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Brief communication: Nye was right!

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Abstract. Despite decades of study, predicting crevasses penetration depths remains controversial. Nye provided one of the earliest estimates of crevasse penetration depths. Recently, a new theory, called the horizontal force balance (HFB), challenges Nye's model, suggesting crevasses can penetrate much deeper than predicted by Nye. Here we use a numerical model to show that Nye's estimate remains accurate so long as crevasses are closely spaced, but crevasses penetrate deeper as the spacing increases. Moreover, contrary to many parameterizations of crevasses as damage in depth-integrated models, we find that crevasses do not increase the stress in the intact portion of the ice.

1 Introduction

When glacial ice experiences sufficient tensile stress, the ice can break, resulting in near-vertically oriented crevasses. Crevasses are not only precursors to iceberg calving, but can also weaken the ice in shear margins and precondition ice shelves for collapse (e.g., Walker et al., 2024; Alley et al., 2022). However, despite the key role crevasses and iceberg calving play in the dynamics of ice sheets and ice shelves, disagreement remains about how best to estimate key quantities, like crevasse penetration depths (e.g., Bassis et al., 2024).

Attempts to understand crevasse patterns have underpinned some of the earliest studies of ice dynamics and fractures (e.g., Hopkins, 1862). However, Nye (1952) provided one of the first modern attempts to estimate crevasse depths and patterns. Nye initially sought to estimate crevasse penetration depths using the perfect plastic approximation, but quickly generalized his approach to accommodate the emerging discovery that ice deforms according to a power-law creep relationship (Nye, 1952, 1955). In his revised theory, Nye assumed that ice had negligible strength and then proceeded to calculate crevasse depths assuming that crevasses penetrate to the depth where atmospheric pressure within air-filled crevasses balances longitudinal extensional stresses outside of crevasses (Nye, 1955). Recognizing that crevasses also modify the stress field in their vicinity, Nye suggested that this estimate was most appropriate for closely spaced crevasses, asserting that the stress beneath surface crevasses would be unaffected by the presence of crevasses when crevasses are closely spaced (Nye, 1955). This assertion was shown to be true by Weertman (1977) for an infinitely thick glacier and is often referred to as the 'zero stress' model despite the fact that the stress beneath surface crevasses tips is not formally zero because of atmospheric pressure.

The Nye model has since been generalized to include closely spaced bottom crevasses in ice shelves (Jezek, 1984) and, although subsequent numerical and theoretical calculations have demonstrated that isolated crevasses can penetrate much deeper than closely spaced crevasses (e.g., Weertman, 1980; Jiménez and Duddu, 2018; Zarrinderakht et al., 2022), the Nye

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model remains widely used in glaciological applications (e.g., Benn et al., 2007; Sun et al., 2017). Recently, Roger Buck (2023) revisited the Nye zero stress model, claiming that Nye's crevasse depth is only valid for shallow crevasses because Nye's estimate does not satisfy a horizontal force balance (HFB). This modification has strong implications for ice shelf stability because although the original formulation of the HFB focused on the presence of freshwater filled basal crevasses, even when saltwater fills bottom crevasses, the HFB predicts that crevasses within unbuttressed ice shelves should *always* penetrate the entire ice thickness. This estimate, which is independent of size or shape of crevasses, suggests that ice shelves are fragile and should only exist under very limited circumstances—a prediction seemingly at odds with the abundance of ice shelves that surround the Antarctic Ice Sheet. Despite the discrepancy between the fact that many ice shelves continue to exist, the HFB has since been generalized to include depth-dependent temperatures, a finite strength of ice and applied to grounded glaciers (Coffey et al., 2024; Coffey and Lai, 2025; Slater and Wagner, 2025). Here we seek to better understand the conditions when the HFB model applies by using a numerical model to analyze the penetration depths of crevasses in ice shelves. We start, however, by reviewing the Nye and HFB models and recast both of these models into dimensionless form to better understand compare predictions and how that the HFB model predicts that unbuttressed ice shelves should not exist.

