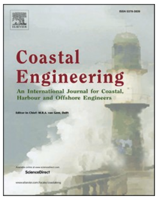
Coastal Engineering 195 (2025) 104646

Contents lists available at ScienceDirect

Coastal Engineering

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



Exploring wind flow dynamics in foredune notches using Computational Fluid Dynamics (CFD)

Thomas A.G. Smyth [a,*], Thomas Pagon [b], Ian J. Walker [c]

[a] *School of Computer Science and The Environment, Liverpool Hope University, Liverpool, UK*
[b] *Division of Geography, Department of Physical and Life Sciences, School of Applied Sciences, University of Huddersfield, UK*
[c] *Department of Geography, University of California – Santa Barbara, California, USA*

ABSTRACT

Coastal dunes offer a wide range of valuable ecosystem services such as protection from erosion, flooding, sea-level rise, and provision of specialised habitat for endangered, endemic, or migratory species. Foredune blowouts and landward migrating parabolic dunes play an important role in many coastal dune settings creating ecological heterogeneity associated with inland sand transport, nutrient supply, and geomorphic disturbance processes. However, as coastal dunes globally are being increasingly stabilised by vegetation and declining in their ecological resilience and functionality, anthropogenic interventions, such as the removal of invasive species and excavation of foredune notches, have emerged to simulate and restore critical aeolian processes required to maintain dune morphodynamics and onshore sediment transport between the beach and inland dunes. This study employed computational fluid dynamics (CFD) modelling to investigate key controls on the wind flow dynamics and sand transport potential within idealised foredune notches of varying widths, slopes, and planform shape (rectangular vs. trapezoidal) for perpendicular and oblique incident wind directions. Compared with empirical findings from similarly engineered notches, our results show that notch width significantly influences shear velocity in the excavated notch 'slot', with narrower notches (25 m wide) enhancing wind flow acceleration and inland sediment transport potential. Spatial patterns of shear velocity throughout notches were also sensitive to incident wind direction, with maximum shear velocities, and consequent inland sand transport potential, occurring when winds were parallel to the orientation of the notch. On the lobes of the notches, shear velocity and sand transport potential were greatest during oblique winds. Our results suggest that a relatively narrow notch (e.g. 25 m as opposed to 50 m or 100 m), aligned with the prevailing wind direction, creates the most favourable conditions for transporting sediment from the beach to the dune behind. These findings underscore the importance of notch design in coastal dune restoration, offering critical insights for optimising interventions aimed at sustaining aeolian sediment transport from the beach to the hinterdune.

1. Introduction

Coastal dunes are dynamic systems that theoretically increase in vegetation complexity and cover landwards from the foredune (Miyanishi and Johnson, 2021). This gradient is primarily caused by a reduction in physical stresses which include sand movement, salt spray and wind disturbance (McLachlan, 1991). Where a vegetated, tall, and laterally uniform foredune exists, this reduction in physical stresses is abrupt, as relatively little sediment is transferred beyond the foredune crest and wind speeds are dramatically reduced in the lee of the foredune (Carter et al., 1990; Bauer et al., 2022; Smyth et al., 2023). To prevent sand 'losses' from the beach and foredune on many managed temperate coastlines, efforts have been made to maintain the lateral uniformity of foredunes through the installation of sand-trapping measures, including brushwood fences and the planting of vegetation on the upper beach and within gaps in foredunes (known as foredune blowouts) (e.g., Ranwell and Boar, 1986; Hilton, 2006; Arens et al., 2013). Due to land use (Gao et al., 2020, 2023; Petrova et al., 2023) and climate change (Jackson et al., 2019), many hinterdune areas beyond the foredune have also become increasingly stabilised by vegetation in the last century. This reduction in dynamism beyond the foredune at many coastal dune locations could be a contributing factor to a reduction in coastal dune biodiversity of 'psammophilous' plant and animal species that thrive in bare sand or disturbed environments, due to a reduction in habitat availability (Wiedeman and Pickart, 1996; Hilton et al., 2000; Pye et al., 2014).

To mitigate the negative impacts of a lack of sediment transfer between the beach and dune hinterland and the resulting loss of sparsely vegetated habitats that favour a wide range of pioneer species, land managers in the Netherlands (e.g., Riksen et al., 2016), Wales (e.g., Pye and Blott, 2017), England (Appendix 1), France (e.g., Laporte-Fauret et al., 2021) and New Zealand (e.g., Nguyen et al., 2021) have created 'notches' in foredunes to provide conduits for aeolian sediment transport between the beach and inland dunes (Figs. 1 and 2). Notches have

---

* Corresponding author.
E-mail address: smytht@hope.ac.uk (T.A.G. Smyth).

https://doi.org/10.1016/j.coastaleng.2024.104646
Received 14 August 2024; Received in revised form 15 October 2024; Accepted 23 October 2024

Fig. 1. Aerial imagery of foredune notches excavated at Merthyr Mawr Natural Nature Reserve, Wales. The aerial photograph highlights the variety of foredune notch morphologies. Aerial photography taken June 15, 2022 and sourced from EDINA Aerial Digimap Service. (High Resolution (25cm) Vertical Aerial Imagery (2022) [JPG geospatial data], Scale 1:500, Tiles: ss8575,ss8576, ss8675,ss8676).

Fig. 2. Vegetation within the 'throat' of a foredune notch in Newborough National Nature Reserve and Forest, Anglesey, Wales. The photograph was taken in April 2019 approximately 5 years after the initial excavation.

also been constructed in the United States of America to encourage overwash events (Schupp et al., 2013), or provide specialised habitat for endangered birds.

Aeolian notches are typically excavated in a rectangular plan view shape (Fig. 1) with a 'V' or 'U' shaped cross-section when viewed from the beach. They vary in width (measured at the height of the adjacent foredune) from 3 m in New Zealand (Nguyen et al., 2021) to over 100 m in the Netherlands (Ruessink et al., 2018). Typically, these anthropogenically constructed landforms are designed to imitate naturally occurring foredune blowouts and parabolic dunes, which act as a sediment transport corridor between the beach and dunes (Carter et al., 1990; Byrne, 1997; Hesp and Pringle, 2001; Anderson and Walker, 2006; Hesp and Walker, 2022). The connection between naturally occurring blowouts and excavated foredune notches is evident from the frequent placement of foredune notches at the sites of relict or active trough blowouts (Pye and Blott, 2013) and the similar patterns of morphological evolution in both landforms (Ruessink et al., 2018).

Foredune notches have been demonstrated to be effective conduits for aeolian sediment transport from the beach to the hinterdune (Ruessink et al., 2018; Riksen et al., 2016; Pye and Blott, 2016; Castelle et al., 2019; Nguyen et al., 2022a). However, the long-term sustainability of aeolian processes within excavated notches has yet to be determined (Ruessink et al., 2018; Castelle et al., 2019). In their review of feedback between biotic and abiotic processes in blowouts, Schwarz et al. (2019) defined blowout 'closure' (i.e. the cessation of active aeolian erosion, transport, and landform growth) when a vegetated incipient foredune spans the blowout throat, thus preventing further erosion of the deflation basin or erosional walls. Similarly, Meerkerk et al. (2007) reported that maximum aeolian activity occurred three years after the excavation of a 60 m wide gap in a Dutch foredune, but once vegetation established and grew across the gap, aeolian processes reduced. In an initial evaluation of dune notch effectiveness in Wales, Pye and Blott (2016) reported that, where sediment supply at the beach was limited, revegetation of the notch 'throat' sometimes occurred (e.g. Fig. 2). The entry 'throat' of foredune notches and blowouts is particularly vulnerable to revegetation due to the deposition of sea wrack and woody debris, which slows near-surface wind flow and encourages sediment deposition, plant colonisation, and incipient dune development (Hesp and Pringle, 2001).

Previous research suggests that the negative impact of revegetation in the throat of blowouts or notches on aeolian sediment transport could potentially be mitigated by adjusting the surface gradient of the notch slope. Ideally, the slope of a foredune notch should be sufficiently shallow at its entrance so that wind speed retardation at the dune toe is minimal but steep enough toward its crest that wind speed acceleration and sediment transport is promoted (Hesp et al., 2015; Piscioneri et al., 2019; Davidson et al., 2022). Topographic acceleration of wind flow within a foredune notch may help prevent closure and/or reduce further management interventions, as regular erosion inhibits colonisation and vegetation (Maun, 2009). In their review of dune rejuvenation trails in Wales, Pye and Blott (2016) also suggested that notches with a convex long profile (i.e. steepens with distance inland) or a steep slope were more effective at transporting sand than those with a flat surface. This hypothesis was anecdotally supported by Simons-Smith (2017) who studied three foredune notches and reported highest wind speeds and sediment transport within the steepest of the notches, although this notch was also best aligned with the prevailing wind direction. Nguyen et al. (2021, 2022a) found that incident wind angle played a crucial role in wind flow dynamics and subsequent sediment transport within notches. In Nuguyen et al.'s (2021) study of a relatively narrow notch (6.5 m), computational fluid dynamic (CFD) modelling revealed that, when the incident wind direction was less than 27° to the orientation of the notch, wind accelerated within the notch, whereas when wind direction was increasingly oblique (>27°), wind speeds within the notch were slower than those observed on the beach. Hesp and Hyde (1996) also reported slowing of wind flow with the deflation basin of a trough blowout during incident winds that were marginally less oblique (23°–25°) than those reported by Nguyen et al. (2021).

The plan form shape of a notch may also be an important factor in controlling wind flow and thus sediment transport and resulting morphodynamics within foredune notches. To date, most notches have been created with a rectangular plan form (e.g. Fig. 1). As an alternative, Pye and Blott (2016) proposed that notches with a trapezoidal form (i.e., a landform that is widest at the 'throat' and gradually narrows with distance inland), would increase wind flow acceleration and potential sediment transport. However, to our knowledge systematic testing of this hypothesis has yet to be conducted.

