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The Impact of Spacing Between Beach Buildings on Aeolian Erosion and Deposition Patterns: A Numerical Study

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Abstract

Sandy beaches are very attractive to people worldwide. The attractiveness of sandy beaches increases the demands for the construction of buildings at the beach-dune interface. These buildings alter the local airflow patterns in the surrounding area which, in turn, induces changes in the aeolian sediment transport and morphological patterns around buildings at the beach. In the present study, the impact of spacing between adjacent buildings in a row on the erosion and deposition patterns in the surrounding area and downstream is studied. A computational fluid dynamics model using OpenFOAM is developed to simulate the three-dimensional airflow patterns around a row of ten full-scale buildings at the beach. The spacing between two adjacent buildings is systematically changed between $0.1w$ and $4w$, where w is the buildings' width. Based on the horizontal wake flow patterns close to the bed, a spacing of $0.9w$ appears to be the critical spacing below which the neighboring buildings significantly affect each other, and the secondary flow structures in the lee of buildings are quite complex. Results show different near-bed erosion and deposition patterns around buildings as the spacing between two adjacent buildings increases. The initial morphological changes around buildings are fully independent and buildings act as isolated buildings when the spacing between buildings increases to $4w$.

Keywords: Airflow around buildings; Aeolian sediment transport; Erosion and deposition patterns; Beach buildings; Computational fluid dynamics (CFD)

1. INTRODUCTION

Sandy beaches worldwide have always been attractive locations for recreational activities. The attractiveness of sandy beaches to visitors has led to the construction of buildings such as holiday cottages, restaurants, sailing clubs, recreational facilities and pavilions at the beach-dune interface (Figure 1). These buildings at the sandy beaches affect the local airflow patterns and as a result the location of erosion and deposition in the surrounding area due to their dimension, geometry, material, elevation on pilings and positioning at the beach (Nordstrom and McCluskey, 1985; Nordstrom, 2004; Jackson and Nordstrom, 2011). On a longer time-scale, these eroding and depositing areas influence the functioning of buildings at the beach, and the local population encounter difficulties of preventing these morphological changes. Furthermore, this might need additional measures in case these morphological changes threaten the flood defense function of the dunes behind the beach.

Figure 1. A row of holiday cottages at a) Kijkduin beach (top view) and b) Egmond beach, the Netherlands.

The influence of buildings' characteristics and positioning at the beach on erosion and deposition patterns in the surrounding area has been of great interest to coastal engineers and geomorphologists (Iversen et al., 1990; Iversen et al., 1991; Sutton and Neuman 2008; Luo et al., 2012; Luo et al., 2014; Luo et al., 2016; Poppema et al., 2021; Pourteimouri et al., 2022). Previous studies showed that the spacing between adjacent buildings in a row strongly affects the nature of the secondary airflow structures, affecting the development and spatial distribution of sediment accumulation in the lee of the spacing between buildings (Bagnold, 1941; Livingstone and Warren, 1996). When the incident wind approaches a row of buildings close to each other, the wind speed through the spacing between two neighboring buildings slightly increases by the funneling effect. The accelerated flow implies an increase in the sediment entrainment capability of the air. However, the decelerated flow due to expansion just behind the spacing leads to the deposition of the carried sediments and the formation of so-called sand drift in the lee of the spacing between buildings (Bagnold, 1941; Pye and Tsoar, 2008). The impact of spacing between a pair of buildings at the scale of wind-tunnel simulations on sand drift evolution, and the first attempts towards understanding the aerodynamic mechanisms that are responsible for the formation of sand drift have been discussed in Luo et al. (2014) and Luo et al. (2016). However, the influence of the spacing in a row of full-scale buildings at the beach on the erosion and deposition patterns both upwind and downwind the buildings is still not fully understood.

In the present study, we use the model by Pourteimouri et al., 2022 to investigate the detailed three-dimensional flow behavior around a row of ten full-scale beach buildings, and the initial morphological changes under a wide range of spacing between neighbor buildings.

