Creep Displacements Induced from Waste Rock Loading

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ABSTRACT: Waste rock deformations were measured on a high altitude dump using survey prisms and inclinometers. Rates of downslope advancement of about 0.2 to 0.5 m/day (70 to 180 m/year) were measured. This waste dump is founded on very thick (greater than 40 m), warm (approximately -0.5ºC) ice-rich permafrost moraine deposits.

From satellite observations and site displacement measurements, it was concluded that the observed displacement was a result of both movement on the ground surface (sliding at the interface of the waste rock dump and foundation) and movement on a shear strain localization surface within the foundation (i.e. creep).This paper describes how the observational data were used to determine the deformation processes and offers potential mitigation solutions for stopping the continued movement of this waste rock dump.

1 INTRODUCTION

Lisiy Glacier is a high altitude glacier (over 4,000 masl) located in a remote area of the Tian-Shan mountain range in Kyrgyzstan. This glacier is in the Kumtor mine project area, which is located about 350 km southeast of the capital of Bishkek and 80 km south of Lake Issyk-Kul, near the border with China (Fig. 1). Prior to mining, the Lisiy Glacier (which includes the Lisiy Cirque Glacier and the Lisiy Valley Glacier) was retreating. When mining started in the region, waste rock and ice was dumped onto the Lisiy Cirque Glacier; the glacier stopped retreating and then started advancing. By the time the glacier started to advance, the original Lisiy Glacer had become more of a rock-glacier due to dumping practices. Because of the glacier advancement, mining operations moved waste placement and started to construct the North-East Valley Waste Rock Dump (NEV-WRD). This waste rock dump (NEV-WRD) was constructed on ice-rich moraine immediately adjacent to the glacier. Moving the location of waste rock placement allowed the cessation of dumping rock onto the Lisiy Glacier area, however the practice of dumping ice mined from various areas of the site onto the glacier was maintained. In time, it was evident that the NEV-WRD was also moving downslope and creep was postulated to be the driving movement mechanism. The collective name for all waste rock dumped in the Lisiy Valley, including the Cirque Rock Glacier and the NEV-WRD, is the termed the Lisiy Valley Dump (LV Dump) or “the Dump”, for ease of reference in this paper. Figure 1 shows a layout of the Kumtor mine site and the location of the LV Dump.

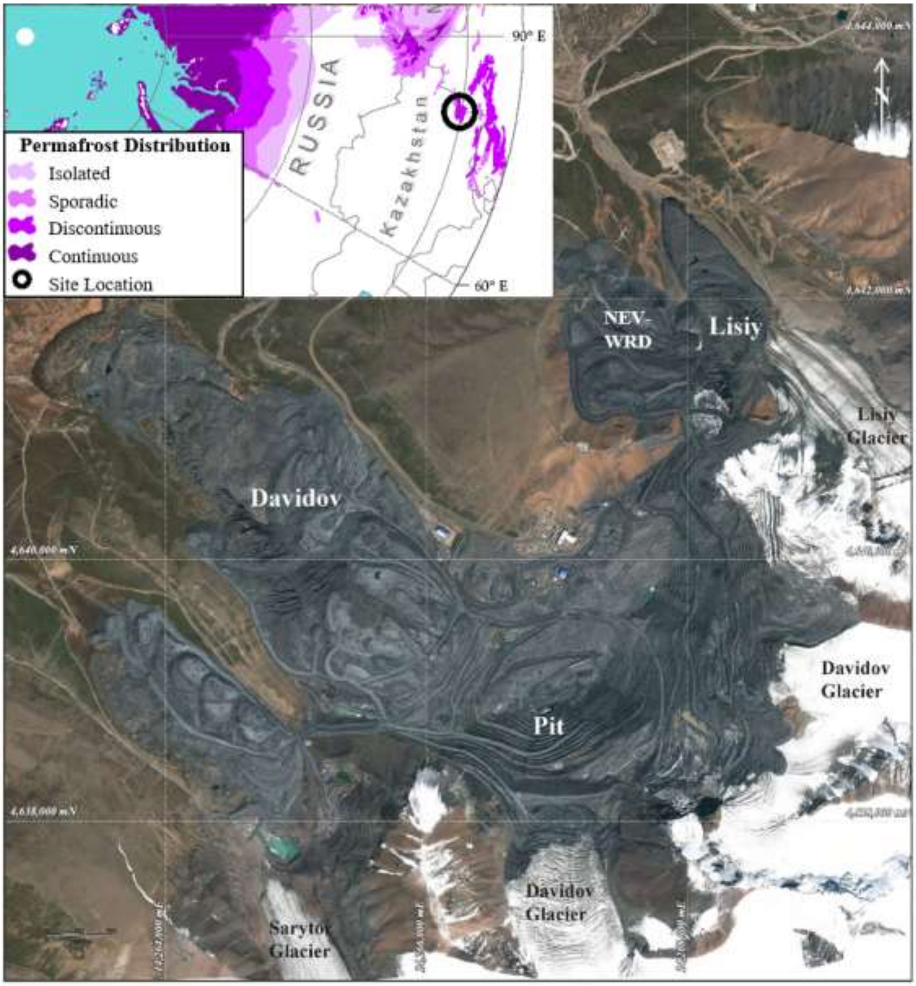

Figure 1. Site study location / location map of the Kumtor mine (in 2016) and surrounding glaciers (some covered in waste rock).

