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Planning passive snowdrift reduction on high-altitude roads with lateral obstacles to wind flow

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ABSTRACT

The prediction of snowdrift formation on high-altitude roads is of interest for road maintenance tasks and planning of ski resorts. In this study a three-dimensional time-dependent computer model of drift formation is presented, that takes into account the effect of natural orographic formations, natural obstacles such as trees, man-made obstacles, the form of the road bed and its adjacent embankments. A 3D air flow model is coupled to a snow transport model and parametrized with time-variable air speed, temperature and snowfall density. The snow transport model takes into account both primary and secondary transport. Domain morphology and surface friction alterations due to accumulated snow are tracked and used in successive calculation time steps.

Direct applications of the resulting tool are discussed: modelling and understanding existing road configurations under different wind and snowfall conditions, but also predicting the effects of proposed alterations to the road bed and the elements around it. With careful design of embankments both above and beneath the roadbed, it is foreseen that airflow can be canalized in such a way to induce passive snowdrift removal with no need for mechanical intervention under favourable conditions. Techniques include embankment profiling and the addition of fixed aerodynamic elements in order to increase secondary snow transport away from the roadbed and into the adjoining spaces. Their possible application to a real-world scenario in Andorra is presented.

Keywords: secondary snow transport, snowdrift, CFD, open-source software, snowdrift reduction

1 INTRODUCTION

Though modern transport technologies can help us face the challenges of maintaining road access during adverse winter conditions in mountain areas, the increasing numbers of vehicles accessing these areas during ski seasons can give rise to difficult situations such as that recorded in Andorra on December 8th 1990, when large quantities of tourists became stranded with their vehicles during an unexpectedly intense snow storm. Even this winter, major roads on high ground in the Jerusalem area were closed to traffic during several days [1] creating inconvenience and potentially dangerous situations for users. However, personal experience shows us that not all road segments are equally exposed to snow drift accumulation; vehicles tend to lose traction and get stuck in a recurring in the same places, causing traffic build-ups behind them.

Primary snow transport occurs when snow is initially deposited through the falling snow process. Secondary transport, on the other hand, concerns wind erosion of already deposited snow in some places, and re-deposition in others. Secondary snow transport mechanisms have received much attention since Masao Takeuchi's seminal work on simple snow transport [2], on which other investigators have built upon in order to study snow transport altered by the presence of obstacles [3] or completely build-up urban scenarios [4].

On the other hand, computer-based models have been introduced to help research the formation of snow-drifts arising from secondary transport. The Prairie Blowing Snow Model (PBSM) was developed in order to model transport in flat environments [5], while the commercial FLOW-3D code was adapted to model snow drift formation around building steps [6] and cubic obstacles [7]. A further development was SnowTran-3D, destined to model fluxes on topographically variable terrain [8] and into which forcing by meteorological data was introduced [9]. The current generation of models include ALPINE3D [10], based on a radiation balance model to take into account snow pack transformation through sublimation.

Both empirical and computer-based models have been used to predict passive techniques to reduce snow accumulation in the form of drifts. The best-known methods include the placing of either artificial [11],[12] or natural [13],[14] snow-fences. These were in the first place placed upwind of the road bed and calibrated to allow snow to accumulate, thus forming a barrier impeding further secondary snow transport onto the road. A further development is leaving a gap at the bottom of the fence, thus increasing efficiency. However, snow fences have been shown to loose effectiveness as slopes increase [15]. As a related development in Arctic regions, triangular vortex generators have been described to keep aircraft runways clear of snow [16], though this technique depends on the high wind speeds present at such locations.

In this work, we model snow formation on high-altitude roads that present high slope formations on one side. We present a computer model based on the OpenFOAM open-source tool-kit, that integrates primary and secondary snow transport models. Snow deposition and subsequent transport is studied in two precise locations in Andorra. Alternative slope formations are modelled and the results discussed. We conclude with several practical recommendations for taking passive snow drift removal techniques into account during high-altitude road design.

