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Wind Speed Prediction in Complex Terrain Using a Commercial CFD Code.

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상용 CFD 프로그램을 이용한 복잡지형에서의 풍속 예측

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Abstract

Investigations on modeling methods of a CFD wind resource prediction program, WindSim for accurate predictions of wind speeds were performed with the field measurements. Meteorological Masts having heights of 40m and 50m were installed at two different sites in complex terrain. The wind speeds and direction were monitored from sensors installed on the masts and recorded for one year. Modeling parameters of WindSim input variables for accurate predictions of wind speeds were investigated by performing cross predictions of wind speeds at the masts using the measured data. Four parameters that most affect the wind speed prediction in WindSim including the size of a topographical map, cell sizes in x and y direction, height distribution factors, and the roughness lengths were studied to find out more suitable input parameters for better wind speed predictions. The parameters were then applied to WindSim to predict the wind speed of another location in complex terrain in Korea for validation. The predicted annual wind speeds were compared with the averaged measured data for one year from meteorological masts installed for this study, and the errors were within 6.9%. The results of the proposed practical study are believed to be very useful to give guidelines to wind engineers for more accurate prediction results and time-saving in predicting wind speed of complex terrain that will be used to predict annual energy production of a virtual wind farm in complex terrain.

Keywords : Parametric study, wind speed, complex terrain, WindSim, CFD

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1. Introduction

Recently, interests on renewable energy sources are getting higher due to high oil prices caused by the earth's environmental pollution and depletion of the fossil fuel [1-3].

Wind Energy is considered as one of the most efficient renewable energies, and lots of new wind farms are constructed every year all over the world.

For construction of wind farms, wind resources of the area of interest must be investigated, beforehand. Accurate analysis and prediction of wind resource especially in complex or mountainous terrain are important because it increases as the altitude gets higher [4-5]. Two popular commercial programs mainly used for wind resource analysis and prediction are WAsP (Wind Atlas Analysis and Application Program) and WindSim [6]. Because WAsP uses a linear topographic model known as BZ-model, it is known that it cannot consider flow separation phenomenon that often occurs on complex terrain. As the result, WAsP is not considered to be suitable for wind speed prediction in complex terrain [7-8]. Unlike WAsP, WindSim is a CFD program based on the Reynolds Averaged Navier-Stokes (RANS) Equation, and it obtains the steady state solution of a three dimensional computational domain of interest. Due to this reason, WindSim is considered more suitable to predict wind speeds in complex terrain than WAsP [9-13].

Although WindSim is considered suitable to predict wind speed in complex terrain, its validation study has been limited to several European countries, so far. Also, unlike the expectation, the predictions from WindSim in the literature were not always more accurate than those from WAsP depending on regions. One of the many sources of the inaccurate results from WindSim is considered due to an inaccurate WindSim modeling. However studies on the accurate modeling of WindSim input parameters are very rare.

Finding suitable design parameters of WindSim are important for a wind farm design and especially siting wind turbines at optimal locations for wind energy production. Also, due to the increasing trend of constructing wind farms in complex terrains, reliable and practical modeling methods to use CFD programs such as WindSim are necessary to be investigated.

About 70% or more of the Korean territory is known to be covered with mountains. However, based on the literature, studies on wind resource predictions using a CFD code in Korea are very limited [14].

Therefore, this study was performed to fulfill two goals. One was to establish a guidance to accurately employ the CFD code, WindSim to complex terrains in Korea to accurately predict wind speed. The other goal was to validate the WindSim modeling and predictions in complex terrain other than European regions. In order for these, two meteorological masts were installed in complex terrain in Korea, and the wind speed and direction for each mast were recorded with the interval of 10 minutes for a year. Then, various modeling parameters of WindSim input variables for accurate predictions of wind speeds were investigated by performing cross predictions of wind speeds at the masts using the measured data.

2. Modeling

2.1 Sites

As shown in Fig. 1, the two sites used for wind speed measurement and prediction in this study are located in complex terrain.

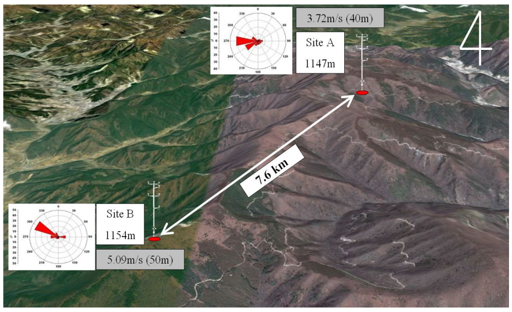


Fig. 1. Topography including sites A & B.

