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Technical note

Modelling of flexible aquatic plants from silicone syntactic foams

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ABSTRACT
In experiments with vegetated flows, natural plants are often represented by artificial surrogates, which eliminate effects of plants physiology to easy fit the experimental set-ups. Using surrogates of flexible aquatic plants, the buoyancy and rigidity are supposed to match those in tissues of the natural plants. This paper introduces a new technique for manufacturing composite surrogates from silicon syntactic foams and reports on laboratory tests, which illustrate that such surrogates respond to flow similarly to the natural plants. Practical applications are illustrated by examples from recent field-based experiments.

Keywords: Biomechanics; field studies; hydraulic models; laboratory studies; vegetated flows

1 Introduction

The last two decades have seen an increasing attention to vegetated flows and their experimental study (Järvelä, 2005; Nepf, 2012; Nikora, 2010; Okamoto et al., 2016; Sand-Jensen & Pedersen, 1999). Typically, hydraulic experiments are carried out under idealized laboratory conditions, in which appropriate representation of aquatic vegetation ensures both realism and practical value (Frostick et al., 2011). There are three major methods: (1) replanting/growing natural plants inside the experimental facilities (Cornacchia et al., 2018; Järvelä, 2005; O'Hare et al., 2007; Sand-Jensen, 2008; Shucksmith et al., 2010; Siniscalchi & Nikora, 2012); (2) mimicking aquatic vegetation with terrestrial/aquarium plant species (Carollo et al., 2002; Kouwen & Unny, 1973; Nepf, 2012; Sand-Jensen, 2003; Wilson, 2007; Wilson & Horritt, 2002); and (3) using artificial surrogates of natural plants (Fryer et al., 2015; Ghisalberti & Nepf, 2002; Nikora et al., 2013; Okamoto et al., 2016; Ortiz et al., 2013; Sand-Jensen, 2003; Vettori & Nikora, 2018, 2020). To overcome the issues of scale reduction and oversimplification, hydraulic experiments are also carried out with natural aquatic plants *in situ* (Lacy & Wyllie-Echeverria, 2011; Sand-Jensen & Pedersen, 1999), in natural river environments with replanted vegetation (Sukhodolov & Sukhodolova, 2012; Sukhodolova & Sukhodolov, 2012), and in large-scale outdoor facilities (Rominger et al., 2010) with the use of artificial surrogate vegetation (Sukhodolov et al., 2017). The success of the experiments with live aquatic vegetation depends on careful husbandry of the plants, while the use of surrogate vegetation offers many advantages for experimental control (Vettori & Rice, 2020).

The physiology of living plants can be seriously stressed in laboratory environments by tap water and insufficient irradiance even within five days of storage (Vettori & Rice, 2020). The volume of aquatic plants controlled by aerenchyma or air-vesicles significantly changes within minutes when plants are exposed to air (Westlake, 1965). Even in field-based experiments intensive growth rates can cause twofold changes of plant biomass within the period of a week (Sukhodolova, 2017). Surrogates eliminate many difficulties related to vegetation handling and using them is often the only possibility available to the experimenter. Although recent studies warn that simplified

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morphologies in surrogates may result in weaker drag forces and altered reconfiguration properties, they are certainly capable of successfully simulating the basic features that can be retained by a proper design and manufacturing process (Fryer et al., 2015; Vettori & Nikora, 2020).

The similarity criteria guiding the manufacturing technologies of surrogates depend on the flow characteristics, plant morphology and biomechanical properties of prototype vegetation species (Luhar & Nepf, 2011; Miler et al., 2014; Vettori & Nikora, 2018). The most important criteria can be represented by a pair of dimensionless numbers expressing relationships between flow and biomechanical properties: the ratio of drag force to elastic force or the Cauchy number, C_a; and the ratio of drag force to buoyancy force, C_b. Previous studies were mostly focused on the similarity to the Cauchy number, assuming that the buoyancy force is negligible because the density of plant-tissue is usually neutrally buoyant in marine environments (Gaylord & Denny, 1997; Luhar & Nepf, 2011; Vettori & Nikora, 2018; Table 1). However, by exposing mechanical stress on water plants in highly dynamic environments (e.g. rivers and surf zones), the flow affects plant morphology and their biomechanical properties through the mechanism of phenotypic plasticity (Puijalon et al., 2007, 2011; Puijalon & Bornette, 2006). Therefore, many freshwater and some marine plants control the balance of forces primarily by buoyancy while the low rigidity of their tissues enhances flexibility and ensures higher rates of survival. Buoyancy of such plants is enhanced either morphologically by sporting air-vesicles and floating leaves or internally by micro air-vesicles or aerenchyma tissue (Fig. 1).

