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Using Computational Fluid Dynamics to determine suitable foredune morphologies in New Zealand

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ABSTRACT

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The Ocean Beach Domain in Dunedin, New Zealand has an ongoing issue with persistent scarping leading to high maintenance, poor public access, and potential hazards due to the infill used to create the foredune. The ongoing cost of replacing sand and repairing erosion damage has led the local council to explore the possibility of a more sustainable long-term solution. A foredune will still be required but the question is how much space between the beach and foredune is needed to alleviate the current issues.

Computational Fluid Dynamics modeling has therefore been used to identify suitable future foredune morphologies in this situation. The scenarios modelled were; the current unfeasible Marram grass covered steep foredune system; the relatively untouched (1890) morphology; and interim positions that accommodate the coastal processes by retreating the foredune system. Additional three-dimensional simulations using LIDAR data to recreate the topography give a relationship between the dune system and the dominant direction of the wind flow. The success of these proposed dune morphologies is discussed in terms of sand transportation, fit to the council's ongoing management goals which includes protection of low lying houses and an analysis of the success of using such numerical simulation in coastal planning. Numerical simulation is shown to present the opportunity to help with future coastal management scenarios. This work has shown that the current dune morphology at the Ocean Beach Domain is unrealistic but that there are alternative profiles that could satisfy both public and council imperatives.

ADDITIONAL INDEX WORDS: *Sand transportation, Wind flow, CFD, Marram grass*

INTRODUCTION

The Ocean Beach Domain in Dunedin, New Zealand has an ongoing issue with persistent scarping leading to high maintenance costs, reduced public access, and the establishment of hazards for those using the beach. These conditions developed as a result of past interventions, including the introduction of Marram grass and the disposal of waste in backdune areas. The current Marram grass covered steep foredune system is really a scarp cut into the old landfill, with a Marram "dune" perched on top, as a result of sand being blown up and over the scarp. Over the last 100 years a wide, gently-sloping, back-beach area has been replaced by an artificial terrace that is subject to erosion during storm-surge conditions and which results in accelerated flows and sand export during onshore winds. Maintaining the current hinterland uses a large amount of public resources in terms of time and finances. The current topography creates a hard land/sea interface with the artificial steep foredune system. The present study is part of a larger project to determine a sustainable long-term solution to problems associated with scarping and aeolian sedimentation. Therefore the objectives of the study are:

- To determine if a solution to the foredune can be established along this coastline
- To determine how much the topography of the hinterland would need to be modified
- To provide a viable method to assess the viability of different modification scenarios using fluid dynamics numerical modelling

METHODS

Wind Data

In forecasting environmental impacts in coastal zones, long-term wind data is preferable. The wind data used in this study were recorded at two weather stations; Lawyer's Head and Taiaroa Head, Dunedin. The long-term wind data at Taiaroa Head can possibly be used to predict projected changes in wind speed and associated natural processes (e.g. wave height and shoreline erosion) in the South Dunedin area. The wind data at the Lawyer Head directly represent wind statistics in the South Dunedin area, however, the data is available only from the years 2005 to 2008. The historical wind data at the Taiaroa Head is available from 1971 to 2006 so has more long term applicability.

Therefore, a statistical index "correlation coefficient" was employed to find the correlation between the data obtained from the two weather stations. The value of correlation coefficient ranges from -1 to 1, where -1 represents a perfect inverse relationship between the two wind data set, while a correlation coefficient of 1 represents a perfect linear relationship. The onshore (73 to 253 degree) wind data at Lawyers Head were compared to the data at Taiaroa Head. The hourly wind speed and direction from 2005 to 2008, which are available at the Lawyer Head weather station, were tested with the wind data recorded at the Taiaroa Head weather station over the same period. Instrumental errors in the data sets were removed, yielding the total data points employed in the correlation analysis of 18,102 points. The correlation coefficient of the wind speed measured between these two sites were all over 0.75 (0.75 for 2005, 076 for 2006, 0.77 for 2007, 0.76 for 2008).