The purpose of this study is to use computational fluid dynamics (CFD) modelling to examine wind flow and surface shear stress dynamics for a range of idealised notches that differ in width (25 m, 50 m, and 100 m), deflation basin slope (6°, 8°, and 12°), and deflation basin shape (rectangular and trapezoidal) for winds perpendicular and oblique (45°) to the orientation of the notch. Modelled values of shear velocity provide an indirect measure of sand transport potential as high shear velocity values typically indicate regions where sediment transport may be initiated and/or sustained (Baas, 2019; Smyth and Hesp, 2015). Computational fluid dynamic modelling, rather than morphodynamic modelling e.g. van Westen et al. (2024), was selected for this study due to the high performance of fluid dynamic models in complex dune topography compared to measured data (Smyth, 2016; Delgado-Fernandez et al., 2018; Lamy et al., 2024) and the high level of indeterminacy in sediment flux and bed levels models, which are strongly governed by site specific factors such as grain size, moisture, slope and sediment supply (Bauer et al., 1996). The findings of this research are intended to provide valuable insights on how artificial foredune notches function to better inform management decisions on coastal dune restoration. In this study we define the 'effectiveness' of a foredune notch in terms of how well a notch design facilitates areas of high shear velocity and thus by proxy, sand transport potential. Understanding wind flow and potential sediment transport is crucial for guiding future excavation efforts and maximising the longevity of such interventions, especially since longevity is cited as a key advantage of foredune notch excavation over other management methods used to maintain or create dynamic dunes (Ruessink et al., 2018).

2. Methods

2.1. Notch morphology

A notch, or gap, in a foredune consists of a 'slot' that connects to an elevated topography inland of the foredune, referred to as the 'lobe' (Fig. 3). The terms 'deflation basin', 'erosional wall', and 'depositional lobe', which are common geomorphic features in natural blowouts and parabolic dunes, are not used here because they would be associated with natural geomorphic processes vs. anthropogenic excavation. Rather, this study focuses on simulating wind flow dynamics and sand transport potential within an early stage, artificially engineered, notched foredune.

The idealised foredune notch topographies examined here were based on a constructed notch within a 14 m tall foredune at Ainsdale Sand Dunes National Nature Reserve excavated in May 2022 (Fig. 4 and Appendix 1). A total of six notch topographies were modelled to test how notch slope, width and shape impacted wind flow dynamics (Table 1 and Fig. 4). The sidewalls of each 'slot' were steeply sloped (45°, Fig. 4) consistent with those measured on the foredune notch at Ainsdale Sand Dunes National Nature Reserve (Appendix 1). Due to the height of the foredune in this study (14 m) and the 45° walls of the notch slot, a width of 25 m was the minimum that could be feasibly investigated. Moreover, extensive research has previously been conducted to understand how wind direction affects wind flow and sediment transport dynamics in foredune notches less than 10 m wide (Nguyen et al., 2021, 2022a, 2022b).

To test how the mid-axis slope of a notch might impact wind flow dynamics, slope angles of 6°, 8° and 12° were tested on 25 m wide notches (Table 1). These slopes are representative of the range of slopes measured from digital terrain models of Ainsdale Sand Dunes National Nature Reserve (England) and Merthyr Mawr Natural Nature Reserve (Wales). Wind flow modelling within narrower dune notches in New Zealand (<10 m wide) also had a similar slope of 8.6° (Nguyen et al., 2021). Morphologies 1–3 (Table 1) which varied by slope were structured so that the lobe contained an identical volume of sand, i.e. the mass of the dune was conserved and moved landward to make a lobe. As a result, the notch with the shallowest slope (6°) was also the longest (122 m) and the lowest in elevation (10 m) (Table 1 and Fig. 6).

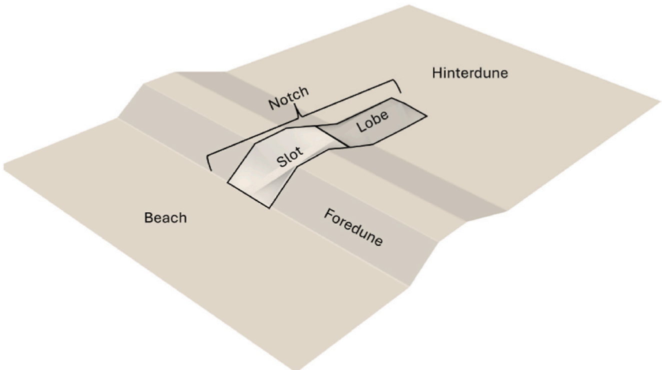


Fig. 3. Topographic surface of an artificially designed notch (Notch #2 in Table 1) with key geomorphic features labelled.

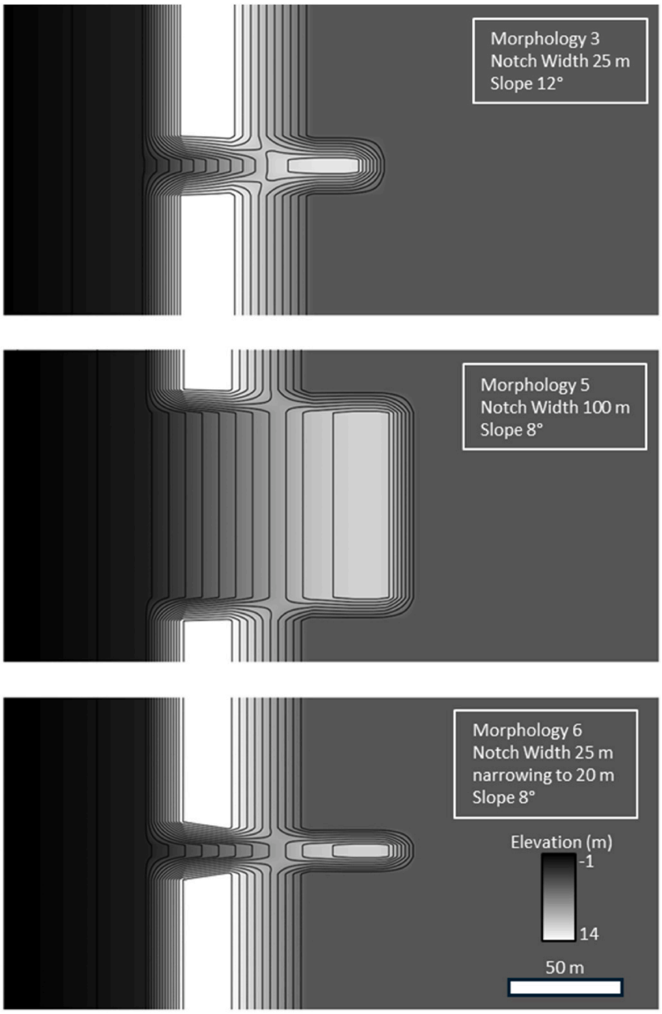


Fig. 4. Plan view topographic maps of notch morphologies 3, 5 and 6. Contours are at 1 m intervals. The selected topographies offer distinct variations in slope, width, and planform, enabling a comprehensive analysis of how these factors influence wind flow dynamics.

Table 1
Morphometric properties of the dune notches tested.

Morphology	Slope	Width	Slot – lobe combined Length	Max. Elevation	Planform
1	6°	25 m	122 m	10 m	Rectangular
2	8°	25 m	106 m	11 m	Rectangular
3	12°	25 m	90 m	12 m	Rectangular
4	8°	50 m	106 m	11 m	Rectangular
5	8°	100 m	106 m	11 m	Rectangular
6	8°	25 m	106 m	11 m	Trapezoidal

To study the impact of notch width on wind flow dynamics, 50 m and 100 m wide notches (Morphologies 4 and 5, Table 1 and Fig. 4) were modelled with a mid-axis slope of 8°. Although foredune notches this wide are less common globally, slot widths between 50 and 100 m have been excavated in the Netherlands (Ruessink et al., 2018). To test how the planform shape of a notch may impact wind flow, a trapezoidal shaped notch with a slope of 8° was also tested (Fig. 4). The planform of this notch narrowed from 25 m at the beach entrance of the slot to 20 m where it transitioned to the lobe (Morphology 6, Table 1 and Fig. 4). The lobe of the trapezoidal shaped notch (Morphology 6) was identical to the lobe of the equivalent foredune notch with a rectangular planform

(Morphology 2, Table 1).

2.2. Wind flow modelling

Wind flow over each notch morphology was modelled using the open-source CFD software OpenFOAM (Weller et al., 1998). The SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm was employed to solve the Navier-Stokes equations which provides a steady-state, averaged solution for flow (Serra and Semiao, 2021). Turbulence was modelled using the Renormalization Group Theory (RNG) k-ε method, as it accounts for smaller scales of motion and offers improved predictions for separated flows compared to the original k-ε model (Smyth, 2016). An upwind spatial discretisation scheme was utilised to ensure all simulations achieved convergence, as this method effectively minimises numerical diffusion and enhances stability. Calculations were deemed complete once the residual of each iteration was below 0.0001 for Ux, Uy, and Uz. This modelling approach was employed due to its excellent agreement with field measurements of wind speed and wind direction over both a foredune (Lamy et al., 2024) and a parabolic dune (Smyth et al., 2020).