Table 1 Density of natural aquatic plants

Plant species	Density ($kg\,m^{-3}$)
Freshwater species	
Butomis umbellatus[1]	588–769
Chara foetida[1]	435–667
Cyperus fuscus[1]	910
Eichhornia crassipes[1]	769
Myriophyllum verticcillatum[1]	769
Nitella mucronata[1]	943
Potamogeton pectinatus[1]	625–833
Scirpus locustris[1]	270–385
Sagittaria sagittifolia[2]	573–717
Vallisneria spiralis[3]	580–690
Cabomba caroliniana[3]	620–710
Marine species	
Eisenia arborea[4]	1025–1050
Halodite wrightii[5]	913
Thalassia testudinum[5]	913
Zostera marina[5]	673
Saccharina latissima[6]	819–1059

[1]Westlake (1965), [2]Sukhodolova (2008), [3]present study, [4]Gaylord and Denny (1997), [5]Luhar and Nepf (2011), [6]Vettori & Nikora (2018).

Surrogates of aquatic plants with naturally looking blade morphology are commercially manufactured to decorate aquariums and they are often used in biological studies (Grutters et al., 2015; Warfe & Barmuta, 2004). Even though these surrogates reproduce well quantitative measures of shape complexity such as the fractal dimension, their material densities are larger than the water density and they are more rigid than natural plants (Grutters et al., 2015). In this respect, they are identical to terrestrial plants because their vertical posture in the flow is maintained by flexural rigidity. In hydraulic research it is common to manufacture surrogates which match the similarity requirements (Fryer et al., 2015; Rominger & Nepf, 2014; Vettori & Nikora, 2020). In the cited studies, the surrogates were made of vinylpolysiloxane or polyethylene with densities ranging from 1024 to 1092 $kg\,m^{-3}$ and Young's modulus ranging from 0.23 to 5 MPa.

This paper informs on a new approach in physical modelling of flexible aquatic plants with variable buoyancy from silicone syntactic foams. The objectives of this study were threefold: (1) to introduce the theoretical concept illustrating the importance of buoyancy force for maintaining the posture in flexible aquatic plants; (2) to elaborate an inexpensive technique for manufacturing surrogate plants with required buoyancy; and (3) to

