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Wanjun Tang

China Coal Research Institute, China Coal Technology & Engineering Group

Fengming Li

China Coal Research Institute, China Coal Technology & Engineering Group

Gaoxiang Xiang (✉ xianggx@nwpu.edu.cn)

Northwestern Polytechnical University School of Mechanics Civil Engineering and Architecture

Mengwei Liu

Beijing Research Institute of Land Renovation and Ecological Restoration Technology, China Coal Technology & Engineering Group

Research Article

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Posted Date: August 18th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-716676/v1>

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Version of Record: A version of this preprint was published at Environmental Science and Pollution Research on January 4th, 2022. See the published version at <https://doi.org/10.1007/s11356-021-18160-4>.

Investigation on flow field characteristics in an open-pit coal mine

Wanjun Tang^{1,3}, Fengming Li^{1,3}, Gaoxiang Xiang^{2,*} and Mengwei Liu^{1,3}

(1. China Coal Research Institute, China Coal Technology & Engineering Group, Beijing 100013, China;

2. School of Mechanics, Civil Engineering & Architecture, Northwestern Polytechnical University, Xi'an 710129, China;

3. Beijing Research Institute of Land Renovation and Ecological Restoration Technology, China Coal Technology & Engineering Group, Beijing 100013, China)

*Corresponding author: G. X. XIANG. E-mail address: xianggx@nwpu.edu.cn.

Abstract

In this paper, the atmospheric flow field characteristics in a deep open-pit mine are investigated numerically and theoretically. A theoretical model on the recirculation length based on the energy equation is used, a total variation diminishing (TVD) difference scheme with second order accuracy is used to solve the NS equations with a standard two-equation $k-\varepsilon$ turbulence model. The effects of elevated inner dump on the flow field characteristics of the open-pit mine are analyzed detailly with the same inflow parameters. The results show that a recirculation zone exists in the open-pit mine due to the reflux from the high-pressure zone to the low-pressure zone. As the height of the inner dump increases, the flow becomes more complicated, the low-pressure zone and the recirculation zone becomes bigger. The elevated inner dump makes it difficult for the internal fluid to flow to the outside, which results in the increase of the dust concentration. At last, the influences of key parameters on flow field are conducted by normalizing the depth of the lowest direct current flow on the windward slope. The sensitivity analysis is done by study each influencing factor. This paper offers an effective way to study the flow field characteristics in an open-pit coal mine, which is essential to the dust pollution control of open-pit mine.

Keywords: Open-pit mine; Elevated inner dump; Atmospheric flow field; Sensitivity analysis.

1. Introduction

Spraying water is commonly used for dust suppression in open-pit mines (Peng et al. 2019). A more economical approach is to spray a mixture of a suitable dust suppressant and water (Wang et al. 2019). But some open-pit mines in environmentally vulnerable areas of Northwest China are extremely short of water (Zhou et al. 2016; Hu et al. 2014). In these areas, groundwater and annual rainfall is scarce. There are no rivers or lakes on the surface and local people live by collecting rainwater. The water for these mines needs to be transported from other places, spraying water is not suitable for these extremely water-short open-pit mines.

Inner dumps are useful for reducing transportation distance in flat coal seam mining (Tang and Cai 2018). In general, the total inner space is adequate, there can be insufficient space during special periods, for example, when the mining area turns or when the mining area crosses a coal seam anticline. Elevating the inner dump is a common countermeasure, as the method is economically advantageous because it does not reselect the outside dump, which means the transportation distance is shortened. But the dust concentration increases significantly with the elevating of the inner dump. Furthermore, the concentrations of NO, SO₂ and some other elements also increase significantly (Sosg et al. 2013). Evidently, elevating the inner dump may change the surrounding topography of the mine and have a significant influence on the air flow in and around the mine. It may also affect the dissipation efficiency of dust and other pollutants in the mine (Tian et al. 2008). The accumulation and dispersion of dust, truck tail gas, blasting products and so on are affected. This in turn worsens air quality in the mine which not only threatens the health of the workers in the mine, but also affects operational efficiency of the equipment (Vaupel et al. 2009).

