Barchan vs Monopile: what happens when a barchan dune finds an obstacle in its path?

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ABSTRACT: The impact of barchan dunes colliding with one another has been well observed, understood and modelled. But what happens when there is an immobile obstacle, an Offshore Wind Farm (OWF) monopile foundation, in one's path? At the case study OWF a monopile was installed ~45 m downstream of the slip-face of an approaching barchan dune. Six bathymetric surveys, over a 20 year period, are analysed capturing the impact of the monopile on the dune's evolution. The dune migrated relatively consistently, at a rate of 20 to 25 m/year. The re-appearance of the jack-up rig spudcan footprints in the wake of the barchan indicates that the dune does not exchange material with the seafloor and that the sedimentary composition of the two must be distinct.

1 INTRODUCTION

Barchan dunes have been studied in subaerial settings, both terrestrial e.g. deserts (Hugenholtz & Barchyn, 2012) and extra-terrestrial e.g. on the surface of Mars (Parteli et al. 2014); as well as in subaqueous settings (Berné et al. 1989, Ma et al. 2014). The advent of repeat satellite observations has made documenting the behaviour of subaerial dune migration less challenging in comparison with their subaqueous counterparts, which have attracted fewer studies due to the limited number of repeat observations in the marine environment.

The crescent-shaped barchan dunes form when the current (or wind) cannot set in motion all sedimentary particles or when there is a sand deficit. They can be formed under a uni-directional current or a bi-directional current where there is a strong asymmetry. In Figure 1 the terminology used to describe the dune morphology is defined. Material is transported from the toe of the dune up the stoss slope, where it is then deposited on the slip face, the result of which is a net migration towards the direction that the horns point. Barchan dunes in marine environments can have annual migration rates of upwards of 70 m/year (Berné et al. 1989). Commonly barchan dunes are described by their horn-to-horn distance (width) and horn-to-toe distance (length).

Typically dunes are found in large groups, known as fields. Within a field barchans vary in both size and mobility, with small dunes migrating at faster rates. As a result, smaller dunes frequently catch-up to larger dunes resulting in collisions. Rather than combining into a singular larger dune, a smaller dune ejects from the larger dune. If a barchan dune gains material from the surrounds it can eventually become destabilised. Once sufficiently large a dune may 'calve' a smaller barchan dune from their downstream side (Worman et al. 2013).

Whilst the collision of one barchan with another is well documented and understood the impact of a barchan colliding with a physical obstacle has not yet been documented in scientific literature. However, the interaction between non-barchan bedforms, e.g. linear sandwaves, with objects, e.g. a cylinder, has been studied numerically (Margalit, 2017). In Margalit's model it is observed that the presence of a monopile mostly affects sandwave migration on the lee-side of the monopile by limiting the migration speed and blocking the sediment transport. In the same model sand is observed to build up on the upstream side of the monopile.

The main aim of this study is to analyse the morphological evolution of a barchan dune as it passes an obstacle (in this case a monopile). The secondary aim is to assess the impact of the dune on the scour pit at the base of the monopile of interest for the management of wind farm assets.

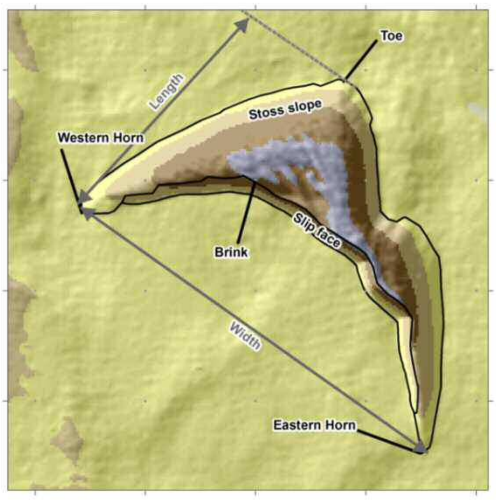

Figure 1. Nomenclature used to describe barchan dune.