2.3. Boundary conditions

The computational domain for each morphology was created using the native OpenFOAM mesh generation tool 'BlockMesh'. The cell size in each domain decreased from a maximum size 2.8 m (W) x 1 m (L) x 7.7 m (H) at the boundary of the computational domain to 0.2 m (W) x 1 m (L) x 0.2 m (H) at the centre of the computational domain where the foredune notch was situated (Fig. 5). In each case a steeply scarped foredune with a 40° 'seaward' slope extended 75 m north and south from the wall of the foredune notch to the edge of the computation domain (Fig. 5). A tall scarped foredune was modelled as its height and steep slope angle make it difficult for large quantities of sediment to be blown inland as wind speed and shear velocity are dramatically reduced at the dune toe (Piscioneri et al., 2019; Hesp and Smyth, 2021), making it a realistic site for dune notch excavation. Infront of the foredune a 'beach' with a slope of 2° extended 64 m from the inlet boundary to the dune toe. Landward of the foredune a flat 'hinterdune' surface extended 165 m from the lee of the foredune to the outlet of the computational domain so that any downwind complex flow patterns could be fully resolved (Fig. 5).

The surface for all computational domains was given a uniform surface roughness constant (z_0) of 0.00005 m which is the equivalent of sand (Bagnold, 1960). For all scenarios the incident wind speed was defined as 12 m s^{-1} at 10 m above a surface ($u_* = 0.41$). Both onshore (0° to the dune crest) and oblique (45° to the foredune crest) winds were simulated for notch morphologies 1–5 (Table 1). Only onshore winds were simulated for notch morphology 6 (Table 1). For all simulations vertical profiles of wind speed (U), turbulent kinetic energy (k) and energy dissipation (ε) at the inlet boundary were defined using equations (1)–(3) (Richards and Hoxey, 1993; Blocken et al., 2007):

$$U(z) = \frac{u^*}{k} \ln\left(\frac{z+z_0}{z_0}\right) \tag{1}$$

$$\kappa(z) = \frac{u_*}{\sqrt{C_\mu}} \tag{2}$$

$$\varepsilon(z) = \frac{u_*^3}{k(z+z_0)} \tag{3}$$

Where z is the height above the surface, k is the von Kármán constant (0.41), z_0 is the surface roughness length and C_μ a constant of 0.09.

To gain a better understanding of aeolian dynamics in each notch, shear velocity (u_*) was calculated at the surface of each computational domain and wind flow streamline tracers (U) were seeded on the beach surface 14 m from the dune toe and 1 m above the surface at 4 m intervals as evidenced in Figs. 4–6.

3. Results

3.1. Flow responses to changes in notch slope

3.1.1. Onshore incident wind

For onshore wind conditions within the slot of each notch, the maximum values of shear velocity were approximately constant regardless of slope (0.66–0.67 m s^{-1}). Maximum values were modelled 22 m downwind of the beach-notch 'opening' for all dune slopes (Fig. 6). The lowest values of shear velocity occurred at the entrance of the slot, where there was a transition from the relatively shallow beach slope (2°) to the steeper foredune notch slope (6°–12°) (Fig. 6). The minimum shear velocity decreased with increasing slope from 0.38 m s^{-1} on the 6° slope, to 0.34 m s^{-1} on the 12° slope (Table 2). The average shear velocity along the central transect of each slot was equal regardless of slope (0.58 m s^{-1}).

On the lobe, the maximum values of shear velocity for each respective wind direction were lower than the values modelled in the slot and

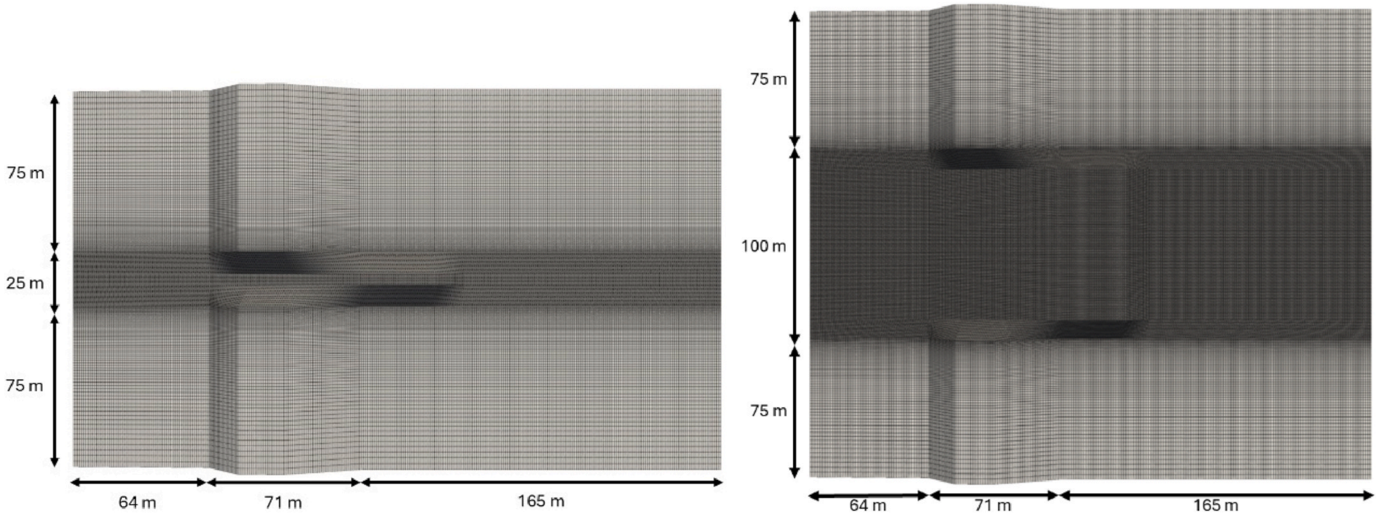


Fig. 5. Surface of the computational domain for notch #2 (left panel) and notch #5 (right panel). A summary of all notch morphologies is available on Table 1. Lines denote the cell boundaries at the wall.

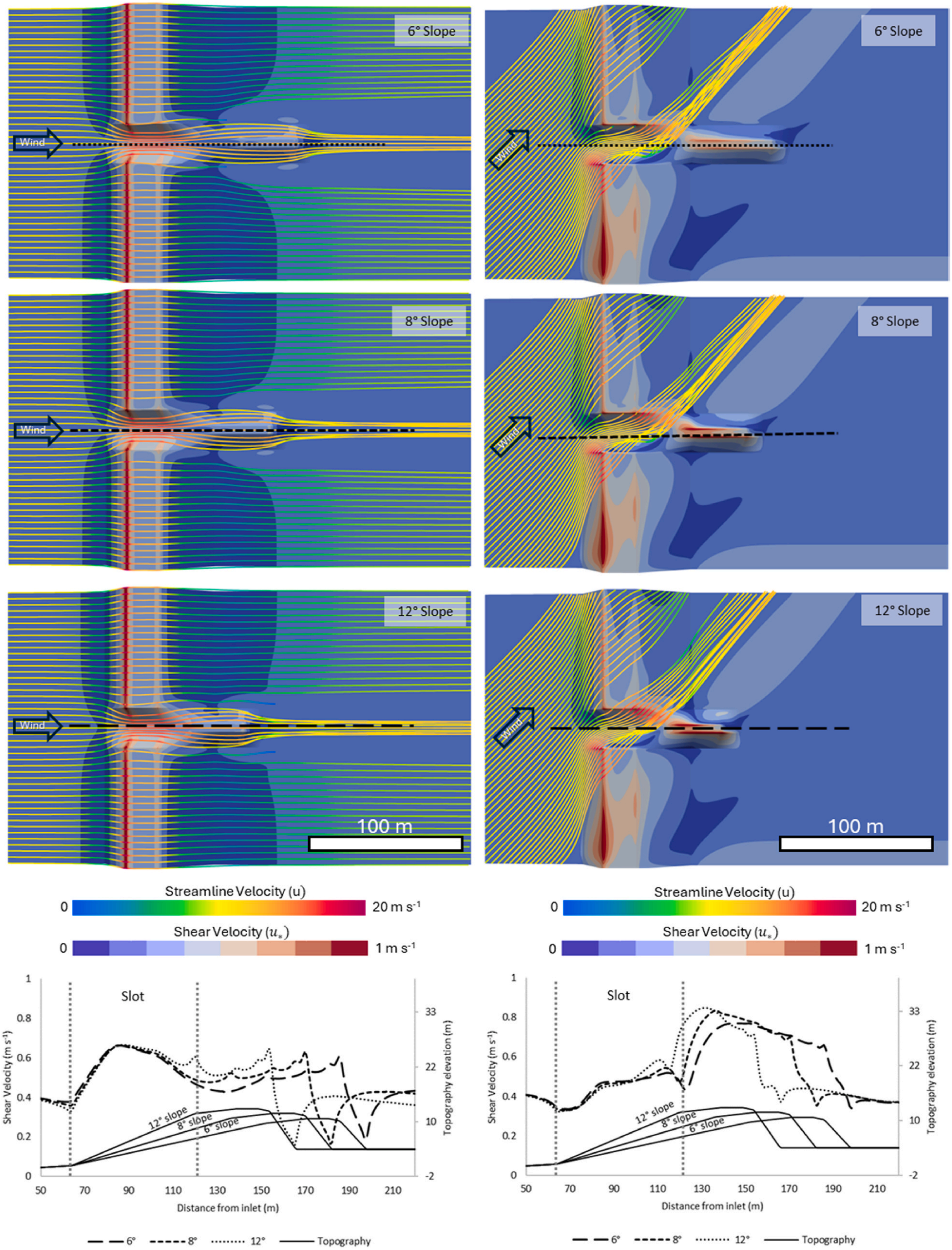


Fig. 6. The upper six panels show shear velocity on the surface (lower colour scale) and streamwise streamline velocity (upper colour scale) through 25 m wide dune notches with 6°, 8° and 12° slopes. The bottom two panels show shear velocity (dashed lines) and topography along the centre of the bed for each notch. Panels on the left are for incident wind flow parallel to the orientation of the notch and panels on the right are for incident wind flow 45° oblique to the orientation of the notch.