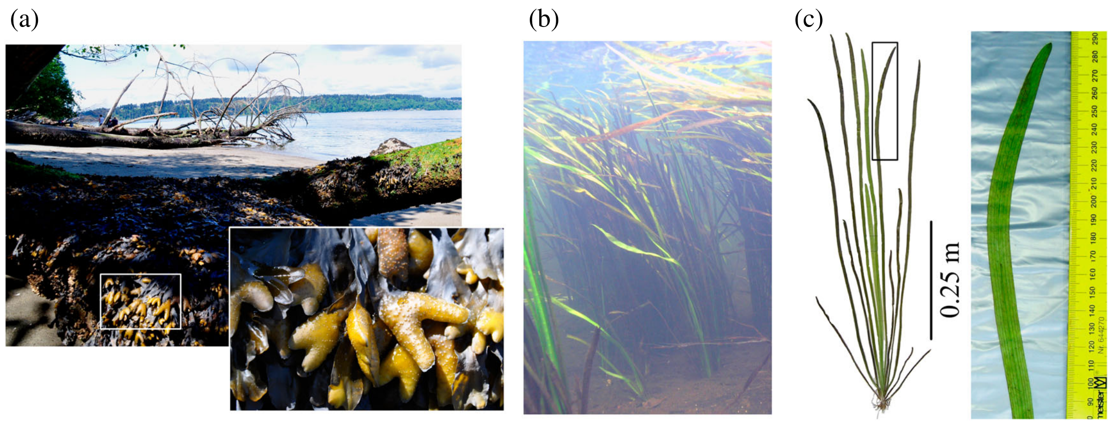

Figure 1 Examples of flexible aquatic plants with the buoyancy-dominant forces balance: (a) flat wrack *Fucus spiralis* brown algae in a marine tidal zone (inset shows air-vesicles), (b) arrowhead *Sagittaria sagittifolia* in a lowland river, and (c) typical arrowhead plant (inset illustrates part of a blade)

illustrate the basic behaviour of surrogates and their application for modelling large-scale patchy formations.

2 Theoretical framework

Hydraulic studies of vegetated flows predominantly focus on the effects of assemblages of aquatic plants rather than individual plants, though biomechanical properties of plants define their posture in the water column. The posture of plants is represented by a bending angle β (Fig. 2a), which varies along vegetation patches because of sheltering effects. Mimicking this behaviour is one of most important aspects for studies of hydrodynamics on a patch scale and the following analysis focuses on the role that buoyancy plays in governing the posture of flexible aquatic plants in running waters.

An individual plant can be schematized by a flexible cantilever beam of length L, width W, and thickness d (Fig. 2a). In a uniform open-channel flow, the beam attains a dynamically stable posture with deflection angle $\alpha = 90 - \beta$ when the drag force $F_D = 0.5\rho C_d {U_a}^2 WL \cos(\alpha) = F_{D_0}\cos(\alpha)$ is balanced by a buoyancy force $F_B = gWLd(\rho_0 - \rho)$ and the reaction force of the beam $F_R = 3EI_a\delta_b L^{-3}$ due to flexural rigidity of its material, where C_D is the drag coefficient, U_a is the mean flow velocity, EI_a is flexural rigidity, g is the gravitational acceleration, δ_b is deflection length, and ρ_0, ρ are density of water and beam material, respectively. In the coordinate system with axis y_1 aligned with the direction of plant reaction force (Sukhodolova, 2008):

$$F_{D_0}\cos^2(\alpha) = F_B\sin(\alpha) + F_R \tag{1}$$

Assuming that $\delta_b = L\sin(\alpha)$ (Fig. 2a) and, respectively, $F_R = F_{R_0}\sin(\alpha)$ with $F_{R_0} = 3EI_aL^{-2}$, Eq. (1) can be rewritten as:

$$\cos^2(\alpha) = 2\phi\sin(\alpha) \tag{2}$$

where $\phi = 0.5(F_B + F_{R_0})/F_{D_0}$ is the ratio between the integral effect by buoyancy and rigidity forces, determined by biomechanical properties of the plant and the drag force exerted by the flow. The positive solution of the quadratic Eq. (2) consistent with the physical considerations is:

$$\sin(\alpha) = \sqrt{\phi^2 + 1} - \phi \tag{3}$$

The asymptotic behaviour of Eq. (3) is represented by two cases: (a) when rigidity dominates the balance ($F_{R_0} \gg F_B$), and (b) when buoyancy is dominant ($F_{R_0} \ll F_B$). In the first case, Eq. (3) can be solved for small deflections ($\alpha \leq 20°$) and $\mathsf{C_a}$ is a sufficient criterion for reproducing the posture (Fig. 2b). In the second case, the ratio is defined by the buoyancy ratio, which is for flexible plants with $\alpha \geq 30°$ $\phi = 0.5F_B/F_{D_0} \leq 1$, and Eq. (3) transforms into:

$$\sin(\alpha) = 1 - \phi \tag{4}$$

This shows that for highly buoyant aquatic plants the similarity on the Cauchy number is insufficient for proper modelling of the plants posture, while ensuring the similarity on the buoyancy ratio is mandatory in manufacturing surrogate flexible aquatic plants.

