NUMERICAL INVESTIGATION OF THE IMPACT OF THE INLAND TRANSPORT ON BED EROSION AND TRANSPORT OF SUSPENDED SEDIMENT : PROPULSIVE SYSTEM AND CONFINEMENT EFFECT

by

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ABSTRACT

In the last few years, transport by inland waterways has experienced rapid growth thanks to the development of a new generation of larger and more powerful ships. This new generation of ships has a high ecological quality in terms of CO2 emission. However, their impact on the navigation environment has increased especially on the erosion of channel bed and banks. This phenomenon of erosion is mainly caused by the turbulent flow around the ship caused by its movement as well as its propulsive system. Hence, for a better prediction of this phenomena, it is essential to simulate accurately the flow around the ship.

The evaluation of the impact of the ship passage on the erosion phenomenon has been treated in the past by different methods: empirical, analytical and numerical. In the present work we propose to study this phenomenon of erosion applied on the channel bed numerically by the method Computational Fluid Dynamics (CFD). Several values of depth (h) to draught (T) ratio, ship advance ratio and sediment size (d_{50}) were simulated to assess the impact of each parameter on the bed shear stress. The results of this work clearly show the influence of each parameter tested.

1. INTRODUCTION

Transport by inland waterways is considered as a complement to rail and road transport. In the last year's a lot of attention. This mode of transport is known by its ecological quality in term of CO2 emission compared to road and rail transport. However, despite the reduced amount of CO2 emitted, this mode of transport still has a significant negative impact on the environment, which is the erosion of banks and the bed of inland waterways as well as the re-suspension of existing polluting particles and contaminants. This impact becomes more and more visible with the arrival of the new generation of ships with large size and their very powerful propulsive system.

The presence of suspended sediment in inland waterways leads to difficult problems for the development and maintenance of channels. To these problems are added the quality of the water. In fact, sediments trap many elements such as metals of industrial origin. There can be transport or accumulation of these pollutants which may be re-suspended under the effect of hydrodynamics of the water often disturbed by ships passage. These re-suspension can contribute to transport of pollutants from a polluted area to a unpolluted area.

The understanding and control of interactions at the water-sediment interface are extremely complex due to the presence of several processes of natures and spatiotemporal scales very different. The hydro-sedimentary processes are governed by the action of friction exerted by the water on the bed of the channel. It is generally accepted that sediment transport is carried out in two modes: bedload on the channel bed and suspension in the water.

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Numerical modeling of the sediments suspension phenomena is often carried out on a large scale by models such as Saint-Venant or Boussinesq SMAOUI ET AL. (2011). The recourse to this type of model is mainly related to the simplifying assumptions adopted. These models use empirical formulas for estimating shear stress applied on sediments using average velocities. Recently, and thanks to the rapid development of computing resources, fully models based on Navier-Stokes equations are used to model sedimentary transport, BROVCHENKO ET AL. (2007). The coupling between the fluid model and the sediments transport models can be strong (simultaneous resolution of the both equations) or weak (alternative resolution). The advantage of these models is the high precision of the shear stresses estimation on the channel bed.

Hence, in the present work a fine numerical study was conducted to assesses the impact of the inland transport on the inland waterways. The influence of the under keel clearance, the propeller advance and size of sediments coefficient have been tested for several. In this study to simulate the flow around the propelled ship the (CFD) based on Unsteady Reynolds-Averaged Navier-Stokes (URANS) was used. This model was coupled with a sedimentary transport model to simulate the re-suspension of sediments. The both models were verified and validated using an experiment data. For this investigation the flow is considered with free surface and turbulent. An inland ship with twice propellers and four rudders was selected for this investigation.

2. MATHEMATICAL MODELS

2.1 Mathematical models

2.1 Fluid flow equations

The simulation of the flow around the ship was carried out using the steady Reynolds Averaged Navier-Stokes (RANS) equations for incompressible flow with free surface. The governing equations for mass and momentum conservation are given as follow:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial P}{\partial x_j} + \frac{\partial \left(\rho \overline{\acute{u}_i \acute{u}_j}\right)}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_i}{\partial x_i}\right)\right] \tag{2}$$

$$\rho = \sum_{n=1}^{2} \alpha_n \rho_n \ , \qquad \mu = \sum_{n=1}^{2} \alpha_n \mu_n \tag{3}$$

Where$x_i (i = 1,2,3)$ are Cartesian coordinates; ρ is the density of the water and t is the time; $u_i (i = 1,2,3)$ are Cartesian velocity components, P and μ are pressure and dynamic viscosity respectively; α is the phase fraction and $n = 1,2$ represents the fluid phase number (water and air); δ_{ij} is the Kronecker delta; $\acute{u}_{i(j)}$ denotes the fluctuating velocity; $-\rho \acute{u}_i \acute{u}_j$ is the average Reynolds stresses which can be written in the following form:

$$-\rho\overline{\acute{u}_i \acute{u}_j} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\left(\rho k + \mu_{ij}\frac{\partial u_i}{\partial x_i}\right)\delta_{ij} \tag{4}$$

The (SST) $k-\omega$ turbulence model was chosen to close the equations (1) and (2) and to predict accurately the hydrodynamic forces near–wall regions. The air-water interface in the free surface was modeled using the Volume of Fluid method (VOF).

