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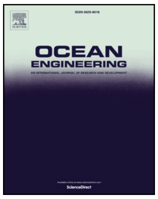

Initial dilution equations for wastewater discharge: Example of non-buoyant jet in wave-following-current environment

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ABSTRACT

In this study, three semi-empirical equations are developed to quantify the wave effect on the initial dilution of wastewater discharge, which usually forms a turbulent jet. To develop the equations, data from a non-buoyant jet in a wave-following-current environment, which is realised using a three-dimensional large eddy simulation model, are used with 27 cases in total. The effects of the wave-to-current velocity ratio, jet-to-current velocity ratio, and Strouhal number are considered in the equations. The initial dilution equations, which focused on the jet visual area, cross-sectional minimum dilution, and vertical location of the cross-sectional minimum dilution, have vital relationships with the characteristic length scale. The reliability of the present equations is discussed by comparing them with existing equations for a jet in a crossflow-only environment. The applicability range of the present equations is illustrated by comparing them with data for a jet in a crossflow-only environment and data for other cases of a jet in a wave-following-current environment. The three equations provide references for the conceptual design of wastewater discharge. This study reveals that a surface wave with low energy has a positive effect on the initial dilution of wastewater discharge.

1. Introduction

Wastewater, including domestic waste streams and brine from desalination plants, is continually discharged into coastal communities. Such pollutants are potential threats to local marine environmental and ecological systems (Roberts et al., 2010; Stark et al., 2016a). Their disposal, which usually forms a jet discharge, should be managed in a manner that local concentration levels are reduced to the lowest possible extent and the adverse effects are minimised. The mixing process of jet is divided into the near-field dilution (initial dilution hereafter) and far-field dispersion according to different spatial and temporal scales (Roberts, 1999; Choi and Lee, 2007). Because the initial dilution has a major effect on the prediction accuracy, it has been studied extensively in the modelling of wastewater transport, especially in the last decade (Zhao et al., 2011; Muhammetoglu et al., 2012; Chan et al., 2013).

Local hydrodynamics, which is related to the discharge site, is one of the primary factors that determine the jet dilution (Voutchkov, 2011; Marti et al., 2011; Purnama and Shao, 2015; Stark et al., 2016b). In coastal areas, tidal currents and surface waves are the dominating hydrodynamic factors. Previous studies (Lee and Neville-Jones, 1987; Yuan et al., 1999; Muppidi and Mahesh, 2005; Cavar and Meyer, 2012) have mainly focused on the effects of currents on the initial dilution of wastewater, simplified as a turbulent jet in crossflow. Four largescale coherent structures can be identified from a turbulent jet in crossflow, namely jet shear layer vortices, horseshoe vortices, wake vortices, and counter-rotating vortex pair (CVP) (Kelso et al., 1996). Among these, CVP is a salient feature of the jet, which mainly contributes to the deformation and periodic roll-up of the shear layer (Kelso et al., 1996; Marzouk and Ghoniem, 2007). Because of the existence of the CVP structure, the concentration distribution at the downstream cross-section follows the pattern shown in Fig. 1. This pattern indicates that the cross-sectional maximum concentration (or cross-sectional minimum dilution) is not located on the centreline. The ratio of the cross-sectional maximum concentration to the centreline maximum concentration is in the range of 1.0–1.5 with an average value of 1.2 (Chu, 1996). In addition, owing to the limitations of experimental measurement, the centreline maximum concentration and its location (defined as the jet trajectory) are usually chosen to represent the characteristic behaviour of dilution. Lee and Chu (2003) summarised the equations developed by different researchers as follows:

$$\frac{S_{c0}d}{L_{m0}} = C_1\left(\frac{x}{L_{m0}}\right)^{c_2} \tag{1}$$

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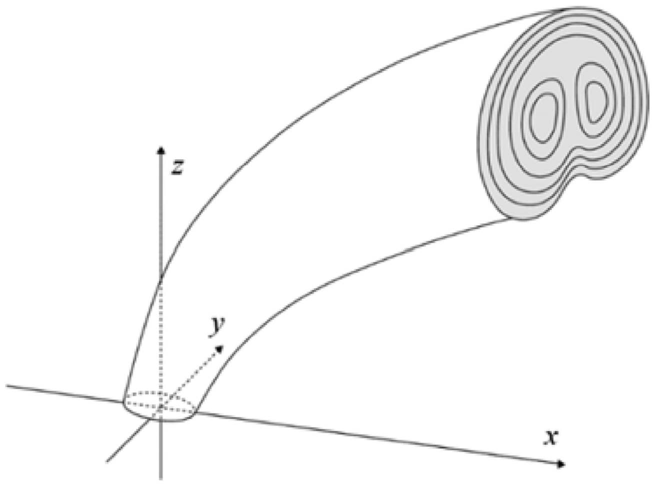

Fig. 1. Concentration distribution at downstream cross-section of jet in crossflow (contour interval = (1-e^{-1})C_m/6, outmost concentration contour = e^{-1}C_m, C_m is the maximum scalar concentration in the transverse planes, x is along the crossflow direction, z is along the jet discharge direction, and y is the transverse direction).