Therefore, it is necessary to study the influence of elevating the inner dump on the atmospheric flow field in the pit. Based on the influence mechanism, corresponding measures for dust reduction are presented (Silverster et al. 2009). As these dust reduction methods are based on the variation mechanism of the airflow field and do not require water sprinkling, they are suitable for use in open-pit mines in water deficient areas. There are three methods to investigate the atmospheric flow field in the open pit, theory, numerical simulations and experiments. Due to the limitation of experimental conditions and development of the CFD (Computational fluid dynamics) (Yang et al. 2019; Teng et al. 2014; Teng and Jiang 2012), most of the research focuses on numerical simulation (Tartakovsky et al. 2013; Pedro et al. 2021; Wang et al. 2021; Ma et al. 2020; Li et al. 2021; Zhang et al. 2018). Tang used Fluent to study the dust move in the pit and escape rate and time out of the pit (Tang and Cai 2018). Ma investigate the effect of spraying on coal dust diffusion in a coal mine based on a numerical simulation and experimental spraying results (Ma et al. 2020). There are relative few theoretical studies on the flow field of the open pit, including flow field characteristics, recirculation zone, dust transport and concentration distribution.

This paper presents a detailed numerical analysis of the atmospheric flow field characteristics in a deep open-pit mine. Mathematical and physical models are presented in section 2. In section 3, both the theoretical and numerical investigations on the flow field characteristics in the pit are shown. The effects of the height of inner dump on the pressure, velocity and structures are discussed in detail. Finally, the essential points of this paper are summarized in section 4.

68 **2. Mathematical and physical models**

Fig. 1 Sketch of the simplified pit basin model.

Figure 1 presents a simplified computational model of a deep open-pit mine. The left boundary in the x direction is the free-flow boundary and the inflow velocity u_0 is selected as 2 m/s. The right boundary is the outlet boundary, the upper boundary in the z direction, the front boundary and the back boundary in the y direction are the far-field boundary. The bottom boundary is the solid wall, including the inner dump, the slope and the pit bottom. The angles of the working slope, end wall and inner dump slope are 25° , 45° and 23° respectively. The depth of the pit is 200 m. The width of the pit bottom is 200 m and the width of the pithead is 1000 m. The bench height of the inner dump is 30 m. The top platform width of the inner dump is 200 m. For the far-field condition, the research scope is the space within 500 m above the mine. As is shown in Figure 1, the atmospheric flow field model is formatted by expanding 500 m, the mine and dump are taken as the benchmark.

Fig. 2 Sketch map of longitudinal section with elevated inner dump and control volume used to apply the energy equation.

Figure 2 shows the sketch map of longitudinal section with elevated inner dump. α_1 and h_1 represents the angle and height of the lee side slope, α_2 is the angle of the windward slope and h_2 is the height of the elevated inner dump. The open pit is an abrupt expansion compared to the inner dump, usually in the vertical direction of the slope. According to previous and our investigations, as the slope angle α_1 and the height of the inner dump h_2 are large sufficient, the flow is separated and the flow field characteristics in the up far field region remain unchanged. This problem can be treated as one problem of the open channel flow. The recirculation length is defined as L and can be solved by the energy equation.

The flow enters the control volume in left section of area $A_1=h_0*d$, with average velocity $u_0=2\text{m/s}$ and pressure p_0 , where d is the width of the inner dump in the y direction. The head in this inflow section is thus $H_0 = \beta_0 \frac{1}{2} \rho_0 u_0^2 + p_0$, where β_0 is the Coriolis kinetic. The flow leaves the control volume through the right section of area $A_2=h_r*d$, with average velocity u_1 and pressure p_1 . The head in this section is thus $H_1 = \beta_1 \frac{1}{2} \rho_1 u_1^2 + p_1$. Two terms traduce the head losses from the left section to the right section, considering two independent sources of dissipation:

J_r accounting for the singular head loss in the recirculation and J_f accounting for the linear head loss due to bottom wall friction. which can be solved by:

$$J_f = \frac{1}{2} \rho u_0^2 \frac{LS}{h_1 + h_2} (1 + R_h^2), \quad J_r = \frac{1}{2} \rho u_1^2 (1 - R_h^2) \quad (1)$$

where $S = \lambda (h_1 + h_2)/(8d)$, it is related to the the Darcy-Weisbach head loss coefficient λ and that the equivalence $\lambda = 4c_f$. The energy equation expresses the head balance through the control volume,

$$H_0 - H_1 = J_f + J_r \quad (2)$$

The recirculation length L can be obtained by:

$$\underbrace{\frac{LS}{h_1 + h_2}}_{T_1} = \underbrace{\frac{p_0 - p_1}{\frac{1}{2} \rho u_0^2} \frac{1}{1 + R_h^2}}_{T_2} + \underbrace{\frac{\beta_0 - \beta_1 R_h^2}{1 + R_h^2}}_{T_3} - \underbrace{\frac{(1 - R_h)^2}{(1 + R_h^2)}}_{T_3} \quad (3)$$

where R_h is the expansion ratio and defined as $R_h = (h_r - h_1 - h_2)/h_r$. T_1 is related to the head loss due to wall friction, T_2 is indeed related to the pressure variation, while T_3 is related to the kinetic energy variation, T_4 is related to the Borda - Carnot-like head loss.

This paper solves the NS equations with a TVD difference scheme of second order accuracy (Yang et al. 2019; Teng et al.2014; Teng and Jiang 2012), the turbulence model uses a standard two-equation turbulence model, including a turbulent kinetic energy equation and a diffusion equation, as follows:

$$\frac{\partial(\rho\kappa)}{\partial t} + \frac{\partial(\rho\kappa u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial \kappa}{\partial x_j} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k \quad (4)$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial(\rho\varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + C_{1\varepsilon} \frac{\varepsilon}{\kappa} (G_k + C_{\mu} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{\kappa} + S_\varepsilon \quad (5)$$

Where, G_k is the κ generating term due to the turbulent kinetic energy caused by the mean velocity gradient;

G_b is the κ generating term of the turbulent kinetic energy due to buoyancy;

Y_M is the contribution of pulsating expansion in compressible turbulence;

$C_{1\varepsilon}$, $C_{2\varepsilon}$, C_μ are empirical constants;

σ_k , σ_ε are the Prandtl numbers corresponding to the turbulent kinetic energy κ

and the dissipation rate ε ;

S_k , S_ε are the source items defined by the user according to the calculation cases.

The computational mesh uses the orthogonalized uniform structured mesh and the mesh quantity is 5 million. Mesh independence tests are performed to ensure that all the results produced are independent of the type of mesh chosen for numerical simulations. Two numerical objects are conducted, including the inner dump elevated and not elevated. By comparing the flow field characteristics under the same inflow conditions and the pit conditions, the effects of the elevated inner dump on the flow field in the pit are investigated.

3. Results and discussion

3.1 The flow field in the pit

(a) Velocity

(b) Velocity component in the x direction

Fig. 3 Velocity contours of flow field on cross section at $y=1000\text{m}$.

Figure 3 presents the numerical results of velocity contours on the symmetry plane at $y=1000\text{m}$.

The velocity components are predefined as u , v , and w directions, corresponding to the x , y , and z directions respectively. As the inflow direction is x positive, the positive value of u indicates that the direction of the air flow has no change, and the negative value represents the reflux. It can be seen from the Figure 3b that the negative regions exist at the bottom of the pit and the leeward slope, and the bottom area of the mine has complicated wind direction. As is shown in Figure 3a, the discontinuous eddies in the bottom of the mine have been extended and communicated into a large area of vortex. The generated mechanism of vortex is the pressure discrepancy inside and outside of vortex. As the air pass through an open-pit mine, the gas in the pit will flow in the same direction, and a low-pressure area will be formed in the mine. Under the action of the high-pressure airflow, the air will flow from the high-pressure zone to the low-pressure zone and a vortex will be formed.

