Technical Report 151

A STRAIGHT-WALL CUT-AND-COVER SNOW TRENCH

by

Wayne Tobiasson and Donald L. Rissling

OCTOBER 1966

U.S. ARMY MATERIEL COMMAND
COLD REGIONS RESEARCH & ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

DA Task IVO25001A13001

LIBRARY
OCT 16 1967
ROCKY MOUNTAIN STATION
Distribution of this document is unlimited
Technical Report 151
A STRAIGHT-WALL CUT-AND-COVER SNOW TRENCH

by

Wayne Tobiasson and Donald L. Rissling

OCTOBER 1966

U.S. ARMY MATERIEL COMMAND
COLD REGIONS RESEARCH & ENGINEERING LABORATORY
HANOVER, NEW HAMPSHIRE

DA Task IVO25001A13001

Distribution of this document is unlimited
PREFACE

The straight-wall cut-and-cover snow trench described in this report was constructed to house the tests performed by USA CRREL Project 33, Feasibility Study of Pile Foundations in Snow.

The design and construction were supervised by Mr. D. L. Rissling, former Project Leader, Construction Engineering Branch, USA CRREL under the general direction of Mr. Kenneth A. Linell, Chief, Experimental Engineering Division, and the immediate direction of Mr. Edward F. Lobacz, Chief, Construction Engineering Branch. The pile test program was initiated by Mr. Rissling during the fall of 1962 and extended by Mr. Austin Kovacs through the present.

The authors wish to acknowledge consultation generously given by Messrs. R. Benert, N. Costes, A. Kovacs, R. Rommel and R. Waterhouse and field assistance by contract students, Messrs. F. Brown, R. Evers, K. Goering and H. Morrison. The authors are indebted to Messrs. K. Linell, E. Lobacz, S. Reed and A. Kovacs for their technical review of the manuscript.

The construction could not have been performed without the cooperation of the U. S. Army Polar Research and Development Center (now the U. S. Army Research Support Group) and the 588th Engineer Construction Battalion, Fort Belvoir, Virginia.

Colonel Dimitri A. Kellogg was Director of the Cold Regions Research and Engineering Laboratory during the publication of this report and Mr. W. K. Boyd was Chief Engineer.

USA CRREL is an Army Materiel Command laboratory.
## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preface</td>
<td>ii</td>
</tr>
<tr>
<td>Summary</td>
<td>vi</td>
</tr>
<tr>
<td>Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Design</td>
<td>1</td>
</tr>
<tr>
<td>Site selection</td>
<td>1</td>
</tr>
<tr>
<td>Trench dimensions</td>
<td>2</td>
</tr>
<tr>
<td>Processed snow abutments</td>
<td>2</td>
</tr>
<tr>
<td>Sheet-steel endwalls</td>
<td>4</td>
</tr>
<tr>
<td>Rolling doors and door frames</td>
<td>6</td>
</tr>
<tr>
<td>Construction</td>
<td>8</td>
</tr>
<tr>
<td>General</td>
<td>8</td>
</tr>
<tr>
<td>Preparation of abutments</td>
<td>10</td>
</tr>
<tr>
<td>Excavation of trench and ramps</td>
<td>12</td>
</tr>
<tr>
<td>Construction of timber scaffold</td>
<td>15</td>
</tr>
<tr>
<td>Erection of 41-ft span arch</td>
<td>15</td>
</tr>
<tr>
<td>Installation of snow fence</td>
<td>16</td>
</tr>
<tr>
<td>Installation of header beams and door frames</td>
<td>17</td>
</tr>
<tr>
<td>Erection of endwalls</td>
<td>17</td>
</tr>
<tr>
<td>Installation of steel slat rolling doors</td>
<td>20</td>
</tr>
<tr>
<td>Construction of emergency exit</td>
<td>20</td>
</tr>
<tr>
<td>Erection of the Jamesway office</td>
<td>20</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>22</td>
</tr>
<tr>
<td>Thermocouples</td>
<td>22</td>
</tr>
<tr>
<td>Vertical control</td>
<td>22</td>
</tr>
<tr>
<td>Arch seat levels</td>
<td>23</td>
</tr>
<tr>
<td>Floor arching study</td>
<td>26</td>
</tr>
<tr>
<td>Cross sections</td>
<td>28</td>
</tr>
<tr>
<td>Snow accumulation</td>
<td>31</td>
</tr>
<tr>
<td>Performance</td>
<td>32</td>
</tr>
<tr>
<td>General</td>
<td>32</td>
</tr>
<tr>
<td>Entrances</td>
<td>32</td>
</tr>
<tr>
<td>Roof system</td>
<td>36</td>
</tr>
<tr>
<td>Conclusions</td>
<td>37</td>
</tr>
<tr>
<td>Literature cited</td>
<td>38</td>
</tr>
</tbody>
</table>

