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Modeling of Surface Roughness for Flow over a Complex Vegetated Surface

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***Abstract*—**Turbulence modeling of large-scale flow over a vegetated surface is complex. Such problems involve large scale computational domains, while the characteristics of flow near the surface are also involved. In modeling large scale flow, surface roughness including vegetation is generally taken into account by mean of roughness parameters in the modified law of the wall. However, the turbulence structure within the canopy region cannot be captured with this method, another method which applies source/sink terms to model plant drag can be used. These models have been developed and tested intensively but with a simple surface geometry. This paper aims to compare the use of roughness parameter, and additional source/sink terms in modeling the effect of plant drag on wind flow over a complex vegetated surface. The RNG k-ε turbulence model with the non-equilibrium wall function was tested with both cases. In addition, the k-ω turbulence model, which is claimed to be computationally stable, was also investigated with the source/sink terms. All numerical results were compared to the experimental results obtained at the study site Mason Bay, Stewart Island, New Zealand. In the near-surface region, it is found that the results obtained by using the source/sink term are more accurate than those using roughness parameters. The k-ω turbulence model with source/sink term is more appropriate as it is more accurate and more computationally stable than the RNG k-ε turbulence model. At higher region, there is no significant difference amongst the results obtained from all simulations.**

***Keywords*—**CFD, canopy flow, surface roughness, turbulence models

I. INTRODUCTION

MODELING atmospheric flow over various surfaces has received increasing attention in the past decade [1]. Such models provide a means of addressing environmental problems including flow over vegetated surfaces. Further, in coastal areas, the models can be used to investigate morphological changes in sand dunes due to sediment erosion/deposition over time. Sediment transport mainly occurs in the surface layer where airflow is affected by the condition of the surface. Vegetation has the ability to form a dense cover over a surface [2, 3], and therefore shields the sediment from wind by extracting momentum from the airflow [4, 5].

Vegetation cover and its influence on surface roughness add considerable complexity to computational modeling of flow. When sand is transported over a vegetated surface, threshold velocity at the surface is an important parameter to capture. Generally, modeling has been at a broad scale where surface conditions have been simplified mathematically through the roughness parameters in the modified law of the wall. This wall function has been incorporated with the aim of circumventing the computationally excessive grid requirement particularly in the viscous sublayer. For large-scale atmospheric flows, this method has been proved accurate when broad characteristics of flow are concerned and the flow statistics near the surface are not of interest [6-8]. This is because the boundary of the surface layer can be considered thin enough when the large-scale flow at higher elevation is calculated. However, the use of roughness parameters in the modified law of the wall provide no information of the turbulence structure within the canopy region as the vegetation-related parameters, such as leaf area density (LAD), cannot be taken into account.

In focusing on surface flow complexity, plant drag can be accounted for not only by incorporating surface roughness parameters but also by introducing source/sink terms. As such, modified transport equations can be derived to establish mean momentum, turbulent kinetic energy and turbulent kinetic dissipation rate. The use of source/sink terms has been investigated intensively, but generally studies have used a simple surface geometry [9-13].

It is questionable which method of modeling the surface roughness is more suitable when large-scale flow is computed but the turbulence in the near-surface region is also of interest. The use of roughness parameters in the law of the wall returns broad flow statistics for a whole computational domain. This approach requires less computational grid in the viscous sublayer, thereby resulting in faster computing time. This is particularly desirable for three dimensional flows where the computing is intensive. In contrast, the use of additional source/sink terms provides more detail within the canopy region. However, it requires more terms in the transport equations, which makes the simulation become more computationally expensive.

To our knowledge, there have been no attempts to test the performance of these two methods (using roughness parameters, and source/sink terms) to model the surface roughness for flow over a large-scale complex vegetated surface. In this study, flow over a vegetated sand dune is investigated. The turbulent statistics within the canopy region are main parameters to capture as it is a function of the rate of sand transport which plays an important role in morphological change.

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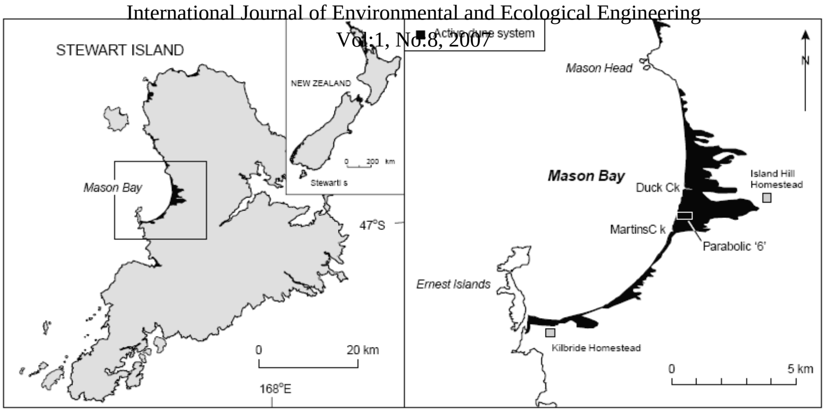