Figure 4 shows the pressure contours and streamlines on different cross section along the y direction. The vortex structures along the spanwise distribution at the bottom of the pit can be seen from the stream lines. At $y=700\text{ m}$, the main vortex structure is on the lee side slope, the pressure

on the windward slope and the pit is obviously larger than the lee side slope, which causes a recirculation and forms a vortex. As the cross section moves from 700 m to 1300 m along the y direction, the vortex structure shows an increasing trend and the high-pressure zone on the windward slope becomes small. The pressure in the vortex is obviously smaller than that in the nearby area. It can be seen that only a small part of the fluid in the pit exchanges with the external fluid, and the internal dust always moves in the depression, and only a small part is taken out.

Figure 5 shows the contours of the velocity component w and the pressure on cross section in the incoming direction. The blue negative value area represents the air sinking to the bottom and the red area represents air rising at the windward slope. An obvious recirculation area is presented in Figure 5b. A big positive current area appeared on the leeward side, representing rising air flow. On the windward side, the lower part of the slope becomes the downdraft, and the upper part becomes the updraft. When the downdraft flow reaches the pit bottom, it turns into a reflux flow. The returning air reaches the leeward side and becomes updraft. Then, the returning updraft air is mixed with the direct-current air flow and a big eddy occurs in the pit. The pressure inside the pit is lower than that outside, which makes it difficult for the internal fluid to flow to the outside and results in the increase of the dust concentration.

(a) Pressure contours and streamlines on the cross section at $y=700$ m.

(b) Pressure contours and streamlines on the cross section at $y=1000$ m.

(c) Pressure contours and streamlines on the cross section at $y=1300$ m.

Fig. 4 Pressure contours and streamlines on different cross section.

(a) Contours of the velocity component w

(b) Pressure contours

Fig. 5 Velocity and pressure contours on the cross section in the incoming direction.

3.2 Effects of the inner dump heightening on flow field characteristics

(a) $h_2=30\text{m}$

(b) $h_2=60\text{m}$

(c) $h_2 = 90\text{m}$

(d) $h_2 = 120\text{m}$

Fig. 6 Velocity component u in the x direction with different height of inner dump on cross section

at $y = 1000\text{m}$.

(a) $h_2 = 30\text{m}$

(b) $h_2=60\text{m}$

(c) $h_2=90\text{m}$

(d) $h_2=120\text{m}$

Fig. 7 Pressure contours with different height of inner dump on cross section at $y = 1000\text{m}$.

In order to investigate the influence of inner dump heightening on flow field characteristics, four computational cases with height of inner dump at $h_2 = 30\text{m}$, 60m , 90m , 120m are conducted. The energy loss in the flow field of open pit consists of two parts, the loss in the recirculation J_r and the loss due to the bottom wall friction J_f . As the height of inner dump increases, the expansion ratio R_h decreases, the energy loss due to the recirculation J_r and wall friction J_f

increase. The increased energy loss makes the flow field more complex, including the increasing recirculation length, complex pressure, velocity and streamline distribution. The theoretical analysis is verified by numerical simulations. Figure 6 presents the velocity component u in the x direction with different height of inner dump on cross section at $y = 1000\text{m}$. The direction of the wind is from negative x -axis to positive x -axis, and the color represents the magnitude of the wind speed. As the height of inner dump increases, the area of negative u in the pit increases, the dark red value of u beyond the pit gets bigger, which indicate the increasing of the recirculation zone. Figure 7 shows the pressure contours with different height of inner dump. With the elevating of the inner dump, the high-pressure zone on the left of the inner dump get bigger, the area of low-pressure zone in the pit increases and the vortex develops. As the inner dump elevates, the depth of the lowest direct current flow on the windward slope of the pit decreases continuously, which indicates that the proportion of dust can be spread directly getting smaller and smaller. The increasing height of inner dump changes the flow field significantly compared with the no-elevated flow field. The low-speed zone is always higher than the ground and becomes larger and larger, indicating that the fluid at the bottom of the pit has mixed with the external fluid.