The LV Dump continues to advance downslope, with the rate dependent on the rate of loading. The rock glacier is moving downstream in the direction of Lisiy Creek, which is the same direction as the meltwater channel of Lisiy Glacier. The adjacent NEV-WRD is moving perpendicular to Lisiy Creek and is slowly cutting off flow in the creek.

Continued mine life, at least up to 2023, requires continued expansion of the LV Dump. If the LV Dump continues to advance, Lisiy Creek will be blocked off resulting in the potential of a moraine (soil and rock) blockage/dam and a subsequent flooding hazard. In addition, if the LV Dump continues to advance downstream, important surface infrastructure would have to be relocated prior to the planned end of mine life.

The objective of this study was to develop technically and economically viable options that could slow down the LV Dump long enough to preclude the need to relocate important surface infrastructure prior to 2023, while also demonstrating control with regard to management of glacier movement. Mitigation options also required that flow be maintained in Lisiy Creek (which is fed in part by glacial meltwater).

2 LISIY VALLEY DUMP MOVEMENT (KINEMATICS)

2.1 *Lisiy Cirque Glacier (Rock Glacier) Displacement*

2.1.1 Displacement History (1998–2016)

Movement of the Lisiy Glacier with the LV Dump on its surface is a consequence of the waste rock and ice load dumped on the Lisiy Glacier. Jamieson et al. (2015) reconstructed the advancement history of the Lisiy Cirque Glacier with the LV Dump on the surface over a period of 15 years (from 1999 to 2014) based on interpretation of satellite images (Fig. 2). During this period, the terminus of the Cirque Glacier advanced around 1.2 km. Much of the movement occurred in the first 6 years (Fig. 3). The main features related to the movements reported by Jamieson et al. (2015), and reproduced in Figures 2 and 3, can be summarized as follows:

- *1998–2002:* The Cirque Glacier (and the Valley Glacier) was retreating;
- *1999:* Most of the Cirque Glacier was covered with waste rock, including the Cirque Glacier's accumulation zone (i.e. the area above the glacier firn line, above which is characterized by glacial material left from previous years that has properties or is at an intermediate stage between snow and ice);
- *1999–2002:* The covered portion of the Cirque Glacier accelerated downhill, forming a terminus of advancing ice-covered waste rock;
- *2003:* The Cirque Glacier (covered with waste rock) progressed downslope and connected to the main body of the Lisiy Valley Glacier. As a result, the terminus began to advance;
- *2004:* The advance/movement of the Cirque Glacier terminus was around 700 m by 2004. This movement occurred at a relatively constant rate of around 230 m/year (around 0.64 m/day);
- *2004–2009:* As the Cirque Glacier continued to move and overcome the Valley Glacier, the rate of the Cirque Glacier decreased to a very low and relatively constant value;
- *2010:* The volume of mined ice (from the pit) began to increase steadily as this material was placed with the waste rock on andaround the historic Cirque Glacier area.
- *2012–2013:* Both glaciers advanced. The Cirque Glacier portion covered with waste rock advanced much faster and moved ahead of the Valley Glacier;
- *2013–2014:* The whole terminus became covered with waste rock, as was the trunk of the Cirque Glacier.

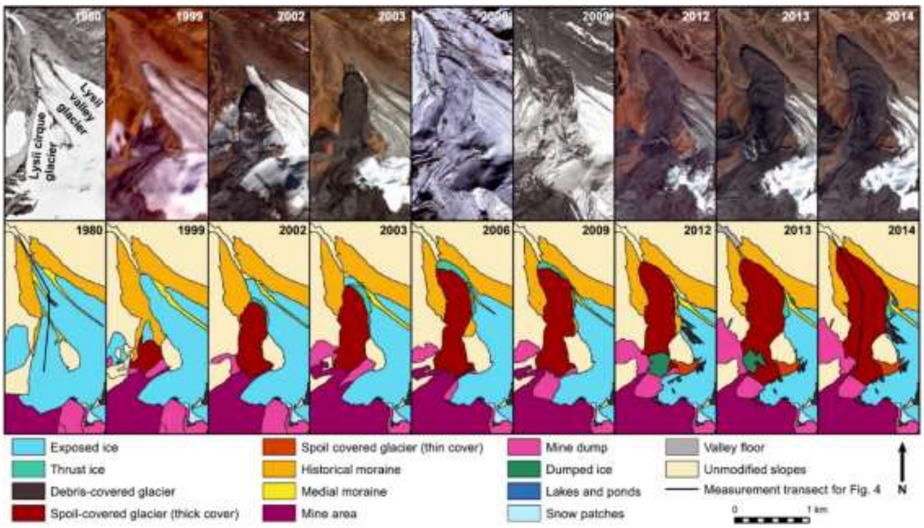

Figure 2. Select time series of glacier and landcover changed for the Lisiy Glacier between 1999 and 2014. Top: high-resolution satellite imagery. Bottom: classification of surficial geology and glacier ice/debris cover. Extracted from Jamieson et al. (2015).

Although the volume of waste rock and ice loaded onto the glacier was not quantified, Jamieson et al. (2015) assumed, based on satellite imaging, continuous waste rock and ice loading at the head of the Lisiy Cirque Glacier during their observation period.

