ロシア・サハリン市街地におけるデブリ被覆が人工積雪の融解に及ぼす影響
Debris-modulated ablation of anthropogenic snow patches in urban Sakhalin, Russia

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1. Introduction

Dozens of scientific papers on snow hydrology and snow science are published annually in peer-reviewed literature. Despite this, we are still facing practical unresolved questions about daily life in snow-bound regions, and in particular about snow disposal after street cleaning operations.

Urban areas that experience heavy snowfall, such as Sapporo (Japan) and Yuzhno-Sakhalinsk (Russia), face considerable challenges associated with winter street cleaning and snow disposal. The sheer volume of snow represents a serious burden, not only on local authorities and land management agencies, but also for the environment. Regular disposal of dirty snow may lead to the formation of perennial snow patches, which generate polluted meltwater. This meltwater presents a significant cumulative threat to local environments, plants, rivers, aquatic ecosystems and soils. In Yuzhno-Sakhalinsk, for example, a range of negative ecological effects has been observed after snowmelt, including vegetation damage and dead trees, soil degradation, formation of swamps, eroded roads, flooding of nearby structures, and the deposition of refuse (*Podolskiy et al., 2015*).

The intention of this investigation is to highlight how glaciological knowledge and techniques from remote areas could be applied to address geotechnical challenges associated with urban snow storage. The original results of this study have been recently published (*Podolskiy et al., 2015*), and the purpose of this discussion is to disseminate the findings more widely and encourage Japanese snow scientists and practitioners to proceed with further in-depth investigations of the effects of snow disposal on local environments.

2. Snowmelt patterns

Snow tends to melt quickly in early spring in low-elevation mid-latitude regions. However, anthropogenic redistribution of snow during street cleaning operations causes some snow patches to survive the summer ablation season, and thus become perennial cryospheric features. Recently, we investigated two giant anthropogenic perennial snow patches on the outskirts of the town of Yuzhno-Sakhalinsk. These snow patches can reach heights of 10–20 m, with areas and volumes of 15 ha and $\sim 1 \times 10^6$ m^3, respectively. This volume of snow is comparable to that produced by street cleaning in much larger cities such as Montreal, Canada. The results of the study showed that snow patches' longevity is likely related to the insulating effect of surface debris composed of refuse and lithogenic material (*Podolskiy et al., 2015*). This layer of debris is gradually formed from refuse and lithogenic materials mixed with snow, and may have grass growing on its surface by June. The growth of vegetation on debris-covered glaciers is rare, but has been reported by *LaChapelle and Post* (*2000*).

Figure 1 shows photographs of two snow patches in Sapporo and Yuzhno-Sakhalinsk. There is a sharp contrast in the amount of refuse in remnant snow at each site, with the Sapporo snow being much cleaner. The cultural difference in the amount of refuse left in streets therefore has an important effect on the physical behaviour of these cryospheric objects. Furthermore, the layer of refuse appears to behave similarly to debris on glaciers, in that it plays a key role in controlling summer ablation (Fig. 2).

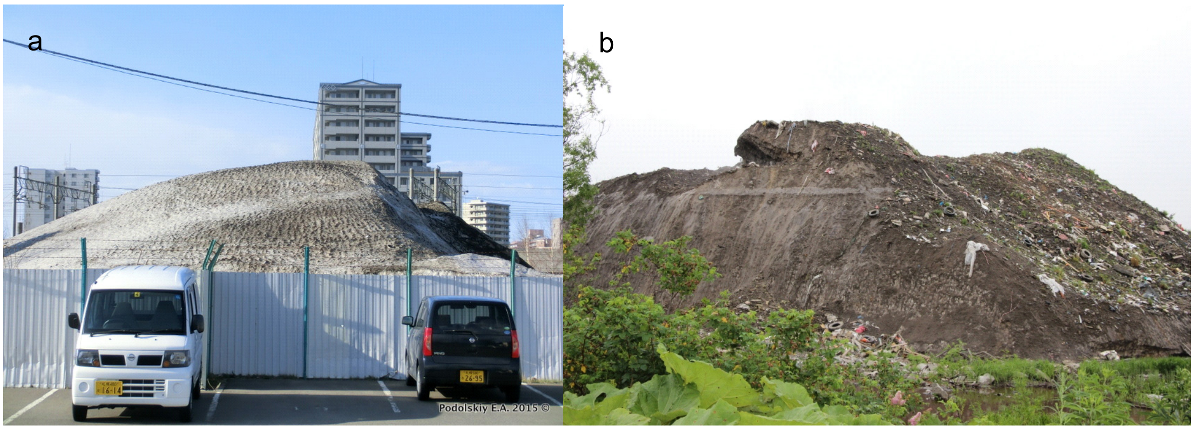

Fig. 1: a) Snow patch near Sapporo Station (photograph taken by E. A. Podolskiy in April, 2015);
b) Snow patch #2, Yuzhno-Sakhalinsk (photograph taken by V. A. Lobkina in July, 2011).

