applied gradient pressure and the fine particle as well as the actual wall roughness. Fluent software was used to construct a two-dimensional model of the problem.

This had enabled to estimate the wall shear stress which was found to be non uniform along the hole length. Erosion rate was then estimated by using a classical law of erosion. Its variations as affected by the applied gradient pressure, fluid density as well as the actual fluid/soil interface roughness were analyzed. Predicting erosion rate at the start of piping formation can be done by the proposed model. In particular, wall roughness and clay fine particles concentration were found to increase noticeably the erosion rate.

Keywords: Piping, erosion, turbulence, $k-\varepsilon$ model, concentration of clay, wall roughness.

1. INTRODUCTION

Soil erosion is a complex phenomenon that yields at its final stage to insidious fluid leakages under hydraulic infrastructures, known as piping, and which can provoke their failure. Many dam ruptures have occurred throughout the world due to piping, some of these events are reported in reference [1]. Such catastrophic accidents can generate human casualties and material losses with dramatic consequences at the social and economic levels.

Internal erosion is a progressive degradation of soils which is induced by the flowing of water through the porous medium. Many research activities related to the experimental and theoretical characterization of this phenomenon are reported in the literature such as [2], [3] and [4].

Several experiments were designed to reproduce this mechanism in laboratory conditions. Recently, the Hole Erosion Test (HET) has been introduced, figure 1. This test has been the subject of multiple investigations both experimentally and theoretically. Many HET experiments were carried out on several kind of soils, [2] and [3]. Modeling of this test has also been presented [4]. In all cases this test proved to be simple, fast, and well adapted to perform surface erosion characterization during piping development.

A simplified one dimension modeling of the HET was introduced in [5]. This modeling proved to be sufficient in explaining the erosion phenomenology related to piping problem. It yields a comprehensive description of the erosion initiation and kinetics for a given soil constitution. This rudimentary model enables also to evaluate the influence of the hydraulic conditions on piping kinetics.

Aspects associated to the two-dimensional nature of the HET are also present in the problem as it could be seen in figure 2. The objective of this research is to use the commercial CFD code Fluent to model the turbulent flow that develops in the tube during the HET by using the RNG $k-\varepsilon$ based turbulence model. The aim is to determine the shear stress and erosion rate taking place at the wall interface by considering the effect of clay concentration variations and wall roughness.

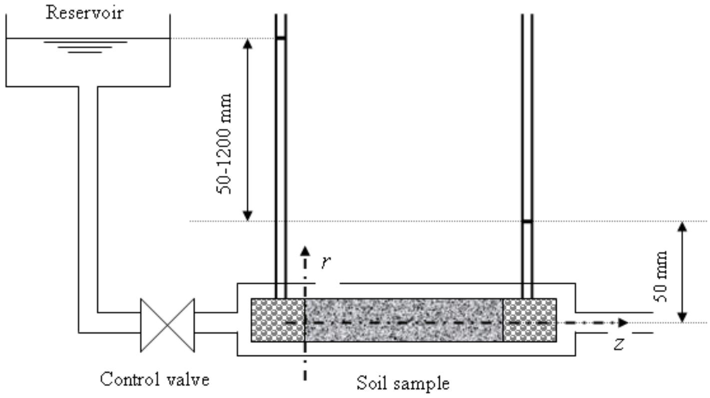

Figure 1. Schematic representation of the HET

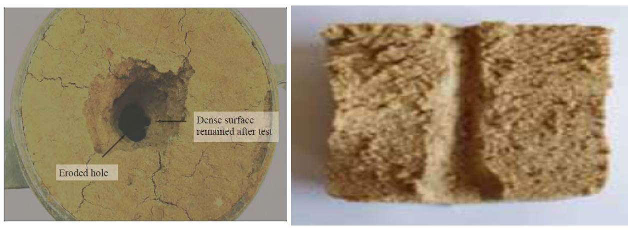

Figure 2. Sample tested with the HET [3]

2. TWO-DIMENSIONAL MODELING APPROACH OF THE HET

The turbulence modelling is achieved by means of Fluent software package. Fluent is a general purpose Computational Fluid Dynamics (CFD) code that has been applied to various problems in the fields of fluid mechanics and heat transfer. Fluent is especially appropriate for the complex physics involved in mass transfer and considers mixtures by modeling each fluid species independently or as a homogenized medium, [6-7].

Flow taking place inside the tube during HET 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 to determine them in terms of known quantities. Various turbulence models have been proposed in the literature and there is no single turbulence model which could be universally 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 accepted computational cost. Reference [8] 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 [9] has become the most popular one when dealing with practical engineering flow calculations. This model relies on phenomenological considerations to perform closure of equations.