Topographical mapping from Kumtor mine of the LV Dump between 1999 and 2014 suggest that between 2004 and 2010, no waste rock or ice was loaded at the head of the Lisiy Cirque Glacier. These maps confirm loading resumed in 2011. This could therefore be an alternative explanation for the cessation of movement between 2004 and 2010 (Fig. 3).

Available displacement data between 2014 and 2016 was reviewed and found to be focused around the nearby but not immediately adjacent Davidov Glacier area (with limited data around the LV Dump). The primary sources of pre-2016 data around the LV Dump area (primarily boreholes with inclinometers and piezometers installed in them) are shown on Figure 9.

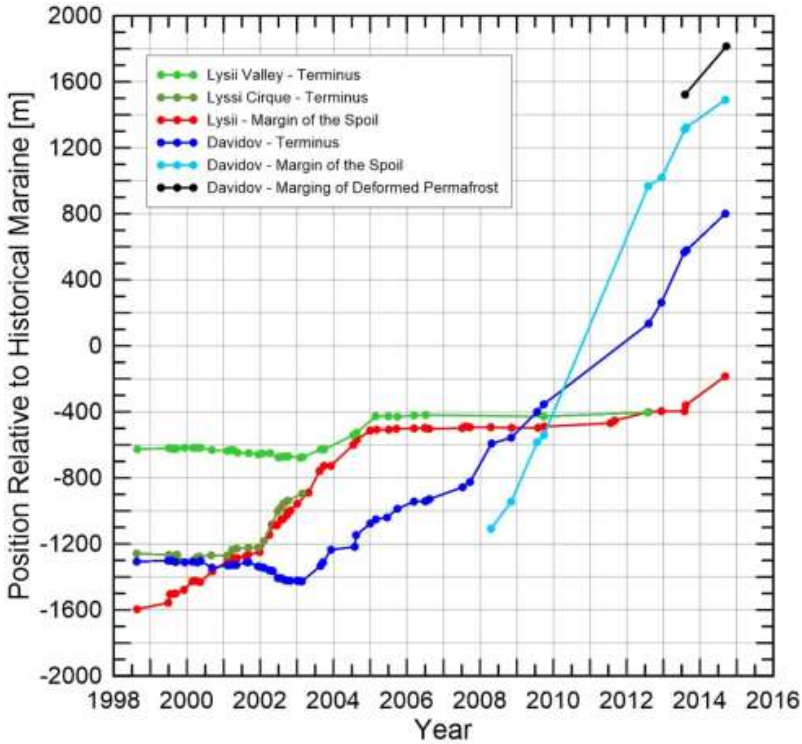

Figure 3. Glacier terminus and spoil margin position for the Lisiy and Davidov Glaciers. Positions are measured relative to the fronts of the most prominent historical moraines in the respective valleys. Extracted from Jamieson et al. (2015).

2.1.2 Lisiy Rock Glacier – 2017 Displacements

Topographical mapping of the Lisiy Cirque Glacier, now covered with waste rock (*aka* Lisiy Rock Glacier), at the end of October 2017 suggest that the glacier is moving in two directions (Fig. 4). Cross sections A and B in Figures 4 and 5 coincide with these movement directions.

Measurements carried out between August and October 2017 at surface monitoring points located approximately along cross sections A and B (Fig. 5) showed that the Lisiy Rock Glacier moved almost in the same North-West direction following the alignment of Lisiy Creek. For the purposes of interpreting the data, it is assumed that waste rock and ice were not discharged onto the Rock Glacier during this period.

Between August and October 2017, the Lisiy Rock Glacier moved with a relative constant average velocity of approximately 0.22 m/day. The average thickness of the Lisiy Rock Glacier in October 2017 was 40 m, varying between 41 m and 48 m along section A and between 31 m and 45 m along section B (Fig. 5).

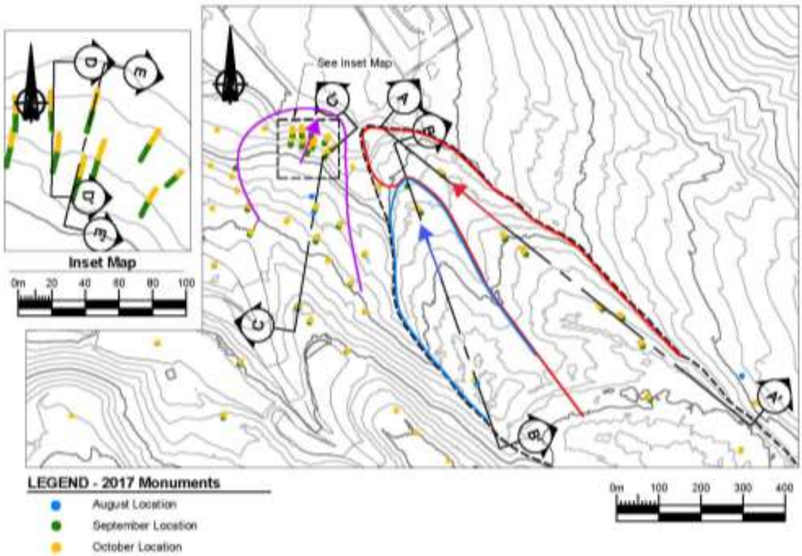

Figure 4. General movement directions of the Lisiy Valley Dump (blue and red) and the North-East Valley Waste Rock Dump (purple) as of October 2017.

