INFLUENCE OF THE TURBULENT WAKE DOWNSTREAM OFFSHORE WIND TURBINES ON LARVAL DISPERSAL

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RESUME : *Notre étude se concentre sur les impacts des fondations d'éoliennes (monopile et gravitaire) sur la dispersion larvaire des espèces bentho-pélagiques colonisant ou trouvant refuge au niveau des substrat durs de telles structures artificielles. Une modélisation numérique couplée est utilisée dans cette étude. Elle combine un modèle Eulérien (OpenFoam), résolvant les équations 3D de Navier-Stokes pour calculer l'hydrodynamique, et un modèle Lagrangien (Ichthyop), résolvant une équation d'advection prenant en compte les processus de dispersion horizontale et verticale. Deux phénomènes résultant de l'interaction pieux-courant sont mis en évidence: les effets de sillage turbulent et l'apparition de tourbillons en fer à cheval près du fond. Ces différents phénomènes sont analysés dans une configuration 2D à l'échelle locale pour une fondation puis pour un réseau de fondations afin de comprendre leurs influences sur la dispersion des larves. Après des tests de sensibilité, le modèle de turbulence de type RANS (Reynolds Averaged Navier-Stokes) k-omega SST est choisi pour reproduire les tourbillons en fer à cheval et le sillage turbulent avec un temps de calcul moindre. Ensuite, pour ces mêmes fondations monopile et gravitaire, des simulations de dispersion larvaire pour un type spécifique de larves, transportées passivement et sans comportement vertical, sont effectuées. Les résultats montrent une période de rétention près des fondations et une circulation des larves qui suit le sillage turbulent.*

MOTS CLEFS : Mécanique des fluides environmentale, energies marines renouvelables , dispersion larvaire, couplage Eulerien-Lagragien.

ABSTRACT : *Our study was focused on the impacts of wind turbine foundations (monopile and gravity base) on larval dispersal from bentho-pelagic species colonizing and living on the hard substratum of such artificial structures. On the basis, numerical modelling is used that combines the Eulerian model (OpenFoam), solving the 3D Navier-Stokes equations to compute the hydrodynamics, and the Lagrangian model (Ichthyop), solving an advection equation considers horizontal and vertical dispersion processes. Two phenomena resulting of the piles-current interaction are highlighted: the turbulent wake and the appearance of* *horseshoe vortices near the bottom and around the structure. The different phenomena are analysed in a 2D configuration at the local scale with one and several foundations to understand their influences on the dispersion of the larvae. This helps to evaluate the influence of the turbulence/fondation interactions and to choose The RANS (Reynolds Averaged Navier-Stokes) k-omega SST turbulence model to reproduce the horseshoe vortices and turbulent wake with less computing time. Then, with the same monopile and gravity base foundations larval dispersal simulations for one specific type of larvae with passif transport and without vertical behavior are performed. The results show a retention phase near the foundations and circulation of the larvae that follow the turbulent wake.*

KEYWORDS: Environmental fluid mechanics, marine renewable energy, larval dispersal, Eulerian-Lagragian coupling.

1. INTRODUCTION

When the European Union (EU) rushes to increase their production of marine renewable energy, France has already two Offshore Wind Farms (OWFs) under construction since 2021 in the Bay of Seine (Figure 1). One OWF is located off Courseulles-sur-Mer for a total power approximately 450MW count 64 turbines. Another OWF is being installed near Fécamp of total power approximately 500MW (71 turbines). For each farm, a type of foundation was chosen according to the depth and seabed characteristics. Courseulles-sur-Mer OWF has essentially a sandy-gravelly bottom area like it has indicated in the bibliography (Larsonneur 1982; Rivier et al., 2016; Pezy et al., 2021) and a water depth varie between 20 and 30 m (Rivier et al., 2016). It is recommended to implement monopile structure as the better foundation according to Sánchez et al., (2019) and Lavanya et al., (2020). For the second OWF off Fécamp, most of the bottom is flat and the depth varies between 30 to 39 m above mean sea level and the sedimentary cover is mainly composed of gravel. Thus, for this situation and considering the height of the surface waves, the gravity base foundation presents the relevant technical yet economical solution for the Fécamp site.