2 BACKGROUND

Infrastructure

The study area is in a windfarm development off the east coast of the UK. In this paper a singular monopile foundation will be considered, this foundation was installed in 2010 (ahead of the passage of a barchan dune). The pile has an outer diameter of 5.8 m and was installed using a jack-up rig, leaving spud-can depressions to the northeast of the pile (Fig. 2f).

Site conditions

The seabed level at the case study monopile foundation is on average -25 m relative to the Lowest Astronomical Tide (LAT). Locally spring tidal ranges are typically around 3.4 m.

The site is tidally dominant with a tidal flow towards the northeast during the ebb phase and to the southwest during the flood phase. Tidal velocities are flood dominated, with average bed current speeds approximately 0.4 m/s, whilst peak current speeds are approximately 1 m/s.

The wave distribution is bimodal and is proximally aligned with the tidal flow, with waves approaching both from the north-northeast and south-southwest. The largest waves approach the site from the north-northeast, with a 1 in 10 year significant wave height of 4.0 m.

One kilometre to the northwest of the study barchan is a northeast-southwest aligned linear sandbank with a height of 18 m. This sandbank is still active and sediment mobility calculations confirm that locally sediments are mobile for approximately 80% of the time.

The seabed around the sandbank comprises largely sand and gravelly sand, which makes up a veneer generally not exceeding 1 m thickness. Beneath this is a layer of London Clay.

Data

Six surveys are available for analysis (Table 1, Fig. 2). Five of these (2004, 2009, 2013, 2014 and 2014) were collected using commercial operations related to the wind farm development, these have a vertical uncertainty of ±0.3 m or less. Whilst the 1995 data have been sourced from the UKHO INSPIRE portal and likely have a much larger vertical and horizontal uncertainty.

Table 1: Details of surveys

Survey	Grid resolution (m)
(a) 1995	25
(b) July 2004	20
(c) March to May 2009	2
(d) May 2013	1
(e) July to August 2014	0.5
(f) August to September 2015	0.5

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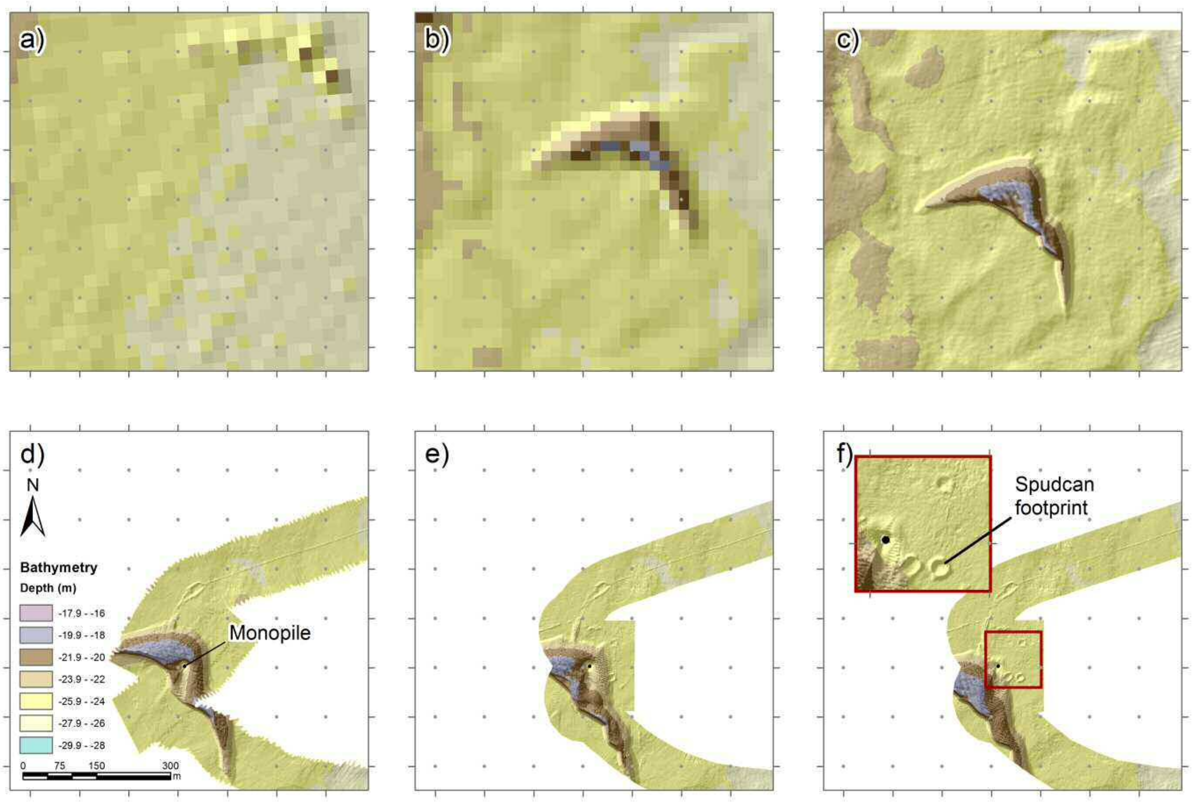