Table 2
Maximum, minimum and average shear velocities (m s^{-1}) along the central axis of the notch during onshore and oblique incident winds in foredune notches with 6°, 8° and 12° slopes.

	Slot						Lobe					
Wind Dir.	Onshore			Oblique			Onshore			Oblique		
Notch Slope	6°	8°	12°	6°	8°	12°	6°	8°	12°	6°	8°	12°
Max.	0.66	0.66	0.67	0.52	0.54	0.59	0.61	0.63	0.65	0.77	0.83	0.85
Min.	0.38	0.36	0.34	0.33	0.33	0.32	0.18	0.17	0.16	0.35	0.35	0.37
Average.	0.58	0.58	0.58	0.44	0.44	0.45	0.47	0.48	0.49	0.65	0.68	0.70

increased with slope from 0.61 m s^{-1} at 6° to 0.65 m s^{-1} at 12°. It is worth noting that the height of the depositional lobe also increased with steepness (Table 1) and that shear velocity and near surface wind speeds increase with dune height (Parsons et al., 2004). The lowest values of shear velocity on the lobe occur at the transition between the lobe and the flat ‘hinterdune’ that extends downwind of the lobe. This minimum value decreased slightly with notch slope from 0.18 m s^{-1} for the 6° slope to 0.16 m s^{-1} for the 12° slope. The average shear velocity was 0.10 m s^{-1} lower on the lobe compared to the slot and marginally increased with notch slope and height from 0.47 m s^{-1} (6°) to 0.49 m s^{-1} (12°).

The patterns of near surface wind flow are very similar for all three dune slopes during directly onshore winds. Fig. 6 shows that in each case streamlines close to the notch were channelled into the landform and became compressed within the slot. Once streamlines exited the slot, they expanded over the lobe before narrowing again in the lee.

3.1.2. Oblique incident wind

During oblique incident wind conditions, the maximum shear velocity values within the slot were lower than during onshore winds (Table 2). During oblique winds the maximum value also occurred further downwind within the slot than during onshore wind, at approximately 45 m inland from the entrance of the notch at the transition between the slot and lobe, compared to 22 m from the slot entrance as was observed for onshore winds. Unlike the maximum value modelled within the slot during onshore winds which stayed almost identical for all slopes (0.66–0.67 m s^{-1}, Table 2), the maximum shear velocity increased with notch slope from 0.52 m s^{-1} (6°) to 0.59 m s^{-1} (12°). The minimum shear velocity within each slot was consistently around 0.33 m s^{-1}, regardless of notch slope. Average shear velocity values with the slot were also relatively constant between 0.44 and 0.45 m s^{-1}.

The maximum values of shear velocity of all the simulations conducted in this investigation were modelled on the lobe during oblique wind flow. These values also increased with dune slope from 0.77 m s^{-1} (6°) to 0.85 m s^{-1} (12°). These maximum values were modelled immediately downwind of the slot – lobe transition and gradually decreased to a minimum shear velocity between 0.35 and 0. 37 m s^{-1} where the lobe ended and became hinterdune. Similar to the pattern exhibited for the maximum values, the average shear velocity on the lobe increased with notch slope and height from 0.65 m s^{-1} (6°) to 0.70 m s^{-1}(12°).

The streamlines seeded on the beach for all notch slopes (Fig. 6) show that streamlines downwind of the notch became channelled into the slot of the notch and underwent substantial steering so that they became near parallel to the orientation of the notch. As streamlines exited the slot they converged and reorientated in the direction of the oblique incident wind, forming loose corkscrew vortices (Fig. 6).

3.2. Flow responses to changes in notch width

3.2.1. Onshore incident wind

During onshore wind conditions the maximum shear velocity value within the slot of each landform decreased with notch width from a maximum of 0.66 m s^{-1} at 25 m wide to 0.53 m s^{-1} at 100 m wide. The profile of shear velocity through the central transect of the notch also changed with notch width. The 25 m wide notch had a distinct peak in shear velocity 22 m downwind from the beach side entrance of the landform whereas the profile of shear velocity along the centre of the 50 m and 100 m wide notches was smoother and exhibited a more gradual increase in shear velocity with elevation (Fig. 7). The minimum values of shear velocity in the slot were all modelled at the beach-notch transition, where a reduction in pressure and thus a stagnation in flow occurred. The 25 m wide notch had the lowest shear velocity (0.36 m s^{-1}), while very similar values were modelled within the slots of the 50 m and 100 m wide notches (0.40 m s^{-1} and 0.39 m s^{-1} respectively). The average shear velocity within each slot decreased with width from 0.58 m s^{-1} in the 25 m wide notch to 0.49 m s^{-1} in the 100 m notch.

On the lobe of the foredune notch wind velocities peaked at the crest of the lobe (Fig. 7) and increased with notch width (Table 3). The minimum values of shear velocity on the lobe exhibited no clear trend with width (Table 3 and Fig. 7). The location of the minimum value occurred immediately downwind of the crest for the 100 m and 50 m wide notches and further downwind at the transition between the lobe and hinterdune for the 25 m wide notch. The minimum shear velocity modelled in the lee of the crest of the 100 m wide lobe was also the lowest value modelled across any transect in this study (0.13 m s^{-1}).

The wind flow streamlines in Fig. 7 show that lateral streamline compression within the slot and streamline expansion on the lobe became less pronounced as foredune notch width increased. This was most evident in the 100 m wide notch where no streamline compression was perceptible along the central transect of the slot and lobe (Fig. 7).

3.2.2. Oblique incident wind

During oblique incident wind conditions, the maximum shear velocity values within the slot of the notch were again lower than during onshore winds (Table 3) and did not steadily decrease with increasing width as observed during onshore winds. Instead, the maximum shear velocities for the 25 m and 50 m wide slots are almost identical (0.54 and 0.55 m s^{-1} respectively), while the maximum shear velocity in the 100 m wide notch was substantially lower (0.48 m s^{-1}).The minimum shear velocity recorded at the notch-beach transition did however increase with width, with the 25 m notch recording the lowest value (0.33 m s^{-1}) and the 100 m wide notch recording the highest minimum value (0.39 m s^{-1}). The average shear velocity on each slot is almost identical, ranging from 0.44 m s^{-1} to 0.45 m s^{-1} (Table 3).

The maximum shear velocity recorded through the central transect of the lobe was higher on the 25 m notch (0. 83 m s^{-1}) than either the 50 m or 100 m wide notches (0.69 m s^{-1} and 0.71 m s^{-1} respectively). The spatial variation of surface shear was also markedly different for each lobe with all of the 25 m wide lobe being subject to relatively high velocities (Fig. 7) while only the edges of the 50 m wide lobe were exposed to high shear velocities. Unlike the 25 m and 50 m wide lobes, the 100 m wide lobe had a large zone of substantially reduced shear velocity (Fig. 7). This difference in spatial patterns of flow was reflected in the average shear velocities on the notch (Table 3), which decreased with notch width from 0.68 m s^{-1} for a 25 m wide notch to 0.55 m s^{-1} for a 100 m wide notch. This decrease in shear velocity is likely the consequence of enhanced lateral streamline compression in the narrower notch (Fig. 7).

