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On the numerical modelling of the Jet Erosion Test

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Evaluating the erodibility of a soil, both in terms of erosion threshold (initiation) and erosion rate (progression), is critical for the evaluation of the safety of water retaining structures. Indeed different soils can erode at different rates. However, the relationship between the erosion parameters and the geotechnical and chemical properties of soils remains largely unknown.
The jet erosion test appears to be an efficient and simple means for quantifying the two erosion parameters involved. The first parameter is the critical stress while the second parameter is the erosion coefficient. A simplified model of this test has been drawn up by G. Hanson et al to interprete the experimental curves. Few attempts have been made so far to modelthe whole process, however.
The aim of this study is to simulate the impinging jet and to take into account the erosion of the soil by means of computational fluid dynamics (CFD) numerical modelling. The key point was the time dependence of the problem, due to erosion processes, however the turbulent flow could be considered as steady because of the assumption of low kinetics erosion assumption.
The results of the present modelling study are compared to the simplified model and to experimental data. This comparison is a first confirmation of the validity of the simplified model as a means of assessing the critical stress and the erosion coefficient with jet erosion tests.

Key words
Erosion, turbulence, critical stress, erosion coefficient, impinging jet.

I INTRODUCTION

A large number of experimental studies on jets with stagnation points has been carried out since the beginning of the 20th century. In the field of fluid mechanics applied to erosion, the case of immerged circular jets with stagnation points has been dealt experimentally in particular by [Beltaos et al. 1974, Hanson et al. 1990, Looney et al. 1984, Poreh et al. 1967, Viegas et al. 1986]. A large number of empirical and semi-empirical formulas has been derived to characterise the evolution of different flow variables. In the framework of the jet erosion tests,[Hanson 1990] has proposed a semi-empirical model of the evolution of the tangential stress as a function of the erosion time.

The problem of a jet with a cut-off point on a plane surface attracted many numerical mathematicians, as it presents a simple geometry with complex physics, especially regarding turbulence [Craft et al. 1993, Jaramillo et al. 2008, Narumanchi et al. 2005]. However, there are practically no numerical modelling studies of erosion due to a turbulent flow of a jet with stagnation point. In the case of the erosion of a sediment bed, [Kostic et al. 2009] performed a study on scouring around bridge piers. In the framework of a thesis [Zaki et al. 2008] studied non traversing penetration by a water jet.

The present study focuses on the innovative numerical modelling of the erosion of a cohesive soil by a turbulent jet flow that presents a stagnation point. The numerical results obtained are compared to the experimental results obtained with the Jet Erosion Test (JET), and more specifically the erodimeter developed by [Hanson et al. 2004], which was used to study the resistance of soils to erosion both in the laboratory and *in-situ*.

II FLOW NUMERICAL MODELLING

The method developed is a mixed Euler – Lagrange model, of turbulent Navier-Stokes type with displacement of the interface and remeshing. The originality of this method is the fact that only two domains are considered, fluid and solid, separated by a singular interface, and not by a 3rd fluidised solid domain. Each phase is diphasic: the soil is a compact assembly of grains containing water, and the flow containing grains is in dispersed phase, as the concentrations of minority phases are inversely proportional to the distance to the interface. The hypothesis of diluted flow, which experiment tests showed is relevant, enables to neglect the presence of particles in the flow. The hypothesis of a saturated soil makes it possible to neglect the influence of water particles in the solid phase. The solid is modelled using parameters that characterise the displacement at the interface, where the given erosion law is introduced and thus tested.

