Analysis of Open Pit Mining Airflow Using Real Topography Data: Effects of Near-Surface Mesh Refinement on Velocity Fields

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Abstract. Mine-stack-piles in mining areas can significantly affect local air quality due to emission and dispersion of particulate matter that pose heath risks to nearby communities. This study applies Computational Fluid Dynamics (CFD) to analyze the airflow over a mine-stack-pile using high-resolution real topography data. The computational mesh was carefully generated with local refinements and prismatic layers near surface to accurately resolve the atmospheric boundary layer. The height of the first prism layer was defined to achieve an appropriate y+ range for the wall function approach, which is essential for correctly estimating the wall shear stress and the friction velocity. The Reynolds-Average Navier-Stokes (RANS) equations were solved using k-ε Realizable turbulance model. Special attention was given to the near-wall region, since the accurate prediction of the velocity profile and shear stress near the surface directly influences the modeling of particle resuspension and emission. Results highlight the importance of detailed mesh design and appropriate near-wall treatment to predict zones with higher potential for particulate matter emission. The proposed methodollogy supports more effective dust control strategies in mining operations, contributing to improved air quality management.

Keywords: dry stack tailings, CFD, eddy viscosity, near-wall flow, particulate matter dispersion.

Introduction

Open-pit mining and dry stack tailings storage are widely used in the mining industry due to their operational necessity. However, these structures, which are subject to wind action, can significantly impact local air quality through the emission of particulate matter (PM), which poses risks to human health, especially for nearby communities. Fine particles, such as $PM_{2.5}$, are of particular concern due to their ability to penetrate deep into the human respiratory system, contributing to respiratory and cardiovascular diseases [1].

Understanding the interaction between complex terrain features and atmospheric flow is essential for predicting areas prone to particle resuspension and emission. Traditional empirical or semi-empirical approaches often fail to capture the detailed influence of real topography on local wind patterns and surface shear stress, which are key factors in estimating dust emissions. In this context, Computational Fluid Dynamics (CFD) has emerged as a powerful tool for resolving airflow over irregular surfaces, allowing for more accurate assessments of emission hotspots and the development of effective dust control strategies [2, 3, 4].

Although CFD has recently been applied in some studies with real topography data to simulate flow over complex lands, their number remains limited and most of them still rely on simplified domain or do not resolve the near-wall region at mining areas. The main contribution of this work lies in the special attention given to mesh refinement and the careful control of the first prism layer height to ensure an appropriate $\mathbf{y}^+$ range. This approach improves the accuracy of wall shear stress predictions, which is critical for modeling wind erosion and particulate matter resuspension in open-pit mining environments.

The main objective is to evaluate how detailed mesh design and appropriate inflation layers affect the

prediction of the friction velocity and wall shear stress — critical parameters for modeling particulate matter resuspension. By applying the Reynolds-Averaged Navier–Stokes (RANS) equations with the k–ε Realizable turbulence model, the study aims to provide reliable results that support better air quality management in mining operations.

Methodology

Digital Terrain Model (DTM) of a real topography from a mining municipality in Minas Gerais was obtained by a partnership with it's city hall. A clipping was made on the mask layer to select the region of interest, which could be either an open pit mining, a dry stack tailing as it was, or other exposed land subject to wind action and consequently to wind erosion. This phenomenon lead to emission of particulate matter as known to lead to respiratory, cardiovascular and other serious disease [1] and has attention as dry stack tailings disposal increased since the collapse of the Feijão and Fundão dams [11].

QGIS Desktop 3.34.4, a geoprocessing information software, was used to perform a clipping of 687,0 m x 845,0 m. The chipped area corresponds to an isolated mine tailing impoudment located near the urban zone of the municipality. The corresponding GeoTIFF raster elevation data (DTM grid size of 5.0 EPSG:31983 – SIRGAS 2000 / UTM zone 23S) was converted into a three-dimensional STL surface model. This format is readable by Space Claim, a computer aided designer software from Ansys Inc. and preserves all surface details of interest, as slopes, benches, corners and deposition areas. The ground surface was moved up 300 m to define the height of the top of the atmosphere. The atmosphere domain dimensions are defined to minimize boundary effects, with sufficient lateral and vertical extent to capture the development of atmospheric echoes over the tailings pile.