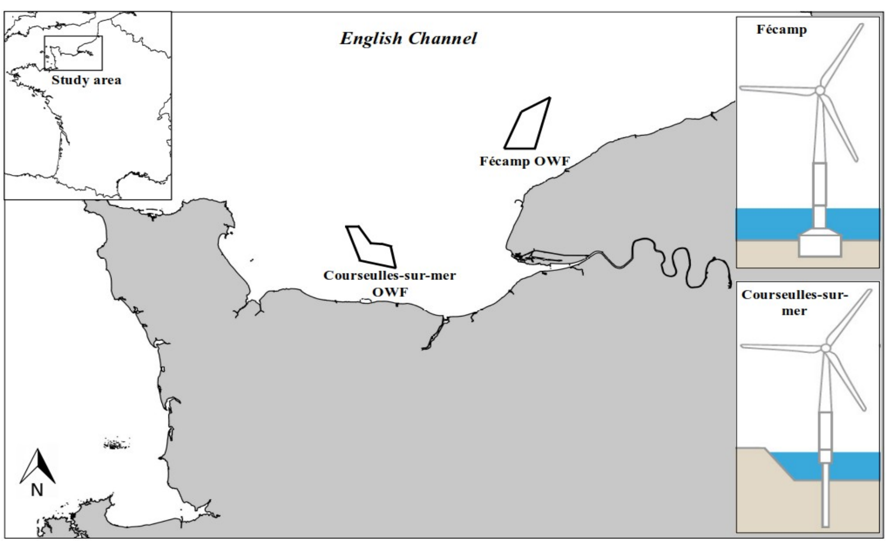


Figure 1. French offshore wind farms under construction in the Bay of Seine area (Courseulles-sur-Mer and Fécamp coasts, black marks).

Nowadays, one of the major environmental concerns is the hydrodynamic changes induced by the Offshore Wind Turbines (OWT). Those changes have been considered by several researchers like Sarpkaya et al., 1976 and Kawamura et al., 1984 as one of the firsts who were interested in the flow around cylinder followed by others such as Alari et al., (2012); Christensen et al., (2013); Rivier et al., (2016); Rogan et al., (2016). This changing in the flow around cylinder may also concern benthic and pelagic species. It is therefore essential to study the biological impacts (Dannheim et al., 2020) and understand the role of wind farms on the dispersal of these species at the planktonic larval phase. Review papers discuss about the possible impacts and if they are positive or not for the benthic species (e. g. Adams et al., 2014; Bergström et al., 2014; Clark et al., 2014; Floeter et al., 2017; Van Berkel et al., 2020). To complement these analyses, we propose here to simulate the flow around wind turbines and then to evaluate how larval are dispersed.

The paper is organized as follows: After a short introduction, Section 2 describes the hydrodynamic model and its coupling with the dispersion model. Results are presented and briefly discussed in Section 3. Conlusions are dressed in Section 4.

2. METHODOLOGY

2 Hydrodynamic model

To accurately simulate fluidstructure interactions, one of the best solution is to use CFD (Computational Fluid Dynamic) modeling, and the OpenFOAM model (Greenshields, 2016) for example. However, CFD is costly in terms of computing time and as a results not suitable at regional scales (Bay of Seine containing the two OWFs). Therefore, this study focuses on local scale for each type of structure (monopile and gravity base). The numerical model OpenFoam solves three-dimensional Navier-Stokes equations (1), (2) on a structured mesh using the RANS (Reynolds Averaged Navier Stokes) approach fro turbulence:

- continuity equation :

$$\frac{\partial \rho}{\partial t} + \rho \ \operatorname{div} \vec{u} = 0. \tag{1}$$

- momentum equation :

$$\rho \frac{\partial \vec{u}}{\partial t} = -\nabla p + \mu \nabla^2 \vec{u}. \tag{2}$$

With ρ the fluid density, $\vec{u}$ the fluid velocity vector, p the pressure and μ the fluid dynamic viscosity. The turbulence model k-ω SST (Shear Stress Transport) (Menter, 1994), based on a turbulent viscosity, is used for reproducing the turbulent flow in less computation time. This model is a two equations (3) and (4) eddy-viscosity model :

$$\frac{\partial \rho k}{\partial t} + \nabla(\rho u k) = \nabla.(\Gamma_k \nabla k) + \widetilde{P_K}. \tag{3}$$

$$\frac{\partial \rho \omega}{\partial t} + \nabla(\rho u \omega) = \nabla.(\Gamma_k \nabla \omega) + P_\omega - D_\omega + y_\omega. \tag{4}$$

With k the turbulent kinetic energy, ω the turbulent dissipation rate. D_ω, y_ω are the cross diffusion and dissipation terms, respectively. To study the flow around the monopile, we used a method which consists in setting a mesh refinement box around the foundation to capture strong velocity gradient, as shown in Figure 2.