The altitude of site A, located slightly off the top of a mountain, is 1,147m. The site B in the figure is located on top of a mountain and its altitude is 1,154 m. A meteorological mast (MM) having a height of 40m was installed at site A. A 50m high MM was installed at site B. The distance between the two masts in sites A and B was about 7.6 km. Most of the terrain in Fig. 1 is covered with trees.

The RIX(Ruggedness IndeX) representing a degree of complexity of topography [15, 16] was calculated and found to be 20.63% and 32.23%, respectively, for A and B. A flat site has an RIX value of 0 %. An RIX value of 30% means that about one third of the terrain is steeper than the critical slope which is normally 0.3. Terrain having RIX values higher than 20 % is normally considered highly complex.

The annual averaged wind speed measured at the sites A and B were found to be 3.72m/s and 5.09 m/s, respectively

2.2 Measurement Data

The 10 minute averaged measurement data for one year is converted into the well known Weibull probability density function for simplicity. Compared to about 52,000 measurement data sets, Weibull probability density function requires only two parameters to describe the annual wind characteristics. As shown in Eq. (1), the two parameters in Weibull probability density function, A and k, are known as the scale factor and the shape factor, respectively.

$$f(V)=\frac{k}{A}\left(\frac{V}{A}\right)^{k-1}\exp\left[-\left(\frac{V}{A}\right)^{k}\right] \qquad (1)$$

where V is the wind speed, f is the frequency of occurrence of the wind speed, k is the shape factor, A is the scale factor, and exp is the exponential function. The scale and shape factors are related to the wind speed, and its distribution shape, respectively. In WindSim, wind direction is sectored by a 30 degree interval and the parameters A and k to best describe the measurement wind speed and frequency of occurrence are calculated for each sector. As long as the parameters are found, the wind speed average is estimated using

$$\overline{V}=A\Gamma\left(1+\frac{1}{k}\right) \qquad (2)$$

where $\overline{V}$ is the averaged wind speed and Γ is the gamma function known as

$$\Gamma(x)=\int_{0}^{\infty}e^{-t}t^{x-1}dt \qquad (3)$$

Table 1 shows the Weibull representation of the measured data at each site. When converting the measurement data to the Weibull probability density function, conversion errors of 2.15% and 0.39 % occurred for sites A and B, respectively. These errors were considered small for this study.

Table 1. Measurement data and Weibull fitted parameters.

Site	Weibull Data			$\overline{V}_{measured}$ [m/s]
	A[m/s]	k	$\overline{V}$ [m/s]	
A	4.23	1.57	3.77	3.72
B	5.77	1.98	5.14	5.09

2.3 WindSim modeling

WindSim is a CFD program developed solely for application to the field of wind energy using the well known Phoenics code [17]. WindSim models the atmosphere above the ground as a three dimensional mesh system and apply the, time-averaged, RANS equation to each cell in the mesh system to obtain a three dimensional wind flow solution. The standard k-epsilon turbulence model is normally used. Unlike a time step approach to solve flow fields, WindSim starts from initial boundary conditions specified by users and obtain a time averaged steady-state solution.

The three dimensional (3D) calculation domain of WindSim is limited by the map boundaries in the horizontal x and y directions, and by the ground at the bottom and the upper boundary height at the top in the vertical z direction.

The atmospheric boundary layer where the wind speed varies with the altitude was assumed to be 500m, which is known in literature to be the most used by scientists to describe the height of geostrophic wind [18]. Above the atmospheric boundary layer, the wind speed was fixed to be a constant value, 10m/s. The effect of a constant speed of the atmospheric boundary layer on the speed prediction is known to be small [18]. Above the atmospheric boundary layer there exists an upper layer. The upper boundary height is automatically determined by WindSim depending on sites and high enough to avoid a blocking effect on the wind flow [19] in any locations of the map. Normally, it is the order of several kilometers.

Along the x and y boundary of the 3D calculation domain below the atmospheric boundary layer, a log profile of wind speed is applied as a boundary condition in WindSim. This is known to be equivalent to the fact that infinite plain terrain is connected to the x and y boundaries [19].