Fig. 1 Location of 'parabolic 6' at Mason Bay, Stewart Island, New Zealand (figure taken from Hilton 2006)

Fig. 2 Photograph of the study site Mason Bay , Stewart Island, New Zealand (in front of the foredune)

Fig. 3 Mast cup anemometers were installed at 0.2 m, 0.5 m, 1 m, 2 m and 5 m heights

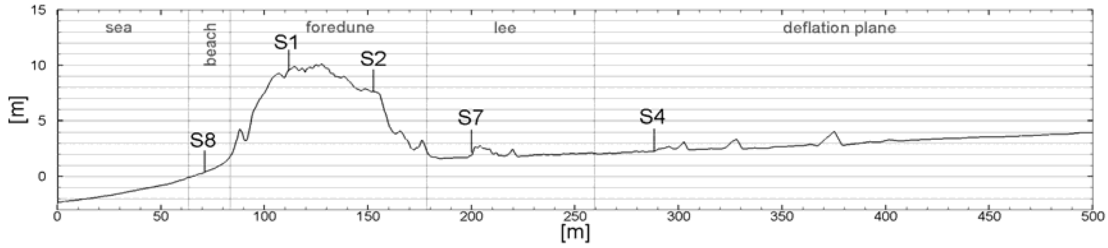


Fig. 4 Measurement station: beach (S8), top of foredune (S1), foredune brink (S2), lee of foredune (S7) and deflation plane (S4)

This paper aims to compare the use of roughness parameters and additional source/sink terms in modeling the effects of plant drag on wind flow over a complex vegetated surface. All numerical results were compared to the experimental results obtained from a study site at Mason Bay, Stewart Island, New Zealand.

II. METHODOLOGY

A. Experimental

Wind speed data was measured across a parabolic 6 over two days at Mason Bay, Stewart Island, New Zealand (Figs.1 and 2). Mast cup anemometers were placed at height 0.2m, 0.5 m, 1 m, 2 m, and 5 m above the ground (see Fig. 3). The first measurement station is at the beach (S8) and the rest are situated at the top of foredune (S1), back of foredune (S2), lee of foredune (S7) and deflation plane (S4) (see Fig. 4). The periods of measurement varied between 20-40 minutes at 3 second intervals.

To minimize the effect of gusting, log-linear regression was used to fit through the mean velocity for each elevation. R^2 was employed to test the integrity of the measured data [14]. R^2 value equals to unity indicates the regression line perfectly fits the data, while R^2 value equals to zero indicates no linear relationship between the regressor and the response variable. The measured data obtained in the period producing the highest value of R^2 was used as the period of the steadiest wind.

B. Numerical

The present work has been conducted by using the numerical solution method, Computational Fluid Dynamic (CFD). The CFD code Fluent (Fluent Inc.) is used to solve the Reynolds-Averaged Navier-Stokes equations and the continuity equation using the finite volume method.

The effect of plant drag was accounted for in the flow field by two means; by using wall roughness parameters in the modified law of the wall equation, and by adding additional source/sink terms into a set of transport equations for the mean momentum, turbulent kinetic energy and turbulent

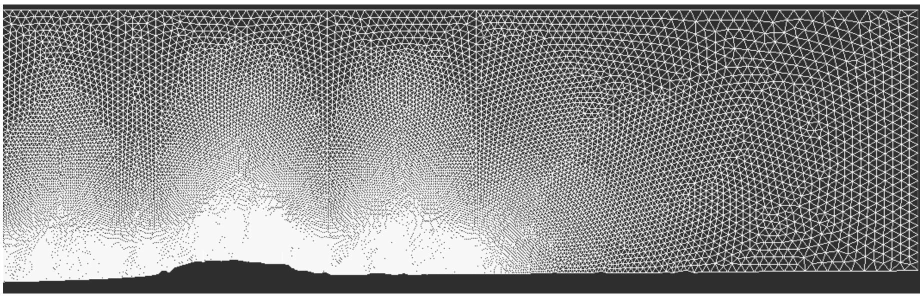


Fig. 5 Computational Domain and mesh resolution: 500 m x 150 m in x-z plane

dissipation rate. The renormalization group (RNG) k-ε turbulence model with the non-equilibrium wall function was tested with both cases. In addition, the k-ω turbulence model, which is claimed to be computationally stable [15], was employed with the source/sink terms. Summary of the simulation cases is shown in Table 1.

