MODELLING BARRIERS FOR COAL DUST SUPPRESSION

Airborne dust originating from the transport and storage of raw coal has detrimental effects on the environment. Warkworth Mining is seeking to reduce the dust emissions caused by the dumping of raw coal at their facility in Singleton, NSW. The suggested strategy was the construction of windbreaks, for which commercial designs exist. The MISG was asked to advise on the placement and design of such windbreaks.

The problem was approached by studying results in the literature on windbreak design, selecting a few possible configurations, and then testing these by solving numerically for the wind velocity around the dumping site. It was concluded that a long fence on the upwind side of the dumping hoppers would provide moderate protection, but would interfere with current operating procedures. As a better option, a long downwind fence immediately behind the hoppers would provide a similar reduction in the dust emission, and allow more effective use of water sprays. Although fine details of the fence design could not be modelled numerically, we concluded that it was desirable for the fence to have an angled overhang in the vicinity of the hoppers, and a porous section near the base to reduce turbulent flows.

1. Introduction

Dust emission from raw coal can be a significant problem during transport, storage and processing, especially since most of these operations take place in the open air. The rate of dust production depends mainly on the proportion of small particles in the coal (less than 0.02 mm) and the wind velocity at the surface of the coal. If the moisture content of the coal is more than 5%, then dust emission is low, since the smaller particles have bonded together to form larger ones (Nakai, 1986). However if the moisture content is in excess of 8% then the coal is difficult to process.

The effect of wind velocity depends on the distribution of particle diameters. Particles larger than 1 mm roll along the ground, a mode of transport known as surface creep. Those particles between 0.02 mm and 1 mm in size will bounce along the surface in relatively smooth trajectories, within a few centimetres of the ground. This is known as saltation. Particles smaller than 0.02 mm can become suspended in the air, and it is these particles which are responsible for the airborne pollution. In this case the terminal falling velocity of the particles is exceeded by the vertical air velocities in eddies, and the transport is dominated by turbulent diffusion. For suspended particles, the overall rate of transport is roughly proportional to the cube of the wind-speed (Bagnold, 1971; Kind, 1990). Thus if windbreaks can be used to give a moderate reduction in the wind-speed near the coal surface, then there will be a large decrease in the amount of coal dust carried by the wind.

At Warkworth Mining's facility at Singleton, NSW, coal from the open-cut mine is taken by truck to be dumped into one of two below-ground hoppers, from where it is removed by a conveyor belt to feed the crushing process. The dumping area is on top of a hill, and on windy days obvious clouds of coal dust are generated when each load is dumped. In winter the prevailing wind direction is from the west, and so the dust is carried across the river flats and the public road to the east. This is undesirable both for the environment and for public relations. In summer the prevailing winds are from the south-east, and so dust fallout will occur on the mine site itself, which is not so serious.

Of the obvious solutions, water sprays are in use, but only with limited success. The sprays are at ground level, and wet the coal as it enters the hopper. However when the wind velocity increases, the water jets are blown off target, and their effectiveness diminishes. The other likely approach is to erect windbreaks to reduce the wind velocity at the two hoppers where the coal is being dumped. The use of windbreaks is very common in the coal industry, especially to protect stockpiles (Cai, Chen and Soo, 1983; Billman Stunder and Arya, 1988; Borges and Viegas, 1988; De Faveri *et al.*, 1990; Xuan and Robins, 1994). Warkworth supplied a brochure which gave details of a design of fence developed by a Japanese company for the purpose of dust suppression, and currently in use at a Japanese power station owned by Warkworth's parent company. The fence is constructed from metal pressed into a square tooth profile. The bottom section of the fence is solid, and the upper section is perforated by an array of circular holes.

Warkworth's proposed problem was to understand how the erection of such barriers would affect the airflow and the motion of coal dust, and to find the best barrier design in terms of strength, perforation size and density.

In the MISG discussion, it quickly became apparent that the geometry of the site and the practical constraints of the dumping operation would largely dictate where windbreaks could be constructed. Given the extensive literature on the performance of porous windbreaks on level surfaces, we could then estimate which locations would be most effective. These considerations are discussed in Section 2.

Although an upwind barrier would be reasonable in terms of dust suppression, it would interfere with dumping into the overflow area. In Section 3, attention is thus focussed on the use of a downwind barrier. In this situation the effect of the dump truck on the air-flow becomes important. Using finite element package FASTFLO, a series of numerical calculations were done in two dimensions for the air flow over a porous barrier with and without the truck. The porosity was modelled by means of an effective viscosity within the barrier. In order to relate this to a real porosity, a series of calculations were done varying the viscosity, and these results were roughly calibrated using literature data for the reduction in mean velocity in the lee of the fence. The use of an overhang on the fence was also considered, in the hope that this would help control the direction of the airflow where the coal dust was being produced.

In Section 4, we give our conclusions on the placement and structure of the fences. The finer details of the fence design (such as given in the supplied brochure) were beyond the resources of our numerical approach, and could only be analyzed qualitatively on the basis of literature values.