The solution procedure from WindSim consists of two parts. In the first part, it calculates the wind velocities at each sector and grid point using the provided boundary conditions such as the wind speed above the boundary layer height and the log profile of velocity without knowing the measured wind data. After finishing the wind field calculation, WindSim knows the velocity vector in any grid point relative to the other grid points. In the second phase, WindSim uses the measured wind data which is the sectorwise wind speed and the frequency of occurrence to obtain the wind velocity relative to the measurement point for the whole map.

3. Parametric Study

A total of four input parameters that

affect the wind speed prediction of WindSim were selected and used for the parametric study. As mentioned in the previous section, two sites located in complex terrain in Korea were selected and meteorological masts were installed to obtain data including wind speed and direction for one year. WindSim was used to predict the wind speed of one site using the data measured at the other, vice versa. When predicting wind velocities, only one input parameter out of four was varied and all the others were fixed to be constants

3.1 Map Size

In wind resource prediction programs, a map size means the size of the solution area, and it determines the size of the terrain information included when the prediction of wind resource around a certain position of interest is made. If the prediction position is located too close to the map boundary, the surrounding terrain information cannot be included when the solution to the governing equation is made for the position. Therefore relatively large prediction error is expected. On the other hand, if the map size is too large, the time required for modeling and analysis increases dramatically. Also due to the limited computer resources and the limited number of cell elements that the program can handle, the cell size must get larger as the map size gets larger. This often causes high prediction errors. Therefore, the relationship between the prediction errors and the map size is very important. However, research on this matter is very limited and cannot be found in the literature.

For the parametric study of the map size, as shown in Fig. 2, the distance between the two sites and the map boundary was set to L. Then, L was varied from 1km to 5km and the wind speed of A and B were predicted. When predicting the speed of A, the measured data at B was used, and vice versa.

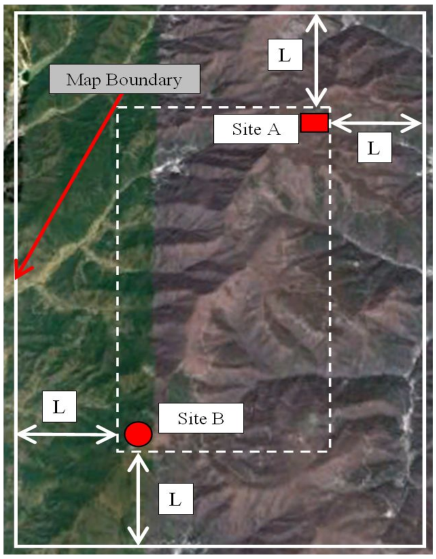


Fig. 2. Variation of topographical map size

The cell size in x and y direction was fixed to be 50 m. The number of cells in z direction was chosen to be 30. For the z-cell size, it is related to the number of cells in z direction and height distribution factor. The height distribution factor is defined as the ratio of the cell size at the ground to that at the upper boundary. The height distribution factor (HDF) was chosen to be 0.01. As the HDF decreases, the cells in z direction get closer to the ground.

As shown in Table 2 and Fig. 3, as the map size changes, the wind speed prediction also changes. When the distance between the prediction site and the x and y boundaries of the map was between 1km and 3km, the change rates of the prediction were large. As the map size further increased, the rate decreased, and became less than 0.8% when the map size reached 5 km.

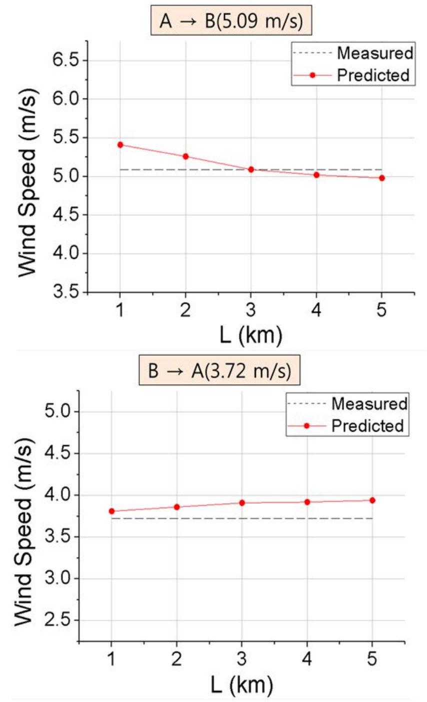


Fig. 3. Change Rate of Wind speed predictions for different map sizes.

Table 2. Predicted wind speed with change of map sizes. Dimensions in m/s.

