Three-dimensional flow simulation over a complex sand dune system

S. J. Wakes[1], T. Maegli[2], K. J. M. Dickinson[3] & M. Hilton[4]
[1]*Department of Design Studies, University of Otago, New Zealand*
[2]*CSAFE, University of Otago, New Zealand*
[3]*Department of Botany, University of Otago, New Zealand*
[4]*Department of Geography, University of Otago, New Zealand*

Abstract

Invasive, non-indigenous plants such as marram grass (*Ammophila arenaria)* have been used extensively in New Zealand to stabilise dune systems but this activity has resulted in a loss of indigenous biodiversity as well as significant changes in dune morphology. The restoration of natural dune systems has become a focus for some of the least modified coastal regions with associated concerns as to what effect marram grass eradication or other such interventions may have on dune stability.

An ongoing project at Mason Bay, Stewart Island, New Zealand has examined all aspects of marram grass invasion and eradication. This paper concentrates on the initial three-dimensional CFD model that simulates the wind flow over this complex dune system compared with field data with detailed LIDAR data used to recreate the complex topography of the dune system. Various modelling options are assessed for their accuracy in emulating the field data. The topography was found to greatly affect the results, making it difficult to determine the actual wind flow pattern over such a complex system. The effectiveness of three- versus two-dimensional CFD modelling is therefore discussed in terms of accuracy, practicality and complexity and the feasibility for practical planning purposes is also explored.

Keywords: complex topography, computational fluid dynamics, coastal dune systems, marram grass, field data, LIDAR.

www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/CENV080211

1 Introduction

There is considerable pressure, from both human and non-human causes, on the coastal systems and their guardians (Shah *et al* [1]). As a consequence it is desirable that those responsible for coastal planning should understand the complex mechanisms involved in the beach/dune environment before they make decisions about management of resources. Computational Fluid Dynamics (CFD) is a tool that could provide useful comparative information to help in this process. However, before such advances can happen there needs to be confidence in the results obtained from the numerical modelling approaches. CFD has the advantage over repeat collection of field data in that it allows remote locations to be modelled and multiple future scenarios to be compared using on-site experimental data as base inputs.

1.1 Dunes in New Zealand

In New Zealand and other places around the world there is often considerable interaction between humans and the coastline (Werner and McNamara [2], Nordstrom *et al* [3]). Coco and Murray [4] indicate that there is now more interest in predicting the effects of sediment transportation such as erosion with a view to how this may affect coastal living and other issues. With the risk of storm damage and the perceived unstable nature of dune systems and beaches, efforts go towards stabilization to protect areas beyond the beach foredune. In the past in New Zealand this activity has been undertaken primarily using introduced grass species such as marram grass (*Ammophila arenaria*). This particular grass behaves in a different manner to native grasses and sedges and the effect of extensive planting is to bind the sand, build larger beach foredunes and alter the geomorphological development path of many coastal dune systems.

The main focus of the larger project is establishing the distribution, development and impact of *Ammophlia arena* (marram grass) on the extensive network of coastal dunes. Marram grass was introduced to Mason Bay, Stewart Island in the 1950's and had the effect of steepening the foredune, displacing much of the native flora, affecting habitat and altering the dune formation processes. Work is in progress to eradicate this non-indigenous invasive species. There is a fear locally that by removing the marram grass there will be massive sediment release and transportation leading to the large foredune being redistributed over a large area inland.

1.2 Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics (CFD) has moved from its traditional use in aerospace and automotive engineering applications to more diverse applications. This has introduced different and interesting multi-physics challenges and in some cases extensive and complex topography (Wood [5]). The use of CFD in the natural environment is increasing (Baker [6]), but it has often been limited to idealised situations such as isolated hills or dunes without vegetation or sediment transport (Lubitz and White [7] and Takahashi *et al* [8]). These cases have led to important advancements in the application of CFD understanding of wind flow speedup (Hesp *et al* [9]) but there has been little extension of this approach to more realistic landscapes.