The flow is described by incompressible Navier-Stokes equations integrated by the finite volume method. The modelling is performed with Fluent software. The nonstationary turbulent flow is converted into a stationary flow with the main fluctuations averaged statistically, in conformity with the RANS method (Reynolds Average Navier Stokes):

$$\begin{cases} \nabla\cdot\mathbf{u}=0 \\ \rho_w\left[\dfrac{\partial\mathbf{u}}{\partial t}+(\nabla\mathbf{u})\cdot\mathbf{u}\right]=\nabla\cdot\mathbf{T} \end{cases}, \qquad (1)$$

$$\mathbf{T}=\underbrace{-p\mathbf{I}}_{\text{static pressure}}+\underbrace{2\mu_w\mathbf{D}(\mathbf{u})}_{\text{viscous stresses}}\underbrace{-\rho_w\overline{\mathbf{u}'\otimes\mathbf{u}'}}_{\text{turbulent stresses}}, \qquad (2)$$

$$\mathbf{D}(\mathbf{u})=\frac{1}{2}\left[\nabla\mathbf{u}+(\nabla\mathbf{u})^T\right], \qquad (3)$$

where ρ_w is the water density, p the static pressure, $\mu_w=10^{-3}$Pa.s is the water molecular viscosity, $\rho_w=10^3$kg/m^3 is the water density, $\mathbf{T}$ is the stress tensor, $\mathbf{u'}$ is the velocity fluctuations in comparison to the average velocity $\mathbf{u}$ and $\mathbf{D}(\mathbf{u})$ is the symmetrical part of the average velocity gradient.

The closure problem caused by statistical averaging is solved with a Reynolds Stress Model (RSM) [Launder et al. 1975], k-ε [Shih et al. 1995] or k-ω [Menter et al. 2003] turbulence model.

III EROSION MODELLING

The erosion law most commonly used in the literature [Bonelli et al. 2006, Chanson 1999, Frenette et al. 1997, Graf 1971, Lachouette et al. 2008, Lagrée 2000] is:

$$\dot{m}=\begin{cases} k_{er}\left(\tau-\tau_c\right) & if\ \tau>\tau_c \\ 0 & otherwise \end{cases}, \qquad (4)$$

where m is the eroded mass flow rate, $k_{er}=k_d/\rho_s$ is the kinetic erosion coefficient, ρ_s is the soil density, τ is the shear stress and τ_c is the critical shear stress exerted by the flow on the soil.

According to the erosion law, the displacement of the interface at a given point only depends on the shear stress exerted by the fluid on the material at the given point. In the case of a flow normal to the interface, the shear stress is nil at the stagnation point, it then increases until its maximum, before it decreases again as it draws away from the stagnation area. It is expected to have the the form of a geometric singularity in the stagnation area, as it is shown in the schematic representation of the resulting stress profile and the figure that illustrates erosion. When carrying out the Jet Erosion Tests, experimental observations showed that the curve of the erosion chart does not correspond to the theoretical curve induced by the erosion law. Depending on the tested soil, the erosion depth varies, the diameter of the erosion figure varies, and no central peak or a singular point is observed at the centre of the eroded figure.

Let us consider the case of erosion induced by a turbulent jet flow, the turbulent fluctuations of the instantaneous values at the stagnation zone of the jet, as well as the flutter of the jet in 3D geometry, make it possible to smooth the peak of the non eroded soil of (4). Therefore at a point of interface M_Γ, Ω_{stag} the stagnation zone of the flow of the jet defined between the cut-off point and the maximum of the tangential stress on the water/soil interface denoted τ_{max}, the erosion law (4) could be modified as described in equation (5). This form of the erosion law remains valid whatever the configuration of the flow; in the case of a non normal flow at the water/soil interface, Ω_{stag}=Ø and equation (5) is the same as (4).

$$\dot{m} = \begin{cases} k_{er}\left(\tau_{max} - \tau_c\right) \text{ if } \tau < \tau_{max} \text{ and if } M_\Gamma \in \Omega_{stag} \\ k_{er}\left(\tau - \tau_c\right) \quad \text{if } \tau > \tau_c \text{ and if } M_\Gamma \notin \Omega_{stag} \\ 0 \quad \text{otherwise} \end{cases}, \tag{5}$$