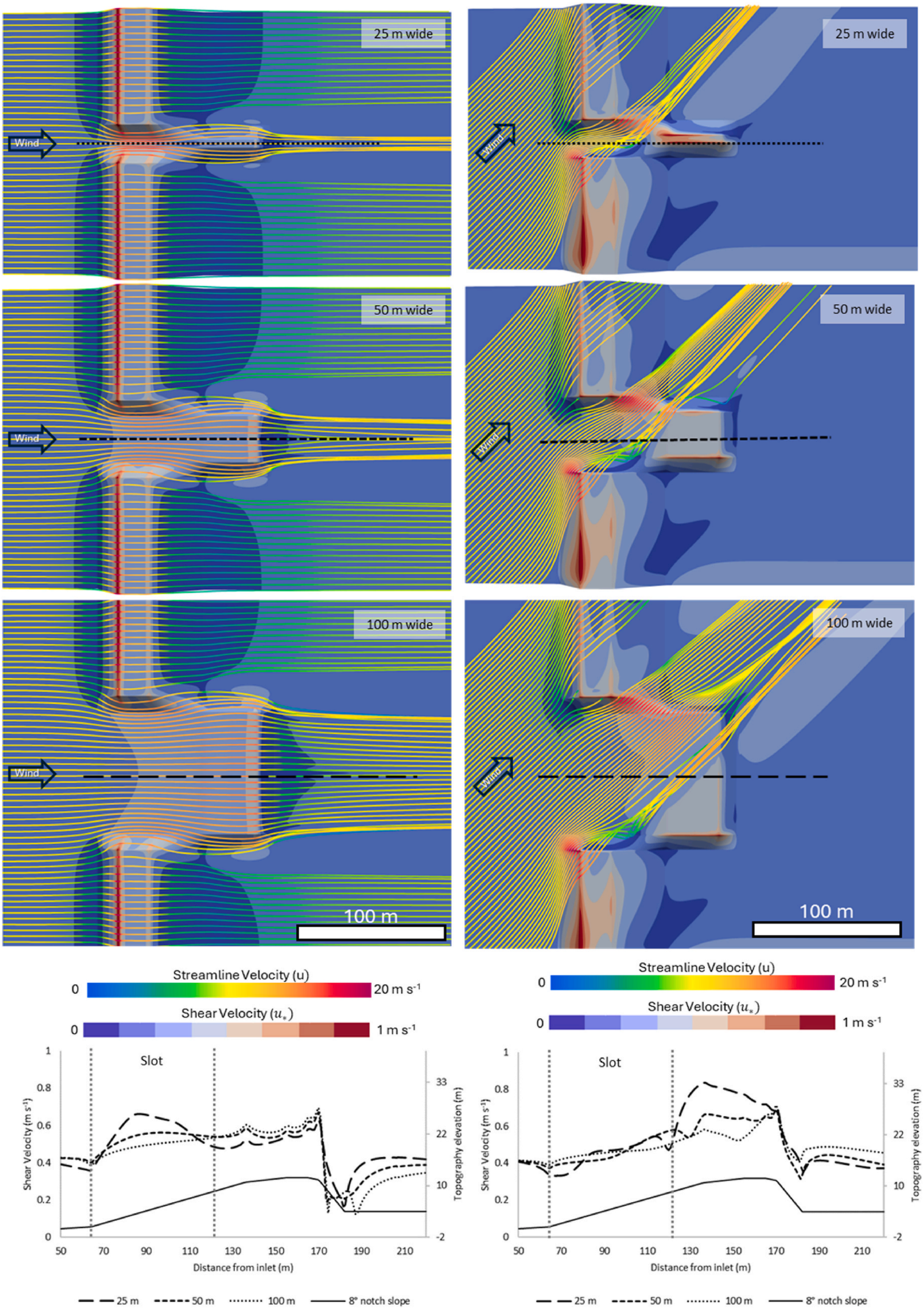


Fig. 7. Upper six panels show surface shear velocity and streamwise streamline velocity for 25 m–100 m wide notches during onshore and oblique incident wind conditions. Bottom two panels show shear velocity and topography along a central transect for each landform. Panels on the left are for incident wind flow parallel to the orientation of the notch and panels on the right are for incident wind flow 45° oblique to the orientation of the notch. All notches have a slope of 8°.

Table 3
Maximum, Minimum and average shear velocities (m s^{-1}) along the central axis of the notch during onshore and oblique incident winds in foredune notches with varying widths.

	Slot						Lobe					
Wind Dir.	Onshore			Oblique			Onshore			Oblique		
Notch Width (m)	25	50	100	25	50	100	25	50	100	25	50	100
Max.	0.66	0.56	0.53	0.54	0.55	0.48	0.63	0.67	0.70	0.83	0.69	0.71
Min.	0.36	0.40	0.39	0.33	0.37	0.39	0.17	0.19	0.13	0.35	0.32	0.41
Average.	0.58	0.53	0.49	0.44	0.44	0.45	0.48	0.51	0.53	0.68	0.59	0.55

The wind flow streamlines for oblique flow showed that the spatial extent to which wind flow became steered parallel to the axis of the notch decreased with notch width (Fig. 7). At the edges of the walls on the slot, wind flow was steered parallel to the notch axis for all landform widths however in the 50 m and 100 m wide notches there was negligible wind flow steering in the centre of the notch. The streamlines in Fig. 7 also demonstrate how the location of the corkscrew vortices discussed in section 3.1.2. occur progressively more over the lobe as the notch became wider. Fig. 7 also shows that during oblique winds, wind speeds are much higher at the upwind edge of the notch entrance compared to the downwind.

3.3. Flow responses to changes in notch shape

To examine how the shape of the slot impacted shear velocity, onshore incident winds were simulated for a slot with a ‘rectangular’ plan view morphology (25 m wide throughout) and a slot with a slight trapezoidal morphology (tapered from 25 m at the entrance to 20 m wide at the lobe). Within the slot of both landforms the maximum and minimum shear velocities were essentially identical (Table 4). Fig. 8 and Table 4 demonstrate, however, that within the trapezoidal notch, maximum shear velocities were sustained for a greater distance along the central transect of the landform, resulting in a marginally higher average shear velocity.

On the lobe the maximum shear velocity was marginally greater on the straight notch, whilst the lowest shear velocity value was marginally higher on the trapezoidal notch. Overall, the average shear velocity value for both lobes is 0.48 m s^{-1}, approximately 0.06 m s^{-1} greater than was modelled on the beach.

4. Discussion

The focus of this article was to assess how foredune notch slope, width and shape impacts the potential efficacy and longevity of artificial foredune notches to act as a conduit for sediment transport between the beach and hinterdune.

4.1. Impact of slope on flow dynamics within artificial notches

Previous research has shown that, as a windward dune slope becomes steeper, the area of wind flow retardation at the foot of the dune slope intensifies, increasing the potential for sediment to be deposited (Hesp and Smyth, 2021; Walker and Hesp, 2022). In this study, within

Table 4
Maximum, Minimum and average shear velocities (m s^{-1}) during onshore incident winds in a notch that has a consistent width of 25 m (straight) and a notch that tapers from 25 m at its windward entrance to 20 m wide at the lobe (trapezoidal).

	Slot		Lobe	
Notch Shape	Straight	Trapezoidal	Straight	Trapezoidal
Max.	0.66	0.66	0.63	0.61
Min.	0.36	0.36	0.17	0.18
Average.	0.58	0.59	0.48	0.48

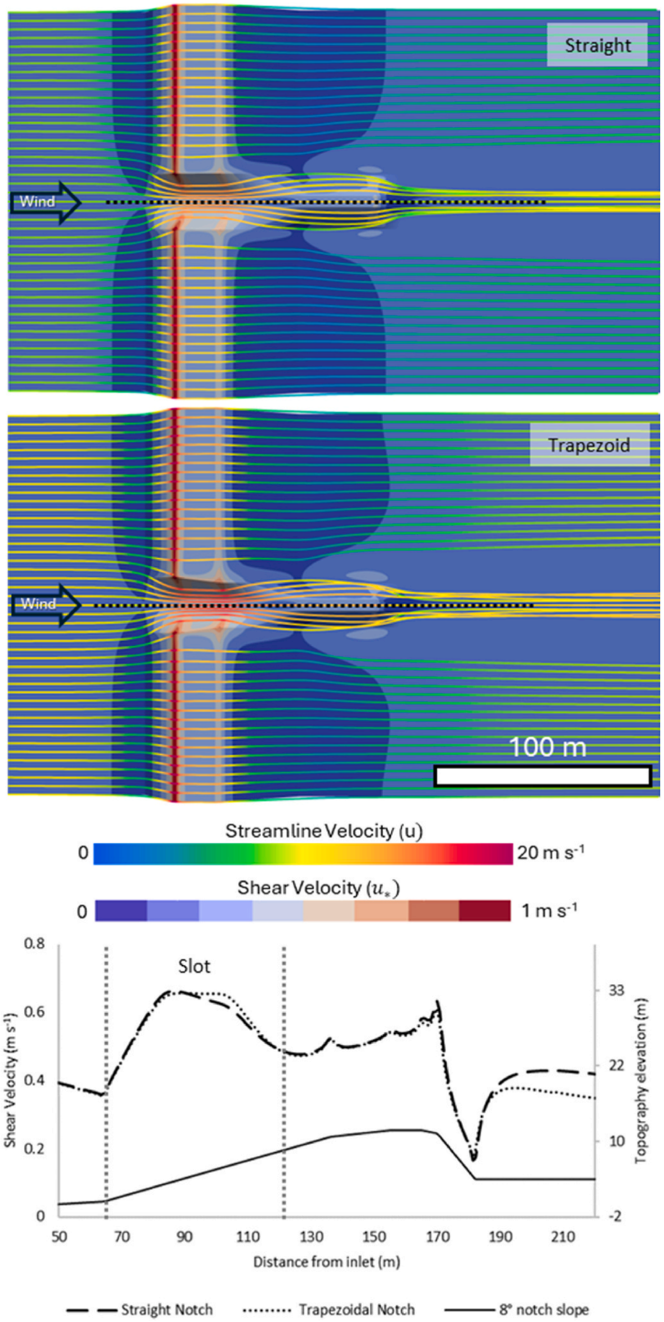


Fig. 8. The upper two panels show surface shear velocity and streamwise streamline velocity for a notch with a 25 m straight planform and a trapezoidal notch that narrows from 25 m at its entrance to 20 m at the lobe during incident winds parallel to the orientation of the notch. The bottom panel shows shear velocity and topography along a central dashed transect for each landform. All notches have a slope of 8°.

the slot of the foredune notches during onshore winds, a reduction in shear velocity with increased slope did occur due to an increase in pressure at the beach-notch boundary creating an adverse pressure gradient. However, reduction in shear velocity with slope was slight (0.04 m s^{-1} between the 6° and 12° slopes) and the influence largely constrained to the entrance of the slot. During oblique winds the difference between the minimum shear velocity value for each slope was negligible as the increased angle of approach essentially 'flattens' the apparent dune slope, reducing any topographically forced wind speed deceleration. Similar findings have been observed over coastal foredunes where the angle of approach has been found to strongly influence the degree of deceleration and secondary flow deflection response at the dune toe (Walker et al., 2006, 2017; Hesp et al., 2015; Hesp and Smyth, 2016). A distinct change in wind and shear velocity with slope was also demonstrated at the entrance of each notch during oblique winds (Figs. 6 and 7). At the upwind edge of the notch entrance, shear velocities are substantially higher than at the downwind edge. We interpret that this distinct difference is due to the angle of approach by the incident wind. At the upwind edge wind is deflected alongshore by the steep foredune slope before entering the notch, whereas as the downwind edge of the notch, oblique incident winds abruptly meet the steep slope at the foredune-notch transition resulting in lower shear velocities at the foredune-notch transition. Shear velocities on the downwind notch wall do however rapidly increase with distance inland from this low at the foredune-notch transition, while shear velocities on the now 'sheltered' upwind wall decrease with distance inland (oblique winds in Figs. 6 and 7) A similar process of wind "*attacking the facing (exposed) lateral wall*" of a blowout during oblique winds in Australia is described by Carter et al. (1990, pg. 239). Carter et al. (1990) report that these frequent oblique wind result in the formation of both an asymmetric deflation basin and lobe. On the notch lobe in this study, shear velocity increased with slope for both onshore and oblique winds, however this increase in shear velocity may be driven by the increased height of the lobe, rather than the steepness of the slope and resulting vertical streamline compression.