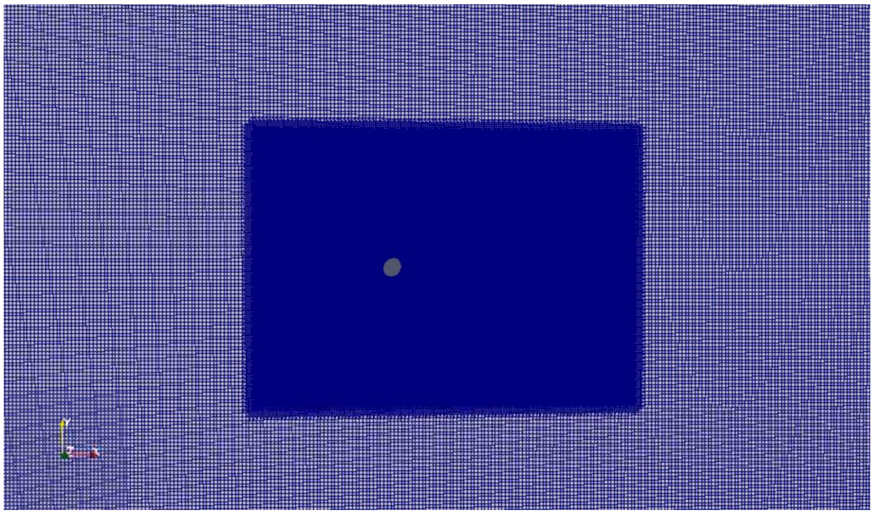


Figure 2. Mesh zones aroud the monopile foundation (gray) – horizontal view. (the visual mesh shift is coming from ParaView visualization)

The numerical configuration at local scale is centered on a structure in which is similar to those off Courseulles-sur-Mer. That is represented by a circular cylinder with a diameter D = 0.65 m in 1/10 numerical scale and water depth h = 3.28 m divided into 16 line sigma segments. For the gravity base foundation case, the only changes are the structure dimensions with a top diameter D = 0.75 m and a base diameter D = 3.2 m. The simulations for the two pile shapes were performed in a uniform velocity field all over the domain in x-axis direction. The forcing velocity is equal to 0.3 m/s after applying Froude scaling on realistic values to ensure 1/10 scale. No meteorological forcing was applied and the seabed is assumed to be flat.

2.2 Eulerian-Lagrangian coupling

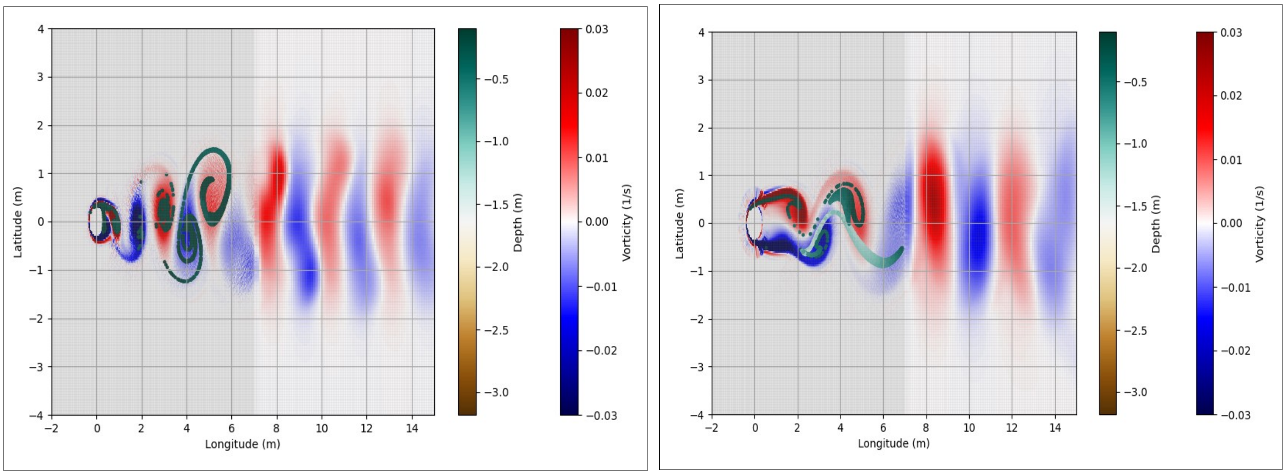
We used coupled biological and hydrodynamic models to track individually particles. That is an offline coupling, where the Lagrangian transport model, Ichtyop (Lett et al., 2008), is forced by the flow velocity computed by OpenFoam. The Lagrangian tracking follow particles movement (Davidson et al., 1995) using :