2 Crevasse depths in the Nye zero stress and the horizontal force balance models

For simplicity, we focus on an idealized ice shelf with uniform ice thickness H overlying an inviscid ocean with density ρ_w, with vertically aligned basal and surface crevasses at regular interval w, as illustrated in Figure 1. We assume the ice shelf undergoes uniform, depth-independent extension with far field deviatoric stress τ_{xx}. To aid the exposition and facilitate comparison with numerical models, we consider uni-axial flow, ignoring transverse stresses. However, our formulation can easily be generalized to include transverse deviatoric stress. Defining the height of bottom crevasses d_b and the depth of surface crevasses d_s we are interested in the crevasse penetration ratio $r = (d_s + d_b)/H$. Following Bassis and Ma (2015), we start by defining the dimensionless stability number $\mathcal{S}$,

$$\mathcal{S} = \frac{\rho_i g H \left(1 - \frac{\rho_i}{\rho_w}\right)}{2\tau_{xx}}. \tag{1}$$

Here ρ_{ice}=910 kg/,^{3} denotes the density of ice, ρ_w=1020 kg/m^3 the density of ocean water in which the ice shelf is submerged and $g = 9.81$ m/s^2 is the acceleration due to gravity. The parameter $\mathcal{S}$ is related to the 'buttressing number' K_b used by Roger Buck (2023) with $\mathcal{S} = 2/(1 - K_b)$. Next, recalling that at the calving front of an isothermal ice shelf

$$\tau_{xx} = \frac{\rho_{ice} g H \left(1 - \frac{\rho_i}{\rho_w}\right)}{4}, \tag{2}$$

we see that $\mathcal{S} = 2$ ($K_b = 0$) corresponds to a freely-spreading ice shelf, $\mathcal{S} > 2$ ($K_b > 0$) to increased buttressing, and $\mathcal{S} < 2$ ($K_b < 0$) to a situation that occurs when stress is concentrated near sharp pinning points and along shear margins.

We can recast the Nye model for crevasse penetration ratio r in the form:

$$r = \frac{1}{\mathcal{S}}, \tag{3}$$

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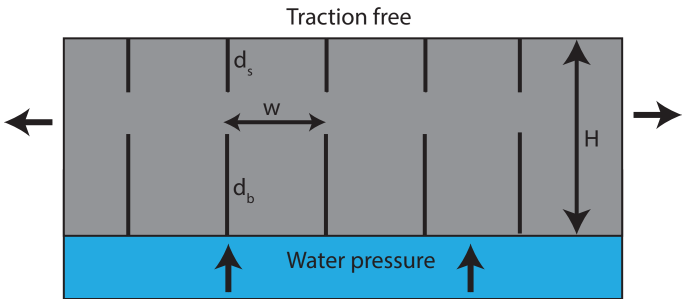

Figure 1. Sketch of the geometry considered. We assume that arrays of surface and bottom crevasses with width w and depths d_s and d_b are co-aligned, initially narrow and embedded in an ice shelf with uniform thickness H. Water pressure acts as a restoring force and we apply displacement or velocity boundary conditions along the left and right edges of the domain to impose a constant deviatoric stress τ_{xx} on the domain.

showing that in the Nye model, the combined depth of surface and bottom crevasses penetrate about half of the ice thickness ($r = 1/2$) when $\mathcal{S} = 2$ and requires $\mathcal{S} = 1$ for crevasses to penetrate the entire ice thickness. We can similarly express the crevasse depth associated with the HFB (Roger Buck, 2023) in terms of the dimensionless parameter $\mathcal{S}$:

$$r = 1 - \sqrt{1 - \frac{2}{\mathcal{S}}}. \tag{4}$$

from which it is evident that, unlike the Nye model, crevasses will penetrate the entire ice thickness when $\mathcal{S} = 2$. This is the fundamental conundrum of the HFB: because the dynamic boundary condition at the calving front of ice shelves requires that $\mathcal{S} \sim 2$ near the calving front of ice shelves, in the absence of permanent buttressing, ice shelves should continually shed bergs until floating ice ceases to exist. This result appears to be at odds with the numerous ice shelves observed today.

