Estimating the risk of glacier cavity collapse during artificial drainage: The case of Tête Rousse Glacier

O. Gagliardini, F. Gillet-Chaulet, Geoffroy Durand, C. Vincent, P. Duval

GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L10505, doi:10.1029/2011GL047536, 2011

Estimating the risk of glacier cavity collapse during artificial drainage: The case of Tête Rousse Glacier

O. Gagliardini,[1,2] F. Gillet-Chaulet,[1] G. Durand,[1] C. Vincent,[1] and P. Duval[1]

Received 22 March 2011; revised 20 April 2011; accepted 25 April 2011; published 28 May 2011.

[1] During the summer of 2010, the presence of a pressurized water-filled subglacial-cavity of at least 50,000 m^3 was detected within the Tête Rousse Glacier (French Alps). Artificial drainage was started to avoid an uncontrolled rupture of the ice dam, but was interrupted soon after to evaluate the capacity of the cavity-roof to bear itself. The risk was that the release of pressure within the cavity during the artificial drainage would precipitate the collapse of the cavity roof and potentially flush out the remaining water flooding the valley below. An unprecedented modeling effort was deployed to answer the question of the cavity roof stability. We set up a model of the glacier with its water cavity, solved the three-dimensional full-Stokes problem, predicted the upper surface and cavity surface displacements for various drainage scenarios, and quantified the risk of the cavity failure during artificial drainage. We found that the maximum tensile stress in the cavity roof was below the rupture value, indicating a low risk of collapse. A post drainage survey of the glacier surface displacements has confirmed the accuracy of the model prediction. This practical application demonstrates that ice flow models have reached sufficient maturity to become operational and assist policy-makers when faced with glaciological hazards, thus opening new perspectives in risk management of glacier hazards in high mountain regions. **Citation:** Gagliardini, O., F. Gillet-Chaulet, G. Durand, C. Vincent, and P. Duval (2011), Estimating the risk of glacier cavity collapse during artificial drainage: The case of Tête Rousse Glacier, *Geophys. Res. Lett.*, *38*, L10505, doi:10.1029/2011GL047536.

1. Introduction

[2] The history of the city of Saint Gervais Mont Blanc, in the French Alps, is deeply marked by the 1892 disaster which killed 175 persons, after the unexpected release of 100,000 m^3 of water contained in a hidden cavity inside the Tête Rousse Glacier. During the summer 2010, the presence of a pressurized water-filled cavity of at least 50,000 m^3 was confirmed, threatening again the residents down the valley [*Legchenko et al.*, 2011; C. Vincent et al., A potential catastrophic subglacial lake outburst flood avoided in the Mont Blanc area, submitted to *Geophysical Research Letter*, 2011] (and see Figure 1). To avoid a repetition of the 1892 disaster, an unprecedented initiative was launched to drain the water cavity under a high altitude glacier. Artificial drainage was started to avoid an uncontrolled failure of the ice dam [*Mathews*, 1963; *Haeberli*, 1983] (and see the short discussion regarding the evaluation of this risk in the auxiliary material).[1] The drainage of the pressurized water-filled cavity started on the 26 of August 2010 and was interrupted 5 days later, after the pressure in the cavity was reduced by 0.3 MPa to approximately balance the ice load of the cavity roof. The local authorities then requested an expert's evaluation to be made within a few days to investigate the stability of the cavity roof, the risk of collapse during further draining, and consequent water pressure release. The chronology of the operations is given in Table S1 of the auxiliary material.

[3] In this paper, we describe how in a very short time we responded to this request. The model used for this study is summarized in Section 2 and more details can be found in the auxiliary material. In Section 3, we present how we estimated the risk of breakout by comparing modeled tensile stress magnitude with measured ice tensile strengths from different techniques. Measurements of the surface displacements during the draining phase were used to control the daily surface displacements and afterwards for post-validation of the modeling, as presented in Section 4.