2.2 Sediments transport equations

The governing equation for suspended load is a standard convection diffusion equation. The numerical treatment for this transport equation is similar to the momentum equations.

$$\frac{\partial \rho c}{\partial t}+\nabla.[\rho(u-u_s)c]=0 \qquad (1)$$

$$u_s=\langle 0,0,-w_s\rangle$$

Where C is the volumetric sediment concentration and w_s is the settling velocity of sediment particle. For suspended sand particles and depending to the sediment diameter range, the following equations are used to compute w_s, VAN RIJN, L. C. (1984):

$$\begin{cases} w_s=\dfrac{(s-1)gd_{50}^2}{18\nu} & if\ d_{50}<100\,\mu m \\ w_s=10\dfrac{\nu}{d_{50}}\left(\left[1+\dfrac{0.01(s-1)g\rho d_{50}^2}{\nu^2}\right]^{0.5}-1\right) & if\ 100\,\mu m < d_{50}<1000\,\mu m \end{cases}$$

with $s=\rho_s/\rho$

The resolution of the transport equation assumes knowledge of the boundary conditions especially on the free surface and the channel bed.

In the present work, the absence of the transfert of the sedimentery material is assumed on the free surface and a constant concentration of sediment is assumed on the channel bed (C_a). Where:

$$C_a=\frac{0.035}{\alpha}\rho_s\frac{d_{50}}{(z_a-z_0)D_*^{0.3}}\frac{\left(\tau_b-\tau_{b,cr}\right)^{1.5}}{\tau_{b,cr}}$$

Where, α is an empirical paramètre, z_0 is the bed roughness, τ_b is the shear bed stress generated by the flow near to the bed. $\tau_{b,cr}$ the critical shear bed and D_* is a parameter depending to the sand particles given as:

$$D_*=d_{50}\left(\frac{(s-1)g}{\nu^2}\right)^{1/3}$$

The critical shear bed stress is deduced from the Shields curve. In the present investigation we use the formula proposed by YALIN, M. S. (1977

$$\tau_{b,cr}=(\rho_s-\rho)gd_{50}\left(\frac{0.186}{1+0.2\varpi}+0.045\left(1-0.98e^{-0.01\varpi}\right)\right)$$

Where ϖ is a dimensionaless parameter :

$$\varpi = \left[\frac{(s-1)gd_{50}^{3}}{\nu^{2}}\right]^{0.5}$$

2.2.1 Sediments scaling method

This investigation was done at the scale 1/25. For the sediments scaling, the following formula determined from the equation of the Shields number was used:

$$n_s = \frac{n_L}{0.29} \approx 86.2$$

Where, $n_s$is the sediment scale factor and n_L is the length scale factor, here, equal to 25.

3. SHIP DESCRIPTION

The ship selected for this investigation is an inland container cargo of 135m of long and 11.40m of width (see Fig. 1). This ship is equipped by two propellers type VP1304 with five blades and four rudders type fishtail (also called Schilling rudders). The ship form was put on the scale 1/25th. Its characteristics dimensions are presented in Table 1.

Figure 1: Ship geometry

4. Table 1 Geometric parameters of ship hull

	Length (L_{PP})	Beam (B)	Draft (T)	Block coefficient (C_B)	Wetted surface (W_S)	Cross area of ship (C_S)
Real model	135 m	11.4 m	2.5 m	0.899	2104.8 m²	34.114 m²
Scaled model (1/25)	5.4 m	0.456 m	0.1 m	0.899	3.367 m²	0.0545 m²

Table 1: Geometric parameters of ship hull

4. VERIFICATION AND VALIDATION OF THE NUMERICAL MODELS

4.3 Verification and validation of the numerical models

The verification and validation of the hydrodynamic model of the hull and propellers were presented and detailed in previous works KAIDI ET AL. (2017) and KAIDI ET AL. (2018). Hence, for this investigation only the verification and validation of the sediments transport model and the scaling method were considered. For that, the experimental data of Vin Rign trench tests were used. Fig. 2 shows the configuration setup and its dimensions.

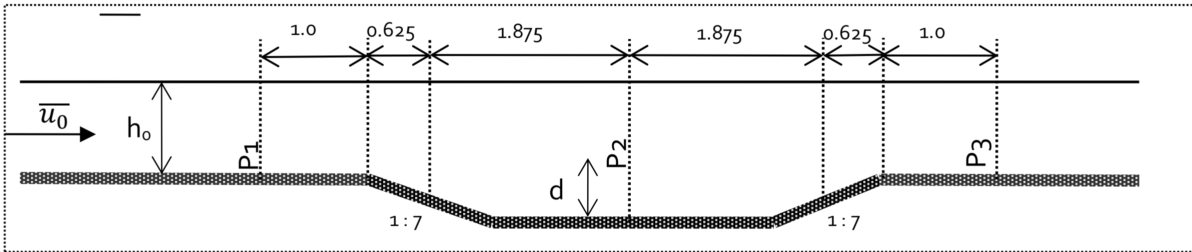

Figure 2: trench setup and dimensions

The velocity inlet condition was applied on the trench inlet, while the pressure outlet condition was applied on the outlet boundary. The trench bottom was considered as roughness wall (Ks=0.025). The sides and the top of the trench were modeled as a symmetry plane condition.