2.1 Numerical model

To test the assumptions of the HFB model and compare predictions to the Nye model for a range of crevasse spacing, we modified an existing a finite element model that solves the quasi-static conservation of momentum for a slab of ice (Berg and Bassis, 2020). We implemented both an incompressible elastic (Young's modulus E$= 1$ GPa) and incompressible power-law viscous model (ice stiffness B$= 1$ Pa s$^{1/3}$) to examine both linear elastic and non-Newtonian effects.

We assume shear tractions vanish along all boundaries and apply either a depth-independent horizontal displacement (for the elastic model) or horizontal velocity (for the viscous model) that corresponds to a constant horizontal deviatoric stress τ_{xx} for a flat ice shelf (Figure 1). We also conducted a handful of simulations for isolated crevasses using 'stress' boundary conditions, for which we set the horizontal velocity at the left-edge of the domain to zero and applied a horizontal traction boundary condition to the right side of the domain given by $\sigma_{xx}^{\infty} = 2\tau_{xx} - \rho_i g(s - z)$, corresponding to the analytic traction for an initially flat ice shelf.

We also need to enforce the hydrostatic pressure boundary condition at the ice shelf base. Defining the normal to the surface $\mathbf{n} = (n_x, n_z)$ and effective displacement $\boldsymbol{u}^* = (u_x^*, u_z^*)$ where $\boldsymbol{u}^*$ is equal to the elastic displacement $\boldsymbol{u}$ for the elastic rheology

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and $\boldsymbol{u}^* = \dot{\boldsymbol{u}}\Delta t$ where Δt is the time step for the viscous rheology, we write the normal force at the ice shelf bottom as:

$$\sigma_{nn}(x,t) = -\rho_w g b(x,t) + (\rho_w - \rho_i) g u_z^* n_z. \quad (5)$$

A similar traction condition holds along the top surface:

$$\sigma_{nn}(x,t) = -\rho_i g u_z^* n_z, \quad (6)$$

These boundary conditions are analogous to the boundary conditions applied to perturbations by Bassis and Ma (2015), but differ slightly from 'sea spring' frequently used as a restoring force (Durand et al., 2009; Berg and Bassis, 2020) because we include the buoyancy force associated with the displacement of ice by water and vice versa. We use a time step $\Delta t = 30$ days using the method of Berg and Bassis (2020) to remove the time step dependence of the viscous problem. We tested our numerical implementation using a flat ice shelf to ensure that the velocity/displacement fields correspond to the analytic solutions.

To simulate narrow cracks in the ice, we introduce triangular notches with crevasse walls initially (nearly) in contact. We then performed simulations varying crevasse depths and calculated the horizontal effective stress $\sigma_{xx}^{\text{eff}} = \sigma_{xx} + P_w$ with P_w the hydrostatic pressure of the ocean. Evaluating the effective stress directly ahead of the crevasse for each crevasse depth, we interpolated to find the depth or height where the stress vanishes. For elastic problems, we also examined the stress intensity factor using the displacement correlation method (Jiménez and Duddu, 2018) and change in elastic potential energy associated with crevasse depths. All three methods yielded similar crevasse depths.

To examine the effect of crevasse spacing, we exploited symmetries to lower computational cost and conducted simulations with crevasses located in the center domains extending one half of the spacing ($w/2$) to the left and to the right of the crevasse. We verified the accuracy of this method by comparing to simulations with larger domains and arrays of crevasses and further supplemented these calculations using resolution tests to ensure numerical convergence. Typically, our simulations typically had ∼19,000 nodes with increased node density near crevasse tips and intact regions between crevasses.