In terms of wind direction the correlation coefficient increased from 0.56 for all wind speeds to 0.8 for wind speed greater than 15m/s. Therefore the wind data at Taiaroa Head was deemed suitable to use, especially as it is the higher wind speeds that are involved in sand transportation that are of more interest. Figure 1 shows the frequency of winds at Taiaroa Head that exceed the minimum wind speeds for sand storm events (over 6m/s) and potentially contribute to sediment transportation (Pattanapol, 2008, Wang et al., 2003).

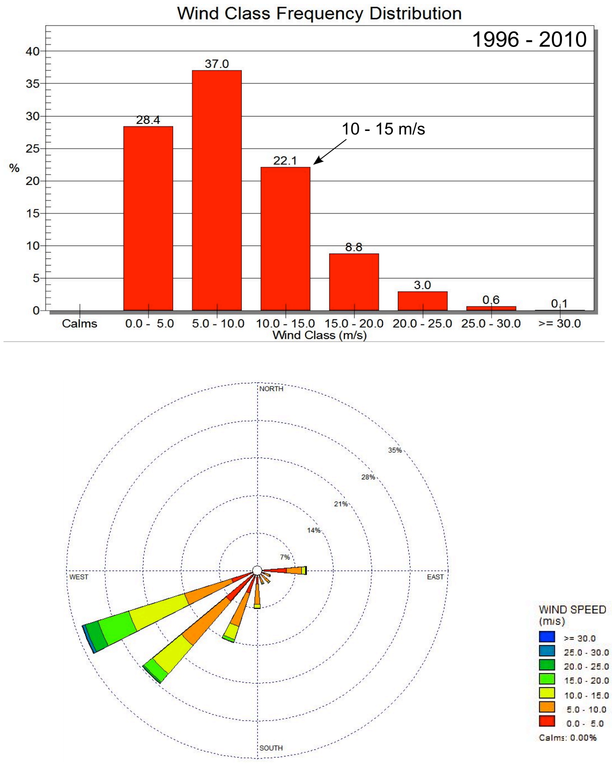


Figure 1: Wind classes and direction of wind at Taiaroa Head 1996 to 2010

Computational Fluid Dynamics

Computational Fluid Dynamics numerical modeling is used to identify current, historic and suitable future foredune and hinterland morphologies in the study area. The present work has been conducted by using the numerical solution method, Computational Fluid Dynamics (CFD). The CFD code Fluent is used to solve the Reynolds-Averaged Navier-Stokes equations and the continuity equation using the finite volume method (Shaw, 1992, Fluent, 2003). In this study, the steady state Reynolds-Averaged Navier-Stokes (RANS) equations are considered with the RNG k-ε model (Yakhot and Orszag, 1986). The RNG k-ε model performed well in predicting flow with associated sand transport in two dimensions. In three dimensions, the performance of the RNG k-ε model is on par with the Detached Eddy Simulation (DES) model at the layers above ground surfaces (Pattanapol, 2010).

The inlet mean velocity profile was set by using the power law

$$u(z) = u_{ref}\left(\frac{z}{z_{ref}}\right)^{\alpha} \tag{1}$$

where u_{ref} is reference velocity at reference height, z_{ref}. The exponent α is a coefficient that varies dependent upon the stability of the atmosphere and is set to 0.143 for neutral stability condition. The inlet profiles for k and ε used in this study are defined as follows;

$$k(z) = \frac{u_*^2\left(1 - z/\delta\right)^2}{\sqrt{C_1 C_2}} \tag{2}$$

$$\varepsilon(z) = \frac{u_*^3\left(1 - z/\delta\right)^2}{\kappa\left(z + z_0\right)}\frac{1 + 5.75z}{z_0} \tag{3}$$

where δ is gradient height (20m). C_1 and C_2 are closure constants (0.5478 and 0.1643 respectively) (Pattanapol, 2010).