In the analysis of airflow over complex terrain, Silva [5] recommends that the outlet boundary condition should be positioned over a uniform region of the terrain to minimize potential numerical stability problems. According to the author, placing the boundary over flat terrain helps prevent complex recirculating flows within the computational domain, which can lead to numerical convergence issues. This is particularly relevant because complex features such as dune crests may generate highly distorted grid cells, where grid lines intersect at steep angles, resulting in excessive numerical diffusion and difficulties in achieving a stable solution.

The computational mesh was generated using Ansys Meshing. A hybrid mesh was chosen, consisting of tetrahedral elements in the central region of the domain and prismatic elements near terrain surface, to adequately resolve the atmospheric boundary layer, shown at Figure [9,10]. The additional surfaces were grouped and labeled within the computational domain to distinguish them from the real topography features. In Ansys Meshing, the grouping was carried out using the Virtual Topology tool to simplify the geometry and facilitate mesh generation. In line with this recommendation and supported by the guidelines of Versteeg & Malalasekera [6], the present study adopted sufficiently extended lateral domain to ensure that the outlet region remains free of flow recirculation or adverse pressure gradients, thus preserving the accuracy and stability of the CFD solution.

Approximately 14 million elements were inserted, with local refinement over the surface, close to walls, along the flow development zone. For this purpose, 30 inflations layers with a growth rate of 1.185 were adopted at final mesh. The greatest computational effort was devoted to the development and testing of meshes, summary presented at Table . At first, a 50m element size and 0,005m of first layer thickness for 20 layers of prism with a growth rate of 1.2 achieved approximately 9m of prism layer from the surface of the terrain, although, a range y+ out of waited conducted a refining until an expected range of 30-300 was achieved, as defined by Ansys Manual Chapter 4: Near-Wall Treatment [7].

The friction velocity is a key parameter that is calculated internally by the CFD code and directly affects the near-wall mesh resolution. The dimensionless wall distance ($\mathbf{y}^+$) is also provided as an output by the CFD solver, which computes it by multiplying the normal distance from the wall by the friction velocity and dividing by the kinematic viscosity. The friction velocity, which is fundamental for defining the thickness of the first layer, is determined according to the equation (1), where y is the first layer of prismatic elements, u_{fric} is the riction velocity and ν is the kinematic viscosity.