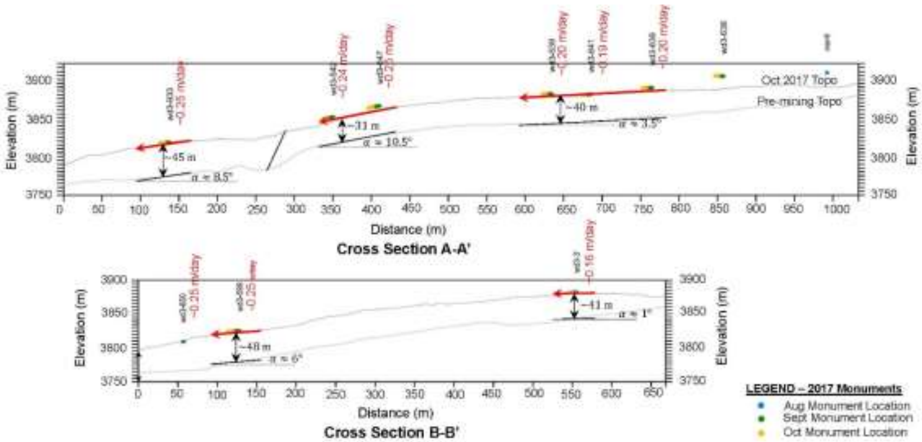

Figure 5. Movements of the Lisiy Rock Glacier along section A and B

2.1.3 North-East Valley Waste Rock Dump (NEV-WRD) – 2017 Displacements

There is no data available on the slope displacement of the NEV-WRD toward Lisiy Creek before August 2017. Between August and October 2017, the displacement of the NEV-WRD slope were measured at surficial monitoring points.

For purposes of interpreting the data, again it is assumed that there was no discharge of waste rock in the NEV-WRD during the period of surficial monitoring. Cross sections through the NEV-WRD aligned with the measured North-East displacements are shown in Figure 6 (cross section C, D and E).

Like the movements of the Lisiy Rock Glacier, the monitoring points on the NEV-WRD displaced almost parallel to the ground surface, and their rates correlate to the slope of the ground surface. Along cross section C, approximately 40 m in waste rock thickness, movement was variable with rates between 0.24 and 0.36 m/day between August and October 2017. In the same period, the NEV-WRD moved at a rate between 0.41 m/d and 0.55 m/d along cross sections D and E, with higher rates at the steeper upper sections of the slope. The measurements at the nearby available inclinometer (locations shown in Figure 9) also showed that the NEV-WRD moved toward Lisiy Creek like a rigid body on the surface of the ice-rich moraine with a velocity of 0.75 m/day. After two days of observations, the borehole for the aforementioned inclinometer was sheared off.

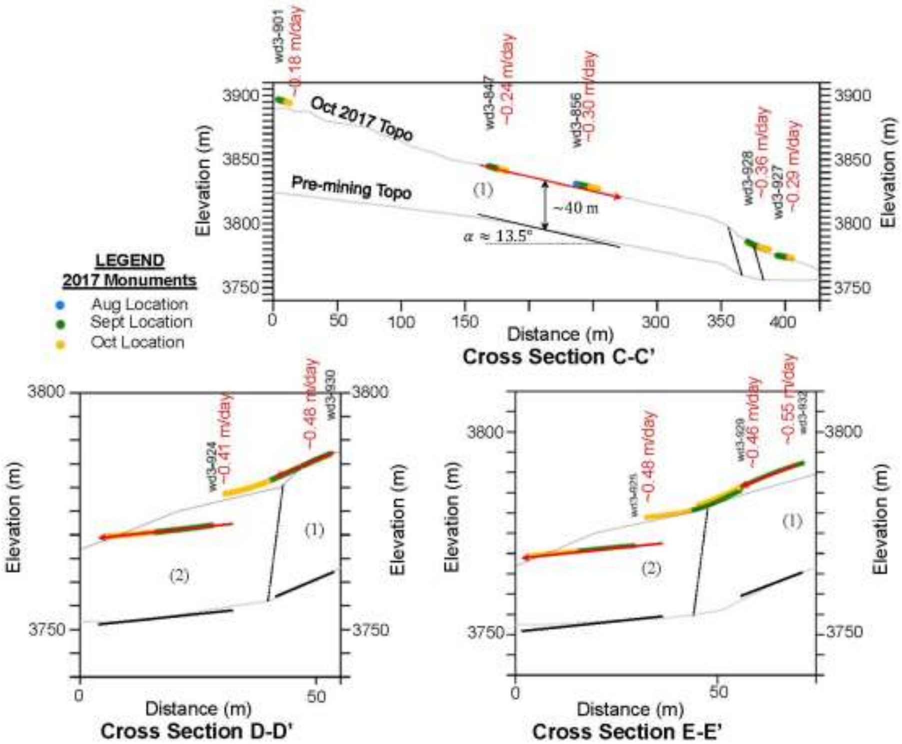

Figure 6. Movements of the NEV-WRD along section C, D and E.