	Map Size [km]				
	1	2	3	4	5
A→B[m/s]	5.41	5.26	5.09	5.02	4.98
B→A[m/s]	3.81	3.86	3.91	3.92	3.94
Cell No.[x10^3]	59.5	98.9	147.8	206.4	274.5
Cal. time[hour]	6.0	9.5	14	22	28.5

This is due to be the fact that the log profile of wind shear (horizontal wind speed over height) used as a boundary condition by the WindSim program causes errors in predicting wind speeds of locations near the x and y boundaries. A logarithmic profile of wind shear is known to occur at flat terrains, therefore applying that profile as a boundary condition to the boundaries of the map implies that the given topography in the map is surrounded by flat terrains. This is, however, different from the actual topography. If the map size is small, the prediction site is not far enough from the artificial flat terrain created by the boundary condition and the logarithmic profile at the boundary will affect the actual profile on complex terrain. If the map size is large enough, however, although the topography of the map is surrounded by flat terrains, the effect of the flat terrain on the wind shear will disappear for regions that are far enough away from the map boundaries.

As the map size increases, the sites A & B gets further and further away from the boundaries, and the effect of the log profile boundary condition on the wind speed prediction gets smaller and smaller. Therefore if the change in prediction errors are considered, the distance between the prediction site and the map boundary should be at least 5 km or larger.

However, as the map size increased, the number of cells used in the simulation increased, and finally the calculation time considerably increased, too. Therefore, it should be careful not to have the map size too big for an efficient calculation.

3.2 Cell Size

A parametric study of the cell size was performed. The map size was set to be 5km based on the findings in the previous section. The cell size was varied regularly with an interval of 25m from 100m to 50m. As the cell size decreased, the number of cells increased. Due to the limited cell numbers that WindSim can handle, a cell size of 25m wasn't be possible. In order to make the cell size slightly smaller than 50m, a “refinement” option in WindSim was used. The smallest cell size achieved was 30.5 m. If the refinement area is selected in the map, a smaller constant cell size is applied inside the area and the cell sizes gradually get larger as they get further away from the area. The refinement area was set to be 1km away from both the measurement mast and the prediction position as shown in Fig. 4.

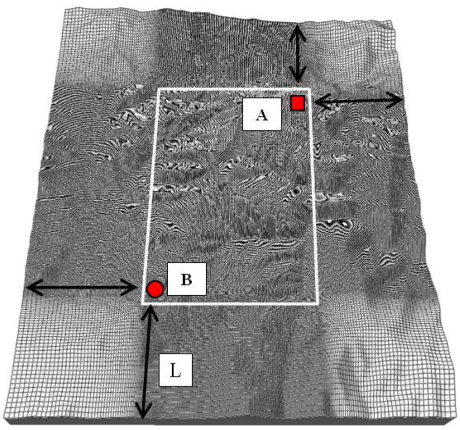


Fig. 4. Topographical map for parametric study of cell size.

As shown in Table 3 and Fig. 5, the result shows that as the cell size decreases, the wind speed prediction from WindSim approaches the measured value. Also when the cell sizes changed from 30.5m to 100.0m, the change in wind speed prediction was within 2.36 %. Although the change rate of prediction looks somewhat large, a smaller cell size couldn't be achieved due to the large size of the map.

Table 3. Predicted wind speed with change in cell size.

	Cell Size			
	30.5	50.0	75.0	100.0
A=>B [5.09m/s]	5.09	4.97	4.9	4.8
Change Rate from 5.09 m/s [%]	-	2.36	3.73	5.70
B=>A [3.72m/s]	3.88	3.95	3.99	4.06
Change Rate from 3.88 m/s [%]	-	1.80	2.84	4.64
Cell Number [x10,000]	27.6	27.5	12.1	6.9
Cal. Time [hour]	30	21	8	4.3

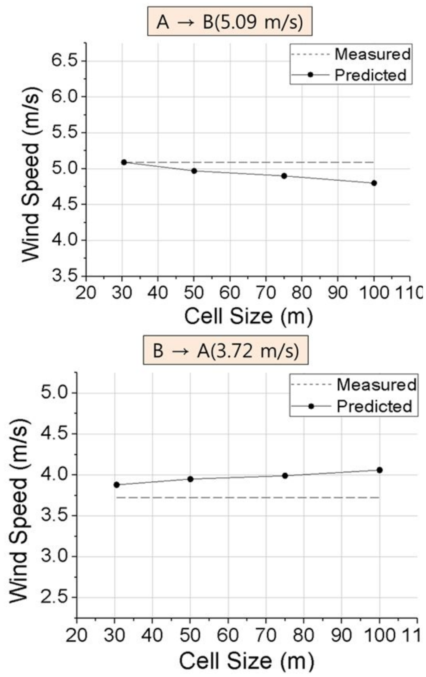


Fig. 5. Predicted wind speed for different cell sizes in x and y direction.

