Borehole Measurements of Dynamic Basal Drainage Adjustments During Sliding Accelerations: Bench Glacier, Alaska

Toby Warren Meierbachtol

The University of Montana

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BOREHOLE MEASUREMENTS OF DYNAMIC BASAL DRAINAGE
ADJUSTMENTS DURING SLIDING ACCELERATIONS:
BENCH GLACIER, ALASKA

By
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B.A. Geology, Whitman College, Walla Walla, WA, 2003

Thesis
presented in partial fulfillment of the requirements
for the degree of
Master of Science
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Missoula, MT

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Artificial perturbations of borehole water levels, or slug tests, are a commonly employed means of characterizing the glacier hydrologic system. Results documenting the influence of slug testing on a field of boreholes and its change with time, however, are scarce. Slug tests were performed on Bench Glacier, AK in 21 boreholes over three field seasons during an annual late spring glacier speed up event. Fifty four slug tests were conducted, with water level monitoring in up to five boreholes adjacent to the slugged borehole. Seven of the slug tests were performed in conjunction with dye dispersion tests to identify water pathways within the slugged borehole following perturbation.

Underdamped and overdamped slug test responses show a high degree of connectivity among boreholes connected via the glacier bed. The nature and degree of connectivity is temporally variable, suggesting that the drainage network at the bed is highly dynamic on time and space scales of hours and 10’s of meters, respectively. The changes we document in slug test responses over time and space can be used to constrain explanations for the cause of the underdamped response. Examination of the underdamped response necessitates an understanding of the process(es) acting as the spring to produce the oscillatory water level behavior. We propose that coherent air packages are a likely means of producing the compliance needed to generate the underdamped slug test response, and that these air packages may exist within the glacier at the tips of subglacially propagated fractures. Synthesis of slug testing with other methods of study, such as video observation and dye tracing, helps lend insight into the governing processes at the glacier bed.
ACKNOWLEDGEMENTS

First and foremost I would like to thank my advisor, Dr. Joel Harper for not only providing me with the opportunity to carry out my research in an area as beautiful and interesting as Bench Glacier, but also for his continued assistance and insight during the writing process. I would also like to thank my committee members, Dr. Jesse Johnson, and Dr. William Woessner for their edits and comments on this paper. Credit also goes to my field partners, Tim Tschetter and Jessica Bleha for their assistance on the glacier. I would also like to thank the NSF-OPP Arctic Natural Sciences program for funding the field the Bench Glacier project. The University of Montana geosciences faculty and staff deserve thanks, particularly Christine Foster for her patience and help with travel plans and paperwork. To all my friends in Missoula: Ed, Anthony, Joni, Heidi, and the bike crew; thank you for giving me much needed reprieves from my work. Lastly, but most importantly, I’d like to thank my family: my parents Tony and Suzanne, my sisters Elie and Becca, and Sophie. Without their endless support, care, and need to be walked, this work would not have reached completion. Thank you.
PREFACE

Chapter 1 of this thesis, titled “Borehole Response Tests and Their Implications for Glacier Hydrologic Processes: Bench Glacier, Alaska,” is written in manuscript form with the intent of submitting it to the Journal of Geophysical Research. As a result, text and figures are organized with an emphasis on conciseness.

Data presented from 2002 and 2003 was collected and processed by Shaha [2004], and is here reprocessed and interpreted in conjunction with new data from the 2006 field season.
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CHAPTER 1: DYNAMIC BASAL DRAINAGE ADJUSTMENTS DURING SLIDING ACCELERATIONS FROM BOREHOLE RESPONSE TESTS: BENCH GLACIER, ALASKA

1.1. Introduction

The response of ice masses to global temperature rises is becoming increasingly important. Enhanced surface melting of snow and ice masses can alter the subglacial hydrology by increasing the amount of water routed to the bed. However, while subglacial hydrologic processes impact glacier flow dynamics, the relation between glacier motion and basal mechanics is still poorly understood [Clarke, 2005]. Generating a concrete understanding of the dynamics of the system thus necessitates detailed study. Various techniques have been employed in attempts to generate insight into the processes active at the bed of glaciers; one such technique is the slug test.

The slug test involves artificially perturbing the static water level in a well or borehole and measuring the response to that perturbation. These tests are conducted by either injecting a set volume of water in the well or borehole, or inserting (slugging) and removing (bailing) a sealed pipe to induce an instantaneous change in water level. Slug tests were originally performed in conventional hydrogeological settings to determine aquifer transmissivity and hydraulic conductivity. Various models have been created to estimate these parameters [Bouwer and Rice, 1976; Kabala et al., 1985; Kipp Jr, 1985; McElwee and Zenner, 1998; Van Der Kamp, 1976]. Slug test responses range from overdamped, which is characterized by a logarithmic water level recovery towards the initial condition, to an underdamped response in which the water level oscillates about the initial level following perturbation and is damped towards an equilibrium. A critically
damped slug test response is an intermediary, in which the water level rapidly recovers to some equilibrium without oscillating. Overdamped responses are typically related to low transmissivities, while underdamped responses commonly occur in aquifer settings with high transmissivities in wells with long borehole column lengths [Bredehoeft et al., 1966; Fetter, 2001].

Slug tests have become common and valuable experiments in glacial settings to estimate subglacial hydraulic properties. Slug tests were first conducted in glacier boreholes by Hodge [1976] during borehole drilling. He found oscillatory responses to be induced when: 1) an englacial cavity was intersected during drilling, and 2) the water level was perturbed by submerging the drill tip in the borehole. Stone and Clarke [1993] developed a model that described radial flow through a homogenous, permeable medium in which diffusion, transmissivity, and turbulent transport heavily influenced subglacial water flow. Results from the model were then applied to actual slug test responses to calculate hydraulic properties of sediment at the bed of Trapridge Glacier, Yukon, Canada. Iken et al. [1996] used slug tests to produce a conceptual model for the drainage network at Gornergletscher, Valais, Switzerland. The authors interpreted underdamped slug test responses to be associated with a drainage network consisting of well connected discrete passageways on clean bedrock. They suggested the observed oscillatory response was caused by compression of the water and overlying ice. In contrast, overdamped slug test responses collected on the glacier were interpreted to represent laminar flow in the subglacial sediment layer. One hundred and sixteen slug and bail tests were conducted by Kulessa and Hubbard [1997], 43 of which were performed using pressure transducers in adjacent boreholes to evaluate spatial connectivity at the bed of Haut Glacier d’Arolla,
Switzerland. No subglacial linkages were detected in the tests. Kulessa et al. [2005] used these data to calculate the subglacial sediment transmissivities using techniques frequently used in aquifer settings.

Here borehole slug data are presented from field experiments conducted during 3 years on Bench Glacier, Alaska. Slug tests were conducted in a grid of closely spaced boreholes, and water levels were monitored in up to five adjacent boreholes to generate a spatial field of slug test responses for each experiment. Tests were conducted over a ~1 month period in each field season to elucidate temporal dynamics. Borehole dye tracing was incorporated in seven of the slug tests to isolate borehole water flow dynamics during the slug response. These data reveal time and space evolution of the subglacial hydrologic system and give new insights to the mechanism responsible for generating oscillatory response curves.

1.2. Field Site and Setting

Slug tests were conducted in June of 2002, 2003, and 2006 on Bench Glacier, AK (Figure 1.2.1). Bench Glacier is a temperate glacier located in the Chugach Mountain Range, approximately 40 km from the Pacific Ocean. Bench Glacier spans about 1200 m in elevation, has a simple geometry and relatively shallow surface slope of ~10°, and an average elevation of 1300 m. The glacier is approximately 7.5 km long with a surface area of about 7.5 km², and reaches a maximum thickness of about 200 m. The glacier has been characterized as having a hard bed from penetrometer tests and borehole video inspection [Harper et al., 2005], however patchy sediment packages are possible at the bed.
All boreholes were drilled using standard hot water methods near the glacier center line. Borehole diameters were approximately 12 cm. In 2002 nine pairs of boreholes were drilled at multiple sites spanning the length of the glacier. In 2003, a grid of 16 boreholes was drilled with borehole spacing approximately 20 m on orthogonal coordinates. In 2006, we drilled 2 borehole clusters down glacier from the 2003 grid consisting of a three borehole triangle with 8.5 m spacing, and a grid of four boreholes with 20 m spacing on orthogonal coordinates.

Figure 1.2.1: Topographic map of Bench Glacier, including borehole slug test sites from 2002, 2003, and 2006. All borehole sites are located below the ELA.
Slug tests from all field seasons were conducted prior to or during well-documented spring rapid sliding events [Anderson et al., 2004; Harper et al., 2005]. This speed-up is associated with the change from a winter drainage mode to a summer mode, and is composed of two individual events (Figure 1.2.2). In 2002, the first of two rapid sliding events began on day 145 and continued for about one week. Glacier velocities returned to background levels (0.04 – 0.07 m d⁻¹) until day 165 when the second speed-up event initiated, lasting for about a week [Anderson et al., 2004]. The spring speed-up events in 2003 and 2006 were about 2 weeks in duration, with individual speed-up events lasting approximately 5 days. The 2003 speed up event was particularly well documented [Harper et al., 2005]. Water levels were monitored by a network of boreholes spanning the glacier length, and showed a distinct shift on day 157, at which time borehole pressure variations became synchronous. The onset of water level synchronicity occurred in conjunction with a 9-fold increase in glacier velocity, which reached a maximum of ~.18 m d⁻¹. Water storage measurements showed a distinct drop in storage associated with a velocity decrease after the first glacier speed-up on day 158. The spring speed-up in 2006 occurred about 2 weeks later in the year, and was slightly attenuated compared to its 2003 counterpart. The first velocity peak (magnitude ~14 cm/day) occurred on day 162, was followed by a decline in velocity, and ramped up again, peaking at slightly over 11 cm/day on Julian day 167. These data provide a hydrological framework for the period during which slug tests were performed, showing that the subglacial system was likely in a transition phase and linked to rapid sliding of the overlying ice.
1.3. Methods

1.3.1. Slug Test Procedure

Slug tests were performed by injecting a 75 l volume of water into a borehole. This injection was as instantaneous as possible, taking no more than 20 seconds to complete. Water levels were recorded in the slugged borehole and up to 5 adjacent boreholes with 15 psi Omega PX26-015GV pressure transducers. The pressure transducers were set in boreholes at least 20 minutes prior to slug injection to thermally equilibrate and document pre-slug water level trends, and continued to record water levels for 20 – 30 minutes after water level recovery to document post-slug trends. Water levels were measured at 2 second intervals and logged on a datalogger. Sixteen slug tests were performed in 6 boreholes in 2002, 20 slug tests were conducted in 10 different boreholes in 2003, and 18 more slug tests were performed in 5 different boreholes in 2006.