TABLE 1
SUMMARY OF SIMULATION CASES

Simulation case	Description
(A)	Plant drag effects were simulated using roughness parameters in the RNG k-ε model + the non equilibrium wall function
(B)	Plant drag effects were simulated using source/sink terms in the RNG k-ε model + the non equilibrium wall function
(C)	Plant drag effects were simulated using source/sink terms in the SST k-ω model.

1) Turbulence models

In this study, the steady state Reynolds-Averaged Navier-Stokes (RANS) equations are considered with the RNG k-ε model and the SST k-ω model, which are indicated in Eqs. (1) to (5) (see notation for terms description).

$$\frac{\partial}{\partial x_i}\rho(u_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial x_j}(\rho u_j u_i) = \frac{\partial}{\partial x_j}\left[\mu_\tau\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\delta_{ij}k\right] - \frac{\partial G_k}{\partial x_i}+\rho g_i + S_u \tag{2}$$

$$\frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_\tau}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k - \rho\varepsilon + S_k \tag{3}$$

$$\frac{\partial}{\partial x_j}(\rho\varepsilon u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_\tau}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}G_k - C_{2\varepsilon}\frac{\rho\varepsilon^2}{k}+S_\varepsilon \tag{4}$$

The transport equation for the specific energy dissipation rate (ω) is defined as follows;

$$\frac{\partial}{\partial x_j}(\rho\omega u_j) = \frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_\tau}{\sigma_\omega}\right)\frac{\partial \omega}{\partial x_j}\right]+G_\omega - Y_\omega + S_\omega \tag{5}$$

In modeling canopy flow with the source/sink terms applied for plant drag, the combination of RNG k-ε model and the non-equilibrium wall function is the best combination for the mean wind speed prediction. In the study, various turbulence models; the standard [16], the renormalization-group (RNG) [17], the realizable k-ε [18] and the SST k-ω model [19] were tested with the wall function (the standard, the non-equilibrium and the enhanced wall function) on a flat surface. R^2_{overall} (the average R^2 for the prediction of flow within and above canopy region) was proposed as an index for evaluating the accuracy of the predictions. The RNG k-ε model with the non-equilibrium wall function returned the highest R^2_{overall} value of 0.87 for the mean velocity, and 0.59 for the turbulent kinetic energy (the best R^2_{overall} for the turbulent kinetic energy is 0.61). In this study, this combination of turbulence model and wall function was used with the roughness parameters and with the source/sink terms in modeling the effect of plant drag.

In addition, the SST k-ω model was employed in this study as it is claimed to be computationally more stable and less sensitive to lower boundary condition than the k-ε models [13]. However, the constants in the source/sink term models need to be modified when the SST k-ω model is employed. It is found that the value of α_p and α_d (in Eq. 16) should be modified from the standard value of 1.5 for both α_p and α_d to 3.2 and 0 [12] respectively, while the standard value of β_p (= 1) and β_d (= 4) can be used. For canopy flow over a flat surface, these setting for the SST $k-\omega$ model returned similar results of those obtained from the $k-\varepsilon$ models.

2) Computational domain and boundary condition

For atmospheric flows modeling, there should be no influence from the upper boundary on the flow within the computational domain. Thereby setting the domain height is important. The domain height of 100 m (or higher) is recommended in the study of Wakes et al. [20] in which the effect of a Marram covered foredune is investigated by using CFD. In this study, the two dimensional computational domain was set to 500 m x 150 m in x-z plane.

The surface was divided into five zones; sea, beach, grass covered foredune, lee and deflation zone. At each surface, roughness parameters are set corresponding to the surface type. Only at the vegetated surface (foredune) that the surface roughness was modelled by two means: using the roughness parameters in the modified law of the wall, and the source/sink terms.

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

$$u(z) = u_{ref}\left(\frac{z}{z_{ref}}\right)^{\alpha} \tag{6}$$

where u_{ref} is reference velocity at reference height (z_{ref}) and was set to 10 m/s at 2 m. following the observed data at S8 (beach). 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 similar to those in the study of Li Liang et al. [21] in which canopy flow over a model forest was investigated, and are defined as follows;

$$k(z) = \frac{u_*^{\,2}(1-\frac{z}{\delta})^2}{\sqrt{(C_1 C_2)}} \tag{7}$$

$$\varepsilon(z) = \frac{u_*^{\,3}(1-\frac{z}{\delta})^2}{\kappa(z+z_0)} \cdot \frac{1+5.75z}{z_0} \tag{8}$$