2. Placement of barriers

A plan of the dumping area is shown in figure 1. The trucks come from the mine along the haul road and towards the hoppers, with the direction of the traffic flow as indicated. The hoppers, which are about 10 metres square, are represented in the figure by the two squares inscribed with an H. The driver reverses the truck up to one of the hoppers (depending on which hopper is free of other vehicles). Usually the approach is from the north side of the hopper, unless a coal spill has blocked the way. The driver pushes a button which remotely activates the water sprays. The load of coal is then tipped into the hopper, which is below the ground level. Judging from the video presented by Warkworth, the action of tipping raises a cloud of fine coal dust, which rises into the air above the hopper. The maximum elevation of the end of the truck tray when tipping is about 10.5 metres above ground level, so the dust cloud reaches up to this height. If the wind is strong, the cloud moves rapidly downwind, and even in the absence of wind it quickly disperses. If the wind velocity exceeds 100 km/h then operations are suspended, so in terms of dust suppression we need only consider wind speeds in the range 20–80 km/h.

The trucks are of 120 tonne capacity, and are about 11 metres long and 5 metres high. The restricted vision of the driver, the requirements of safety and the sheer size of the vehicles dictate that the road past the hoppers must be wide (about 50 metres), visibility on approach should not be reduced, and no obstacles should be within 10 metres of the hoppers, horizontally or vertically.

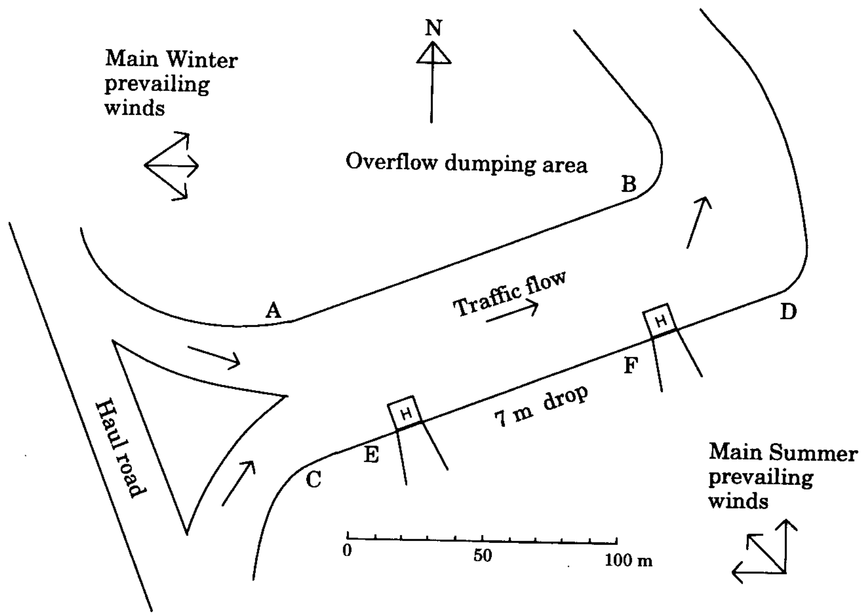

Figure 1: Ground plan of the dumping site at Warkworth's Singleton mine. The two squares labelled H represent the dumping hoppers.

The region marked "Overflow dumping area" in figure 1 is used when either the moisture content of the coal is too high for processing or both hoppers are out of operation. Access is thus needed from the south side. Periodically this overflow area is cleared of coal heaps by a bulldozer.

The whole of the dumping area is on the top of a hill, with the overflow area being slightly higher than the road. On the south side of the hoppers, the land drops 7 metres in a steep grade, and the conveyor belts and the processing plant are at this lower level.

Thus on pragmatic grounds, the most obvious location for a fence would be behind the hoppers, on the line from C to D in figure 1. A fence on the other side of the road, along the line A to B, would restrict access to the overflow dumping area, but a partial fence along this line might still be an option. Short fences could also be built at right angles to the line C—D. For reasons of access and visibility they could not project more than 10 metres into the roadway, and they could not be closer than 10 metres to the hoppers, so E and F would be possible locations. In this case only two sides of each hopper would now be accessible, which would reduce the efficiency of operation slightly.

The literature on the design of windbreaks is mostly based on either field experiments or wind-tunnel tests, although there has been some analytical work (e.g. Counihan, Hunt and Jackson, 1974; Cai, Chen and Soo, 1983) and some numerical calculations (e.g. Wilson, 1985; Crosby, Mathews and Du Plessis, 1990). We shall attempt to summarize the insights of all this work as it applies to our problem. Denote the height of the fence by H and the length by L. The air near the surface of the earth (within about 100 metres if the ground is smooth) forms a turbulent boundary layer with a characteristic roughness scale which we shall denote by z_0, usually estimated as about 10% of the mean physical height of upwind terrain (Papesch, 1992). Denote by ϕ the geometric porosity of the windbreak i.e. the ratio of the area of openings to the total area of the windbreak. Denote the integral length of turbulence in the lateral direction (parallel to the windbreak) by λ, for which a reasonable value is 40 metres (see Gandemer, 1981).