CFD is concerned with the continuity and Navier-Stokes equations that describe non-linear fluid flow. These conservation equations are discretized and model used for various physical phenomena. The use of models for physical processes requires the validation of numerical results against experimental data.

1.3 Scope of the work

This paper describes the initial simulations for wind flow undertaken over a complex three-dimensional dune topography with varied roughness. The objectives of this work more specifically, are to:

- Ascertain the effectiveness and accuracy of three versus two-dimensional numerical modelling
- Assess the feasibility of using numerical simulation as an effective coastal management tool
- Assess the complexity of the simulation procedure

This paper discusses the development of the three-dimensional simulations and shows the comparisons between the field and two-dimensional data. The work uses a surface roughness index to simulate the vegetation cover and does not model sediment transportation in this instance. Details on the form of the equations, turbulence model and associated wall function can be found in Shaw [10].

2 Previous work

Previous work (Wakes *et al* [11], Wakes and Maegli [12]) tackled some aspects of complex topography, using fieldwork and two-dimensional numerical simulation, from *parabolic* situated behind the beach foredune situated at Mason Bay. The field was undertaken along a surveyed transect dissecting the central line of *parabolic 6*, then modelled two-dimensionally and used for comparison in this work. Measurements were taken at 8 sites ranging from on the beach at the foot of the foredune to the foot of the lobe at the end of the deflation zone, figure 1.

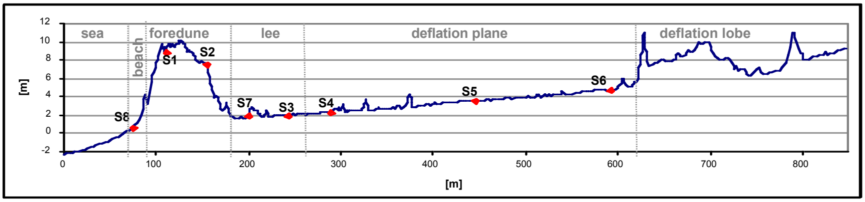


Figure 1: Transect of the two-dimensional work undertaken numerically and in the field showing the measurement sites.

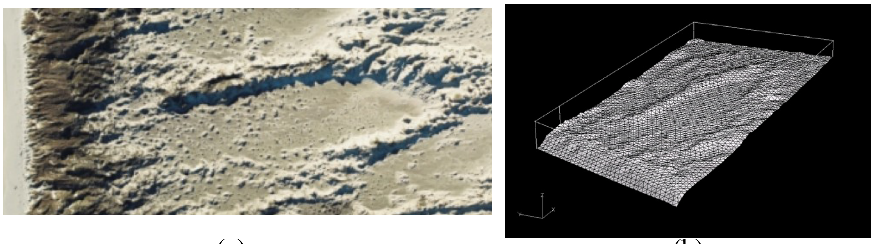
The field wind velocity data was averaged over 5 minute intervals with some sites extensively covered in marram grass up to 40cm in height, rendering some of the lower height measurements less accurate. This work has informed the three-dimensional modelling as it has established the most appropriate turbulence model as the k-ε RNG and that the domain can be divided to maximise computational resources with an acceptable lose of accuracy.

3 Numerical model

As with the two-dimensional simulations (Wakes *et al* [11]) the two-equation k-ε RNG turbulence model was used with standard wall functions. Due to the computer capacity it was not possible to have a domain containing the whole three-dimensional dune system and was therefore split into front (foredune) and back (deflation) sections (Wakes *et al* [11]). It was determined that over a range of 6-10m/s the wind profiles for the numerical simulations when non-dimensionalised were coincident. Therefore we treated the wind profile velocities as non-dimensionalised with the velocity taken at 5m to allow for easy comparison. Thus an inlet velocity of 8m/s for both the two and three-dimensional simulations was used. A customised file was created with roughness heights that varied over the surface which were generated by the grid coordinates.