2. Methods

A three-dimensional computational fluid dynamics model using OpenFOAM was developed. The simpleFOAM solver was used, which solves the Reynolds-Averaged Navier-Stokes (RANS) equations for turbulent and incompressible flows in their steady states. The blockMesh and snappyHexMesh utilities in OpenFOAM were used for the three-dimensional mesh generation within the domain. The commonly-used $k-\varepsilon$ turbulence closure model was implemented to solve the turbulent airflow structures that formed around the buildings. A detailed description of the numerical model and the governing equations can be found in Pourteimouri et al., 2022.

2.1 Numerical Model Setup

A three-dimensional computational domain with a row of ten buildings in the center, shown in Figure 2, is considered. The definitions and the values of the parameters shown in Figure 2, are given in Table 1. The domain inlet is located at $x = 0$ (m), where the fully-developed logarithmic mean wind velocity profile, u, turbulence kinetic energy, k, and turbulence dissipation rate, ε, are applied as the inlet boundary conditions using the equations proposed by Richards and Hoxey (1993). The atmospheric boundary layer parameters used in this study are given in Table 2. The no-slip wall boundary condition was applied to the bottom wall of the domain and the buildings' side walls. The total number of grids used in the domain is approximately 3.5 million, consisting of coarser grids far from the buildings, $\Delta x = \Delta y = \Delta z = 1$ (m), and finer grids close to the buildings and near the bed, $\Delta x = \Delta y = \Delta z = 0.25$ (m).

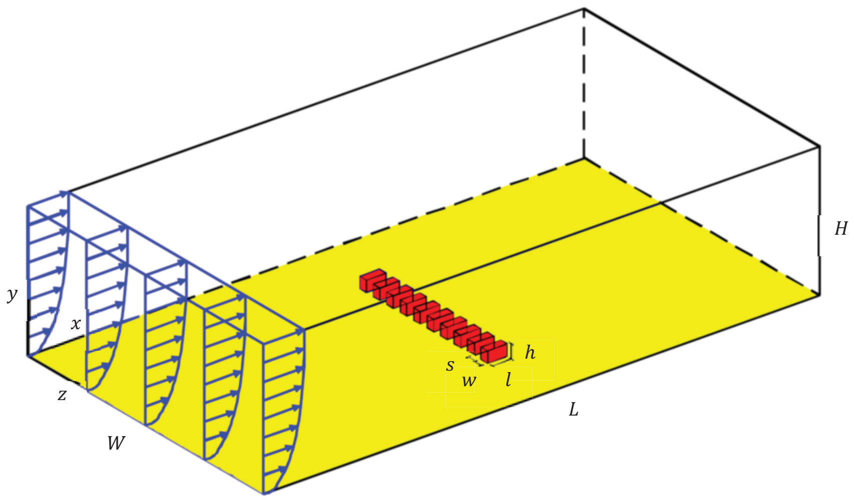

Figure 2. Schematic of the computational domain with a row of ten buildings in the center.

Table 1. Definitions and values of the geometric parameters of the domain and the row of buildings (Poppema et al., 2021).

	DEFINITIONS	VALUES
$\boldsymbol{L}$	Length of the domain (m)	150.0
$\boldsymbol{W}$	Width of the domain (m)	150.0
$\boldsymbol{H}$	Height of the domain (m)	50.0
$\boldsymbol{l}$	Length of each building (m)	6.0
$\boldsymbol{w}$	Width of each building (m)	2.5
$\boldsymbol{h}$	Height of each building (m)	2.5
$\boldsymbol{s}$	Spacing between two neighbor buildings (m)	$0.25 - 10$

Table 2. Definition and the values of the atmospheric boundary layer parameters (Poppema et al., 2021).

	DEFINITIONS	VALUES
$\boldsymbol{u_{ref}}$	Reference wind speed (m/s)	17.0
$\boldsymbol{y_{ref}}$	Reference height at which the reference wind speed is applied (m)	1.8
$\boldsymbol{y_0}$	Aerodynamic roughness length (m)	0.00001
$\boldsymbol{y_g}$	Ground level (m)	0.0