The reason why the wind speed prediction from the program is affected by the cell size is that the cell size is considered as the resolution of the terrain model which depicts the actual terrain. As shown in Fig.6, if the cell size is large, the resolution of the terrain model becomes low. For flat terrains, the low resolution of the terrain doesn't play much role on the wind speed prediction because the actual terrain can be accurately depicted by the low resolution terrain model.

However for complex terrain, the low resolution of the terrain model will actually change the topography of the terrain from the actual topography of the terrain, and as a result, the mountains might become substantially lower.

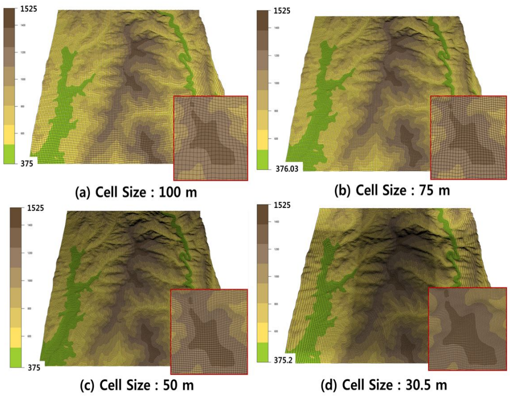


Fig. 6. Terrain according to cell size

This, in the end, affects the prediction of the terrain.

The topography of the terrain model never becomes exactly the same as that of the actual terrain because the cell size is finite. However, as the discrepancy due to the finite resolution decreases, the wind prediction errors associated with it will decreases and in the end will be within a certain error limit.

3.3 Z-cell Numbers and HDF

Both cell numbers in z direction and height distribution factors are related to the cell size (resolution of the solution) in z direction. The upper boundary of the three dimensional solution domain is automatically determined by WindSim high enough to avoid a blocking effect on the wind flow. In complex terrain, the upper boundaries often reach several kilometers. As mentioned before, the height distribution factor (HDF) is defined as the ratio of the cell size at the ground to that at the upper boundary. The ratio of the height/width/length between the first and last cell according to HDF is defined as [19]

$$\triangle h^{*} = \frac{L}{\frac{nc(n-1)}{1-c} + \sum_{i=1}^{n-1} i} \tag{4}$$

and

$$\triangle h_1^{*} = \frac{\triangle h^{*} c(n-1)}{1-c} \tag{5}$$

In Equations (4) and (5), L is the distance over which the distribution is applied, n is the number of elements (cells) within L, c is the height distribution factor and equals to h_1^*,h_n^*,,h_1^*,is the size of the first element (height / width / length of firstcell), and h_n^* - The size of the last element(height/width/length of last cell)

As the HDF decreases, the cells in z direction get closer to the ground. Therefore, it determines the cell sizes in z direction in conjunction with the z cell numbers.

For wind energy applications, the solution especially lower than 500 meters are important, because the maximum height from the ground to the tip of the rotor blade of modern multi-megawatt wind turbines is less than 300 meters. Moreover, for this study, the measurement heights of the wind speeds and direction from meteorological masts are 40 and 50 meters, therefore it is important to find out a suitable z cell resolution relatively close to the ground.

For the simulation, the cell number in z direction was fixed to be 30 and the HDF was varied. The map size was 5km, and the cell size in x and y direction was 30.5 m with refinement option, like before. Table 4 shows the first five cell heights from the ground in z direction for three different HDF values. For each HDF value, Min and Max means the locations where the distance between the altitude of the ground and the upper boundary are minimum and maximum, respectively. For other locations, the cell heights in z direction are between the values of Min and Max.

Table 4. Cell height in z direction with various HDF (Height Distribution Factor).