4.2. Impact of notch width on flow dynamics within artificial notches

Within the slot of each foredune notch, shear velocity decreased with landform width for both onshore and oblique incident winds (Table 3). In the narrowest notch morphology, the maximum shear velocity occurred 22 m downwind from the entrance of the notch (Fig. 7). This zone of maximum shear velocity closely matches the 'zone of major erosion' within a trough blowout studied by Hesp and Hyde (1996) in Myall Lakes National Park, NSW, Australia. This region of increased shear stress at the entrance of the narrowest notches is caused by the lateral compression of streamlines as flow enters the landform, which decreases as the landform becomes wider (Fig. 7). Fig. 7 also demonstrates that during oblique incident winds, as notch width increased, the amount of wind flow steering within the slot decreased. A similar phenomenon was observed in parabolic dunes whereby the degree of wind flow steering parallel to the axis of the landform was governed by the landform's width and depth (i.e. the deeper and narrower the deflation basin the more wind flow was steered parallel to the orientation of the deflation basin (Smyth et al., 2020)). Thus, it appears that flow dynamics in the 25 m wide foredune notches in this study closely resemble those in relatively narrow trough blowouts, whereas the aeolian dynamics of wider notches (≥50 m) are more akin to those within relatively wide and shallow parabolic dunes (Smyth et al., 2020).

4.3. Impact of oblique winds on notch evolution

In this study, the shear velocity in the slot was highest during onshore winds. A conclusion supported by empirical findings by Nguyen et al. (2021, 2022a) who indicated that wind speeds were greatest in slot of a 6.5 m wide foredune notch when incident wind flow was parallel to the axis of the landform. During onshore winds this study showed that shear velocity dramatically increased along the slope of the slot up until the transition to the foredune lobe (Fig. 6). During oblique winds this increase in shear velocity along the central axis of the slot is smaller (Fig. 6 and Table 2) and a pronounced decrease in shear velocity occurred at the slot-lobe transition point (Fig. 6). This decrease in velocity may encourage sediment deposition at this location, potentially limiting the effectiveness of the foredune notch to act as a conduit of windblown sand from the beach to the hinterdune. Vegetation growth has also been observed at this location (Fig. 9) on recently constructed foredune notches at Ainsdale Sand Dunes National Nature Reserve that are oriented oblique to the prevailing wind direction (Fig. 10).

In contrast to shear velocity in the slot, our results show that shear velocity on the lobe was greatest when incident winds were oblique to the notch (Figs. 6 and 7). Hence, we hypothesise that where a notch is constructed in an orientation that is not aligned with the prevailing wind direction, the lobe has the potential to become an erosional rather than a depositional feature as would be expected in a naturally occurring foredune blowout (Laporte-Fauret et al., 2022) or within a notch that is aligned with prevailing wind direction (Laporte-Fauret et al., 2021). This process may be exacerbated in narrower, steeper notches (e.g. 25 m wide) where relatively high values of shear velocity in the slot can occur and where near surface wind flow becomes reoriented to the incident wind direction as it exits the slot. Where this process is sustained, we theorise that the notch lobe may expand asymmetrically. An example of this potential asymmetrical evolution can be observed at Ainsdale Sand Dunes National Nature Reserve, England. Using Sentinel satellite imagery collected at 12-month intervals shortly after excavation, Fig. 10 shows that the spatial extent of the foredune slots appears to remain relatively constant while the lobes migrate in the direction of the prevailing south westerly (251°) wind.

4.4. Contributions and limitations

This study demonstrates how Computational Fluid Dynamics (CFD) modelling can substantially contribute to assessing the potential effectiveness of foredune notch design for enhancing inland aeolian sediment transport. CFD allows for the simulation of spatially continuous fields of surface shear velocity (u_*) and wind flow (U), which are critical for determining aeolian transport potential and for inferring subsequent patterns of sand transport, erosion, and deposition. The ability to visu-

Fig. 9. Vegetation growth in a foredune notch at the slot-lobe transition at a site where prevailing winds are oblique to the orientation of the landform. The location of the vegetation growth coincides with the decrease in shear velocity modelled at the slot-lobe transition point during oblique winds in this study. (Photograph taken in May 2024 at Ainsdale Sand Dunes National Nature Reserve, England).

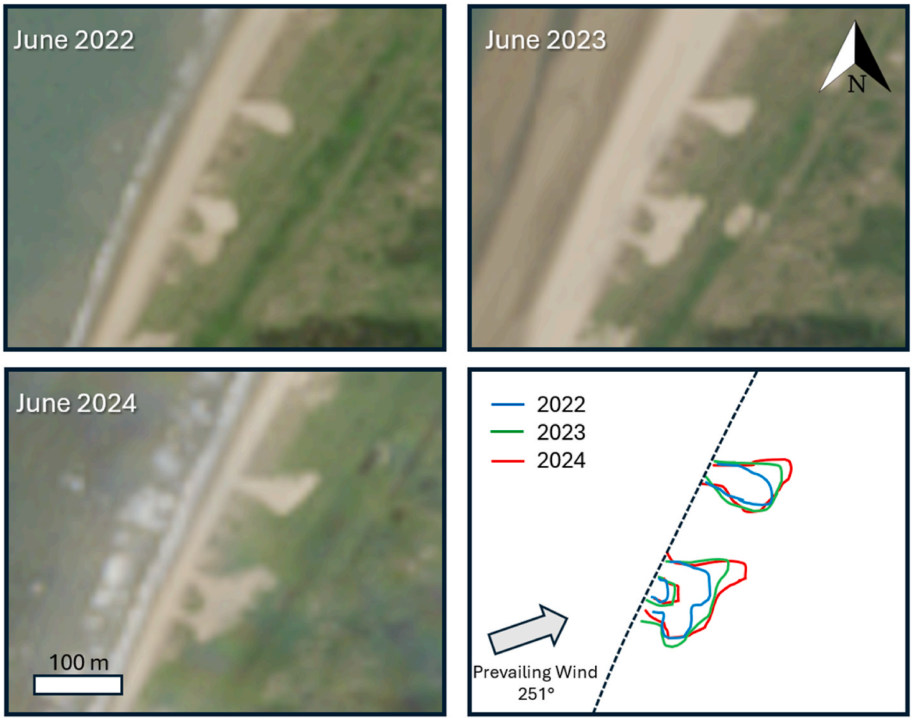


Fig. 10. Sentinel-2 True colour satellite imagery of the evolution of foredune notches excavated in May 2022 at Ainsdale Sand Dunes National Nature Reserve, England from 2022 through 2024. The imagery demonstrates the asymmetric expansion of the notch lobe in relation to the prevailing wind direction that is oblique to landform orientation. Prevailing wind direction is based on average above threshold velocity winds (>6 m s^{-1}) at Crosby Meteorological Station location on the coast 10 km south between June 2022 and June 2024.

alise flow behaviour and related morphodynamic responses provides valuable insights into potential flow-form-transport behaviours important for dune notch performance and maintenance, such as minimising flow stagnation to reduce deposition and encouraging vertical and lateral streamline compression to maintain sediment transport. All modelling in this study was performed on a standard desktop computer utilising only free software (Linux operating system, OpenFOAM for CFD and Paraview for visualisation). Thus, CFD offers great potential to test and analyse several iterations of notch design at a site, even with limited empirical observations, provided sufficient boundary conditions, including regional climatology and detailed dune morphology data (e.g. Digital Elevation Models) exist.

An important factor not considered in this study is sediment flux. Sediment flux only occurs when shear velocity exceeds a threshold value. This threshold is controlled by a range of local factors including grain size, moisture, vegetation and slope (Baas, 2019). By not modelling sediment flux, this article focuses solely on the wind flow dynamics in foredune notches and does not capture the associated sediment transport processes that are critical to dune morphology. Consequently, while the CFD model provides insights into airflow patterns, it does not account for how these wind flows may interact with sediment to drive erosion, deposition, or dune evolution.

Sediment availability on the beach has also been discussed as an important control on the geomorphic evolution of foredune notches. Castelle et al. (2019), studying foredune notches in Truc Vert, France, reported that notches constructed in 2017 were rapidly filled with wind-blown sand from the beach, in response to a large supply of sediment to the beach following large storms in 2013 and 2014. In contrast to having an abundance of available sediment, notches may also experience a lack of sand-sized sediment on the beach (e.g. Fig. 2 and Pye and Blott, 2016) to feed onshore sand delivery. The resulting reduction in aeolian sand transport could not only reduce the effectiveness of a notch for delivering sand inland, but also the related lack of disturbance associated with aeolian transport (e.g., abrasion, burial, exhumation) could result in increased vegetation growth potentially , promoting closure of a notch. Bare sand surfaces comprising of relatively gentle slopes are particulary at risk as there is limited disturbance from avalanching and slumping (Castelle et al., 2019; Smyth et al., 2023).

It should also be noted that only two wind directions were analysed in this study. An incident wind that was directly parallel to the orientation of the notch and a second that was 45° oblique. Further research on the impact of a broader range of wind directions is required to more exhaustively understand how the performance of a foredune notch changes with wind direction.