## ILLUSTRATIONS

<table>
<thead>
<tr>
<th>Figure</th>
<th>Illustration</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Site conditions</td>
<td>2</td>
</tr>
<tr>
<td>2.</td>
<td>Location of trench relative to Camp Century</td>
<td>3</td>
</tr>
<tr>
<td>3.</td>
<td>General dimensions of trench</td>
<td>4</td>
</tr>
<tr>
<td>4.</td>
<td>Abutment design parameters</td>
<td>5</td>
</tr>
<tr>
<td>5.</td>
<td>Abutment design loads</td>
<td>5</td>
</tr>
<tr>
<td>6.</td>
<td>Sheet-steel endwall</td>
<td>6</td>
</tr>
<tr>
<td>7.</td>
<td>Door frame components</td>
<td>7</td>
</tr>
<tr>
<td>8.</td>
<td>Construction summary</td>
<td>9</td>
</tr>
<tr>
<td>9.</td>
<td>Excavation of east and west abutment trenches (cuts 1-6)</td>
<td>11</td>
</tr>
<tr>
<td>10.</td>
<td>Backfilling east and west abutment trenches with processed snow</td>
<td>11</td>
</tr>
<tr>
<td>11.</td>
<td>Final two cuts in processed snow to arch seat grade (cuts 14 and 15)</td>
<td>12</td>
</tr>
<tr>
<td>12.</td>
<td>2 x 12-in. timbers placed on east abutment</td>
<td>12</td>
</tr>
<tr>
<td>13.</td>
<td>Ram hardness of processed snow abutments</td>
<td>13</td>
</tr>
</tbody>
</table>
### CONTENTS (Cont'd)