2.2 Deriving Initial Morphological Changes from Airflow Patterns

We are interested in understanding the influence of spacing between buildings at the beach on potential erosion and deposition patterns that develop around the buildings. The well-known sediment transport models in previous studies denote that the sediment transport rate is a third-order function of wind velocity field, $q \propto U^3$(Bagnold, 1936; Kawamura, 1951; Hsu, 1971; Lettau, 1978; White, 1979). In the present study, we assume that the entrained sediment particles move at the near-bed wind speed, and the vertical component of the velocity field is negligible. Therefore, the sediment transport rate is written in the following form:

$$q \propto \left(\left|\overrightarrow{U_H}\right|^2 \overrightarrow{U_H}\right) \qquad [1]$$

where q (kg/m/s) is the sediment transport rate, and the index H shows the horizontal near-bed wind velocity field. According to Exner equation for sediment continuity, the bed elevation through time changes proportionally with the convergence of sediment transport rate as follows:

$$\frac{\partial z_b}{\partial t} \propto -\nabla . q \qquad [2]$$

where z_b (m) is the bed elevation relative to a fixed datum i.e. ground level, and t (s) is the time. Therefore, a positive convergence (i.e. negative divergence) of the third-order horizontal near-bed wind velocity field denotes deposition ($\frac{\partial z_b}{\partial t} > 0$), while a negative convergence (i.e. positive divergence) of the third-order horizontal near-bed wind velocity field denotes erosion ($\frac{\partial z_b}{\partial t} < 0$). This can be formulated as follows:

$$\begin{cases} -\nabla . \left(\left|\overrightarrow{U_H}\right|^2 \overrightarrow{U_H}\right) > 0 & \rightarrow \quad Deposition \\ -\nabla . \left(\left|\overrightarrow{U_H}\right|^2 \overrightarrow{U_H}\right) < 0 & \rightarrow \quad Erosion \end{cases} \qquad [3]$$

3. RESULTS

In this study, the impact of spacing between buildings at the beach on airflow patterns and the implications for the initial erosion and deposition patterns that develop around buildings and in the downstream are investigated. For this purpose, we assume a row of ten full-scale buildings at the beach, which is similar to the configuration of holiday cottages in Kijkduin beach, the Netherlands (Figure 1a). The spacing between adjacent buildings is systematically changed between $0.1w$ and $4w$, where w is the width of each building, while the other geometric and atmospheric parameters remain unchanged. For the sake of brevity, we only present the results of the most interesting spacings, including $0.1w$, $0.7w$, $0.9w$, $1.5w$ and $4w$. Furthermore, we focus on investigating the airflow patterns in a near-bed horizontal plane, $y = 0.25$ m, which is located at a level equal to ten percent of the buildings' height. The reason is that the main motivation for this study is the potential implications for sediment transport, which is mostly restricted to an elevation close to the bed.

3.1 Near-Bed Airflow Patterns

Figure 3 shows the near-bed horizontal wind speed and 2D streamline around and behind a row of ten identical adjacent buildings with different spacings. Results show that the wind field in the lee of a row of beach buildings close to each other is very complex due to the presence of the bleed airflow that intrudes through the spacing between two neighbor buildings, and the displaced airflow that moves around the lateral walls of the buildings. To better understand the flow behavior when approaching the buildings, going through the passages and moving downstream, the streamwise wind velocities, u, along the domain centerline (i.e. in the center between the two central buildings) for different spacings are shown in Figure 4.