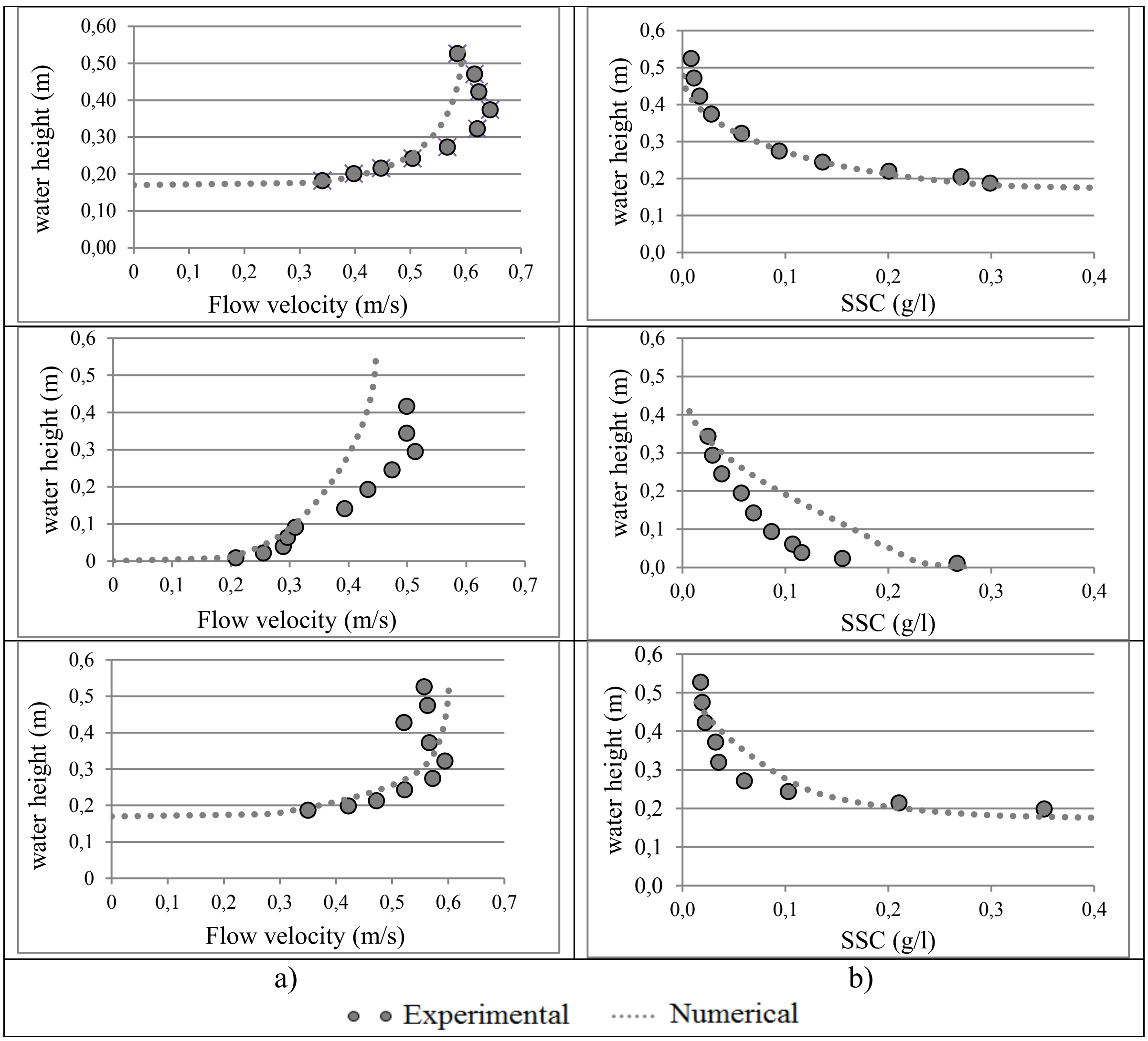

Figure 3: Comparison between numerical and experimental results of the physical model : a) flow velocity and b) the SSC

The vertical variation of the flow velocity and the suspended sediment concentration (SSC) computed in three different locations of the trench (in the inlet, center and outlet of the trench) were compared to the measured data (see Fig. 3). A good agreement between the computed results and data was observed in the inlet and outlet of the trench. Where the relative error for the flow velocity don't exceed 8% observed near to the free surface. For the SSC the relative error is about 5%, observed at the middle of the water column. However, in the trench center a discrepancy between the computed and measured data was noted in the flow velocity and SSC. This discrepancy is probably due to the ignorance of the free surface. The same remarks and observations were noted for the scaled model 1/25 (see Fig. 4.).