The numerical scheme of the erosion law (5) in the Euler equation of the first order leads to:

$$\mathbf{x}(t+\Delta t, \mathbf{X}) = \mathbf{x}(t, \mathbf{X}) + \begin{cases} k_d \Delta t(\tau_{\max} - \tau_c)\mathbf{n} \text{ if } \tau < \tau_{\max} \text{ and if } M_\Gamma \in \Omega_{stag} \\ k_d \Delta t(\tau - \tau_c)\mathbf{n} \text{ if } \tau > \tau_c \text{ and if } M_\Gamma \notin \Omega_{stag} \\ 0 \text{ otherwise} \end{cases}, \tag{6}$$

$$\tau = \left\|\boldsymbol{\tau}\right\| = \sqrt{(\mathbf{T}\cdot\mathbf{n})^2 - (\mathbf{n}\cdot\mathbf{T}\cdot\mathbf{n})^2}\,, \tag{7}$$

where $\mathbf{n}$ is the normal and τ the norm of the tangential stress at the face of the interface.

IV RESULTS

The geometry of the calculation domain is fully representative of the configuration of the Jet Erosion Test performed experimentally. The principle underlying the Jet Erosion Test is explained in [Hanson et al. 2004]. The main characteristics of the modelled empirical test, called SC12, are, for the flow: a differential pressure of 3.10^4Pa and an initial nozzle/surface distance from the sample of 14.65cm; and, for the material: a critical erosion stress of 11Pa and an erosion kinetics coefficient of 1.10^{-5}m².s/kg. The SC12 test was performed at Cemagref by F. Mercier and S. Bonelli, and data inversion was performed by geophy*Consult*, using the model of [Hanson et al. 2004] enhanced by [Pinettes et al. 2011].

Once the geometry is that of the empirical test, two studies are performed at nil erosion time: first a study aimed at warranting that the results are independent of meshing refinement, secondly a study of the influence of the turbulence model considered.

The first study to ensure that the results are independent of the meshing used permitted estimating the error generated by the refinement of the meshes considered and the choice of a mesh to optimise the pertinence of the results and calculation time. As for the study of the influence of the turbulence model on the results, the RSM, the k-ε and the k-ω turbulence models, were studied in comparison to the experimental data of [Beltaos et al. 1974, Hanson et al. 1990, Looney et al. 1984, Poreh et al. 1967, Viegas et al. 1986], for different variables characteristic of the flow and at different levels of the flow. An average of the errors percentages is performed for each main flow variables.

As for the flow velocity, the results obtained for the three turbulence models are in rather good accordance with the empirical results found in literature, in particular the RSM model, which leads to an error of about 3%. The results on pressure for the three models differ significantly from the results found in the literature. The k-ω model nevertheless presents results more in line with the empirical formulas than the RSM model, with average relative errors of 20% and 37% respectively. The k-ε model led to pressure values far below the maxima found in literature, with an error ranging from 65 to 100% according to the empirical model considered. The results on the half width of the pressure profile show the same trend. On the contrary, the results on the maximum shearstress are closer to the results in the literature in the case of models k-ε and RSM, with errors of 10 and 12% respectively, while they are very different from the empirical formulas in the case of model k-ω (82%).

Globally, the RSM model turned out to be the best model with respect to the empirical results found in literature, model k-ω nonetheless lead to better results for the pressure while model k-ε lead to better results for the shearstress, which are both key flow variable for the erosion laws (4) and (5).

Figure 1 gives the evolution of the erosion profiles for turbulence models k-ω and k-ε. In conformity with the results obtained during the mesh independence study, during which it could be seen that the shearstress was clearly lower in the case of turbulence model k-ε than in the case of model k-ω, the erosion turned to be lower in case of k-ε model than in case of k-ω model. At the end of the erosion process, when the shear stress became lower than the stress threshold at every point of the interface and the erosion of the soil stopped, the maximum scouring in the case of the k-ε model was about 1.74cm, while it was about 5.03cm in the case of the k- ω model.