$$\frac{d\vec{p}_p}{dt}=\vec{u}_p. \tag{5}$$

with $\vec{p}_p$ the particle position and $\vec{u}_p$ the velocity of water particles at the position $\vec{p}_p$. Larval particles were released at the surface and at 2 m under the surface in front of the structure. They have a passive motion that follows the flow. No forcing data has been assigned which corresponds the first stages of larvae phase affirmed by Adams et al., (2014).

3. RESULTS AND DISCUSSION

In both cases of structure, the numerical model correctly reproduces the characteristics of the flow, particularly the Von Karman vortex streets (Figure 3). They are more visible for monopile structure than for gravity one. Their 3D structures, resulted after the interaction between water motion and the cylinder when Reynolds number R_e is high (e.g. Alari et al., 2012). This vortex shedding also affects the sea bottom. Other phenomena noticed thanks to the 3D plot is the horseshoe-vortex downflow (Figure 4). This vortex located in front of the pile surrounds it, as described by Petersen et al., (2015). The vorticity magnitude (Figure 5) around the monopile and particularly the turbulent wake are in agreement with the former results of Kanaris et al., (2011).



(a) *(b)*

Figure 3. Horizontal view (lon-lat) for depth on the surface of vorticity magnitude with larval particles (dots colored by depth position) after 25s of release at the surface in front of the pile. (a) monopile structure and (b) gravity base structure.