		Distance [m]				
		1	2	3	4	5
1.0	Min	69.8	209.5	349.2	488.8	628.5
	Max	89.0	267.0	445.0	623.0	801.0
0.5	Min	46.6	141.3	239.2	340.3	444.7
	Max	59.3	180.0	304.8	433.7	566.7
0.01	Min	1.4	8.9	25.8	52.2	88.0
	Max	1.8	11.3	32.9	66.5	112.1

The result is shown in Table 5 and Fig 7. As can be seen in the table, the variations were small but when the HDF was 0.01, the wind speed prediction from WindSim was the closest to the measured value. As the lowest cell height decreases from 69.8m~89.0m to 1.4m~1.8m, the prediction errors decreased. Also when the HDF reached 0.1, the lowest cell height became lower than the prediction height, and the changes in prediction values for the cases of 0.1 and 0.01 in HDF were very small.

Table 5. Predicted wind speed with change in height distribution factor.

	Height Dist. Factor			
	0.01	0.1	0.5	1.0
A=>B (5.09m/s)	5.09	5.06	4.95	4.75
B=>A (3.72m/s)	3.88	3.88	3.99	4.11
Cell No.	2,764,000			
Cal. Time (hour)	30			

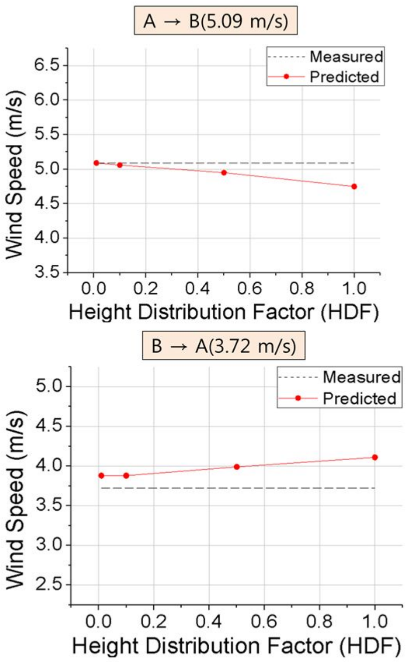


Fig. 7. Predicted wind speed for different cell sizes in z direction.

For the z-cell size, This is considered due to be the fact that as long as the wind flow solutions are obtained at the lower and upper cells compared with the measurement or prediction height, the solution at the height of interest is obtained similarly by interpolation regardless of the number of cells lower than the measurement or prediction height. Therefore, when the prediction or measurement heights are low, it is very important to adjust the cell number in z direction and the height distribution factor to make sure that the first cell height in z direction is lower than the prediction or measurement height.

3.4 Roughness Length

The roughness length represents a friction from the ground surface which affects the wind velocity, and it varies with different state of the terrain. Generally water surface has the smallest roughness length and the center of a large city surrounded by tall buildings has the biggest roughness. For this study, all the analyses are made for complex terrain as shown previously in Fig. 1.

The roughness lengths recommended in literature for complex terrain are slightly different as shown in Table 6. The reason why different roughness lengths exist for complex terrain is that the roughness length of complex terrain depends on the heights, leaves and density of trees.

Table 6. Roughness length variation for forests.

Literature	Rough. L. [m]
Dev. Wind Pow. Proj. [20]	0.3 - 0.5
WAsP[6]	0.4
Int. Wind E. Eng. [21]	0.5

The roughness also depends on the climate of the complex terrain. In other words, the roughness length is the largest in the Summer. To find a suitable annually-averaged roughness length on forest, the parametric study of roughness length was performed. The roughness length was varied regularly with the interval 0.1m from 0.3 to 0.5.

The result is shown in Table 7 and Fig 8. When the prediction of wind speed was performed from site A to site B, the best result was obtained with the roughness length of 0.4m. However, for the prediction from site B to site A, the best result was obtained with the roughness length of 0.5m but the prediction was very close to that with the roughness length of 0.4m.

