Coastal Engineering 84 (2014) 73–80

Contents lists available at ScienceDirect

Coastal Engineering

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

Short communication

Geometrical and mechanical properties of four species of northern European brown macroalgae

M. Paul [a,*], P.-Y.T. Henry [b], R.E. Thomas [c]

[a] Leibniz Universität Hannover, Forschungszentrum Küste, Merkurstr. 11, 30419 Hannover, Germany
[b] Department of Marine Technology, Norwegian University of Science and Technology, Otto Nielsens vei 10, NO-7491 Trondheim, Norway
[c] Department of Geography, Environment and Earth Sciences, University of Hull, Cottingham Road, Hull HU6 7RX, UK

ARTICLE INFO

Article history:
Received 23 May 2013
Received in revised form 4 October 2013
Accepted 14 November 2013
Available online 10 December 2013

Keywords:
Brown macroalgae
Bending modulus
Flexural rigidity
Buoyancy

ABSTRACT

Aquatic vegetation interacts with the flow by posing an obstruction and in return experiences drag and is reconfigured by acting forces. It is suggested that plant buoyancy and stiffness affect these bio-physical interactions and hence should be considered when including vegetation in physical and numerical hydrodynamic models. However, data on these parameters is either lacking for many species or existing information is insufficient to model flexible aquatic vegetation correctly. Previous studies have focused on plant stems, but did not take plant foliage into account. The present study extends the existing knowledge base by providing data for four northern European brown macroalgae and also provides a comparison between the mechanical properties of stem and blade tissue for these species. Specimens of *Alaria esculenta*, *Laminaria digitata*, *Fucus serratus* and *Fucus vesiculosus* were collected from a small tidal inlet in Norway. Other than *F. serratus*, the macroalgae were positively buoyant and all stems showed bending moduli in agreement with previous studies with respect to their order of magnitude. Only *L. digitata* exhibited a significant difference between bending moduli for stems and blades and also between the tip and the base of the blades. However, there were differences in flexural rigidities (product of bending modulus and second moment of cross-sectional area) of both stems and blades and the tip and the base of blades of all but *F. serratus*. This highlights the important influence of cross-sectional area and cross-sectional shape on stiffness.

1. Introduction

It has been recognised that coastal vegetation enhances wave attenuation (Augustin et al., 2009; Méndez and Losada, 2004; Möller et al., 1999; Paul et al., 2012) and that there may be great potential in using vegetation for coastal protection purposes (Feagin et al., 2010; Feagin et al., 2011). Aquatic vegetation reduces fluid velocities by imposing a blockage, causing drag (Bal et al., 2011; Miler et al., 2012), generating turbulence and enhancing roughness (Ghisalberti and Nepf, 2002; Nepf and Ghisalberti, 2008). In return, hydrodynamic forcing leads to plant reconfiguration which can cause leaf shading and impact upon photosynthesis (Bal et al., 2011). These bio-physical interactions are partly governed by geometrical plant properties such as stem and shoot dimensions and density (i.e. number of plants per unit area) (Boller and Carrington, 2006; Bouma et al., 2010; Bradley and Houser, 2009; Fonseca and Koehl, 2006; Möller et al., 1999; Newell and Koch, 2004; Paul and Amos, 2011). Additionally, mechanical parameters, in particular buoyancy and stiffness, strongly influence the drag imposed on vegetation (Nepf and Koch, 1999) and play a significant role in wave attenuation (Bouma et al., 2005; Denny and Gaylord, 2002; Paul et al., 2012; Stewart, 2006).

Advances have been made to numerically simulate the interaction of vegetation with hydrodynamics (Dijkstra and Uittenbogaard, 2010; Luhar and Nepf, 2011), but validation has only been undertaken using surrogate plants. To date, the ability of physical models of plants to mimic real vegetation has mainly been determined by visual observation (Folkard, 2005; Manca, 2010; Paul et al., 2012). However, a more quantitative approach is desirable to increase transferability of results between the field and numerical and laboratory models. A recent study of *Laminaria digitata* based on the data presented here shows that knowledge of mechanical plant properties can aid the production of more realistic surrogates (Paul and Henry, 2013). The effect of the developed surrogates on hydrodynamics was compared with real vegetation under field conditions at the field site used during this study and yielded very good agreement for mean velocity and turbulence profiles adjacent to plant locations (unpublished data). Moreover, detailed knowledge of mechanical plant properties may improve the performance of numerical models that simulate the interaction between vegetation and hydrodynamics through improved parameterisation (Dijkstra and Uittenbogaard, 2010; Méndez and Losada, 2004).