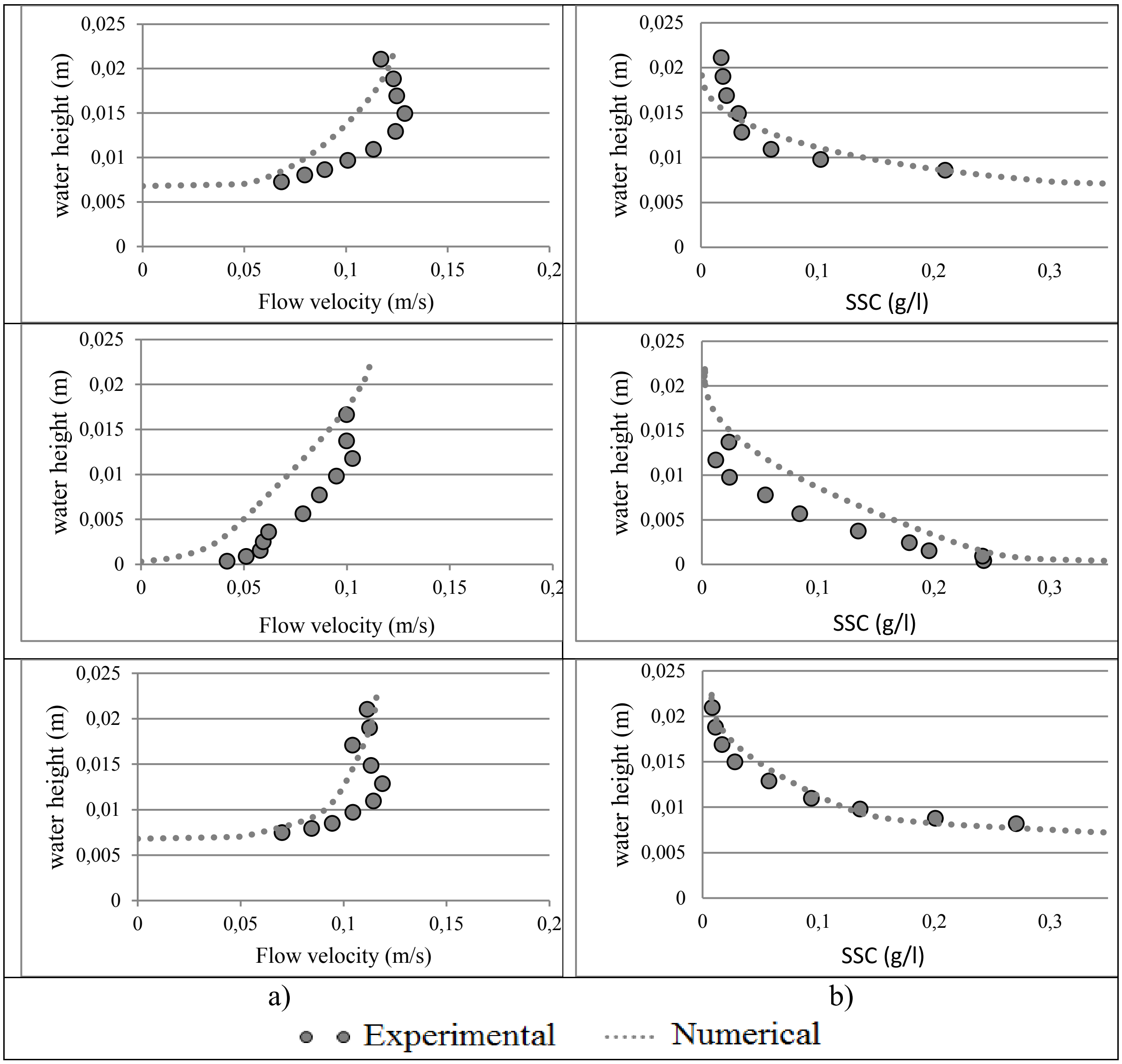

Figure 4: Comparison between numerical and experimental results of the scaled model : a) flow velocity and b) the SSC

4.2 Tested configurations and corresponding boundary conditions

In the present study, all tested configurations are summarized in the table 2. Three parameters were tested : the depth to draught ratio (h/T), the ship advance ratio and the sediments size.

	h/T=1.2	h/T=1.5	h/T=2.0	h/T=3.0
J=0.7	0.55 (m/s)	X	X	X
J=0.9	0.55 (m/s) 1 / 1.6 / 2.4 / 3 (10^{-6}m)	0.55 (m/s)	0.55 (m/s)	0.55 (m/s)
J=1.1	0.55 (m/s)	X	X	X
J=1.3	0.55 (m/s)	X	X	X

Table 2: Tested configurations : The ship speed Vs (m/s), the depth to draught ratio (h/T), the advance ratio (J) and the sediments size (m)

5. RESULTS

5.1 Effect of operating propellers on the sediments suspension

5.1.1 Comparison between bed shear stress caused by a towing and a propelled ship

In this section the impact of the propulsive system on the shear bed stress was studied. To carried out this study, a comparison between a loaded bed during the passage of a towed ship and propelled ship was presented in two different water depth. Fig. 5 (a) shows the shear bed stress generated by the passage of a towed ship for h/T ratio of 1.2 and 1.5, while the Fig. 5 (b) shows the shear bed stress generated by the passage of a propelled ship. The ship speed was set for the both tests to 0.55m/s and the advance ratio was set to 0.90 (73 RPM).