Figure 1.2.2: Regional velocity as measured by 24 velocity stakes spaced along the length of the glacier during the speed-up in 2003. Phase 1 occurred as an upglacier progression, while phase 2 consisted of a synchronous, glacier-wide speed-up. Plot modified from Harper et al. [In Press].
1.3.2. Slug/dye Combination Procedure

I performed dye tracing in conjunction with slug tests to study intra-borehole or englacial hydraulics which may dictate slug test responses. Slug/dye combination experiments were performed by injecting dye at a point in a borehole, followed by a slug test in the same borehole. Dye injection was performed by attaching a test tube containing .002 - .005 ml of Rhodamine WT dye (20% active) to a steel platform. The platform was attached to a cable and lowered to the desired depth, where the test tube was broken via a sliding hammer on the cable. Two submersible fluorometers were then lowered to desired depths to record dye concentrations (Figure 1.3.1). The fluorometers were capable of reading dye concentrations of <1 ~ 60 ppb, measuring it at 2 second intervals and logging to a datalogger. This datalogger was synchronized with the datalogger connected to the pressure transducer to ensure consistency in time. After lowering the fluorometers a slug test was performed according to the method described above.
Figure 1.3.1: Experimental set-up for slug/dye combination experiments. Fluorometers were placed at desired depths within the injected dye package to record dye concentrations. A pressure transducer was placed in the borehole to monitor water levels, and record it on to a separate datalogger. The two dataloggers were time synchronized.
1.4. Results

1.4.1. Response Curves

Underdamped responses, overdamped responses, and near critically damped underdamped responses were documented during the three field seasons (Figure 1.4.1). Table 1.4.1 displays the distribution of responses for each field season. Both types of underdamped responses (Figure 1.4.1 A and C) are grouped in the underdamped response category. In 2002 and 2003, the majority of slug tests produced an underdamped response in the slugged borehole, with the only underdamped responses in 2002 occurring near the glacier’s equilibrium line in boreholes 01 and 02. In contrast, in 2006 the majority of tests produced an overdamped response. Furthermore, the 6 underdamped responses documented in the slugged borehole in 2006 all occurred in the same borehole (BWC 03).

Table 1.4.1: Underdamped and overdamped slug test responses from each field season for slugged and adjacent boreholes.

<table>
<thead>
<tr>
<th>Field Season</th>
<th>Slugged Borehole</th>
<th>Adjacent Borehole</th>
<th>Total number of slug tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Overdamped</td>
<td>Underdamped</td>
<td>Overdamped</td>
</tr>
<tr>
<td></td>
<td>responses</td>
<td>responses</td>
<td>responses</td>
</tr>
<tr>
<td>2002</td>
<td>6</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>2003</td>
<td>9</td>
<td>11</td>
<td>33</td>
</tr>
<tr>
<td>2006</td>
<td>12</td>
<td>6</td>
<td>1</td>
</tr>
</tbody>
</table>
Figure 1.4.1: Variations in slug test responses showing: (A) underdamped, (B) overdamped, and (C) underdamped with a greater degree of damping from 2002, 2003, and 2006. Note 1) the difference in recovery times between the 3 figures, and 2) the attenuation of oscillation peaks between figures (A) and (C).

Maximum drainage velocity and the initial amplitude were calculated for all slugged and adjacent boreholes (Table 1.4.2). Overdamped responses were typically characterized by a higher initial amplitude and slower drainage velocity than oscillatory-type responses. The average period of oscillation was calculated for all underdamped responses based on the first three oscillation peaks. The period of oscillation ranged from 12 – 43 s during all field seasons, with higher periods more common in 2003. The degree of damping in the underdamped response also varied among slug tests. Some experiments showed greater damping of the underdamped response than others, as evidenced by greater attenuation of water level peaks and a faster recovery towards equilibrium (Figure 1.4.1).
Table 1.4.2: Slug test response parameters from the 3 field seasons for slugged and adjacent boreholes.

<table>
<thead>
<tr>
<th>Field Season</th>
<th>Slugged Borehole</th>
<th>Adjacent Borehole</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Overdamped Response</td>
<td>Underdamped Response</td>
</tr>
<tr>
<td></td>
<td>A₁ (cm) V² (cm/s)</td>
<td>P³ (s) A₁ (cm) V² (cm/s)</td>
</tr>
<tr>
<td>2002</td>
<td>265 - 656 0.1 - 5</td>
<td>12 – 36 66 – 225 9 – 63</td>
</tr>
<tr>
<td>2003</td>
<td>190 – 390 0.1 – 19</td>
<td>28 - 43 **66 – 250 9 - 63</td>
</tr>
<tr>
<td>2006</td>
<td>66– 404 0.1 – 3</td>
<td>26 – 30 73 – 152 7 - 22</td>
</tr>
</tbody>
</table>

1 Amplitude (cm)
2 Maximum drainage velocity (cm/s)
3 Period of oscillation averaged over first 3 periods (s)
* Outlier of 59.3%
** Outliers of 2.3, 3.9, 5.9, 6.0, and 11.0%
*** Not possible to determine drainage velocities below 0.29 cm/sec due to noise in the first derivative drainage curve.

1.4.2. Spatial Relationships

Adjacent borehole responses to slug tests are shown in Table 1.4.1. In 2002, 46% of adjacent boreholes showed an overdamped response, and 23% showed underdamped behavior. In 2003, a fairly even distribution of responses was recorded in adjacent holes. Adjacent borehole behavior from slug tests performed in 2006 showed a much higher degree of isolation at the glacier bed. Ninety percent of the 2006 boreholes did not respond to slug tests in another borehole.

Initial amplitude and drainage velocities in adjacent boreholes were typically attenuated from the slugged borehole responses. The period of oscillation in underdamped cases, however, was similar to the parent slugged hole (Table 1.4.2). In all cases, the response in adjacent boreholes did not occur synchronously with perturbation in the slugged borehole, but was lagged by a time ranging from 2 – 12 seconds. Adjacent borehole responses to an underdamped slugged hole typically showed oscillatory
behavior (Figure 1.4.2). In contrast, overdamped responses in the slugged borehole were accompanied by only overdamped responses in adjacent boreholes if any response was documented at all (Figure 1.4.3).

Figure 1.4.2: Response evolution over a 9 day period for a seven borehole network (blue dots) when borehole 08 (red dot) is slugged. Line colors represent the day of slug test. Borehole response trends are variable and do not mimic the slugged borehole trend in all cases.
Figure 1.4.3: A slug test performed in borehole 07 produced overdamped responses in adjacent boreholes. In all tests, adjacent boreholes responded in an overdamped manner if the slugged borehole showed an overdamped response.
1.4.3. Temporal Variability

Temporal complexities in 2003 slug test responses were evident on hourly and daily periods, and across the borehole grid. For example, slug tests conducted in boreholes 09 and 13 on day 156, 2003 show changes in response character on hourly time scales. At approximately 12:00 a slug test was performed in borehole 13, and an underdamped response was noted in both boreholes 13 and 09. Borehole 09 showed an initial amplitude of nearly 23 cm, and an average period of oscillation of 35 sec (Figure 1.4.4). A slug test later that same day at 17:30 in borehole 09 showed a significant dampening of the oscillatory behavior observed 5.5 hours earlier. Borehole 13 showed an initial amplitude of 9 cm, and an average period of oscillation of 40 sec.

![Slug test time series](image)

Figure 1.4.4: Slug test time series. A slug test was performed in borehole 13 at 12:00 on day 156 and water levels were monitored in borehole 09 as shown in Plot A. At 17:30 the same day, borehole 09 was slugged and water levels were recorded in borehole 13 as shown in Plot B. In all plots, borehole 13 is represented in red, and borehole 09 is represented in blue. Dampening in both boreholes increased over the 5.5 hour time span (Plots C and D), showing the average period of oscillation and amplitude respectively, of the two boreholes when a slug test was performed in each.
Complete character changes from underdamped to overdamped, or vice versa were documented on larger time scales in 2003. For example, Figure 1.4.2 shows borehole 08 evolving from an overdamped to an underdamped response over a 9 day period, with adjacent boreholes 12 and 13 following a similar trend. However, the behavior observed in the slugged borehole was not mimicked in all adjacent holes. Borehole connections were also transient, as shown by a new connection that formed between boreholes 03 and 08 between days 155 – 158 (Figure 1.4.2).

Slug tests in different boreholes during the same time interval produced different responses (Table 1.4.3). Water level behavior in boreholes 12 and 13 remained underdamped between days 154 and 163, while water level responses in boreholes 17 and 18 shifted from underdamped to overdamped. From these results, it is evident that slugged and adjacent boreholes show few coherent trends through the time of the slug test experiments in 2003.

Table 1.4.3: Slugged borehole responses in the 2003 field season over time. UD = underdamped, OD = overdamped.

<table>
<thead>
<tr>
<th>Slugged borehole</th>
<th>Julian Day</th>
<th>154</th>
<th>155</th>
<th>156</th>
<th>158</th>
<th>159</th>
<th>160</th>
<th>161</th>
<th>163</th>
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<tbody>
<tr>
<td>08</td>
<td></td>
<td>OD</td>
<td>UD</td>
<td>UD</td>
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<td></td>
<td></td>
<td></td>
<td>UD</td>
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<td>09</td>
<td></td>
<td></td>
<td>UD</td>
<td>UD</td>
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<td>12</td>
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<td>UD</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>OD</td>
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</tbody>
</table>

The character of slug test responses in 2006 changed little over an 11 day period. Neither the slugged borehole nor adjacent boreholes showed phase changes from underdamped to overdamped or vice versa. This stability was persistent on hourly and
daily time intervals. Only one borehole exhibited evolution with time, showing
progressive dampening of an already overdamped response over an interval of 3 days
(Table 1.4.4).

Table 1.4.4: Evolution of slug test parameters in borehole MC 03 from the 2006 field season. Velocity is calculated from given amplitudes and recovery times.