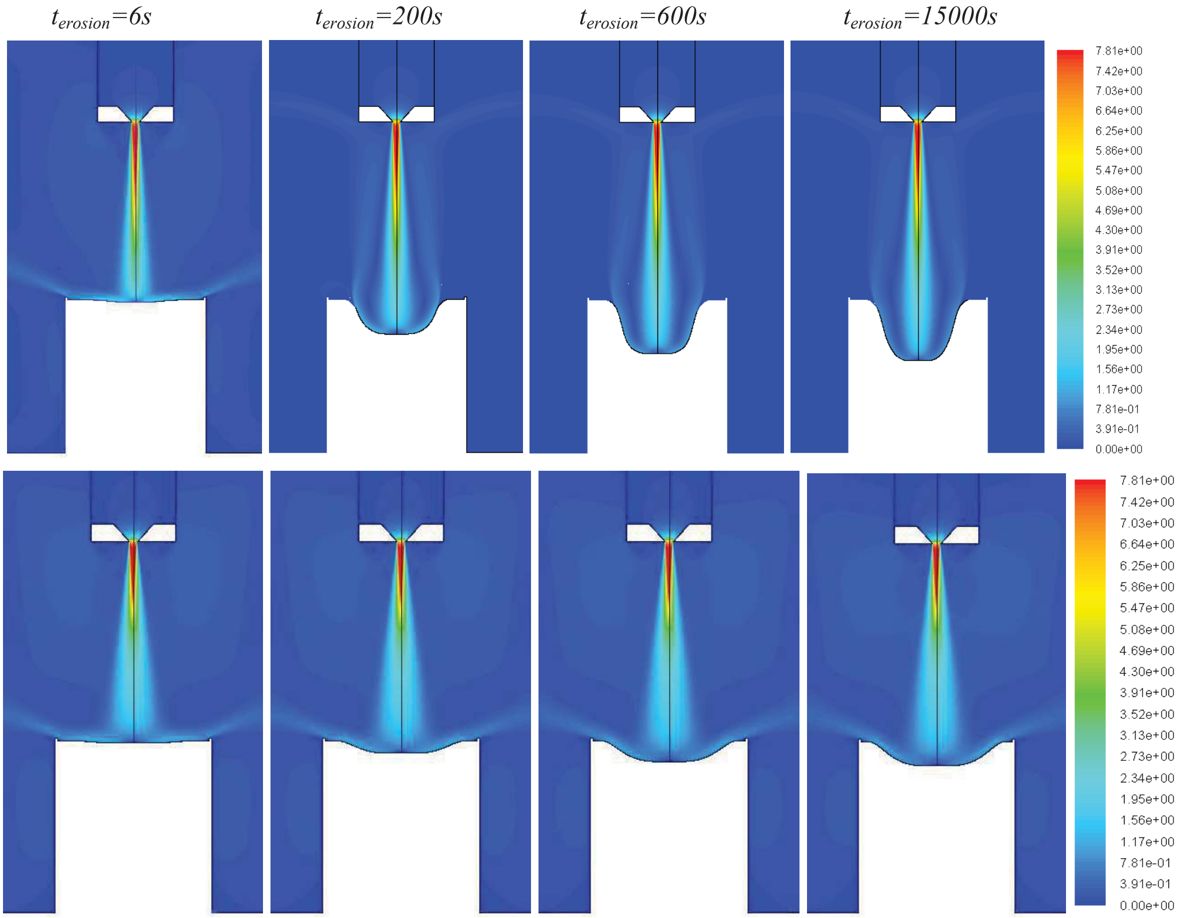

Figure 1: Evolution of soil profiles as a function of erosion time.

Velocity vectors at different erosion times for the numerical simulations of Jet Erosion Test SC12 performed with turbulence models of type k-ω (above) and k-ε (below)

For the study of the hydraulic model without erosion, model k-ε presented a profile and maximum shearstress close to the results found in literature. However, in the framework of models with erosion, the comparison of the maximum scouring depth as a function of the erosion time showed a very good agreement between the numerical results and the experimental results in the case of the model k-ω, see figure 2. The relative error between the numerical and experimental results was equal to 17.7% for the k-ω model and 71.6% for the k-ε model.

Figure 3 shows the evolution of the maximum shearstress as a function of the scouring depth at different erosion times, for models k-ε and k-ω with respect to the results found with the semi-empirical model of [Hanson 1990]:

$$\tau_0 = C_f \rho U_0^2 \text{ and } \tau_i = C_f \rho U_0^2 \left(\frac{l}{J_i}\right)^2 = \tau_0 \left(\frac{l}{J_i}\right)^2, \tag{8}$$

where τ_0 and τ_i are the shearstress at times t_0 and t_i respectively, C_f=0.00416 is the friction coefficient determined empirically, J_i is the maximum depth at erosion time t_i and l is the length of the potential core.