This study also assumed that the hinterdune in lee of the foredune and notch was flat (Fig. 3). Where a secondary dune ridge is present downwind from a dune notch, Nguyen et al. (2024) found that wind speed reduces as the distance between the notch and secondary dune ridge decreases, and that as the slope of the secondary dune ridge increased, wind in the notch slowed increasingly. Our study also did not simulate the influence of vegetation on the dune and its potential impact to near surface flow dynamics. Including surface roughness, such as vegetation, in CFD modelling over sand dunes presents a continued significant challenge due to the complex and variable nature of both vegetation and underlying dune surfaces (Brownett and Mills, 2017). Therefore, accurately capturing the microscale variations in both skin friction and form roughness that, combined, influence airflow and sediment transport over dunes, remains a significant challenge for landscape scale fluid dynamic modelling in dynamic landscapes (Smyth, 2016).

The results of this article are also only valid for the initial excavated shape without subsequent form modification resulting from flow-form-transport interactions. Studies in the UK, Netherlands and France (KPAL, 2015; Ruessink et al., 2018; Laporte-Fauret et al., 2021) have demonstrated that substantial topographic change from the initial excavated form can occur within the first year. Where a foredune notch behaves as an erosional landform as intended, this typically involves the deepening and widening of the slot as well as the downwind migration of the lobe (KPAL, 2015; Ruessink et al., 2018). In cases where the notch axis is not aligned with the prevailing winds, this could also involve differential erosion and deposition along the notch slot and lobe.

4.5. Recommendations for effective foredune notch design

To optimise the design and efficacy of foredune notches, the results of this research indicate three key considerations for notch design. First, narrower notches enhance near surface wind speeds and shear velocity. In turn, this could facilitate more efficient sediment movement between the beach and the hinterland behind the foredune, especially where the prevailing winds are relatively low in speed, yet competent to transport sand. Although a single incident wind speed was investigated in this study (12 m s^{-1}), previous research in blowouts has demonstrated that while wind speed inside the notch is relative to incident wind speed, the patterns of flow steering, acceleration and deceleration remain consistent for a wide range of wind speeds (Smyth et al., 2013). Second, aligning notches with the prevailing wind direction is important for maximising shear velocity within the slot of the foredune notch. In this study winds that are parallel to the notch consistently produced the highest shear velocities along the central transect of the slot in comparison to oblique incident winds (Table 3). Not only do high shear velocities in the notch slot enhance the prospect of sediment being transported from the beach to the hinterdune, but Smyth et al. (2023, 2024) also found that relatively steep windward slopes are less likely to be colonised by vegetation.

Finally, regular and systematic monitoring of notch morphology is essential for identifying and addressing significant changes in notch form. Although this research does not present topographic monitoring data, it highlights the potential value of such monitoring when combined with wind flow measurements and fluid dynamic modelling to better understand the evolving performance of foredune notches in delivering sediment inland. However, we acknowledge that large uncertainties remain due to the limitations of the modelling employed (section 4.4). If regular topographic surveys are not feasible, satellite or aerial imagery, as demonstrated in this study, can still provide valuable insights into how the slot and lobe are evolving over time (e.g., Figs. 9 and 10). Implementing systematic monitoring, whether through topographic surveys or remote sensing, can facilitate adaptive management by allowing for timely interventions, such as slot reprofiling or vegetation removal, to sustain the functionality of the landform as a conduit for aeolian sediment transport.

5. Conclusions

The computational fluid dynamic modelling of idealised foredune notches in this study revealed that the impact of slot slope on wind flow deceleration at the beach-notch transition is noticeable but relatively minor within the range of tested notch slopes (6°–12°). Instead, our findings indicate that notch width and alignment to prevailing winds could be more important factors in notch design, as shear velocities along the slot decrease as the notch widens, and misalignment to prevailing winds generate potential erosional and depositional zones that could alter notch morphodynamics, evolution, and efficacy. The wind flow modelling in this study also showed that shear velocity patterns throughout the notch are sensitive to the direction of the incident wind, with maximum shear velocities occurring within the slot for onshore winds and on the lobe for oblique winds. Additionally, the study demonstrates that narrowing the width of the dune slot from the beach toward the lobe may extend the zone of maximum shear velocity along the notch floor. Overall, our results suggest that to optimise foredune notch expansion along its axis, where possible notches should be excavated parallel to the prevailing above-threshold velocity winds at the site, rather than perpendicular to the dune crest. To maximise sediment transport within the slot of a foredune notch we also recommend that the excavated slot is relatively narrow (~25 m) as this encourages wind flow acceleration, particularly during wind events that are parallel to notch orientation.

CRediT authorship contribution statement

Thomas A.G. Smyth: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Thomas Pagon:** Writing – review & editing, Conceptualization. **Ian J. Walker:** Writing – review & editing, Visualization, Conceptualization.

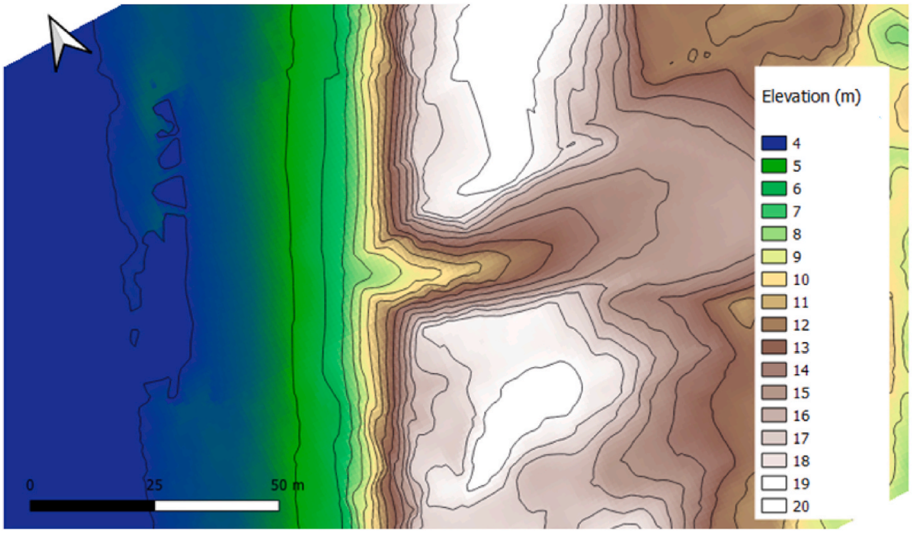
Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We wish to thank Dave Mercer and Natural England for generously facilitating access to Ainsdale Sand Dunes National Nature Reserve. The real-time kinematic global navigation satellite system (RTK-GNSS) used in the study was funded by the Royal Society grant RG170467. The authors sincerely thank the three reviewers for their valuable time, insightful feedback, and constructive comments that have greatly improved this article.

Appendix



Appendix 1, November Appendix 1. Topography of a foredune notch at Ainsdale Sand Dunes National Nature Reserve, England. The notch constructed in May 2022 and the topographic surface mapped using real-time kinematic global navigation satellite system survey (RTK-GNSS) in November 2022.

Data availability

Data will be made available on request.

References

Anderson, J.L., Walker, I.J., 2006. Airflow and sand transport variations within a backshore–parabolic dune plain complex: NE Graham Island, British Columbia, Canada. Geomorphology 77 (1–2), 17–34.

Arens, S.M., Mulder, J.P., Slings, Q.L., Geelen, L.H., Damsma, P., 2013. Dynamic dune management, integrating objectives of nature development and coastal safety: examples from The Netherlands. Geomorphology 199, 205–213.

Baas, A.C., 2019. Grains in motion. Aeolian Geomorphology: A New Introduction, pp. 27–60.

Bagnold, R.A., 1960. The Physics of Blown Sand and Desert Dunes. Methuen, London.

Bauer, B.O., Davidson-Arnott, R.G., Nordstrom, K.F., Ollerhead, J., Jackson, N.L., 1996. Indeterminacy in aeolian sediment transport across beaches. J. Coast Res. 641–653.

Bauer, B.O., Hesp, P.A., Smyth, T.A., Walker, I.J., Davidson-Arnott, R.G., Pickart, A., et al., 2022. Air flow and sediment transport dynamics on a foredune with contrasting vegetation cover. Earth Surf. Process. Landforms 47 (11), 2811–2829.

Blocken, B., Stathopoulos, T., Carmeliet, J., 2007. CFD simulation of the atmospheric boundary layer: wall function problems. Atmos. Environ. 41 (2), 238–252.

Brownett, J.M., Mills, R.S., 2017. The development and application of remote sensing to monitor sand dune habitats. J. Coast Conserv. 21, 643–656.

Byrne, M.L., 1997. Seasonal sand transport through a trough blowout at pinery provincial Park, ontario. Can. J. Earth Sci. 34 (11), 1460–1466.

Carter, R.W.G., Hesp, P.A., Nordstrom, K.F., 1990. Erosional landforms in coastal dunes. In: Coastal Dunes. Form and Process, pp. 217–250.

Castelle, B., Laporte-Fauret, Q., Marieu, V., Michalet, R., Rosebery, D., Bujan, S., et al., 2019. Nature-based solution along high-energy eroding sandy coasts: preliminary tests on the reinstatement of natural dynamics in reprofiled coastal dunes. Water 11 (12), 2518.

Davidson, S.G., Hesp, P.A., DaSilva, M., Da Silva, G.M., 2022. Flow dynamics over a high, steep, erosional coastal dune slope. Geomorphology 402, 108111.

Delgado-Fernandez, I., Smyth, T.A., Jackson, D.W., Smith, A.B., Davidson-Arnott, R.G., 2018. Event-scale dynamics of a parabolic dune and its relevance for mesoscale evolution. J. Geophys. Res.: Earth Surf. 123 (11), 3084–3100.