2 MATERIALS AND METHODS

A 3D computer model of primary and secondary snow transport has been constructed, implementing a mixed Euler-Lagrange model in two steps.

In the first step, the Reynolds-Averaged Navier-Stokes equations for incompressible flow are solved using the CFD tool-kit. The κ-ε turbulence model [17] is used in conjunction with a simple slip boundary layer condition and solved with the PISO method [18]. This model is in essence identical to that used in our previous work [19].

In the second step, a simple Lagrangian model is constructed to follow the movement of individual snow particles in two stages (Figure 1). In the first stage, low wind conditions typical of heavy snowfall are used to calculate primary snow deposition during the initial snowfall period. In the second, secondary wind transport is modelled in the higher wind conditions typical of a post-fall time period, during which existing surface snow is eroded by wind and re-deposition results in snow-drift formation and compaction.

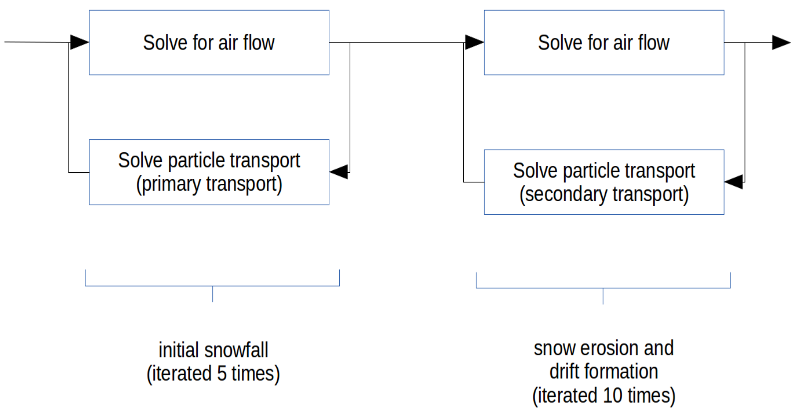

Figure 1. Model block diagram.

We consider snowfall heights of 8 kg/hour/m^{-3} and snow particle vertical speeds of 0.7 m/s, giving an average snow density $\rho_{snow} \simeq 3.10^{-3}$ kg.m^{-3}, while the average density of the air fraction $\rho_{air} \simeq 1$ kg.m^{-3}. With this large difference in average densities of the fluids, no Boussinesq approximation in possible [20], leading to separate modelling of both flows, implementing a one-way coupling to reduce computation overhead.

The existing OpenFOAM libraries for solving particulate motion within a fluid such as *solidParticleFoam* were not used. The rationale behind this decision was two-fold. On the one hand, snow parcel movement is complex to implement, specially during secondary transport, and for this reason a specific solver within the OpenFOAM infrastructure would have had to be implemented. On the other hand, individual snow parcel tracks are do not react between each other within a singly-coupled system, and for this reason their simulation may be treated as independent computations that are implemented using traditional programming techniques.

3 RESULTS AND DISCUSSION

In Andorra, heavy snowfall situations are often associated with north-western winds, caused by a cold Atlantic front in combination with low pressures over Europe [21]. The wind direction for situation analysis is from the North in situations. With this parameter, three different situations have been modelled.

3.1 The road to Cortals d'Encamp

Taking as an example the secondary road to Cortals d'Encamp, Andorra, this road has been cut into the mountain side on either side of the Riu dels Cortals valley arriving at the funicular terminus station at the top of the valley. The river in this valley runs from East to West, while winter snowstorms in this region come in from the north or north-west, running down the hillside from right to left in Figure 2.

