Using Computational Fluid Dynamics to investigate the effect of a Marram covered foredune: initial results

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Abstract

New Zealand coastal dune systems have been invaded by Marram grass (*Ammophila arenaria*) over the last 50 years. This is thought to have had a significant effect on the ecosystem biodiversity and coastal geomorphology. Care needs to be taken if eradication is to be undertaken that the dune systems are not unstabilised and more problems are caused. Marram grass was originally planted as a sandbinder and has created massive foredunes on exposed coasts Cooper [1], Wiedemann and Pickart [2] and Elser [3] that has major implications for the geomorphic development of transgressive dune systems. Little work has been done to study the impact of these foredunes on the development of downwind dunes.

Initial work is being undertaken to model the flow over a particular coastal dune system at Mason Bay, Stewart Island, New Zealand with a typical marram covered foredune with a transgressive parabolic dune downwind. Previous work, Hart et al [4], has compared a two-dimensional slice of the topography as of 2003 (marram) and 1958 (pre-marram) numerically to understand the pattern of wind on the foredune and more importantly in the deflation zone. This paper compares Computational Fluid Dynamic (CFD) modelling of the existing topography with experimental wind measurements. Emphasis will be on the validation of the numerical model data. The protocol needed in taking account of the roughness of the different surface coverings over the surface will be discussed. Validation of two-dimensional transects through the dune complex will inform the resulting three-dimensional model. A protocol for modelling in the future will be ascertained in terms of roughness values to use dependent on vegetation present, mesh size, turbulence model to use and domain size.

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1 Introduction

This paper is concerned with the initial two-dimensional modelling of wind flow over a complex dune system. It is essential that validation of the numerical results is undertaken with experimental wind data. This not only allows confidence in the results but also highlights the strengths and deficiencies in the model. This modelling protocol then allows further numerical simulation both in two and three-dimensions to be used with confidence. This is important as experimental work is often difficult or not possible for every scenario of wind velocity and direction required to be modelled. The advantage of using numerical simulations is that wind velocity, direction and other parameters can be changed easily and comparisons made.

2 Background

2.1 Dunes systems

Active coastal dune systems of late-Holocene age are widespread in New Zealand. Early accounts, those of Cockayne [5], for example, indicate these dune systems had a sparse or discontinuous vegetation cover of specialist dune species. The majority of active dunes in New Zealand now bear little resemblance to these early descriptions. Marram grass, *Ammophila arenaria*, a vigorous European sandbinder, was planted widely to stabilise dunes. It became naturalised and spread to virtually all coasts.

Marram grass forms massive foredunes on exposed coasts, Cooper [1], Wiedemann and Pickart [2], Elser [3] which may be significantly higher and wider and more regular alongshore , Hesp [6], compared with foredunes associated with indigenous species. The development of this dune form has major implications for the geomorphic development of transgressive dune systems. Along many exposed sandy coasts, including the windward coasts of New Zealand, these systems comprise mobile parabolic dunes. The development of a massive foredune complex may create a significant barrier to wind flow and sand movement, sheltering the pre-existing dunes that lie downwind and starving the entire system of sand. This process, in turn, may lead to a loss of dune and dune system function and result in a decline in biodiversity. Although these new foredunes have been recognised for some time (e.g. Cooper [1]), there has been little attempt to determine their impact on the development of downwind dunes.

2.2 Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) solves numerically the continuity and Navier-Stokes equations that govern the time-averaged velocity and pressure distribution within a fluid space, Shaw [7]. These equations are discretized and solved within a geometry split into a mesh for calculation purposes. Various assumptions are made due to the complex nature of the equations such as the treatment of the turbulence and wall roughness. Although it is possible to model turbulent flow through having a fine enough grid of cells this technique is only possible for the simplest of geometries. It is not then possible with the computer power available for such complex topography as this. Therefore models are needed to take account of the effect of turbulence within the flow. Three turbulence models are compared within this work, all based upon the most commonly used, the standard k-ε two-equation model.

The two-equation k-ε turbulence model, Launder and Spalding [8], evaluates the components of the stress tensor by introducing the eddy viscosity concept, assuming that the stress tensors are proportional to the mean velocity gradients and the turbulent (eddy) viscosity is estimated using the Kolomogorov-Prandtl expression.

The RNG (Renormalisation Group) k-ε model differs from the standard by the inclusion of an additional sink term in the turbulence dissipation equation to account for the non-equilibrium strain rates and employs different values for the various model coefficients. The high Reynolds number form of this model has proved successful for the calculation of separated flow, much more so than the standard k-ε model.