where δ is gradient height (20m). C_1 and C_2 are closure constants (0.5478 and 0.1643 respectively). The energy dissipation rate (ε) is reformulated in terms of the specific dissipation rate (ω) by the following relationship;

$$\omega = \frac{\varepsilon}{C_\mu k} \tag{9}$$

C. *Accounting for plant drag*

1) *Using wall roughness parameters in the modified law of the wall*

For the turbulent wall-bounded flow, wall roughness effects are considered to be significant. The wall roughness effects can be conveniently accounted for through the law of the wall modified for roughness which is defined as follows;

$$\frac{u_p u^*}{\tau_w / \rho} = \frac{1}{\kappa}\ln\left(E\frac{\rho u^* y_p}{\mu}\right) - \Delta B \tag{10}$$

where E is constant (=9.793), $u^* = C_\mu^{\,1/4} k_p^{\,1/2}$ and ΔB is a function of the non-dimensional roughness high $K_s^{\,+}$, where K_s is the physical roughness height (m.)

In Fluent (Fluent Inc., 2005), the physical roughness height is defined as follows;

$$K_s \approx \frac{E}{C_{ks}} Z_0 = \frac{9.793}{C_{ks}} Z_0 \tag{11}$$

which yields K_s=20z_0 for C_{ks} =0.5 and K_s =30z_0 for C_{ks} =0.327, where z_0 is roughness length.

In this study, C_{ks} is set to 0.5 and the values of z_0 for all surfaces (excluding sea) were calculated from the observed wind speed profile. The corresponding K_s values for the surfaces are shown in Table 2.

TABLE II
ROUGHNESS HEIGHT, K_s (M) FOR THE SURFACES

	Surface				
	Sea [22]	Beach	Vegetated foredune	Lee	Deflation
K_s (m)	0.02	0.05	0.25	0.19	0.05

2) *Using additional source/sink terms*

Beside the use of the wall roughness parameters through the modified law of wall, plant drag can be taken into account by adding the additional source/sink terms, S_u , S_k and S_ε into Eqs. (2),(3) and (4). The commonly used momentum sink term [11, 13, 23] is parameterized by

$$S_u = -C_d A|U|u_i \tag{12}$$

where $|U| = (u_i u_i)^{1/2}$ is the absolute value of the spatially averaged wind speed, C_d is the drag coefficient = 0.2 (≈ 0.1-0.3 for most vegetation) [11] and A is the leaf area per unit volume of space or leaf area density (LAD) ($m^2 m^{-3}$), which can vary with height z (m).

The next term S_k is for representing the mechanism that the mean flow is broken into wake turbulence by the vegetation elements, therefore losing kinetic energy [10]. The commonly used source term S_k for plant drag flow simulation [11, 13] was proposed by Sanz [24] and is defined as follows;

$$S_k = S_p - S_d \tag{13}$$

with

$$S_p = \beta_p C_d A|U|^3 \tag{14}$$

$$S_d = \beta_d C_d A|U|k \tag{15}$$

where β_p is the fraction of mean flow kinetic energy being converted to wake-generated energy by canopy drag, and β_d is the magnitude of energy losses from interactions with obstacles [24]. For the standard k-ε model, the standard value of β_p and β_d are 1 and 4 respectively [13].

The last additional term for accounting for plant drag is S_ε. A number of formulations for S_ε have been proposed by researchers [10, 25, 26]. However, these S_ε terms are similar to the original formulation proposed by Green [10], but with a difference in magnitude of the model constants.

As model parameterization for the other k-ε models relation to wall functions has not been studied, this study then used the analytical model proposed by Green [10], and the formulation is as follows;

$$S_\varepsilon = C_d A(\alpha_p \beta_p \frac{\varepsilon}{k} U^3 - \alpha_d \beta_d \frac{\varepsilon}{k} U\varepsilon) \tag{16}$$

where α_p and α_d are the adjustable model constants. The analytical values are both 1.5. For the SST $k-\omega$ model the valued of α_p and α_d were modified to 3.2 and 0 respectively (see section *B*).

III. RESULTS

The mean wind speed is the main parameter of interest as it is proportionally related to the rate of sediment (sand) transport which plays an important role in coastal dune morphology. The predicted mean wind speeds were normalized by U_5, the wind speed at 5 m height at the same location. R_2 were employed to evaluate the correlation between the predicted data and the field data, and were calculated from two height scales; 0 – 1 m (near-surface) and 0 – 5 m (full scale field data). The prediction results obtained by using the roughness parameters in the modified law-of-wall, and the source/sink term models in the turbulence models were different especially at the vegetated foredune zone.