2. Description of the Model

[4] Responding to an operational request to evaluate glaciological hazards is quite uncommon, and specific tools are currently lacking to comply with such requests. We used the finite element Elmer/Ice code, which has been widely used for various academic applications in ice flow modeling [*Zwinger et al.*, 2007; *Gagliardini and Zwinger*, 2008; *Durand et al.*, 2009; *Gagliardini et al.*, 2010]. Most ice flow models use asymptotic approximations of the Stokes equations, thus discarding some components of the stress tensor. At such a scale and because of the presence of the cavity, all the stress components are of the same order and the complete Stokes equations have to be solved. Here, we performed three-dimensional full-Stokes simulations, which gave us a complete analysis of the state of stress within the glacier, and more specifically the maximum tensile stress. The Stokes equations were coupled with the transport equations for the upper surface and cavity surface, to determine the cavity closure and surface displacements as a function of time for various drainage scenarios. Ice is assumed to behave as a non-linear viscous material and damage is not accounted for, so that results are only valid until the appearance of a crevasse or a large crack. Ice is assumed to be temperate over the whole glacier, even though slightly negative temperatures have been measured on the lower part of the glacier, downstream of the cavity

[1]LGGE, CNRS, Université Joseph Fourier-Grenoble 1, Saint-Martin d'Hères, France.
[2]Institut Universitaire de France, Paris, France.

0094-8276/11/2011GL047536

[1]Auxiliary materials are available in the HTML. doi:10.1029/2011GL047536.

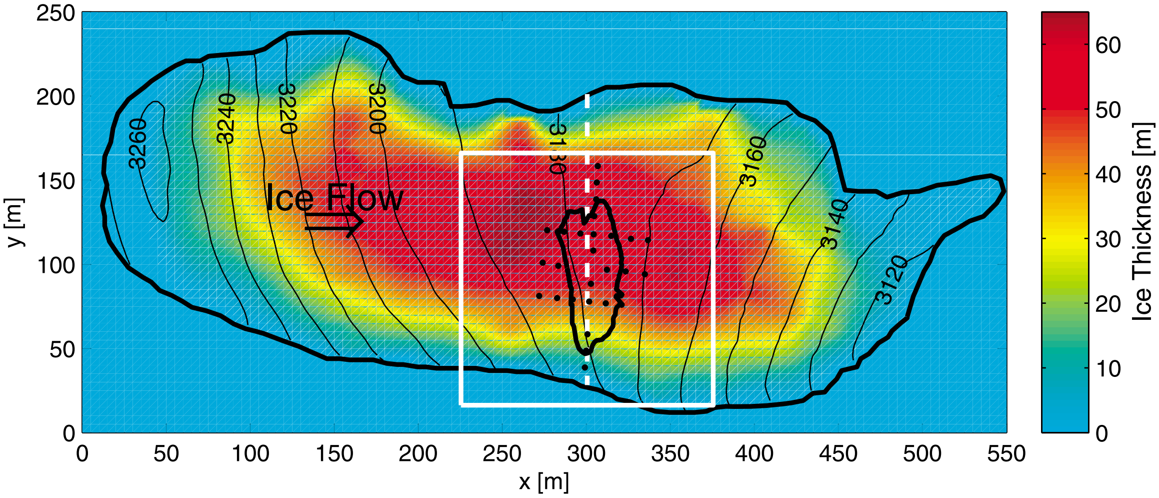

Figure 1. Surface elevation (isocontours) and ice thickness (isocolor) of Tête Rousse Glacier. The 27 stake locations are indicated by black dots and the horizontal extent of the cavity contour as measured by the sonar is represented by the black line. The white dashed line shows the position of the vertical cutting plane used in Figure 2. The white box indicates the surface area plotted in Figure 3.

[*Vincent et al.*, 2010]. Basal boundary conditions assume no sliding outside the water cavity and the water pressure within the cavity is applied on the lower ice surface of the cavity roof. The water pressure evolution with time is given by the drainage scenario (see Figure S1 of the auxiliary material). During the closure process, the no slip condition is applied to the points becoming progressively in contact with the bed. Due to the short time period covered by the simulations, the accumulation/ablation flux on the upper free surface is assumed to be nil. The finite element mesh, covering the whole extent of the glacier (approximately 8×10^4 m^2), is based on the 2007 surface Digital Elevation Model (DEM) [*Vincent et al.*, 2010] adjusted from the 2010 measurements, on the bedrock DEM and on the cavity topography which was obtained by sonar measurements. A horizontally-unstructured mesh was used, with small elements (5 m) in the vicinity of the cavity and larger ones (20 m) at the margins of the glacier. All the equations, numerical values and details regarding the model are given in the auxiliary material.