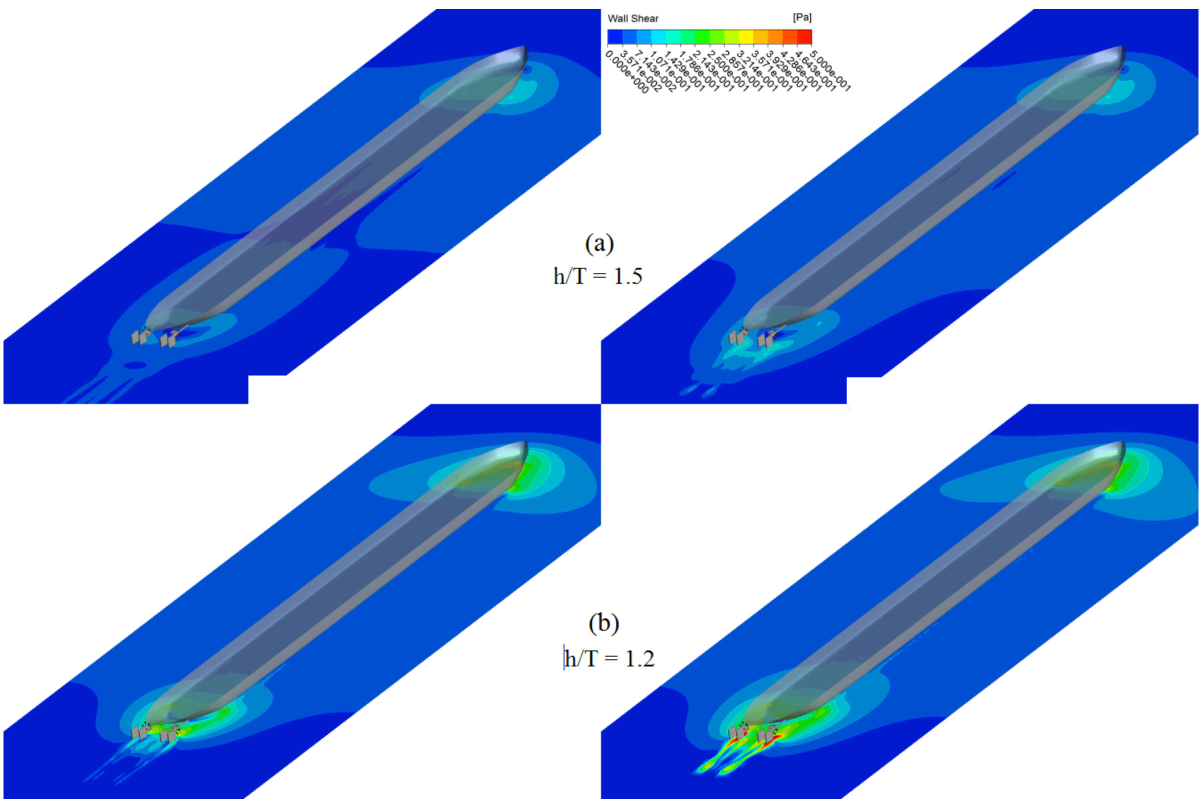

Figure 5: Bed shear stress for towed and propelled ship : a) h/T =1.5 and b) h/T=1.2

In can be seen clearly from these figures that the bed shear stress observed in the ship bow for the both h/T ratio is almost unchanged. While, the bed shear stress in the ship stern zone increases especially around the propellers. The Fig. 6 illustrates a comparison between the computed SSC along the midline of the ship for a towed and propelled ship in very shallow water case. The SSC was taken at the height of 0.015m from the channel bed. The both curves have the same allure in the ship bow, however, in the ship stern the SSC increases significantly to reach a 1.52 g/l which corresponds to 3.6 times the SSC computed in the case of a towed ship. These curves also give an idea about the length of the impacted area behind the ship and the repartition of the SSC.

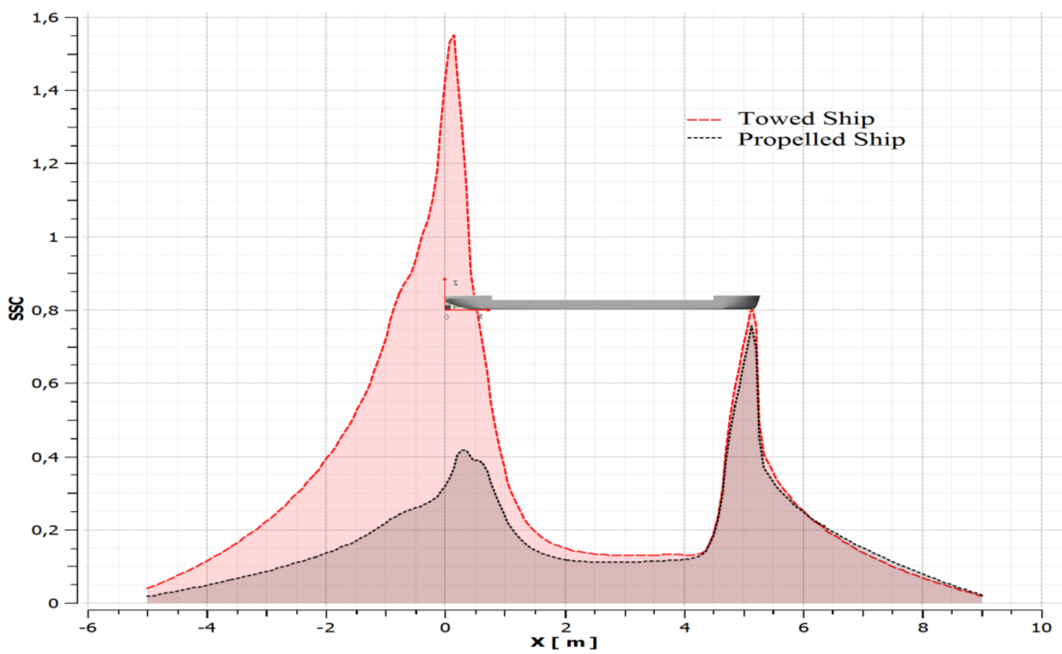

Figure 6: SSC (g/l) distribution on the midline of the ship for towed and propelled ship

5.1.2 Effect of the ship advance ratio (propeller thrust)

Several advance ratios (0.7, 0.9, 1.1 and 1.3) were tested to assess the influence of this parameter on the bed shear stress and the suspension of the sediments. The ship speed is supposed constant and equal to 0.55m. Hence, the variation of the advance ratio is done by the variation of the propeller turning rate. This investigation was done in very shallow water h/T=1.2.

For the same ship speed it can be observed that when the advance ratio is varied the concentration of the suspended sediment vary in the bow and the stern of the ship. Fig.7 presents the SSC variation along the midline of the ship. It can be seen that the SSC increases with advance ratio decrease. The increase noted in the bow zone is weak compared to the ship stern zone, where, the SSC computed for the lower value of the advance ratio is greater than 5 times the SSC computed for the higher value. This increase is caused essentially by the propeller jet which increase by propeller turning rate increse.