<table>
<thead>
<tr>
<th>Julian Day</th>
<th>Amplitude (cm)</th>
<th>Water level recovery time (min)</th>
<th>Mean velocity (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>157</td>
<td>167</td>
<td>43.7</td>
<td>.06</td>
</tr>
<tr>
<td>158</td>
<td>258</td>
<td>185.8</td>
<td>.02</td>
</tr>
<tr>
<td>159</td>
<td>310</td>
<td>&gt;416</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>

1.4.4. Slug/dye Tests

Of the seven slug/dye combination experiments I performed in 2006, five were performed in a borehole known to oscillate when slugged. In each of the five tests the dye package was flushed away from fluorometers placed at the bottom of the borehole in response to a slug test (Figure 1.4.5). However, a significant time lag existed between the drop in dye concentration at the two fluorometers located at 162 and 164 m depth. The fluorometers were input to the same datalogger, hence the time difference in concentration changes cannot be an artifact of the time measurement. Thus the initial motion of the dye was from top to bottom of the borehole.

Figure 1.4.5 also displays dye return pulses recorded by the fluorometers. The lower fluorometer recorded a significant dye return after initial disappearance, while the upper fluorometer recorded only a very slight increase in dye concentration. Dye returns were in phase with the water level peak recorded by the pressure transducer, indicating water level oscillations corresponded to oscillating water motion at the bottom of the borehole. Furthermore, a stronger return dye signal in the lower fluorometer implies that
the return pulse travels up the borehole from the bed, reaching the lower but not the upper fluorometer.

Results from the slug/dye combination experiments show that water motion at the bottom of the borehole follows the water level trends measured by the pressure transducer near the water surface. This will become important in interpreting the cause of the oscillatory response.

Figure 1.4.5: Slug/dye experiment performed on day 169, 2006, showing water level (blue line), and changes in dye concentration at depths of 162 m (green line), and 164 m (red line) below snow surface. The fluorometer placed at the bed of the glacier (164 m) captured a dye return curve, while the fluorometer 2 m above lacked any return.
1.5. Discussion

### Mathematical Notation

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y(t)$</td>
<td>Water level</td>
</tr>
<tr>
<td>$t$</td>
<td>Time</td>
</tr>
<tr>
<td>$A$</td>
<td>Initial Amplitude</td>
</tr>
<tr>
<td>$C$</td>
<td>Viscous damp. const.</td>
</tr>
<tr>
<td>$M$</td>
<td>System water mass</td>
</tr>
<tr>
<td>$\omega_0$</td>
<td>Angular frequency</td>
</tr>
<tr>
<td>$K$</td>
<td>Spring constant</td>
</tr>
<tr>
<td>$f$</td>
<td>Frequency</td>
</tr>
<tr>
<td>$B_m$</td>
<td>Bulk compressibility of material</td>
</tr>
<tr>
<td>$P$</td>
<td>Pressure</td>
</tr>
<tr>
<td>$V$</td>
<td>Volume</td>
</tr>
<tr>
<td>$V'$</td>
<td>Initial material vol.</td>
</tr>
<tr>
<td>$w_{\text{max}}$</td>
<td>Max. deflection at the center of a circle</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Poisson’s ratio</td>
</tr>
<tr>
<td>$P_w$</td>
<td>Pressure of added water slug</td>
</tr>
<tr>
<td>$r_d$</td>
<td>Radius of deformation</td>
</tr>
<tr>
<td>$E$</td>
<td>Elastic modulus of ice</td>
</tr>
<tr>
<td>$V_e$</td>
<td>Effective volume</td>
</tr>
<tr>
<td>$D$</td>
<td>Plate stiffness factor</td>
</tr>
<tr>
<td>$h_i$</td>
<td>Ice thickness</td>
</tr>
<tr>
<td>$w(0)$</td>
<td>Max. uplift at the center of a plate</td>
</tr>
<tr>
<td>$r_u$</td>
<td>radius of uplift</td>
</tr>
<tr>
<td>$R_b$</td>
<td>Radius of borehole</td>
</tr>
<tr>
<td>$L_f$</td>
<td>Fracture length</td>
</tr>
<tr>
<td>$D_f$</td>
<td>Fracture diameter</td>
</tr>
<tr>
<td>$H_a$</td>
<td>Air package height</td>
</tr>
<tr>
<td>$H_w$</td>
<td>Hydraulic head</td>
</tr>
<tr>
<td>$V_0$</td>
<td>Initial air volume</td>
</tr>
<tr>
<td>$L_c$</td>
<td>Length of connecting path</td>
</tr>
</tbody>
</table>
Slug test results from the three field seasons provide uniquely extensive data that reveal characteristics of the subglacial drainage network. However, it is necessary to understand the physical processes causing the oscillatory water level behavior in order to interpret the hydrologic significance of the time/space changes in slug test responses I observed. Here I present likely and unlikely processes which could produce the underdamped response, and incorporate this into the broader framework of the nature of the subglacial drainage network during the spring speed-up event.

1.5.1. The Underdamped Response

The water level change in an underdamped response can be described as a damped simple harmonic oscillator, defined by Potter [1978] as:

\[ y(t) = A e^{-\frac{t}{2M}} \cos(\omega_0 t - \delta) \]  

(1)

where:

\[ \omega_0 = f * 2\pi \]  

(2)

Here \( y(t) \) is the water level height at any time \( t \), \( A \) is the initial amplitude of the response, \( C \) is the viscous damping constant, \( M \) is the mass of water in the system, and \( (\omega_0 t - \delta) \) is the frequency component of the oscillatory response. In this case the frequency of the response is related to the spring constant \( (K) \) by:

\[ f = \frac{1}{4\pi M \sqrt{4KM - C^2}} \]  

(3)

A decaying exponential function fit to the peaks of the oscillations can be used to derive \( C \), leaving \( K \) as an unknown.
Various mechanisms exist in the glacial setting which can act as the spring and provide the compliance necessary to produce an oscillatory response with frequencies matching those from the actual slug tests. Here I analyze seven possible mechanisms that could accommodate the observed underdamped responses. Calculations for the possible mechanisms were made by Shaha [2004], with additional interpretation presented here. Calculations of possible mechanisms generating underdamped responses are based on slug test BG03_158_08 in borehole 08. The average period of the response in this experiment was 29.5 sec/cycle. Other characteristics of the response include: a first water level maximum of 1.1 m above static water level, a first minimum of -0.89 m and a second maximum of 0.67 m. Pressure changes were calculated using the first maximum, while volume changes were determined from the difference between the first minimum and second maximum.

1) Sediment Compression

Water flow through a subglacial sediment package and the resulting compression of the package skeleton has previously been used to explain slug test responses [Kulessa et al., 2005; Stone and Clarke, 1993]. The sediment package volume needed to provide the compliance for an oscillatory response of given amplitude can be calculated as:

\[ V = \frac{\Delta P}{B_m \Delta V / V'} \]  

where \( B_m \) is the bulk compressibility of the sediment, \( \Delta P \) is the change in pressure associated with the added slug of water, \( \Delta V \) is the change in volume necessary to accommodate the volume of water added, and \( V' \) is the initial volume of sediment. To test this at Bench Glacier \( 1 \times 10^8 \) N m\(^{-2}\) is used for the bulk compressibility of the subglacial sediments [Stone and Clarke, 1993], and results in a necessary sediment package volume
of 242 m³ to induce the oscillatory behavior observed in the slug test. Giving a coherent package a reasonable thickness of 0.1 m requires a radius of 27.75 m, but observation of over 50 boreholes on Bench Glacier via penetrometer tests, borehole video, and drill tip monitoring during drilling shows no evidence of such an extensive sediment package. Reducing the package thickness requires an even greater radius, which would be evidenced in the slug test responses by ubiquitous underdamped responses in adjacent boreholes, yet this is not the case. Furthermore, accounting for the evident changes in response character of slugged and adjacent boreholes on a daily time scale is difficult by sediment compression. For example, Figure 1.4.2 shows a response change from overdamped to underdamped in boreholes 03, 07, 08, and 13 between days 155 and 158. Explaining this evolution by sediment compression requires that all boreholes connect to a sediment package at the bed, presumably by sliding on to it. To achieve this, the glacier would have to slide on the order of 40 m to connect all boreholes to a package. Given a maximum observed glacier velocity during the speed-up of ~0.3 m d⁻¹, this is clearly not feasible. Hence, I conclude that it is highly unlikely that sediment compression provides the spring source which induces oscillatory behavior at Bench Glacier.

2) Water Compression

The bulk modulus of elasticity equation (4) is used to evaluate the likelihood of water compression providing the compliance necessary to produce observed water level oscillations. Using $2.27 \times 10^9$ N/m² for the bulk compressibility of water [Stone and Clarke, 1993], a water volume of about 3700 m³ is needed to generate the observed oscillations. This volume is unreasonably large for an ice mass of Bench Glacier’s size. However, if such a volume did exist, given that the compression wave travels through
water at 1497 m s\(^{-1}\), the adjacent boreholes would be expected to oscillate in phase with the slugged borehole if they were connected to the same volume of water. Instead, adjacent borehole responses are lagged by up to 12 sec, and in some cases oscillate out of phase with the slugged borehole. As a result, it is highly unlikely that compression of subglacial waters could cause the underdamped response observed in our slug tests.

3) Compression of Ice

In the ice compression model, the induced pressure from the slug test temporarily deforms a circular area of the glacier sole. The elastic compression produces the underdamped response. This calculation was performed by Iken et al. [1996], and is given by [Timoshenko and Goodier, 1982]:

\[
\begin{align*}
  w_{\text{max}} &= \frac{2(1-\nu)^2 P_v R_d}{E} \\
  \text{max}^2 w_v &= \frac{P_v V_e}{\pi} \\
  E &= \frac{2\pi(1-\nu)^2 P_v r^3}{E}
\end{align*}
\]

Here \( w_{\text{max}} \) is maximum deflection at the center of the circle, \( \nu \) is Poisson’s ratio (~0.33 for ice), \( P_v \) is the pressure of the added slug of water, \( R_d \) is the radius of deformation, and \( E \) is the elastic modulus of ice (~9.6x10\(^9\) Pa). The resulting volume change from deformation is given by:

\[
V_e = \pi r^2 w_{\text{max}}
\]

Substitution of equation (6) into equation (5) yields:

\[
V_e = \frac{2\pi(1-\nu)^2 P_v r^3}{E}
\]

Using equation (7) and assuming a uniformly distributed load along the bed of the glacier, a minimum radius of deformation of 15.76 m is necessary to produce the oscillatory response documented. While this is a reasonable radius of deformation, the ice compressibility model has difficulty accounting for the overdamped responses in slugged
and adjacent boreholes. Given the assumption that Bench Glacier overlies a hard bed, underdamped responses would be expected in all slug test experiments. In fact, both underdamped and overdamped behavior is exhibited by boreholes and mode switching is common. These facts lead me to conclude that ice compression is an unlikely means of providing the spring compliance needed to generate Bench Glacier’s oscillatory behavior.