2.2 *Movement Mechanism (Kinematics)*

Measurements suggest, in the relative short period between August and October 2017, that the Lisiy Rock Glacier and the NEV-WRD were displaced through a translational movement mechanism. The mechanism is compounded of several distinct, almost rigid bodies with internal sliding surfaces. The movement (direction and rate) is dictated by the natural topography. The rigid body translational movement mechanism was confirmed by three days of measurements at one inclinometer located at the NEV-WRD. From satellite observations and displacement measurements at surficial monitoring points, it is not possible to infer whether the Lisiy Rock Glacier and NEV-WRD move:

- on the ground surface (sliding at interface of the glacier-foundation and dump-foundation), or
- on a shear strain localization surface within the foundation, or
- because of shear deformation of the foundation caused by the weights of the Lisiy Rock Glacier and the NEV-WRD.

However, the mode of movement can be inferred from inclinometer measurements. Since there were no inclinometer measurements available in the vicinity of the Lisiy Rock Glacier, inclinometer measurements of the Davidov Glacier (approximately 4 km away) were used to infer the movement mode of the Lisiy Rock Glacier based on the similarity of movements and characteristics of the foundations (translational movement, constant rate, slope of the ground surface, and foundation soil type). While the measurements of additional inclinometers (Fig. 9) in this nearby Davidov glacier indicate a movement due to the shear deformation of the foundation, the measurements at the available inclinometer at the NEV-WRD shows that movement is on the original ground surface. These modes of movement are strongly dependent on the slope of the ground surface. The average slope of the ground surface underneath the Lisiy Rock Glacier is constant and around 4°. The ground surface slope underneath of the NEV-WRD vary between 15° and 20°. The greater the ground surface slope, the greater the shear stress at the base, and the movement can explain the influence of the shear strength at the interface between the NEV-WRD and the moraine. For a gentle ground surface slope, such as 4°, movement of the glacier on the foundation surface is less likely to occur, since the shear stress is much smaller than the expected shear strength at the Rock Glacier-foundation interface.

3 DISPLACEMENT MODEL

A displacement model was developed to study engineering solutions to slow down the movement of the LV Dump along the Lisiy Creek alignment. The main components of the LV Dump that were considered included the permafrost foundation, the glacial ice, and the waste rock material on top of the glacial ice.

The site foundation condition comprises warm permafrost with an average temperature of -0.5ºC (to a maximum of approximately -1.2ºC at 10 m depth below existing ground). The foundation material contains fine-grained, ice-rich till (i.e., glacial moraine). Considering there is no temperature data available from the glacial ice, it is assumed that the ice temperature across the Lisiy Rock Glacier is lower than the temperature of the ice-rich soils in the foundation. As generally stated in the description of glacier movements (Ingólfsson et al. 2016), meltwater from the glacier interacting with the foundation was not considered in the model as it was unable to be separated out of the data set. Therefore, the potential impact of this meltwater on the movement was not assessed in detail. Consideration of meltwater however was incorporated into the final proposed mitigation in terms of allowing meltwater to flow down the existing Lisiy Creek, and through stability and sliding analysis.

As discussed in Section 2, it is not possible to definitively confirm the displacement mode from displacement measurements at surficial monitoring points, and therefore the measurement results are used to infer the following for development of the displacement model:

- The occurrence of deformation at approximately constant rates under a constant stress state (no rock and ice loaded in the zones of the monitoring points) would suggest that the observed displacements are due more to creep strains than movements on the ground surface. The latter would show undefined deformation rates, like in a failure state, since the strength in the LV Dump foundation interface should be exceeded to allow movement of the LV Dump on the ground surface;
- Creep shear strains are not expected in the waste rock material; the movements should have been due to constant creep strain rates in the ice-rich till in the foundation and ice in the Lisiy Rock Glacier;
- Considering temperature-dependent creep properties of ice and ice-rich till, with temperatures in the foundation near the phase change, the movements were very likely due to constant creep strain rates in the ice-rich foundation soil; and,

– The influence that meltwater from the glacier and/or unfrozen water in the foundation may have influenced the displacements. However, it is difficult to quantify this with the available data set, therefore it has not been considered in the development of the model.

Figure 7 presents the model developed taking as reference basal motion modes of rapid ice-glacier flows (extracted from Ingólfsson et al. 2016). In general, the model considers that the movement of the LV Dump is due to:

(i) Creep deformation of the ice-rich till in the foundation

(ii) Basal displacement (sliding at the glacier-foundation interface)

(iii) Creep deformation of the glacial ice

Engineering solutions to slow down the movement consider creep deformations (i) and (iii) only, as it is unlikely that sliding at the glacier-foundation interface occurs, and if so, it was not possible to estimate with the available data.