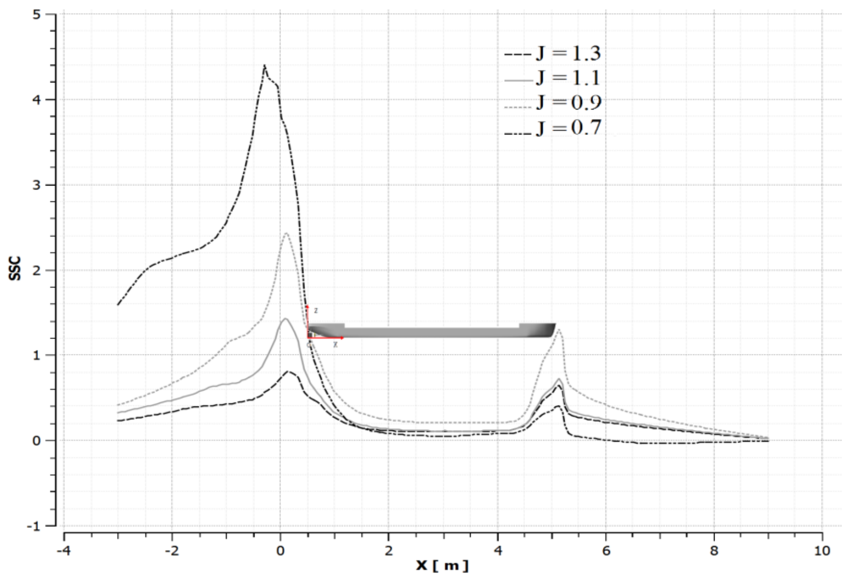

Figure 7: SSC (g/l) distribution on the midline of the ship according to advance ratio

5.2 Confinement effect

5.2.1 Shear bed and SSC distribution as a function of h/T ratio

The shear bed stress distribution was plotted for four h/T ratios. Here, the ship speed was set to 0.55m/s and the propeller turning rate was set to 470 tr/min (*J*=0.90). The ship draught was considered unchanged and was set to 0.1m. Hence, to test the confinement effect only the water depth was changed. The tested values of h/T ratio are 1.2, 1.5, 2.0 and 3.0 where, each value represent a type of waterways (confined, shallow, medium deep and deep waters). These values of h/T ratio correspond to the following depth Froude numbers (0.101, 0.090, 0.078 and 0.064).

The Fig.8 below show the bed shear stress caused by the passage of propelled ship and its distribution according to h/T ratio. From these figures, it can be observed that the propeller effect is felled by the bed only in very shallow, shallow and medium deep waters. However, this effect is more visible when the ratio h/T is less or equal to 1.5 (shallow water). This effect is more important when the ship is sailing in very shallow water (h/T =1.2), where, the computed shear stress value is 3.5 times more important compared to the shallow water and 12 times compared to medium deep water. In deep water the impact of the ship passage and its propulsive system is insignificant and the numerical results show that the hull effect is dominant than the propeller effect.

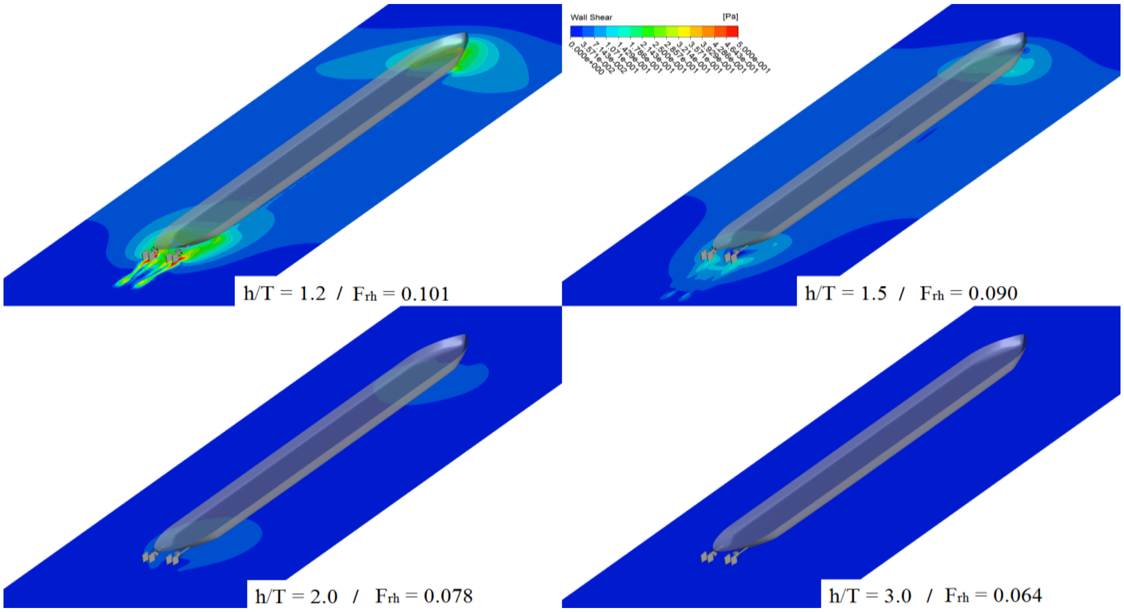

Figure 8: Bed shear stress according to the h/T ratio

The Fig. 9 shows the concentration of the suspended sediment along the midline of the ship located at a height of 0.015m from the channel bed. From these curves it can be noted that the SSC is very important in the both zones where the bed shear stress is significant. From these results we note that in all cases except in very shallow water, the concentration in the bow and the stern of the ship is almost the same. In very shallow water the SSC is considerable in the ship stern than in the bow, where, the computed SSC on the ship stern is almost doubled regarding to the ship bow. The main raison of this amplification is the accelerated propellers jet that erode the channel bed. Compared to the shallow water, the SSC computed in the very shallow water is 7 times larger. In medium and deep waters the SSC is about 0.22 and 0.10 g/l respectively.