$$y^+ = \frac{y.u_{fric}}{\nu} \tag{1}$$

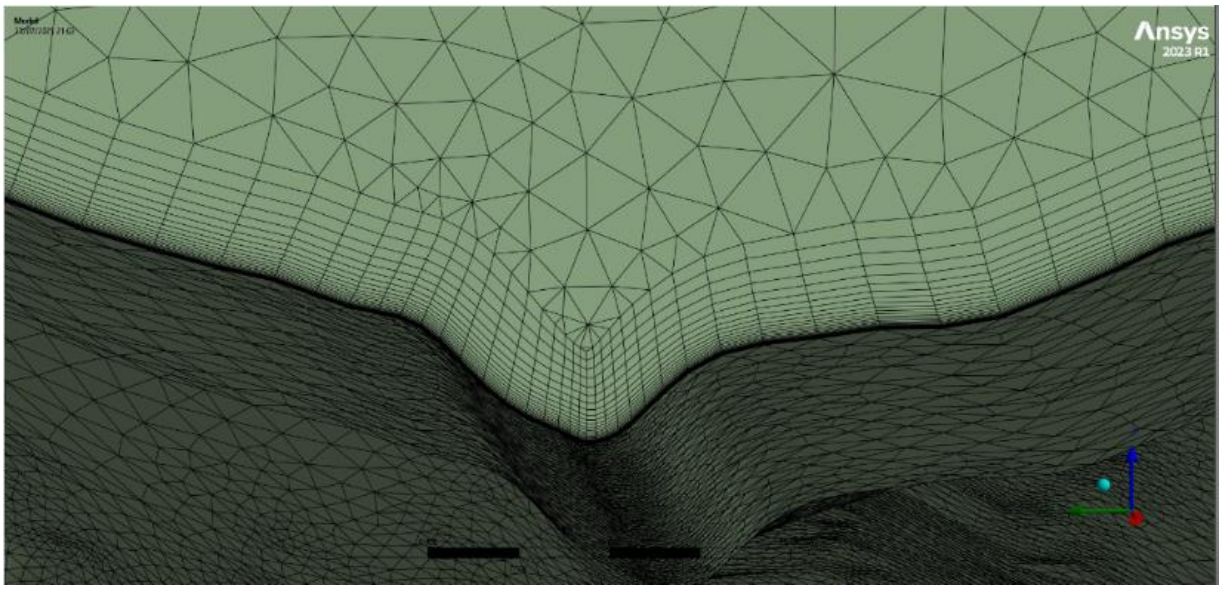


Figure 1: Prism layers above the ground surface illustrating the inflation zone of Mesh 8 within the computational domain.

Table 1: Configuration of the prism layers of the evaluated meshes, including number of layers, height of the first layer, growth rate, total height of the layers and range of wall y+ values obtained in the simulation.

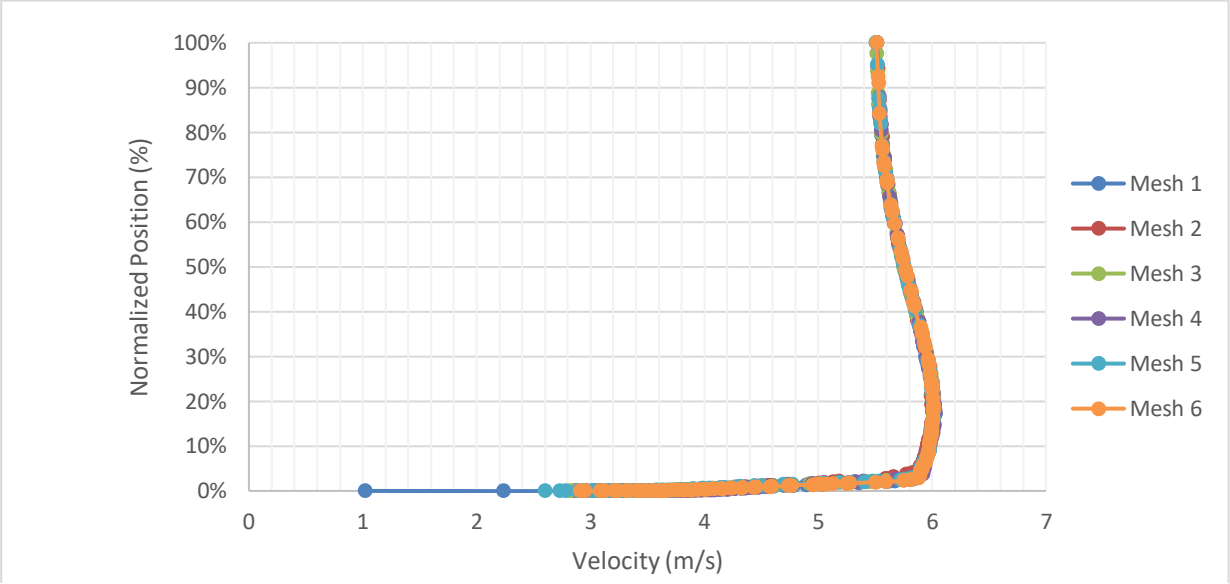
Mesh	Number of Prism Layers	First Layer Height (m)	Growth Rate	Height of Prism Layers (m)	Range Wall y+
1	20	0.005	1,2	9,24	32,45-717,52
2	30	0.0036	1,2	4,22	1,55-57,04
3	30	0.0036	1,24	9,39	2,81-51,47
4	30	0.0041	1,233	9,40	3,0-65,0
5	30	0,005	1,223	9,26	3,05-80,77
6	30	0,01038	1,1885	9,74	6,99-163,03