At the beach (S8), all simulation results agreed well with the experimental data. R_2 calculated from the normalised wind speed U/U_5 at 0 – 5 m height are close to 1. In the near-surface region, the prediction accuracy of the RNG model with the source/sink terms are slightly lower than those using the RNG with the roughness parameters and the $k-\omega$ model with the source/sink terms.

In the foredune region, all simulations returned their lowest accurate results. At the front of the foredune (S1), where the surface is the most complex and is covered by Marram grass, all simulations results were less accurate compared to the results obtained at the beach. Using the source/sink terms in the turbulence models significantly improved the prediction accuracy especially in the near wall region (see Fig. 7a and 8).

The results obtained at the back of the foredune (S2), where the surface is more plane than S1, confirmed the advantages of using the source/sink terms as the R_2 value are significantly higher than those using the roughness parameters (see Fig.7a). There is no difference in the prediction accuracies obtained by using the source/sink terms in different turbulent models. However, at higher lever, the RNG model with the source/sink terms returned the lowest accurate results at both S1 and S2 (see Fig. 7b).

There are two measurement stations behind the foredune; at lee (S7) and deflation plane (S4). At these positions, there is no significant difference amongst the results obtained from all simulations. The prediction accuracies are similar to those obtained at the beach where R_2 values are all over 0.95 for both the near-surface and higher level.

The prediction accuracy of the turbulence statistics on the dune can be assessed by using the parameter called fractional speed-up ratio which represent the increase in mean wind speed over the dune, and is defined by

$$S(x,y') = \frac{\Delta U}{U_0(y')} = \frac{U(x,y') - U_0(y')}{U_0(y')} \tag{17}$$

where $U(x,y')$ is the wind speed at height y' above the local surface, $U_0(y')$ is the wind speed at height y' above the reference flat surface in front of foredune.

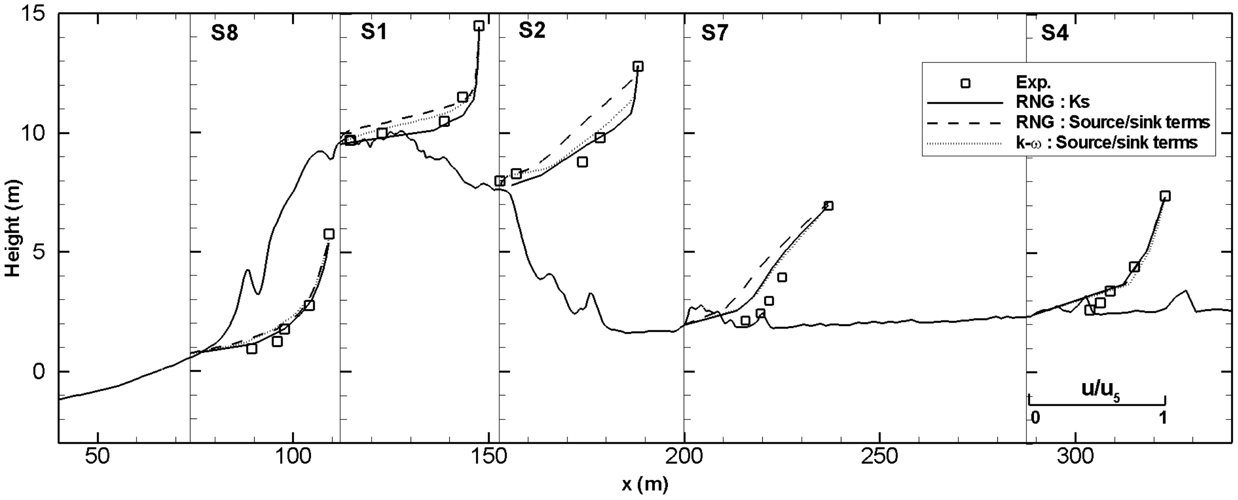
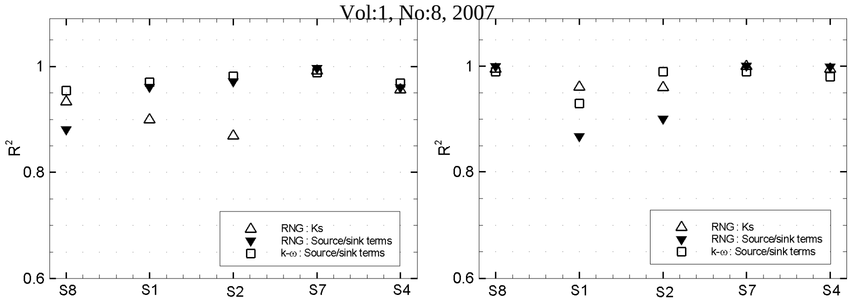


Fig. 6 Comparison of normalised U/U_5 wind speed at all measurement stations. U_5 is the wind speed at 5 m height at the same location.