If the mean wind velocity on approach is denoted by U_0, and the kinematic viscosity of air by ν ($\approx 1.5 \times 10^{-5} \text{m}^2\text{s}^{-1}$), then the Reynolds number based on the fence height ($U_0 H/\nu$) will be in excess of 10^5 for $H \approx 10$ m and moderate wind speeds. Under these conditions the flow pattern is not very sensitive to the Reynolds number, and the sheltering effect is mostly dependent on H/z_0 and ϕ (Raine and Stevenson, 1977; Ranga Raju *et al.*, 1988). In the near wake of a porous barrier, a Reynolds number based on the size of the pores ($Re_p = U_0 d/\nu$, where d is the hole diameter) has also been shown to be important (Xuan and Cermak, 1994).

The idea of a windbreak is to exert a drag on the airflow, causing a net loss of momentum and so a sheltering effect downwind. At the same time there is a shear force on the flow, particularly from the top of the windbreak, which leads to increased turbulence. Quantitative assessment of the protection provided by a windbreak is usually some combination of the reduction in mean wind speed and the increase in turbulence, depending somewhat on the intended application. For example, to improve pedestrian comfort one is interested in maximizing protection at head level over a large area (Gandemer, 1979), while for coal dust emission the crucial location is at the surface of the coal pile. A solid windbreak, which would at first seem best, has the disadvantages that it causes a strong upward deflection of the approach flow and a region of large-scaled separated flow in the lee, where turbulent eddying is strong (Raine and Stevenson, 1977). If the windbreak is made more porous, then there is a bleed flow of air through the barrier and the region of separation moves further downwind, with a significant reduction in turbulence for $\phi > 0.2$ (a similar conclusion is reached in the work of Castro (1971) on plates normal to an air-stream).

The region of protection provided by a single moderately porous fence is roughly triangular in vertical cross-section, extending from the fence to a point at ground level about $20H$ downwind, and about 1–$2H$ upwind (Raine and Stevenson, 1977). The region of shelter (in units of H) is reduced somewhat as H/z_0 decreases, or when the wind direction is not normal to the barrier. The latter effect is mainly due to the finite length of the barrier when the angled wind comes around the corner, and it is especially important in the near wake (see Gandemer, 1981). For applications in which downwind shelter in the distant wake at some height is desired, the optimum porosity is usually estimated at $\phi \approx 0.5$, with the fence being more porous towards the top (Gandemer, 1979; Billman Stunder and Arya, 1988). For protection of the near wake (the area of maximum shelter), the optimum porosity is $\phi \approx 0.2$, and the porosity of the lower part of the windbreak is the crucial factor (Gandemer, 1981). Near the ends of the windbreak, an excess wind velocity develops, which can be alleviated by making the barrier porous at these corners, and by putting in an upwind right-angle corner of length about H (Gandemer, 1979). Particularly for the protection of the near wake, the windbreak should be long relative to λ (the integral scale of lateral turbulence) and H (say $L/H > 20$), which also reduces the significance of the corner effects (see Gandemer, 1981).

Sometimes the object in need of wind protection is itself large enough to change the air flow, as is the case with the large piles of coal found in storage yards. Here it has been suggested that a windbreak 1.4 times the pile height and about 1 pile height upwind is best (Borges and Viegas, 1988; Billman Stunder and Arya, 1988; De Faveri *et al.*, 1990).

Another variety of application is the design of snow and sand fences. Here the objective is to cause a sufficient reduction in the mean wind speed (without creating too much turbulence) that the wind-borne material deposits in drifts or dunes. Thus one is more interested here in the areas within 8 to $10H$ upwind and downwind of the fence, and in the structure of the near wake. In spite of this difference in application, the design considerations are much the same as before. A typical snow fence is made of wooden slats equally spaced to give a net porosity of 0.5, and has a gap at the bottom about $0.1H$ high. This results in large drifts on the downwind side but little upwind drift (see Iversen, 1981). A typical sand fence is increasingly porous towards the top, with an overall porosity of about 0.3. In this case the upwind drifts are much larger than the downwind ones (see Bofah and Al-Hinai, 1986). For a fixed total porosity, the near wake seems to be most affected by Re_p, the Reynolds number based on hole size. The aim is to keep the scale of the turbulence small, since then it is easily dissipated. Scattered results in the literature suggest that this is best achieved by keeping Re_p small, say less than 100–200, which in practice means using small circular holes with a diameter of the order of millimetres (see Raine and Stevenson, 1977; Perera, 1981; Xuan and Cermak, 1994).