Figure 2. Panels showing the bathymetry for a) 1995, b) 2004, c) 2009, d) 2013, e) 2014 and f) 2015

3 RESULTS AND DISCUSSION

Dune morphology

Whilst barchan dunes are often found grouped with numerous other dunes (fields) the dune studied here had only two neighbouring dunes, one 1.8 km and another 3.2 km to the north-northeast.

The case study dune was moderately asymmetrical with the eastern horn being 1.4 times the width of the western horn in 2009. The dune had a width of approximately 370 m and a length of approximately 190 m. A peak in dune height, 6.9 m, was observed in 2013 when the crest dune was aligned with the monopile.

Superimposed atop the stoss slope of the dune were megaripples with a height of 0.1 – 0.3 m and a wavelength of 5 – 7 m. These were visible in the latest three surveys, though are likely still present in the earlier years and are not visible due to lower resolutions of the surveys.

The slip face of the dune had an average slope of 30°, near the angle of repose (~32°), and hence consistent with an actively migrating bedform. In the 2015 data a 5 m long step can be seen in the slip face (Fig. 3), which similarly to the top of the dune, had bedforms superimposed.

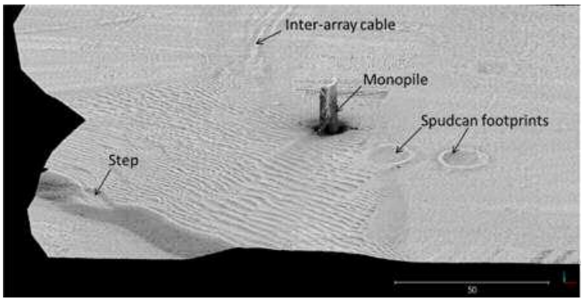

Figure 3. 2015 bathymetry with PCV hillshade. Horizontal scale is in metres.

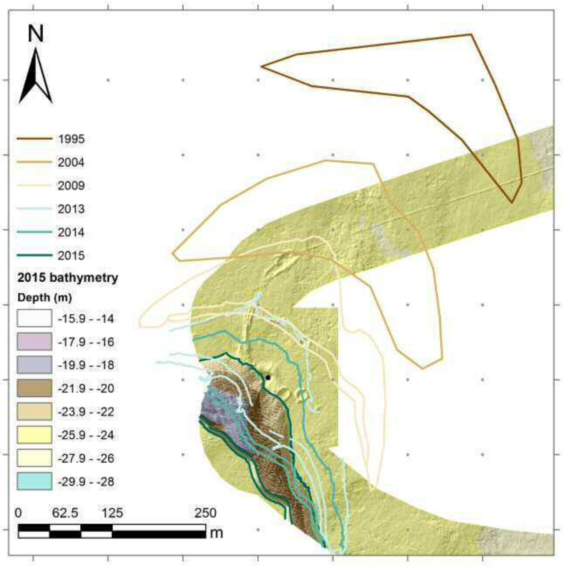

Figure 4. Outline of barchan footprint for each survey overlaid on the 2015 bathymetry.

