Deposition patterns around buildings at the beach: Effects of building spacing and orientation

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**ABSTRACT**

Airflow at the beach creates sand deposition patterns around buildings. To assess how initial deposition patterns depend on the orientation of a building relative to the wind direction and on the spacing between buildings, a series of one-day field experiments was conducted with cuboid scale models, in which 34 configurations were tested. Scale models placed further apart than 2 to 3 times the building width created deposition patterns that were similar to those for stand-alone buildings, where downwind deposition tails were the sum of the individual buildings’ effects where these overlapped. For smaller spacings, between 0.5 and 2 times the building width, deposition patterns fundamentally differed from those for individual buildings, indicating a different type of airflow developed between the buildings. This created more complex depositional patterns that depended on the gap width. Rotation of an individual building relative to the wind direction induced an asymmetry in the downwind deposition patterns. A new rule of thumb quantitatively relates the asymmetry in the length of the deposition tails behind a building to the angle of the wind relative to the building and the length/width ratio of the building.

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1. Introduction

Although people might regard buildings as passive structures, simply standing in their environment, buildings can actually affect and shape their surroundings profoundly. Buildings act as obstacles to the wind, thereby changing the wind field and creating complicated airflow patterns (Hunt, 1971; Peterka et al., 1985). In sandy environments, such as deserts, beaches and dunes, these airflow patterns affect aeolian sediment transport, creating patterns of deposition and erosion (Nordstrom and McCluskey, 1984; Poppema et al., 2021b). This can pose problems, if for instance walkways or buildings entrances get blocked by building-induced deposition (Nordstrom and Jackson, 1998; Jackson and Nordstrom, 2011). It can even have repercussions for flood safety, if local scour around buildings creates a weak spot in the dunes (Nordstrom and McCluskey, 1984).

With coastal tourism and the demand for buildings at the beach increasing (Hall, 2001; Malavasi et al., 2013), knowledge about these deposition and erosion patterns is useful for coastal managers and local authorities who have to decide if, or under which restrictions, buildings are permitted along the coast. Quantitative understanding of building-induced erosion-deposition patterns can provide scientific support for regulation on the placement of buildings: for instance on the allowed size, location and orientation of buildings (Nordstrom and McCluskey, 1984). In addition, this knowledge helps to design and place buildings in such a way that unwanted deposition effects and the need for frequent sediment removal are minimized. Moreover, spatial designers have recently started explicitly utilizing building-induced effects to steer sediment to desired locations (e.g. for dune widening) (Van Bergen et al., 2021). Such designs need rules of thumb on how deposition and erosion depend on building placement and characteristics (Wijnberg et al., 2021).

Extensive research exists on airflow around bluff bodies such as buildings, often idealized as cuboid objects and also referred to as square cylinders (Hunt, 1971; Peterka et al., 1985; Martinuzzi and Tropea, 1993; Baskaran and Kashef, 1996; Bai and Alam, 2018). Wind approaching a building creates a downward flow at the upwind building face, creating a recirculation vortex directly upwind of the building. When this vortex is deflected downwind, a horseshoe vortex arises (Fig. 1). Flow separation at the top and sides of a building creates a recirculation zone behind the building. Some distance downwind, flow reattaches to the surface, with the downwind recirculation length generally less 1.5 building heights for approximately cubical buildings (Wilson, 1979; Fackrell, 1984; Luo et al., 2012). However, the horseshoe vortex remains present far longer, and turbulence and wind speed can remain affected at a downwind distance of 10 to 30 times the building height (Peterka et al., 1985).

For beach buildings placed directly at the surface, so not on stilts, deposition patterns generally follow this airflow pattern. (Nordstrom and McCluskey, 1984). This creates deposition a small distance upwind of
2. Methodology

2.1. Set-up experiments at the beach

Five experiments were conducted at a wide, flat part of the beach, each with different configurations of scale models to examine the effect of building orientation and the distance between buildings (experiment A–E, Fig. 3). The scale models, consisting of cuboid wooden boxes of 0.5 × 1 × 0.5 m (w × l × h), were placed at the beach surface when the wind was sufficiently strong for sand transport to occur (more than approximately 6 m/s). The resulting deposition patterns were recorded the next day, so deposition patterns had one day to develop. Depending on the wind conditions, this entailed 4 to 15 h of wind stronger than 6 m/s (Fig. 5). For experiment A, deposition was measured three days after placing the models instead of one day, but during the last two days there was no sediment transport due to low wind speeds (2–5 m/s).

Deposition patterns were measured after one day, to focus on the direct effect of buildings. Over time, as deposition and erosion depth increase, morphological feedback would interact with the deposition patterns, as the topography will (under fixed wind conditions) start sheltering the bed and partly cancel out the airflow effects induced by a building (McKenna Neuman et al., 2013; McKenna Neuman and Bédard, 2015). The scale model size was chosen to be large enough to represent sedimentation effects around full scale buildings. This has been shown in a previous field experiment we did (Poppema et al., 2021b) in which deposition patterns around small scale models and a full-scale model compared quite well. For these smaller scale models, the most important scaling effect is that deposition develops more quickly than around real buildings. The effect of other scaling issues is most likely limited, based on the limited importance of scaling effects in our experiments (Poppema et al., 2021b) and in similar experiments on the accumulation of snow around scaled buildings in a natural environment (Okawa and Tomabechi, 2000; Liu et al., 2018).