3 Results

We first examined the crevasse penetration ratio r for different values of the dimensionless stability number $\mathcal{S}$ (Figure 2). For comparison, we also show theoretical penetration ratios for (1) the Nye model (2) the HFB model and, (3) Weertman's model for shallow bottom crevasses, which predicts crevasses should penetration a factor of $\pi/2$ deeper than Nye's model (Weertman, 1980). Starting with closely spaced crevasses ($w = H/16$), we find that our simulated crevasse depths for both the viscous and the elastic rheologies closely track the Nye model for all values of $\mathcal{S}$ with both non-linear viscous and elastic rheologies yielding comparable results (Figure 2a). The HFB model converges to the Nye limit for large $\mathcal{S}$, but predicts dramatically deeper crevasses as $\mathcal{S}$ approaches 2

To test if the HFB model performs better for more widely spaced crevasses, we next examined the glaciologically plausible, but modest spacing $w = 4H$. Here we see that crevasses penetrate deeper for both the viscous and elastic rheologies compared

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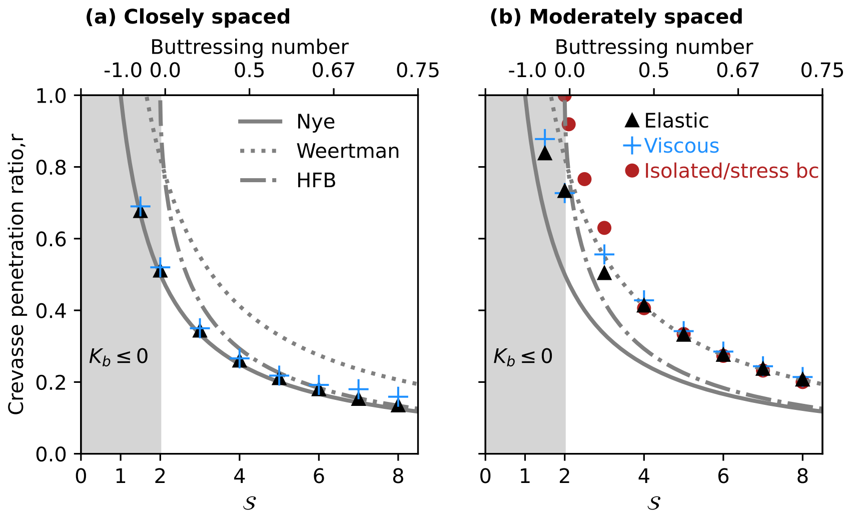

Figure 2. Crevasse penetration ratio by stability number $\mathcal{S}$ and buttressing number K_b for simulation results with crevasse spacings of (a) $H/16$ and (b) $4H$. Red circles in (b) show crevasse penetration results for isolated crevasses subject to a stress boundary condition instead of a displacement boundary condition. The gray shaded region corresponds to parameters with zero or negative buttressing.

to their more closely spaced counterparts. For larger $\mathcal{S}$ (and correspondingly modest crevasse penetration ratios), our simulations closely track the Weertman model. However, as $\mathcal{S}$ decreases, we see that our simulated crevasse depths deviate from the Weertman model and the effect of the rheology on crevasse penetration depths becomes more apparent. However, even in this case neither elastic nor viscous simulation results are well approximated by the HFB model. As an additional test, we also considered isolated crevasses subject to stress boundary conditions. Here we see that crevasses penetrate the entire ice shelf thickness when $\mathcal{S} \sim 2$, consistent with the HFB model and previous numerical results (e.g., Jiménez and Duddu, 2018; Zarrinderakht et al., 2022). However, crevasse penetration ratios diverge from the HFB model for larger $\mathcal{S}$ and eventually converge to the Weertman model as penetration ratios diminish.

To more deeply explore the effect of crevasse spacing on crevasse penetration ratios, we also calculated penetration ratios for a suite of spacings, focusing on unbuttressed ice shelves (Figure 3). We find that, as hinted at in Figure 2, crevasse penetration depths converge to the Nye depth as the crevasse spacing decreases and this remains true irrespective of the rheology. We further see that crevasse penetration ratios increase as the spacing between crevasses increases, although there are some discrepancies between elastic and non-linear viscous models.