The sand transport was modelled using the modified Volume of Fluid (VOF) multiphase flow model. The movement of sand in the suspension and saltation layers were modelled by adding source terms into the continuity equations of sand phase and a velocity correction term in the momentum equation (Alhajraf, 2004).

For the suspension layer:

$$\frac{\partial}{\partial x_j}(u_j \rho \alpha_p) = -\beta_{sus}\frac{\partial}{\partial x_j}(\alpha_p(1-\alpha)u_{rel\,j}) \tag{4}$$

For saltation layer:

$$\frac{\partial}{\partial x_j}(u_j \rho \alpha_p) = \beta_{sal}\frac{\partial}{\partial x_j}(\alpha_p(1-\alpha)u_{rel\,j}F(u_t^*, u_*)) \tag{5}$$

and the velocity correction term:

$$S_i = -au^2\alpha_p \tag{6}$$

where $\beta_{sus} = 0.05$ and $\beta_{sal} = 1.05$ are the model coefficients for the suspension and saltation layers respectively. u_{rel} is the algebraic relative velocity, α_p is the volume fraction of sand, and $a = 0.84$ is the velocity damping coefficient.

Spatial Scales

A large spatial scale domain was established to investigate the three-dimensional wind flow across the study area, including the effects of headlands to the south of the study area. The topography was taken from LIDAR data, surveyed by the Otago Regional Council (ORC). This was smoothed for the CFD simulations, figure 2.

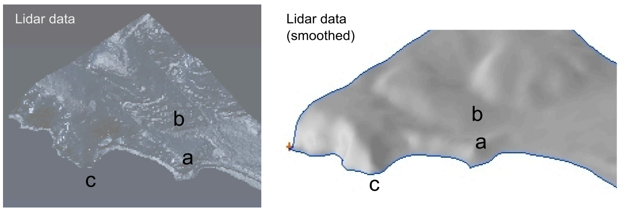


Figure 2: LIDAR data and smoothed CFD geometry with three comparison points indicated

A simplified three-dimensional foredune was employed in a simulation to investigate the pattern of sand transport under an approaching wind speed from South West. The approaching wind speed was modelled using the power law wind profile with a reference wind speed of 6 m/s at 5m above the surface. Sand was patched in front of the foredune, and repeatedly supplied every computational iteration. The unlimited supplied sand allows the steady state pattern of sand to be formed. The direction of sand transport is in the same direction as the wind flow, and extending toward NE with a sand/air volume ratio of 10%.

According to Pattanapol (Pattanapol, 2010), sand will accumulate in the grass region. Trapped sand will eventually become a foredune. The height of the foredune can be determined by the maximum incident wind speed, in which higher wind speed will create lower foredune. However, vegetation cover was not taken into account in this study. The main concern of this study is to preliminarily investigate flow statistics once the topography has changed.

Smaller scale two-dimensional simulations were based upon existing and proposed dune profiles at one particular typical cross-section in the area. Therefore the initial scenarios modeled, figure 3, were:

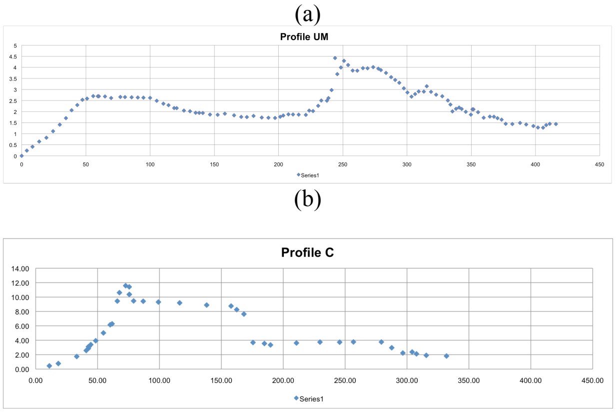
- the current profile (C)
- the unmodified 1890 morphology (UM)

These profiles can be seen to be radically different and the high Marram grass covered foredune that exists currently was non-existent in 1890. In viewing the wind flow over these profiles, figure 4, it can be seen that the topography has a significant effect. In the current profile, figure 4b, the wind speed up along the front slope is too high for sand to accumulate and it is likely to be transported onto the plateau beyond the foredune. The future scenarios need to resolve this issue as it is one aspect of the current topography that is less than ideal.