The dust suppression problem at the Singleton site is reminiscent of the protection of coal piles, since we are trying to reduce the air velocity in the region up to 10 metres above the hopper i.e. around the tip tray of the truck as the coal is dumped. Since we are primarily concerned with winds from the north and west (which blow dust towards the river flats and a public road), the above summary suggests that a fence along the line A—B of height 10 metres and of porosity 50% would be best. The fence would then be about 4 fence heights from the hopper, which would provide a reduction of 40–50% in the mean wind velocity without creating excessive turbulence. But as observed this would cut access to the overflow dumping area. Given the expense of building such a structure, it is tempting to consider constructing it in two sections, with a 60 metre long fence on the line A—B opposite each of the hoppers. This would allow some access to the overflow dumping area. If the wind was from the north then this arrangement would provide reasonable protection. However, given the position of the gap between the fences, this would not protect either of the hoppers if the wind was from the west.

The major alternative is a fence of height 10 metres along the line C—D. On aerodynamic grounds this might seem less satisfactory, since when the wind is from the north or west (the situation of most concern for dust problems), this fence is about 10 metres downwind of the north side of the hoppers. In terms of the area protected, windbreaks are of course much better for downwind shelter, and most of the published data concentrates on this aspect. However in the problem under consideration the area to be protected is relatively small in lateral dimensions (less than 1 fence height) and is close to the barrier. Furthermore, turbulence should not be as significant as in downwind situations, since most of the turbulence is caused by the shear exerted on the wind by the elements of the fence. The wind-tunnel measurements of Perera (1981) show that for a solid fence, at $1.25H$ upwind and a height of H, there is a 35% reduction in wind velocity, while at a height of $0.5H$ the reduction is 55%. For a fence with $\phi = 0.1$ the reduction at height $0.5H$ is about 45%. The numerical results of Wilson (1985) for a fence with $\phi = 0.5$ indicate that at $1.25H$ upwind and a height of $0.4H$, the reduction should be about 30%. This is roughly consistent with the analysis of the downstream wake, which suggests that the reduction in wind velocity should be proportional to $(1 - \phi)$ (see Perera, 1981). Without information about turbulence in this region, one cannot be definitive about the effect on dust emission, but the wind velocity data seems to indicate that quite good protection would be obtained from a low porosity fence along C—D. For a solid fence there is a small recirculation region near the base of the fence, which in this case is just above the hopper, and which would then contribute to keeping the dust in suspension. As well, the action of dumping creates a small up-draught as the coal displaces air. For these reasons, some porosity at the base of the fence would be desirable to eliminate the recirculation.

For economic reasons, we should also consider whether the fence along C—D could be built in two sections without too much loss of protection. The results on downwind protection suggest that for $H = 10$ m, L should be of the order of 100–200 m. As the gap between the hoppers is about 100 m, it is best to make the fence continuous rather than leaving a gap halfway between the hoppers. At present there is a short fence behind each hopper, a few metres high and the same width as the hopper. It is quite possible that the presence of this fence makes the dust situation worse than if it were absent. This is because the fence causes an acceleration of the airflow around the corners and a little way above the fence, which may contribute to the difficulty of controlling the water-sprays and limiting the dust emission. Similar considerations weigh against erecting short fences at right angles to C—D, for example at locations E and F. Since for safety reasons they could not project more than 10 metres into the roadway, with a westerly wind blowing there would again be some acceleration of the airflow around the corner, which could increase the wind-speed at the point of dumping. This acceleration effect could be reduced by making these barriers quite porous ($\phi \approx 0.5$), but given that $L/H = 1$ it is hard to be sure of their effect on the basis of published data for $L/H \gg 1$. For structural reasons it would be desirable to have some such right-angle braces, but unless it can be verified that they would not increase dust emission, they should not be built close to the hoppers.

We have not concentrated on any of the other structural challenges associated with building a 10 metre high fence that can withstand winds in excess of 100 km/h. However for design purposes it is useful to know the wind drag on such a fence, which can be estimated as follows. Define the drag coefficient C_D by

$$C_D = \frac{F}{\frac{1}{2}\rho U_0^2 A}$$

where F is the drag force on the fence, U_0 is the upstream wind velocity, ρ is the density of the air and A is the cross-sectional area of the fence. For a fence with $\phi = 0.5$, $C_D = 0.7$, while for a solid fence $C_D = 1.3$, with some reduction in C_D as H/z_0 decreases i.e. as the terrain becomes rougher relative to the fence height (see Raine and Stevenson, 1977 and Xuan and Cermak, 1994 for wind tunnel results, and Wilson, 1985 for numerical results — note that Wilson does not use the factor of 1/2 in his definition of the drag coefficient). For obvious reasons the drag on the fence is strongly correlated with the reduction in downwind velocity caused by the fence.