All experiments were conducted at the south side of the Sand Motor in the Netherlands (Fig. 2), on the newly accreted beach area. The beach at this location is very flat with a 1:500 slope, and approximately 400 m wide, ensuring large fetch lengths (200 m for the offshore wind of experiment C, more than 500 m for the obliquely onshore winds of the other experiments). The median grain size at the Sand Motor is 335 μm (Hoornhout and De Vries, 2019).

To determine the effect of the orientation of an individual building relative to the wind, experiment A consisted of 9 scale models placed at the beach simultaneously, each with a different orientation to the wind (Fig. 3a, Table 1). A windvane was used to achieve the desired angles between scale models and wind direction, as prevailing during the set-up of each experiment.

To determine the effect of building spacing, experiment B consisted of six groups of three scale models (Figs. 3b, 4), with gap width G varying between 0 and 2 m (Table 1). Scale models were placed with the short axis parallel to a base line, and the base line perpendicular to the wind. For experiment C this was extended with a seventh group, with a gap width of 3 m. Resulting gap ratios G/L range between 0 and 0.86, where G/L is the centre-to-centre distance of the scale models compared to the baseline, with building faces forming a staggered line (Fig. 3d). Here, centre-to-centre distances of scale models were kept the same as in previous experiments.

The wind speed and direction, shown in Fig. 5 and Table 1, were measured using a 2D Windsonic ultrasonic anemometer, at 1.8 m high
and using a sampling frequency of 0.2 to 0.6 Hz. In experiment A, the WindSonic was likely not properly aligned to the north, given that the direction of sand ripples in areas without scale models was consistent with a wind direction from a somewhat more northerly direction than derived from the WindSonic data. The average direction of the deposition tails downwind of the scale models was also in line with this more northerly wind direction, which deviated by 12° from the Sonic-derived wind direction. In the analysis of experiment A, we therefore used a corrected wind direction.

On the last day of experiment A, the WindSonic and Wenglors stopped recording due to an empty battery. For experiment C, they were not employed because of a thunderstorm. In both cases, wind data were retrieved from a public KNMI weather station at Hoek van Holland (KNMI, 2020), at 9 km distance. This station measured the hourly averaged wind speed and direction at 15 m above the ground. Windspeed measurements were converted to a height of 1.8 m, as measured by the WindSonic anemometer in the other experiments, using a constant difference of 2 m/s, based on a comparison of WindSonic and KNMI measurements for the other experiments.

The height of the saltation layer was measured by a vertical array of 10 Wenglor laser particle counters (see Hugenholtz and Barchyn, 2011; Duarte-Campos et al., 2021). The Wenglors were positioned between 0.05 and 1 m above the bed. The saltation layer height varied between 0.2 and 0.3 m, so in all cases lower than the scale models. Furthermore, for experiment B and C a time-lapse video with a 10 s sampling interval was recorded by a camera mounted 5 m above the beach. For the time-lapse of experiment B, see supplementary material S1.

The sedimentation patterns around the scale models were measured using structure-from-motion photogrammetry (Westoby et al., 2012; Fonstad et al., 2013). Photos were taken from a height of 5 m, using either a Phantom 4 Pro drone or an Olympus E-PL7 camera on a telescopic stick (Table 2). Drone photos are of a 20 megapixel resolution, taken with a fixed 8.8 mm lens (74° horizontal angle of view). Photos taken with the Olympus camera are of 16 megapixel resolution, with a 20 mm lens (47° horizontal angle of view). With these camera properties and image shooting distance, the typical pixel footprint size of individual photos was approximately 1 mm. Scale bars were dispersed throughout the experimental area for referencing. In addition, ground control points were measured using a Leica GS14 RTK GPS, with an accuracy of approximately 2 cm.

2.2. Structure from motion photogrammetry

Agisoft Metascan was used for the structure-from-motion (SfM) photogrammetry, following the same workflow as Poppema et al. (2021b). The horizontal resolution of the constructed DEMs and orthophotos was...
Table 1
An overview of the conducted experiments. Wind conditions characterize only the period during which sediment transport occurred (wind speed over 6 m/s). Orientations of experiment A are as measured, relative to the dominant wind direction, hence explaining the irregular interval between tested orientations.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Survey date</th>
<th>Variables tested</th>
<th>Gap width G [cm]</th>
<th>Gap ratio g* [−]</th>
<th>Orientation baseline to wind [°]</th>
<th>Orientation object to baseline [°]</th>
<th>Wind speed [m/s]</th>
<th>Wind direction</th>
<th>Variation wind dir. [σ;°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>15-4-2019</td>
<td>Object orientation</td>
<td>–</td>
<td>–</td>
<td>21; 32; 35; 51; 70; 81; 93; 112; 173</td>
<td>0</td>
<td>7.3</td>
<td>NNE</td>
<td>6</td>
</tr>
<tr>
<td>B</td>
<td>12-4-2019</td>
<td>Gap width</td>
<td>0; 25; 50; 100; 150; 200</td>
<td>0; 0.33; 0.5; 0.67; 0.75; 0.8</td>
<td>90</td>
<td>0</td>
<td>8.3</td>
<td>NNE</td>
<td>13</td>
</tr>
<tr>
<td>C</td>
<td>25-4-2019</td>
<td>Gap width</td>
<td>0; 25; 50; 100; 150; 200</td>
<td>0; 0.33; 0.5; 0.67; 0.75; 0.8; 0.9</td>
<td>90</td>
<td>0</td>
<td>8.3</td>
<td>SSE</td>
<td>16</td>
</tr>
<tr>
<td>D</td>
<td>14-5-2019</td>
<td>Gap width, group orientation</td>
<td>0; 25; 50; 100; 150; 200</td>
<td>0; 0.33; 0.5; 0.67; 0.75; 0.8</td>
<td>60</td>
<td>0</td>
<td>8.1</td>
<td>N</td>
<td>12</td>
</tr>
<tr>
<td>E</td>
<td>15-5-2019</td>
<td>Gap width, object orientation</td>
<td>0; 3; 21; 56; 91; 127</td>
<td>0; 0.06; 0.29; 0.53; 0.65; 0.72</td>
<td>90</td>
<td>45</td>
<td>7.8</td>
<td>NNE</td>
<td>7</td>
</tr>
</tbody>
</table>