3 Materials and methods

3.1 *Silicone syntactic foam*

Silicone polymers have a wide range of applications requiring high-tech materials, such as the automobile industry, aerotechnique, food production, construction, medicine, and electronics (Ackermann & Damrath, 1989). Lightweight flexible materials, called silicone foams, are fabricated by the expansion of a gas inside a plastic mass during polymerization processes (Bhowmick & Stephens, 2001). However, the void spaces produced by gas inside common silicone foam are interconnected, which limits their application in liquids.

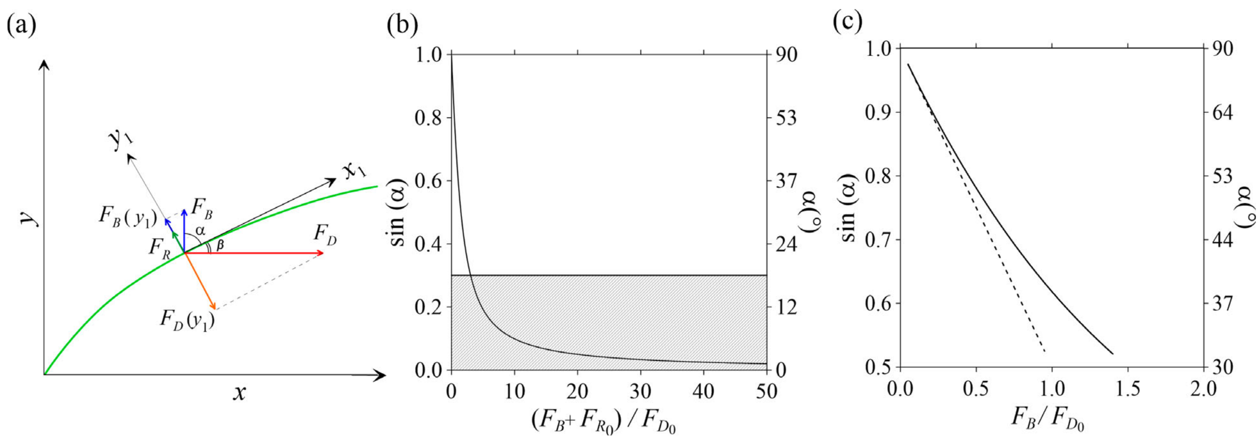

Figure 2 (a) A scheme of the balance of forces, (b) deflecting angle as a function of ratio of forces (shaded area shows the region of similarity by the Cauchy number), and (c) deflecting angle as a function of ratio of forces for flexible plants (solid line: Eq. (4); dashed line: Eq. (3))

Syntactic silicone foam was developed specifically as improved buoyancy material for marine applications. These foams are composite materials in which hollow microspheres, or other small hollow particles, are dispersed (Puterman et al., 1980). Thereby the voids inside the material are enclosed within the hollow particles and are isolated from each other. Glass microspheres are typical light-weight fillers for composite polymeric materials of different kinds (Budov, 1994).

3.2 *Manufacturing surrogate plants from silicone syntactic foam*

Manufacturing of surrogate plants involves the process of moulding and requires two main components: a rubber base composed of a silicone polymer with additives and a filler to adjust the density of the foam. In the original state, the silicone rubber is a liquid, which converts to solid by curing, vulcanizing, or catalysing. The method of conversion depends on the complexity of the shape of the surrogate and the method of moulding. For instance, manufacturing complex shape surrogates by injection moulding or 3D printing involves a prolonged curing process (Chen et al., 2019). Two-part curing systems (silicone base-hardener) are preferable in mass production of the simply shaped surrogates because they cure fast on their own at room temperature. In our study, we focus on a simple-shaped aquatic plant with linear primary foliage, which is characteristic of many natural plants and consistent with the theoretical approach of our study (Figs 1b, c and 2).

We used an addition-cross-linked precision silicone rubber Alpa Sil EH 10:1 as a mould. This material is highly elastic, medium soft rubber with Shore A Hardness (SAH) ranging from 26 to 28 and the density of 1.1 g cm^{-3} (Kunz & Studer, 2006). This material has low viscosity, it pours well during the moulding phase and becomes mechanically stable after remoulding. Modulus of elasticity of Alpa Sil EH 10:1 is 0.996 MPa, which is determined as the ratio between SAH values and elasticity (Gent, 1958; Kunz & Studer, 2006). Alpa Sil EH 10:1 comes in two components of the same density – a polymer, and a hardener. The moulding material is made by mixing the polymer and the hardener in the ratio 10:1 by volume. The liquid phase of the mixture is about 25 minutes at room temperature and the remoulding time is about 2 h.