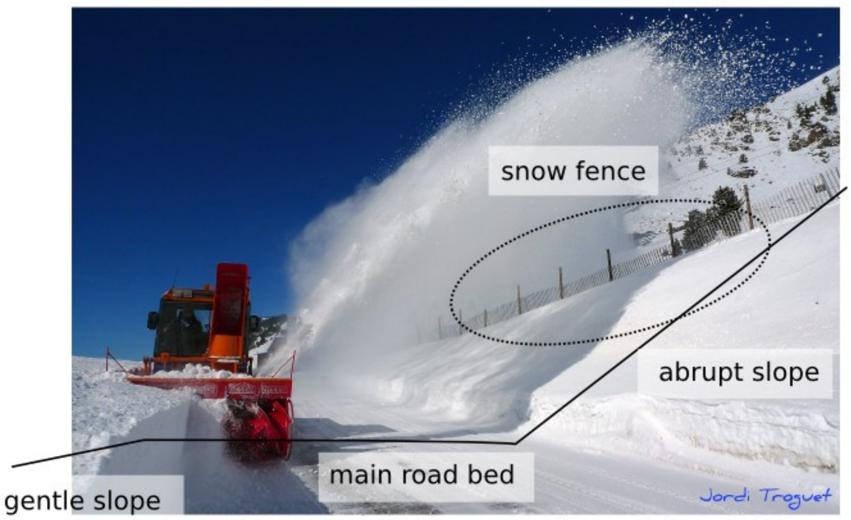

Figure 2. Snow bank formation at Cortals d'Encamp, Encamp, Andorra.
Photo credit: Jordi Troguet © 2012.

In this Figure, it can be seen that the slope into which the road-bed has been cut is rather abrupt, while a locally more gentle slope has been reserved to the left side of the image, that runs down into a further vertical slope to the next curve in the road lower down.

This is a less-transited road that has its importance both for agricultural activities (in summer) and for tourism (in winter). Being a secondary road, passive means of reducing snow cover are suitable for reducing dependency on the snow-ploughs that may have to prioritize work on major roads with heavy traffic. We thus note the presence of segments of snow fence on the slope above the road bed as a means to reduce drift formation, and the fact that snow turbines must be used instead of the more economical blade ploughs to clear accumulated snow fall, perhaps due to the lower service frequencies.

In this scenario, three different slope profiles have been modelled (Figure 3), all with average slope 2:1 into which the road-bed has been cut. In all cases modelled, the bed in comprised in horizontal coordinates 20 to 30 (dimensions in meters). The model has been submitted to five 20cm partial falls of snow (blue dotted lines) comprising the first stage, after which ten individual periods of secondary transport have been implemented (dotted red lines), with snow cover ending at the final position denoted by a continuous red line.

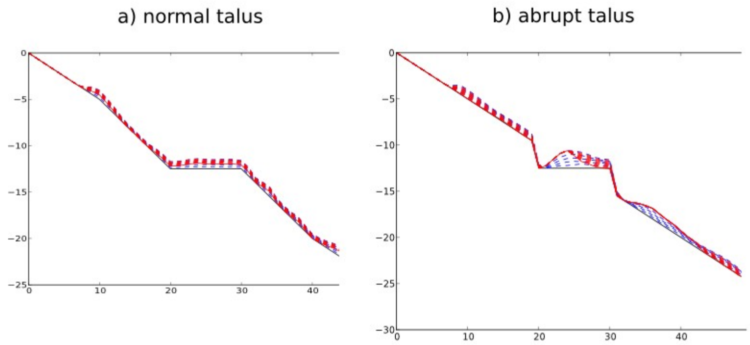

Figure 3. Snow deposition and secondary transport with three different slope profiles. Wind direction is from the reader's left.

In sub-figure (a), the existing slope has been shown. Snow-fall coming from the top of the slope has deposited a regular layer of snow on the road bed, which has then been eroded by subsequent stronger wind up to half of its depth.

In sub-figure (b), the same situation has been modelled, but with a steeper slope immediately to either side of the road bed. This configuration gives rise to an area of relatively low air flow above and to the left of the road bed. Snow particles have the time to drop and accumulate on the road-bed itself, forming a snow-drift of considerable dimensions (up to 3m). However, the abrupt convex form to the right of the road-bed tends to accelerate airflow in contact with the surface, and subsequent secondary transport is increased eroding the snow-drift and transporting part of its material down-slope and -perhaps- on to the next road curve situated beneath this segment.