approximately 2 mm. Ground control point accuracy was generally at least 25 mm and scale bar accuracy at least 1 mm. Light conditions (Table 2) affect photogrammetry (Brunier et al., 2016; Chiba and Thiis, 2016), with e.g. sunny conditions creating contrast-rich photos, but also sharp shadows around scale models (Fig. 9). Nevertheless, this did not cause noticeable differences in accuracy, with especially the DEMs also showing clear details in shadowed regions.

2.3. Methodology of data analysis

2.3.1. Measuring deposition patterns

The DEM and orthophoto were first assessed visually, to qualitatively describe the nature of deposition patterns and identify the differences between different configurations. For the experiments on gap width, elevation profiles were additionally extracted from the DEM to quantitatively compare the deposition height and length around scale models. For the experiments on building orientation, the length of the downwind deposition tails was measured to quantitatively analyse their asymmetry. These tails were measured following Poppema et al. (2021b). A tailored image thresholding algorithm (Fig. 6) was applied to the orthophoto to distinguish deposition areas, based on their lighter colour and more uniform appearance. Then, as a control, these lengths were compared to a manual estimate based on visual inspection of the orthophoto and the DEM. In cases where both lengths differed significantly (>10%), algorithmically detected edges were checked, and incorrectly or unlikely drawn edges were corrected.

2.3.2. Linking building orientation to deposition length

The effect of a rectangular building’s orientation to the wind was examined based on the length of the downwind deposition tails. The length of the left and right deposition tail depends on the amount of sand transport around each building side towards that tail. We will now develop a rule of thumb on how the fraction of sediment steered to the left and right of a building (αL and αR in Fig. 7) depends on the building orientation and building shape. Fraction αL and αR are defined relative to the total sediment transport downwind, so excluding the upwind deposition volume (i.e. αL + αR = 100%).

To quantify the sediment partitioning to the downwind deposition tails, we examine the contribution of each wind-facing wall separately, under the premise that the contribution of each wall can be determined independently (Fig. 7). For each wind-facing wall, its orientation and length determine (1) its effective width projected perpendicular to the overall wind direction (e.g. in Fig. 7b Weff,L = L sin 𝜃L) and (2) to what degree it steers sediment to either side (αL, wall and αR, wall in Fig. 7c and d). The effect of both wind-facing walls is then combined to determine what fraction of the sediment transport the entire building steers to either side (αL and αR in Fig. 7b), using the effective width of the walls to take into account the amount of sand approaching each individual wall.

In case of a rectangular object oriented perpendicular to the wind (Fig. 7a), there is only a single wind-facing wall, with flow separation in front of this wall creating a recirculation vortex that is wrapped around the building (Fig. 1) and transports sand equally to both sides. For an object at an oblique angle to the wind, there are two wind-facing walls, and the orientation of each individual wall determines how that wall divides sediment between both sides: a more wind-perpendicular wall will divide sand more evenly, while a wall more parallel to the wind will steer sand mostly to one side. For instance, the wall in Fig. 7d – which is almost wind-perpendicular – steers slightly more sediment to the right than to the left. Because this wall acts as a strong

![Fig. 4. A sketch of the set-up of experiment B (scale models not drawn to scale).](image-url)
obstacle to the wind, a recirculation vortex forms, which also creates substantial sediment transport to the left. For the left wind-facing wall—which is almost parallel to the wind (Fig. 7c)—wind and sand can easily flow along the wall without being blocked, so the vast majority of sand transport towards this wall is steered to the left.

Changes in a wall’s orientation have a gradual effect on the division of sediment to both sides. As a wall’s orientation becomes more aligned with the dominant wind direction, wind increasingly follows the wall instead of being blocked and diverted to two sides. Consequently, a larger fraction of the sediment transport approaching this individual wall is steered parallel to the orientation of the wall, and a smaller portion is recirculated to the other side. However, even walls almost parallel to the wind can still steer sediment to both sides. For example, at the wall of Fig. 7c, a small fraction of the sediment transport towards this wall will still flow towards the right-hand tail (the yellow arrows in Fig. 7c). This is due to a small rightward airflow upwind of the building, and due to the rightward airflow found downwind of the recirculation cell that develops directly behind the building. This is as indicated by

![Image](image_url)

**Fig. 5.** The wind conditions during the experiments. The horizontal dashed line indicates the critical wind speed for sediment transport to occur, vertical dotted lines indicate the start and end of each experiment (i.e. the moment scale models were placed and that deposition patterns were surveyed).