In order to understand the atmospheric flow field characteristics in the deep open-pit mine clearly, the three-dimensional streamlines and pressure contours on cross section at different height of inner dump are shown in Figure 8. As the inner dump is elevated to 30m, the low-pressure zone begin to get bigger and the reflux region is on the negative y -axis of the open-pit mine. With the dump elevated to 60m, the high-pressure disappear on the positive y -axis and the low-pressure fills the pit, the recirculation zone exists on both side of the y -axis and is full of the whole open-pit mine. As the height of the inner dump is increased to 90m and 120m, the

228 flow becomes more complicated, the recirculation zone becomes bigger and exists both inside and
229 outside the open-pit mine. With the elevating of the inner dump, the depth of the lowest direct
230 current flow on the windward slope of the pit decreases continuously, which is not conducive to
231 the diffusion of the dust.

(a) $h_2=30\text{m}$

(b) $h_2=60\text{m}$

(c) $h_2=90\text{m}$

(d) $h_2=120\text{m}$

Fig. 8 Three-dimensional streamlines and pressure contours on cross section at different height of inner dump.

3.3 Mathematical model and sensitivity analysis

Figure 9 presents a simplified air flow field model of an open-pit mine. The air flows through the open-pit mine and complex flow configurations are formed. According to the above numerical results and previous researches, the flow field can be divided into the direct current areas and the circumfluence areas [11-13]. As is shown in Figure 9, DA is the lee side slope, AB is the bottom of the pit and BC is the lee side slope. DE is the boundary line between these two areas, the upper part is the direct current area and the lower part is the circumfluence area. DMQC is boundary between the disturbed and undisturbed flow field by the open-pit mine. The flow field above line DC is the far-field condition, which is the same as the inflow condition. The flow field below line DC is very complex. φ_1 is the angle between the horizontal plane and line DM and represents the disturbed flow field above the horizontal line, φ_2 and φ_3 are the angles for disturbed flow field in the open-pit mine, which represent the flow direction that consistent with the direction of incoming flow. Some of air flow to the right slope and go outside directly, the rest air flow back and forms the vortex region. M_2 is the central point of the whole recirculation zone.

Fig. 9 Sketch map of flow field in an open-pit mine.

In order to study the sensitive parameters, the line DE is assumed as a straight line by connecting directly to point D and point E. As position E is the depth of the lowest direct current

flow on the windward slope of the mine, it does not affect the position of E by simplifying the curve DE into a straight line.

Fig. 10 Sketch map of longitudinal section with elevated inner dump.

By simple deduction, the length of each section can be obtained as follows.

The depth of the lowest direct current flow on the windward slope with non-elevated inner dump:

$$EP = CD \frac{\sin \alpha_2 \sin \beta}{\sin(\alpha_2 + \beta)} \quad (6)$$

The depth of the lowest direct current flow h_r on the windward slope with elevated inner dump:

$$FO = CG \frac{\sin \alpha_2 \sin \beta}{\sin(\alpha_2 + \beta)} \quad (7)$$

The back distance at the pithead:

$$DG = h_2 (\cot \beta - \cot \alpha_1) \quad (8)$$

The depth of the direct current area near the windward side decreases h_d due to the elevating of the inner dump:

$$\begin{aligned}
 h_d &= h_r - h_r' \\
 &= EP - FO \\
 &= (CD - CG) \square \frac{\sin \alpha_2 \sin \beta}{\sin(\alpha_2 + \beta)} \\
 &= \frac{DG}{\cot \beta + \cot \alpha_2} \\
 &= h_2 \square \frac{\cot \beta - \cot \alpha_1}{\cot \beta + \cot \alpha_2}
 \end{aligned} \tag{9}$$

The depth of the lowest direct current flow on the windward slope is normalized in this paper.

Due to the elevation of the inner dump, the change of the depth of the lowest direct current flow on the windward slope can reflect the change of the direct current range in a mine, but it cannot reflect the ventilation in different mines. Therefore, the mine depth is used to normalize the index to make it a general index to describe the ventilation condition in any open-pit mine. This standardized index is named the coefficient of ventilation ϕ , and the formula is:

$$\phi = \frac{h_r}{h_1} \quad (10)$$

Obviously, the range of ventilation coefficient ϕ is $[0,1]$. When $\phi = 0$, there is no direct current region of the corresponding mine. When $\phi = 1$, the corresponding direct current area can reach the bottom of the pit. Other values are between the two cases. For example, $\phi = 0.5$ indicates that the bottom of the direct current zone reaches half way down the windward side. The index can be used for ventilation comparison between different mines and is very intuitive.

