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Pioneering CFD Software for Education & Industry

PHOENICS Validation Example

Wind Energy Simulation

Introduction

The limitations of the European Wind Atlas methods for calculating wind conditions in complex terrain are well known. The requirement for the application and validation of CFD models is growing. Meso-scale models are applied to describe the state of the atmosphere, but micro-scale flow models are needed to resolve the small-scale variations of wind speed and turbulence within a wind farm in complex terrain.

The following describes the application of PHOENICS for Wind-farm Micrositing purposes by the German Wind Energy Institute, DEWI:

- The relevant flow phenomena determined by comprehensive measurement campaigns in flat and complex terrain, is given for two typical problems.
- Verification of the CFD model results against measurement data show that complicated flow patterns can be simulated.
- CFD simulation provides a comprehensive solution for the flow field and hence sets a new standard for the description of site conditions; especially concerning parameters relevant for the loads on the wind turbines in complex terrain, like turbulence, wind speed gradients and flow inclination.
- The potential advantages of using CFD methods are clear.

Flow Models Applied in Wind Energy

Despite their known limitations European Wind Atlas methods are seen as 'the standard' for wind energy purposes. The limited flow model capabilities consist of a set of simplified descriptions of wind flow in the atmospheric boundary layer, based on semi-empirical correction models. Another class of models, the so-called mass-consistent models, apply only to a subset of the physical flow equations, which are solved numerically. The result is that such mass-consistent models have limitations similar to the European Wind Atlas method.

A more realistic flow simulation, based on the numerical solution of a more complete set of flow equations, is achieved with dynamic wind flow models. Such models can be divided into meso-scale atmospheric models and micro-scale CFD models.

Meso-scale atmospheric models, usually based on weather prediction research or atmospheric dispersion simulation, provide a complete set of atmospheric phenomena, like radiation or clouds.

A limitation of the meso-scale atmospheric models is that the finest resolution is typically in the order of 1×1 km^2 - too coarse to resolve small-scale variations.

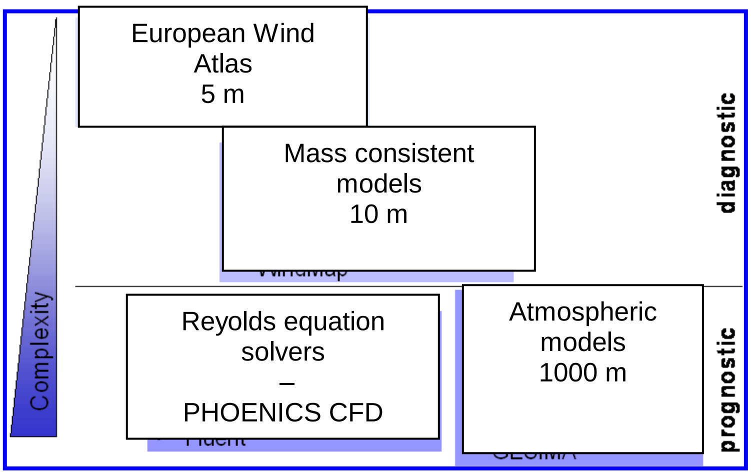

Figure 1: Overview of flow models applied for wind energy purposes.

Flexible general-purpose CFD packages, like PHOENICS, can be adjusted to the specific application requirements (e.g. wind modelling in the boundary layer). In the case of PHOENICS, such application-specific adjustments can be facilitated through the "INFORM" feature that allows flexible adjustments without the need for low-level solver modifications.

CFD models comprise a higher order turbulence model, are flexible regarding the calculation grid used, work efficiently, and are validated for many application cases. The horizontal resolution, for wind energy purposes, is in the order of 20m and is thus capable of resolving small-scale height structures. The generation of turbulence by the topography and its transport can be simulated using the standard k-ε turbulence model.

Wind Profile Verifications

The following investigations were conducted by DEWI on the basis of a micro-scale model using PHOENICS, adjusted specifically to the atmospheric boundary layer environment. PHOENICS was validated against measured data obtained from a 130m mast near to DEWI’s test site on the coast of the North Sea. Its high quality, long term data provide a reliable wind profile measurement of the wind speed at heights of 11m, 32m, 62m, 92m and 126m, with additional meteorological measurements to determine the temperature stratification. The wind profile measurement was compared to the calculation for different scenarios on the basis of, firstly, the logarithmic wind profile, and then, CFD simulation.