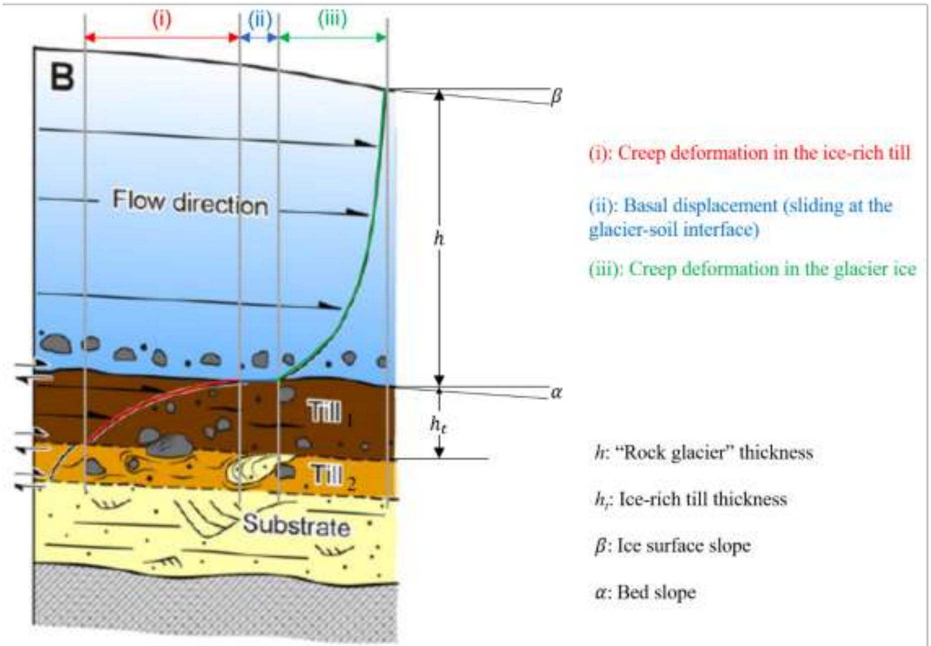

Figure 7. Displacement model. Deforming bed model graphic extracted from Ingólfsson et. al (2016) and further annotated.

4 CREEP PARAMETER OF THE ICE-RICH TILL

Figure 3 includes long-term total displacements measured for the Lisiy Cirque and Davidov Glaciers using high-resolution satellite Landsat and Aster imagery (Jamieson et al. 2015). To determine the creep parameter A of the ice-rich till in the foundation of the LV Dump, the total displacement of the nearby Davidov Glacier was used, since that data set was the most complete and offers the greatest certainty. Sufficient similarity in flow mass and foundation conditions makes the Davidov data suitable to estimate the creep parameter A for use in the foundation of Lisiy Glacier.

In accordance with the model in Figure 7, total displacement is the sum of both the creep displacements in the foundation (i) and in the glacial ice (iii), neglecting the basal displacement (ii), and the total displacement can be determined from the Davidov data in Figure 3. The deformation flow velocity v_i due to creep strains in the glacial ice is determined by the creep equation (Cuffey and Paterson 2010):

$$v_i = \frac{2hA_i}{n+1}(\tau_b)^n \quad (1)$$

Where:
- h is the Davidov Rock Glacier thickness[1] (glacier + waste rock),

[1] The shear strain occurs throughout the height of the Rock Glacier

- A_i is the temperature-dependent creep parameter of the glacial ice,
- n is a model parameter ($n = 3$ for ice and ice-rich soils), and,
- τ_b is the shear stress at the base of the glacier, considering rigid body movement of the rock glacier.

The creep parameter A_i changes with the annual change in the temperature of the ice-glacier. For an assumed average annual temperature of -5℃ in the ice-glacier A_i = 2.9E-08 kPa^{-3}year^{-1}.

Considering rigid body movement for the Davidov Rock Glacier, τ_b in Equation (1) is determined by:

$$\tau_b = (\gamma_{wr} h_{wr} + \gamma_i h_i) \sin \alpha \quad (2)$$

with
- $\gamma_{wr} = 24$ kN/m^3: Unit weight of the waste rock;
- $\gamma_i = 9$ kN/m^3: Unit weight of the glacial ice;
- h_{wr}: Waste rock thickness,
- h_i: Glacier thickness, and
- α: Slope of the ground surface.

The deformation velocity due to creep strains in the foundation ice-rich till is:

$$v_t = v - v_i \quad (3)$$

based on the displacement model in Figure 7, with v as the total displacement velocity of the Davidov Rock Glacier according to Figure 3.

The strain rate $\dot{\gamma}_t$ due to creep strains in the ice-rich till with the thickness h_t will be:

$$\dot{\gamma}_t = \frac{v_t}{h_t} \quad (4)$$

The creep parameter A of the of the ice-rich till is determined by:

$$A = \frac{\dot{\gamma}_t}{(\tau_t)^n} \quad (5)$$

Assuming shear deformation in the till parallel to the to the ground surface, the shear stress τ_t in the till layer will be

$$\tau_t = \gamma_t h_t \sin \alpha \quad (6)$$

with the unit weight γ_t of the ice-rich till in the foundation.

Table 1 includes the calculations of the creep parameter A for the Davidov Glacier thickness $h_i = 120$ m, an average ground surface slope of $\alpha = 5°$, an average glacial ice temperature of5℃ and some waste rock thicknesses h_{wr} as reported in Jamieson et al. (2015).

The thickness of the ice rich till was assumed to be $h_t = 15$ m based on the measurements at the Davidov inclinometers. Finally, the unit weight of the ice-rich till was assumed to be $\gamma_t = 20$ kN/m^3. Based on this analysis, the average value of the creep parameter for the site ice-rich low salinity till is 3.5 E-04 year^{-1} kPa^{-3}.