**Table 2**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Camera</th>
<th>Number of photos</th>
<th>Weather conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Olympus E-PL7</td>
<td>1026</td>
<td>Mostly sunny</td>
</tr>
<tr>
<td>B</td>
<td>Olympus E-PL7</td>
<td>953</td>
<td>Mostly cloudy</td>
</tr>
<tr>
<td>C</td>
<td>Olympus E-PL7 + Phantom 4 Pro</td>
<td>139 + 968</td>
<td>Cloudy, occasional rain</td>
</tr>
<tr>
<td>D</td>
<td>Phantom 4 Pro</td>
<td>2181</td>
<td>Sunny</td>
</tr>
<tr>
<td>E</td>
<td>Phantom 4 Pro</td>
<td>2428</td>
<td>Sunny</td>
</tr>
</tbody>
</table>

**Fig. 6.** Example of the determination of the tail length, for the scale model at a 70° angle to the wind. The orthophoto (left) was binarized (middle), with white pixels indicating bright areas and hence (likely) deposition. Then the edges of the largest deposition areas were detected (right, with blue lines for the edges) and the length from the scale model to the downwind end of the deposition areas was measured.

the black arrows in Fig. 7c (c.f. Luo et al., 2012, especially the streamlines in their Fig. 5).

As a first approximation of this process, we propose to describe the division of sediment by a wall to its left and right side using linear interpolation between the two extremes, i.e. interpolation between the (almost) wind-parallel walls fully steering sediment to the left or right. For a single wall, this can mathematically be described as a fraction \( \alpha_L = \frac{\theta}{180} \) of the sediment being steered to the left, and a fraction \( \alpha_R = 1 - \alpha_L \) to the right, where the angle \( \theta \) is defined according to Fig. 7. For a wall perpendicular to the wind \((\theta = 90°)\), this indeed amounts to \( \alpha_L = \alpha_R = \frac{1}{2} \), so half the sediment being steered to either side.

For a building with an obliquely approaching wind, the contribution of both wind-facing walls has to be combined, taking into account the effective wind-facing width of both walls. Hence, the total fraction of the sediment steered to the left can be calculated as the weighted average of the fractions steered to the left by each wall \((\alpha_{L,\text{left wall}} = \frac{\theta_L}{180} \text{ and } \alpha_{L,\text{right wall}} = \frac{\theta_R}{180})\):

\[
\alpha_L = \frac{\alpha_{L,\text{left wall}} \cdot W_{\text{eff,L}} + \alpha_{L,\text{right wall}} \cdot W_{\text{eff,R}}}{W_{\text{eff,L}} + W_{\text{eff,R}}} \tag{1}
\]

The rightward steered fraction of the building is then simply equal to \(1 - \alpha_L \), just as for a single wall. Alternatively, for rectangular buildings Eq. (1) can be rewritten in terms of only angle \( \theta_R \) and the width: length ratio of a building, by directly calculating the steered fractions and effective widths and using \( \theta_L = \theta_R + 90° \). This results in Eq. (2), with building width \( W \) measured at the right wind-facing wall, and length \( L \) at the left wall (Fig. 7b).

\[
\alpha_L = \frac{\theta_R}{180} + \frac{0.5}{\tan(\theta_L) \cdot \frac{W}{L} + 1} \tag{2}
\]

Fig. 8 sketches how the orientation of scale models in the experiments affects their effective width and expected partitioning of sediment transport. This will be used to correlate the asymmetry in the expected sediment partitioning to the asymmetry in the measured lengths of deposition tails.

3. Results

3.1. Effect of building orientation

Depositional patterns around individual scale models placed at various angles to the wind revealed the effect of building orientation (Experiment A). In general, the patterns were similar for all orientations, with deposition upwind of the scale models and downwind...
deposition in two tails (Fig. 9a, b). The orientation of the upwind deposition ridge was oriented somewhere between perpendicular to the main wind direction and parallel to the upwind building face, but closer to the former. This is illustrated in Fig. 9b. Along the front of the scale model erosion generally occurred, especially at corners. There was little deposition next to the building, so upwind deposition and downwind deposition tails were mostly separated, rather than forming a continuous horseshoe shape.

Another observation is that the two deposition tails downwind of a scale model often differed in length (Fig. 10a). This asymmetry also shows in the deposition pattern of Fig. 6. The expected asymmetry in the fraction of sediment steered to the left and right ($\Delta \alpha$) and the observed asymmetry in the tail lengths ($\Delta L$) show a quite strong linear correlation ($r = 0.79$, Fig. 10b). 

$$\Delta \alpha = \alpha_L - \alpha_R \quad \text{and} \quad \Delta L = L_{\text{left}} - L_{\text{right}} = L_{\text{left}} + L_{\text{right}}.$$ 

The slope of the trendline between $\Delta \alpha$ and $\Delta L$ is 1.16, with a 95% confidence interval of 1.16 ± 0.65. Note that a trendline without
intercept is used in this case to ensure tails are of equal length for wind perpendicular to the building. Based on this linear relation, it is shown in Fig. 10c that the proposed sediment flow partitioning concept, based on wind angle and building length and width (Eq. (1)), is consistent with the observed asymmetry in tail lengths.

3.2. Effect of building spacing

For experiment B, on the effect of building spacing (Fig. 9c), scale model groups with no gap or very small gaps showed a single upwind deposition area, with maximum deposition height in front of the middle scale model. This was the case for gap ratios \( g^* = G/\lambda \) of 0 and 0.33 (Fig. 11). For wider gaps, the deposition height directly upwind of the gaps decreased, so local maxima were formed in front of the individual scale models. As a result, one can recognize the individual upwind deposition areas of the three scale models for the configurations with \( g^* = 0.67 \) and larger. For the first two set-ups, the upwind deposition was generally higher and continued further upwind than for the larger gap widths, as visible in the centreline cross sections in Fig. 12a. Also the peak in the upwind deposition height of these two set-ups was higher and located further upwind from the building edge, especially for the continuous scale model (no gaps, \( g^* = 0 \)).