3. Evaluating Risk of Break-Off

[5] We first ran a simulation hypothesizing an instantaneous drainage of the cavity, which can be seen as the worst-case scenario for the roof stability. The maximum eigenvalue of the Cauchy stress tensor is shown in Figure 2 and it is compared to a simulation of the case where there is no cavity below the glacier. The configuration of the Tête Rousse Glacier is such that, with no cavity, tensile stresses are only located at the surface in the upper part of the glacier. The presence of the cavity modifies both the distribution and the intensity of the tensile stresses in the whole glacier. A first area subject to large tensile stresses lies at the surface of the glacier upstream of the cavity. Consequently, surface crevasses could possibly open up, and if they are large and long enough, this could lead to the collapse of the whole cavity roof. A second tensile stress area is located between the top of the cavity and the compressive arch. This configuration could lead to the breaking-off of ice blocks that could finally cause the collapse of the cavity roof. As shown in Figure 2, the maximal tensile stress obtained is 0.20 MPa. An evaluation of the sensitivity of the maximal tensile stress to the geometry of the cavity was further carried out. Uncertainties regarding the modeled tensile stress were estimated by performing several simulations with different cavity geometries. All these cavities, with the same volume of 50,000 m^3 which corresponds to the water volume effectively pumped out of the glacier, were constructed from various geometrical shapes. From these simulations, the 1σ error on the tensile stress was estimated to be ±0.04 MPa.

[6] Glacier ice tensile strength is characterized by its strong variability as it depends on many internal variables: it decreases with increasing crystal size, increasing water content or increasing temperature. The risk of collapse can be estimated by comparison with measured laboratory and in-situ tensile strengths and the risk that a flaw propagates. Compilation of values obtained from laboratory experiments on ice samples indicates a value of 0.8 ± 0.4 MPa for temperate ice [*Schulson and Duval*, 2009]. This should be regarded as an upper bound since it does not account for the actual heterogeneity of a glacier. In-situ mean tensile strength, measured from the displacement of surface stakes and concomitant observation of crevassed areas, gives lower values ranging from 0.09 MPa to 0.32 MPa [*Vaughan*, 1993]. For temperate ice, assuming a fracture toughness K_{IC} of 100 kPa m$^{1/2}$ [*Schulson and Duval*, 2009], the minimal flaw size that can initiate critical crack propagation under a tensile stress of 0.2 MPa is around 8 cm. Such flaws are relatively common in temperate glaciers, in the form of water lenses located on ice grain boundaries, or veins containing liquid water at three-grain intersections [*Raymond and Harrison*, 1975].

[7] By comparing these values with the modeled tensile stress in the glacier, the chance of the cavity roof collapse was estimated to be low, but could not be excluded. We therefore recommended regular surveys of the surface topography during the artificial drainage to detect any early signs of cavity collapse. A network of surface stakes was