(a)

(b)

Fig. 7 R^2 value of the mean velocity calcuated from (a) 0 to 1 m height , and (b) 1 to 5 m height

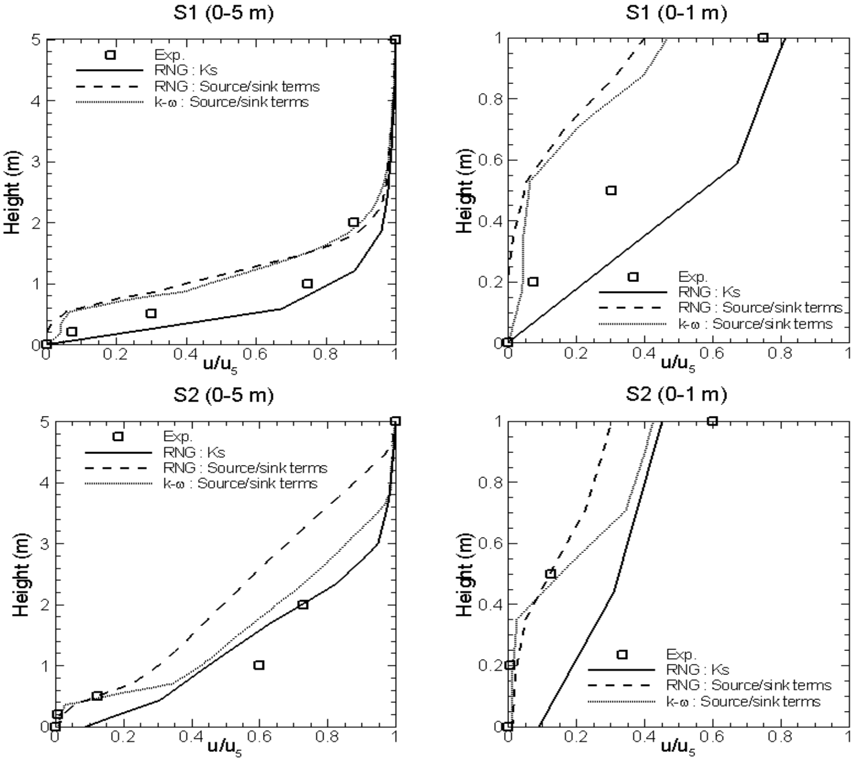


Fig. 8 Comparison of the mean wind speed at the foredune (S1and S2) at two height scales (0-5 m and 0 -1m). Solid lines, dashed lines and dotted lines denote the use of the RNG turbulence model with the roughness parameters, the RNG turbulence model with source/sink terms, and the *k-ω* turbulence model with the source/sink terms respectively. Square symbols denote the field data.

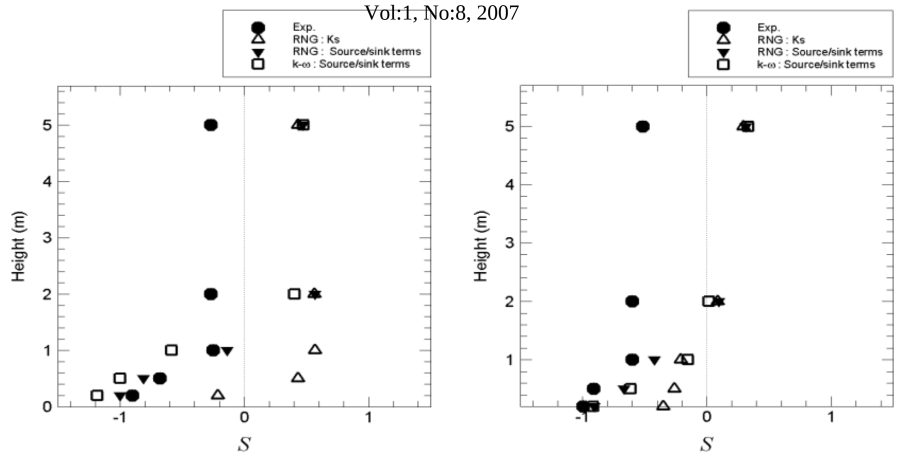
The fractional speed-up ratio at the positions S1 and S2 were compared to the wind speed at S8 (beach). In the near-surface region, the predicted speed-up ratio by using source/sink terms in the turbulence models agree well with the experimental data where the speed-up ratios are negative for both cases (see Fig. 9). Using roughness parameter returned less accurate results in this region (see Fig. 9a). At both S1 and S2, all predicted speeds up ratios at higher level are positive while the observed speed-up ratios are negative. There is no significant difference between the predicted results in this region.