The main influencing factors of h_d include the direct current area descent angle β , the lee side angle α_1 , the windward edge angle α_2 , and inner dump elevation h_2 .

The effect of independent lifting of each factor on h_d is shown in Table 1:

Table 1 The results of comparative simulation are summarized

Independent variable name	Middle variable name	Rise and fall of independent variables	Rise and fall of middle variables	Rise and fall of h_d
β	$\cot \beta$	Fall	Rise	Rise
		Rise	Fall	Fall
α_1	$\cot \alpha_1$	Fall	Rise	Fall
		Rise	Fall	Rise
α_2	$\cot \alpha_2$	Fall	Rise	Fall
		Rise	Fall	Rise
h_2	NULL	Fall	NULL	Rise
		Rise	NULL	Fall

As the angle of the direct current zone β decreases, or the angle of the lee side α_1

increases, or the angle of the windward side α_2 increases or elevating and increasing of inner dump h_2 , it can lead to an increase in h_d .

The increase of h_d means that the direct current zone shrinks, which is not conducive to the discharge of dust and other pollutants in the pit. The direct current area, the direct current area ratio and the depth of lowest direct current flow on the windward slope and the direct current zone reach three indicators, which reflect the dust dissipation conditions in the mine. The depth of lowest direct current flow on the windward slope can be used as an important index to describe whether the flow field in the open-pit is lead to dust dispersion.

4. Conclusion

In this paper, a combination of numerical simulation considering the turbulence and theoretical analysis of the simplified model is used to investigate the flow field characteristics in an open-pit mine. The main conclusions of this paper are as follows:

1. The generated mechanism of the recirculation zone in the open-pit mine is the pressure discrepancy in the flow field. As the air pass through an open-pit mine, the gas in the pit will flow in the same direction, and a low-pressure area will be formed in the mine. Under the action of the high-pressure airflow, the air will flow from the high-pressure zone to the low-pressure zone and a vortex will be formed. This makes it difficult for the internal fluid to flow to the outside and results in the increase of the dust concentration.

2. As the height of the inner dump increases, the expansion ratio R_h decreases, the energy loss due to the recirculation J_r and wall friction J_f increase, the low-pressure zone begin to get bigger, the flow becomes more complicated, the recirculation zone becomes bigger and exists both inside and outside the open-pit mine. The depth of the lowest direct current flow on the windward

slope of the pit decreases continuously, which is not conducive to the diffusion of the dust.

3. Based on the numerical results, the model is further simplified into a convenient mathematical model. The formula for calculating the variation of the flow field in the mine with the increase of the height of the inner dumping ground is derived. Through a sensitivity analysis of the main influencing factors (direct current area descent angle β , lee side angle α_1 , windward edge angle α_2 , inner dump heightening h_2) of flow field variation, the influence of four factors is clear.

Acknowledgements and funding

This project is supported by the special project of science and technology innovation and entrepreneurship fund of China Coal Technology & Engineering Group (2019-ZD004), the Fundamental Research Funds for the Central Universities of China (Grant No.31020170QD087 and 310201906zy009) and the China Postdoctoral Science Foundation funded project (2021M692633).

Author Contributions Tang Wanjun: software, visualization, and preparation.

Li Fengming: Data curation and Investigations

Xiang Gaoxiang: conceptualization, methodology, writing-original draft.

Liu Mengwei: literature survey.

Availability of data and material Available on demand.

Decorations

Code availability Not applicable.

335 **Ethics approval** Not applicable.

336 **Consent to participate** Not applicable.

337 **Consent for publication** Not applicable.

338 **Conflict of interest** The authors declare no competing interests.

339 **Reference**

340 Hu J, Wang Y, Ying Q, Zhang H (2014) Spatial and temporal variability of PM_{2.5} and PM₁₀ over
341 the North China Plain and the Yangtze River Delta, China. *Atmos. Environ.* 95:598-609.