Figure 3a, in which $s = 0.1w$, shows that when the spacing between neighbor buildings is too small, the row of ten buildings close to each other act as a wide rectangular bluff structure, i.e. that the incident wind is perpendicular to the long side of this combined structure. As shown in Figure 4, the bleed flow is negligible. Therefore, the approaching wind is divided into two main branches of flow upwind the bluff structure, moves around the streamwise walls, separated from the two leeward edges and forms two large counter-recirculating vortices in the so-called cavity region just behind the combined structure. The approximate streamwise and cross-streamwise dimensions of this recirculation region is $l_c = 6.9w$ and $w_c = 10.98w$ respectively. As the spacing between buildings increases to $s = 0.7w$ (Figure 3b), the airflow intrudes into the passage between buildings (Figure 4), the bleed flows are separated from the lee edges of the passages, and form two small rotating vortices in the near-wake region just behind the passages. These small vortices are enveloped with two large counter-recirculating vortices that form by the separated flow from the two leeward external edges of the first and last buildings in the row. It should be noted that the longitudinal length of the cavity region is decreased to $l_c = 6.5w$ for $s = 0.7w$. As shown in Figure 3c, the bleed flows are more pronounced for $s = 0.9w$, and the two vortices that form in the near-wake region are strengthened as the spacing between buildings increases. Looking at the location of the flow reattachment points in the near-wake region behind the individual buildings, it is obvious that the two small recirculating vortices are displaced from in the lee of the passages towards just behind the buildings with increasing the spacing between the buildings. Furthermore, the two large vortices that were formed by the separated flow from the two external edges downwind the first and last building in previous simulations do no longer develop. However, the streamlines are still intertwined due to these deflected flows from the first and last buildings. The impact of neighbor buildings on each other becomes less significant for $s = 1.5w$, and the streamlines are slightly inclined inwards (Figure 3d and Figure 4). The buildings act as ten individual buildings, and the streamlines downwind the cavity regions are virtually parallel to the incident wind direction when the spacing between buildings increases to $s = 4w$ (Figure 3e). Furthermore, it can be understood from Figure 4 that the larger the spacing between buildings, the more quickly the streamwise wind velocity along the centerline of the buildings is recovered downstream.

3.2 Near-Bed Initial Erosion and Deposition Patterns

Figure 5 shows the initial near-bed morphological changes around and behind a row of ten identical adjacent buildings with different spacings. These initial near-bed morphological changes are inferred from the convergence of the third-order horizontal near-bed wind velocity field as shown in Eq. [3]. Results show that the spacing between buildings strongly influences the location, spatial extent and the rate of development of the eroding and depositing regions surrounding the buildings and in the downstream.

The erosion and deposition patterns around buildings very close to each other, $s = 0.1w$, is similar to that of the development around a broad rectangular building when the longest face of the building is perpendicular to the incident wind direction (Poppema et al., 2021; Pourteimouri et al., 2022). As shown in Figure 5a, a continuous deposition region (blue-shaded colors) occurs in front of the buildings and in some distance from the upwind faces. Two large and intense eroding regions (yellow and red-shaded colors) develop around the upwind external edges of the first and last buildings. Furthermore, two deposition tails form starting from some distance away from the external faces of the first and last buildings in the row, extending to downstream of the buildings. It is also seen that the eroding regions happen directly along the two external faces of the imaginary broad building, bounded on the outside by the inner surface of the deposition tails, and extend downstream. Results show that the upwind deposition region becomes closer to the front face of the buildings when the buildings are located further away from each other. In addition, as the spacing between buildings increases, the size of the eroding regions around the upwind external edges of the first and last building decreases, while new eroding regions just around the upwind internal edges of the buildings develop and grow (Figures 5b-e). The two downwind deposition tails become shorter with increasing the spacing between buildings. The inner deposition tails in the passages between buildings start to develop for spacings greater than $s = 0.7w$. The reason is that the streamwise wind velocity through the spacings significantly increases, specifically for $s = 0.7w$ and $s = 0.9w$, but at a small distance downwind the flow velocity decreases. This reduction in velocity reduces