4) Intra-borehole Processes

Underdamped slug test responses may be caused by processes occurring within the slugged borehole, such as compression/dilation of the borehole itself, or compression of air bubbles trapped along the borehole walls. However, results from the slug/dye tests show that water motion at the bottom of boreholes is in direct response to, and in phase with the surface water level behavior. This suggests that water acts as a homogenous entity throughout the length of the borehole and exits the bottom, where an external medium or process acts as the spring to create the underdamped response. Furthermore, if processes within the borehole were responsible for creating the underdamped response, all slug tests would produce oscillations. The fact that this is not the case is further evidence suggesting that intra-borehole mechanics do not provide the spring system for generating an underdamped response.

5) Direct Interaction with Adjacent Boreholes

Oscillatory behavior observed in the three field seasons may be induced by temporary accommodation in adjacent boreholes, or effectively “sloshing” of water back and forth between holes. For such a mechanism to be plausible, the oscillatory responses in slugged and adjacent boreholes must be exactly out of phase and oscillate at the same frequency. However, this is not exhibited in slug test results. Initial responses in adjacent
boreholes were typically lagged by up to 12 seconds from the initial perturbation, and water levels commonly oscillated at different frequencies (ie. Figure 1.4.4 B) such that slugged and adjacent boreholes oscillated in phase with each other. Furthermore, the sum of adjacent borehole water level amplitudes was consistently a fraction of the slugged amplitude. This suggests that the water volume is initially accommodated by a different source, which subsequently influences both the slugged and adjacent boreholes. As a result, I conclude that direct borehole interactions are unlikely to induce the observed oscillatory water level behavior.

6) Uplift of the Glacier

Detachment of the glacier from the bed and resulting elastic uplift in response to a slug test may produce underdamped water level behavior. Here the study is limited to radial flow and a uniformly distributed pressure across the bed, as this provides the minimum value for the radius of uplift. This approach utilizes a plate stiffness factor (D) which, following Sechler [1952], is calculated as:

$$D = \frac{Eh_i^3}{12(1-\nu)^2}$$

(8)

where $h_i$ is the ice thickness, and $E$ and $\nu$ are previously defined. Simplifying the uplift to a conical geometry yields:

$$w(0) = \frac{P_wR_w^4}{64D}$$

(9)

where $w(0)$ is the maximum uplift at the center of the plate. The volume of uplift then necessary to accommodate the slugged volume of water is:

$$V_c = \frac{1}{3} \pi R_w^2 [w(0)]$$

(10)
By substituting equation (9) into equation (10), the minimum radius \( R_u \) of uplift can be calculated. Using a measured ice thickness of 185 m, a minimum radius of ice uplift of 97 m is necessary to accommodate the change in volume induced by the slug test. The approximation of conical uplift introduces an error of 1.8 m into the final value for the radius which is insignificant for this purpose. Given the 80 x 80 m dimensions of the 2003 borehole grid, a radius of uplift of nearly 100 m would cause all boreholes in the grid to respond in an oscillatory manner to a slug test. This is clearly not the case, which leads me to conclude that ice uplift is not a viable option for providing the compliance necessary to produce our oscillatory responses.

7) Compression of Air

Compression of air within the glacier may provide the compliance necessary to produce the underdamped slug test response. Air is far more compressible than water or ice, and as such could prove to be a realistic possibility to induce oscillatory water level behavior if compressed.

As shown in equation (3), the oscillation frequency in the case of simple harmonic motion is governed by the mass of the system (M) and spring constant (K) of the source medium. Appendix A shows the derivation of K as represented by an englacial air package. From equation (25), it can be seen that K is inversely proportional to the initial volume \( V_0 \) of the air package. The mass of water in the system can be related to a water volume, so the oscillation frequency is governed by the volume of water in the system \( V_w \) and the initial volume \( V_0 \) of the air package. By inputting known values from slug testing into equation (25), a range of air volumes can be calculated for different water volumes in the system that will generate an oscillatory response with frequency of 29.5
sec\(^{-1}\) (Figure 1.5.1). For example, if the slugged borehole is connected to an air source via a network containing 25 m\(^3\) of water, the water level in the borehole will oscillate at 29.5 sec\(^{-1}\) with an air source of .145 m\(^3\) (Figure 1.5.1). Results from modeling show that when subjected to elastic compression, air packages of reasonable size will produce oscillations with frequencies observed in the field. Furthermore, an approximate energy balance shows air compression to be a reasonable mechanism. The energy generated from air compression exceeds the kinetic energy from water motion, suggesting that the remainder is lost to heat conduction in the ice and frictional forces. However, for air compression to remain a viable option for producing oscillatory behavior, a means of generating and maintaining coherent air packages within the glacier must exist.
Figure 1.5.1: Modeled slug response curves. A) Water volumes and corresponding air volumes necessary to produce oscillatory air compressions with a frequency of 29.5 s\(^{-1}\). The red star represents the input parameters for modeling in Plot B, (water volume = 25 m\(^3\), air volume = 0.145 m\(^3\)). Modeled oscillatory water level behavior (red line) to observed (black line) results show that a borehole connected to an air package of 0.145 m\(^3\) via a subglacial system containing 25 m\(^3\) of water oscillates at frequencies matching those observed in the field.
Air may be imbedded in the glacial system through a variety of sources. Atmospheric gases entering the glacial system through surface inputs such as moulins are likely to be inherent in subglacial water as dissolved gases. Air is also introduced to the subglacial system through frictional heating and subsequent melting of bubbly ice as subglacial water flows along the bed. Martinerie et al. [1992] calculated air contents of 120 mm$^3$/g of ice in a polar climate at an elevation approximately equal to the median elevation of Bench Glacier (1400 m), which corresponds to an air content of about 11% by volume. This value can be assumed to be a minimum, as the total volume of gas per unit mass of ice typically increases by about 0.2 mm$^3$/g with a 1 K increase in temperature [Paterson, 1994], and Bench Glacier is located in a more temperate region than Martinerie’s Antarctic study site. Borehole video observation of upwelling bubbles in significant concentrations confirms the existence of air in the glacier in notable quantities (Figure 1.5.2).

![Figure 1.5.2: Photograph from borehole video documenting upwelling air bubbles. Borehole diameter is approximately 12 cm. Upwelling gas bubbles have been documented on numerous occasions on Bench Glacier during video observation of boreholes (Photo courtesy of J. Harper).](image)
I propose that fracture propagation upwards from the bed of the glacier provides a likely means of creating coherent air packages by depressurization and exsolution of dissolved gases during fracture inception. As fractures propagate upwards into the ice, the overburden pressure decreases accordingly. Thus, as pressurized subglacial water rises to fill the newly opened void, depressurization occurs, resulting in the exsolution of gases. The exsolved gases coalesce at the fracture tip, resulting in a coherent air package connected to the bed of the glacier via the newly formed fracture.

Englacial fractures have been documented on various glaciers [Fountain et al., 2005; Harper and Humphrey, 1995; McGee et al., 2003], and were noted again in video imaging on Bench Glacier in 2006. Video imaging boreholes shows these fractures to be ubiquitous, averaging about 2 fractures per length of borehole on Bench Glacier. Radar profiling of Bench Glacier during the 2003 and 2006 field seasons also shows evidence of englacial fractures existing at depth in the glacier [Bradford et al., 2005]. Subglacial propagation of fractures has been documented under jökulhlaup conditions [Roberts et al., 2000; Roberts et al., 2002]. In some cases, propagation extended to the ice surface [Roberts et al., 2000]. Analytical investigations of subglacial fracture propagation have shown the process to be a realistic occurrence on grounded glaciers when subglacial water pressures are sufficiently high [Van Der Veen, 1998]. Subglacial water pressures during the 2003 and 2006 field season were consistently at or above 90% of ice overburden, with localized pressures likely higher. This provides a realistic mechanism for propagating fractures from the bed of Bench Glacier during the study period. Further evidence for subglacial fracture propagation comes from borehole video observations of an opening fracture at depth in the glacier [McGee et al., 2003]. Formation of the fracture
was accompanied by turbidity in the borehole, thought to result from subglacial sediment disturbance during propagation.

In a simple conceptual model of a borehole connected to an englacial fracture via a subglacial pathway (Figure 1.5.3), oscillatory water level behavior can be generated in the borehole by elastic compression of this air package. Following this model I check the feasibility of the water and air volumes from Figure 1.5.1. While data constraining fracture geometries is scarce, our borehole video observations allow some inferences to be made as to their nature. Fractures appear to be planar, steeply dipping (60 - 90°), and are documented at all depths within the glacier. However, it is unclear if near-surface fractures are subglacial or surficial in origin. From borehole video estimations, I assume that the diameter of the fracture (D₁) is 0.06 m. To accommodate the 25 m³ volume used in the modeling in Figure 1.5.1, and assuming an ambiguous fracture height (H₁) of 35 m, the fracture length (L₁) must be 11 m. This requires an air package height (Hₐ) of 0.22 m to achieve the 0.145 m³ air package necessary to generate oscillations with a frequency of 29.5 sec⁻¹. I do not propose that the oscillatory behavior we observed was necessarily a result of a fracture with these exact dimensions. Rather, the purpose of the exercise is to demonstrate that the modeling result corresponds to reasonable real world dimensions.
Figure 1.5.3: Simplified conceptual model of the interconnected system at the bed of Bench Glacier. Boreholes 1 and 2 are connected via a subglacially propagated fracture with an air package at the tip and dimensions $H_a \times L_f \times D_f$. Slug testing borehole 1 results in compression of the air package in the fracture, causing an oscillatory response in boreholes 1 and 2.
1.6. Hydrologic Implications

Spatial results from slug testing of Bench Glacier suggest that the drainage system at the bed is composed of discrete pathways that are irregularly linked just prior to and during a spring speed-up event. This system is similar to the “slow” network detailed by Fountain and Walder [1998], in which the glacier bed consists of cavities connected by inefficient discrete flow paths. Spatial and temporal slug test results from the 2003 field season suggest that this “slow” drainage network is highly dynamic during the transition from a winter to summer drainage system. While broader scale connectivity is maintained during the slug testing period, as suggested by synchronous water pressure behavior within the borehole grid [Harper et al., 2005], the slug test results provide strong evidence showing that localized subglacial linkages are highly dynamic on the spatial scale of 10’s of meters, and the temporal scale of hours. The picture emerging is then one of a system of opening and closing irregular linkages, which connect each other and existing cavities as the glacier rapidly slides across the bed. In this scenario there is a circular relationship between sliding and the drainage system, in which the nature of the drainage network directly influences the glacier sliding rate, which in turn creates a dynamic readjustment of the drainage configuration. In this scenario the variations we observed on short time and space scales are driven by an increase in the glacier velocity.