In this study, different approaches in modelling surface roughness returned different results in the establishment of flow separations behind the foredune. In Fig. 10, the shaded areas represent the zone of the reverse-flow and approximately equals to half size of wakes.

Using roughness parameters produced a shorter overall reattachment length behind the foredune, compared to those using the source/sink terms. Moreover, it cannot capture the small wakes along the dune. On the other hands, these small wakes can be captured by using the source/sink terms in the turbulence models.

IV. DISCUSSION

In general, the roughness parameters in the modified law of wall can be employed in a large scale flow modeling to represent the effect of roughness. It performs well for the flow statistics at higher elevations above the surface. However, it cannot capture the flow statistics at the near-surface region. For the flow over a vegetated surface, as in this study, the source/sink terms can be used with a complex surface. It returned more accurate predictions in the near-surface region and returned similar results at higher



(a) (b)

Fig. 9 Fractional speed up ratio at (a) front of the foredune (S1), and (b) back of the foredune (S2)

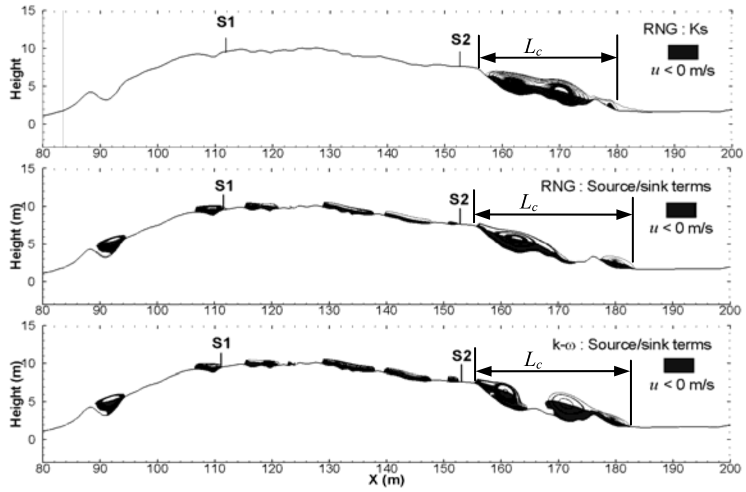


Fig. 10 Comparison of the simulation results showing the recirculation zone along and behind the foredune. Shaded areas are where the mean winspeed is lower than 0 m/s. L_c is the overall recirculation length behing the foredune.

elevations compared to those using the roughness parameters. Two major reasons limiting the use of the roughness parameters in this kind of problem are I) the near-wall meshing requirement, and II) an inability to characterize the characteristics of vegetation over the surface.

When roughness parameters is used in a modified law of the wall, a distance y_p (see Fig. 11) is required to be larger than the physical roughness height K_s of the surface ($y_p > K_s$) [27] . This limits the resolution of the near wall mesh especially when the value of K_s becomes greater. Using source/sink terms overcomes this problem as it represents the effect of surface roughness without the need of K_s ($K_s = 0$), thus allowing higher mesh solution (smaller y_p) in the viscous sublayer.

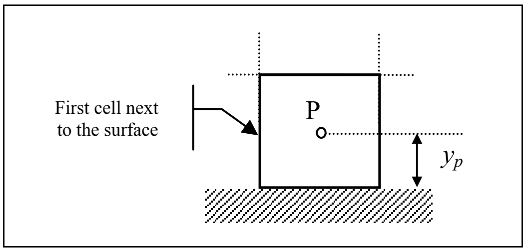


Fig. 11 Schematic of the first cell next to the surface

The roughness parameters can be used for the general wall-bounded flows where the physical roughness is not very high. The source/sink terms models are more appropriate when the surface roughness is a function of surface characteristics. For vegetated surface, the leaf area density (LAD) is an important vegetation parameter. This parameter can be included in the source/sink terms, resulting in more accurate predictions in the near-surface region.