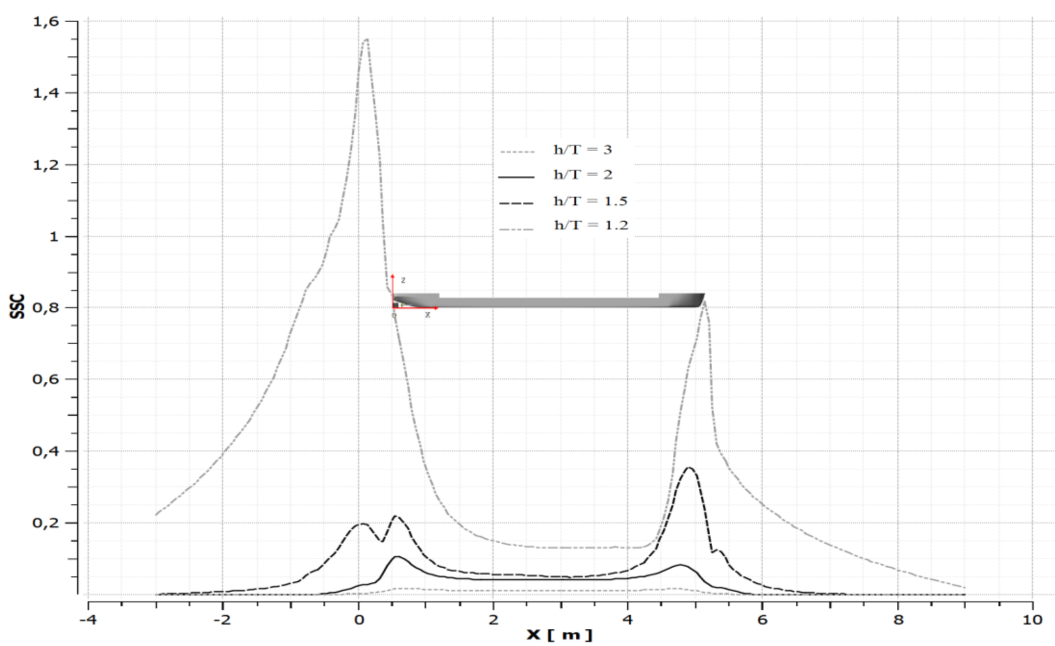

Figure 9: SSC (g/l) distribution on the midline of the ship according to the h/T ratio

5.3 Sediment size effect

The sediment size is one of the most parameters that can be taken into account to assess the SSC evolution and distribution. In this section we test four scaled sizes of sediments, $1.0*10^{-6,}$ $1.6*10^{-6}$, $2.4*10^{-6}$ and $3.0*10^{-6}$m (that corresponds to $0.0864*10^{-3}$, $0.138*10^{-3}$, $0.207*10^{-3}$ and $0.260*10^{-3}$ m). The ship speed, the ship advance ratio and the h/T ratio were set to 0.55m/s, 0.90 and 1.2 respectively.

The Fig. 10 shows the SSC distribution caused by the ship passage on the fluid domain. From this Figure it is observed that when the sediment size is small, the impacted zones are more larger especially at the ship stern. The numerical outcomes of the SSC are plotted along the midline of the ship and presented in the Fig. 11. It is shown that the SSC increase with sediments size decrease to reach 2 g/l for the smaller size of the sediment, while, the value of the SSC is less than 0.8 g/l in the case of larger size.

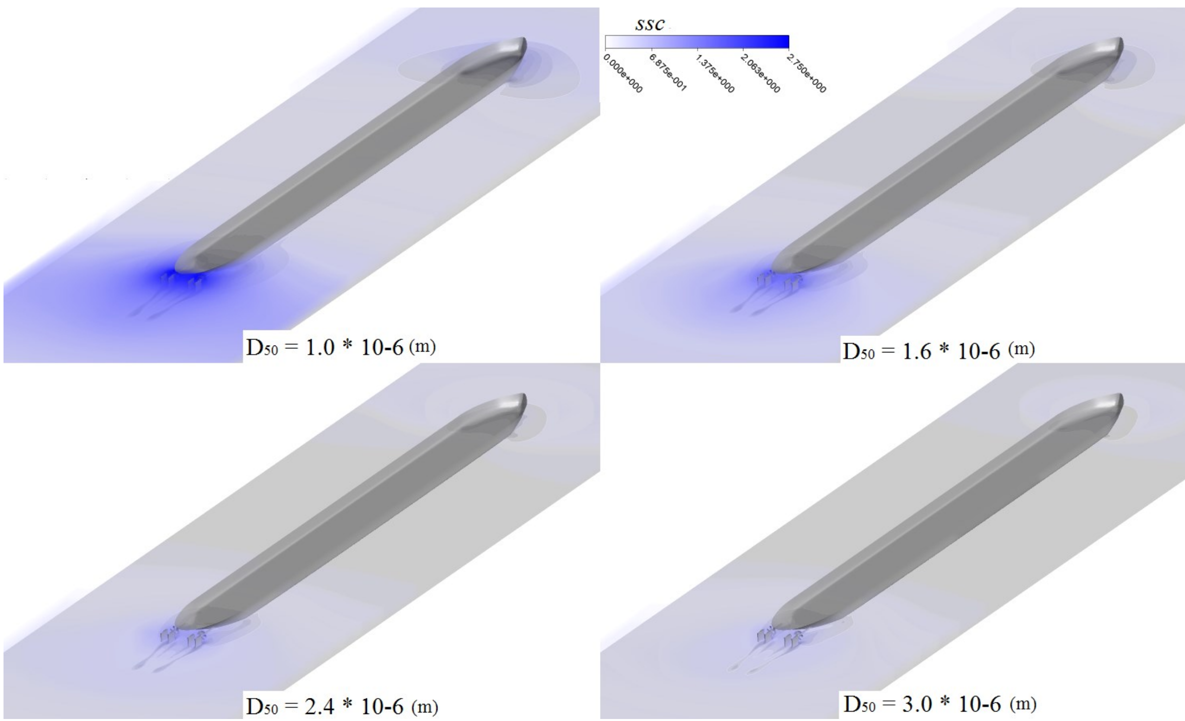

Figure 10: Volume representation of the SSC (g/l) distribution on the water according to sediments size