Cavities and linkages at the glacier bed may also intersect fractures extending into the ice. The environment present at the bed during the transition period, with high basal water pressures and a dynamic stress field from increased velocities, likely promotes initiation of such fractures. By connecting boreholes to the fractures via these subglacial features, a means of inducing oscillatory behavior in response to slug tests that explains
the observed spatial variability is introduced. Boreholes exhibiting underdamped water level responses are linked by a subglacial pathway that intersects a fracture.

The underdamped responses observed recovered faster than boreholes that exhibited overdamped behavior, suggesting that underdamped boreholes were connected to a system with greater transmissivity than overdamped boreholes. Connection to a planar fracture of significant length, which is proposed in the previous modeling, increases the potential for further connections to be made to higher transmissivity systems by increasing the connected area at the bed. If a borehole was connected to a fracture that did not intersect a high transmissivity system, damped oscillations would be expected, followed by a subsequent slow recovery. Indeed, this was observed at Bench Glacier as shown in Figure 1.6.1. Thus, subglacially connected fractures may have important implications beyond influencing slug tests. The features likely add another dimension to the subglacial hydrological system, providing another mechanism for transporting water along the bed.
Figure 1.6.1: Slug test response behavior exemplifying an initial oscillatory response, followed by a slow recovery towards equilibrium.

The slower recovery times observed in overdamped slug tests implies that the drainage network in the immediate vicinity has less capability for rapid water transport than the drainage system associated with underdamped slug test behavior. However, results show that the underdamped slug responses are temporally variable as well. For example, the decrease in mean velocities with time in Table 1.4.4 suggests that the transmissivity of the system decreased over the time period. We have shown that flow through sediment packages is unlikely at the bed of Bench Glacier, so the decrease in transmissivity must be a product of a change in the nature of the drainage network. In this instance, evolution of the network is towards a greater degree of isolation.
In the “slow” drainage model, the transient nature of the drainage network likely results in temporary connections to subglacially propagated fractures. Thus, subglacial pathways that were previously connected to englacial fractures may lose connection as the pathways reposition themselves, while isolated subglacial linkages become connected to existing englacial fractures. Such an explanation accommodates the temporal variability observed in slug test responses.

Increasing the volume of water to which the spring system is connected can also change the nature of slug test responses. Introducing greater volumes of water to the connected drainage network effectively increases the mass in the mass – spring system. Thus, as more water is added to the underdamped system while maintaining a constant air package volume, the slug test response becomes progressively more damped (Figure 1.6.2). Increasing the volume of connected water in the system is unlikely to account for complete phase changes from underdamped to overdamped, as this necessitates adding an unreasonable volume of water. However, Figure 1.6.2 shows that increasing the volume of water in the system can modulate the dampening of the system. It is important to note that it is not necessary to increase the volume by adding water to the subglacial system. Instead, increasing the volume in the system can be achieved by connecting with existing water bodies which were previously isolated.
Figure 1.6.2: Modeled relationship between slug dampening and water volume. By keeping the air volume static and increasing the volume of water connected to the system (hence increasing the mass), oscillatory behavior induced from slug testing becomes more damped.
1.7. Conclusions

Repeated slug tests were conducted in a network of boreholes on Bench Glacier, AK during a dynamic drainage phase change in which the glacier was transitioning from a winter to a summer mode. Underdamped and overdamped slug test responses in slugged and adjacent boreholes, and their spatial and temporal characteristics comprise a unique data set and lend insight into the processes existing at the bed of the glacier. Results from the slug tests illustrate two main features of the drainage network existing beneath Bench Glacier during the transition period: 1) proposed discrete flow paths are transient on spatial scales of 10’s of meters, and 2) the spatial distribution and character of these pathways is dynamic on an hourly scale. An explanation of the mechanism(s) responsible for generating the underdamped response observed in the experiments must accommodate these spatial and temporal elements of slug testing. Elastic compression of a subglacial sediment package, compression of water at the bed and in the borehole, elastic compression of the overlying glacier ice, processes occurring within the borehole itself, direct influences from adjacent boreholes, and elastic uplift of the glacier have been analyzed and shown to be highly unlikely to account for the underdamped slug test responses and their high degree of variability. Modeling shows air compression to be a viable means of inducing oscillatory responses to slug testing. Air packages are a reasonable occurrence in the glacier at the upper tip of subglacially propagated fractures. Englacial fractures are sufficiently common, can accommodate required air and water volumes with sensible geometries, and could account for the spatial and temporal variability exhibited by the slug test responses when coupled to the transitory nature of the subglacial drainage pathways. Such an explanation for the mechanism controlling the
oscillatory behavior in slug tests implies significant amounts of water could be stored in
the glacier with a direct connection to the bed. This could prove important to water’s role
in glacier sliding.
APPENDIX A: DERIVATION OF THE SPRING MODEL EQUATION

The following is the derivation of the model equation for an underdamped slug test response via compression of an air package, following Shaha [2004]. Refer to Figure 1.5.3 for definition of variables (X_b, L_c, D_f, H_a, and r_b).

We begin with the initial pressure in an air cavity of initial volume ($V_0$), which is defined as:

$$P_0 = \rho_w g h_w$$

(11)

The volume change in the air cavity due to the slug test (the effective volume) comes from the initial amplitude of the slug and is defined as:

$$V_e = \pi \rho_b^2 X_b$$

(12)

The new volume of air in the fracture is:

$$V = V_0 - V_e$$

(13)

Or:

$$V = V_0 - \pi \rho_b^2 X_b$$

(14)

Assuming that air behaves as an ideal gas where $P_0 V_0 = PV$, then:

$$P = \frac{P_0 V_0}{V}$$

(15)

By substituting Eq. (13) into Eq. (15) and simplifying, pressure is defined as:

$$P = \frac{P_0}{1 - \frac{V_e}{V_0}}$$

(16)

We assume that $\frac{V_e}{V_0}$ is small, thus according to series expansion $\left(\frac{1}{1+t} = 1 - t\right)$, Eq. (16) simplifies to:
\[ P = P_0 \left(1 + \frac{V}{V_0}\right) \quad (17) \]

Or:

\[ P = P_0 + P_0 \left(\frac{V}{V_0}\right) \quad (18) \]

The effective pressure can be defined as \( P_e = P - P_0 \), which leads to:

\[ P_e = P_0 \left(\frac{V}{V_0}\right) \quad (19) \]

According to Hooke’s Law for an ideal spring:

\[ F = KX_b \quad (20) \]

The effective force of the air compressions is given by:

\[ F = P_e A_b \quad (21) \]

Where:

\[ A_b = \pi r_b^2 \quad (22) \]

Thus by substituting Eq. (21) into Eq. (20) and solving for \( K \):

\[ K = \frac{P_e A_b}{X_b} \quad (23) \]

Substituting Eq. (19) into Eq. (23) yields:

\[ K = \frac{P_0 V_e A_b}{V_0 X_b} \quad (24) \]

Substituting Eq. (24) into Eq. (3), the frequency equation, yields the equation upon which the model is based:
In Eq. (25), the frequency \( f \), initial pressure \( P_0 \), area \( A_b \), effective volume \( V_e \), and amplitude \( X_b \) can be derived from the slug test data. The damping constant \( C \) can be calculated by fitting an exponentially decaying function to water level peaks. Thus, the mass of the system \( M \), and initial volume of the air cavity \( V_0 \) are left as the unknowns which must be defined to generate oscillations with the desired frequency.

\[
f = \frac{1}{4\pi M} \sqrt{\frac{P_0 V_e}{4 \left( \frac{V_0}{X_b} \right) M - C^2}}
\]
APPENDIX B: INSTRUMENT DEVELOPMENT

New instrumentation was developed in this study for performing dye tests in boreholes during the 2006 field season. Here the construction of fluorometers fabricated to measure dye at the bed of the glacier and the dye injection apparatus are discussed.

B.1. Dye Injection Apparatus

The dye injection apparatus was built for the purpose of injecting dye at a remote point within the glacier, and consisted of a platform to hold the dye-filled test tube, and a sliding hammer. The apparatus was constructed using 1/8”, 1x19 steel cable with a breaking strength of 2100 lbs, a large washer, a garden hose reel, and a 4 inch and 6 inch length of hollowed out steel bar. The washer was attached by epoxy to the 4 inch length of the steel bar to increase surface area, and the apparatus was fixed to the end of the steel cable to act as a smashing platform. The cable was marked at 5 m increments to a length of 220 m for manual depth measurements. The cable was then strung through a 6 inch length of the steel bar, allowing the bar to slide freely along the cable, thus acting as the sliding hammer. This system was attached to the garden hose reel, which allowed me to transport the apparatus efficiently and maintain control of the cable and platform during lowering. A photo of the set up and apparatus schematic can be seen in Figures B.1 and B.2 respectively.
Figure B.1: Photo showing the cable reel box, smashing platform, and attached test tube prior to lowering. The aluminum pole through the reel box was pushed ~2 ft into the snow to keep the box stationary.