Downwind of the scale models, deposition behind the gaps, which we call the inner tails, developed differently from the outer tails at the

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**Fig. 11.** Digital elevation models around scale models with various gap widths (experiment B), with wind coming from below. Black dotted lines indicate the location of the cross sections plotted in Fig. 12. Elevations are relative to a fitted linear surface (fitted per subplot), to highlight local differences caused by erosion and deposition.
outside of a building group. The set-up without gaps showed only outer deposition tails. For small gap widths (g* = 0.33 and g* = 0.5), inner tails formed as well, but the outer deposition tails remained wider and longer than the inner tails (Fig. 11). In the gap between the scale models and directly downwind of the gaps, erosion occurred, as also visible in Fig. 12c from the negative bed levels between y = 0 and y = 1.5 m. Some distance downwind of the gap this changed into deposition, forming the inner tails. When gap widths increase further, the erosion in and directly behind the gap disappeared. Consequently, inner tails started just in between the scale models for a gap ratio of 0.67. They were still smaller in length and width compared to the outer tails, but larger in height. For gap ratios of 0.75 and 0.8, the inner tails were similar in length compared to the outer tails, with inner tails at g* = 0.8 wider and lower than at g* = 0.75. Overall, this amounts to inner tails being higher than outer tails, and to a trend of outer tails becoming smaller with increasing gap widths, while inner tails become larger.

The gap width affected not only the size of the deposition tails, but also their planform shape. At the larger gap ratios, both the inner and outer tails were roughly oval in shape. However, at the smaller gap ratios of g* = 0.33 and 0.5, the inner tails instead had a more triangular shape, while the outside tails remained roughly oval. Additionally, a smaller difference could be found in the presence of sand ripples. Ripples were largely absent from the inner tails at g* = 0.33, while all the other inner and outer tails of other set-ups showed ripples.

Comparing the two experiments on gap width (B and C), the patterns in the repeat experiment (C) are consistent with the general deposition patterns described above (B). However, patterns developed at a slightly oblique angle to the building (10° to 15°) in experiment C, caused by a change in wind direction during the experiment (Fig. 5). Also, the morphological patterns in experiment C were about half as high as in experiment B, likely as the result of rain during the experiment having decreased sediment transport rates. The lower deposition height made it more difficult to distinguish scale-model-induced deposition on DEMs from bed level variation already present in the undisturbed beach. Nonetheless, overall deposition patterns were quite comparable, as shown in Fig. 13 for one of the set-ups. For a complete overview, with all the set-ups of experiment C, see supplementary material S2.

3.3. Results complex configurations

For complex configurations, with groups of three buildings placed at an oblique angle to the wind, buildings were placed in two different configurations (Fig. 3c, d). For experiment D, the baselines of the entire scale models groups were oriented at a 60° angle to the wind. Here, inner and outer tails obtained a similar size for gap ratios of 0.75 and larger (Fig. 14). This gap ratio amounts to a gap width of 1.5 m perpendicular to the building, which effectively results in a gap of 0.8 m perpendicular to the wind (Fig. 14c). For smaller gap ratios, the inner tails were clearly shorter than the outer tails. Compared to experiment B and C, which had the scale model groups oriented perpendicular to the wind, more deposition occurred in the lee directly behind the scale models, occasionally forming a sharp ridge. For the smallest gap widths (g* = 0.33 and g* = 0.5), deposition from the inner tail and the lee of the scale models in addition partially merged with the outer tail (Fig. 14a). Lastly, viewing in the downwind direction, the left-hand outer tail was generally slightly higher than the right-hand tail.

For the second configuration (experiment E), where the baseline of objects was kept perpendicular to the wind and scale models were rotated individually at a 45° angle to the wind, similar results were observed. Also here a minimum gap ratio of 0.75 was required for inner tails to be comparable in length to the outer tails. This amounts to a gap of 0.9 m perpendicular to the wind direction. Deposition directly in the lee of scale models was again larger than for experiment B and C, but slightly less pronounced than for experiment D.

4. Discussion

4.1. Building orientation

The tails of the obliquely oriented individual scale models were asymmetrical: the left and right tails often had different lengths. Our sediment partitioning theory, which we developed to predict which fraction of the sediment flow passes along the left or right side of a building, showed significant correlation with the asymmetry in the tail lengths. The slope of the linear fit between sediment partitioning asymmetry and tail length asymmetry was 1.16, with a 95% confidence interval from 0.51 to 1.81.
To estimate tail asymmetry for buildings of arbitrary length:width ratio, we simplify the result to tail length asymmetry being equal to the expected sediment partitioning asymmetry, based on the large confidence interval around the 1.16 slope. This assumes that the sediment transport volume steered to each side is proportional to both the volume and length of each deposition tail; and thus that the left and right tail only differ in length, but have the same width and height. Hereby, the sediment partitioning method of Section 2.3.2 can be used as a rule of thumb to estimate how the asymmetry in deposition patterns for individual buildings, of arbitrary cuboid geometry, depends on the building shape and orientation (Fig. 15). It follows that maximum tail asymmetry develops when the angle (θ) between the wind and the shortest side of the building is about 65 to 70 degrees. In addition, the physical reasoning behind the rule does not depend on buildings having right-angled corners, so the rule can also be applied for buildings consisting of straight walls at angles other than 90°, as long as they are mostly uniform in height.