Three scenarios were therefore trialled in terms of their effectiveness in modifying this behaviour. The coastal processes that need to be accommodated by retreating the foredune system include the excessive sand transportation over the foredune, the scarping due to coastal erosion, and the consequential costs that ensue. Each of these proposed solutions would therefore require a different amount of work and disruption and each could cause differing public feedback. The three potential profiles (figure 5) are:

- a proposed profile with the foredune shifted backwards (M1)
- a proposed profile with a different slope to the foredune (M2)
- a proposed profile with a smaller front dune as a barrier for wave run-up (M3).

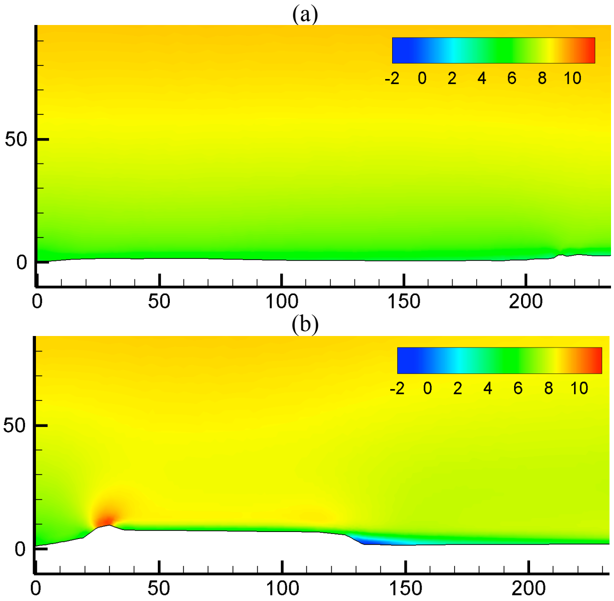
(a)



(b)

Figure 3: (a) UM (b) C profiles at equivalent positions

(a)



(b)

Figure 4: Velocity contours for (a) UM and (b) C profiles

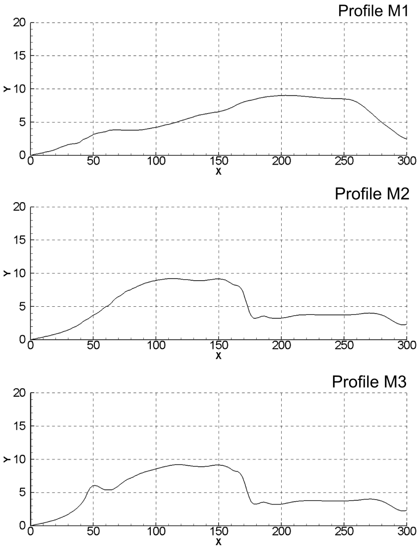
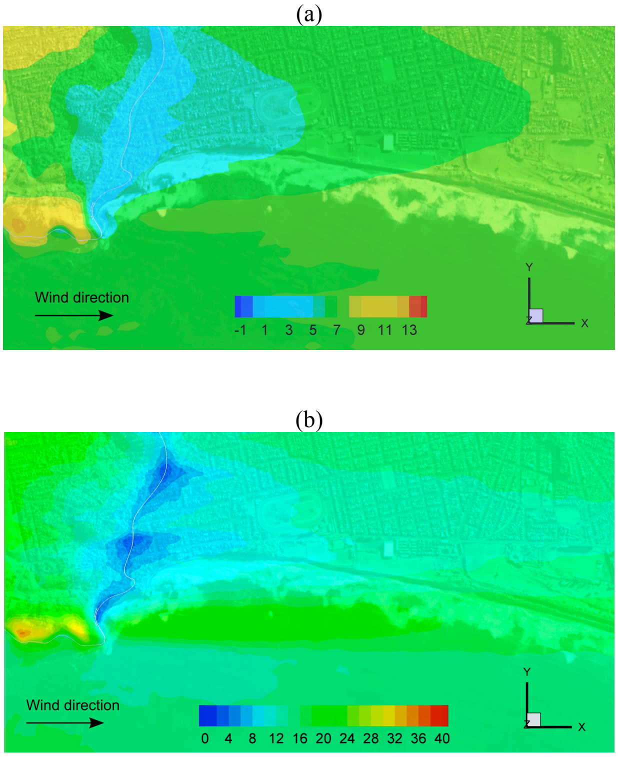