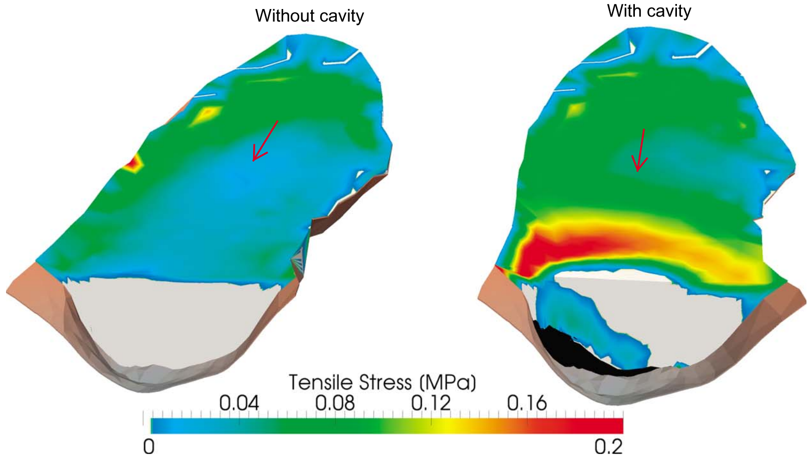

Figure 2. Maximal tensile stress (left) without cavity and (right) with an empty cavity. Only the upstream part of the glacier is represented and the vertical cutting is done along a transverse direction above the cavity centre, as indicated in Figure 1. Negative values are in white and represent areas with a compressive state of stress. The bedrock elevation is represented with the grey scale and the cavity in Figure 2 (right) is represented in black. The red arrows represent the mean ice flow direction (+*x*).

installed and the surface area was observed closely to detect the opening of crevasses.

4. Rate of Closure of the Cavity

[8] As shown in Figure 1, the surface network consisted of 27 stakes positioned on the glacier surface above the cavity, and their displacements were measured using a theodolite everyday when the weather allowed it. The greatest daily vertical displacement measured was 1.0 cm, slightly smaller than that predicted by the model for a hypothetical instantaneous drainage (1.6 cm). Moreover, no sign of crevassing was visually detected on the surface upstream of the cavity. The stake displacements confirmed a mostly viscous regime of deformation without damage to the ice in the vicinity of the cavity. Having been able to provide a correct prediction of surface displacements, the drainage operation was continued with more confidence. However, a post-drainage visit to the cavity showed that heterogeneously fractured ice blocks had fallen down from the cavity roof (Moreau, personal communication, 2010). These observations show the limitations of our modeling which cannot predict precisely fracture damage and ice block falls. It also shows that the opening of cracks is hardly predictable because modeled tensile stresses were greater on the surface than in the cavity roof. However, ice blocks falls from the cavity roof do not damage the above surrounding ice, but only slightly decrease the roof thickness. This should, therefore, marginally affect the general behavior of the cavity closure.

[9] We further used the measurements of the stake displacements as a post-validation of our modeling approach. A new simulation was performed, using the same initial geometry but with the actual draining history, as depicted in Figure S1 of the auxiliary material. Figure 3 compares the measured surface displacements with the modeled ones over a 21-day period. Ice in the vicinity of the cavity is attracted by the cavity, and the resulting perturbation can be seen on all the three components of the surface displacement vector. In the main flow direction (+*x*), the surface displacements increase upstream of the cavity and decrease downstream. Both the measurements and the model indicate a small area of upstream-orientated displacements just downstream of the cavity. Measured surface velocities from 2007 to 2009 range from 0.11 to 0.15 cm d^{-1} [*Vincent et al.*, 2010], which corresponds approximately to a longitudinal displacement of 2.5 cm over the 21 days of measurement, in agreement with the model without cavity presented in Figure 3. Simulations with and without a cavity indicate that the presence of the cavity modifies these local displacements by factors up to 5, ±10 and 20, respectively in the longitudinal, transverse and vertical directions. For the two horizontal components, modeled and measured velocities agree very well both in terms of maximal value and pattern. However, the model overestimates the maximal vertical displacement by 40%, and the pattern is less accurately reproduced than for the horizontal components. Geometry approximations, and more particularly from the bedrock DEM, are probably at the root of the modeled overestimation.

[10] This comparison performed using the actual drainage scenario validates the model and adds confidence in its results *à posteriori*. Finally, after running the simulation for a longer time period, we determined that, in the absence of water refilling and if the collapse of the roof does not occur, it will take more than 2 years to completely close the cavity. Therefore, regular observations of how the cavity evolves during the coming years, in terms of refilling and closure, will be necessary.