$$\frac{Z_{m0}}{L_{m0}} = C_3\left(\frac{x}{L_{m0}}\right)^{c_4} \tag{2}$$

$$L_{m0} = \frac{M_0^{1/2}}{u_0} = \frac{\sqrt{\pi}}{2}\frac{dw_0}{u_0} = \frac{\sqrt{\pi}}{2}dR_{jc} \tag{3}$$

where S_{c0} is the centreline minimum dilution, Z_{m0} represents the vertical location of the centreline maximum concentration, x is the downstream distance from the jet orifice, L_{m0} is the characteristic length scale of the jet in crossflow, M_0 is the initial momentum flux, u_0 is the crossflow velocity, w_0 is the initial velocity of the jet, R_{jc} is the jet-to-current velocity ratio, d is the jet diameter, and C_1–C_4 are constants. The values of C_2 and C_4 are approximately 0.66 and 0.33, respectively, whereas the values of C_1 and C_3 are in the ranges of 1.0–1.27 and 1.51–1.77, respectively (Lee and Chu, 2003). It should be noted that the above equations are not applicable to cases in which the dilution is very close to the jet orifice ($x/L_{m0} < 0.5$). Based on these equations, we can intuitively understand the effect of the current on the initial dilution.

Unlike tidal currents, surface waves have temporal scales of several seconds, which lead to swaying of the jet trajectory. Several researchers have investigated the interaction of surface waves with non-buoyant jets (Mossa, 2004; Xu et al., 2014), negatively buoyant jets (Ferrari and Querzoli, 2015), and positively buoyant jets (Chin, 1987; Hwung et al., 1994; Lin et al., 2013). A consistent conclusion is that the surface waves enhance the interaction between the jet and the ambient water and serves as an additional source of mixing; thus, the surface wave may have a positive effect on the initial dilution of the jet discharge. Ryu et al. (2005) and Hsiao et al. (2011) found that the wave-to-jet momentum (or velocity) ratio is a key factor that describes jet-wave interaction. Sharp et al. (2014) investigated the turbulent buoyant plumes discharged into a wave environment and obtained the average increase in the dilution between wave and no-wave cases, which is expressed as

$$\frac{S_1}{S_0} = 1 + 6\frac{u_w}{w_0} \tag{4}$$

where S_1 and S_0 are the centreline dilution with waves present and under stagnant conditions, respectively, and u_w is the maximum wave-induced horizontal velocity at the jet orifice, which is related to the wave height H, wave period T, and water depth h. According to the linear wave theory, u_w is defined as,

$$u_w = \frac{\pi H}{T}\frac{\cosh(kh_0)}{\sinh(kh)} \tag{5}$$

where k is the wave number, and h_0 is the height of the jet orifice.

The above semi-empirical equations for the initial dilution (Eqs. (1)–(4)) only consider current or wave effects, and therefore should be modified for discharge sites in wave-current environments such as coastal waters. Relevant studies conducted so far have been limited to the characteristics of the velocity and concentration distribution of a non-buoyant jet under the combined effect of waves and current (Abdel-Rahman, 2004; Xia and Lam, 2004; Xu et al., 2016, 2017). A quantitative analysis of the initial dilution of the jet discharge in a wave–current environment is still lacking.

Following the work of Xu et al. (2017), this study aims to extend the semi-empirical equations for crossflow-jet dilution to a wave-following-current environment and quantise the effect of surface waves on jet discharge. It should be noted that a wave-current environment means that the wave and the current propagate in the same direction. Considering the complexity of negatively buoyant discharges, this study focused on a vertical non-buoyant jet. We believe that a detailed study of the initial dilution of a non-buoyant vertical round jet in a wave–-current environment would serve as a useful reference for future studies on the corresponding buoyant cases.

2. Methodology

2.1. Dimensional analysis

The initial dilution, S, of a non-buoyant vertical round jet in a wave–current environment can be expressed in the following functional form:

$$S = f_1(d, w_0, h_0, h, H, T, u_0) \tag{6}$$

The wave force near the jet orifice has a critical influence on the swaying of the jet body and the average dilution. Hence, the maximum wave-induced horizontal velocity at the jet orifice position is usually selected as the wave characteristic velocity in previous studies (Chin, 1987; Sharp et al., 2014; Xu et al., 2017).

In addition, the wave frequency ω ($\omega = 2\pi/T$) is another characteristic parameter that can affect the jet initial dilution. Therefore, Eq. (6) can be expressed as

$$S = f_2(d, w_0, u_w, \omega, u_0) \tag{7}$$

Xu et al. (2017) expressed Eq. (7) as follows using three dimensionless parameters:

$$S = f_3(R_{jc}, R_{wc}, St) \tag{8}$$

where R_{wc} and St are the wave-to-current velocity ratio and Strouhal number, respectively. They are expressed as

$$R_{jc} = \frac{w_0}{u_0} \tag{9}$$

$$R_{wc} = \frac{u_w}{u_0} \tag{10}$$

$$St = \frac{d\omega}{2\pi u_0} \tag{11}$$

The jet initial flow flux Q_0 and the jet initial momentum flux M_0 are expressed as:

$$Q_0 = \frac{1}{4}\pi d^2 w_0 \tag{12}$$

$$M_0 = \frac{1}{4}\pi d^2 w_0^2 \tag{13}$$

The jet body in the wave–current environment is deflected by the current, and simultaneously, the body sways because of the wave-