Figure 2 shows a wind direction sector with low and uniform roughness length, neutral temperature stratification and wind direction coming from inland. The wind profile calculated by PHOENICS compares well with the profile for all measured heights. The extrapolation of the wind speed value, measured from 11m up to the highest anemometer at 126m, was achieved with an error <1%. One should not assume that such a small error margin can be achieved for all cases; however, the close match of the CFD results to these measurements is clear, and also true for other situations and directions.

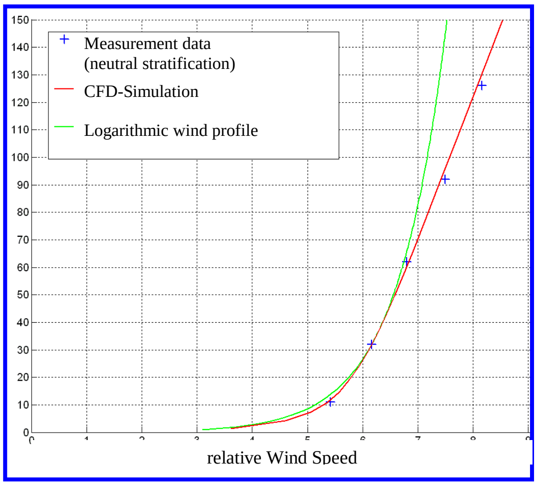

Figure 2: Wind profile as calculated with the logarithmic wind profile and the CFD methods, relative to the 32m measurement value.

The logarithmic wind profile systematically under-predicted the wind speed at the upper height levels, whereas CFD did not. This effect is observed for neutral stratification cases, although such an effect is often associated with stratification influence. So the effect seems to be one of pure turbulence, which can be accurately simulated using an appropriate turbulence model.

Hyperlink to PART 1: Flow Simulations at Oberzeiring Site (shown in doc below)
Hyperlink to PART 2: Site Assessment in Complex Terrain (shown in doc below)

Conclusion and Outlook

The results give an insight to the potential of flow modelling using CFD, but it should also be emphasised that the modelling of complex flow patterns requires effort. On the other hand, the uncertainties of energy yield prognoses based on the European Wind Atlas Methods are obvious. Such uncertainties increase in proportion to the complexity of the sites. Also, current hub heights often exceed the scope of validity of the underlying surface layer similarity theory.

At the same time the demand for accuracy increases, with a requirement for a more complete view of the flow - including turbulence and further load-relevant properties. Hence, there is a strong need for accurate CFD analyses, for which the capabilities of PHOENICS to calculate the wind flow conditions have been demonstrated.

Reference

M. Strack, V. Riedel: State of the Art in Application of Flow Models for Micrositing. Proceedings of German Wind Energy Conference DEWEK 2004, Wilhelmshaven, 2004.

PART 1: Flow Simulations at Oberzeiring Site

SODAR (SOnic Detection And Ranging) measurement data and wind farm energy yield data from the wind farm Oberzeiring was evaluated to verify the complex-terrain flow-modelling capabilities, and to show the complexity of the flow phenomenon itself.

Figure 3: Photo of the Oberzeiring wind farm.

The Oberzeiring wind farm (Figure 3), located in Austria, is the highest wind farm in Europe and has been operational since end-2002.

The site is very complex with steep, long slopes, large height differences and special orographic structures, which have a considerable effect on the wind flow.

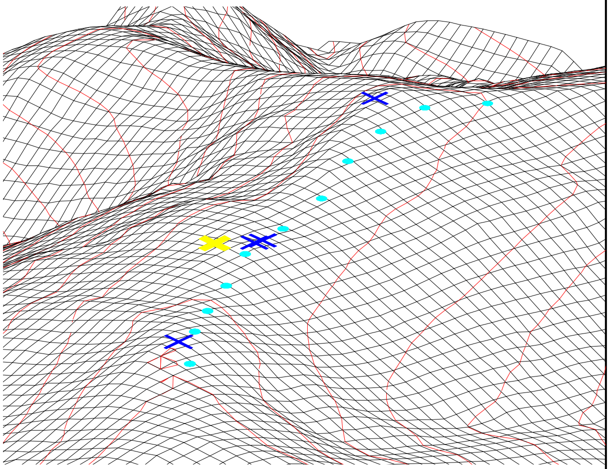

Figure 4: Overview of the orography of the Oberzeiring site. Each red contour line = 100m height difference.
Legend: • wind turbine positions,
+ SODAR measurement positions,
+ measurement mast positions.