The realisable k-ε model contains a new formulation, from the standard k-ε model, for the turbulent viscosity and a new transport equation for the dissipation rate. This model is likely to be better for flows involving rotation, boundary layers under strong adverse pressure gradients, separation and recirculation, [9].

The wall roughness within the software is treated as a modified law-of-the-wall, [9]. Two input parameters are required, the roughness height and the roughness constant. The standard defaults are based upon uniform sand-grain roughness and these need to be altered to account for other roughness. Within these simulations it is recommended that the maximum roughness constant is used as there is no clear relationship between type of roughness and constant value Triesch and Bohnet [10]. The roughness height is determined from the experimental data in each of the zones of the profile.

3 Methodology

3.1 Experimental

The experimental data was taken over 2 days at Mason Bay, Stewart Island, New Zealand. A mast with cup anemometers placed at heights 0.2m, 0.5m, 1m, 2m and 5m above ground was used. Measurements were taken over periods varying between 20-40 minutes at 3 second intervals. The measurement stations are shown in figure 1 with the low tide mark at 65m. The beach is the far left of the profile and the geometry goes from the foredune (S8, S1, S2 & S7), the deflation zone (S3, S4, S5) to the start of the lobe of the transgressive dune (S6). The two sites considered in detail in this paper are S2 at the back of the foredune and S7 in the lee of the foredune. These two sites represent contrasting flow regimes that will give an exacting test for the numerical simulation results. A change in direction was observed as the wind flowed from the beach up the foredune. By site S2 the direction of the wind was normal to the foredune. In the lee of the foredune there is a chance of stagnant or recirculating flow that gives an exacting comparison with numerical data.

The raw wind data needs to be averaged to minimise the effect of gusting. One of the most accepted methods of doing this is by using the R^2 values to test the integrity of the averaging period. The nearer the R^2 value is to unity the better the data fit is to, in this case, the standard logarithmic curve, Sherman et al [11] and Woodley [12]. The period chosen for sites S2 & S7 was 5 minutes with R^2 values of 0.97 and 0.836 respectively. These averaged wind profiles were then used in the comparisons with numerical results. The roughness heights for the numerical simulations were determined from the roughness length using that the roughness length is approximately 8% of the roughness height, Wang et al [13]. The roughness length was taken as the intercept from a log-linear regression equation of the measured wind data for stations within each zone of differing vegetation cover.

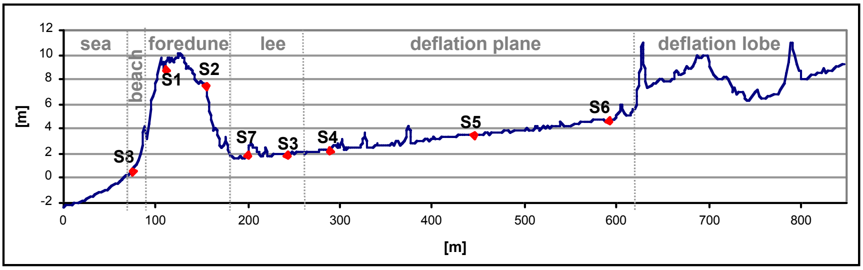

Figure 1: Schematic indicating the positions of the measuring stations.

3.2 Numerical

The numerical model was taken to be initially a two-dimensional slice of the dune topography, taken through the axis of the parabolic dune. The numerical geometry was determined from survey data consisting of 200 points at roughly 2m intervals with some concentration on areas with rapidly changing gradients where necessary. In all cases the inlet velocity profile is based on a 8m/s constant wind velocity over a sea of roughness 0.0125m, Perianez [14]. The upper surface was given a symmetry boundary condition with the right hand boundary as an outflow. The results are non-dimensionalised to allow ease of comparison by the velocity at 5m above the surface for both the experimental and numerical data respectively.

Table 1 shows the cases tested with the changes variables in bold. For case R1 the roughness height is set along the entire surface as 0.05m (sand roughness). For case R2 the surface is split into four zones shown in figure 1, as beach (roughness height 0.05m), foredune (0.24m), lee (0.19m) and deflation (0.05m). For the mesh size the significant parameter was the size of the first cell size. One of the cases M1 followed the recommendation from the software [9] that it was roughly double the roughness height, and the second case M2 tried a smaller cell size, approximately equal to the roughness height.

Table 1: Summary of numerical cases.