Improvements of the standard $k-\varepsilon$ model such as the RNG $k-\varepsilon$ model have been made, [10]. This model was derived by using a rigorous statistical technique (called renormalization group theory). In comparison with the standard $k-\varepsilon$ model, RNG model includes refinements which significantly improve the accuracy for rapidly strained flows. In contrast with the standard $k-\varepsilon$ model which is rather designed for high-Reynolds-numbers and for which the effective viscosity is constant, the RNG theory provides an analytically derived differential formula for the effective viscosity that accounts also for low-Reynolds-number effects. Use of this feature requires however an appropriate treatment of the near-wall region. These advantages make the RNG $k-\varepsilon$ model more accurate and reliable for a wider class of flows than the standard $k-\varepsilon$ model.

Because of its relevance which was stated through various investigations, use is made subsequently of the RNG $k-\varepsilon$ model. The governing equations of this model are recalled in the following.

The RNG $k-\varepsilon$ has a special form of the transport equations which contain the additional term R_ε . In a two-dimensional axisymmetric configuration, these equations write

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

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

where r is the radial coordinate, z the axial coordinate, t the time, u the radial velocity, v the axial velocity, k the kinetic energy of turbulence, ε the dissipation, ρ the density, μ_t the viscosity, $\alpha$the inverse effective Prandtl number for both k and ε, $C_{1\varepsilon}$ and $C_{2\varepsilon}$ are constants having values that are derived analytically by the RNG theory: $C_{1\varepsilon}$ = 1.42, $C_{2\varepsilon}$ = 1.68.

For further details about the RNG $k-\varepsilon$ theory, a complete description can be found in [11] and [12]. These references give hints regarding how to deal with the boundary conditions in order to enhance accuracy of modelling.

The classical linear erosion law states that erosion rate, which corresponds to the amount of mass departure due to erosion per unit time and by unit surface area writes

$$\dot{\varepsilon}_{er}=c_{er}(\tau-\tau_s) \qquad (3)$$

where c_{er} and τ_s are constants depending on the considering soil material.

The erosion rate $\dot{\varepsilon}_{er}$ is related to time variation of local radius by

$$\dot{\varepsilon}_{er}=\rho_d dR/dt \qquad (4)$$

where ρ_d is the dry density of soil.

The erosion law predicts that $\dot{\varepsilon}_{er}$ is proportional to the amount of shear exceeding the shear threshold limit τ_s .

3. RESULTS AND DICUSSION

In the standard HET, the fluid domain is axisymmetric and extends over 117 mm in the axial z-direction and 3 mm in the radial r-direction. The domain is oriented such that the inlet section is at left and the outlet section is at right. Modeling under fluent has been performed by using water density and dynamic viscosity at the temperature 20°C for which $\rho=1000\ \mathrm{kg/m^3}$ and $\eta=\rho\mu=0.001\ \mathrm{Pa.s}$. The erosion constants used are: $c_{er}=5.5\times10^{-4}\ \mathrm{s/m}$ and $\tau_s=7\ \mathrm{Pa}$. These correspond to a specific soil sample containing 50% kaolinit clay and 50% of sand that was tested in [13].

Viscosity and density of the eroding flow vary as function of clay concentration. Considering various water-clay mixtures the experimental values of density and dynamic viscosity at 20°C are given in table 1 as function of the clay mass concentration.

Table 1. Homogenized density and viscosity for water-clay mixtures as function of clay concentration

Clay concentration %	Density of the mixture ($\mathrm{kg/m^3}$)	Viscosity of the mixture ($\mathrm{Pa.s}$)
0 (C0)	1000	0.001
1.8	1005	0.00177
2.6	1011	0.00189
3.85 (C1)	1020	0.00194

In a previous work [14], the computation of the flow taking place inside the tube of the HET has been performed and has shown that the shear stress is not uniform along the tube length. The shear stress depends also on clay concentration as shown in figure 3.