3.1 Geometry modelling

One of the major issues with modelling complex geometries is accessing the data to build the numerical surface model required. As has been observed (Wakes *et al* [11]), compatibility of numerical software can at times be limited. Manual manipulation is therefore required to convert geometric data from the LIDAR dataset available into a form suitable for the CFD software. A regular grid in the x-y plane with varying height (z) was required for a surface to be draped over. The protocol for this process was time consuming and dependent on the requirements of the CFD software used. The dataset consisted of 15,586 vertices and was 285m wide with 57 rows and 640m long with 128 columns. Figure 2 shows the aerial photograph of parabolic 6 and the final surface mesh used respectively. Comparison of the aerial photograph with the initial surface mesh is good.



(a) (b)

Figure 2: (a) Aerial photograph of parabolic 6 and (b) initial surface mesh.

3.2 Size of domain

The original LIDAR data started only 10m before the foredune and this proved to be insufficient to establish a wind profile. Therefore extra beach strips of 10m and 40m were added to the dataset and results compared. The two-dimensional simulation under predicted the field data for site S8 whereas at heights above 1.5m the three-dimensional simulations all slightly over predicted (figure 3). This situation is reversed for site S1 and for site S2 where all simulations are close to the field data. The extra length made a difference to the results, most noticeably at site S8, indicating that it was preferable to add 40m in total onto the length of the domain.

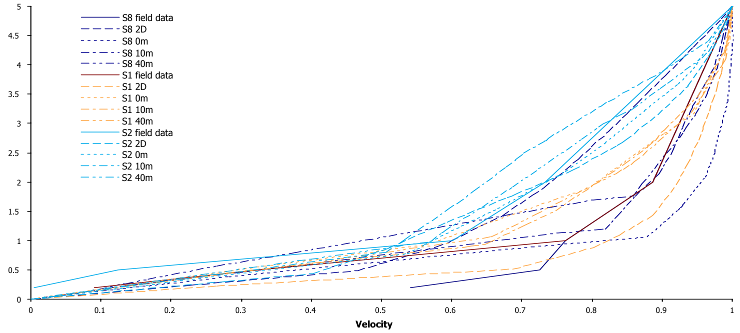


Figure 3: Graphs showing the wind profiles for three different domain lengths at sites.

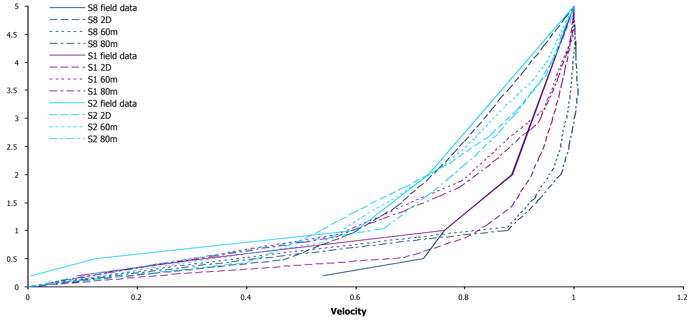


Figure 4: Graphs showing the wind profiles for the effect of domain height change for sites.

Figure 4 shows the comparison between 2 domain heights between these two heights and it seems there is little difference between the two tested. It would therefore be acceptable to use a lower domain height if made necessary by computer capacity limitations.

3.3 Grid adaption

Grid adaption is a technique that allows the refinement of the grid in the places that require it in an automated or manual fashion. Computer resources are therefore not wasted by the inclusion of unnecessary cells (Fluent [13]). Solution adaptive grid refinement is based on an evolving flow field. There are various techniques used but hanging node boundary and geometry based adaption were used in this work. More detail on the specific techniques can be found in Fluent [13]. An initial volume mesh quality with a maximum skewness of 0.78 (Abanto *et al* [14]) was desired. The volume was meshed initially using Tripave on the surface and Tet hybrid volumes within Gambit with a surface mesh size of 2m. A growth rate of 1.25 was applied to concentrate more cells around the surface before adaption was applied.