An inability in predicting the wind speed-up ratio near the surface confirms the disadvantages of using the roughness parameters for this type of problem. In the surface layer, using the roughness parameters return a more positive speed-up ratio at the front of foredune (S1) compared with using the source/sink terms where the speed-up ratio is generally negative. This negative speed-up ratio agrees with the experimental data in this study. It is arguable that the positive wind speed-up ratios (by using the roughness parameters) at this location (S1) agree with the experimental results of others, e.g. Parsons et al.[28]. However those studies were carried out over a simple surface and without the presence of vegetation on the surface. Generally, the wind speed-up on a crest is lower for rough surface and higher for smoother surface. A study carried out by Neff and Meroney [29] in which the vegetation influence on wind

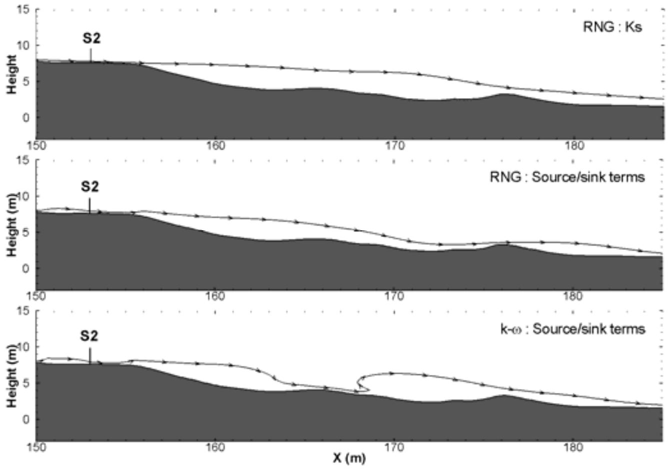


Fig. 12 Comparison of contour plots of the mean velocity just above the S2 surface

power availability showed that removal of vegetation leads to an increase in the speed-up ratio on the crest. This implies that the use of roughness parameters (which produces higher wind speed-up) cannot capture the details of the surface roughness especially for the vegetated surface and, therefore, produced smoother flow over a surface. In Fig. 12, the contour line of the mean velocity just above the S2 surface show that the flow in the surface layer predicted by using the roughness parameters are less affected by the surface roughness compared to those using the source/sink terms.

Establishment of wake in the lee side is another important flow feature in addition to the speed-up. The overall reattachment lengths predicted by using the roughness parameters are shorter than those using the source/sink terms. This result agrees with the wind tunnel study carried out by Cao et al. [30] showing that the reattachment length behind a simple hill is larger for the rough hill and becomes shorter for the smoother hill.

By employing the source/sink model to account for surface roughness, reasonable predictions of the mean velocity can be achieved. However, as the surface is complex, the results might vary from case to case. In addition, the prediction results cannot be entirely compared with many available experimental results where the simple surfaces are employed in the wind tunnel and without the presence of vegetation on the surface. This underlines the need for further studies in modeling flow over a complex surface, especially for the vegetated surface, in order to increase prediction accuracy of the predictions for this type of flow.

V. CONCLUSIONS

The RNG and the $k-\omega$ models with source/sink terms implementation returned more accurate predictions at the complex surface zone, especially in the near-surface region. There is no significant difference between the results obtained from all simulation at higher elevation. The wind speed-up ratios at the front of the foredune obtained by using the source/sink terms are negative and agree well with the experimental data, while it is more positive when using the roughness parameters. The reattachment lengths behind the foredune predicted by the roughness parameter are shorter than those using the source/sink terms. This result was compared to the wind tunnel experiment carried out by Cao et al. (2006) and implies that the details of the surface roughness are better captured by the use of the source/sink terms. It can be concluded that the roughness parameters can be used only when the flow statistics in the surface layer are not of interest, and the parameters for characterizing the surface roughness characteristic are not required.

NOTATIONS

A	leaf area index
C_d	drag coefficient
$C_\mu, C_{1\varepsilon}, C_{2\varepsilon}, \sigma_k, \sigma_\varepsilon$	adjustable turbulence model constants
g_i	gravity component
h	height of canopy
k	turbulent kinetic energy
k_p	turbulent kinetic energy at the center point of the wall-adjacent cell to the bottom surface
G_k	production of kinetic energy
G_ω	production of ω
$S_u, S_k, S_\varepsilon, S_\omega$	additional source/sink terms
u	spatially averaged wind speed in x-direction
u_i	Reynolds-averaged velocity components
u_p	velocity at the center point of the wall-adjacent cell to the bottom surface
u^*	Friction velocity
x_i, x	Cartesian coordinates
y_p	distance form the center point of the wall-adjacent cell to the bottom surface
Y_ω	dissipation of ω
z	vertical distance
z_0	roughness height

Greek symbols

$\alpha_p, \alpha_d, \beta_p, \beta_d$	additional source/sink terms coefficients
δ	gradient height
δ_{ij}	Kronecker delta: 1 if $i=j$, 0 if $i\neq j$

ε	turbulent kinetic energy dissipation rate
κ	Von Karman constant
ρ	fluid density
τ_w	wall shear stress
μ	dynamic viscosity
μ_τ	turbulent eddy viscosity

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