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>Depth-density profiles of east and west processed snow abutments</td>
<td>13</td>
</tr>
<tr>
<td>15</td>
<td>Excavation pattern for trench and south ramp</td>
<td>14</td>
</tr>
<tr>
<td>16</td>
<td>Peter snow miller completing cut 13</td>
<td>14</td>
</tr>
<tr>
<td>17</td>
<td>Peter snow miller beginning cut 14</td>
<td>15</td>
</tr>
<tr>
<td>18</td>
<td>Ski-mounted timber scaffold used for erection of the corrugated steel arch</td>
<td>16</td>
</tr>
<tr>
<td>19</td>
<td>Erecting the corrugated steel arch</td>
<td>16</td>
</tr>
<tr>
<td>20</td>
<td>Aluminum-slat snow fence placed upwind of trench</td>
<td>17</td>
</tr>
<tr>
<td>21</td>
<td>2 x 6-ft header beam footing in wall recess</td>
<td>18</td>
</tr>
<tr>
<td>22</td>
<td>Positioning the south header beam</td>
<td>18</td>
</tr>
<tr>
<td>23</td>
<td>Fabrication of south upper endwall on timber supports</td>
<td>19</td>
</tr>
<tr>
<td>24</td>
<td>Lifting the south upper endwall into position with a military Type 22b crane</td>
<td>19</td>
</tr>
<tr>
<td>25</td>
<td>Section through steel slat rolling door</td>
<td>20</td>
</tr>
<tr>
<td>26</td>
<td>Interior of north endwall showing header beam and rolling door system</td>
<td>21</td>
</tr>
<tr>
<td>27</td>
<td>Drift snow behind the north rolling door</td>
<td>21</td>
</tr>
<tr>
<td>28</td>
<td>Foundation for Jamesway office</td>
<td>22</td>
</tr>
<tr>
<td>29</td>
<td>Location of thermocouples</td>
<td>22</td>
</tr>
<tr>
<td>30</td>
<td>Temperature profiles</td>
<td>23</td>
</tr>
<tr>
<td>31</td>
<td>Location of BM-1 and arch seat points</td>
<td>23</td>
</tr>
<tr>
<td>32</td>
<td>Strain rate variations with depth</td>
<td>24</td>
</tr>
<tr>
<td>33</td>
<td>Deformation rates relative to the deep bench mark</td>
<td>26</td>
</tr>
<tr>
<td>34</td>
<td>Cross-section locations</td>
<td>28</td>
</tr>
<tr>
<td>35</td>
<td>Location of cross-section pegs</td>
<td>29</td>
</tr>
<tr>
<td>36</td>
<td>Detail of points C, D, and E</td>
<td>29</td>
</tr>
<tr>
<td>37</td>
<td>Station 0+75, basic triangulation net</td>
<td>29</td>
</tr>
<tr>
<td>38</td>
<td>Obtaining cross-section measurements with the &quot;Tobiasson Cold Grip&quot;</td>
<td>30</td>
</tr>
<tr>
<td>39</td>
<td>Cross-section closure of station 0+75</td>
<td>30</td>
</tr>
<tr>
<td>40</td>
<td>Snow accumulation at the trench</td>
<td>31</td>
</tr>
<tr>
<td>41</td>
<td>North ramp after a storm</td>
<td>32</td>
</tr>
<tr>
<td>42</td>
<td>Deformation of the north rolling door</td>
<td>33</td>
</tr>
<tr>
<td>43</td>
<td>Two methods used to seal the trench</td>
<td>34</td>
</tr>
<tr>
<td>44</td>
<td>South end of trench in February 1963</td>
<td>34</td>
</tr>
<tr>
<td>45</td>
<td>Above-surface trench access</td>
<td>35</td>
</tr>
<tr>
<td>46</td>
<td>Buckling of south endwall</td>
<td>37</td>
</tr>
</tbody>
</table>

#### TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.</td>
<td>Excavation productivity</td>
<td>10</td>
</tr>
<tr>
<td>II.</td>
<td>Construction productivity</td>
<td>10</td>
</tr>
<tr>
<td>III.</td>
<td>Arch seat elevations</td>
<td>25</td>
</tr>
</tbody>
</table>
SUMMARY

During the summer of 1962, a straight-wall cut-and-cover snow trench was constructed at Camp Century, Greenland, to house tests performed by USA CRREL Project 33, Feasibility Study of Pile Foundations in Snow.

In this report, the parameters used to design the trench and the equipment and methods used in the construction are presented and evaluated. Time-motion studies covering all phases of construction are included as a guide for the planning and evaluation of similar construction. Performance is discussed and documented by instrumentation installed in the trench.
A STRAIGHT-WALL CUT-AND-COVER SNOW TRENCH

by
Wayne Tobiasson and Donald L. Rissling

INTRODUCTION

Because of the adverse climatic conditions on the Greenland Ice Cap, an undersnow trench was constructed to protect the research activities of the project team conducting USA CRREL Project 33, Feasibility Study of Pile Foundations in Snow.

The undersnow trench is not new to the Arctic, as shown by the original cut-and-cover trench techniques used at Camp Fishtrench and Camp Century in Greenland and as described by Waterhouse (1960). In many ways, the design and construction of this trench exemplify the principles of past arctic trench design and construction.

Generally speaking, the efforts of 18 men, several pieces of heavy equipment and 1 1/2 months' time provided a most satisfactory test facility.

This report presents a general discussion of the design, construction and instrumentation of the trench, and describes performance for a 3-yr period since its erection. Included with the construction discussion are productivity rates which should prove useful in the planning of similar construction.

