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A computational study of particulate emissions from Old Moor Quarry, UK

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ABSTRACT

This paper presents an evaluation of a buoyancy-modified $k-\varepsilon$ dust dispersion model for predicting fugitive dust deposition from a surface quarry. The dust clouds are modelled as volumetric emissions and their dispersion simulated by coupling the flow-field with stochastic tracking of the particulates. The coefficients of the turbulence model are modified and source terms are added to the turbulence equations to permit simulation of both adiabatic and diabatic atmospheric stability conditions. These modifications ensure compatibility with Monin-Obukhuv similarity scaling of the atmospheric surface layer. Also, mesoscale wind direction variability is included. The Monin-Obukhuv scaling parameters have been derived from routine meteorological data recorded during a month-long monitoring campaign conducted at the quarry. Dust deposition measurements from a network of Frisbee deposition gauges are used to validate the predictions of the CFD model. A number of statistical performance metrics have been applied to evaluate the degree of uncertainty in the predictions. The dust deposition predictions of the CFD model are compared to those of the UK-ADMS, to demonstrate how the treatment of the terrain in the CFD model improves the accuracy of the deposition predictions.

1. Introduction

Conventionally, dispersion modelling has involved the application of Gaussian-based models such as the UK Atmospheric Dispersion Modelling System (UK-ADMS) and the US Environmental Protection Agency equivalent, AERMOD, to predict the dispersion of fugitive dust plumes from quarry emission sources and to ensure regulatory compliance. However, whilst these models have relatively fast solution times and are able to predict dust dispersion under a range of meteorological conditions, Gaussian model algorithms offer an over-simplified resolution of the flow-field over complex terrain and are therefore more suited to modelling dispersion of gaseous plumes emitted from elevated sources over gradually undulating terrain. In this regard, Lowndes et al. (2008) concluded that the reliability of conventional Gaussian model predictions is reduced where the entrainment and dispersion of fugitive dust is complicated by in-pit and surrounding topography as well as the dynamic nature of dust emissions.

Furthermore, within a typical quarry, the terrain gradient is likely to exceed the 1:3 limit for reliable application of the complex terrain algorithms in Gaussian models. Indeed, work by Silvester et al. (2009) demonstrates that the accuracy of Gaussian models is challenged by complex terrain and they are unable to account for in-pit fugitive dust retention due to these terrain effects. As a result, they significantly over-predict the long-range transport of particulates by as much as 60%. Consequently, the use of Gaussian models to inform the selection and implementation of fugitive dust abatement strategies for compliance with environmental regulations is likely to result in over-design of these abatement systems. As far as the Environmental Agency is concerned, conventional dispersion models are fit for purpose, their over-predictions ensuring that quarries consistently operate within a large factor of safety with regard to dust abatement. However, whilst the conservativeness of Gaussian models may be favourable for environmental protection, it is uneconomical for quarry operators. A need therefore arises to develop new dispersion models which can handle complex terrain and, by extension, resolve the internal flow regimes which occur as a result of significant perturbation of the Atmospheric Boundary Layer (ABL) by pit topography. Ultimately, these models will safeguard against considerable over-design of dust abatement systems, thus proving beneficial for quarry productivity and operating costs.

Zanetti (1990) describes dispersion modelling as an important intermediate step in the design and implementation of emission reduction and control measures. To this end, a number of Gaussian models with improved algorithms such as UK-ADMS, AERMOD and CALPUFF are approved for use by the UK Environmental Agency to support Environmental Impact Assessments submitted as part of current or future planning and permitting applications for quarry installations (Appleton et al.,

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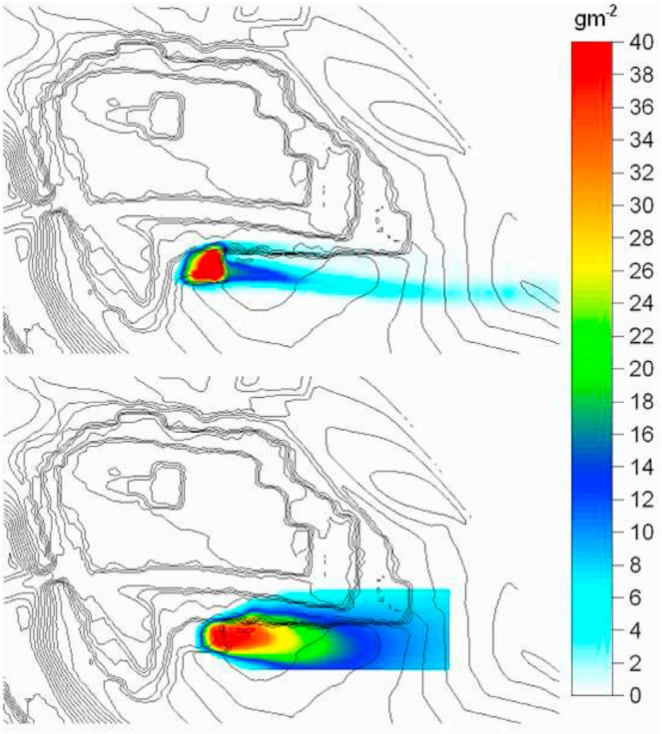

Fig. 1. A comparison of the particulate deposition predictions obtained using FLUENT (top) and UK-ADMS (bottom) to model dispersion at a UK quarry under neutral atmospheric conditions from Silvester et al. (2009).