Gao, J., Kennedy, D.M., Konlechner, T.M., 2020. Coastal dune mobility over the past century: a global review. Prog. Phys. Geogr. Earth Environ. 44 (6), 814–836.

Gao, J., Kennedy, D.M., McSweeney, S., 2023. Patterns of vegetation expansion during dune stabilization at the decadal scale. Earth Surf. Process. Landforms 48 (15), 3059–3073.

Hesp, P.A., Hyde, R., 1996. Flow dynamics and geomorphology of a trough blowout. Sedimentology 43 (3), 505–525.

Hesp, P.A., Pringle, A., 2001. Wind flow and topographic steering within a trough blowout. J. Coast Res. 597–601.

Hesp, P.A., Smyth, T.A., 2016. Jet flow over foredunes. Earth Surf. Process. Landforms 41 (12), 1727–1735.

Hesp, P.A., Smyth, T.A., 2021. CFD flow dynamics over model scarps and slopes. Phys. Geogr. 42 (1), 1–24.

Hesp, P.A., Walker, I.J., 2022. Coastal dunes. In: Treatise on Geomorphology. Elsevier, pp. 540–591. https://doi.org/10.1016/b978-0-12-818234-5.00220-0.

Hesp, P.A., Smyth, T.A., Nielsen, P., Walker, I.J., Bauer, B.O., Davidson-Arnott, R., 2015. Flow deflection over a foredune. Geomorphology 230, 64–74.

Hilton, M.J., 2006. The loss of New Zealand's active dunes and the spread of marram grass (Ammophila arenaria). N. Z. Geogr. 62 (2), 105–120.

Hilton, M., Macauley, U., Henderson, R., 2000. Inventory of New Zealand's Active Dunelands, vol. 157. Department of Conservation, Wellington, p. 30.

Jackson, D.W., Costas, S., González-Villanueva, R., Cooper, A., 2019. A global 'greening'of coastal dunes: an integrated consequence of climate change? Global Planet. Change 182, 103026.

KPAL, 2015. Kenfig Dune Rejuvenation Works Topographic Survey March 2015. NRW Evidence Report No. 100. Kenneth Pye Associates Ltd., Solihull.

Lamy, A., Smyth, T.A., Robin, N., Hesp, P.A., 2024. Using Computational Fluid Dynamics (CFD) to investigate airflow and sand transport on a human-made coastal foredune dominated by offshore wind: impact of the shape variability. Coast Eng. 191, 104534.

Laporte-Fauret, Q., Castelle, B., Michalet, R., Marieu, V., Bujan, S., Rosebery, D., 2021. Morphological and ecological responses of a managed coastal sand dune to experimental notches. Sci. Total Environ. 782, 146813.

Laporte-Fauret, Q., Castelle, B., Marieu, V., Nicolae-Lerma, A., Rosebery, D., 2022. Foredune blowout formation and subsequent evolution along a chronically eroding high-energy coast. Geomorphology 414, 108398.

Maun, M.A., 2009. The Biology of Coastal Sand Dunes. Oxford University Press.

McLachlan, A., 1991. Ecology of coastal dune fauna. J. Arid Environ. 21 (2), 229–243.

Meerkerk, A.L., Arens, S.M., Van Lammeren, R.J.A., Stuiver, H.J., 2007. Sand transport dynamics after a foredune breach: a case study from Schoorl, The Netherlands. Geomorphology 86 (1–2), 52–60.

Miyanishi, K., Johnson, E.A., 2021. Coastal dune succession and the reality of dune processes. In: Plant Disturbance Ecology. Academic Press, pp. 253–290.

Nguyen, D., Hilton, M., Wakes, S., Simons-Smith, T., 2021. Incident wind angle and topographic steering through excavated foredune notches. Geomorphology 395, 107982.

Nguyen, D., Hilton, M., Wakes, S., 2022a. Aeolian sand transport thresholds in excavated foredune notches. Earth Surf. Process. Landforms 47 (2), 553–568.

Nguyen, D., Hilton, M., Wakes, S., 2022b. Wind flow dynamics and sand deposition behind excavated foredune notches on developed coasts. Earth Surf. Process. Landforms 47 (7), 1698–1719.

Nguyen, D., Wakes, S., Hilton, M., 2024. The influence of backdune morphology on air flow dynamics through an excavated foredune notch. Aeolian Research 67, 100929.

Parsons, D.R., Walker, I.J., Wiggs, G.F., 2004. Numerical modelling of flow structures over idealized transverse aeolian dunes of varying geometry. Geomorphology 59 (1–4), 149–164.

Petrova, P.G., de Jong, S.M., Ruessink, G., 2023. A global remote-sensing assessment of the intersite variability in the greening of coastal dunes. Rem. Sens. 15 (6), 1491.

Piscioneri, N., Smyth, T.A., Hesp, P.A., 2019. Flow dynamics over a foredune scarp. Earth Surf. Process. Landforms 44 (5), 1064–1076.

Pye, K., Blott, S.J., 2013. A geomorphological survey of Welsh dune systems to determine best methods of dune rejuvenation. CCW Contract Science 1002.

Pye, K., Blott, S., 2016. Dune rejuvenation trials overview report. Natural Resources Wales Evidence Report Series Report No: 296, 140pp, Natural Resources Wales.

Pye, K., Blott, S.J., 2017. Evolution of a sediment-starved, over-stabilised dunefield: kenfig burrows, south Wales, UK. J. Coast Conserv. 21 (5), 685–717.

Pye, K., Blott, S.J., Howe, M.A., 2014. Coastal dune stabilization in Wales and requirements for rejuvenation. J. Coast Conserv. 18, 27–54.

Ranwell, D.S., Boar, R., 1986. Coastal Dune Management Guide. Institute of terrestrial Ecology.

Richards, P.J., Hoxey, R.P., 1993. Appropriate boundary conditions for computational wind engineering models using the k-ϵ turbulence model. J. Wind Eng. Ind. Aerod. 46, 145–153.

Riksen, M.J., Goossens, D., Huiskes, H.P., Krol, J., Slim, P.A., 2016. Constructing notches in foredunes: effect on sediment dynamics in the dune hinterland. Geomorphology 253, 340–352.

Ruessink, B.G., Arens, S.M., Kuipers, M., Donker, J.J.A., 2018. Coastal dune dynamics in response to excavated foredune notches. Aeolian Research 31, 3–17.

Schupp, C.A., Winn, N.T., Pearl, T.L., Kumer, J.P., Carruthers, T.J., Zimmerman, C.S., 2013. Restoration of overwash processes creates piping plover (Charadrius melodus) habitat on a barrier island (Assateague Island, Maryland). Estuar. Coast Shelf Sci. 116, 11–20.

Schwarz, C., Brinkkemper, J., Ruessink, G., 2019. Feedbacks between biotic and abiotic processes governing the development of foredune blowouts: a review. J. Mar. Sci. Eng. 7 (1), 2.

Serra, N., Semiao, V., 2021. ESIMPLE, a new pressure–velocity coupling algorithm for built-environment CFD simulations. Build. Environ. 204, 108170.

Simons-Smith, T., 2017. *Wind Flow and Sediment Transport through Foredune Notches during Oblique-Onshore Incident Winds* (Masters Dissertation. University of Otago).

Smyth, T.A., 2016. A review of Computational Fluid Dynamics (CFD) airflow modelling over aeolian landforms. Aeolian research 22, 153–164.

Smyth, T.A., Hesp, P.A., 2015. Aeolian dynamics of beach scraped ridge and dyke structures. Coast Eng. 99, 38–45.

Smyth, T.A., Jackson, D.W., Cooper, J.A.G., 2013. Three dimensional airflow patterns within a coastal trough–bowl blowout during fresh breeze to hurricane force winds. Aeolian Research 9, 111–123.

Smyth, T.A., Delgado-Fernandez, I., Jackson, D.W., Yurk, B., Rooney, P., 2020. Greedy parabolics: wind flow direction within the deflation basin of parabolic dunes is governed by deflation basin width and depth. Prog. Phys. Geogr. Earth Environ. 44 (5), 643–660.

Smyth, T.A., Rooney, P., Yates, K.L., 2023. Dune slope, not wind speed, best predicts bare sand in vegetated coastal dunes. J. Coast Conserv. 27 (4), 27.

Smyth, T., Fox, B., Rooney, P., Bodenbender, B., De Vries-Zimmerman, S., O'Keeffe, N., 2024. Patterns and controls of topographic change within the deflation basins of a trough and bowl coastal blowout. Earth Surf. Process. Landforms.

Walker, I.J., Hesp, P.A., Davidson-Arnott, R.G., Ollerhead, J., 2006. Topographic steering of alongshore airflow over a vegetated foredune: greenwich dunes, prince edward island, Canada. J. Coast Res. 22 (5), 1278–1291.

Walker, I.J., Davidson-Arnott, R.G., Bauer, B.O., Hesp, P.A., Delgado-Fernandez, I., Ollerhead, J., Smyth, T.A., 2017. Scale-dependent perspectives on the geomorphology and evolution of beach-dune systems. Earth Sci. Rev. 171, 220–253.

Weller, H.G., Tabor, G., Jasak, H., Fureby, C., 1998. A tensorial approach to computational continuum mechanics using object-oriented techniques. Comput. Phys. 12 (6), 620–631.

van Westen, B., de Vries, S., Cohn, N., van Ijzendoorn, C., Strypsteen, G., Hallin, C., 2024. AeoLiS: numerical modelling of coastal dunes and aeolian landform development for real-world applications. Environ. Model. Software 106093.

Wiedemann, A.M., Pickart, A., 1996. The ammophila problem on the northwest coast of north America. Landsc. Urban Plann. 34 (3–4), 287–299.