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* Corresponding author. Tel.: +49 511 7629233.
E-mail addresses: paul@fzk-nth.de (M. Paul), pierre-yves.henry@ntnu.no (P.-Y.T. Henry), R.Thomas@hull.ac.uk (R.E. Thomas).

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http://dx.doi.org/10.1016/j.coastaleng.2013.11.007

However, mechanical parameters are not commonly established during field monitoring of aquatic vegetation and hence data is lacking to adequately consider bio-physical processes in physical and numerical models.

A number of past studies have presented data for mechanical properties, especially Young's bending modulus, with most data being available for riparian vegetation (e.g. Freeman et al., 2000; Ostendorp, 1995). Recently, engineering properties of the salt marsh plant *Spartina alterniflora* were evaluated, which yielded a bending modulus of 1.41 ± 0.71 GPa for healthy, fully developed stems (Feagin et al., 2011). This value is similar to bending moduli obtained for the seagrasses *Zostera marina* (0.4–2.4 GPa) (Luhar and Nepf, 2011) and *Posidonia oceanica* (0.47 ± 0.06 GPa) (Folkard, 2005). Other aquatic species that have been investigated to date yielded lower values, indicating that they are more flexible. Miler et al. (2012), for instance, analysed four fresh water species and observed bending moduli of 12.5–90 MPa, with one species being too fragile for testing. Several other studies have addressed macroalgae (Dubi, 1995; Harder et al., 2006; Koehl, 1979; Stewart, 2004), yielding values between 3.5 MPa (*Durvillaea antarctica*) and 109.4 MPa (*Laminaria hyperborea*). It should, however, be noted that all previous studies focused on plant stems only and did not evaluate the mechanical properties of leaves or blades.

The present study adds to the existing datasets by presenting geometrical and mechanical properties of four species of brown macroalgae from a field site in Norway. Moreover, and to our knowledge, for the first time, data for blade sections are also presented. Together with the data for stems of the same specimens, this identifies differences between plant parts that may be of importance for future modelling activities.

2. Methods

2.1. Site

The study site is a small tidal inlet located at the entrance of Trondheimsfjord, Sør-Trøndelag, Norway (Fig. 1a). The inlet is approximately triangular in planform, with its mouth to the northwest. The deepest parts of the inlet are to the centre and northeast, where the depth is between 25 and 30 m. A delta, formed of coarse sand and broken shells, has been deposited in the northwest corner of the inlet (Fig. 1b). This delta is fed by a channel which connects the inlet to the fjord. The channel is 15 m wide and up to 4 m deep at the bridge that marks the seaward margin of the inlet (Fig. 1b). The bed of the outlet channel is formed of gravel and cobbles. The outlet channel is pinned to the northern edge of the delta and thus the depth of water over the delta shallows from west to east and from north to south. For much of the delta, the average water depth above the flat sandy bed is 0.5 m.

The site is well sheltered from waves and the speed of the current in the study area is entirely dependent upon tidal forcing. In the sampling area, the tidal range varies between 0.3 m during neap and 1 m during spring tides; tides are semi-diurnal, strongly asymmetric and flood-dominated. During the sampling period (May 2012) maximum velocities of 0.4 m s^{-1} during flood tides and 0.15 m s^{-1} during ebb tides were observed in the sampling area. Flow velocities increase towards the mouth of the inlet and can reach up to 6 m s^{-1}. The catchment area of the inlet is negligible (1.9 km^2). Therefore the salinity in the inlet is close to the values found in the fjord (31 ± 4 ppm), and varies depending on the thermal and tidal conditions. A more detailed site description can be found in Thomas et al. (2013), who evaluated the effect of macroalgae presence on the mean and turbulent flow fields at the location.