342 Li L, Zhang R, Sun J, He Q, Kong L, Liu X (2021) Monitoring and prediction of dust
343 concentration in an open-pit mine using a deep-learning algorithm. *J. Environ. Health Sci.*
344 19:401-414.

345 Ma Q, Nie W, Yang S, Xu C, Peng H, Liu Z, Guo C, Cai X (2020) Effect of spraying on coal dust
346 diffusion in a coal mine based on a numerical simulation. *Environ. Pollut.* 264(2):114717.

347 Pedro B, Teresa M, Patricia C, Natalia M, Zhuang X, Li B, Li J, Shanguan Y, Dominguez A, Fran
348 K, Xavier Q (2021) Comprehensive evaluation of potential coal mine dust emissions in an
349 open-pit coal mine in Northwest China. *Int. J. Coal Geol.* 235: 103677.

350 Peng H, Nie W, Yu H, Cheng W, Bai P, Liu Q, Liu Z, Yang S, Xu C, Hua Y, Guo C, Ma Q (2019)
351 Research on mine dust suppression by spraying: Development of an air-assisted PM₁₀ control
352 device based on CFD technology. *Adv. Powder Technol.* 30(11):2588-2599.

353 Silvester SA, Lowndes IS, Hargreaves DM (2009) A computational study of particulate emissions
354 from an open pit quarry under neutral atmospheric conditions. *Atmos. Environ.* 43(40):6415-6424.

355 Sosa G, Vega E, González-Avalos E, Mora V, López-Veneroni D (2013) Air Pollutant
356 Characterization in Tula Industrial Corridor, Central Mexico, during the MILAGRO Study.
357 BioMed Res. Int. 2013(10):521728.

358 Tang W, Cai Q (2018) Dust distribution in open-pit mines based on monitoring data and fluent
359 simulation. Environ. Monit. Assess. 190(11):632.

360 Tartakovsky D, Broday DM, Stern E (2013) Evaluation of AERMOD and CALPUFF for
361 predicting ambient concentrations of total suspended particulate matter (TSP) emissions from a
362 quarry in complex terrain. Environ. Pollut. 179:138-145.

363 Teng HH, Jiang ZL, Ng HD (2014) Numerical study on unstable surfaces of oblique detonations. J.
364 Fluid Mech. 744(2):111-128.

365 Teng HH, Jiang ZL (2012) On the transition pattern of the oblique detonation structure. J. Fluid
366 Mech. 713:659-669.

367 Tian L, Lucas D, Fischer SL, Lee SC, Hammond SK, Koshland CP (2008) Particle and gas
368 emissions from a simulated coal-burning household fire pit. Environ. Sci. Technol. 42(7):2503-8.

369 Vaupel K, Klenk U, Schmidt E (2016) Emissions from open pit mines-A challenge for air
370 dispersion modeling. Gefahrstoffe Rnhaltung Der Luft 76(1-2):14-18.

371 Wang X, Wei X, Du Y, Wang D (2019) Effect of water-soluble polymers on the performance of
372 dust-suppression foams: Wettability, surface viscosity and stability. Colloid. Surface. A.
373 568:92-98.

374 Wang ZM, Wei Z, Jiskani IM, Ding XH, Liu ZC, Qiao YZ, Luan B (2021) Dust reduction method
375 based on water infusion blasting in open-pit mines: a step toward green mining. Energ. Source.
376 Part A.1-15.

377 Yang P, Ng HD, Teng H (2019) Numerical study of wedge-induced oblique detonations in
378 unsteady flow. *J. Fluid Mech.* 876:264-287.

379 Zhang H, Nie W, Liu Y, Wang H, Jin H, Bao Q (2018) Synthesis and performance measurement of
380 environment-friendly solidified dust suppressant for open pit coalmine. *J. Appl. Polym. Sci.*,
381 135(29):46505.

382 Zhou X, Cao Z, Ma Y, Wang L, Wu R, Wang W (2016) Concentrations, correlations and chemical
383 species of PM_{2.5}/PM₁₀ based on published data in China: Potential implications for the revised
384 particulate standard. *Chemosphere* 144:518-526.