Figure 4 shows a small section from the digital terrain data. A comprehensive measurement campaign was performed to measure the wind conditions. Wind measurements at four locations were performed. The mean wind conditions were calculated using PHOENICS and compared to the wind speed measured at the 65 m mast.

In Figure 5 this variation is shown as colour map, in the left-hand map for a wind direction of 327°, and 331° for the right-hand map. A wind direction change of 4° leads to a 3% change in the relative wind speed.

This sensitivity to the wind direction is extreme and was not expected. The effect was also observed when evaluating the energy yield data from the wind farm.

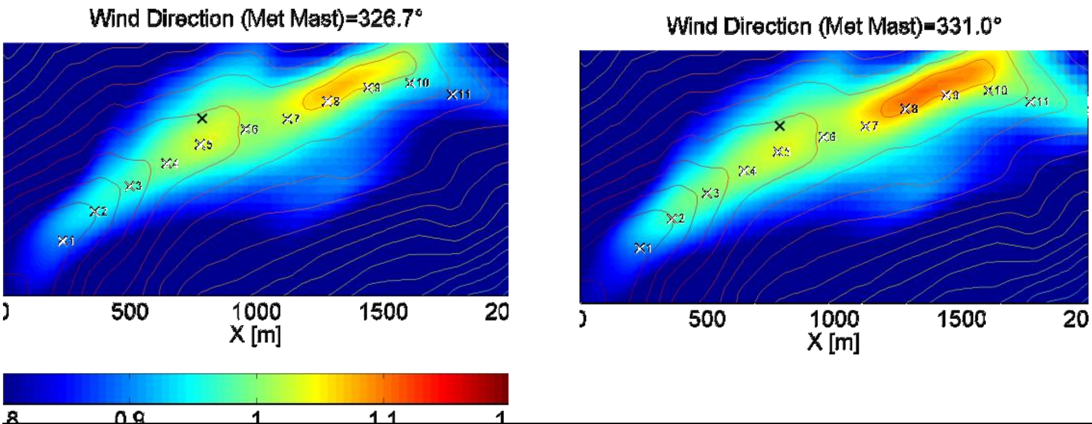

Fig 5: Spatial variation of mean wind speed on the site and its variation with wind direction changes.

Systematic evaluation of the flow fields for slightly-changing wind directions indicates that strong sensitivity is caused by the orographic speed-up effects, and that flow separation occurs at the northern slope where the flow behaves differently when passing a particular height structure westwards, than when passing eastwards. The effect shows that simulation of the flow conditions for this wind farm has to be performed with high resolution if the result is to be realistic. A simulation with fixed wind direction sectors would not make sense at the Oberzeiring site.

Figure 6 shows the variation of the energy yield at the wind farm, as observed, as calculated by a Wind Atlas Method, and as calculated by PHOENICS. The variation is large, but much better using CFD. The average deviation of the CFD results is 2.3%, whereas the Wind Atlas average deviates by 9.1%. The PHOENICS results correspond well, whereas the Wind Atlas model cannot precisely extrapolate the wind conditions measured at hub height for the different wind turbines.

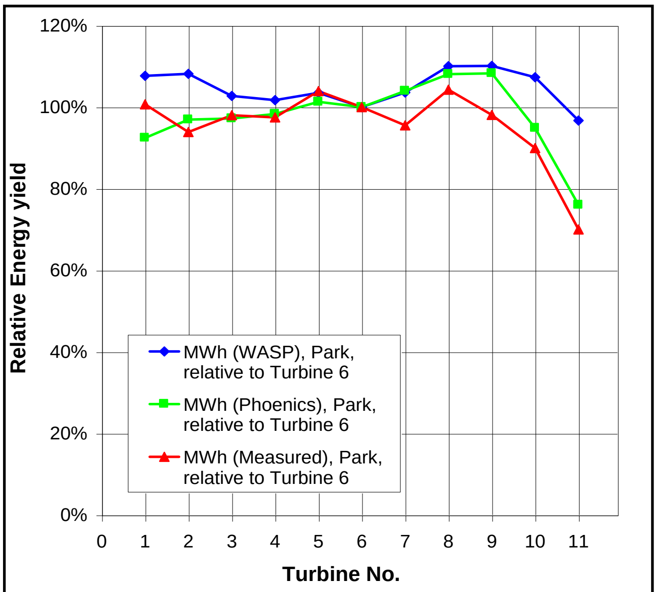

Figure 6: Comparison of the energy yield variation at the wind farm, as measured, as calculated by Wind Atlas method and as calculated by CFD.