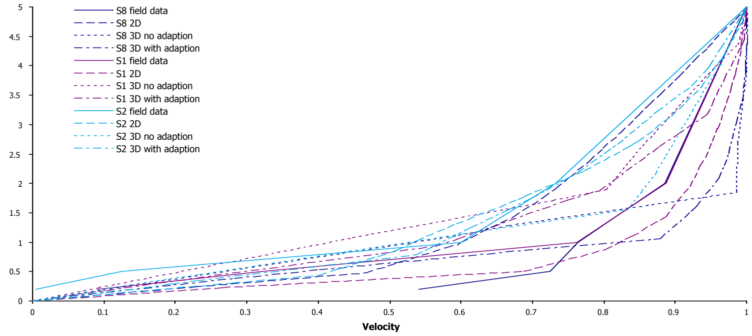
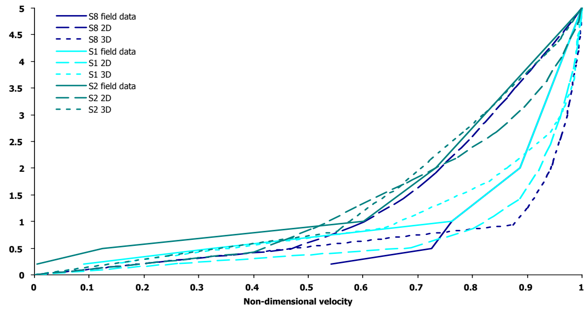


Figure 5: Graphs showing the wind profiles for sites S8, S1 and S2 showing the effect of grid adaption in the three-dimensional simulations.

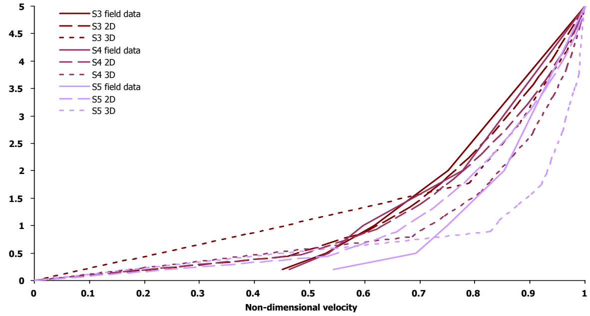
The three-dimensional simulations with and without adaption are compared to the field and two-dimensional data (figure 5). Adaption gives much closer predictions of the flow than for when no adaption was applied compared to the field data. For example, at site S2 both the three-dimensional with adaption and two-dimensional results are very close to the field data whereas the three-dimensional simulation without adaption gives a very poor comparison. Adaption therefore allows more targeted placement of cells in areas of rapid change in geometry or flow variables and better accuracy in the results near to the surface.

4 Final three-dimensional simulation results

Figure 6 shows the wind profiles from the final simulations, detailed in table 1. The runs within the foredune zone the three-dimensional simulations are a closer approximation to the field data. The comparison site at the foot of the foredune, S8, gave the worst predictions. However, even in this case the general flow trend was picked up by the three-dimensional simulation. None of the simulations



(a)



(b)

Figure 6: Final wind profiles for the (a) foredune zone and (b) deflation zone.

Table 1: Final three-dimensional simulation details.