For maintaining the required buoyancy of the surrogates, the density of silicone rubber is reduced by adding glass microspheres into a liquid silicone mass. In this study we used commercially available water-insoluble, chemically stable borosilicate glass microspheres with average particle sizes ranging from 30 to 110 μm and a nominal density of 0.12 g cm^{-3}. The amount of glass microspheres added to the silicon rubber mass was calculated according to the principle of mass conservation as:

$$V_G = \frac{\rho_S - \rho_E}{\rho_S - \rho_G} V_E \tag{5}$$

where V_G and V_E are the volume of glass microspheres and the mixture, respectively, and ρ_S, ρ_G and ρ_E are densities of silicone, glass bubbles and of the mixture, respectively. The syntactic foam was prepared by carefully mixing the silicone polymer with the glass microspheres and a dye for colouring the silicon mass, then the hardener was added.

Immediately after adding the hardener, the mixture was poured onto smooth plastic boards, shaped by sweeping into the 1.5 mm thin layers, and left to harden. After two hours of hardening, the foams were removed from the boards and their surfaces were treated with a fine grit sandpaper to increase the surface roughness for reducing stickiness of the material. The resultant sheets of silicon foam were cut into 1 cm wide and 30 cm long stripes. At the final stage we performed control measurements of buoyancy by immersing the stripes into a vessel filled with water and measuring the displaced volume.

3.3 *Laboratory tests of surrogate plants*

In order to illustrate the ability of the silicone syntactic surrogates to mimic the posture of natural plants, laboratory tests were completed in the hydraulic laboratory of the Leichtweiß-Institute for Hydraulic Engineering and Water Resources, Technische Universität Braunschweig, Germany. These tests were performed in a 32 m long, 60 cm wide and 40 cm deep laboratory flume. Drag forces were measured with a drag force sensor described in detail by Schoneboom et al. (2008). The sensors were mounted in a box below the flume bottom in the test section ensuring that the sensors did not disturb the flow. Measurements of bending angles were made by taking photographs with a side-view camera.

The design of the laboratory tests focused on the posture of positively buoyant blade-shaped surrogates as a result of a balance with a drag force. To illustrate how the posture of surrogate changes with the flow velocity, three grades of silicone surrogates were prepared corresponding to the densities 600, 650 and 700 kg m^{-3}. Ten identical surrogate plants were prepared for each grade of density and were tested independently for assessing variation.

The density range of the silicone surrogates corresponded to the densities of the two natural aquatic plants *Vallisneria spiralis* and *Cabomba carolineana* (Table 1), which were used in this study for comparison (Fig. 3). The natural plants were aquarium plants grown in artificial facilities, similar to the experimental facilities of this study. The plants of those species were selected to match the lengths and average width of the surrogates because these characteristics determine the buoyancy force acting on the samples. *C. carolineana* was selected because of the contrasting morphology of its foliage, which can affect the balance of forces by increasing the drag force due to the micro-roughness. Both the natural plants and surrogate models were tested at a range of the mean flow velocities ranging from 0.02 to 0.4 m s^{-1}. This