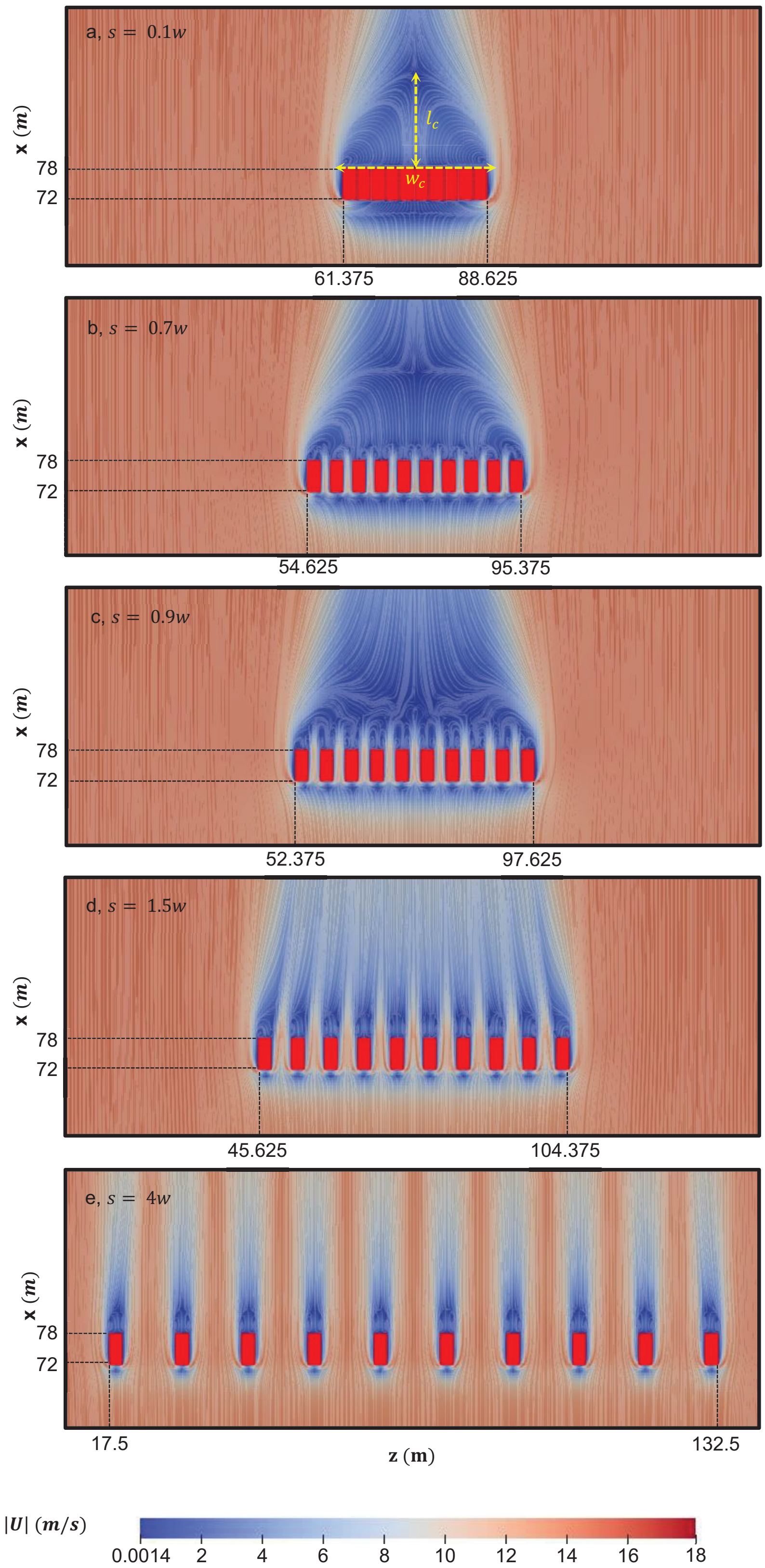

Figure 3. The impact of building spacing on wind speed (color) and direction (streamlines, shown with white lines) at a horizontal near-bed plane, $y = 0.25$ m. The spacing between two neighbor buildings, s, is varied as a) $0.1w$, b) $0.7w$, c) $0.9w$, d) $1.5w$ and e) $4w$.