The original Warkworth proposal put some emphasis on the role of fences in causing dust fallout on the downwind side. Here the literature cited on sand

and snow fences is relevant. In such applications, the fences need to be long (in order to protect large areas), and for practical reasons not very high, since the vast majority of the mass transport in wind-blown sand and snow occurs within a couple of metres of the ground (Kind, 1990). In the case of coal, there are more small particles, for which suspension is the dominant means of transport. Furthermore, in the dumping problem surface creep and saltation can be ignored, since the coal in the hopper is below ground level. Thus unlike the applications in trapping sand or snow, we are primarily interested in suspended particles, and the source of the particles has a vertical extent of 10 metres. With that proviso, the main conclusion seems to be that a porous fence ($\phi \approx 0.3$) is to be preferred, with greater porosity towards the top, but also with some holes near the bottom to weaken the base vortex (Bofah and Al-Hinai, 1986). This should produce some fallout of dust on both the upwind and downwind sides of the fence. As analyzed above, the holes in the fence should preferably be kept small.

So on the basis of literature data on the performance of windbreaks, and a consideration of the geometry of the site, constraints of the operation, and overall cost, the suggested option would be a continuous windbreak along the line C—D, of height at least 10 metres and extending as far as possible past the hoppers on either end. A balance between the requirements of reduction in mean wind velocity and low turbulence suggests a low porosity, of say $\phi = 0.2$.

3. Numerical testing of barrier design

It is clear from the above discussion that although we can glean some insights from the literature on windbreaks, our application is non-standard in several respects. For a windbreak placed along the line C—D, we are interested in protection of two upwind dumping areas. As the emission of dust occurs while dumping is in progress we must also take into account the aerodynamic effect of the truck. Given these complicating factors, we turned to numerical simulations, using CSIRO's FASTFLO package, a general purpose finite-element code for solving partial differential equations, with modules written for specific applications. In principle, if we had enough time and computational resources we could use this to do computations on the full three-dimensional problem, but within the scope of the MISG only two-dimensional solutions were investigated.

In order to solve the Navier-Stokes equations for a weakly compressible flow at very high Reynolds numbers, we used a $k - \epsilon$ closure scheme to model turbulence, which has been found to be satisfactory for modelling the near wake, but overestimates the effect of the fence in the far wake (see Wilson, 1985 for a comparison of simulation with experiment). Since we have a set of nonlinear

PDE's, the numerical solution proceeds by iteration. The key to avoiding convergence difficulties was to keep the computational domain large, typically $20H$ high, $10H$ upwind of the fence and $70H$ downwind. Otherwise the boundary conditions imposed at the inlet, outlet and the "ceiling" led to instabilities in the iterations and artifacts in the flow. Typically we used a Reynolds number of about 10^5. The flow pattern should be relatively independent of the Reynolds number when it is above 10^4, and very large values of the Reynolds number led to additional stability problems. We ignored the turbulence of the approach flow, and allowed the standard vertical velocity profile to develop between the inlet and the fence. Thus our results should overestimate the sheltering effect of the fence. Since the upwind terrain at the Singleton site (the overflow dumping area in figure 1) has a mean physical height of perhaps 2–3 m, the appropriate value of H/z_0 should be between 30 and 50. The numerical results of Wilson (1985) suggest that the near-wake is not particularly sensitive to H/z_0, although the Raine and Stevenson's (1977) summary of previous tests shows a wider scatter. On the basis of these comparisons, the overestimate in our numerical results for the reductions in mean wind velocity is of the order of 10%.

Porous regions were modelled by an effective viscosity, specified by a local Reynolds number which we denote by Re_v. This avoided the complications of modelling the fine detail of the fence structure. To calibrate this effective viscosity against an actual porosity, we did a series of calculations for a single barrier on flat ground, increasing Re_v from 2 to 20000. By comparing the reduction of mean wind velocity in the lee of the fence with the isotachs given by Raine and Stevenson (1977), we estimated that $Re_v = 2$ corresponded to $\phi = 0.6$ and that $Re_v = 20$ corresponded to $\phi = 0.2$. This calibration could be done more accurately by examining the downwind vertical profiles and comparing to the empirical relation discussed by Perera (1981). Wilson (1985) used a pressure-loss coefficient k_r to model the fence porosity, and calibrated this against theory and experiment. As a check one could compute k_r in our model for various values of Re_v.

The specific design questions that we attempted to address by simulation were as follows:

- Would it be beneficial to have an overhang on the fence?
- Should the fence be porous, and if so how should the porosity be distributed?
- What is the effect of the truck on the flow patterns near the fence?