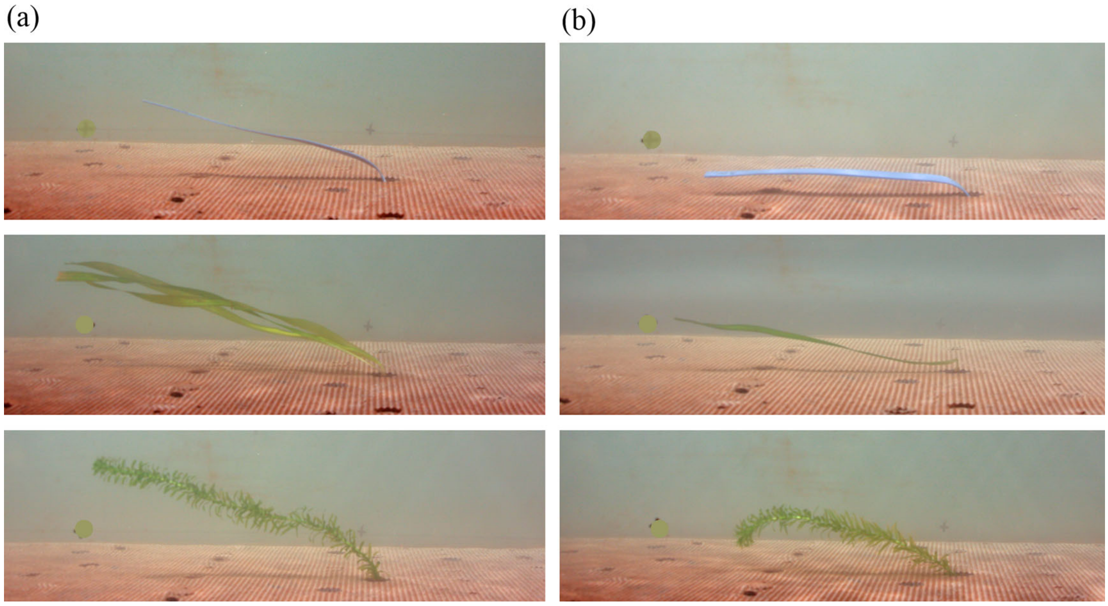

Figure 3 Illustrations of laboratory tests: (a) $U_a = 0.10\,\mathrm{m\,s^{-1}}$, and (b) $U_a = 0.18\,\mathrm{m\,s^{-1}}$ (upper row is a surrogate plant with $\rho_E = 700\,\mathrm{kg\,m^{-3}}$, middle row is *V. spiralis*, and lower row is *C. caroliniana* plant)

velocity range is characteristic of natural lowland rivers with an abundant seasonal growth of aquatic plants (Sukhodolov & Sukhodolova, 2010).

4 Results

The laboratory tests consisted of two sets. In the first set, the surrogates with densities of 600 and 700 $\mathrm{kg\,m^{-3}}$ and the natural plants were exposed to a range of velocities ranging from 0.02 to 0.38 $\mathrm{m\,s^{-1}}$. In these tests, only bending angles of the plants were measured. In the second set, the surrogates of average density of 650 $\mathrm{kg\,m^{-3}}$ and the natural plants were tested to determine the drag force acting on the plants in the range of velocities from 0.10 to 0.40 $\mathrm{m\,s^{-1}}$. Because of limited sensitivity of the drag sensor resulting in low accuracy, the plants and surrogates in this set were not tested at velocity of 0.02 $\mathrm{m\,s^{-1}}$. The results of the laboratory tests are illustrated in Fig. 4.

The laboratory tests show that a difference of about 10% in the density of the material in surrogate plants can result in the differences between deflection angles of about 20° at low velocities and $F_B/F_{D_0} \sim 1$ (Fig. 4a), which is consistent with Eq. (4) (Fig. 2c). The difference in bending reduces with an increase of velocity and this is also correctly predicted by the theoretical framework (Fig. 2c). The tests with the natural plants indicate that deflection and bending angles and their variation with the flow velocity were similar to those measured for the surrogates, and this is also consistent with the scaling framework defined by Eqs (1)–(4). The trends in the bending angles of the surrogates, indicated by the dashed lines in Fig. 4a, form a compact envelope bounding the dynamics of deflection angles observed in the tests with natural plants.