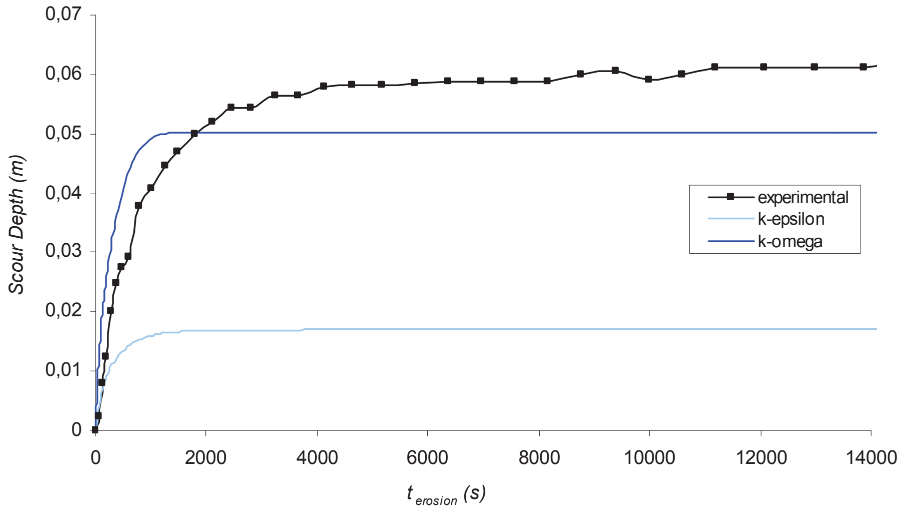

Figure 2: Evolution of the scouring depth as a function of the erosion time.
Results obtained with models k-ε (light) and k-ω (dark) with respect to the experimental results (squares).

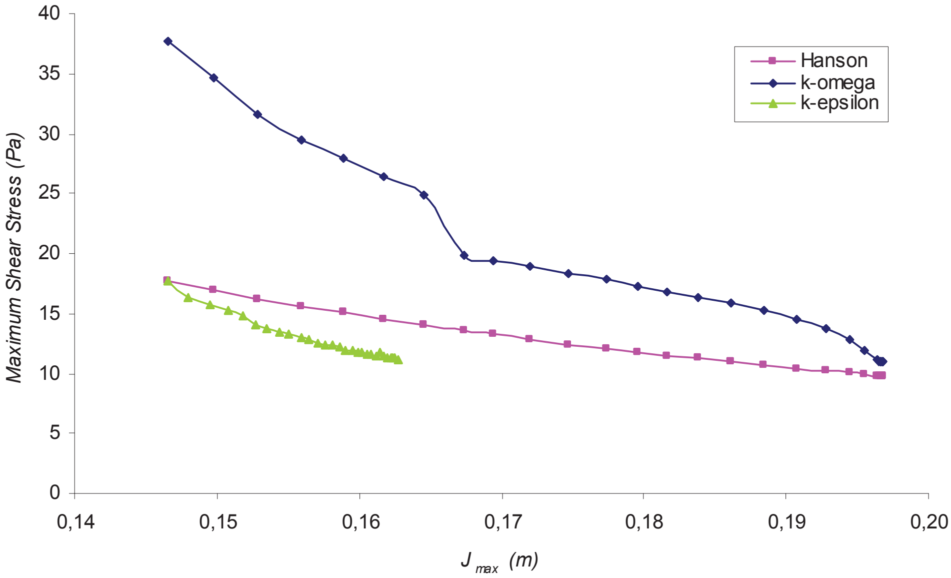

Figure 3: Evolution of the maximum tangential stress as a function of the scouring depth.
Results obtained by models k-ε (green triangles) and k-ω (blue lozenges) with respect to the results obtained with the semi-empirical model of Hanson (pink squares)