Overall, we find that the Nye model is remarkably accurate so long as crevasse spacing is small. To understand why, we examined the ratio of the depth-averaged deviatoric stress in the uncrevassed portion of the ice shelf between crevasses $\bar{\tau}^c_{xx}$ to the imposed deviatoric stress τ_{xx}. We call this quantity the stress concentration and this is shown in Figure 3b. We see that, exactly as Nye (1955) asserted, when crevasses are closely spaced crevasses, the stress in the intact portion of ice between crevasses is unaffected by the presence of crevasses and there is no stress concentration. This is because the influence of

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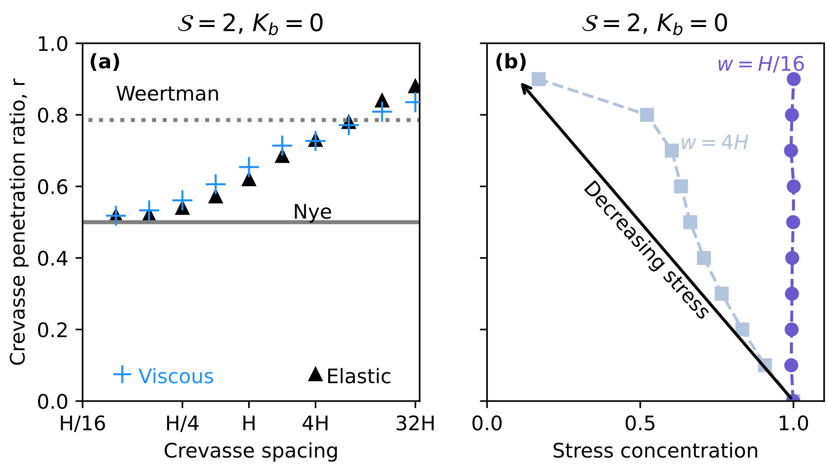

Figure 3. (a) Crevasse penetration ratio as a function of crevasse spacing for the elastic and viscous rheology for an unbuttressed ice shelf ($\mathcal{S} = 2$, $K_b = 0$). (b) Ratio of the depth averaged deviatoric stress between crevasses to the background deviatoric stress τ_{xx} imposed.

adjacent crevasses cancel each other out. Moreover, ever for more widely spaced crevasses ($w = 4H$), we find that crevasses actually reduce the stress in the intact portion of ice. This is partly a consequence of flexural deformation associated with bottom crevasse resulting in a compressive stress in the ice shelf in the intact region above the bottom crevasse. In fact, for small crevasse depths, the decrease in stress is proportional to $(1 - r)$ as opposed to increased by $(1 - r)^{-1}$ as conventionally assumed in damage mechanics (e.g., Sun et al., 2017).

4 Discussion and conclusions

We conclude that Nye was right; Nye's original theory for the depth of closely spaced crevasses is an excellent approximation when crevasses are closely spaced. Of course, crevasses will never be evenly spaced. However, even when examining irregularly spaced crevasses, additional numerical experiments show that the Nye model remained approximately correct. Although the HFB model may prove to be a useful empirical model, the conditions under which it is valid remain murky.

There are, nonetheless, questions that remain. For example, we have not addressed the stability of closely spaced crevasse configurations. Moreover, our crevasse depth was based on the horizontal stress and not the largest principal stress. This is because crevasse paths may no longer be vertical when the largest principal stress diverges from the horizontal stress. Furthermore, we have treated the bottom crevasses that penetrate above the waterline cavalierly, as air filled without account for the fact that these pockets would be isolated from the atmosphere nor have we accounted for the turbulent flow of water into crevasses.

We conclude by noting that, contrary to many depth-integrated models that seek to parameterize crevasses by analogy with damage, we find that closely spaced crevasses do not amplify stresses in the intact portion of ice shelves. Instead, closely spaced crevasses have no impact on the stress between crevasses whilst widely spaced crevasses in ice shelves actually decrease the

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deviatoric stress in the intact portion of the ice shelf. This suggests that the way we parameterize crevasses in large-scale numerical models may need to be re-examined.

Code availability. All code to reproduce the figures and results of this study will be available as a Zenodo archive once the lead author finishes adding comments to the code so that it is actually usable.

Author contributions. The project was conceived by J.N.B. and S.B.K. J.N.B performed all simulations and drafted all figures. M.F. and T.M contributed to project discussions. No AI, generative or otherwise, was used in this work and all awkward phrasing, misplaced semi-colons and poorly commented code are solely attributed to the lead authors discretion and poor taste.

Competing interests. The authors declare no competing interests and the work here was solely motivated by curiosity.

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