Figure 5: Alternative profiles used in the numerical modelling

RESULTS

Large Scale Simulations

The large scale three-dimensional topography simulations indicates the southern half of the study area is relatively sheltered from the prevailing southwest winds. This section of coast contained a foredune and related dune forms prior to human modification of the system. The eastern half of the study area is fully exposed to the prevailing onshore winds. This section of the pre-modified dune system contained nabké dune forms characteristic of a transgressive dune system. Sedimentation occurred primarily alongshore. The sand cloud is seen to extend toward the North East, figure 6. For winds of 15m/s there would be potentially a considerable amount of sand transported along the beach and across the seaward edge. The actual wind speeds would be much higher at the crest of the stoss face of the foredune due to acceleration.


(a)

(b)

Figure 6: Velocity contour for approaching wind speed (at 5m) of (a) 6m/s and (b) 15m/s

The wind approaches the dune at the west end first where the velocity speeds up. This velocity is higher than the velocity of the adjacent geometry to the east. The higher velocity results in higher dynamic pressure therefore the wind flow tends to be pushed toward the North East, and so does the sand cloud, figure 6.

Figure 7 shows a transient sequence of sand deposition predicted in the simulations. It can be seen that as time increases the sand deposition stabilises and is predominantly in the direction of wind flow. The wind approaches the face of the foredune from the West and accelerates so that wind speeds are higher than flows immediately to the East. Sedimentation is not normal to the shoreline but towards the North East due to the flow pressure skewing the flow.

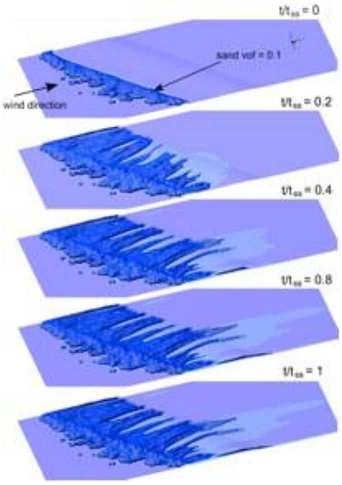


Figure 7: Sand transportation over a transient sequence. Sand cloud was represented by plotting an iso-surface of the low volume fraction sand (sand volume / air volume = 10%). Time is non-dimensionalised by the steady state time t_{ss}.

Small Scale Two-Dimensional Simulations

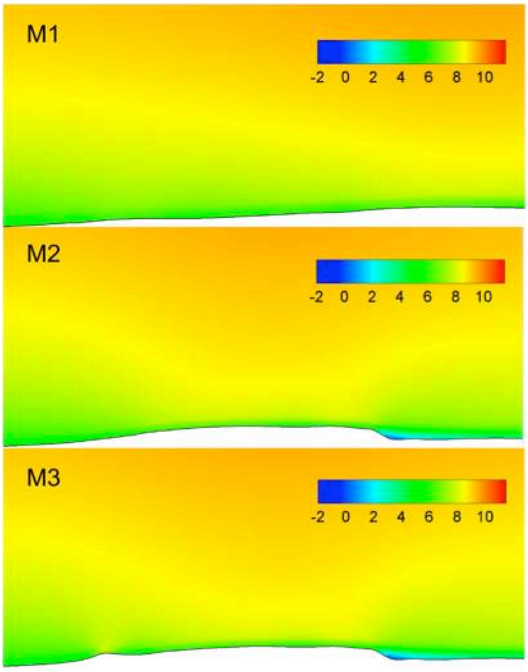


Figure 8: Wind velocity contours over the modified profiles.

