Cold Regions Science and Technology 132 (2016) 33–43

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

A new methodology for planning snow drift fences in alpine terrain

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ARTICLE INFO

Article history:
Received 10 November 2014
Received in revised form 8 September 2016
Accepted 10 September 2016
Available online 12 September 2016

Keywords:
Terrestrial laser scanning
Snow drift
Snow fence
Blowing snow
Wind field modelling

ABSTRACT

The planning of snow fence constructions in alpine terrain is site-specific and lacks published guidelines. A methodology of snow drift analysis for the evaluation of snow drift constructions is presented. The background to the methodology are recent findings of time series of spatial snow depth maps obtained by laser scanning over a period of several years, where snow accumulation patterns over a whole winter season were similar in different years of observation. It could be concluded that the knowledge of spatial snow distribution at annual peak accumulation provides a reliable basis for the planning of drift constructions. It was hypothesized that snow accumulation patterns at a new project site could be assessed using a combination of snow mapping via terrestrial laser scanning and high resolution numerical wind field modelling. Modelling results localized areas of large vertical and horizontal wind speeds, which coincide with extrema of wind stress on the snowpack surface. TLS surface maps provided the spatial snow depth distribution, and erosional and depositional zones were apparent. Insufficiencies in fence functioning at the study site were determined and adaptations to fence constructions using existing recommendations could be applied. The functionality of the fences was significantly improved using the presented methodology, so it is recommended that future construction projects consider a similar site evaluation.

1. Introduction

Snow drift is the general term used to describe the re-distribution of previously deposited snow by wind over short and long range distances. Snow drift processes may be more specifically defined as *drifting snow*, which includes only the saltation processes, and *blowing snow*, which refers to suspension processes; the term snow drift will be used here to describe both processes. Furthermore, spatial redistribution of newly falling precipitation, termed *preferential deposition* (Lehning et al., 2008), is another important source of spatial variability in snow deposition. The danger of snow drift arises when the re-deposition area occurs within unfavourable terrain, for example in an avalanche release zone, or when cornice formation is accelerated. Wind drifted snow can create significant loading to the existing snowpack and is a major contributor to the release of slab avalanches. Furthermore, increased snow loading within the release zone can cause damage and loss of functionality of permanent protection constructions.

Permanent constructions against natural hazards are a fundamental element of the protection concept in the European Alps. In the case of snow drift, snow fences are constructed on drift-prone plateaus and function by interrupting the flow of local wind fields. As such, fences mitigate the effect of drifted snow masses by encouraging snow accumulation in defined areas and preventing snow accumulation in hazardous areas. The planning of snow drift constructions in alpine terrain is more challenging compared to that in flat terrain due to the greater site-specificity of each project.

The resulting spatial patterns of snow drift are determined primarily by the small-scale wind fields forced over the local topography and the snowpack properties (Lehning et al., 2008). In order to analyze the wind field, observation or modelling techniques must be of sufficient resolution to resolve the main structures of atmospheric flow in alpine terrain (e.g. speed-up, channeling and flow separation). Without these considerations the resulting descriptions of drift in alpine terrain are inadequate (Raderschall et al., 2008; Mott and Lehning, 2010). A complete review of state of the art numerical wind field and snow drift modelling can be found at Schneiderbauer and Prokop (2011). The Advanced Regional Prediction System (ARPS) is a high resolution, meso-scale atmospheric model developed at the Centre for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma (Xue et al., 2000, 2001). This is a three-dimensional, numerical model based on the non-hydrostatic and compressible Navier-Stokes equations. Although originally suited to the prediction of cyclones, the adapted "Submeso" version (Anquetin et al., 1998) enables the application of ARPS to complex alpine terrain and has previously been applied to small scale wind simulations (cf. Hug et al., 2005; Lehning et al., 2006; Mott et al., 2008;

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http://dx.doi.org/10.1016/j.coldregions.2016.09.010

Raderschall et al., 2008). Wind field modelling can also been approached by other atmospheric models (e.g. Vionnet et al., 2014) or computational fluid dynamics (CFD), in which case the atmospheric components are considered by the inclusion of supplementary codes. Different CDF solvers have also been successfully used in the modelling of wind flows for the analysis of snow drift events (Gauer, 1999, 2001; Hug et al., 2005; Schneiderbauer et al., 2008; Schneiderbauer and Prokop, 2011). Gauer (2002) discussed the use of CFD for numerical snow drift modelling as a decision making tool in the planning of avalanche protection measures and concluded that further verification of such models is necessary. Other trials of numerical snow drift modelling around fence constructions have been published (Uematsu et al., 1991; Sundsbo and Hansen, 1997; Naaim-Bouvet et al., 2002), but lack validation for alpine terrain and is challenging enough even on flat terrain (Wilson, 2004).