The purpose of the report is to present and evaluate design concepts that may prove useful in future cut-and-cover snow trenches.

DESIGN

Site selection

Camp Century, located on the accumulation zone of the Greenland Ice Cap, 150 miles east of Thule Air Base, was selected as the pile test area because of the availability of a year-round facility for the quartering of men and supplies. The oversnow route to Century from Camp Tuto on the ice cap margin is frequently traversed by tractor trains which are capable of handling the large amount of heavy equipment required for the trench construction and pile test program. The site conditions used in the design are shown on Figure 1.

The specific location at Century had to be remote from any physical influence of the water wells and sewage effluent pond, both of which are heat-producing sources capable of radically changing the temperature regime throughout the surrounding snow mass. Since changes in temperature affect the physical properties of snow, proximity to any source of heat had to be avoided. It was advisable nevertheless to locate the trench as near to camp as possible for the convenience and safety of the construction workers and ease of securing and moving heavy equipment. Also, future extensions to the pile testing program might necessitate the construction of an undersnow passageway connecting the trench to the Century complex and the use of camp power.

Wind tunnel and field studies have pointed out that installations of this type should be oriented normal to the prevailing winds to minimize accumulation of drifting snow. The average prevailing wind anticipated for the months of July, August and September was ESE. Since heavy winds also blow from the south, a storm from that direction could dump tons of drifted snow into the trench. As a defense against this possibility, several hundred feet of aluminum slat snow fence were ordered, to be placed upwind of the trench, normal to the prevailing wind where they would precipitate drifting snow before it could reach the trench. Fences have proved effective in winds below 25 knots and, unless storms of gale force occurred, the drift problem should be minor.
A STRAIGHT-WALL CUT-AND-COVER SNOW TRENCH

Figure 1. Site conditions, Camp Century, Greenland (77°11'N, 61°08'W). Elevation, 1830 meters (6000 ft)*; Mean annual temp, -24°C†; Maximum air temp, -3°C**; Minimum air temp, -53°C***; Annual snow accumulation, 2.5 ft*.

Trench dimensions

To provide the headroom required for pile-driving operations, 18-gage, Wonder Building Corporation, 410 GH-XH segmental corrugated steel roof arch with a rise of 17.5 ft and a span of 41 ft was selected. The arch would rest on timber and steel channel arch seats (Fig. 3, Abutment detail) approximately 4 ft below the then existing snow surface. Excavation of the trench would be to a depth of 22 ft beneath the arch seats. The rise of the roof arch (17 ft inside) and the depth of the trench excavation (22 ft) would provide adequate centerline headroom of 39 ft. Sufficient width for the moving of vehicles, positioning and driving of piles and augering of holes would be assured by a 30-ft-wide vertical-wall excavation. Length of the trench, determined primarily by the space required for the pile tests, was set at 200 ft. A 175-ft ramp at each end of the trench would serve as an access for personnel and equipment (Fig. 3).

Processed snow abutments

It was evident from observations of arched trenches in Greenland that the exceedingly high settlement rates of roof arches were caused to a large extent by the low bearing strength of natural undisturbed snow abutments. Stearns' (1959) work on abutments indicates that abutments of processed snow, disaggregated by the action of a Peter snow miller, develop greater bearing strength than natural undisturbed snow abutments.

Immediately after snow is disaggregated, it begins to harden and increase in strength. This phenomenon, known as age-hardening, increases the strength of processed snow to values three to five times the strength of the original natural undisturbed snow as measured by unconfined compression tests.

* Waterhouse, 1960
† Benson, 1959
** Signal Corps Meteorological Records, 1961
Tests conducted in Limestone, Maine, by the Arctic Construction and Frost Effects Laboratory (1949) showed that the hardness of snow one day after compaction was twenty-five times that of uncompacted snow.