The data from SODAR measurement were evaluated as well as the measurement mast data. Figures 7 & 8 (below) show the SODAR profile compared to the CFD results for the respective wind direction sector for a selection of situations.

The variation of the calculated wind profiles is large; sometimes a clear negative profile is calculated, sometimes a positive gradient. The SODAR measurement produces very similar behaviour, except for the lowest wind speed measurement (that may have been disturbed). The results show good correspondence between the PHOENICS simulation and measurement.

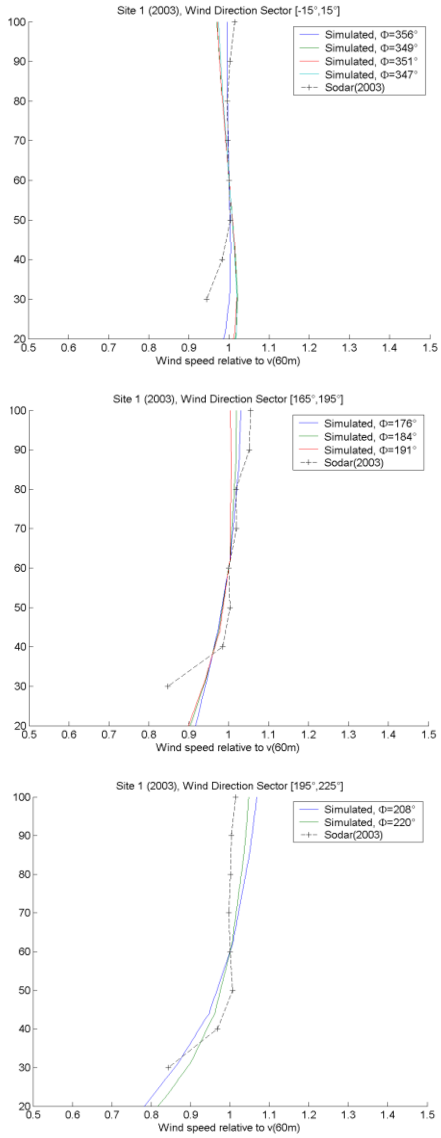

Figure 7: Comparison of different calculated wind profiles to the measured one by SODAR (site 1) at the Oberzeiring site.

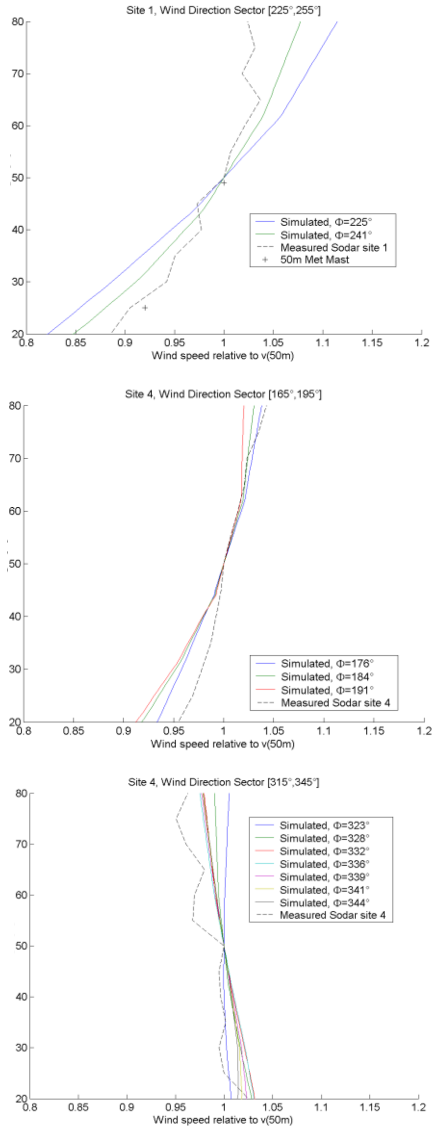

Figure 8: Comparison of different calculated wind profiles to the measured one by SODAR (site 4) at the Oberzeiring site.