Case	Turbulence model	Roughness values	Domain height	Mesh size
Case D1	Standard k-ε	Varied	***60m***	0.5m at surface
Case D2	Standard k-ε	Varied	***100m***	0.5m at surface
Case M1	RNG k-ε	Varied	100m	***0.5m at surface***
Case M2	RNG k-ε	Varied	100m	***0.25m at surface***
Case T1	***Standard k-ε***	Varied	100m	0.5m at surface
Case T2	***RNG k-ε***	Varied	100m	0.5m at surface
Case T3	***Realisable k-ε***	Varied	100m	0.5m at surface
Case R1	RNG k-ε	***Constant***	100m	0.5m at surface
Case R2	RNG k-ε	***Varied***	100m	0.5m at surface

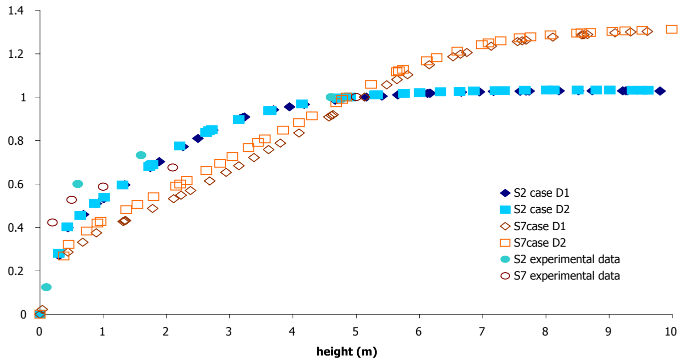

Figure 2: Comparison of domain height for site S2 and site S7.

4 Results and discussion

4.1 Domain size

Setting the domain height is important as this determines the overall size of the computational geometry and mesh. Ideally there should be no influence from the upper boundary on the flow within the computational domain. Two cases were evaluated, 60m and 100m. It can be seen in figure 2 that at site S2 the comparison for the non-dimensionalised velocity against height gives a very good agreement. Figure 2 also shows the comparison at site S7 within the lee of the foredune. This is a much more challenging site near recirculating low velocity flow. The anemometers only measure the general velocity magnitude and therefore may not have fully captured the structure of the flow at this site but even so the comparison is reasonable. There are some differences near to the surface probably caused by this recirculating flow, but the results for the two heights are very close.

Figure 3 shows the velocity magnitude contour plot for both cases. It can be seen that the flow features close (up to 5m above) to the dune surface are similar in both cases. It is the flow above this that shows some differences with the 100m domain showing less influence from the upper boundary. It is therefore recommended that a 100m domain is used for these two-dimensional simulations. This result may have significance for the full three-dimensional model where domain size becomes much more significant in terms of maximising meshing for computer power available. A domain height of 60m could be used with little loss to the results nearer to the surface but this needs to be confirmed in the three-dimensional simulations.

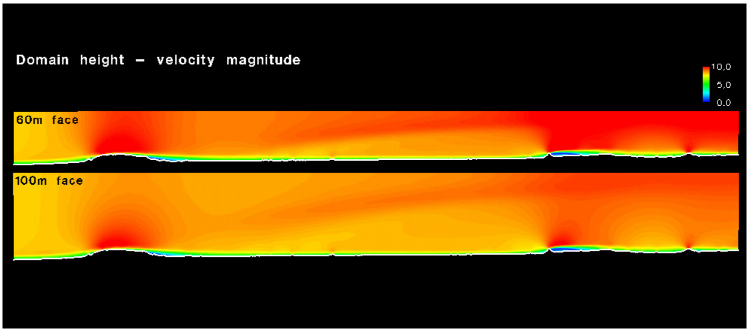

Figure 3: Velocity contours for domain heights of 60m and 100m.

4.2 Mesh size

Figure 4 shows the comparison of the first mesh cell size at the dune surface for site S2. It can be seen that the larger cell size of 0.5m agrees much better than the smaller one. For site S7, the agreement is less good but the shape of the velocity profile from the simulation with a 0.5m cell size is in much better agreement than for the smaller cell size. It therefore is important to ensure that the first cell size is at least twice that of the largest roughness length within the simulation for results to be acceptable. The roughness is taken into account using an adapted law-of-the-wall approximation and as such it is expected that in areas such as in the lee of the fore dune with recirculation that the model does not stand up well, as it is formulated for flow over a flat surface. It is at site S7 that the contrast is the greatest between the experimental and simulated results. The trendline for case M1 is a better fit with the experimental data than for case M2 and this is the recommended mesh size.