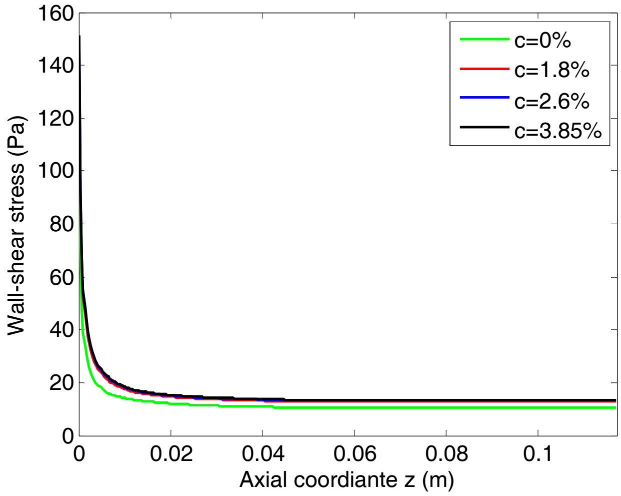

Figure 3. Wall-shear stress as function of the axial coordinate and clay concentration

As shown in figure 3, the shear is maximal at the inlet of the tube and decreases towards the outlet extremity where it is minimal. Equations (3) and (4) predict then a non uniform erosion rate. $\dot{\varepsilon}_{er}$ is maximal at the inlet side and minimal at the outlet side. To model the effect of wall roughness resulting from this non uniform erosion pattern along the tube, we consider the wall state where the erosion has consumed up to 0.9 mm of the tube radius at the inlet extremity of the tube. This gives the wall profile depicted in figure 4. Figure 5 gives the mesh that has been used during CFD simulations under Fluent.

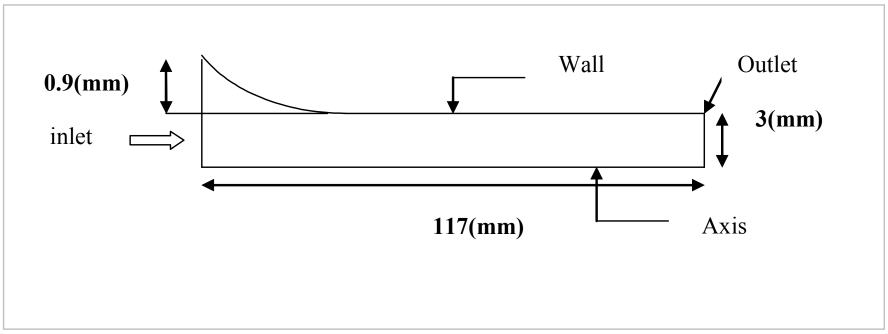

Figure 4. Geometry of the eroded tube

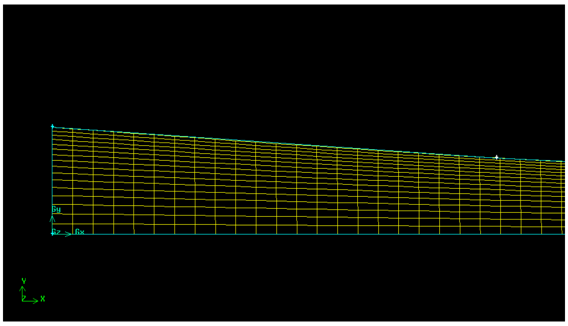

Figure 5. Mesh of the eroded tube

Figure 6 shows shear wall contours for the inlet pressure 3726 Pa and for the two cases of clay concentration (C0: 0%) and (C1: 3.85%).

Figure 7 gives the erosion rate (in 10^{-6} kg/s) for various stages of the eroded tube. This amount is obtained by integrating the erosion law over the whole length of the hole and by multiplying the result by the initial circumference of the hole. It is shown that the actual tube radius has a significant effect on the amount of erosion rate. Erosion is then accelerated near the inlet extremity.

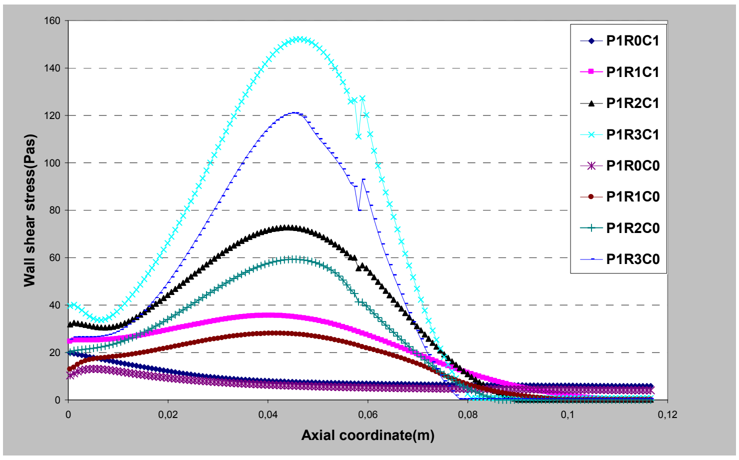

Figure 6. Wall-shear stress obtained for $p_{inlet} = 3726 \text{ Pa}$ as function of clay concentration