2006; Carruthers et al., 2009).

Di Sabatino et al. (2007) note that due to their widespread use, Gaussian dispersion models have benefited from extensive model validation and standardization of modelling protocols, and allow the user to model the contribution of a large number of emission sources simultaneously for many hours of meteorological data within a short time. Gaussian-based modelling packages include a utility to extract terrain data from digital formats available on national databases, removing the need for extensive surveys of landforms surrounding a surface quarry (CERC Ltd, 2011). Moreover, both UK-ADMS and AERMOD are equipped with meteorological pre-processors which are able to compute atmospheric parameters to characterize the atmospheric boundary layer from routine meteorological data, thereby eliminating the need for sophisticated meteorological instruments to directly measure these variables (Carruthers et al., 2009).

However, it is well known that Gaussian model algorithms suffer from several inherent limitations related to over-simplification of the flow-field. In the case of UK-ADMS, the FLOWSTAR algorithm is used to model the flow over complex terrain. This algorithm uses a linearized analytical solution of the momentum and continuity equations and offers a simplified treatment of topography in which the Froude number is used as a critical model parameter in separated flows (CERC Ltd, 2011). The linearization of the flow equations employed in the UK-ADMS complex terrain model algorithm is based on small perturbation theory by Jackson and Hunt (1975) which is restricted to terrain gradients below 1:3. The theory assumes that terrain in-homogeneities produce small perturbations in the flow-field relative to mean flow quantities. However, this assumption is not valid in cases where separation of the flow occurs (Finardi et al., 1997). In the case of surface quarries, the linearized flow model, and hence the complex terrain algorithm, are incompatible with the quarry topography, which produces large perturbations in the atmospheric flow-field.

Additionally, Gaussian models may suffer from inconsistencies among similar model types or different versions of the same model even with the same data set due to intrinsic differences in model algorithms (Hall et al., 2000). For instance, later version of UK-ADMS offer substantially greater terrain resolution capabilities than earlier versions. Equally, the UK-ADMS treatment of complex terrain is vastly different to that of AERMOD (Carruthers et al., 2011). Also, the formulation of the Gaussian equation implies that model accuracy is severely limited at low wind speeds (Holmes and Morawska, 2006). The reliability of Gaussian model approximations is further reduced for near-ground releases because the vertical dispersion of near-ground releases may depart considerably from the Gaussian probability density function (Smith, 1995). Therefore, El-Fadel et al. (2009) recommend that UK-ADMS should only be relied upon as a qualitative prediction tool for dispersion over complex terrain.

There are thus compelling arguments to perform CFD model dispersion studies to produce more realistic models of particulate plume dispersion over complex topography. However, there are few studies in the literature that document the results of CFD investigation of the dispersion and deposition of fugitive dust. Furthermore, the pollutant dispersion studies which incorporate complex terrain effects, such as those by Chatzipanagiotidis and Olivari (1996), Blocken et al. (2008) and Chavez et al. (2011), only consider the neutral stability case wherein the effects of thermal buoyancy are absent. In these studies, the model predictions are typically validated against wind tunnel measurements and there is a scarcity of studies that have attempted to compare numerical model predictions of dispersion with field measurements. In one of the few instances involving field validation, Hong et al. (2011) employ an LES model to simulate the wind field over a test region in South Korea and subsequently use this validated model to predict the dispersion of livestock odour over this area. Their model predictions were found to correlate well with field measurements. In another example, Scargiali et al. (2005) consider the dispersion of chlorine gas over a mountainous, 30 km^2 region in Sicily. To include the effects of thermal buoyancy, they introduce modifications to the RANS equations for turbulent kinetic energy and its dissipation rate. They conclude that predicted ground level concentrations are attenuated by the presence of complex terrain downwind.

The present work considers a variety of atmospheric stability conditions and Li and Guo (2006) describe a comparison between CFD and CALPUFF, a Lagrangian puff model. In the present context, the most interesting aspect is that a number of wind speed/atmospheric stability class cases were considered in the comparison. The CFD implementation of the non-neutral stability cases amounted to using different exponents in the power law describing the inlet velocity profile and specifying an appropriate temperature profile. It was found that the CFD and puff models disagreed both in the near and far field regions, even over the flat terrain considered.

In the wider context of using CFD to model dispersion in challenging topographic environments, Li et al. (2006) offer a review of CFD modelling and practice as applied to street canyons. They identify key challenges, such as the choice between Reynolds-Averaged Navier-Stokes (RANS) and Large Eddy Simulations (LES), the inclusion of buoyancy effects due to insolation and pollution transport in the complex flow fields. There are striking similarities between street canyons and the quarries under investigation in the present work. In Di Sabatino et al. (2008), a comparison between FLUENT and ADMS-Urban is presented, again in the street canyon context. It is interesting that the ADMS-Urban includes a version of the OSPM (Hertel and Berkowicz, 1989) model in the near-field, to deal with the complex flow and dispersion within the street canyons themselves. This has parallels with the near-field modelling of in-quarry flows discussed in the present work.

Again, working in the urban environment, Tominaga and Stathopoulos (2013) review current CFD modelling techniques. They include an interesting discussion on the inclusion of stability effects in CFD models and the extent to which they are important in an environment where mechanically produced turbulence can dominate. It was concluded that the evidence suggests that atmosperhic stability plays a role in a