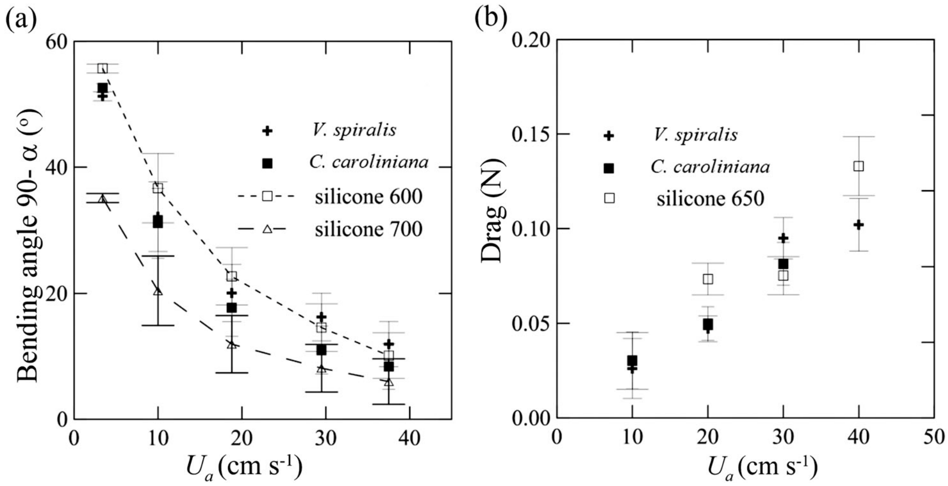

Figure 4 (a) Bending of silicone surrogates and freshwater plants as a function of flow velocity, and (b) drag forces acting on freshwater plants and silicone surrogates at different velocities

In the measurements of the drag forces acting on the plants as a function of flow velocity, we used the silicone plants with the density of 650 kg m^{-3}, which is an average density for the natural plants (Fig. 4b). The values of drag at 10 cm s^{-1} are shown for all plants, though they are difficult to distinguish because of superposition of symbols. The bending angles of *C. caroliniana* plants at 40 cm s^{-1} were too small and the plants collided with the flume bottom, affecting the drag measurements; thus, these data are not presented in Fig. 4b. An agreement between drag forces experienced by the natural and model silicone plants is apparent from this plot. Figure 4b also shows that the drag force reduces with decreasing flow velocity while buoyancy is independent of velocity and remains about 0.02 N. This corresponds to the variation of the ratio F_B/F_{D_0} from 0.1 to 1, which is correctly predicted by the theory (Fig. 2c).

5 Discussion and conclusions

Experimental research implies an idealization, which in studies of vegetated flows is often associated with the use of surrogate plants with a simplified morphology (Luhar & Nepf, 2011; Vettori & Nikora, 2018). Vettori and Nikora (2020) suggest that simplifications of plant morphology reduce drag force and reconfiguration of plant models, though the surrogates reproduce many aspects of live plant dynamics. This highlights the importance of the careful planning of experiments and the role that theoretical assessment of the most essential features of flow and vegetation plays in the success of the studies.

The surrogates used in this study were primarily designed to reproduce the posture of flexible aquatic plants in the range of flow velocities typical for vegetated lowland rivers, allowing for an easy and inexpensive mass production. The flow velocity aspect matters because aquatic plants grow in colonies called patches due to prevalence of vegetative propagation over sexual reproduction (Pringle et al., 1988; Sand-Jensen & Pedersen, 1999). Flow velocities substantially reduce along the patches, causing systematic changes in the posture of plants (Chen et al., 2012; Ortiz et al., 2013). This is an essential feature distinguishing the collective behaviour of flexible aquatic plants from rigid terrestrial vegetation.

The theoretical framework and the experimental tests in this study indicate that our blade-shaped linear surrogates made of the silicone-based syntactic foams are capable of reproducing the posture of aquatic plants in agreement with the predictions of the theory according to Eqs (1)–(4) and similarly to positively buoyant natural plants. Figure 5a and b illustrate the collective behaviour of our silicone surrogate plants in a patch in the laboratory flume. The posture of the surrogate plants adjusts in response to decreasing velocity from the leading edge (Fig. 5b) towards the downstream part of a model patch (Fig. 5a) similarly to the behaviour reported for the patches of *S. sagittifolia* (Sukhodolova & Sukhodolov, 2012).