The proposed flow partitioning theory manages to predict asymmetry in the length of the deposition tails, without explicitly including complicated 3D flow patterns and changes in the airflow topology (Yen and Liu, 2011; Luo et al., 2012). This makes it simple enough to use in rule-based morphological computer models such as Dubeveg (Keijzers et al., 2016) or for design exercises where building-induced deposition is important (Van Bergen et al., 2021). However, the rule of thumb is still based on a very limited amount of observations. Furthermore, only morphological effects (i.e. deposition) were measured, without measurements of airflow or sediment transport around the building and over this topography. Therefore, further research by additional field experiments, controlled wind tunnel experiments, or CFD modelling of airflow around buildings (e.g. Pouteimouiri et al., 2022), would be very valuable to further test and develop the theory. For instance, experiments with more repetitions or buildings with various length:width ratios would help to determine if other fractions than the so far used linearly interpolated steered fractions (i.e. the formula αt = φ(90)) describe the effect of building orientation on sediment partitioning better.

With the focus so far on tail length asymmetry, the question remains how large absolute tail length is. Absolute tail length depends strongly on the effective wind-facing surface of a building and hence on building size (Poppema et al., 2021b). In addition, tail length depends on the sediment flux, and thereby on the wind speed, on local conditions as grain size, surface moisture and armouring and on the time available for deposition to develop. The effect of wind speed and duration also appeared in another experiment for the effect of building orientation, where 10 h of strong winds of 10.5 m/s created deposition tails that had such lengths (± 15 m), that tails of simultaneously placed scale model set-ups mixed and fused together. This also fits our previous result (Poppema et al., 2021b) that especially the downwind length of deposition patterns increases with wind speed, with approximately linear scaling between wind speed and tail length. However, all these factors mainly affect the total sediment flux, rather than the airflow patterns or the division of sediment between both building sides. Hence, they should have little effect on the tail length asymmetry as predicted by the rule of thumb.

In addition, the building orientation to the wind itself might play a role for the absolute tail length, by not only determining the wind-facing surface and the division of flow over both sides, but also creating fundamentally different airflow patterns behind the building. Luo et al. (2012) found that the shape and size of the recirculation cells behind a building (see Fig. 16) depend on the wind angle, and that for sufficiently oblique winds only a single recirculation cell is formed. Although this proves that the type of airflow pattern changes, such changes cannot be linked directly to the deposition length, especially as our experiment showed deposition in two tails stretching out far behind the building (on average 6 m, so 12 times the building height h), while recirculation cells are shorter (2.5 to 3.5 h for Luo et al., 2012) and located more centrally behind the building.

Lastly, the deposition patterns observed in the experiment are the initial deposition patterns that developed after a day at the beach. This short timespan is chosen to examine the effect of a building on a flat beach, without morphological feedback interacting with building effects. The short time span also assured that the wind direction remained reasonably constant during the experiment (the standard deviation was 6° for experiment A). Although variations in the wind

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1 This experiment was not analysed quantitatively, because tail ends were undefined due to tails merging with other deposition features. Supplementary material S3 shows an impression, in which the morphology also illustrates how sediment is diverted around buildings.
direction have had no visible effect, they could have slightly altered the deposition size or shape. Around real buildings at the beach, with continuously changing wind conditions, more complex deposition patterns can develop over time as the cumulative result of multiple independent wind events.

4.2. Gap width between buildings

By varying the gap width between scale models, we observed changes in shape and location of deposition patterns that suggest differences in the nature of the airflow. Upwind of the building groups, the configuration with three continuous scale models without gaps (gap ratio $g^* = 0$) developed a deposition area that extended further upwind, had a larger deposition height and had the crest located further from the building edge than the other set-ups (Fig. 12). This fits the results of Poppema et al. (2021b), that upwind deposition length and upwind separation distance scale with building width and height. Likewise, the upwind separation distance for snow accumulation is also found to increase with building height (Thiis and Gjessing, 1999). The observations from $g^* = 0$ applied – to a lesser degree – to the configuration with narrow gaps ($g^* = 0.33$), showing that at $g^* = 0.33$ the upwind deposition height and location depend directly on the gap width. At gaps of $g^* = 0.5$ and larger, the height and location of the crest of the upwind deposition appeared constant, independent of the gap width. Physically, the larger separation distance between the upwind deposition and the building and the larger downwind deposition length at $g^* = 0.33$ can be explained by most of the wind still being diverted around the building, with limited airflow through the gaps, hence creating a larger rolling vortex upwind of the row of scale models. For gaps even smaller than $g^* = 0.33$, buildings will likely increasingly act as a single building, with little transport through the gaps and airflow tending towards a shared horse vortex system (Yen and Liu, 2011; Luo et al., 2014). Consequently, most of the sand is transported around the building group, creating large outer tails. As the gap width increases, transport increasingly occurs through the gaps instead of around the building group, so inner tails grow larger, while outer tails become smaller. This is similar to how inner tails increased with gap width in a series of experiments on gap width and snow accumulation (Thiis and Jaedicke, 2000, with $g^* = 0.4$; 0.66 and 0.7), although there the inner tail was completely absent at the smallest tested gap width, possibly as the result of the oblique wind angle (64°).

