Estuarine, Coastal and Shelf Science 165 (2015) 10–24

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Drag forces on aquatic plants in nonlinear random waves plus current

Pierre-Yves Henry [a, *], Dag Myrhaug [a], Jochen Aberle [b]

[a] Department of Marine Technology, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway
[b] Department of Hydraulics and Environmental Engineering, Norwegian University of Science and Technology, NO-7491 Trondheim, Norway

ARTICLE INFO

Article history:
Received 7 March 2015
Received in revised form
22 August 2015
Accepted 26 August 2015
Available online 31 August 2015

Keywords:
Nonlinear random wave
Wave plus current
Drag force
Drag coefficient
Stochastic method
Salt marsh

ABSTRACT

Plant-flow interactions are characterised by an assemblage of processes acting at different temporal and spatial scales. In order to mathematically characterise these interactions, such processes have to be parameterised given some simplifications. Typically, drag coefficients are derived from experiments to characterise the plant reconfiguration and wave energy dissipation processes. By reviewing the different plant drag coefficients C_D valid in oscillatory flows, this study first highlights the lack of normalisation of the different existing C_D formulations and identifies possibilities for a standardisation of the formulations for oscillatory and steady flows. Then, by taking into account the wave crest height distribution of a sea state condition, this study further develops a stochastic method to compute the expected wave induced forces on a plant in linear/nonlinear random waves plus current based on two different C_D formulations for waves alone and waves plus current. This method improves the characterisation of the stochastic plant–flow interactions by allowing the calculation of expected values under different random wave plus currents conditions. Results are compared to a classic deterministic approach and some differences are identified, calling for further investigations against experimental datasets. Based on the appropriate C_D formulations, this study finally revealed that wave nonlinearities have a significant effect on expected wave forces for a higher wave activity, and that in presence of an increasing current, the effect of wave nonlinearities decreases while the expected wave forces increase.

1. Introduction

Vegetation is a ubiquitous feature in aquatic environments affecting many physical, chemical, and biological processes across a wide range of spatial and temporal scales (Nikora, 2010; Nepf, 2012; Nikora et al., 2012). The interaction between flow and vegetation has important implications for many ecological and engineering applications and has consequently been in the focus of research in the past decades. A large body of research has focused on the exerted drag forces by mimicking vegetation with stiff elements such as cylinders although most plants are flexible (e.g., Aberle and Järvelä, 2013). Both stiff elements and flexible plants offer resistance to the incoming flow, generating an energy transfer from the flow to the plant, which in turn affects turbulence and wave-patterns. Compared to stiff elements, flexible plants will, under energetic flow conditions (high currents or wave-induced velocities), adopt a streamlined shape and reduce their projected frontal area to reduce their exposure to the flow attack (de Langre et al., 2012; Miller et al., 2012; Siniscalchi et al., 2012; Albayrak et al., 2013). The reconfiguration depends on the plants' mechanical and structural properties and is the key to their survival in high energy flows.

Flexible plants such as salt marsh plants and seagrasses have, among others, been recognised as potential wave-dampers (Feagin et al., 2011; Paul and Amos, 2011; Möller et al., 2014). The adequate design of such natural engineering structures requires an enhanced understanding of the relevant processes and hence of fluid forces (and the corresponding main component, the drag force), energy dissipation (turbulence, wave damping), and plant ecology (plant mechanical and physiological stresses). One of the keys for the adequate description of drag forces can be seen in the parameterisation of a proper plant related drag coefficient C_D (Mendez and Losada, 2004; Möller et al., 2014; Ozeren et al., 2014; Zeller et al., 2014). This parameterisation is presently one of the major difficulties when describing plant–flow interactions not only in coastal but also in fresh water environments (Aberle and Järvelä, 2013, 2015). In general, many different approaches for the parameterisation of drag forces have been suggested for both environments

* Corresponding author.
E-mail address: pierre-yves.henry@ntnu.no (P.-Y. Henry).

http://dx.doi.org/10.1016/j.ecss.2015.08.021
0272-7714/

(Nepf, 2011). However, drag coefficients for flexible aquatic plants have always been derived from experimental datasets as information on plant reconfiguration and wave energy dissipation is required for their determination. Thus, the derived formulations are, in theory, limited to the conditions covered by the experiments.

Moreover, many experimental or numerical studies focused on drag force estimations under simplified boundary conditions (linear waves or current alone; e.g. (Suzuki et al., 2012; Anderson and Smith, 2014; Ozeren et al., 2014) although these estimations are generally more complex in field conditions (Massel et al., 1999; Paul and Amos, 2011; Jadhav et al., 2013). Deterministic approaches are commonly used to characterise random wave conditions, reducing for example the spectrum of wave-induced velocities to a single statistical value (typically the root-mean-square value). These approaches may lead to a misrepresentation of the stochastic plant–flow interactions (Bradley and Houser, 2009; Jadhav et al., 2013; Anderson and Smith, 2014).

After a critical review of the available C_D formulations under wave conditions, this study develops a stochastic method to compute characteristic statistical values of the wave-induced forces on a single plant in various random waves plus current conditions. C_D formulations derived for regular waves by Ozeren et al. (2014) (waves alone) and Hu et al. (2014) (waves plus current) are applied, within their domain of applicability, to each single wave of the narrow-banded irregular wave spectrum. Nonlinear wave effects (long- and short-crested) are included and discussed considering the Forristall (2000) wave crest height distribution. Finally, the method is applied to live salt marsh plants (*Juncus roemerianus*) using the Ozeren et al. (2014) C_D formulations, and discussed in the light of the conclusions of the critical review.