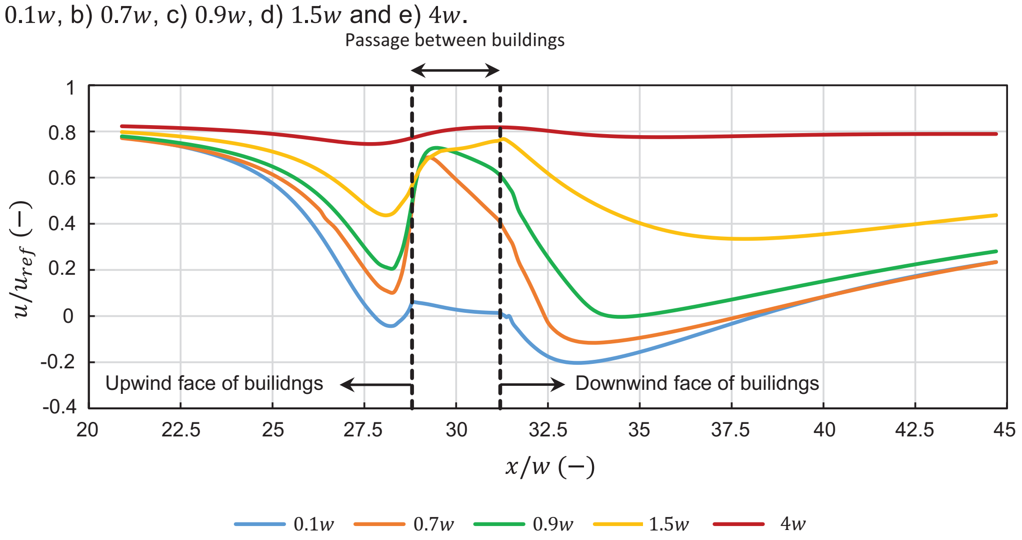

Figure 4. The impact of building spacing on streamwise wind velocity, u, at a horizontal near-bed line, $y = 0.25$ m, along the domain centerline, $z = 75$ m.

the sediment transport capacity and causes deposition both through and downstream of the passages (Figure 4). The downstream length and the rate of deposition in the internal tails increase with increasing the spacing (Figures 5b-d). Furthermore, the rate of the upwind deposition decreases with moving from in front of the two outer buildings towards in front of the middle buildings (Figures 5a-d). Looking at the darker green-shaded colors in the deposition region in front of the entire row of buildings, it is obvious that the flow starts to slow down earlier and more gradual in the center of the row of buildings, whereas it slows down more sudden at the edges of the row. A more sudden reduction of flow will result in larger deposition rates just in front of the upwind face of the buildings. The upwind deposition becomes dented when $s = 0.9w$, and the peaks of the depositions (darker blue-shaded colors) become separated as the spacing between buildings increases to $s = 1.5w$ (Figure 5c, d). Similar to the airflow patterns around buildings when the spacing is $s = 4w$ (Figure 3e), the initial erosion and deposition patterns that develop around the far enough buildings in the row are almost independent from neighbor buildings (Figure 5e). The more detailed discussion on the erosion and deposition patterns around isolated buildings can be found in Poppema et al. (2021), and Pourteimouri et al. (2022).

4. DISCUSSION AND CONCLUSIONS

In this study, the impact of spacing between buildings in a row at the sandy beach on near-bed airflow behavior, and the implications for initial bed level changes were investigated. The findings of this study revealed that the spacing between buildings is a key factor that significantly influences the nature and development of the secondary flow structures around the buildings.

When the buildings are positioned in a very small distance from each other, i.e. $s = 0.1w$, the near-bed airflow patterns and bed level changes are similar to that of the development around a very wide building, which is consistent with what found by Poppema et al., 2021; Pourteimouri et al., 2022. Based on the flow characteristics in the wake of the buildings (Figure 3), the $s = 0.9w$ represents the critical spacing, below which the neighboring buildings are significantly influencing each other. As the spacing between adjacent buildings increases to $s = 4w$, both the near-bed airflow patterns and bed morphology in the surrounding area become mostly independent from neighboring buildings. When the incident wind approaches a row of buildings, the streamwise wind velocity in between buildings decreases substantially in front of the buildings (Figure 4). Results showed that the smaller the spacing between buildings, the greater flow deceleration in front of the row of buildings. This flow deceleration allows the entrained sediments to be released from the air stream and accumulated in the upwind deposition region. As the incident wind enters the passage, the wind velocity increases considerable, especially when $s = 0.7w$ and $s = 0.9w$. This causes the sediment particles to be entrained by the wind. In a short distance downwind, the flow velocity decelerates, leading to the formation of inner deposition tails in the passages and downstream. Results revealed that, as the spacing between buildings increases, the flow recovery at the centerline in between the two central buildings to undisturbed flow downstream of the buildings speeds up (Figure 4).