Figure B.2: Schematic showing the dye injection apparatus in use.
B.2. Fluorometer Construction

Fluorometers capable of reading dye concentrations at depths up to 200 m were needed for the dye injection experiments performed in 2006. Turner Designs Cyclops – 7 submersible fluorometers were used for the experiments. These fluorometers have a small profile and are capable of reading dye concentrations from 1 – 60 ppb when the gain setting is set on high. The fluorometer was soldered to a 220 m length of CAT 5 cable, which was marked at 1 m increments for manual depth determinations. A 250 psi pressure transducer was potted in a 6” length of PVC pipe with epoxy for waterproofing, and soldered to the CAT 5 cable. The fluorometer and pressure transducer were attached to an avalanche probe in the field to prevent the fluorometer from folding back on the pressure transducer during lowering in the borehole. Two fluorometer – pressure transducer combination devices were built prior to the 2006 field season at the University of Montana.
APPENDIX C: INSTRUMENT CALIBRATION

Depth calibrations were performed during the 2006 field season for the 15 psi pressure transducers used in slug testing, as well as the 250 psi pressure transducers attached to the fluorometers. The 2 fluorometers used in the dye testing were also calibrated before and after the field season using prepared samples containing known RWT dye concentrations.

C.1. Pressure Transducer Calibration

The pressure transducers were calibrated after drilling the first borehole in the 2006 field season, and again 10 days later to ensure accurate water level documentation. Calibration of the pressure transducers was achieved by lowering the pressure transducer to an initial borehole depth (typically 0.5 m below the water surface), and taking 10 voltage measurements. This process was repeated at 0.5 m depth increments until 5 depth measurements were taken. The voltages were then averaged, plotted versus water depth, and a linear regression was applied to show the relationship between voltage and depth as shown in Figure C.1. The linear equation for the line was then used to convert voltage readings to a depth below water surface. This procedure was repeated for each pressure transducer.
Figure C.1: Pressure transducer #1 calibration, performed on Julian day 154.

Calibration of the 250 psi pressure transducers was performed in the field according to the procedure described above for the 15 psi pressure transducers. The only difference in procedures regarded the depth intervals at which the readings were taken. A calibration was performed first at depths of 10, 20, 30, 40, and 50 m (Figure C.2). The calibration was then performed again 8 days later using depths of 40, 60, 80, 100, and 120 m. Unfortunately, while calibrating the 250 psi pressure transducers produced both accurate and precise results, when the pressure transducers were used in experiments the resolution was far too coarse to be useful in accurately measuring the depth of the fluorometer. As a result, I manually measured the fluorometer depth using the tape marks on the fluorometer cable during testing.
C.2. Fluorometer Calibration

Calibration of the fluorometers was performed prior to, and after the 2006 field season using prepared samples containing 1, 10, 20, 50, 70, and 100 ppb Rhodamine WT dye (20% active). The fluorometer was placed in a prepared solution and 10 voltage measurements were taken. This was repeated for each solution sample, averages were taken, and plotted as shown in Figure C.3. The gain setting on the fluorometers was set to high, resulting in errors when reading the higher 70 and 100 ppb concentrations. However, the other 4 concentrations provided a sufficient number of points for the linear regression. By finding the equation of the best fit line, the conversion from voltage to parts per billion was made.
Figure C.3: Rhodamine WT concentration calibration performed for fluorometer “blue.” Anomalous points at concentrations of 1 and 10 ppb are likely due to slight variations when preparing calibration solutions. This trend is consistent through every calibration curve suggesting a small variation in concentration of the prepared sample, as opposed to instrument error.
APPENDIX D: DOCUMENTATION OF ENGLACIAL FRACTURES

D.1. Introduction/background

Transmitting meltwater from a glacier’s surface to the bed is an important aspect of glacial hydrology. Efficient routing of meltwater to the bed of a glacier has implications regarding the relation between surficial glacier processes and subglacial mechanics. This is of considerable importance when considering that the volume of water present at the bed of a glacier may directly influence its sliding rate [Harper et al., 2005]. As such, a better understanding of the processes occurring within the glacier that may affect water transport is needed.

Water may reach the glacier bed from the surface through a number of mechanisms. The initiation of englacial water passageways was originally proposed by Shreve [1972], who showed theoretically that water veins exist in ice at 3-grain intersections, and that these veins may connect to form a capillary network within the glacier to transport water. In such a model, larger tubes capture smaller ones, resulting in an arborescent tubular drainage network through the glacier. The existence of water filled passages along 3-grain intersections in the field was confirmed by Nye and Frank [1973] and Raymond and Harrison [1975], however field evidence for the arborescent drainage system within the glacier is scarce. Moulins along the glacier are macro-scale features which potentially act as point sources, routing the majority of surficial water to the bed [Harper and Reeve, in review]. Englacial water transport may also occur at the tips of surface crevasses [Fountain and Walder, 1998]. For water to continually down cut into the ice at the fracture tip, the crevasse must remain water filled. If not, the creep of the ice will pinch off the crevasse tip, isolating the channel from the water source.
above. The isolated water package will then cease to descend once the rate of closure around the pocket equals the rate at which melting occurs at the package bottom.

Englacial voids are relatively recently discovered features, and the role of these voids in routing surficial meltwater is still unknown. Through video observation, *Harper and Humphrey* [1995] documented englacial cavities in each of the 16 boreholes drilled in Worthington Glacier, Alaska. They estimated that discrete englacial structures, which includes voids and conduits, comprise <3% of the ice mass. The documented voids were presumed to be isolated within the glacier.

*Hubbard et al.*, [1998] used electrical resistivity imaging on Haut Glacier d’Arolla, Switzerland to document englacial drainage. The authors mapped a horizontal englacial fracture that hydraulically connected 2 boreholes at a depth of 13 m below the glacier surface using the new method.

Englacial fractures were documented at all depths in Bench Glacier, AK via borehole video monitoring [McGee *et al.*, 2003]. These ubiquitous fractures were laterally and vertically extensive, and were shown to be connected to the subglacial, englacial, and surficial systems. Rapid evolution of the fractures during a dynamic period of glacier motion was also documented.

*Fountain et al.*, [2005] noted englacial voids on Storglaciaren, Sweden through borehole video, and radar observations in 38 of 48 drilled boreholes. The authors showed the majority of documented voids to be fracture-like in geometry, with an average diameter of 4 cm and a steep dip. The orientation of these fractures rotated some 10’s of degrees with depth in the glacier. Fractures within the glacier were shown to be hydraulically active, conducting water at typical speeds of 1 – 2 cm s^{-1}. As a result, the
authors concluded that englacial fractures in temperate glaciers are the dominant pathways for englacial water flow.

Drill tests, slug testing, dye tracer studies, and video borehole observations were performed in June, 2006 on Bench Glacier, AK and show convincing evidence of efficiently connected englacial fractures throughout the glacier. Here test results are presented and some preliminary insights into the implications of the results as to the importance of the fractures as a transport and/or storage mechanism are put forth.

D.2. Drill Tests

D.2.1 Introduction and Methods:

Monitoring water levels in boreholes during drilling is a simple and effective means of documenting englacial fractures and potential connections at the bed of the glacier. Drilling is conducted via hot water methods, creating a water filled hole. Thus, the overlying water in the borehole acts as a continuous potential slug test if englacial voids are intersected during drilling. In this scenario, any encounter with an englacial fracture during drilling would likely result in a subsequent decline in water level in the drill hole.

Six drill tests were conducted in 2006 on Bench Glacier, however the first drill test in borehole MC 02 was performed using a faulty pressure transducer. Results from the other 5 drill tests are presented. Borehole water levels were monitored in the drill hole and adjacent boreholes to document englacial fracture intersection during drilling, and the spatial scale of its influence. The same 15 psi transducers that were employed in slug tests were also used during drill testing, and recorded data at 2 second intervals, logging it onto a datalogger. Transducers were placed in adjacent boreholes prior to drilling at
depths of 4 – 5 m below the water surface. The pressure transducer in the drill hole was installed when the drill had reached a depth of about 30 m. Water levels were monitored throughout drilling, and for a significant period of time after drilling terminated to record water level trends after connection to the bed. Drill depth measurements were made manually at 10 m increments during drilling.

During drilling a well pump was added to the drill hole to pump out borehole water and reuse it in drilling. As a result, borehole water levels often showed artificial water level changes that are artifacts of turning the well pump on and off. Furthermore, the pressure transducer in the drill hole was often raised or lowered to accommodate the changes in water levels. These trends were removed from the data as shown in Figure D.1. In order to do so the water level reference point was changed from the pressure transducer to the static surface of the glacier. This is represented by the change in the y-axis between Figures D.1 A and D.1 B.

**D.2.2. Drill Test Results**

Four of the 5 drill tests recorded significant water level declines as shown in Figures D.1, D.2, and Table D.1. The two drill tests that recorded the greatest water level decline (boreholes MC 03 and BWC 03) produced responses in adjacent boreholes (Figure D.2). All major fracture intersections occurred at depths greater than 100 m below the ice surface, with significant declines in drill hole water levels. Assuming a constant borehole cross sectional area of .011 m², englacial fracture intersection resulted in a water volume drainage of .022 - .157 m³. Maximum drainage velocities in the drill holes were upwards of 52 cm s⁻¹. Interpretation of these results will be covered in the discussion section of this appendix.
Table D.1. Results from 5 drill tests performed showing the depth at which fracture intersection occurred, the estimated water level decline in the drill hole, and any adjacent boreholes that were influenced.

<table>
<thead>
<tr>
<th>Borehole</th>
<th>Fracture intersection depth (m)</th>
<th>Estimated water level decline (m)</th>
<th>Adjacent borehole effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC 03</td>
<td>111</td>
<td>14.3</td>
<td>MC 02</td>
</tr>
<tr>
<td>BWC 01</td>
<td>162</td>
<td>5</td>
<td>--</td>
</tr>
<tr>
<td>BWC 02</td>
<td>133</td>
<td>2</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>140</td>
<td>11</td>
<td>--</td>
</tr>
<tr>
<td>BWC 03</td>
<td>161</td>
<td>12.4</td>
<td>BWC 01</td>
</tr>
<tr>
<td>BWC 04</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>
Figure D.1: Water levels in the drill hole and adjacent borehole during drilling of borehole BWC 02 before (Figure A) and after (Figure B) correction for manual pressure transducer displacement and use of the well pump. Correction for the mentioned water level influences yields a much cleaner plot which clearly shows two distinct points of fracture intersection. The initial decline in water level is linked to the drill depth by vertical pink lines to show depth of intersection.
Figure D.2: Corrected water level documentation for the drill hole (MC 03), and adjacent boreholes during drilling. Note the slight increase in water level in borehole MC 02 when the drill hole presumably intersects an englacial fracture. The second decrease in water level in the drill hole at approximately 9200 seconds is a result of the drill hole connecting with the glacier bed.