The evolution curve of the maximum shear stress as a function of the scouring depth at different erosion times (see figure 3) shows that the results obtained with the k-ε model are excellent at initial time, while they are not satisfactory in the case of the k-ω model. The end of the curve leads to an inversion of this tendency. The slope of the curve of the maximum shear stress as a function of the maximum scouring depth is much higher in the case of the k-ε model than in the case of Hanson's model, which leads to a rapid end of the erosion process. The slope of the curve $\tau_{max} = f(J_{max})$ is also very high, which leads to a reduction of the error with respect to Hanson's results. A clear break of the curve in the case of the k-ω model can be observed for a scouring depth close to 2 cm. Detailed observations of the flow parameters was carried out at different erosion times in order to understand this phenomenon..

A sudden reduction of all the flow variables at the water/soil interface can clearly be seen between the curves at 106.4 and 130.4 s. A change of the flow regime is initiated at a scouring depth of the order of 2 cm, as shown in figure 4.

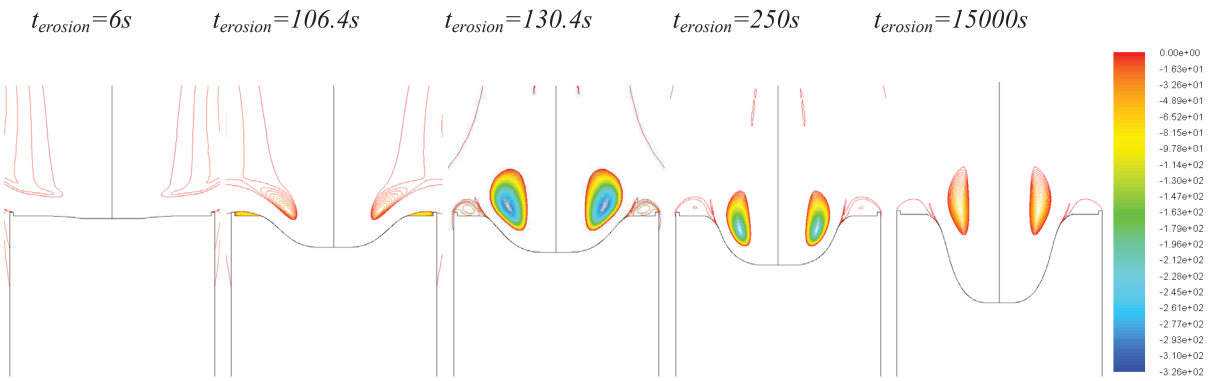

Figure 4: Evolution of the pressure field near the water/soil interface at different erosion time steps.

Pressure field given by the k-ω model. The positive relative pressures are not depicted.

A parametric study of the influence of the critic erosion stress and of the erosion kinetics coefficient was performed. It showed, see figure 5, that a critical shearstress threshold difference of only 2 Pa can generate a difference of the maximum scouring depth of more than 8 mm, while doubling the kinetic erosion coefficient generated a factor two on the width of the curve of the scouring evolution to 95% of the maximum scouring.