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PART 2: Site Assessment in Complex Terrain

Increasingly, megawatt wind turbines are being installed in very complex terrain. These developments increase the need for accurate energy yield- and site-assessments. Such assessments are undertaken to confirm with IEC safety requirements and include the parameters relevant for the wind turbine loading. These include:

- the mean wind speed,
- extreme wind speed,
- ambient turbulence,
- wake turbulence,
- wind shear and
- flow inclination.

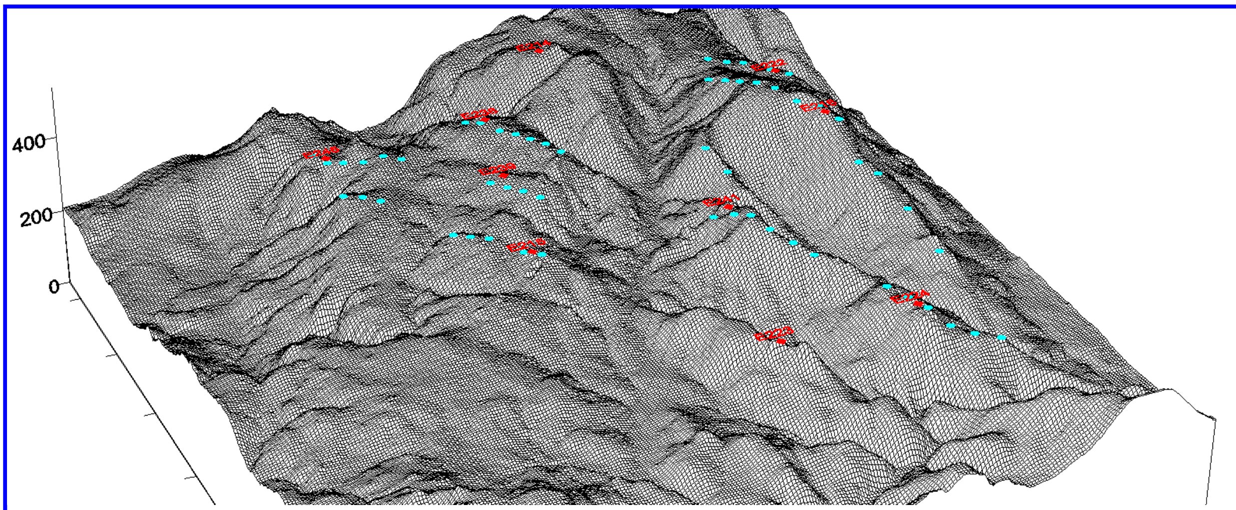

Figure 11: Overview of the wind farm site. Legend: ● wind turbine positions, ✚ measurement mast positions

Most of these required parameters are already part of the flow field results obtained from a CFD simulation. Indeed, many of these parameters are not possible to estimate realistically without performing a flow simulation.

Wind gradients and flow inclination, respective to their maximum values or the values within the rotor area, can be straightforwardly derived from the comprehensive flow-field results produced by CFD, (see Figure 9). Another effect - the generation and transport of turbulence - is shown in Figure 10 (the colour represents the value of the turbulent kinetic energy). In particular, the level of turbulence increases in the region with large wind gradients; e.g. on the top of a hill. This, in turn, affects the adjacent wind turbines through transport of the mean flow.

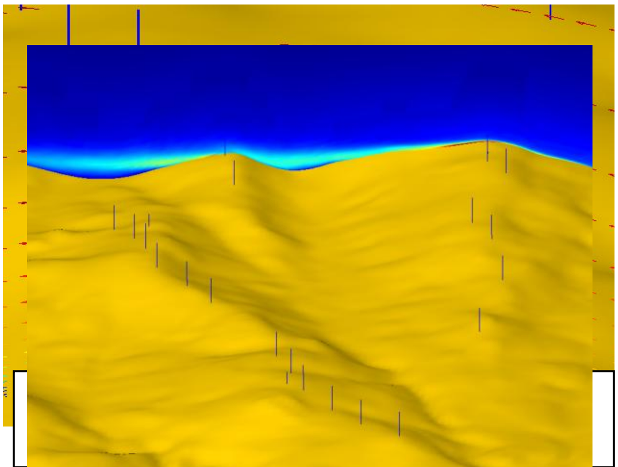

Figure 11 gives an overview of the terrain conditions on site, representing a 7 km × 7 km region in which the height varies from 20m to 640m above sea level. The planned wind farm will have about 50 wind turbines. Ten measurement masts, at a height of 20m to 55m, provide good coverage of the wind farm area and a valuable basis for investigation and verification purposes.