The idea of an overhang was that it would direct some of the air-flow down towards the hopper, carrying the coal dust with it. This would enable the water

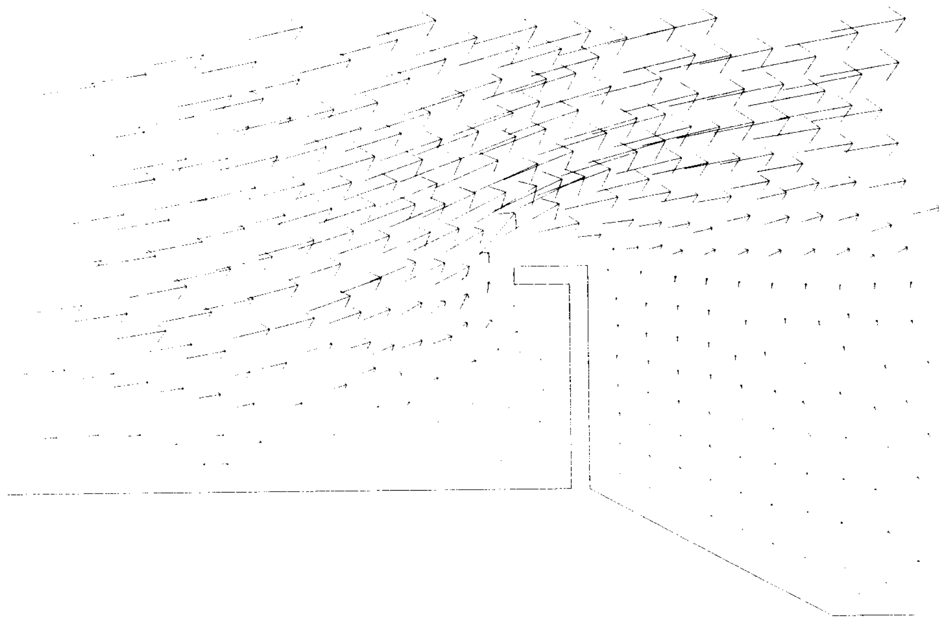

Figure 2: Air velocity in the vicinity of a solid barrier with a right-angle overhang. The length of each arrow is proportional to the local velocity.

sprays to be used more effectively, since at present in high wind conditions the jets of water are blown away from the region where the dust is produced. The disadvantage with this strategy is that a region of turbulent recirculation is created just above the hopper, which tends to keep the dust in suspension. Figure 2 illustrates the flow pattern around a solid barrier with a right-angle overhang. The hopper is located just to the left of the barrier, within one fence height laterally. The wind direction, necessarily being normal to the barrier for a two-dimensional simulation, corresponds to north-west. The drop to the south of the hoppers is shown to scale. Each arrow represents the direction and proportional magnitude of the velocity at that mesh point. By comparison with a straight solid fence, the effect of the overhang is to extend the highly sheltered region immediately adjacent to the fence. The reduction in mean velocity at H upwind and a height of $0.5H$ is about 50%, and at a height of H it is about 30%, which is consistent with the values from published simulations and experiments. However it is noticeable that where the coal is being dumped the direction of air-flow is still upwards, with a very weak recirculation just above the hopper.

The effect of a combination of an overhang with porosity is shown in figure 3. The barrier has $Re_v = 15$, corresponding to $\phi \approx 0.3$. There is a lessening of the displacement flow, so that the direction of flow in the dumping region is more towards the barrier than over it. The area of recirculation just above the

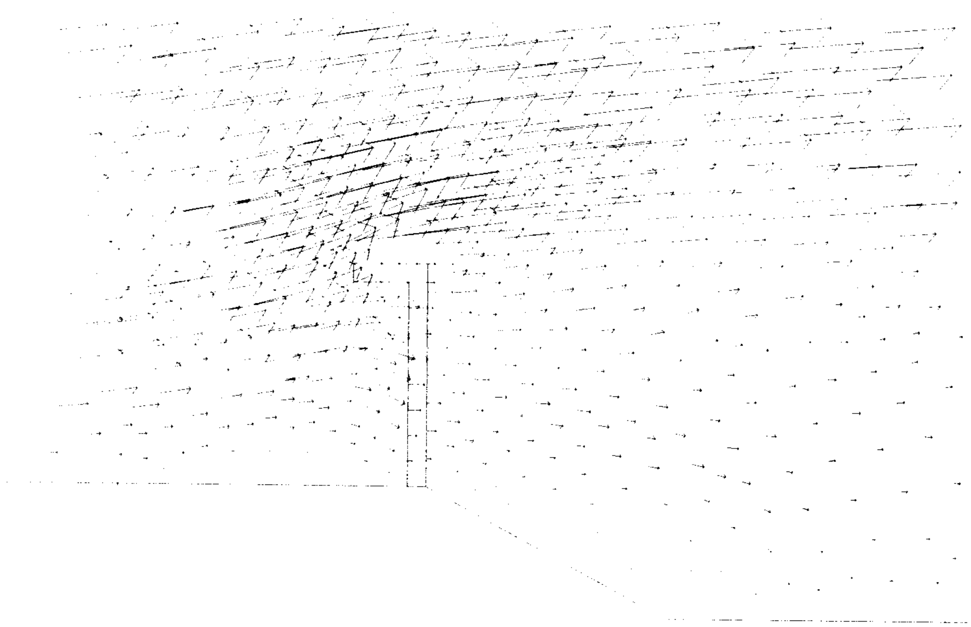

Figure 3: Air velocity in the vicinity of a moderately porous barrier with a right-angle over-hang.

hopper has also been eliminated, as has that immediately downwind. However the reduction in the mean wind velocity upwind of the barrier is also lessened by a factor of about ϕ. In addition, the porosity of the entire barrier largely eliminates the benefits of having an overhang.