Finally, in sub-figure (c), the same road-bed has been placed in between slope sections profiled so as to create a smooth surface for which the wind to flow upon. Snow deposition in consequent all across the road-bed, due to slower air speed (Figure 4) in contact with the surface than in cases (a) and (b). Contrary to expectations, this situation does not permit subsequent wind erosion to evacuate the snow; rather, erosion is confined to the region of the road-bed situated to the right of the figure, leaving a considerable snow-drift occupying the left shoulder and half the road-bed.

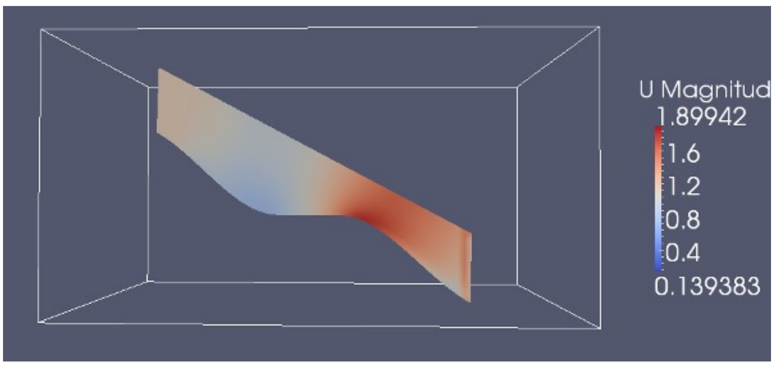

Figure 4. Wind speeds calculated by the model in case (c) above.

We can thus see that slope profiles may have a strong influence both on the initial deposition of snow, and on the subsequent partial erosion and formation of snow-drifts.

3.2 The “Túnel de les dos Valires” access bridge

The tunnel “de les dos Valires” was built in 2012 to connect the parishes of La Massana and Encamp, in Andorra. On the La Massana side, a suspension bridge (“Pont de Lisboa”) was built to connect the tunnel mouth to the existing road infrastructure. The bridge crosses the Valira river valley in the East-West direction, and is subjected to north winds during winter that carry snow whenever a suitable front comes in from the Atlantic, blowing orthogonally across the road bed, from left to right in Figure 5.

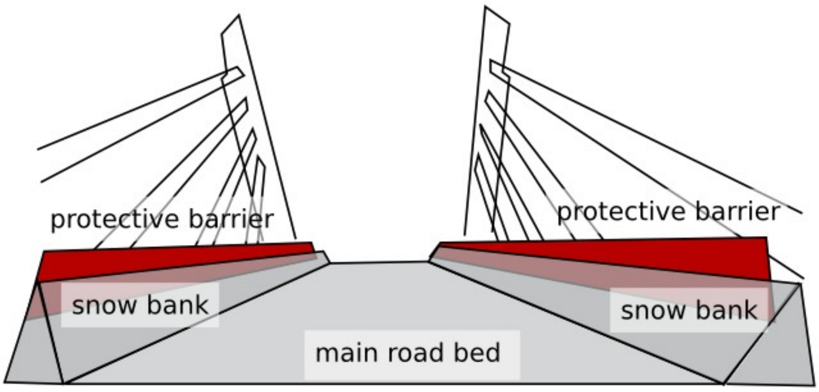

Figure 5. Túnel de les dos Valires access bridge, La Massana, Andorra. Wind direction is from the reader's left.

Both road-beds of this double bridge carry suitable safety equipment, including a protective barrier on each side, situated between the road bed and the suspension cable anchorage points. However, this approximately 1m-high porous barrier acts in winter as a rather effective snow fence, slowing down air flux above the bridge road-bed and allowing snow drifts to form on both sides of the bed.

The mechanical action of snow-ploughs required to clear the road further develop and compact the snow bank on each side, consolidating the obstacle to the crosswind and allowing further snow deposits to accumulate. This situation has been modelled in Figure 6.