D.3. Slug Testing

D.3.1. Introduction and Methods

Slug testing in glacier settings has been primarily performed in boreholes connected to the subglacial network in efforts to characterize the hydrologic system at the bed. In 2006, borehole BWC 03 was drilled in 2 installments. On day 160 the borehole was drilled to a depth of 120 m, and the borehole was temporarily terminated ~40 m above the bed. On day 164 we resumed drilling and finished the borehole to the glacier bed. We performed a slug test on day 161 in the englacially terminated borehole to test for englacial connections which may drain the borehole water. Slug test procedures followed those previously described.
D.3.2. Slug Test Results

Slug tests in an englacially terminated borehole should show no recovery towards an equilibrium. However, as shown by Figure D.3, the slug test in BWC 03 responded in an overdamped manner with a very slow recovery. The maximum amplitude from the slug test was 19% of the slugged water volume, or a 1.27 m rise in the borehole column. The borehole water level was recorded for approximately 233 minutes, during which time a recovery of about 0.2 m was noted. This corresponds to a recovery volume of 0.002 m$^3$. Results from drill testing showed no intersections with water routing voids (Figure D.4). No englacial fractures were documented in borehole video, and one cavity with a thickness of approximately 50 cm was noted at a depth of 82 m.

![Figure D.3: A slug test in borehole BWC 03 showed a distinctly overdamped response, recovering by approximately 0.2 m after 233 minutes.](image-url)
Figure D.4: Drill test results from drilling the first 120 m of borehole BWC 03 show no significant water level declines from fracture intersection in the drill hole (green line). The water level decline occurring after termination of drilling is a result pulling up the drill hose.

D.4. Video Observation

D.4.1. Introduction and Methods:

Each of the 7 boreholes drilled in the 2006 field season were monitored via video camera to document englacial structures. In addition, 5 boreholes (MC 02, BWC 01, BWC 02, BWC 03, and BWC 04) were monitored with a compass attached to the video camera to document fracture orientations. Borehole video was conducted using a small, waterproof camera lens connected to ~210 m of cable, which was marked in 1 m increments. The camera head was equipped with built-in LED light bulbs, the intensity of which could be controlled from the snow surface. The video cable plugged into a portable camcorder, which recorded the video. Video procedure consisted of lowering the camera.
head down the borehole by running it through a shiv, which was centered over the borehole by a tripod (Figure D.5). Borehole depth was orally recorded at 1 m increments during lowering. In all, over 1100 m of borehole was video monitored, accumulating about 7 hours of video documentation.

Generally, void spaces were easily discerned from surrounding ice, as dark void spaces were visually easy to document in white, bubbly ice. However, in clear ice layers distinguishing water-filled space from ice-filled was quite difficult. In such instances, the distinction between void space and glacial ice was made by looking for light reflection along the borehole walls, sharp boundaries between clear ice and voids, and any potential water flow that would imply intersection with englacial structure capable of transporting water. Ice-filled fractures were also noted during video observation. The ice in ice-filled fractures is typically of a different character and color than that in the surrounding ice, making them easy to distinguish.

Estimated aperture diameter, fracture dip, and depth in the glacier were recorded for each planar fracture noted in video. Glacier depth is believed to be accurate to +/- 30 cm, however fracture dips and aperture diameters are visual estimates. Aperture diameter was estimated by referencing the fracture to the borehole diameter, which is about 12 cm across (ie. Figure D.6). Dip was estimated based on the ability to look down the fracture from the camera lens. It should be noted that further aperture estimation error is likely to be introduced in shallowly dipping boreholes, as the true diameter is difficult to see.
D.4.2. Video Results

As shown in Figure D.7, 28 planar fractures were documented in the 7 boreholes, with varying aperture diameters ranging from 1 – 10 cm (ie. Figure D.6). The average aperture diameter for all fractures was 3.68 cm, and the majority (57%) of fractures dipped at an angle steeper than 70°. Using estimated fracture geometries from each borehole, I calculated a first-order percentage of the borehole volume consisting of void space (Table D.2). From these calculations, englacial voids (fractures and cavities) constitute approximately 0.3% of the borehole volume. The origin of these fractures is something which cannot be explicitly concluded from the borehole video. Surface crevasses seldom reach depths greater than about 40 m, thus I conclude that it is highly unlikely any fractures below ~40 m depth originated at the surface.
Fracture orientations (strikes) were taken of 17 englacial fractures in 5 boreholes (Figure D.8). Orientation was taken using 0° N as the reference. The long axis of Bench Glacier has an orientation of approximately 40° W of N. Orientations were also taken on ice filled fractures in the boreholes, providing more data points for distinguishing trends (Figure D.9).

Englacial fractures proved to be far more common in borehole video than conduits or larger, vug-like voids. One conduit, with a diameter of about 4 cm, was documented in an ice-filled fracture (Figure D.10). Englacial cavities were documented 10 times in 5 of the 7 boreholes, and ranged in size from ~4 – 50 cm. In most instances, englacial cavity documentation occurred in a clear ice layer, where it was difficult to distinguish the size of the cavity. As a result, the size range is a very rough estimate.

Table D.2.: Percent void space by volume for boreholes drilled in 2006 as calculated from estimated fracture and cavity geometries from video observations.

<table>
<thead>
<tr>
<th>Borehole</th>
<th>% Void space by volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC 01</td>
<td>0.09</td>
</tr>
<tr>
<td>MC 02</td>
<td>0.16</td>
</tr>
<tr>
<td>MC 03</td>
<td>0.35</td>
</tr>
<tr>
<td>BWC 01</td>
<td>0.29</td>
</tr>
<tr>
<td>BWC 02</td>
<td>0.83</td>
</tr>
<tr>
<td>BWC 03</td>
<td>0.33</td>
</tr>
<tr>
<td>BWC 04</td>
<td>0.04</td>
</tr>
<tr>
<td>Average</td>
<td>0.30</td>
</tr>
</tbody>
</table>
Figure D.6: Planar fracture example from borehole video. Comparison of the fracture aperture diameter to the borehole diameter is given by the red arrows.

Figure D.7: Estimated fracture aperture diameter with depth for all documented englacial fractures. Dip characterization is as follows: Steep dip = 70-90°, Moderate dip = 30-70°, Shallow dip = 0-30°.
Figure D.8: Fracture orientations of englacial fractures vs depth for boreholes MC 02, BWC 01, BWC 02, BWC 03, and BWC 04. Note the 40° orientation of the down-glacier axis.
Figure D.9: Fracture orientation for both ice and water filled englacial fractures.

Figure D.10: An englacial conduit, documented at 75.5 m depth, is located in the bottom left of the figure. The highly reflective disc in the center is the compass used for orientation.
D.5. Dye Tracer Studies

D.5.1. Methods

A dye tracer test was performed in conjunction with slug tests to provide information regarding preferential flow paths through a documented fracture at a depth of 140 m in borehole BWC 02. Dye packages were injected at the fracture and at the bottom of the borehole (Figure D.11). Two fluorometers were then lowered down the borehole; one was placed at the bottom of the borehole (170 m depth), and the other was placed just above the fracture at a depth of ~139.25 m. A pressure transducer was lowered to ~5 m below the water surface to record water level, and a slug test was performed according to previously described methods. After two hours of recovery time, the fluorometer at the fracture (139.25 m depth) was lowered 25 cm, to a depth just below the fracture. Another slug test was performed and changes in dye concentration and water level were documented.

Figure D.11: Dye and fluorometer set up prior to slug testing borehole BWC 02.
D.5.2. Results

As shown in Figure D.12. (A), the first slug test resulted in dye-contaminated water being flushed from the upper fluorometer while the water in the lower fluorometer remained stagnant. When the fluorometer was lowered to a depth just below the fracture intersection, a slug test resulted in dye concentrations remaining stagnant in both boreholes (Figure D.12. B).
Figure D.12: Plots A and B show dye responses (red and green lines) to water level perturbation (blue line) by means of a slug test in borehole BWC 02. Note that when slug tests are performed, dye just above the fracture is flushed from the fluorometer (green line in Plot A), while dye just below the fracture remains stagnant (green line in Plot B).
D.6 Discussion

Multiple lines of evidence exist showing that englacial fractures are common and pervasive throughout Bench Glacier. Borehole video observations provide the most concrete evidence for the presence of void spaces, however water transport can be difficult to detect from borehole video. While no obvious conductance of water through fractures was observed in video, drill tests and the slug/dye test can be used to further test the ability of fractures to transport water.

Significant water level drops occurred in 80% of the tests, indicating that connections with lower pressure, water routing structures are relatively common at points along the glacier. Furthermore, the depths at which significant water level decline occurred in drill tests correlates with englacial fractures documented in video. Thus, it is likely that water level decline during drill tests is a result of intersection with an englacial fracture. Assuming this to be the case, fractures must connect to locations of either low pressure or high transmissivity with the ability to accommodate the influx of water from the borehole. The majority of fractures were characterized as having dips steeper than 70°, thus it is likely that the source to which the fractures are connected is the glacier bed. Fracture connection to the bed is further confirmed by borehole observations on Bench Glacier in 2003 in which formation of a fracture was observed in video, and accompanied by turbidity. This turbidity was assumed to be related to subglacial sediment disturbance, suggesting that the fracture propagated from the glacier bed. Initiating fractures at the bed of the glacier necessitates that these fractures extend to significant heights within the glacier, as water level declines during drill testing occurred at heights greater than 50 m above the glacier bed. It should be noted that not all documented fractures in video
caused water level declines during drill testing. Thus, not all englacial fractures are efficiently connected to a significant storage source such as the glacier bed.

Results from the slug and dye tracer study performed in borehole BWC 02 confirm efficient water routing through fractures. Slug testing the borehole resulted in water being routed through the fracture, with a sharp flow boundary just below the englacial feature. In contrast to drill tests, the slug/dye study was completed in a borehole that was already connected to the bed of the glacier, suggesting that the fracture is connected to an area of the bed with a higher transmissivity than the bottom of the borehole. Thus, the drainage network at the bed of the glacier is spatially variable with respect to transmissivity. Highly transmissive areas along the bed efficiently route water, while other sections consist of a slower flow regime with less capacity for immediate storage.