In the present study, we neglected the impact of moisture which may influence the rate at which the erosion and deposition patterns develop, see e.g. Silva et al., 2018. In addition, we assumed a uniform aerodynamic roughness length, y_0, over the domain which may cause some inconsistencies with the real situation at beach,

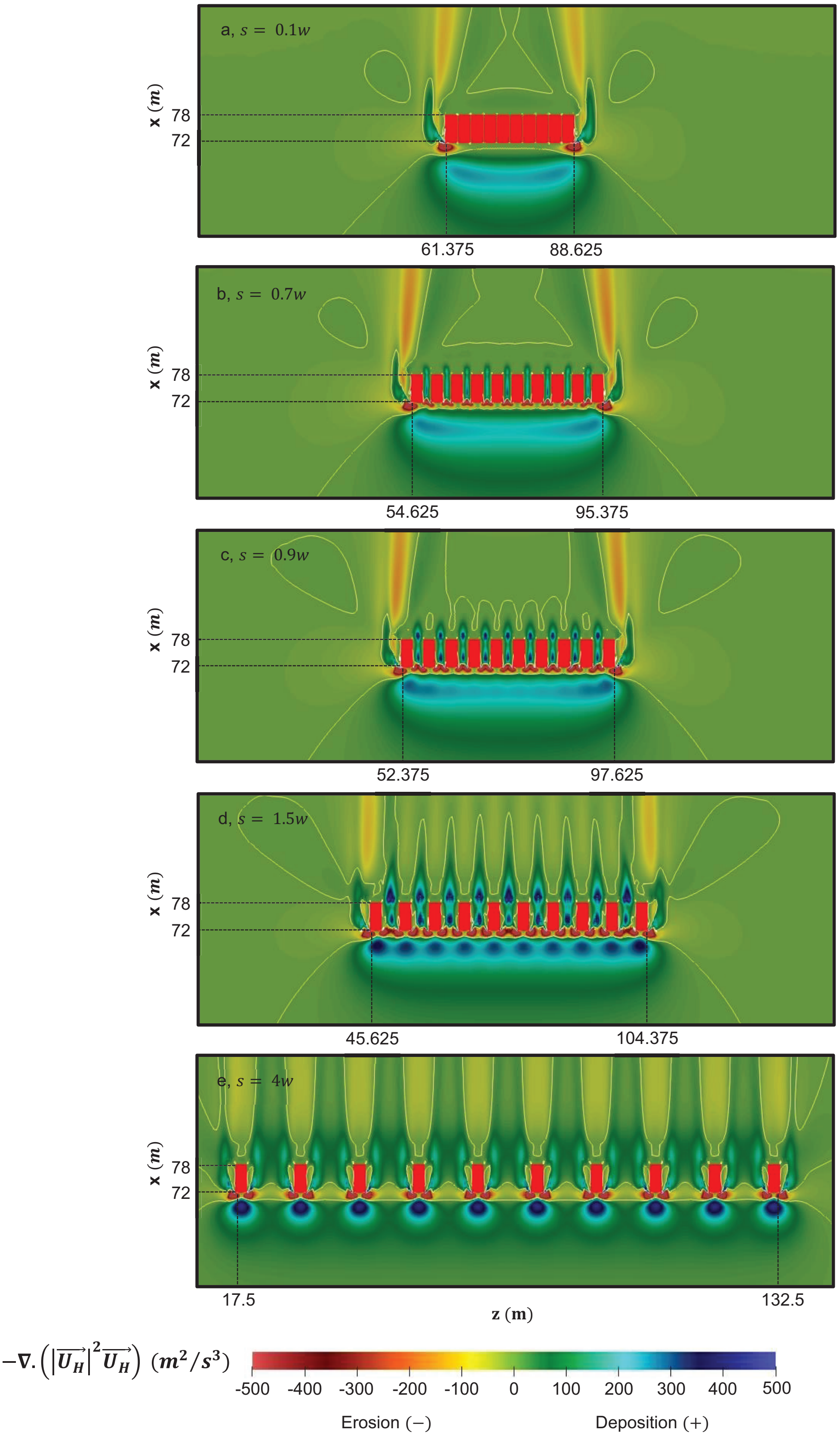

Figure 5. The impact of building spacing on initial erosion and deposition patterns at a horizontal near-bed plane, $y = 0.25$ m. The spacing between two neighbor buildings, s, is varied as a) $0.1w$, b) $0.7w$, c) $0.9w$, d) $1.5w$ and e) $4w$. The white lines are zero contours.

where the sand ripples form. These sand ripples change the near-bed airflow, thus the bed morphology.

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