The air flow around a more complex design, combining an overhang with partial porosity, is shown figure 4. Here the overhang is angled, which increases the effective height. The barrier has a porous lower section, again with $\phi \approx 0.3$. Some of the airflow is now directed down by the overhang, and now the presence of the porous section prevents the formation of a large recirculation region both upwind and downwind. The reduction in the mean air velocity H upwind is very similar to that observed for the solid barrier with overhang, since the overall porosity of the barrier is low. So in this design there is benefit from both the overhang and the porous section.

The effect of the truck is more difficult to model, since we are doing an inherently three-dimensional problem in only two dimensions. As a consequence, any shape that we use to represent the profile of the truck will overestimate the effect, since in practice the air can come around the side of the truck etc. Indeed, as observed before in relation to side fences, there will be some acceleration of air around the sides of the truck. Figure 5 shows the flow pattern over the stylized

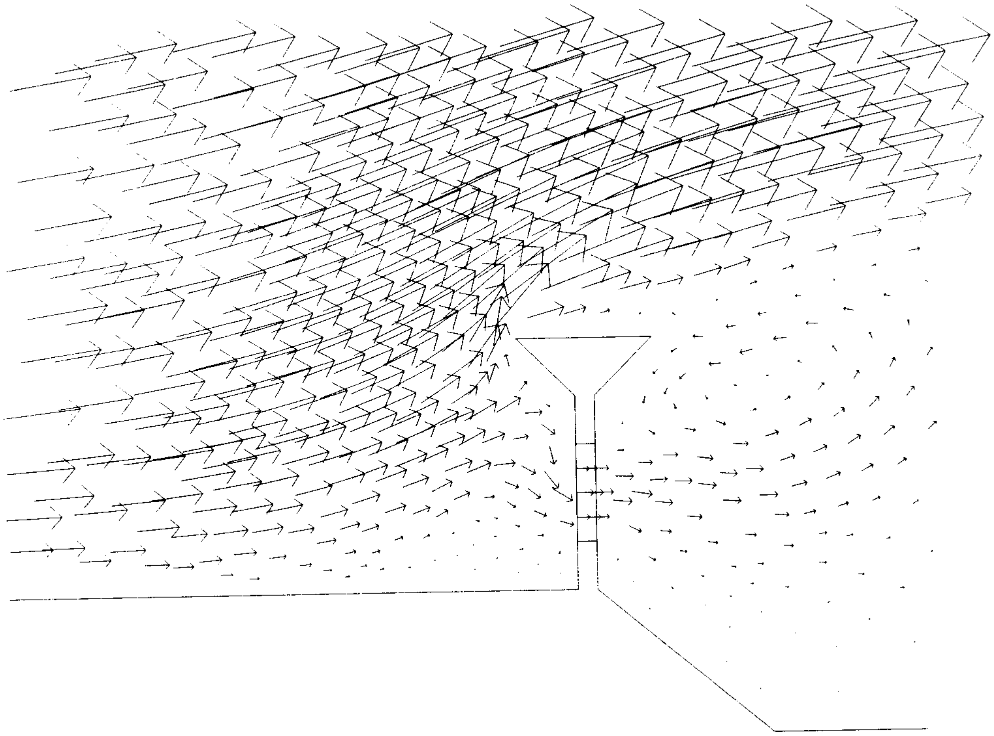

Figure 4: Air velocity around a barrier with an angled overhang and a porous lower section.

truck as it is dumping into the hopper. We assume that the truck dumps from the north side of the hopper, the most usual situation and the only one that we can handle in two dimensions. The largest vertical side represents the tip-tray when upright. As we had hoped, the flow passing the top of the tip-tray is largely diverted downwards by the overhang, which should assist in dust control. The air velocity between the truck and the hopper is very much reduced, an effect similar to that observed between two parallel windbreaks. There is a large region of recirculation between the truck and the fence, with a weak flow through the porous section. Both these effects will be largely overestimated because of the three-dimensional nature of the truck, so the reality will be closer to figure 4 than to figure 5. When the tray is vertical, it is higher than it is wide, and there is a rough comparison to the results of Castro (1971) for plates held normal to an air-stream. Taking the width of the tray as 3–4 metres, then we might expect a region of much reduced velocity but significant turbulent intensity to extend about 10 metres downwind of the tray when vertical. As of course the truck is already present in the current operation, it is clear that by itself it cannot