This research highlights the challenges associated with understanding these anthropogenic cryospheric features, as well as key operational and geotechnical questions that remain to be tackled. For instance, there are currently no suitable disposal methods or water treatment facilities to prevent meltwater from degrading the environment.

Fig. 2: Fedchenko Glacier, Tajikistan, Pamirs (photograph taken by E. A. Podolskiy in August, 2009).

3. Using *in situ* monitoring with numerical modelling for geotechnical applications

Using 4 years of monitoring data, chemical analysis and numerical modelling, we attempted to provide a first-order estimation of water discharge and associated pollution from anthropogenic snow patches. As previously mentioned, we argue that snow patch behaviour is modulated not only by meteorological conditions, but also by debris cover that is exposed at the surface by melting snow and affects the temporal evolution of the snow patch (Fig. 2).

The mass balance model is based on a temperature index, which is a common approach in glaciology. This model was validated using available *in situ* measurements (snow patch height, surface snow density etc.) and meteorological observations from the station at Yuzhno-Sakhalinsk. The introduction of a variable ablation factor as a function of debris height and debris properties resulted in a more realistic representation of long-term snow patch behaviour.

Initially, melting intensifies due to the darkening effect of debris cover, but it ceases once debris reaches a critical thickness, sufficient to protect the snow patches from atmospheric heat. Melting parameters were found to be highly sensitive to model assumptions. Nevertheless, for the two main snow patches of Yuzhno-Sakhalinsk the following observations were made across a wide range of ensemble of simulations:

- Peak melt rates ≈ 50 - 150 mm w.e. day (≈ typhoons);
- Peak water discharge of up to 15,000 m^3 d^{-1} (≈ 625 m^3 h^{-1});
- Annual water discharge ≈ up to 1,000,000 m^3;
- Ablation ≈ function of debris (modulation and overall reduction);
- Debris cover over both snow patches had similar thicknesses (≈ 20 cm), but properties differed based on the type of disposed materials;
- Surface runoff > infiltration (≈ swamps and streams).

Here, we just note that the examples above suggest several interesting points. For example, the peak melt rates are comparable to precipitation rates during regional typhoons and correspond to significant discharge of polluted and cold water during summer season. Next, even if debris cover has similar thicknesses at both study sites, its effects may differ from site to site due to different type of refuse disposed from different areas of the town. Furthermore, calculation of surface runoff for both sites shown that it exceeded infiltration into soil. This explains the observed formation of swamps and active streams around the sites. Also, given that chemical analysis of snow from the snow patches documented slightly acidic *pH* (this is actually surprising for snow usually mixed with deicing materials), it is possible to expect an existence of a so called ‘acid flush’ known from Hydrology, which has extended duration, compared with natural snow melting.

To avoid repetition of previously published materials, we refer the reader to the original paper for more details and sensitivity tests (*Podolskiy et al., 2015*).

4. Ecological threat or alternative source of energy?

Little is known about chemical processes within snow patches, due to the complex mixture of material, water, and possibly photochemical reactions. Degraded vegetation is a clear indicator of environmental damage from meltwater, but the extent and exact causes of environmental degradation around snow patches remain to be confirmed. To help understand the interactions between snow patches and the surrounding environment, ongoing monitoring and regular chemical analyses are necessary. This work will help optimize snow disposal methods and minimize environmental damage.

As shown in Table 1, snow disposal practices differ by country, and it is common for snow to be simply stored at surface sites or dumped in rivers. In some cases, technological solutions for snow disposal have been proposed to reduce harmful environmental effects. For example, harvesting snow in summer for cooling facilities or cold storage has been explored in Sweden and Japan (Table 1).

Table 1: Examples of existing snow disposal practices in cold regions (note that this list is not exhaustive).

Country	Examples of existing practice
Canada	disposal to sewer chutes, rivers, surface cites, quarries
Japan	disposal to rivers, surface cites, quarries, cooling of buildings, experimental vegetable storage
Norway	disposal to sea
Russia	melting, disposal to surface sites or to rivers
France	disposal to rivers
Sweden	cooling of a hospital

However, before designing efficient and sustainable strategies for meltwater use, additional basic knowledge must be developed. The key research directions to be pursued include the following:

1. The ablation regime of snow patches using ablation stakes, density profiles, or Digital Elevation Models from drones ('structure from motion' approach; e.g., *Kobayashi et al., 2015*),
2. The effects of debris,
3. *pH* of melt water, and investigation of an extended acid 'flush' in spring and summer,
4. Meltwater and snow chemistry (photo-chemical reactions),
5. Influence on soils and vegetation,
6. Knowledge-based guidelines for disposal strategies and site preparation and maintenance.

Snow disposal presents many unsolved environmental questions and technical challenges. Smart geotechnical solutions are worthy of further investigation, and will be beneficial for both the snow cleaning community (local authorities) and consumers requiring refrigeration. We believe that Japanese snow scientists possess not only valuable knowledge and experience, but also an 'appetite' for working with Russian scientists to improve our understanding of this poorly understood environmental problem.

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