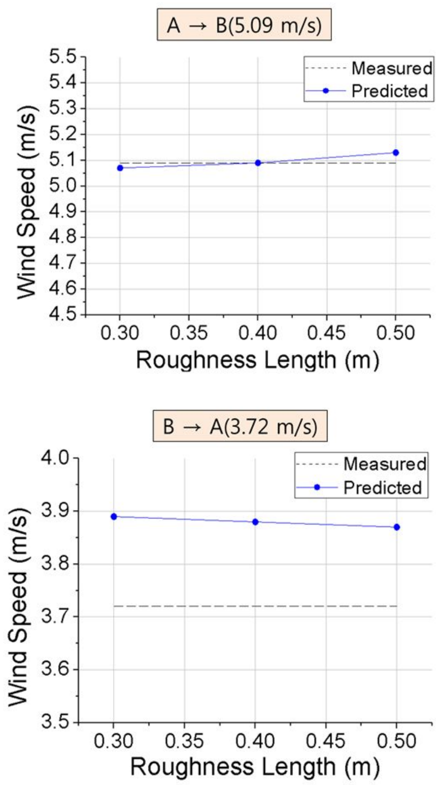


Fig. 8. Predicted wind speed for different roughness length

Table 7. Predicted wind speed with change in roughness length

	Roughness Length(m)		
	0.3	0.4	0.5
A=>B (5.09m/s)	5.07	5.09	5.13
B=>A (3.72m/s)	3.89	3.88	3.87

3.5 Suitable Parameter Selection

The selected parameters for a better WindSim prediction, obtained from the parametric study are presented in Table 8.

Table 8. Selected parameters

Parameter	Value
1. Map Size	5km
2. x, y Cell Size	30.5/34m
3. z Cell Numbers	30
4. Height Dist. Factor	0.01
5. Roughness Length	0.4 m

They were used for wind speed predictions and the results are shown in Table 9.

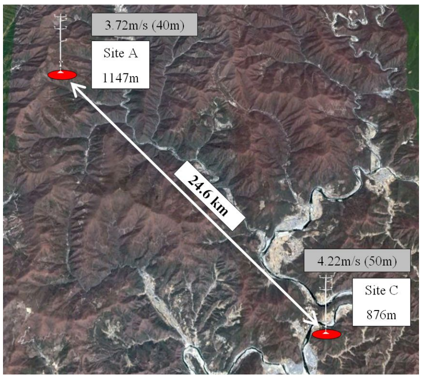
Table 9. Results with optimized parameters

	Measured	Predicted	Error(%)
A=>B	5.09	5.13	0.78
B=>A	3.72	3.87	4.0
Cell No.	2,764,000		
Cal. Time (hour)	Modeling	Simulation	Total
	24	31.3	55.3

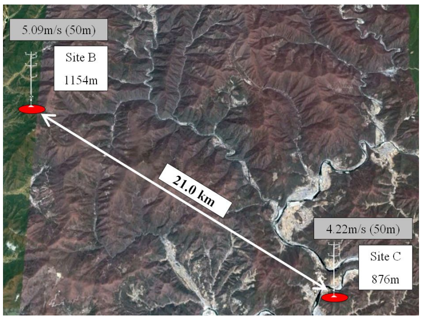
As shown in the table, the prediction error was 0.78% when site B was predicted using the data measured at site A, and it became 4.0% when site A was predicted using the data measured at site B. Considering that sites A and B are located in complex terrain, the results are found to be excellent. For the calculation time, it took about three days to complete the WindSim simulation with a computer having a quad core processor, 16 Giga bytes of memory and a 64-bit operating system.

4. VALIDATION

For a validation of the result, a meteorological mast having a height of 50 m was installed at a location named site C with an altitude of 876m in complex terrain in Korea and the parameters obtained from the parametric study were used. The RIX value of site C was 37.80 %, which means the terrain is highly complex. The predictions of wind speed were made for C from both A and B. The first case included sites A and C and was named location I. The second case included sites B and C and was named location II. Descriptions of the two locations are presented in Fig. 9. The measured annual wind speed for site C was 4.22 m/s. For the two locations, the two sites where meteorological masts are installed are separated by 21km and 24.6 km, respectively.



(a) Location I



(b) Location II

Fig. 9. Topography of application locations.

For the two locations I and II, the map sizes are larger than that used for the parametric study because the distance between the two measurement sites are 21.0km and 24.6km, respectively, and therefore the cell size had to be larger. In WindSim, the cell size cannot be specified by the user but rather determined by the map size and the maximum allowable cell numbers. Therefore it couldn't be possible to set the cell size exactly the same for all different locations. The cell size was selected to be close to 75m for comparison. Table 10 shows the parameters used for the simulation.

Table 10. Input Parameters for parametric study and validation

	Study	Location I	Location II
Map Size(X*Ykm)	14x17	24x22	20x28
x, y Cell Size	30.5x34.0	74.0x84.0	78.0x77.0
z Cell Numbers	30	30	30
HDF	0.01	0.01	0.01

As shown in Tables 11 and 12, for the two cases, the prediction errors were within 6.9 %. The prediction results are considered excellent because the measurement and prediction sites are about 25 km away and located both in complex terrain.