Table 1: Calculation of Creep Parameter *A* of the Ice-Rich Till

Component	Sym-bol	Units	Calculation Period 23/03/2006	26/09/2009	29/07/2012	Source
Waste rock thickness	h_{wr}	m	63	55	113	Jamieson et al. (2015)
Shear stress base of the glacier	τ_b	kPa	226	209	330	Equation (2)
Flow velocity of glacial ice (-5°C)	v_i	m/year	30.9	23.5	123.3	Equation (1)
Total velocity	v	m/year	108.0	158.0	185.0	Jamieson et al. (2015)
Deformation velocity due to creep strains in the ice-rich till	v_t	m/year	77.1	134.5	61.7	Equation (3)
Shear strain rate in the till	$\dot{\gamma}_t$	sec-1	1.63E-07	2.84E-07	1.30E-07	Equation (4)
Creep Parameter of the till	A	kPa-3 year-1	2.87E-04	5.02E-04	2.30E-04	Equation (5)

At warmer temperatures (above -3°C), the creep parameter *A* is very sensitive, and tends toward high values. In addition, the *A* creep parameter is also sensitive to salinity. The *A* parameter is not well constrained in the literature for ice-rich soils at temperatures between -3°C and 0°C. Since the temperature of the site permafrost foundation is -0.5°C, the site creep parameter presents considerable uncertainty.

Figure 8 presents a sensitivity calculation for two values of *A* that vary by one order of magnitude. The figures show the significant impact that values of *A* have on the creep strain rates,when structures (e.g., embankments, waste rock dumps, etc.) of different heights are placed on creep-susceptible layers of different thicknesses.

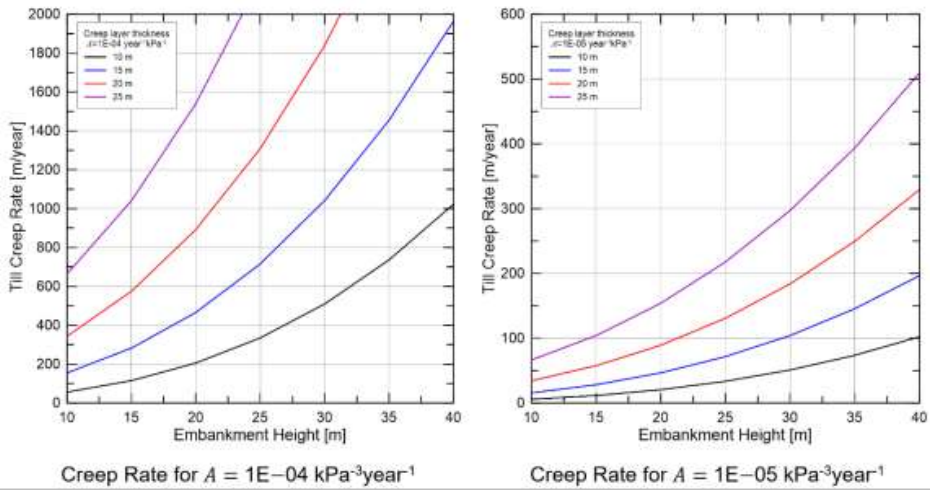

Figure 8. Glacial till creep rates as a function of creep parameter, till thickness and embankment height (rock loading).

5 ALTERNATIVES TO SLOW DOWN THE GLACIER MOVEMENT

The outlined movement mechanism, displacement mode, and calculated creep strains confirmed that unless dumping is ceased, the only way to slow down movement of the LV Dump was to provide a resisting force within the upper 15 m of the foundation soil, or to remove and replace that material with ice-poor soil. Subsequently four alternatives were studied to achieve these goals; (1) piles, (2) ground freezing, (3) conventional buttress, and (4) Glacier Retention Structure (GRS):

Both piles and ground freezing are technically feasible alternatives to slow down the movement of the LV Dump. However, they were found to be not economically feasible. More importantly, the time to implement these alternatives would be in the order of many years, which in itself is not considered a practical solution.

A conventional buttress founded on ice-rich till will significantly increase the shear stress in the till due to its weight. High shear stresses will activate creep deformations in the till, which in turn will cause large movement of the buttress. Therefore, a conventional buttress founded on ice-rich till is not technically feasible.

A GRS, designed and constructed according to specific design principles, especially those related to removing and replacing the ice-rich till in the foundation, is the least expensive, and is a technically feasible solution to slow down the movement of the LV Dump. After confirmation of initial sliding and stability analysis, this alternative was determined to be well suited to the activity and experience of the site. The GRS would need to be constructed downstream of the current LV Dump, and after it has been constructed the flow-through system would need to be connected to the terminus of the Lisiy Galcier. Figure 9 presents a plan view, and Figure 10 is a cross section of the conceptual GRS design.