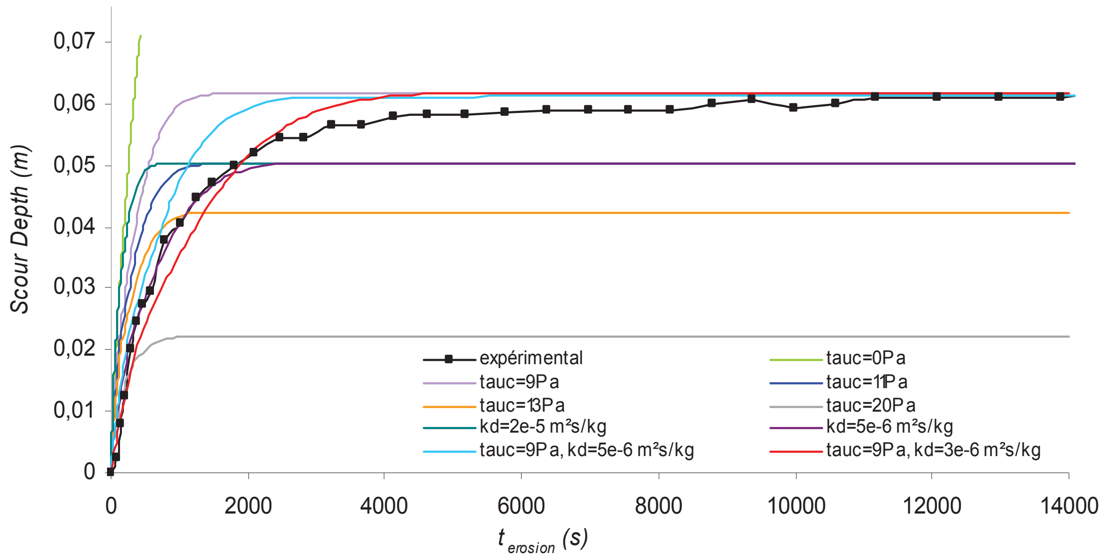

Figure 5: Parametric study of the influence of the critical shearstress and of the kinetic erosion coefficient.

Scouring depth in function of erosion times, results obtained for several critical shear stresses and $k_d=1e^{-5}$m².s/kg, for several kinetic erosion coefficient and τ_c=11Pa, and for τ_c=11Pa with $k_d=5e^{-6}$m².s/kg and $k_d=3e^{-6}$m².s/kg.

V CONCLUSION

In the context of the study of the safety of embankment hydraulic structures, the present work dealt with the numerical modelling of erosion phenomena. The objective was to formulate a relevant model of the Jet Erosion Test and validate its model of interpretation.

The modelling method developed was of mixed Euler-Lagrange type: for the flow, a Navier-Stokes turbulent type model with adapted remeshing was run using the ANSYS Fluent software with a Lagrangian type interface displacement code developed by us. The hypotheses of slow erosion and diluted flow led to the formulation of a sequential uncoupled model of erosion.

Given the limits of the so-called classical erosion law brought to light, the latter was improved significantly, and the instability of turbulence phenomena undoubtedly made it possible to smooth the peaks of the non eroded soil at the jet stagnation point.

The results obtained by the modelling method developed on the jet flows were first validated at nil erosion time with respect to the results found in literature. The study of the turbulence model's influence on the results of modelling without erosion showed that the RSM model globally presented the best agreement with the experimental results. However, the difficulty of implementing it and the long calculation times required did not permit its use for erosion modelling. The turbulence models of type k-ε and k-ω were used instead and turned out to deliver highly complementary results, the first being better for the modelling of the shear stress, while the latter was better for the modelling of the pressure. Both 2-equation models were thus used in parallel for the modelling of the same JET test.

However, the implementation of a k-ω type turbulence model turned out to be more relevant in the framework of numerically modelling the erosion of a soil by a turbulent jet. For the case of model k-ω the JET test modelled provided results that agreed with experimental results to within 18%.

The present work hence provided a means for validating the model used to interpret the Jet Erosion Test. The parametric study of the influence of the critical shear stress and the kinetic erosion coefficient enabled to simulate the amplitude of the consequences of the errors on these two parameters. This study also enabled to show that recirculation zones appear when the convexity of the water/soil interface becomes large.

Since the JET test interpretation model was partially validated by the numerical models presented above, the differences of order of magnitude found between the kinetic erosion coefficient and/or the critical shear stress found with Hole and Jet Erosion Tests show that at least one of these parameters cannot simulate both the normal and tangential flows. As the anisotropy of the material is not expected to be responsible for these differences, it seems that the kinetic erosion coefficient is not only an intrinsic function of the material but also depends on the configuration of the flow.

VI REFERENCES AND CITATIONS

Beltaos S. and Rajaratnam N. (1974) - Impinging circular turbulent jets, *J. Hydraulic Div., ASCE,* 100(HY10): 1313–1328.

Bonelli S., Brivois O., Borghi R. and Benahmed N. (2006) - On the modelling of piping erosion, *Comptes Rendus de Mécanique,* Vol. 8-9 n° 334**,** pp. 555-559.