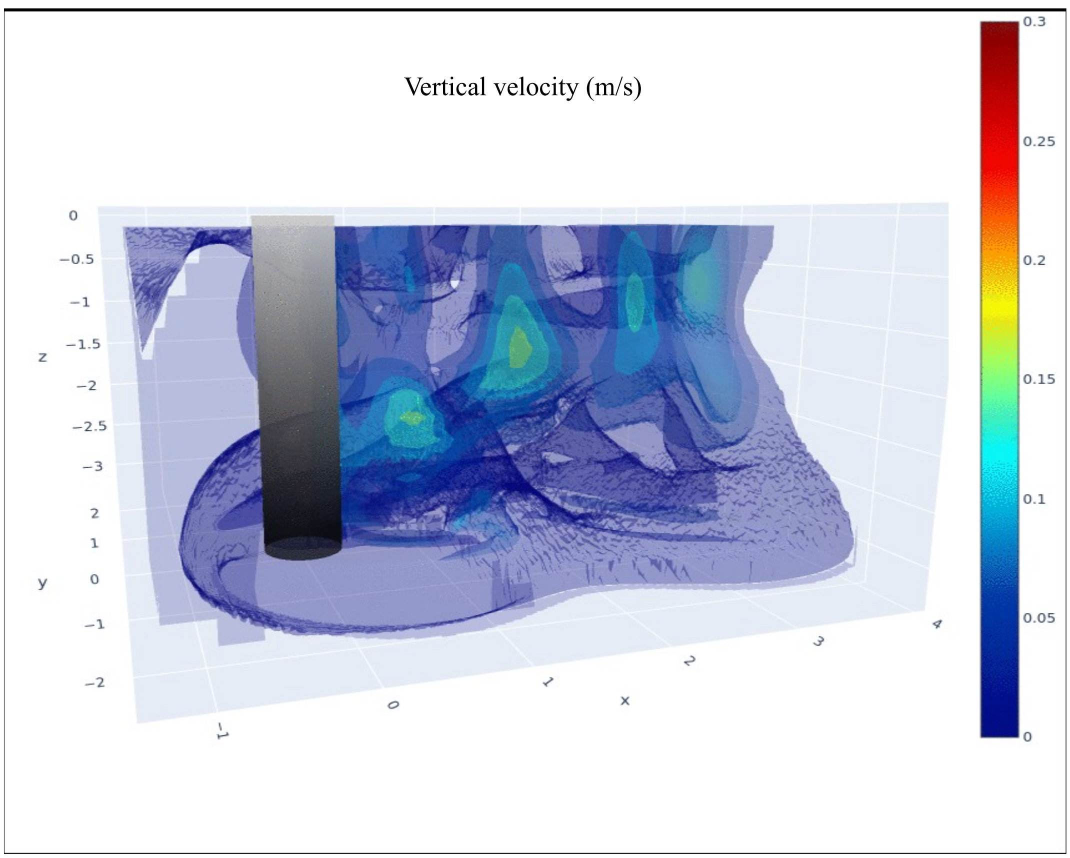


Figure 4. 3D visualization (x=longitude, y=latitude, z=depth) of the vertical velocity Uz close to the monopile.

The first simulations with the monopile foundation show that the dispersion is conditioned by the wake vortices. The vertical motion of the particles is mainly forced by the vertical component of the flow velocity Uz. The results are similar for a particle released at the surface and at 2 m under the surface (Figure 6).