5. Conclusions

[11] In this paper, we have demonstrated that ice-flow models are now sufficiently mature that they can be used in an operational context to assist policy-makers faced with glaciological hazards, thus opening new approaches to risk management of glacier hazards in high mountain regions [*Haeberli et al.*, 1989]. Within a few days, we provided an estimate for the maximal tensile stress expected within the

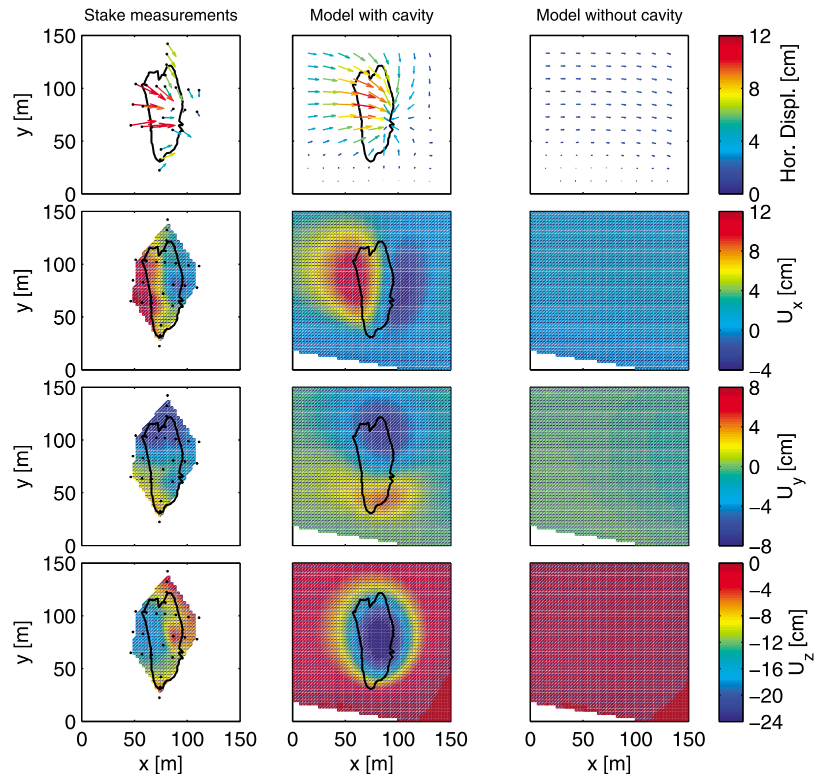

Figure 3. (top) Vector of the horizontal surface displacements and (top middle) longitudinal, (bottom middle) transversal and (bottom) vertical surface displacements above the cavity from the 14th of September to the 6th of October 2010 (21 days) in (left) centimetres measured from the 27-stakes surface network and modeled (middle) with the cavity and (right) without the cavity. The black line represents the measured horizontal extent of the cavity contour and the 27 stakes are indicated by black dots. Arrows in Figure 3 (top) represent the horizontal displacements at scale 200 relative to the figure axis. The restricted square area depicted in this figure is located on the whole glacier in Figure 1. Mean flow is from the left to the right along the (+*x*) axis.

Tête Rousse Glacier, as well as the order of magnitude of expected surface displacements induced by the artificial drainage of the water filled cavity. This information enabled a relatively safe drainage operation.

[12] In the future, because of global warming, we may have to face an increasing number of glaciological hazards in mountainous regions. For example, increased atmospheric temperature, and the concomitant increase of summer melting, leads to an increase of ice temperature and a potential switch from cold to temperate basal conditions of high altitude alpine glaciers [*Vincent et al.*, 2007]. Answering the question of the future stability of these glaciers will require state-of-the-art ice flow models which include all the relevant mechanics and physics to properly describe the coupling between basal friction, temperature and water contents.

[13] Nevertheless, for either a subglacial water-filled cavity or a change in the basal sliding conditions, the most important is certainly to be capable of detecting the hazard in time. For the Tête Rousse Glacier, the cavity was detected because of its history. More academic research work is certainly needed to understand the key processes which lead to the formation of a water filled cavity. In this context, the particular case of Tête Rousse Glacier will certainly increase our knowledge on that point and allow to identify other glaciers which may fulfil these conditions. Such glaciers would then have to be monitored to confirm or not the presence of a water filled cavity.