Results

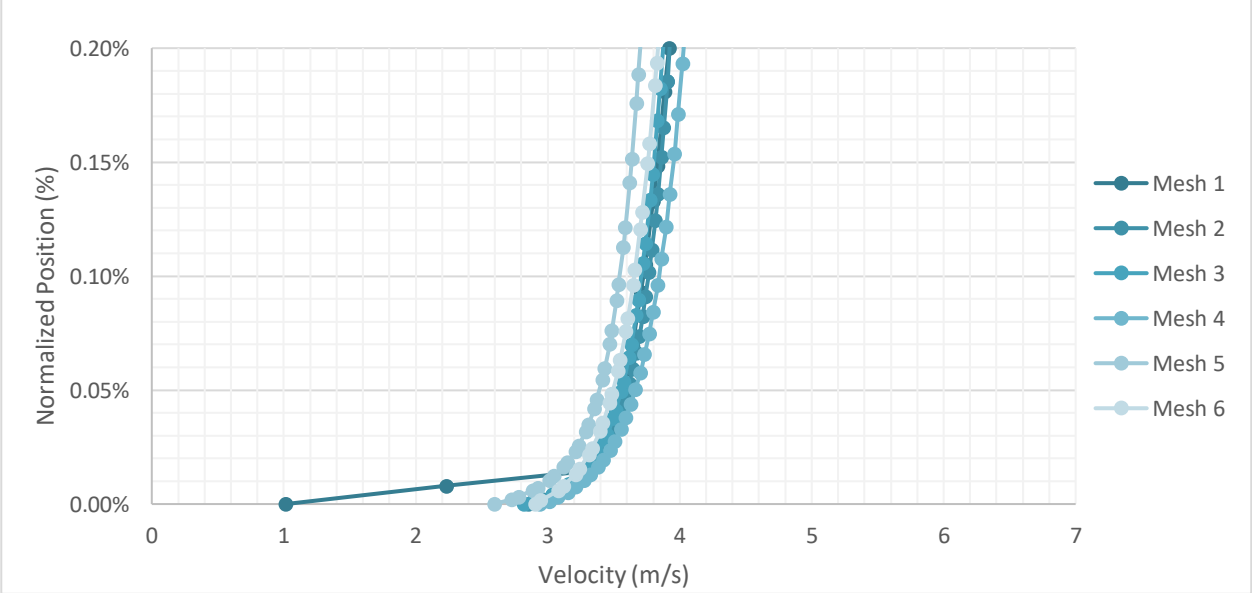
For the events occurring in the atmosphere, it was observed that the surface mesh treatment does not have a significant influence on the results, as shown in Graphic 1, which presents the velocity field profile from the ground surface up to the top of the atmosphere, indicating little variation in the overall behavior. However, for phenomena occurring at the surface level, mesh refinement proves to be relevant. Graphic 2 presents velocity fields profiles from the ground surface up to approximately 0.50 cm in heights for different meshes. It was observed that the refined mesh results in distinct velocity behaviors immediately above the ground. These are the regions where the processes of interest are concentrated and where the data used for the emission estimation calculations are collected, following the methodology proposed in the USEPA's AP-42.

Therefore, selecting a finer mesh near the surface contributes to a more accurate representation of real conditions, increasing the reliability of the estimates generated. After running an initial calculation, the resulting $\mathbf{y}^+$ distribution can be checked in the post-processing stage. If the resulteing $\mathbf{y}^+$ values lies outside the recommended range, it is necessary to adjust the thickness of the first cell adjacent to the wall in the unstructured mesh. By refining or coarsening this first layer and re-running the simulation, the desired $\mathbf{y}^+$ range can be achieved. The present study investigated na external flow representing wind incidence over a large area. The development of a logarithmic velocity profile was the typical behavior expected under such conditions. As shown in Graphic 2, all

simulations captured this trend.



Graphic 1: Comparison of mesh performance based on the central velocity profile within the computational domain, from the ground surface up to the top of the atmosphere.



Graphic 2: Comparison of mesh performance based on the central velocity profile within the computational domain, from the ground surface up to approximately 0.50 cm in height.

The mesh sensitivity test is a fundamental step in numerical studies, as it ensures that the results obtained are not unreal or dependent on inadequate discretization settings. In the present work, the comparison between different mesh configurations revealed significant variations in the distribution of the y+ parameter, which is an output from ANSYS Fluent calculated based on the friction velocity, itself a function of the shear stress applied over the surface. Figure (a) shows the y+ contour resulting from the simulation using Mesh 1, where only about half of the domain falls within the recommended y+ range, as indicated in Table . In contrast, Mesh 6, (b) presents the y+ contour, in which 97.15% of the domain is within the desired y+ range. These results demonstrate that Mesh 6 provides greater accuracy in representing near-wall flow behavior, thereby increasing the reability of the

simulation outputs.