Dune evolution

Figure 4 shows the outline of the footprint of the dune identified from each repeat bathymetry survey overlain on the latest, 2015, bathymetry. The dune displayed a fairly constant rate of migration towards the southwest, ranging between 20 and 25 m/yr, with the exception of 2014 to 2015 period where the toe migrated by 42 m/yr. During this period the dune migrated more towards the west-southwest.

For the 2013/2014 period considerably large waves with significant wave heights greater than 5 m approached from the south-southwest. Potentially these waves may have prevented the horns from keeping up with the rest of the dune body, causing the dune to flatten out.

From 2009 onwards the barchan dune presented a sinusoidal face, similar to that of a transverse bedform. Since this pattern is observed in 2009 it cannot be as a response to the installation of the monopile. Equally, at this point in time the eastern horn was elongated relative to the western and there was a second, smaller eastern toe. From 2009 to 2013 the eastern horn continued to break away from the main dune. This event appeared to mimic the stages leading up to a 'calving' event as described by Ma et al. (2014).

However, by 2014 the main western dune had caught up to re-join the eastern horn. A smaller dune will calve off a large dune's horn when the host barchan cannot supply enough sand. It is unknown as to why in this case the calving event did not go through to completion. This could be related to the disturbance in the flow field due to the monopile.

Scour at the base of monopile

Scour is the process by which flow past an obstacle (in this case the monopile) is altered initiating flow acceleration and an increase in turbulent intensity, which in turn leads to the suspension and removal of sediment.

A relatively symmetrical circular scour pit had formed at the base of the pile by 2013 (three years after the installation of the monopile), although it likely formed almost immediately after the pile was installed but this timestep is missing. Whilst the local scour was relatively symmetrical, with an average extent of 6 m, the scour pit had formed a downstream wake through the barchan dune which extended to a distance of 70 m from the pile (see Fig. 2d). We note that the direction of the scour wake is to the south, oblique to the southwesterly migration direction of the dune reflecting the direction of the residual transport as well. This shows that scour wakes around hard objects in bedform fields do not necessarily make an accurate indication for the residual transport direction. The dominant flow to the southwest interacts with the dune form, leading to flow divergence downstream of the brink of the dune (Allen, 1968) which controls the southerly scour wake direction.

Commonly the level at the base of a scour pit is compared with the ambient seabed level to give a scour depth. However, at the study location the bed level locally will have changed as the dune passed the pile. Therefore, care must be taken when choosing the level with which the base of the scour pit is compared with. If the scour level compared with the bed level at the edge of the scour pit (which aligned with the crest position in 2013) then we see much larger scour depth, reaching a maximum of 6.8 m in 2013 (Table 2). This is comparable with empirical observations which suggest a scour depth on the order of 1.3 times the pile diameter in sand (Sumer et al. 1992). This suggests that scouring through the barchan dune is similar to scouring in a flat bed of sandy sediments.

Table 2: Scour development

Year	Maximum scour pit level (mLAT)	Ambient sea-bed level (mLAT)	Bed level at edge of scour pit (mLAT)	Maximum scour depth compared with ambient level (m)	Maximum scour depth compared with edge of scour pit (m)
2013	-26.3	-24.7	-19.5	1.6	6.8
2014	-26.5	-24.7	-21.7	1.8	4.8
2015	-27.0	-24.7	-24.4	2.3	2.6

Relative to the ambient seabed the scour depth progressed at a rate comparable to neighbouring monopiles, giving a maximum scour depth of 2.3 m in 2015 (Table 2). Even from the first time-step after the installation of the monopile (2013) the level at the base of the scour pit was deeper than the ambient bed level, i.e. it had scoured the full depth of the barchan dune and then maintained scour into the underlying seabed.