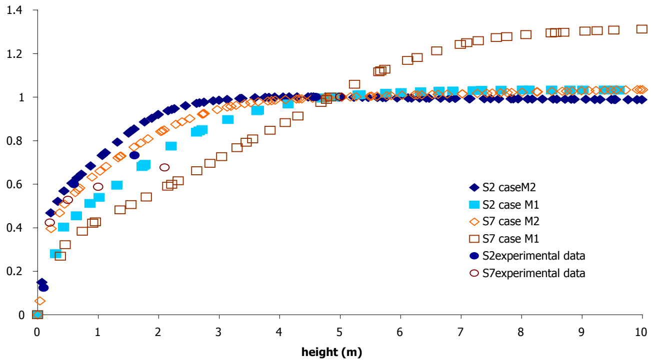

Figure 4: Comparison of 1st cell size at site S2 and site S7.

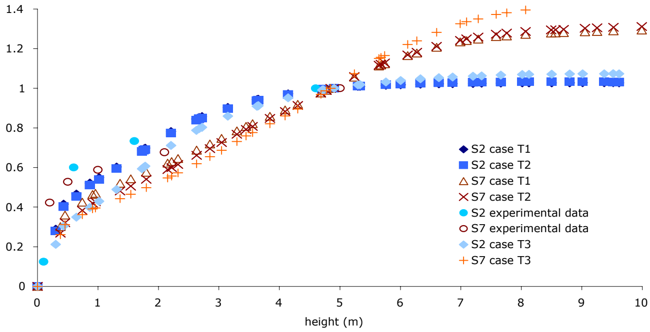

Figure 5: Comparison of turbulence models for site S2 and site S7.

4.3 Turbulence model

Three turbulence models, the standard, RNG and realisable two-equation k-ε, were tried. Figure 5 shows that comparison at site S2 between these and the experimental data. It can be seen that there is very little difference between the standard and RNG turbulence models and that the comparison between the numerical and experimental data is good but with some underestimation of velocity near the surface. This probably due to the use of a law-of-the-wall adapted to roughness. For the realisable model the predictions up to 5m is not as good a fit to the experimental data.

Figure 5 also shows the comparison at site S7 of the numerical and experimental data. Again the comparison between the standard and RNG turbulence models is good with some deviation from the experimental close to the surface. This is to be expected with the complexity of the flow at this site, with recirculation and possible limits to the experimental data due to possibly changing direction of the wind. The realisable model predicts much higher velocities above 5m and deviates from the trendline. The RNG model is therefore an acceptable choice for a turbulence model and this follows recommendations from other work, Parker and Kinnersley [15] and Parsons et al [16].

4.4 Roughness values

Figure 6 shows that for both sites S2 and S7 that the use of a variable roughness along the profile has a small effect on the velocity profile. For site S2 case R2 with the varied roughness values follows more closely the experimental data than case R1 with a constant sand roughness. For site S7 close to the surface the experimental and numerical data is not such a good fit as expected with case R2 giving higher velocity predictions than case R1 above 5m. It is advantageous to model the roughness height as accurately as possible as the roughness influences other factors such as flow separation and momentum transport Tachie et al [17] and van Boxel et al [18].

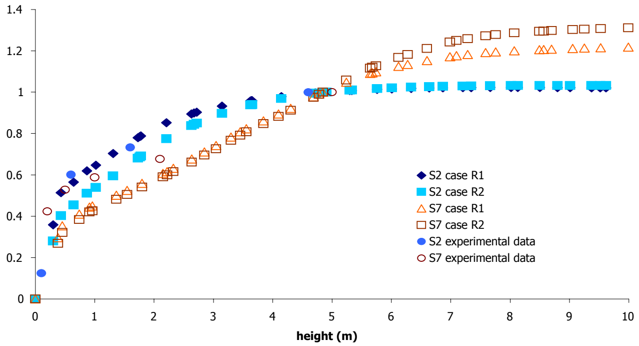

Figure 6: Comparison of distribution of roughness values at site S2 and site S7.

5 Conclusions

The following conclusions can be drawn from this work:

- The validation of the two-dimensional simulation against experimental data is good.
- The two-equation k-ε RNG turbulence model is an acceptable compromise between accuracy and speed of the simulation.
- The first cell size should be at least double the largest roughness height within the simulation.

- It is important to vary the roughness height within a profile to distinguish the different zones of vegetated surfaces.
- It appears that a lower domain height can be used for a two-dimensional models but the domain height may be more significant for three-dimensional models and needs to be tested further.
- CFD has fared well in its use with a complex surface in comparison with experimental data. This bodes well for the three dimensional model.
- The protocol for the three-dimensional modelling will initially be with the recommended turbulence model (RNG), first cell size (0.5m), domain height (100m) and with varied roughness where appropriate as found in this paper.

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