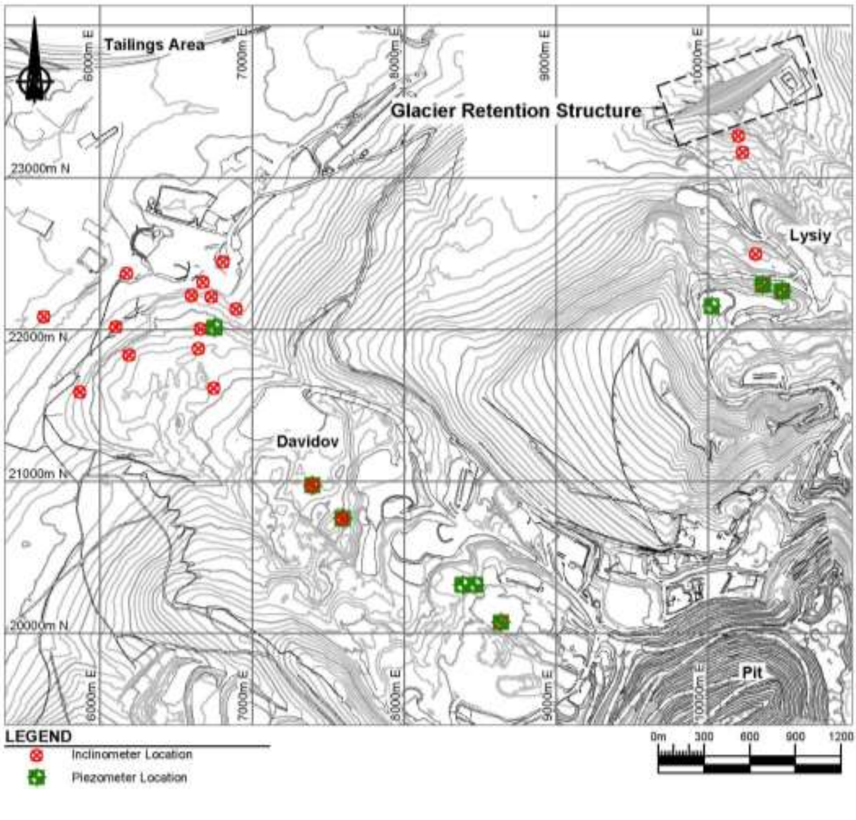

Figure 9. Glacier Retention Structure location and available inclinometer and piezometer data locations.

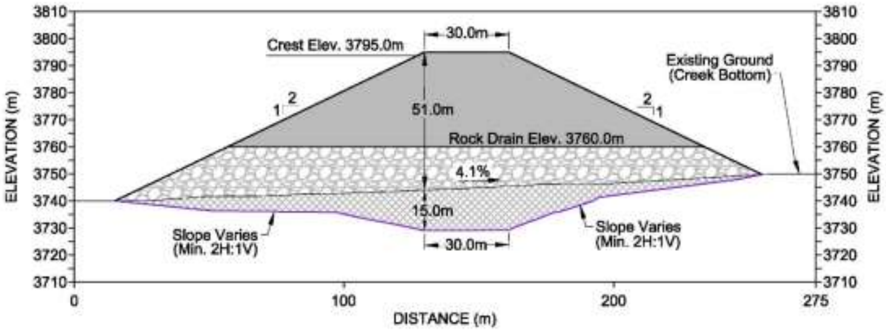

Figure 10. Typical cross sections through center of the conceptual Glacier Retention Structure

6 CONCLUSION

This paper presents a practical example of how monitoring data (satellite imagery and surficial monument surveying), coupled with laboratory test data, can be used to back-analyze and confirm movement mechanisms for waste rock placed on ice and ice-rich till material. The case study confirmed that, to slow down the movement of the Lisiy Valley Dump, a resisting force within the upper ice-rich till layer must be provided, temperature dependent creep properties of the ice-rich till must be modified, or the ice-rich till must be removed and replaced by ice-poor soil (such as waste rock). Performance and monitoring data of the proposed mitigation measures were unavailable at the time of writing this paper. If the proposed Glacier Retention Structure (GRS) is constructed, then the performance of the GRS would be the subject of a future / subsequent paper.

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REFERENCES

Cuffey K, Paterson, W.S.B. 2010. The physics of glaciers. 4th edition. Academic Press (Elsevier). ISBN 9780123694614.

Ingólfsson, Ó., Benediktsson Í. Ö., Schomacker, A., Kjær, K.H., Brynjólfsson, S., Jónsson, S.A., Korsgaard, N.J., & Johnson, M.D. 2016. Glacial geological studies of surge-type glaciers in Iceland — Research status and future challenges. *Earth-Science Reviews* 152, 37–69. January 2016.

Jamieson, S.S.R., Ewertowski, M.W., & Evans, D.J.A. 2015. Rapid advance of two mountain glaciers in response to mine-related debris loading. *Journal of Geophysical Research: Earth Surface* 120, 1418–1435. DOI 10.1002/2015JF003504

Leinenkugel, J.H. 1976. Deformation and strength behavior of cohesive soils. Experimental Results and their Physical Interpretation (in German). PhD. Dissertation. Institute for Soil Mechanics and Rock Mechanics, KIT. Heft No. 66.

LLC Technology. 2016. Results of geophysical explorations to determine the areas of high ice content in soils of the Kichi-Sarytor, the Chon-Sarytor (Centralnaya) Valleys and the Lysyi Glacier Valley. Report prepared by LLC Geotechnology. 2016.

Schwarz, W. 1987. Dowels in clayey soils (in German). PhD. Dissertation. Institute for Soil Mechanics and Rock Mechanics, KIT. Heft No. 105.