Increased ultimate strength (high value of Young's modulus) of disaggregated "Peter snow" was implied by Nakaya (1959). Wuori's field investigation (1960) showed that compaction and vibration of "Peter snow" by a D-8 LGP tractor produced a much harder material (Fig. 4) as measured by the Rammsonde, a cone penetrometer designed by Haefeli (1939).

Stearns concluded that 1150 lb/ft was a safe bearing value against an immediate fracture failure for "Peter snow" abutments. The average failure load for his tests was 3850 lb/ft but the safe bearing value was derived from the smallest value obtained, using a safety factor of 2.0. The loads were applied 3 to 6 in. from the edge of narrow, isolated, uncompacted, processed snow abutments and his safe bearing value applied to large continuous abutments is very conservative.

Approximating the annual snow accumulation for the pile test site at 2.5 ft (Fig. 4), over 5 years will pass before the snow surface rises above the arch apex. Assuming all the snow in the spandrel as dead load acting directly on the arch seat, the bearing load would not exceed 2380 lb/ft during that time (Fig. 5).

The information obtained by Stearns together with that obtained from measurement of existing trenches indicated that a 3-ft thick pad of processed snow, compacted by the mechanical action of a D-8 LGP tractor, would provide an excellent abutment for support of the arch seat and roof arch load of the trench. The 3 ft of processed snow should be enough to provide sufficient distribution of stress so that the contact pressure on the natural snow below the abutments is reduced below that which would be exhibited by direct bearing of the roof arch on the natural snow.
Sheet-steel endwalls

Since severe weather conditions on the ice cap could cause excessive amounts of blowing snow to drift into the trench if the ends were left open, endwalls were utilized. Figure 6 illustrates the sheet-steel endwall (Wonder Building Corporation Type 400s) which completely seals off the trench from the underside of the roof arch to the base of the trench floor.

The cut-and-cover trench, a cavity in snow, is subjected to viscous stress-strain phenomena, causing the vertical walls to bow inward with time. In addition, trench floor observations by Waterhouse (1962) have shown that wall-floor intersections settle faster than the floor centerline, resulting in a crowning effect. The resulting forces would tear and buckle the sheet-steel endwalls if they were rigidly connected to the arch, wall and floor.

The endwalls should be firmly secured to the metal arch only. Buckling and tearing would be abated by sandwiching the sheet steel between two layers of 3/4-in. plywood rigidly connected to the snow wall (Fig. 6). The plywood sandwich would grip the sheet steel enough to prevent movement under normal load and displacement but would allow the sheet metal to slip during periods of excessive load or displacement.
A STRAIGHT-WALL CUT-AND-COVER SNOW TRENCH

Figure 4. Abutment design parameters.

Figure 5. Abutment design loads.
The base of the endwalls along the trench floor would hang free in a hollowed-out recess thereby preventing damage from trench-floor crowning. A slip-joint connection would be made between the endwall and the door-frame structure for lateral support of the endwall skin (see endwall-header beam slip joint detail, Fig. 6).

**Rolling doors and door frames**

Incorporation of 14 x 14-ft openings into the sheet-steel endwalls provided an entrance for heavy equipment. A standard gear-chain-operated industrial-type steel-slat rolling door, featuring between-the-jambs installation, windlock and jamb-mounted track guides, covered the opening.

The door frame design considered the influences of wall closure, trench floor crowning, differential settlement of the various structural constituents, and lateral wind and snow pressures. Figure 7 illustrates the structural components. The solutions to various problems associated with the door frame design are listed below.
Problem. The rate of snow densification varies with depth throughout the upper layers of a snow mass. Therefore, foundations having the same unit load but placed at various depths beneath the surface of the snow settle at different rates.

Solution. All door-frame structural elements were rigidly connected to one supporting member, the header beam. The beam rested on two footings placed at the same depth beneath the surface of the snow. The lack of several different foundation configurations protected the door-frame system from differential movements.

Problem. Cut-and-cover snow trench floors crown or arch with time. This phenomenon may affect the lateral stability of an in-place vertical structural member.
Solution. Door jambs were connected to the overhead header beam for support, thus avoiding the influence of floor crowning.