Our more detailed observations on deposition behind the gaps can be compared to findings of Luo et al. (2014), who examined the airflow patterns downwind of two adjacent buildings in a wind tunnel, in order to better understand the formation of aeolian deposition and erosion patterns. Although we mostly examined larger gap widths than Luo...
et al. (2014) ($g^{*} = 0.33–0.86$ compared to $g^{*} = 0.09–0.44$), their airflow measurements help to understand the deposition and erosion patterns we observed. Our set-ups with the smallest gaps ($g = 0.33$ and $g^{*} = 0.5$) showed erosion in between the buildings and directly downwind of the gaps, followed by deposition. For $g^{*} = 0.09$ (so smaller than the smallest gap we tested), Luo et al. (2014) observed very limited airflow through the gap, creating a pair of counter-rotating recirculation cells behind the entire building group, with flow reversal behind the gap. For larger gap widths, the funnelling effect of the buildings created flow acceleration in and directly behind the gap. Upon leaving the gap, wind had space to expand, leading to deceleration at a distance of 0.5 to 1 building heights downwind of the gap. This fits well with our observed erosion in and directly behind the gaps at $g^{*} = 0.33$ and 0.5, where airflow accelerates, closely followed by deposition where the wind decelerates.

These airflow patterns can also explain why our inner deposition tails at $g^{*} = 0.33$ barely displayed any ripples. For relatively small gap widths, the outer recirculation cells are larger than the inner cells (see Fig. 16A) because more airflow is flowing around the building group than through the gap. These outer recirculation cells can wrap around the inner cells, meeting in the centre (Luo et al., 2014). This causes flow reversal where they meet, if the outer recirculation cells are dominant enough (see the flow reversal between point S1 and S2 in Fig. 16a and the red line in Fig. 16c). For slightly larger gaps, and less difference between inner and outer cells, flow is decelerated instead of reversed (see the blue line in Fig. 16c). Given that ripple formation requires saltating grains and sufficient wind speed (Anderson, 1987; Nishimori and Ouchi, 1993), such flow deceleration or reversal likely explains why the inner deposition tails barely displayed any ripples in our results of $g^{*} = 0.33$.

However, our results differ from those of Luo et al. (2014) with respect to the minimum gap width at which flow patterns become similar to those of individual buildings. For Luo et al., their largest gap width of $g^{*} = 0.44$ created balanced recirculation cells behind both buildings, seemingly unaffected by the neighbouring building. So inner and outer recirculation cells were of a similar size, preventing the outer cells from meeting in the centre and hence creating strictly downwind streamlines through the gap (see Fig. 16b). In our result at $g^{*} = 0.5$, the inner and outer deposition tails were still clearly different (Fig. 11), suggesting fundamentally different flow behind the gaps due to the combined effect of closely-spaced scale models. At $g^{*} = 0.67$ our set-up still exhibited inner tails that were narrower and shorter than the outer tails. Only at $g^{*} = 0.75$, inner and outer tails were of a similar shape and size, as would be expected when flow behind the gaps is similar to the flow at the outside of the group.

This difference is likely partly caused by different scale model shapes: our scale models had a square wind-facing surface of $0.5 \times 0.5$ m, while Luo et al. (2014) tested with wider scale models, with a width and height of $0.05 \times 0.025$ m. Given that the size of the recirculation vortex in front of the building (see Fig. 1) increases with both building height and building width (Peterka et al., 1985; Martinuzzi and Tropea, 1993), a relatively taller building creates a larger vortex in front and next to the building (larger relative to the building width). Hence, a larger gap ratio is required for neighbouring buildings to allow these vortices to develop independently of any adjacent buildings. This is consistent with wind tunnel experiments of two adjacent buildings (Stathopoulos et al., 1992), which found that building width w and height h together determine the ratio of the airflow acceleration in the gap between buildings to the acceleration at the outside building corners ($K_{gap}/K_{corner}$). More precisely, the ratio $K_{gap}/K_{corner}$ depended on the relative gap width $G/R$, in which gap width is G divided by the scaling length R for airflow around buildings. Here, $R = \min (w, h)^{2/3}$, $\max (w, h)^{1/3}$, valid for building aspect ratios $w/h$ between 1/8 and 8 (Wilson, 1979).

The gap ratio as used to describe deposition patterns for different building configurations is hence only valid for buildings of equal width and height: it describes the porosity of a configuration to wind and sand transport, but does not take into account the aspect ratio ($w/h$) of the buildings. If building height increases, a larger horseshoe vortex is formed, so a larger gap ratio would be needed to form topologically similar deposition patterns. When interested in buildings with arbitrary aspect ratios, the expected deposition around building groups can therefore best be described using our observations for a configuration with a similar relative gap width (similar G/R ratio), instead of the configuration with a similar gap ratio. In the future, experiments on deposition around building groups with various aspect ratios would be valuable to verify if this scaling using scaling length R indeed holds true.

Overall, these results show that at small to intermediate gap widths, scale models created a shared complex flow and deposition pattern per building group, while for larger gap widths individual scale models acted mostly independently, with deposition similar to the summation of the expected effects of the individual scale models. This transition occurred at a gap width of 2–3 building widths ($g^{*} = 0.67$ to 0.75). Especially the inner tails of $g^{*} = 0.75$ and $g^{*} = 0.8$ could be recognized as being the summed results of the scale models at either side of the gap. For $g^{*} = 0.75$ inner tails were clearly higher than the outer tails, as they are formed by the deposition of two scale models, that occurred at almost the same place, leading to a single tail (per gap) of increased height. For $g^{*} = 0.8$, the tails of the two scale models at either side of the gap were created mostly next to each other, hence forming a deposition area that is wider and lower than for $g^{*} = 0.75$.