2. C_D formulations for an aquatic plant in waves

2.1. Drag forces for regular waves plus current

The simplest approach to derive an expression of the fluid forces experienced by plants is to consider only the main component, i.e. the drag force, and neglecting the plants' swaying motion and inertial force (Mendez and Losada, 2004) resulting in a so-called Morison-type equation. This approach is systematically used in coastal engineering descriptions of plant–flow interaction and the horizontal time-varying force on a plant community per unit volume is thus expressed as:

$$F(t) = \frac{1}{2}\rho C_D b_v N\, u(t)\ |u(t)| \tag{1}$$

where $u(t)$ is the undisturbed horizontal wave-induced velocity at a reference location along or in the vegetation region, t is the time, ρ is the density of water, b_v is the mean plant width (corresponding to the plant area per unit height of the vegetation stand normal to $u(t)$), N is the number of plants per unit area, and C_D is a bulk drag coefficient. It should be noted that the correct calculation of $F(t)$ requires the use of the relative velocity between the fluid and the plants instead of $u(t)$. In addition, there is normally no linear relation between the total force exerted on a plant patch and its number of stems. However, it is common practice to link $F(t)$ and N linearly as described in Eq. (1) so that potential shading effects and interactions with other stems are taken into account by C_D as done in river flows by Lindner (1982) or Li and Shen (1973). In order to provide general results, the dimensional forces computed in this section correspond to the force on one plant per unit area (N chosen equal to 1 by default in Eq. (1)). Eq. (1) is also valid for a flexible plant (Mendez and Losada, 2004; Henry and Myrhaug, 2013). Applying Eq. (1) to oscillatory flows, the maximum horizontal drag force per unit volume within a wave cycle is given by

$$F_{max} = \frac{1}{2}\rho C_D b_v U_w^2 \tag{2}$$

where U_w is the maximum horizontal velocity within the wave cycle. For the case of regular waves plus current $U_{max} = U_w + U$ may be used instead of U_w, where U is the bulk velocity of the steady current. The accuracy of this formulation depends not only on the plant width but also on the definition of the drag coefficient C_D.

2.2. Drag coefficient formulations for oscillatory flows

Formulations for the drag coefficient C_D have generally been derived by determining the ratio F_{max}/U_w^2 from experimental data for different flow conditions. Regarding oscillatory flows, C_D-values have mostly been determined from observations of the wave decay over a vegetation patch following the method first described by Dalrymple et al. (1984), although it is also possible to determine these values using direct measurements of F_{max} and U_w (Hu et al., 2014). In general, two different kind of formulations have been developed for the determination of C_D which are based on the Reynolds number Re and the Keulegan–Carpenter number K_C, respectively, with the corresponding approaches being summarized in Table 1.

Expressing C_D as a function of the Reynolds number Re is the classical expression used in fluid mechanics. For waves the corresponding relationship is mostly written as $C_D = \hat{\alpha} + (\hat{\beta}/Re)^{\gamma}$, where $(\hat{\alpha}, \hat{\beta}, \gamma)$ are non-dimensional parameters, and $Re = U_w b_v/\nu$, where ν is the kinematic viscosity of the fluid. As for steady flow cases, typical for fresh water environments, various parameters $(\hat{\alpha}, \hat{\beta}, \gamma)$ have been suggested for oscillatory flows (Table 1 and (Nepf, 2011)). On the other hand, C_D can also be expressed as a function of the Keulegan–Carpenter number K_C (defined as the ratio between the fluid particle excursion amplitude and the characteristic dimension of the plant) for oscillatory flows. The corresponding expressions can take different forms (Table 1), but the most common expression is $C_D = a\,K_C^b$, where (a,b) are non-dimensional parameters, and $K_C = U_w T/b_v$, where T is the wave period which can be replaced by the spectral peak wave period T_p in the case of random waves. Inertia forces cannot be neglected for relatively small values of K_C (Ozeren et al. (2014)) so that in a coastal environment, approaches based on Eq. (1) are only valid for larger values of K_C (or Re), i.e. when drag forces dominate over inertia forces due to the flow separation and vortex shedding processes in the wake of the plants. However, Bradley and Houser (2009) argued that under lower-energy conditions, wave energy dissipation is driven by relative blade motion, best described by K_C, and not in-canopy turbulent dissipation typical for high-energy conditions (and best described by Re). As a consequence, there exists a range between very low energy and high energy flows where a formulation of the bulk drag coefficient based on K_C seems to describe experimental data better than that based on a Reynolds number (Mendez and Losada, 2004; Lowe et al., 2007; Sánchez-González et al., 2011; Jadhav et al., 2013; Ozeren et al., 2014). This may explain why Möller et al. (2014) observed that the expression for C_D dependent on Re formulation led to over prediction of wave dissipation for low-energy conditions. It should be noted, however, that all of these different formulations neglect the relative velocity of the plant compared to the flow, and doesn't explicitly include reconfiguration processes (bending, pronation), which may lead to inaccuracies in wave forces and energy dissipation estimations (Zeller et al., 2014).

In the case of irregular waves, the bulk drag coefficient C_D varies for each individual wave, depending on the wave height and wave period. Bradley and Houser (2009) argued that plants (seagrasses)