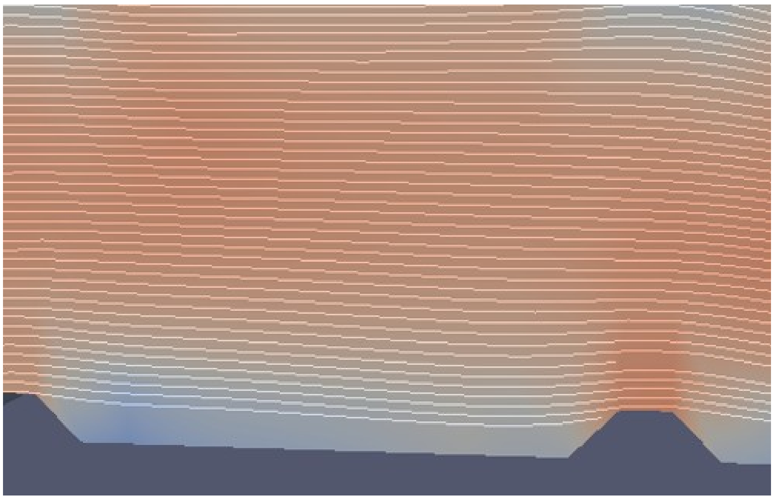

Figure 6. Air flow above the bridge road-bed.

Regions of slow-moving air are observed above the road bed beneath the tops of the lateral snow-banks. This situation permits snow particles to fall directly onto the road-bed without any perturbations. Afterwards, neither can any secondary transport take place since the main flow of air is blocked mainly by the upwind obstacle, though the downwind obstacle has an influence (to the left of Figure 6).

The snow transport stage of the computer model confirms these results (Figure 7). We see an initial deposit of snow that conforms to the surface, taking into account both constructive elements and accumulated snow. This deposit is then reduced by secondary erosion that affects only snow above the lateral guide-rails, leaving the main body in place occupying the totality of the road-bed. This situation could be alleviated by making the guard rails more open to airflow, which could then sweep at least part of the freshly-deposited snow off the bridge..

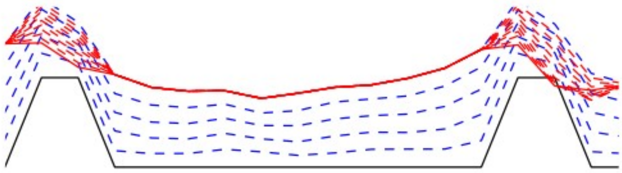

Figure 7. Formation of a thick layer of snow on the bridge road-bed.

3.3 Stationary temporary obstacle on road

When a heavy snowfall is foreseen, orders are often given to keep large vehicles such as trucks and busses off the road. However, forecasts can not always be effective or sufficiently heeded, and such vehicles at times get stuck. Traffic behind them is impeded, and at times also gets stuck, causing difficulties for efficient removal of snow. A further effect that may be taken into consideration is the effect of a large vehicle on air flow around it.

In this third and last model we placed an obstacle of dimensions 3 x 10 x 4m on the mountain road previously studied in section 3.1. Airflow was forced around the front and rear of the immobilised vehicle, but also back up above it. Two areas of slow-moving air are formed up- and down-wind of the vehicle, in blue in Figure 8.

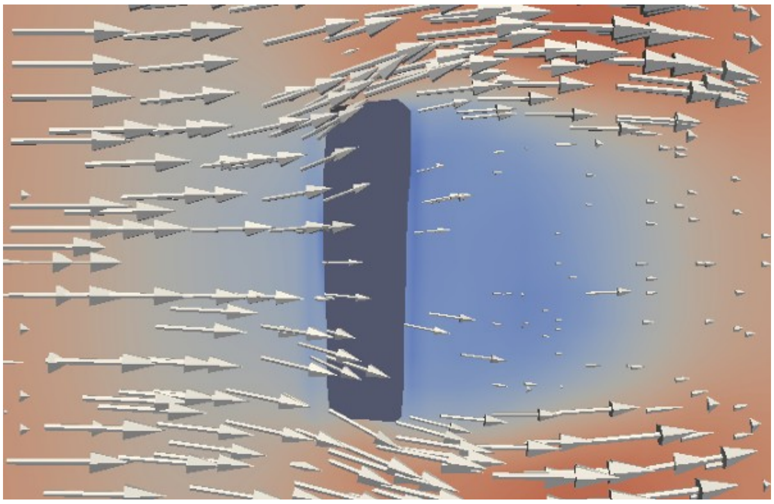

Figure 8. Airflow around a large vehicle, immobilised along the road.