In addition, our results show that deposition behind gaps in between building (i.e. inner tails) can occur at any gap width. Previous studies
searched for a critical gap width above which accelerated airflow through the gaps precludes inner deposition tail formation. From flow velocity, bed shear stress and deposition measurements in a wind tunnel, Luo et al. (2014, 2016) concluded that inner tail deposition may disappear for gaps wider than \( g^* = 0.44 \), which was their largest tested gap width. However, at \( g^* = 0.5 \), so our value closest to 0.44, we still observed inner tail formation, and actually inner tails were even larger at larger gap widths (Fig. 11). Given that deposition occurred, upwind of the buildings and behind the gaps, at all tested gap widths, the more important question is where deposition occurs and how much, rather than whether deposition occurs. For example, the experiments showed stronger upwind deposition for scale models with \( g^* = 0.5 \) compared to \( g^* \geq 1 \). So for buildings with a similar aspect ratio, coastal managers that want to augment sediment transport past a building group to a hinterlying dune, should ensure a gap ratio of at least 1.

4.3. Complex configurations

Deposition patterns observed around the configurations in which gap width and building and baseline orientation where varied in combination (experiments D, E), where largely consistent with those observed for the simpler wind-perpendicular set-ups (experiment B, C), albeit that larger gap ratios were needed before substantial inner tails could form. However, the necessary gap widths become more comparable when using the effective gap width, measured perpendicular to the wind instead of perpendicular to the building (Fig. 14c), which may better characterize the corridor actually open to the wind. In real situations, where buildings experience various wind directions over time, this implies that the effective gap width for the wind will depend on the wind direction. Hence, if a certain gap width is desired, for instance to limit upwind deposition as described above, the dominant wind direction must be taken into account, and possibly the distance between buildings should be increased, to ensure a sufficiently open profile under various wind directions.

A notable difference between the complex configuration results and those of experiment B and C, was the stronger deposition in the lee directly behind scale models. Directly behind a building is a sheltered area with low wind speeds (Luo et al., 2012, 2014), where wind recirculates. Earlier wind tunnel research predicted (Luo et al., 2012) or observed (McKenna Neuman et al., 2013) the lee behind buildings to be a major deposition area, with low wind speeds favouring deposition over erosion. The lack of initial deposition in this area in experiment B and C might be explained by airflow into this area containing little sand. But if the more complicated and messy airflow created by multiple oblique buildings blows sand into the area, the low wind speed in this area will result in deposition.

5. Conclusion

This research aimed to determine how the initial aeolian deposition patterns around buildings at a sandy beach are affected by building spacing and by the orientation of a building and building group relative to the wind. Building spacing determines whether wind and sediment can flow through the gaps between the buildings, thereby determining whether a building group acts as a single large building to the wind, as fully separated buildings, or something in between. Upwind, buildings placed close together (with a gap ratio \( g^* \) of 0.33 for the studied building shape where building height and width are equal) create a single large deposition area of a similar shape as a single large building, but in size falling between that of a single large building and that of wider spaced buildings. Buildings placed further apart (\( g^* \geq 0.5 \)) create deposition with local crests in front of the individual buildings, with deposition slightly lower and shorter in length, but also spread over a wider area. Downwind, the experiments showed little deposition in the lee directly behind the buildings: main downwind deposition was in tails more to the sides, on the outside of the group and behind the gaps. For gap ratios of at least 0.67 to 0.75, the deposition tails behind the gaps (inner tails) and the tails at the outside of a building group (outer tails) were similar in size and shape. For smaller gaps, they differed significantly: a small erosion area formed directly behind the gap caused by accelerated airflow through the gap, followed by a shorter inner deposition tail. These differences show that deposition patterns behind buildings placed close together are formed by a shared complex airflow pattern. For buildings far enough apart - with a gap ratio larger than 0.67 to 0.75 for the studied square wind-facing wall - airflow patterns and deposition effects of a building can be regarded independently of effects by neighbouring buildings. For buildings for which the wind-facing wall is not square, these transitions in deposition and flow typology occur would at smaller gap ratios for relatively wide building (\( w > h \)) and v.v.

The orientation of a building determines how airflow and sediment transport are divided along both sides of a building, which affects the length of the deposition tails behind a building. Based on observed asymmetry in the tail lengths, a new rule-of-thumb was developed, where the sediment partitioning to the left and right depends linearly on the wind angle. This can be used to estimate the asymmetry of deposition tails behind buildings. By focusing on the morphological result of deposition, rather than on complex airflow patterns and sediment transport processes, this rule is simple enough to be used in rule-based morphological computer modelling and in spatial designs aiming to explicitly manage or utilize deposition caused by buildings.

For the spatial design and management of buildings at the beach, these results can be used to minimize the need for sediment removal by optimizing the locations of roads, walkways and buildings. In addition, they support regulation stipulating a minimum distance between buildings- and indicate that this distance should increase if the dominant wind direction is at an oblique angle to the buildings. Lastly, the practice of removing unwanted deposition around buildings inherently results in sediment displacement, so the substantial deposition observed highlighted the importance of rules on where this sediment may be moved to, to prevent this ‘human sediment transport’ from counteracting other coastal management goals.

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Data availability

Raw and processed data related to this article can be found at https://doiOrg/10.1016/j.geomorph.2022.108114, hosted at 4TU.ResearchData (Poppema et al., 2021a).