Rather than having to verify the results of a model, it is possible to measure the actual resulting snow distribution after a snow drift event or season; to do so however, the local topography must be represented at an adequate resolution. Terrestrial laser scanning (TLS) is a technique that enables high resolution mapping of surfaces and the applicability of TLS for monitoring the spatial distribution of snow has been previously verified (Prokop, 2008a; Prokop et al., 2008). This allows measurement of both absolute and relative snow depth changes over a period of time. A methodology is therefore proposed that combines TLS with high resolution wind field modelling for the evaluation of seasonal snow drift (including preferential deposition). This high resolution methodology has already been documented to analyze avalanche starting zones for decision makers (Prokop, 2008b; Prokop and Delaney, 2012; Prokop et al., 2014). The aim of the current study is to apply this methodology to a new test site and to extend it to the assessment and re-planning of existing snow drift constructions.

2. Background to the methodology

The methodology presented in the following sections is based on the outcome of previous unpublished work by the current authors dealing with the evolution of spatial snow depth distribution on slopes in alpine terrain and the literature published in recent years that quantify the inter-annual consistency of snow depth (Deems et al., 2008; Schirmer et al., 2011; Revuelto et al., 2014; Helfricht et al., 2014. In those work it could be concluded that: 1) the snow accumulation patterns over a whole winter season are similar in different years of observation, with variations only in absolute snow depth and 2) single storms from the prevailing wind direction produce similar snow accumulation patterns as the highest seasonal snow depth distribution. The existence of a prevailing wind direction at a site is mandatory for these results. For the planning of snow fences it can therefore be concluded that, if one prevailing wind direction is apparent at an area of interest, the knowledge of the spatial snow depth distribution of even one winter season can provide a reliable basis for the planning and dimensioning of constructions (the overall snow accumulation and wind patterns are important for the planning process rather than a single storm).

3. Study area

The methodology was applied to a new project site, which was chosen based on a request by the local authorities to assess the functioning of existing snow drift constructions. The site is located in western Austria in the province of Vorarlberg, district Bludenz (Fig. 1). As seen in Fig. 1, the topography is steep alpine terrain prone to snow drift events from a prevailing main wind direction. The average elevation is 2300 m. The windward slope of interest has a length of approximately 1 km with an average upward slope of 20°, increasing to 30° in the final 100 m. The ridge is limited in width (8–20 m) and drops off steeply on the leeward side into an avalanche release area that has a width of 120 m and an average inclination of 40°. Fig. 1 provides an aerial view of the existing construction measures: snow drift fences on the ridge with a height of 4 m and running length of 280 m; and snow bridges within the release zone with an average height of 4 m and areal coverage of 120 m^2. These constructions are repeatedly over-snowed in moderate to heavy winters.

4. Methods

The methodology contained four steps: First we used spatial snow depth mapping using TLS and image analysis for the identification of snow fences issues, we further used the information provided by wind field modelling to better understand these issues. Then based on this analysis we made propositions to improve the snow fences. Finally we evaluated the impact of re-planning of the snow fences using TLS measurements. We now explain each step in detail.

4.1. Snow depth mapping

4.1.1. Terrestrial laser scanning

TLS has been previously verified for snow depth mapping (Prokop, 2008a, 2009; Prokop et al., 2008) and numerous applications of this method have been documented (Prokop, 2008a, 2009; Grünewald et al., 2010; Mott et al., 2010; Teufelsbauer, 2009; Wirz et al., 2011; Prokop et al., 2015). In the current study, TLS was used for monitoring the spatial distribution of snow in the windward fetch area. Scans were performed before and after major drift events within the winter season (total of 4 scans). The scanning area covered the length of the fetch (ca. 1000 m × 500 m) up to the point of the snow fences, which allowed for scan completion within 1 h.

The suitable equipment was chosen based on previous experience (Prokop, 2008a, 2009). The Riegl LPM-321 (Riegl® Laser Measurement Systems, Horn, Austria) has the following technical features: wavelength of 0.9 μm, measuring range of 4000 m, beam divergence of 0.8 mRad, resolution of 3 cm at a target range of 100 m, and measurement accuracy of ±5 cm at a target range of 500 m (Prokop et al., 2008; Prokop, 2009). Positioning of repeated scans was exacted using differential global positioning system (GPS) and seven tie points within the scanning area. The resulting point cloud data could therefore be georeferenced and registered, meaning that the data points were transformed from the local coordinate system of the scanner into a referenced coordinate system. Filtering of the data was done using the wedge filtering approach (Panholzer and Prokop, 2013) using RiPROFILE and ArcGIS software and final spatial snow depths were derived by computing the difference in vertical distance of two digital snow surface models.

4.1.2. Image analysis

The quantification of snow distribution on the leeward depositional slope was determined using traditional aerial photography integrated into the ArcGIS environment. Airborne and terrestrial photography were performed between February and early April 2009. Determination of snow heights was derived from percentage coverage of the snow bridges of known heights. Points were set every 5 m along the bridges and the point layer was transformed into a raster of 1 m resolution using nearest neighbour interpolation. The same image analysis was carried out for three other extreme snow years (1999, 2003, 2012).

4.2. Wind field

4.2.1. Automatic local wind station

In the current study, wind data from two regional stations were investigated: 1) Galzig, a mountain station at 2025 m, and 2) Warth, a valley station at 1500 m. Historical meteorological data from regional stations are often used as reference data for a neighbouring area of interest; however, as wind patterns are variable over complex terrain (Winstral and Marks, 2002), regional stations may not be representative