Figure 8 shows the wind velocity contours over the three modified profiles. Interestingly, the differences between the wind fields over the three modified profiles are not significant. The M1 and M2 profiles have the same maximum height, but different in terms of the front slope areas. The M2 require less modification; while in M1, the dune needs to be shifted backward. The benefit of adopting the M3 profile is a protection for the front-slope base of the dune.

The front small dune in M3 acts as a front barrier for the wave run-up. The sheltered area behind the small dune also prevents erosion at the base, and along the front-slope of the dune. There is some wind speed up associated with the small front dune. The sheltered area behind the incipient dune also prevents erosion at the base and along the front slope of the dune. This may have the effect of transporting sand to the foot of the larger dune behind.

DISCUSSION

The two different scales of simulations allow a fuller picture of both the current and potential future situations to be explored. In fully understanding the current and historic situations allowed an informed set of new modified profiles to be developed and analysed. The strength of this type of analysis is the comparison of a number of alternatives that help shape and inform future policy. This is a type of use of simulation that is becoming more commonplace in other industries (Wakes et al., 2010) and this extends the applicability.

From the large scale three-dimensional simulations it is clear that the main areas of sediment transportation are in the North-East. Hence, any future re-development of the western (sheltered) section of the dune system could incorporate areas with low to moderate plant cover, or even areas of bare sand.

The wind speed up at the top of the current profile due to the slope and height of the current foredune profile is not present within the 1890 unmodified profile. The large speedup up the current steep foredune prevents sand accumulation and the sand gets transported further afield, supported by anecdotal evidence.

The profile was modified in order to attempt to prevent such a large speedup. Three alternatives were developed based mainly upon mitigating the erosion and sand transportation issues. It is likely that scenarios M2 & 3 would be affected by wave scarping during episodes of storm surge. Only M1 has the potential to mitigate both forms of erosion. There is still the consideration of the ease and expense with which such a modification could be done that may have a significant influence on which is the optimal. It is not only though the wind profile and sand transportation that will determine which profile might fit the coastal management needs best; other factors such as recreation needs, protection from storm surges, public opinion and aesthetics also play a part.

Interestingly there is little significant difference between the wind fields over the proposed new profiles but importantly the large speedup has been eliminated. The changed wind field will impact on localized sand transportation and this will be another consideration for which profile is preferable.

CFD modeling has proved to be an effective tool to help with the planning process by allowing the comparison of different scenarios that would have been impossible to assess theoretically or physically. It is the comparison of the wind flows and consequently it's effect on the sediment transportation that is of interest. The rapid turnaround of the results supports the use of such analysis. It helps the planners make a more informed decision.

CONCLUSION

This work has shown that the current dune morphology at the Ocean Beach Domain is unrealistic but that there are alternative profiles that could satisfy both public and council imperatives.

Three alternate profiles have been tested that could be viable solutions to the erosion issues experienced on this coastline presently. These would require modification to the current topography but should prove to be a long term solution to the present issues without destabalisation of the coastline. Further work is needed to look at more detailed modelling in terms of sediment transportation over each of the three proposed new profiles. The optimal profile for sediment transportation and other considerations still needs to be determined through further modeling.

CFD provided a good method for comparison of different scenarios. Using CFD for such a planning exercise is feasible as long as the client's expectations are managed and realistic. Data from CFD analysis can be highly useful for laying out any plans, as long as numerical errors, and computation assumptions are clearly recognised.

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