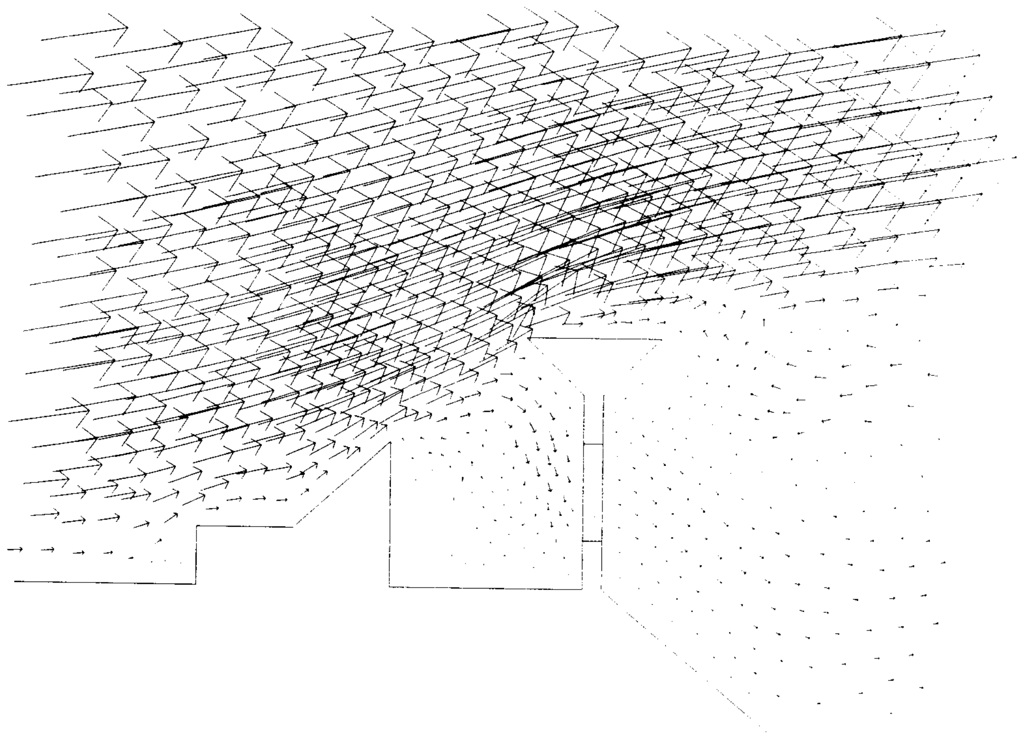

Figure 5: Air velocity over a two-dimensional truck in front of a barrier with an angled over-hang and a porous lower section.

provide much wind protection, especially if the wind direction deviates much from the line of the truck.

Tests were also done for the cases in which the wind was from the opposite direction, and for this reason the fence in figures 4 and 5 has an overhang on both sides. Since winds from the south or east carry the dust back over the mine site, this is not as significant a problem for Warkworth. Also, because the hoppers are then downwind of the barrier, we can make use of the literature results to assess the reduction in wind velocity, the only complication being that the drop to the south increases the effective height of the fence.

The numerical testing, although preliminary in nature, indicates that an overhang should be considered as part of the fence design, because it directs the flow of air downwards and extends the upwind shelter. Since we wish to protect two dumping sites, it should be sufficient to have the overhang only in the vicinity of the actual hoppers and only on the north side of the fence. Bearing in mind the previous discussion on the effects of barrier length, it would seem sufficient to have an overhang of about three metres in width and at least 30 metres long centered around each of the hoppers. The aspect ratio is then sufficient to reduce end effects and the overhang is long enough to cope with winds that are not at right angles to the barrier. Some porosity in the lower section is also desirable to reduce the recirculation and associated turbulence in the region directly above the hopper. The effect of the truck is more difficult to assess, and needs some testing in three dimensions for a quantitative evaluation.

4. Conclusions

The layout and the operating procedure of the Warkworth dumping site are the over-riding constraints on fence placement. A 10 metre high fence of 50% porosity along the line A—B (upwind of the hoppers in the situation of most importance) would reduce the wind velocity at the dumping area by 40–50% without creating excessive turbulence. However this would interfere unacceptably with the use of the overflow dumping area. An equivalent or better degree of shelter could be achieved by a 10 metre high fence along the line C—D, on the south side of the hoppers. The fence should extend as far past the hoppers on both sides as possible. If a section of angled over-hang of 3 metres in width and 30 metres long could be added to the fence near each hopper, this would increase the protection and direct the air flow down towards the hopper. With or without the overhang, a section of moderate porosity ($\phi \approx 0.3$) near the base of the fence would help to reduce recirculation of the air above the hopper, and increase the fallout of dust.

The fine details of the fence design were beyond the resources of our simulations. Information in the literature indicates that small circular holes of a few millimetres or less in diameter would be the best way to make the fence porous, which suggests punched metal sheeting. Estimates of the drag coefficient also give some guidelines for the necessary mechanical strength of the fence construction.

A more accurate quantitative assessment of the reduction of dust emission, taking into account the presence of the truck, local topography and the length of the fence, would require either three-dimensional simulations or wind-tunnel testing. The latter is preferable, since it allows the use of real coal dust and direct measurements of particle emissions.

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