The parameters that cover the most important requirements for IEC site assessment and turbine certification include:

- Wind speed
  - mean, distributions, sector-wise
  - extreme wind speed
- Turbulence matrix
  - dependent on wind speed and direction
  - mean and standard deviation
  - with and without wind farm turbulence
- Flow inclination
- Mean, mean absolute and extreme values
  - situation of occurrence
- Maximum wind speed gradient
  - value and situation of occurrence

Wake turbulence is calculated using two different models; the Frandsen model that represents the latest IEC standard to perform wind-farm wake-assessment for fatigue-load issues; and an Eddy-Viscosity model, which should provide a realistic, not necessarily conservative, result for the wake turbulence.

Figure 12 shows a colour map of the characteristic turbulence intensity defined by the IEC standard. As the IEC proposes values of 18% and 16% for the A and B classes, the map provides clear hints for optimisation of the wind farm's configuration.

It should be noted that not all parameters are verified by measurements, because some of the parameters are difficult or even impossible to measure.

However, it is already apparent that state-of-the-art flow simulation is the ***best possible*** way to estimate these.

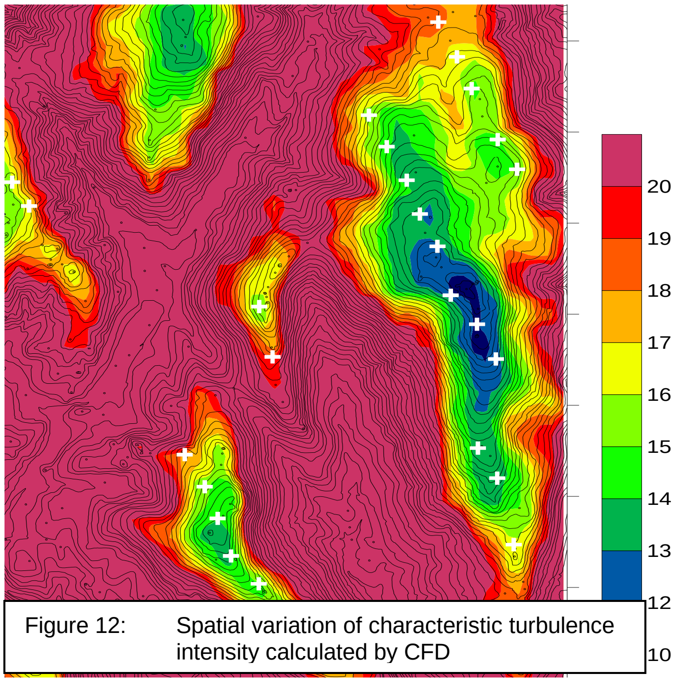

Figure 12: Spatial variation of characteristic turbulence intensity calculated by CFD

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Note on elevation data processing

It is often asked how digital terrain data can be imported into PHOENICS. In practice, terrain data often comes in as height contour lines (e.g. DXF maps or WAsP map files), digitised from 1:25000 or 1:5000 topographical maps. In order to use that to construct a BFC grid with horizontal and vertical grid zooming, the contours must first be carefully interpolated to the defined surface grid nodes. Application of standard 2D-interpolation can lead to defects like terrace forming between lines or overshoots. Therefore the "ray angle interpolation" or one of its refinements may be used. For each grid point a number of equally distributed "rays", and their intersection with the nearby contours, are considered. An interpolation weight is assigned to each ray and its crossing contour, depending on the local angle between ray and contour, thus assigning higher weights to rays crossing a contour at 90° while assigning lower weights for sharper angles. The 3D BFC grid may be constructed on this basis over the surface and exported in ASCII grid format to PHOENICS, where it may be smoothed using the Laplace grid smoothing tool. In order to promote numerical properties, the initial surface may be slightly smoothed only in the vicinity of the outer grid boundaries. The level of detail of the initial height model should fit to your horizontal grid spacing. In any case the resulting surface grid needs to be inspected carefully.

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