Table 11. Prediction results for Location I

	Measured (m/s)	Predicted (m/s)	Error (%)
A=>C	4.22	4.02	4.7
Cell No. ($x10^3$)	195.7		
Calculation Time (h)	Modeling	Simulation	Total
	24	18.7	42.7

Table 12. Prediction results for location II

	Measured (m/s)	Predicted (m/s)	Error (%)
B=>C	4.22	3.99	6.9
Cell No. ($x10^3$)	185.1		
Calculation Time (h)	Modeling	Simulation	Total
	24	14.1	38.1

Figure 10 shows the contour maps obtained using the data from Site A and Site B. As shown in the figure, the two results are consistent and very close.

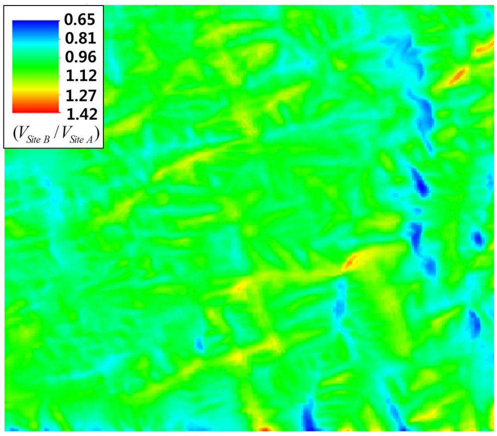


Fig. 10. Wind Resource map (Velocity contour)

Table 13 shows the comparisons of the wind speed predictions from WindSim and a linear code commonly used to wind speed prediction for a wind farm construction [22].

Table 13. Comparison of the prediction results with those from a linear code

	Error(%)	
	WindSim Location I	Linear Code
A=>B	0.78	4.52
B=>A	4.0	15.32
A=>C	4.7	11.85
B=>C	6.9	7.58

The same map size and roughness length with a higher resolution were used. As can be seen from the table, the predictions from the CFD code were consistently better than those from the linear code.

Therefore, this validates that the results from the parametric study are useful enough to be used for WindSim modeling to predict wind speeds in complex terrain in Korea. Also, it shows that the results from WindSim are accurate in predicting wind speeds in complex terrain in Korea.

5. CONCLUSION

Investigations on finding suitable design parameters of WindSim and its validation for wind speed prediction in complex terrain of Korea were performed. Meteorological masts were installed to measure wind speed and direction for one year at various locations, and the data measured were implied for the parametric study. Four different input parameters selected were studied to find out the optimal design values for wind speed predictions. The results of the parametric study are as follows:

(1) For the map size, the distance from the map boundary and the prediction site was found to be at least larger than 5 kilometers. This is due to be the fact that the log wind profile boundary condition used in WindSim produces errors in predicting wind speeds near the map boundary.

(2) For the horizontal cell size, it was found that for the cell size less than about 70m, the change in wind speed prediction was small (less than 4 %) although the cell size was changed from 75m to 30.5m. The wind speed prediction converged when the cell size became about 36m. However, when the cell size changed from 75m to 30.5m, the calculation time increased more than three times.

(3) For the z cell number and the HDF, it was found that at least the first cell height from the ground determined by the two factors should be lower than the measurement or prediction height for accurate prediction of wind speed. As long as the first cell height from the ground is lower than the measurement height and the prediction height, the prediction results were almost the same although the second or the third cell height is higher than the measurement or prediction height.

(4) For the roughness length, values of 0.3m to 0.5m were considered based on the literature and a value of 0.4m was found to be the best for the complex terrain in Korea.

For validation of the parametric study results, the parameters obtained from the study were applied to predict the wind speed of another site in complex terrain, and the results were compared with the measured data. For all the cases, the WindSim prediction errors for wind speed were less than 6.9 %. Also these prediction errors were found to be much smaller than those from the linear code commonly used to predict the wind speed for a wind farm construction. The results of the proposed practical study are believed to be very useful to wind engineers for more accurate prediction results and time-saving in predicting wind speed of complex terrain that will be used to predict annual energy production of a virtual wind farm in complex terrain. However, in this study only one site in Korean complex terrain were considered for validation. Therefore, more validations to more sites in complex terrain are necessary to prove the findings in this study.

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