The low cost of the raw materials and the easy and fast manufacturing of the surrogates enables mass production. Sukhodolov et al. (2017) reported on the first use of silicone syntactic surrogates in field experiments. In their study, a patch with a size of 2 × 5 m was constructed in a model groyne field with a density of 100 individual silicone surrogates per square metre. The study demonstrated that using model vegetation with known properties allows the correct quantitative prediction of flow velocities inside a complex recirculating flow. The surrogate vegetation also demonstrated characteristic monamic response to the large-scale vortices in the mixing layer at the interface between main flow and groyne field (Fig. 5c and d).

This study highlights the importance of buoyancy in the balance of forces responsible for the dynamically stable posture of flexible aquatic plants. It also illustrates the advantages that composite polymer materials offer for the production of inexpensive and easy-to-produce surrogates of such plants for hydraulic studies.

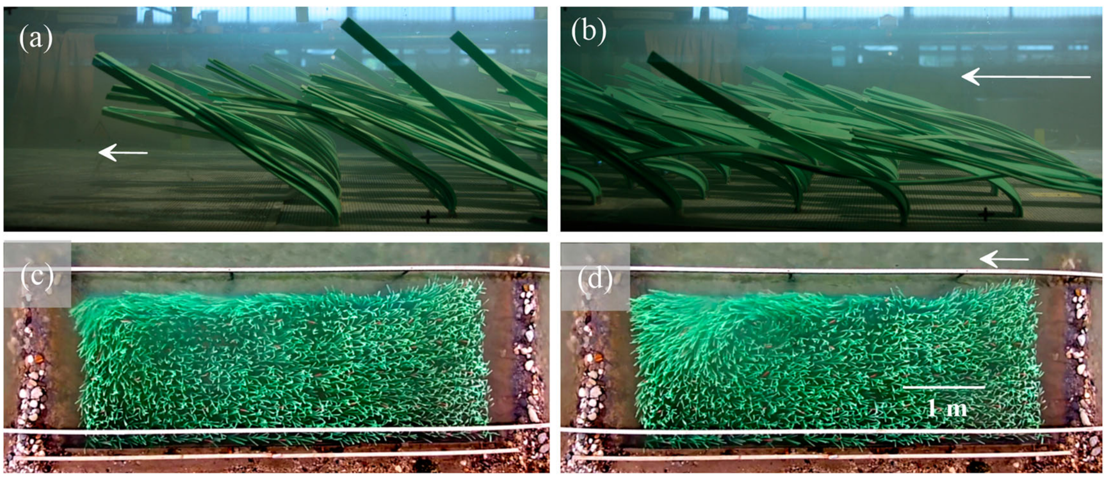

Figure 5 Examples of application of silicone surrogates in the laboratory (top raw) and in the field-based experiments (bottom row): (a) at the trailing edge and (b) at the leading edge of a patch; (c) in a model of vegetated groyne field before the passage of a vortex, and (d) during the passage of a vortex

The main conclusions of this study can be summarized as follows:

- a theory-based framework for downscaling essential biomechanical properties of aquatic vegetation is presented that accounts for the effects of buoyancy;
- a method of manufacturing surrogates of flexible buoyant aquatic plants using silicone-based syntactic foams is developed;
- laboratory tests illustrate that the behaviour of our surrogates in open-channel flow agrees with the theoretical framework and that it is similar to that of natural positively buoyant aquatic plants.

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Notation

$\mathsf{C_a}$ = Cauchy number (–)
$\mathsf{C_b}$ = ratio of drag force to buoyancy force (–)
C_d = drag coefficient (–)
d = thickness of the plant (m)
E = modulus of elasticity (Pa)
F_D = drag force (N)
F_B = buoyancy force (N)
F_R = reaction force (N)
g = gravity acceleration (m s^{-2})
I_a = second moment of area (m^4)
L = length of the plant (m)
U_a = mean flow velocity (m s^{-1})
V_E = volume of the end product (m^3)
V_G = volume of the glass bubbles (m^3)
W = width of the plant (m)
α = deflection angle (°)
β = bending angle (°)
ϕ = force ratio (–)
ρ_0 = density of water (kg m^{-3})
ρ = density of the material (kg m^{-3})
ρ_E = density of end-product (kg m^{-3})
ρ_G = density of glass bubbles (kg m^{-3})
ρ_S = density of silicone (kg m^{-3})
δ_b = deflection length (m)

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