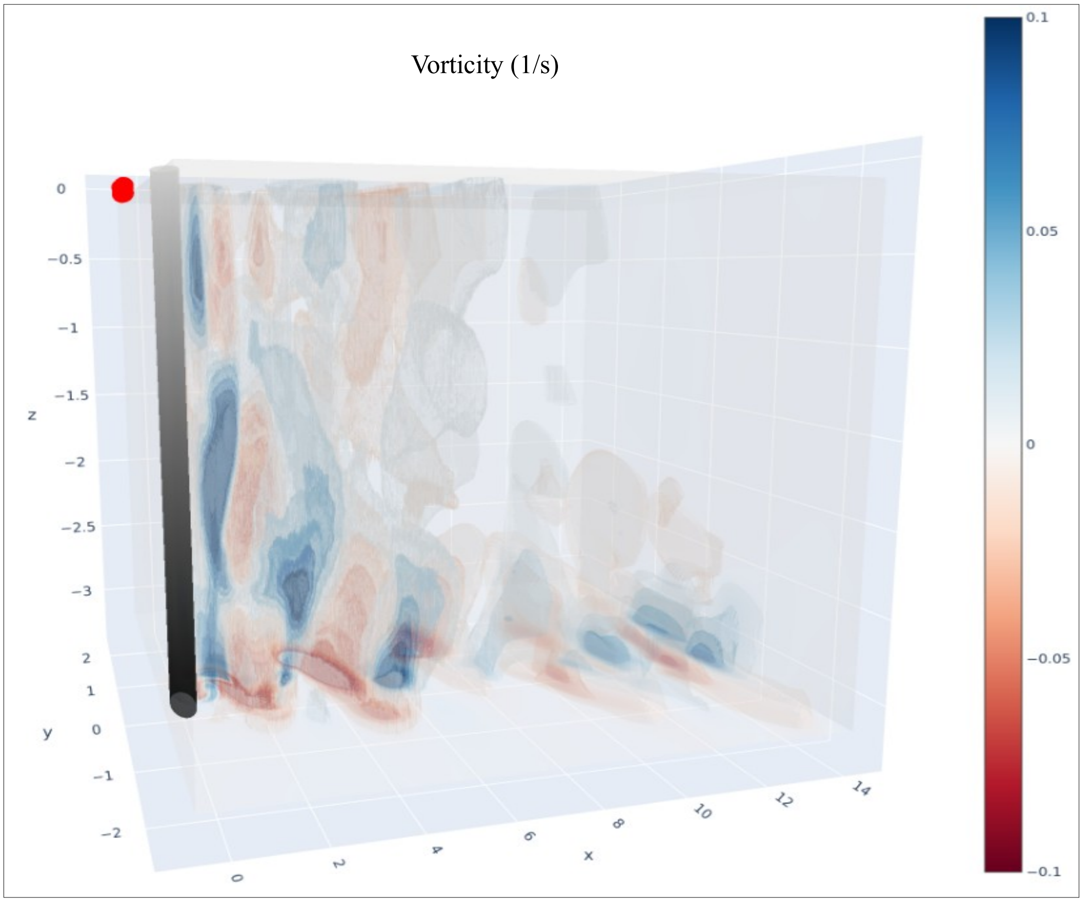
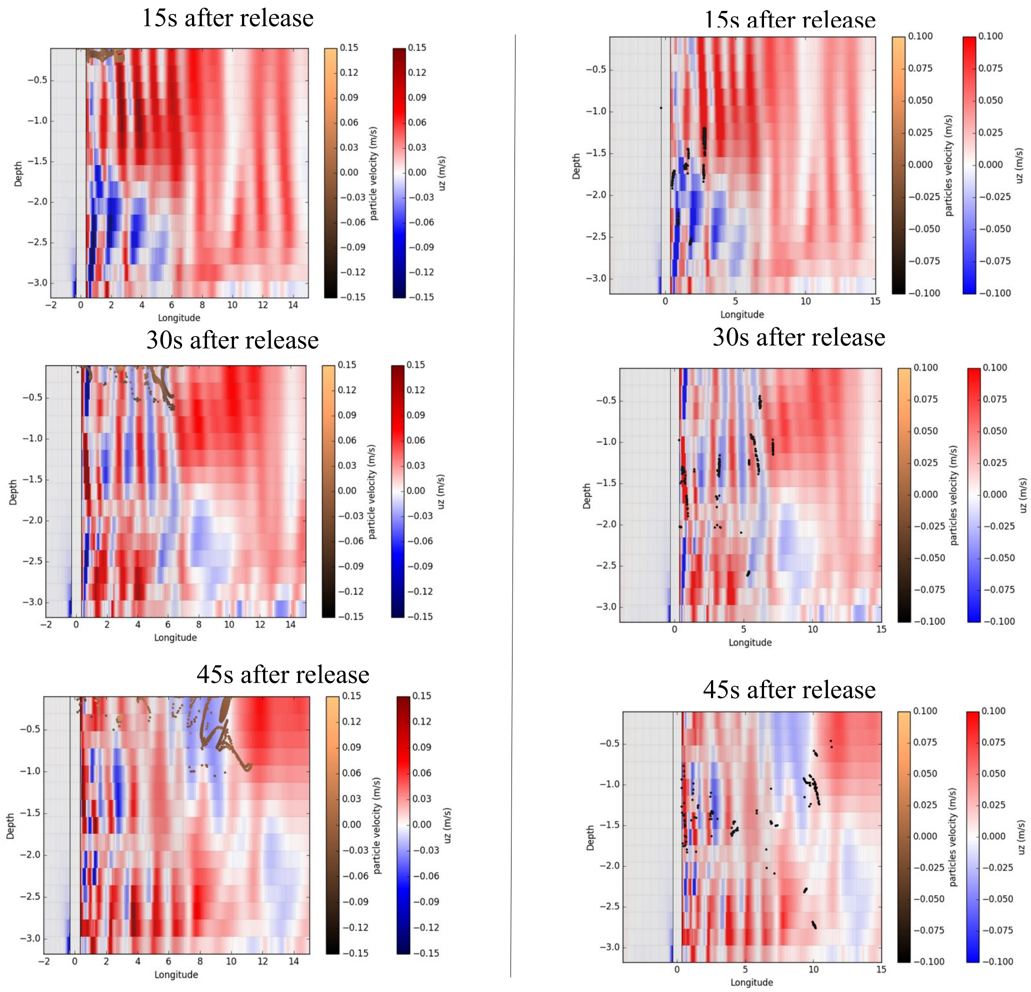


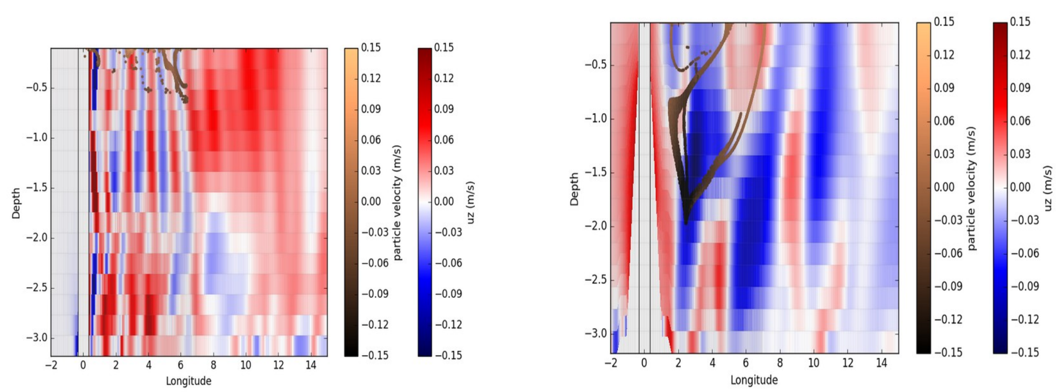
Figure 5. 3D visualization (x=longitude, y=latitude, z=depth) near the monopile (black cylinder) of the magnitude vorticity with initial position of the particles dispersion at the surface (red dots).