	Foredune	Deflation
Geometry	235m long (30m water surface, 10m extra sand strip), 80m high	235m long (extra 30m at both ends of domain), 80m high
Mesh	Initial: 367,044 cells max skewness: 0.805 Final: 1,469,000 cells	Initial: 376,006 cells Max skewness: 0.81 Final: 1,576,800 cells
Adaption	Geometry based (dune surface only, z direction) Boundary (5m z direction, hanging node)	Geometry based (central surface only, z direction) Boundary (5m z direction, hanging node)
Roughness	Water: 0.0125 Sand: 0.05 Dune: 0.24 Lee: 0.19 Deflation: 0.05	Deflation: 0.05
Inlet	Velocity profile over sea surface of roughness Ks=0.0125, wind direction perpendicular to foredune, 200m length domain, Profile at centre of box at 125m used as profile (x, y, z velocity and turbulence parameters)	Velocity profile taken from foredune simulation (x, y, z) velocity and turbulence parameters

predict a velocity speedup between sites S8 and S1 tying in with the field data. In the deflation zone (see figure 1) the two-dimensional simulations are closer to the field data, but with the three-dimensional data tending to over-predict the field data. The lack of cells near the surface means that at all three sites (S8, S1 & S2) the velocity is overestimated at around 1-1.5m from the surface. The shape of the profile is very similar above this and could be speculated that with a better mesh near the surface the three-dimensional simulations in the deflation zone would be more accurate.

In comparison with the field data taken along the central transect of the system the degree of success was varied. There was a distinct difference between the two portions of the domain that were simulated, with those of the deflation zone not comparing as well as those of the foredune zone. This disparity appears to be that in spite of using grid adaption, there were fewer cells near the surface in the three-dimensional case than the two-dimensional simulation. This lack of cells may reflect less change in the geometry or flow variables in the deflation zone since it was reasonably flat, meaning that the adaption process did not incorporate additional cells. In contrast the foredune portion contained more cells near the surface and the comparison is much better. However the overall trends in the field data are picked up by the three-dimensional simulations in both zones.

It is encouraging that the three-dimensional simulations predicted the wind flow over such a complex surface relatively well, as even with grid adaption the mesh was fairly crude. Even so, the three-dimensional results tended to over-predict results from the two-dimensional data. There are difficulties in that we only have field data along a transect along the centreline of the parabolic dune with which to compare the simulation results. However, the results do give some confidence that such a simulation will give reasonable predictions over the rest of the topography.

As expected, in regions of separation, areas of marram grass coverage or close to large structures, such as the lee of the foredune, the comparison between field data and three-dimensional simulation data is not good. It is known that three-dimensional separation is a difficult subject (Tessicini *et al* [15]) and that RANS turbulence models are not the best for this type of flow. The limiting factors with any simulation are usually computer capacity and time, especially when results are needed for planning purposes and so compromises often have to made (Fahey *et al* [16]). In this case the demands of the complex topography dictate that the mesh density gets priority over, for example, a more sophisticated turbulence model. Although there is a loss of transient detail and the predictions of recirculating flow are compromised, simulations such as these can still provide very useful information for coastal planners. Using CFD to inform a planning decision may require a number of different scenarios to be simulated. Interest will not necessarily be in exact values of the flow variables at specific locations but in more broad predictions of the changes in the wind flow over an altered topography. These three-dimensional simulations have shown that CFD is well placed to assist in such comparisons and has considerable potential in this regard.

5 Conclusions

The following conclusions from this work can be drawn:

- Until there is more compatibility of software, modelling complex surfaces in CFD will be time consuming and potentially difficult.
- The practicality of using a numerical modelling technique such as CFD to predict scenarios in coastal planning is feasible but does require skilled users, reasonable computing power and availability of geometric data.
- The complexity of undertaking a simulation of a complex three-dimensional topography is considerable but this work has explored a number of important issues such as turbulence modelling, grid adaption and some initial validation.
- The three-dimensional numerical simulation results give reasonably good agreement for the central transect for which field data was available.
- The effectiveness of the three over the two-dimensional simulations has been demonstrated.
- The future of this work is ongoing, with a project being undertaken to add in sediment transport and a better representation of the vegetation cover and its effect on fluid flow.

Acknowledgement

The authors would like to acknowledge the funding from the University of Otago Research Grant number: 0020030746.

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