During initial snowfall, snow-laden air entering the upstream slow-moving area has time to deposit the snow in this region of the road-bed between the vehicle and the slope above. A large snow-drift forms in this space. Once over and behind the obstacle, little further snow deposits are formed on the other side (Figure 9). During the secondary transport phase, some of the deposits on the vehicle itself may be eroded and transported away from the road, however the drift between the vehicle and the upwind slope is protected by the zone of low wind-speeds and so remains in place.

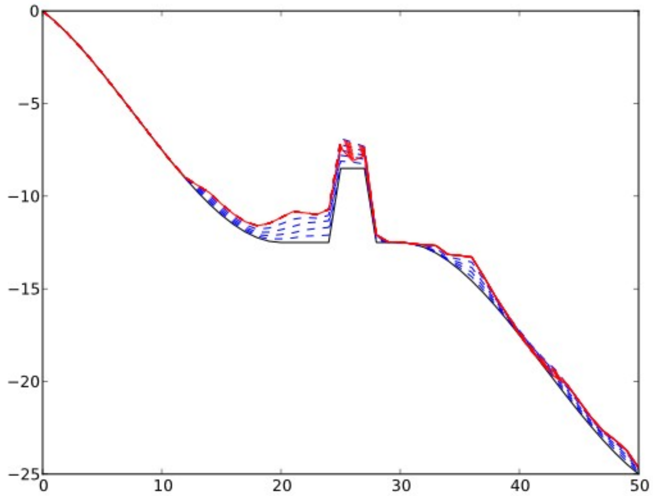

Figure 9. Formation of a snow drift between an immobilised vehicle and the slope above.

If there should arise such a situation where a large vehicle should be temporarily left on the open road during a heavy snowfall, it would seem preferable to place the vehicle as far left as possible, given the circumstances, closer to the mountain slope and upwind of the road-bed. In this place, it could contribute to reducing the load of snow on the road-bed itself. However, it is foreseeable that removal of the vehicle itself would be hampered by the accumulated snow, requiring mechanical removal before initiating vehicle extraction.

4 CONCLUSIONS AND FURTHER REMARKS

In this work, we have constructed a 3D air flow model using an open-source CFD tool-kit, that allows us to model different configurations of high altitude roads, of neighbouring slopes and of other obstacles such as vehicles. Both initial snow deposits and secondary transport are modelled.

Applied to three different scenarios, this computer model shows us in the first place how the forms given to lateral slopes during road construction channel cross-wise air flow. Roads cut into gentle slopes tend to receive more snow deposits on their surface, though if winds are strong enough after the main snowfall episode, secondary transport may partially remove the layer (case (a)). If the cut-out constructed to hold the road is abrupt (case (b)), snow is deposited in an irregular fashion on the road-bed, and a zone of lower air-speeds is formed which does not allow snow evacuation during the phase of erosion. If the slopes on either side of the road are too profiled and hold little asperities, some of the layer deposited will be eroded, but in a partial manner and leaving a snow-drift in place on the inner (mountain) side of the way. Road slope planning is thus important to help evacuate part of the snow layer through passive means.

In the other two scenarios, we have seen how road construction elements such as guard-rails, or large vehicles that remain in place during the snowfall and secondary snow transport affect the formation of snow-drifts on the road-bed. It is clear that these effects may also be expected induced by the presence of road-side constructions such as buildings or containment walls.

On the other hand, little is known about the use of fixed artificial elements such as those presented in [16] to create vortices and channel air-flow into areas of interest. For this reason, it is suggested that further studies, both physical and computer-based, are required to investigate in what form and under which circumstances such elements could help reduce snowdrifts in a passive manner, thus also reducing workload on road maintenance crews and the energy dependency of the country as a whole.

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