[14] **Acknowledgments.** This study was funded by Le Service de Restauration des Terrains en Montagne (RTM) of Haute Savoie (France) and the town of Saint Gervais (France). Computations presented in this paper were performed at the Service Commun de Calcul Intensif de l'Observatoire de Grenoble (SCCI). We thank T. Zwinger and CSC (Helsinki, Finland) for their support in the Elmer/Ice developments. We thank G. Clarke, M. Funk and one anonymous reviewer for their helpful comments which considerably improved the final quality of our paper.

[15] The Editor thanks Martin Funk, Garry Clarke and an anonymous reviewer for their assistance in evaluating this paper.

References

Durand, G., O. Gagliardini, B. de Fleurian, T. Zwinger, and E. Le Meur (2009), Marine ice sheet dynamics: Hysteresis and neutral equilibrium, *J. Geophys. Res.*, *114*, F03009, doi:10.1029/2008JF001170.

Gagliardini, O., and T. Zwinger (2008), The ISMIP-HOM benchmark experiments performed using the finite-element code Elmer, *Cryosphere*, *2*(1), 67–76.

Gagliardini, O., G. Durand, T. Zwinger, R. C. A. Hindmarsh, and E. Le Meur (2010), Coupling of ice-shelf melting and buttressing is a key process in ice-sheets dynamics, *Geophys. Res. Lett.*, *37*, L14501, doi:10.1029/2010GL043334.

Haeberli, W. (1983), Frequency and characteristics of glacier floods in the Swiss Alps, *Ann. Glaciol.*, *4*, 85–90.

Haeberli, W., J.-C. Alean, P. Muller, and M. Funk (1989), Assessing risks from glacier hazards in high mountain regions: Some experiences in the Swiss Alps, *Ann. Glaciol.*, *13*, 96–102.

Legchenko, A., M. Descloitres, C. Vincent, H. Guyard, S. Garambois, K. Chalikakis, and M. Ezerski (2011), 3D magnetic resonance imaging for groundwater, *New J. Phys.*, in press.

Mathews, W. (1963), Discharge of a glacier stream, in *General Assembly of Berkeley: Surface Waters*, *IAHS Publ.*, *63*, 290–300.

Raymond, C., and W. Harrison (1975), Some observations on the behavior of the liquid and gas phases in temperate glacier ice, *J. Glaciol.*, *14*(71), 213–233.

Schulson, E., and P. Duval (2009), *Creep and Fracture of Ice*, Cambridge Univ. Press, Cambridge, U. K.

Vaughan, D. (1993), Relating the occurrence of crevasses to surface strain rates, *J. Glaciol.*, *39*(132), 255–266.

Vincent, C., E. Le Meur, D. Six, P. Possenti, E. Lefebvre, and M. Funk (2007), Climate warming revealed by englacial temperatures at Col du Dôme (4250 m, Mont Blanc area), *Geophys. Res. Lett.*, *34*, L16502, doi:10.1029/2007GL029933.

Vincent, C., S. Garambois, E. Thibert, E. Lefebvre, and D. Six (2010), Origin of the outburst flood from Glacier de Tête Rousse in 1892 (Mont Blanc area, France), *J. Glaciol.*, *56*(198), 688–698.

Zwinger, T., R. Greve, O. Gagliardini, T. Shiraiwa, and M. Lyly (2007), A full Stokes-flow thermo-mechanical model for firn and ice applied to the Gorshkov Crater Glacier, Kamchatka, *Ann. Glaciol.*, *45*, 29–37.

G. Durand, P. Duval, O. Gagliardini, F. Gillet-Chaulet, and C. Vincent, LGGE, CNRS, UJF-Grenoble 1, BP 96, F-38402 Saint-Martin d'Hères CEDEX, France. (durand@lgge.obs-grenoble.fr; duval@lgge.obs-grenoble.fr; gagliar@lgge.obs-grenoble.fr; gillet-chaulet@lgge.obs-grenoble.fr; vincent@lgge.obs-grenoble.fr)