2.2. Species

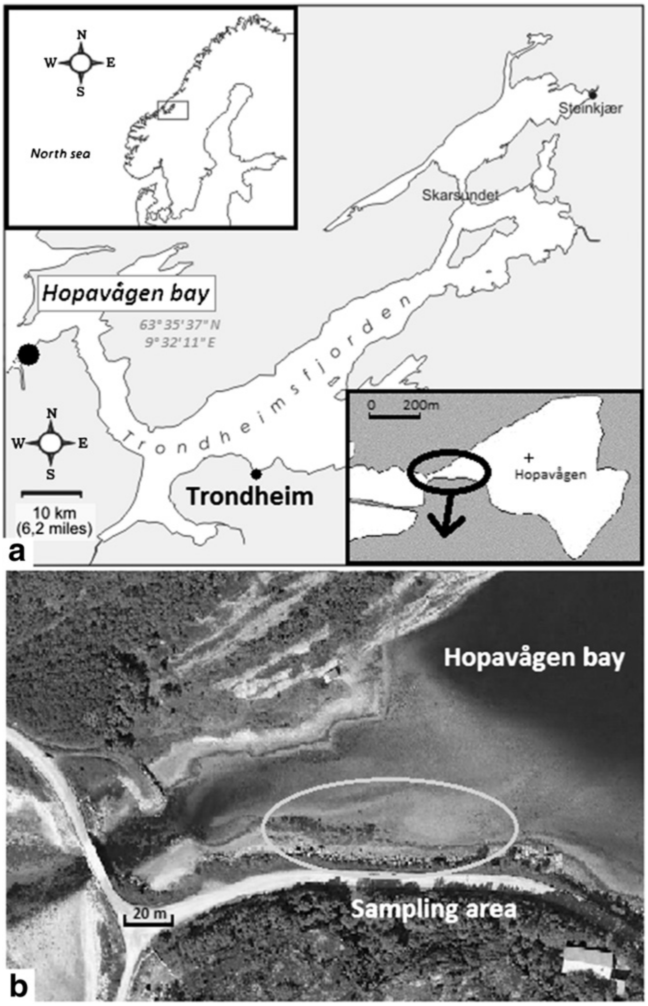

Fig. 1. a) Location of the tidal inlet (Hopavågen bay; 63°35′37″N, 9°32′11″E); b) aerial view of the sampling area (www.norgeskart.no).

Biodiversity in the study area is remarkably high, with many species of algae, molluscs, crustaceans and fish observed in a very small area. Different species of algae cover much of the study area in spring and summer. Most specimens are brown algae, but green algae have also been observed. In this study, samples of four different species of brown macroalgae were collected along the southern shoreline of the outlet channel (Fig. 1b). The species under investigation are *Alaria esculenta*, *L. digitata*, *Fucus vesiculosus* and *Fucus serratus*. All four species colonise hard substrate along the eastern and western shores of the North Atlantic with the *Fucus* species extending south as far as the Azores and Canary Islands. At the study site, rocks, pebbles and mussel shells, both dead and alive, provided the substrate to which plants attach with their holdfast.

A. esculenta (Fig. 2a) colonises the lower intertidal and the upper subtidal zone along rocky shores of the North Atlantic (Dring, 1982). It grows a single stipe from a holdfast that continues as a tapering midrib through the whole blade. In sheltered conditions, *A. esculenta* produces a long stipe and wide lamina base while both stipe and base tend to be shorter under exposed conditions (Widdowson, 1971). The wavy blade is brown in colour, and is very thin, flexible and delicate. Blades typically grow to 0.3–1.5 m in length and may be torn by waves. However, they can reach up to 4 m in length in locations with strong currents and low wave action. Below the base of the blade, flat sporophylls that carry the reproductive organs branch off the stipe (Guiry, 1997).

At its lower depth boundary, *A. esculenta* overlaps with *L. digitata* (Fig. 2b). *L. digitata* also consists of a holdfast, a single stipe and a large (up to 2 m length) oval blade. However, in contrast to *A. esculenta*, the blade lacks a midrib, and is thicker and less flexible than that of *A. esculenta* (Lobban and Harrison, 1997). The substrate conditions in