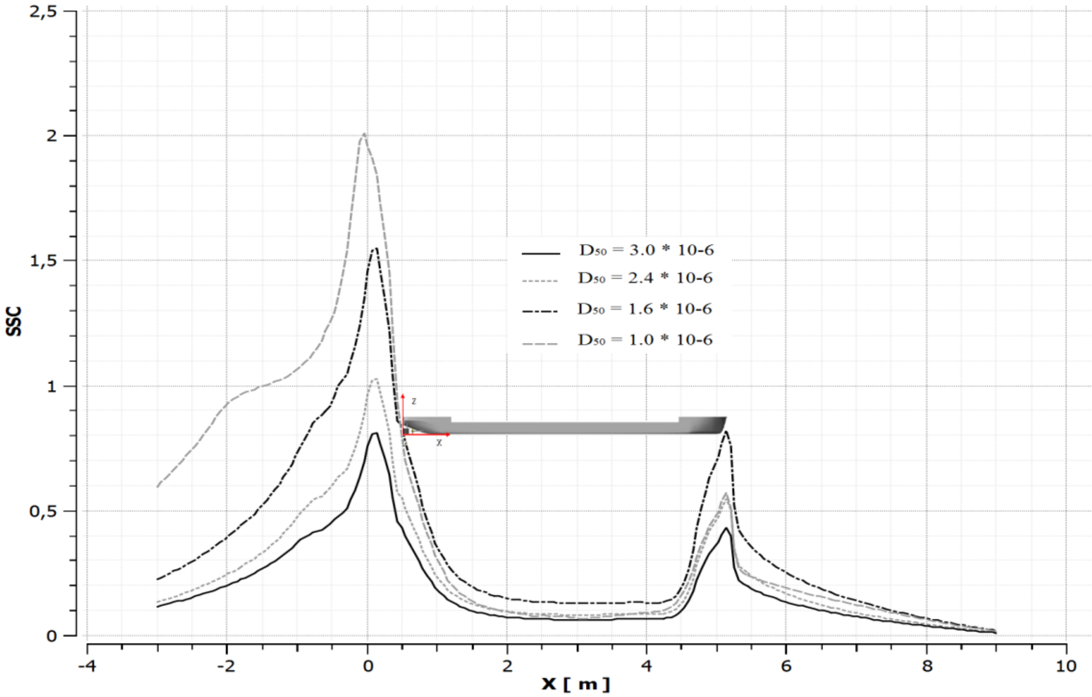

Figure 11: SSC (g/l) distribution on the midline of the ship versus sediment size

6. CONCLUSION

In this paper the evaluation of the impact of the inland traffic on the waterways was treated. The effect of the advance ratio of the ship, the h/T ratio as well as the sediment size was studied using a unsteady CFD model based on Navier-stokes equations with free surface. The (SST) $k-\omega$ turbulence model was used to estimate the viscous forces especially on the channel bed. The frame motion technical was selected to simulate the propellers turning. In this work, the mesh quality around the ship (hull, propellers and rudders) was chosen basing on previous work. The mesh quality on the channel bed was chosen basing on y+ value. The optimal mesh was used to validate the hydrodynamic model and the comparison with measured data showed a good agreement between the both results.

From this investigation it was concluded that the most influential parameter was the h/T ratio. The numerical outcomes of this work have shown firstly the impact of a propulsive system of the ship on the bed shear stress which is significant especially in the ship stern zone. Three parameters were tested thereafter. All of these parameters depends on each other. It was illustrated that the effect of propellers is felt by the channel bed only when the ship is sailing in shallow and very shallow waters. In medium and deep water the propellers effect is negligible. It also was shown during this study that the channel bed erosion increase with the advance ratio and the sediment size decrease.

Observations and remarks noted through this investigation can help to understand the different physical phenomenon related to the inland navigation and can also help to improve the mathematical models for channels design and channel dredging.

7. REFERENCES

Brovchenko, I., Kanarska, Y., Maderich, V., Terletska, K. (2007). 3D non-hydrostatic modelling of bottom stability under impact of the turbulent ship propeller jet. Acta geophys., 55(1), 47-55

Kaidi, S., Smaoui, H., Sergent, P. (2017), Numerical estimation of bank-propeller-hull interaction effect on ship manoeuvring using CFD method. Journal of Hydrodynamics, 154-167, 29 (1)

Kaidi, S., Smaoui, H., Sergent, P. (2018), CFD investigation of the mutual interaction between hull, propellers and rudders for inland container ship in deep, very deep, shallow and very shallow waters. Journal of Waterway, Port, Coastal, and Ocean Engineering.

Smaoui, H., Ouahsine, A., Pham Van Bang, D., Sergent, P., Hissel, P. (2011). On the sediment resuspension induced by te boet trafic : From experiment to numerical modelling. Chapter 3, sediment transport, S. S. Ginsberg, ed., InTech, Vienna, Austria, 55-70

Van Rijn, L.C. (1984): Sediment Transport, Part I : Bed Load Transport. Journal of Hydraulic Engineering, Vol. 110(10) , pp : 1431-1456.

Yalin, M. S. (1977): Mechanics of Sediment Transport. Pergamon Press, 2d edition, New York, 298 pages