Chanson H. (1999) - The hydraulics of open channel flows : an introduction. Butterworth-Heinemann, Oxford U.K.

Craft T., Graham L. and Launder B. (1993) - Impinging jet studies for turbulence model assessment – II. An examination of the performance of four turbulence models, *Int. J. Heat Mass Transfer,* 36 10**,** 12.

Frenette R., Robert J.-L. and Dhatt G. (1997) - Three-dimensional hydro-sediment modelling of free-surface flows over mobile bed, *Proc. Saint-Venant Symposium,* Paris, 29-36.

Graf W. (1971) - Hydraulics of Sediment Transport. McGraw-Hill.

Hanson G. J., Robinson K. M., and Temple D. M. (1990) - Pressure and stress distributions due to a submerged jet. Hydraulic Engineering, Vol. 1. Proceedings of the 1990 National Conference ASCE, San Diego, CA, Jul 30-Aug 3, 1990.

Hanson G. J. and Cook K. R. (2004) - Apparatus, Test Procedures and Analytical Methods to Measure Soil Erodibility In Situ, *Engineering in Agriculture,* ASAE, vol. 20(4): 455-462.

Jaramillo J. E., Pérez-Segarra C. D., Rodriguez I. and Olivia A. (2008) - Numerical Study of Plane and Round Impinging Jets Using RANS Models, *Numerical Heat Transfer,* 213-237.

Kostic M., Majumdar P. and Biswas D. (2009) - Bridges and Environment: Development of an Iterative Scouring Procedure for Implementation in CFD Code for Different Bridge Flooding Conditions, *Proceedings of EPESE'09,* 1790-5095 p. 182-190.

Lachouette D., Golay F. and Bonelli S. (2008) - One-dimensionnal modeling of piping flow erosion, *Comptes Rendus de Mécanique,* Vol. 336, pp. 731-736.

Lagrée P. Y. (2000) - Erosion and sedimentation of a bump in fluvial flow, *C. R. Acad. Sci.,* 328(IIb):869-874.

Launder B. E., Reece G. J. and Rodi W. (1975) - Progress in the Development of a Reynolds-Stress Turbulence Closure, *J. Fluid Mech.,* 68(3):537–566.

Looney M. K. and Walsh J. J. (1984) - Mean-flow and Turbulent Characteristics of Free and Impinging Jet Flow, *J. Fluid Mech,* vol. 147, pp 397-429.

Menter F. R., Kuntz M. and Langtry R. (2003) - Ten Years of Experience with the SST Turbulence Model, *Turbulence, Heat and Mass Transfer 4,* pages 625–632.

Narumanchi S. V. J. (2005) - Hassani V. and Bharathan D., Modelling Single-Phase and Boiling Liquid Jet Impingement Cooling in Power Electronics, *Technical Report NREL,* TP-540-38787.

Pinettes P., Courivaud J.-R., Fry J.-J., Mercier F. and Bonelli S. (2011) - First introduction of Greg Hanson's « Jet Erosion Test » in Europe : return on experience after 2 years of testing, *USSD annual meeting*.

Poreh M., Tsuei Y. G. and Cermak J. E. (1967) - Investigation of a turbulent radial wall jet, *Trans. ASME: J. Appl. Mech.,* 34 457-463.

Shih T.-H., Liou W. W., Shabbir A., Yang Z. and Zhu J. (1995) - A New k-epsilon Eddy-Viscosity Model for High Reynolds Number Turbulent Flows - Model Development and Validation, *Computers Fluids,* 24(3):227–238.

Viegas D. X. and Borges A. R. J. (1986) - An Erosion Technique for the Measurement of the Shear Stress Field on a Flat Plat, *Journal of Physics E: Scientific Instruments,* 19(8):625-63.

Zaki M., Corre C., Kuszla P. and Chinesta F. (2008) - Numerical simulation of the abrasive waterjet (awj) machining: multi-fluid solver validation and material removal model presentation *International Journal of Material Forming,* Volume 1, Supplement 1, 1403-1406.