The tests performed in efforts to isolate englacial water flow have shown that these englacial fractures have the potential to transport water englacially. However, in each case the englacial fractures have responded in a system that is open to the atmosphere and perturbed by an influx of water. Thus, in order to use the induced water transport through fractures as a proxy for flow through fractures in a natural setting, the fractures must be connected to both the glacier surface and bed. Furthermore, the fracture must have access to a continuous source of water to remain open, such as surficial meltwater. If this is the case, then intersecting an englacial fracture during drill testing would only open the fracture to another atmospheric connection, and the flow velocity through the fracture would remain the same as the background velocity prior to intersection. Maximum water level decline velocities in drill tests are upwards of
50 cm s\(^{-1}\), however this contrasts greatly with observations in borehole video, as well as flow velocity estimations of 1 – 2 cm s\(^{-1}\) made by Fountain et al. (2005).

A more likely scenario necessitates that the englacial fracture be closed to the atmosphere prior to intersection during drilling. In this model, the fracture is connected to the subglacial drainage network and maintains the pressure of this system. When the drill hole intersects the englacial fracture, the overlying water pressure in the drill hole greatly exceeds that in the fracture, and water is routed through the void to the bed. Such an explanation seems reasonable as the water pressure in the drill hole exceeds the ice overburden pressure at the bed, and thus flow to the bed of the glacier would be expected with intersection of a fracture. Englacial fractures existing in a closed system with a connection only to the bed implies that they may be play a significant role in storage of water within the glacier, but do not directly influence the transport of surficial meltwater to the bed of the glacier. While a small percentage (.3%) of the borehole volume consists of void space, englacial features may still play a significant role in water storage when projected over a large area of the glacier.
APPENDIX E: SHEET FLOW ALONG THE GLACIER BED

Previous discussion has assumed that flow at the bed of Bench Glacier is strictly through discrete pathways that connect each other and cavities at the bed. Here I introduce an analysis of flow based on the assumption that flow occurs as a sheet between the glacier bed and sole. Analysis of underdamped slug test responses documented in 2006 provides characteristics of this assumed flow. Walder [1982] showed mathematically that sheet flow is unstable at the bed of the glacier due to variations in viscous heat dissipation. However, while a channelized system preferentially forms between the glacier sole and bedrock, the channels may be destroyed as the glacier moves over irregularities at the bed. As a result, sheet flow can exist in a quasi-stable state up to a thickness of a few millimeters.

Multiple methods have been developed to analyze underdamped slug test responses in an aquifer setting and calculate transmissivity and hydraulic conductivity from the oscillatory behavior. One such method is that created by Van der Kamp [1976] to calculate aquifer hydraulic properties in a confined aquifer. By combining the Van der Kamp model with flow through fractures, aperture geometries necessary for water flow at the bed of the glacier to occur as a sheet between the glacier sole and bed can be generated.

E.1. The Van der Kamp Method

The Van der Kamp method employs a curve matching technique to iteratively solve for transmissivity in an aquifer, independent of aquifer thickness. In a glacial setting, the overlying ice can be conceptualized as a confining unit, thus the Van der
Kamp method can be employed to calculate the transmissivity of water flowing between the glacier sole and bed. For the Van der Kamp method to remain valid some basic assumptions must be made regarding the system. Those most pertinent to the glaciological setting are that flow is radial toward or away from the well, and that the aquifer is infinite in horizontal extent. In the Van der Kamp method, the underdamped slug test response is modeled by the water level decay function, which is given as:

\[ H(t) = H_0 e^{-\gamma t} \cos \omega t \]  

(26)

where:

\[ H(t) = \text{the hydraulic head at time } t \]

\[ H_0 = \text{the initial change in hydraulic head} \]

\[ \gamma = \text{a damping constant} \]

\[ \omega = \text{an angular frequency} \]

The damping constant (\( \gamma \)) and angular frequency (\( \omega \)) can be solved by:

\[ \gamma = \frac{\ln[H(t_1)/H(t_2)]}{t_2 - t_1} \]  

(27)

and

\[ \omega = \frac{2\pi}{t_2 - t_1} \]  

(28)

where \( H(t_1) \) and \( H(t_2) \) are two water level peaks at times \( t_1 \) and \( t_2 \) respectively.

Transmissivity is related to equations (26), (27), and (28) by the following equations:

\[ T = b + a \ln T \]  

(29)

and

\[ b = -a \ln[0.79r_s^2S\sqrt{(\gamma^2 + \omega^2)}] \]  

(30)
\[ a = \frac{(\gamma^2 + \omega^2)r_c^2}{8\gamma} \]  

(31)

where

\[ T = \text{the aquifer transmissivity} \]

\[ r_c = \text{the radius of the borehole casing} \]

\[ r_s = \text{the radius of the borehole screen (here assumed to be the same as the casing)} \]

\[ S = \text{the storage coefficient (1x10}^{-5}\text{)} \]

\[ L = \text{the effective water column length} \]

\[ g = \text{the gravitational constant (9.81 m/s}^2\text{)} \]

Transmissivity can be solved iteratively by matching a curve from equation (26) to a slug test response and solving for the damping constant (\( \gamma \)) and angular frequency (\( \omega \)). A spreadsheet created by the USGS (http://pubs.usgs.gov/of/2002/ofr02197/) solves for the damping constant (\( \gamma \)), angular frequency (\( \omega \)), and consequently aquifer transmissivity.

The Van der Kamp spreadsheet model was employed to solve for transmissivity in each slug/dye experiment performed in 2006 (Table E. 1 and Figure E.1). Model responses matched well with actual water level responses, and produced transmissivity values ranging from 0.0068 - 0.0125 m s\(^{-1}\).

Table E.1. Damping constants, angular frequencies, and transmissivities calculated by the Van der Kamp model for 5 slug tests.

<table>
<thead>
<tr>
<th>Slug Test</th>
<th>Damping Constant (( \gamma ))</th>
<th>Angular Frequency (( \omega ))</th>
<th>Transmissivity (ft(^2)/day)</th>
<th>Transmissivity (m(^2)/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<td>0.036</td>
<td>0.262</td>
<td>11646</td>
<td>0.0125</td>
</tr>
</tbody>
</table>
Figure E.1: Van der Kamp modeling (open circles) of an underdamped slug test response (blue line) from slug/dye test 2, performed on day 168. (A) The angular frequency ($\omega$) is calculated by estimating the time between water level peaks. (B) The damping constant ($\gamma$) is calculated by plotting the absolute values of the responses on a logarithmic y-axis and picking the two water level peaks chosen in calculating the angular frequency.
E.2. Transmissivity and Flow through Fractured Media

Water flow at the glacier bed between the impermeable sole and bedrock can be conceptualized as horizontal flow through a single fracture with parallel walls (Figure E.2). Flow through such a fracture can be calculated by the cubic law, which is written as [Delleur, 1998]:

\[
\frac{Q}{\Delta h} = C(B)^3
\]  

(32)

where,

- \(Q\) = flow rate per unit \(\Delta h\)
- \(\Delta h\) = drop in hydraulic head
- \(C\) = constant related to the properties of the fluid and fracture geometry
- \(B\) = fracture aperture

For straight, uniform flow through a fracture, the constant of proportionality (C) is given by:

\[
C = \frac{\rho g W}{12\mu L}
\]  

(33)

where,

- \(\rho\) = fluid density
- \(\mu\) = dynamic viscosity
- \(W\) = fracture width
- \(L\) = fracture length

Substitution of the cubic law into Darcy’s law produces an equation relating the transmissivity through a fracture to its aperture, where Darcy’s law is given by:

\[
Q = KiA
\]  

(34)
then,

\[ T_{fr} = \frac{\rho g}{12 \mu} (B)^3 \]  \hspace{1cm} (35)

where,

\[ K = \text{hydraulic conductivity of the fracture} \]
\[ i = \text{hydraulic gradient} \left( \frac{\Delta h}{\Delta l} \right) \]
\[ A = \text{cross-sectional area} \]
\[ T_{fr} = \text{fracture transmissivity} \]

From equation (E.10), the aperture thickness (B) can be calculated. Assuming that subglacial water is at the freezing point (0°C), the density (\( \rho \)) and dynamic viscosity (\( \mu \)) are given as 999.84 kg m\(^{-3}\) and 1.79 x 10\(^{-3}\) Ns m\(^{-2}\) respectively. Using transmissivity values calculated from Van der Kamp modeling, a range of sole-bed aperture thicknesses can be produced from the slug tests, as shown in Table E.2.

Figure E.2: Schematic diagram showing velocity distribution across an aperture of thickness (B) between the glacier sole and bedrock.
Table E.2: Flow aperture thicknesses (B) as calculated from equation (E.10) for transmissivities calculated from Van der Kamp modeling.

<table>
<thead>
<tr>
<th>Slug/dye</th>
<th>Transmissivity (m/sec)</th>
<th>B (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0068</td>
<td>0.25</td>
</tr>
<tr>
<td>2</td>
<td>0.0118</td>
<td>0.30</td>
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<tr>
<td>3</td>
<td>0.0101</td>
<td>0.28</td>
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<tr>
<td>4</td>
<td>0.0115</td>
<td>0.29</td>
</tr>
<tr>
<td>5</td>
<td>0.0125</td>
<td>0.30</td>
</tr>
<tr>
<td>Average</td>
<td>0.0105</td>
<td>0.28</td>
</tr>
</tbody>
</table>

E.3. Discussion

The calculations shown above assume an unrealistically simplified system, in which likely heterogeneities at the bed, such as bedrock bumps, dips, or other topographical features have been smoothed to create flat surfaces confining the flow aperture. The system also neglects to account for likely flow through discrete pathways, however the results from the calculations lend insight into the magnitude of potential processes influencing flow dynamics at the bed of the glacier. The average aperture thickness value of 0.28 cm further assumes that all induced flow at the bed of the glacier from the slug test is routed through an aperture of such thickness. However, it is likely that flow is dominated by larger, discrete pathways at the bed as suggested by slug test results. Routing flow through other, larger apertures would necessitate a decrease in the thickness of the conceptualized sheet flow between the glacier sole and bed. As a result, while realistic aperture thickness values exist for sheet flow at the bed, it is likely negligible when compared to flow through a linked cavity network.
REFERENCES