The particle vertical movement is explained by the behavior of vortices which was studied by Petersen et al., (2015): particles move up and down with the flow as show in Figure 6 where the red color corresponds to an upward transport and the blue color to a downward transport. For the gravity foundation, which differs from the monopile foundation by its conical base, it is observed a faster movement of the particles on the vertical (Figure 7) comparing to monopile one. Indeed, more intense vertical velocities are generated by the particular shape of the foundation which lead to more larvae retention during the simulation time as shown in Figure 8.



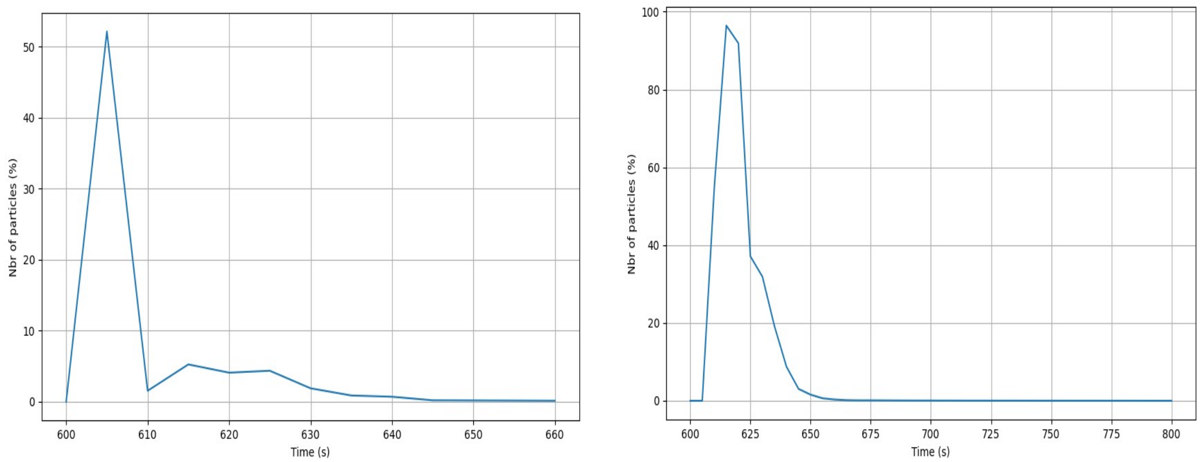
(a) *(b)*

Figure 6. Vertical (x-z : in the latitude layer in the center of the pile) of vertical velocity with larvae (dots colored by depth position): (a) released at the surface layer and (b) release at 2m under the surface layer.



(a) *(b)*

Figure 7. Vertical view (x-z : in the latitude layer in the center of the pile) of vertical velocity with larval particles after 30s from release at the surface layer: (a) simulation with monopile structure (b) simulation with gravity base structure.



(a) *(b)*

Figure 8. Larvae retention over time for (a) monopile and (b) gravity base foundations.

This study was meant to overview the possible effects like Von Karman and turbulence wake which influence the larvae dispersal in local scale of offshore wind farms with two different type of foundations and the numerical model was verified by previous studies in the case of monopile foundation.

4. CONCLUSIONS

In this article, only the local scale is evaluated around a monopile and a gravity base structure on the hydrodynamic impact and its influence on larval dispersal. The following points were observed:

- The Von Karman vertical vortex shedding affects the sea bottom on both types of foundations.
- The particles transport is forced by the vertical velocity (Uz) with its upward and downward behavior.
- A faster vertical movement of the particles with gravity base foundation than the monopile foundation.
- More larvae retention over time with gravity base structures.

All those remarks are valid in the case of uniform velocity with higher Reynolds number, flat bottom and structures dimensions used. Future work will focus on the impact on larval dispersal for the case of monopile and gravity structures at the regional scale of the two offshore wind farms, by coupling the MARS3D circulation model with the Lagrangian Ichthyop model.

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