On average for the four nearest monopile foundations the maximum local scour depth was 1.5 m in 2013, 1.7 m in 2014 and 2.1 m in 2015. The scour depths observed at the study site are all within 0.2 m of the average observed scour depths. This suggests that potentially the presence of the barchan dune has had a limited impact on the progress of the scour into the underlying seafloor and that the maximum scour depth is limited by the rate at which the scouring can occur, which is limited by the presence of London Clays found at a depth of 0.5 to 1 m.

Spudcan depressions

The monopile was installed using a jack-up rig, with four feet (spudcans), positioned to the east of the monopile location. At the time of installation of the monopile the northern most two legs of the jack-up rig would have penetrated into the dune, whilst the southern two were to the south of the dune.

Remarkably the southern two and the north-eastern spudcan depressions were still visible even after the dune had passed over them. The spudcan footprint consists of a 0.2 m deep circular depression with a 0.8 m high ring formed from the displaced material. Locally at foundations which have not been disturbed by bedforms the depth of the spudcan footprints range between 0.5 and 1.7 m. Therefore, it is likely that the depressions at the study site have filled in by 0.3 to 1.5 m.

In 2013 the western-most spud-can depression would have had over 4 m of sand atop it. The re-appearance of a spudcan footprint in the wake of the barchan indicates that the dune does not exchange material with the seafloor and that the composition of the two sediments must be distinct. In the next section the potential source of material for the dune is explored to test this hypothesis.

Formation and degradation of dunes

Whilst the dune studied here is not part of a field of dunes there are two other dunes in the vicinity of the barchan: one 1.8 km to the north-northeast (partially attached to the sandbank) and another 3.2 km to the north-northeast. The dune still partially attached to the sandbank may give a clue as to the origins of the dunes. It seems plausible that dunes might calve off this bank to form solitary barchan dunes.

Geophysical surveys of the wind farm site indicate that the central sandbank is made up of a much higher proportion of sands than the material that makes up the seafloor at the study foundation. This would explain why only the barchan dune is mobile and not the veneer of more gravelly sand at the site.

Barchans are observed to lose sediment from their horns over time (Tsoar, 2001). In most cases this material is replaced by sediment lost from the horns of other upstream barchan dunes. However, it is questioned whether or not the two dunes more than 1 km away will be supplying sediment to our barchan dune. As a result it is likely that the dune will lose material with time and will ultimately degrade or rejoin the bank.

4 CONCLUSIONS

In this paper six repeat bathymetric surveys have been used to track and describe a singular barchan dune as it passes a wind farm monopile foundation. The impact on both the barchan dune itself and the scour at the base of the monopile have been documented.

Even before the installation of the monopile the barchan displayed signs that it was about to undergo a calving event; the eastern horn elongated and a second toe developed. However, in subsequent time-steps the barchan dune gradually reformed into a singular feature. After the slip face of the dune had passed the pile the dune face became flatter, with the western horn lagging behind the central body. The monopile appeared to have a fairly limited impact on the evolution of the dune. Instead it is theorised that the modifications of the dune's morphology result from variations in the prevailing wave regime.

Scouring at the base of the monopile progressed unhindered through the full depth of the barchan dune and into the underlying seafloor. The scour depth relative to the ambient bed level was comparable with that observed around neighbouring monopile foundations. This indicates that the presence of the barchan had a limited impact on the scouring into the seabed.

The depressions made by the jack-up rig spudcan footprints survived the passage of the barchan dune. This implies that utilising the presence of spudcan footprints to infer a benign seafloor environment through site investigations (Harris & Whitehouse, 2015), is incorrect, as here the footprints survive intact even after buried by 4 m sand.

The lack of exchange of material between the spudcan footprints and the barchan dune it is hypothesised that the barchan comprises a higher proportion of sand than the underlying seafloor. This supports the reasoning that the barchan dune has shed from the central sandbank in the wind farm site. This has implications for the longevity of both the sandbank and the barchan dune.

5 ACKNOWLEGMENTS

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