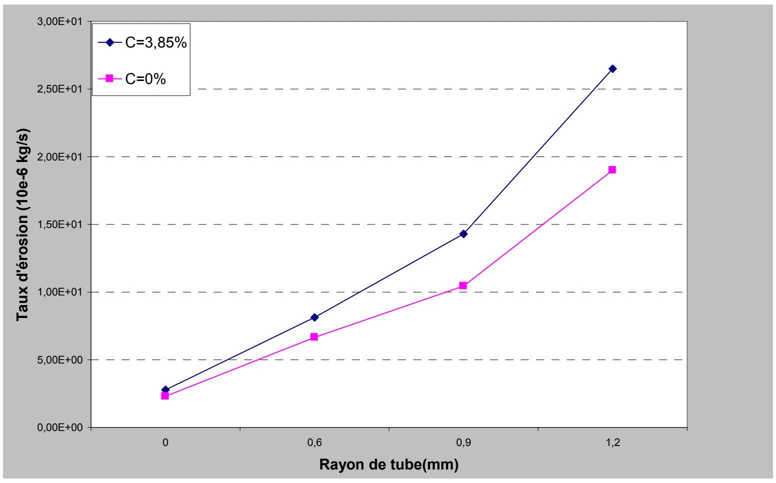

Figure 7. Erosion rate as function of the inlet pressure and clay concentration

4. CONCLUSION

A two-dimensional modeling of the Hole Erosion Test was carried out in this work. Unlike the early models which are essentially one-dimensional, the two-dimensional modeling had shown that the wall-shear stress is not uniform along the hole wall. It was possible then through using a linear erosion law to predict non uniform erosion along the hole length.

Studying the effect of clay concentration has shown that it has not a negligible effect on the wall-shear stress and thus would affect in its turn surface erosion that develops at the fluid soil sample interface. This enabled qualitatively understanding why the eroded profile of the hole wall as observed during experiment is not uniform.

5. ACKNOWLEDGEMENT

The authors would like to thank the Spanish Agency of International Cooperation (AECID) for having supported part of this work.

6. REFERENCES

[1] Foster MA, Fell R., Spannangle M. (2000) The statistics of embankment dam failures and accidents. *Canadian geotechnical Journal* 37(5), 100-1024.

[2] Wan C.F., Fell R. (2004). Investigation of rate of erosion of soils in embankment dams, *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 30, N°4, pp. 373-380.

[3] Wan C.F., Fell R. (2004). Laboratory Tests on the Rate of Piping Erosion of Soils in Embankment Dams, *Journal of Geotechnical Testing Journal*, Vol. 27, No. 3.

[4] Bonelli S., Brivois O., Borghi R., Benahmed N. (2006). On the modelling of piping erosion. *C.R. Mécanique*, 22: 225-244.

[5] Bonelli S., Benahmed N., Brivois O. (2006). *On modelling of the hole erosion test*. ICSE, 3rd International Conference on Scour and Erosion, 1-3 November 2006, Amsterdam.

[6] Escue A., Cui J. (2010). Comparison of turbulence models in simulating swirling pipe flows. *Applied Mathematical Modelling*. doi:10.1016/j.apm.2009.12.018.

[7] Vijiapurapu S., Cui J. (2010). Perforamnce of turbulence models for flows through rough pipes. *Applied Mathematical Modelling*. 34:1458-1466.

[8] *Fieldview Reference Manual, Software Release Version 10*. Intelligent Light, 2004.

[9] Launder B.E., Spalding D.B. *Lectures in Mathematical Models of Turbulence*. Academic Press, London, England, 1972.

[10] Yakhot V., Orszag S.A. (1986) Renormalization Group Analysis of Turbulence: I-Basic Theory. *Journal of Scientific Computing*, 1(1):1-51.

[11] *Fluent 6.2 Users Guide*. Fluent Inc., 2005.

[12] Choudhury D. *Introduction to the Renormalization Group Method and Turbulence Modeling*. Fluent Inc. Technical Memorandum TM-107, 1993.

[13] Pope S.B. *Turbulent flows*. Cambridge University Press, 2000.

[14] Khamlichi A., Dubujet P., Parron Vera M.A., Rubio Cintas M.D., Bezzazi M. (2011). Predicting initial erosion during the Hole Erosion Test by using turbulent flow CFD Simulation. *Applied Mathematical Modelling*.