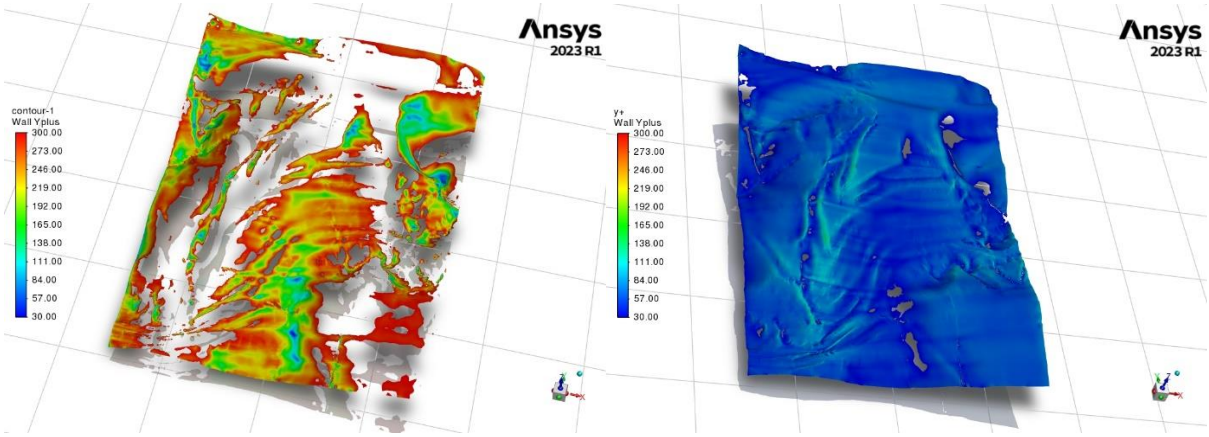


Figure 2: Contour distribution of the y+ parameter in the simulation using (a) Mesh 1 and (b) Mesh 6.

Table 2: Percentage of the surface area within and outside the desired wall y+ range for Meshes 1 and 6.

Mesh	Mesh 1	Mesh 6
Inside desired range of wall y+	51,08%	97,15%
Out of desired range of wall y+	48,88%	2,85 %

Conclusions

The present study demonstrates that careful control of the near-wall mesh resolution through the appropriate definition of y^+ is essential to ensure the accuracy of Computational Fluid Dynamics (CFD) results, especially when predicting wall shear stress and friction velocity over complex mining terrain. The mesh sensitivity analysis, guided by the y^+ criterion, was fundamental to balance computational cost with numerical reliability, enabling the refinement of the prismatic layers until the target range was consistently achieved.

By applying a uniform inlet wind profile for a given wind direction, the simulation results made it possible to identify specific areas of the mine-stack-pile that are more exposed to higher shear stress and, therefore, more prone to wind erosion and particulate matter resuspension. These findings highlight the practical value of combining real topography, mesh independence testing, and near-wall treatment to produce robust predictions that can directly support dust control management. The regions identified with greater susceptibility to wind-driven erosion should be prioritized for intensified mitigation actions, such as surface stabilization, dust suppressants, or operational adjustments, contributing to more effective air quality management in mining environments.

Future studies may adopt a logarithmic wind velocity profile at the domain inlet and incorporate detailed ground surface roughness to better represent site-specific conditions [9, 10]. Including terrain roughness parameters will allow for a more realistic assessment of how local surface characteristics influence near-wall shear stress and, consequently, the wind-driven erosion and resuspension of particulate matter in mining areas. This approach can help refine predictions of critical emission zones and provide CFD-based estimates of particulate emissions, supporting the development of targeted dust control measures adapted to different soil conditions.

The results obtained with the most refined mesh allow for a more accurate identification of the regions with the highest erosion potential, providing reliable support for implementing appropriate control measures, such as watering. Friction velocity is one of other parameters used to estimate erosion potential from fugitive source of particulate matter. Usually, higher the friction velocity, higher the erosion potential associated. Although, in contrast, it was observed that using a less refined mesh can overestimate the erosion potential in areas where such intervention is not required. This difference highlights the importance of adequate mesh refinement to correctly represent the phenomena of interest, avoiding misleading assessments and unnecessary allocation of natural,

technical and financial resources for particulate emission control.

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