Problem. Wind load and drift-snow load upon the face of the rolling door may cause structural damage and malfunctioning.

Solution. Rolling doors were designed for a 40 psf snow load. Windlocks, steel claws that grip the rolling door tracks, prevent excessive deformation of the rolling-door face from wind loads.

Problem. Severe weather conditions may cause excessive accumulation of drift snow in the access ramp and at the face of the rolling door. Successful removal of the drift snow without damaging the door and frame is necessary to preserve usefulness of the entrance and permit raising of the rolling door.

Solution. Timber anchors, designed to resist lateral thrust, could be cut, allowing the jambs, diagonals and rolling door to swing back free of the snow. The rolling door could then be raised to expose the face of the drift snow for removal. The timber anchors could easily be re-spliced to restore the door system.

Problem. Restraint between the endwalls and door frame systems should be avoided. Differential movement between the two systems may cause buckling and tearing of the structural elements.

Solution. No rigid connections were made between the two systems other than sliding cane bolts (Fig. 6), which resist bellowing-out of the sheet steel endwall from negative wind pressures. The sliding cane bolts permit differential movement between the endwall and header beam systems.

CONSTRUCTION

General

On 6 July 1962, 800 ft east of Camp Century, Greenland, construction of the 200-ft-long, 30-ft-wide straight wall cut-and-cover trench began. The construction was performed rapidly and safely. Considering the dangers present while performing heavy construction in an unfamiliar environment and under severe conditions, it is a credit to the construction crew that not one loss-of-time injury was sustained during the entire operation.

Figure 8 shows the various operations performed and the number of workers and hours required during the seven weeks of construction.

Work began at 0700 hr and ended at 1730 with a 1-hr lunch break and two 1/2-hr warm-up period/coffee breaks. Allowing another hour for travel time to and from the trench, the maximum "available" working time per day becomes 7.5 hours.

During the 50-day construction period from 6 July to 25 August, 40 days were spent on the job, 5 Sundays were not worked, and on 5 days severe weather delayed construction. During erection of the sheet steel arch, 7 days were spent on a double shift basis. The total "available" working hours during construction were therefore:

\[
7.5 \text{ hr/day} (33 \text{ days at 1 shift/day} + 7 \text{ days at 2 shifts/day}) =
\]

\[
= 7.5 \left( 33 + 7 \left( 2 \right) \right) = 352 \text{ hr}.
\]

The total hours "tabulated" on Figure 8 equal 268 hr, 21 min.

Only the cutting time of the Peter snow miller is included in the hours worked tabulated for the excavation operation. Time consumed when refueling the machine, warming the engine, driving to the trench, making minor mechanical adjustments and backing out after each cut could account for 30 to 40 additional hours. The remaining 34-44 hr could be allotted to the securing, transporting and staging of supplies and the securing, breakdown, warm-up, refueling and adjusting of equipment.
<table>
<thead>
<tr>
<th>OPERATIONS</th>
<th>JULY</th>
<th>AUGUST</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXCAVATION (PETER PLOW)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>3-00</td>
<td>5-30</td>
</tr>
<tr>
<td>ARCH SEAT (PLACING)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>1-30</td>
<td>5</td>
</tr>
<tr>
<td>TIMBER SCAFFOLD (ASSEM. &amp; ERECT)</td>
<td>5 3-00</td>
<td>5 5-30</td>
</tr>
<tr>
<td>40 FT. SPAN WONDER ARCH (ASSEM. &amp; ERECT)</td>
<td>4 4-00</td>
<td>5 5-00</td>
</tr>
<tr>
<td>UPPER ENDWALL (SOUTH)</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>2-00</td>
<td>2-00</td>
</tr>
<tr>
<td>HEADER BEAM &amp; DOOR FRAME SYSTEMS (NORTH &amp; SOUTH)</td>
<td>6 6-00</td>
<td>7 7-00</td>
</tr>
<tr>
<td>UPPER ENDWALL (NORTH)</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>4-00</td>
<td>5-00</td>
</tr>
<tr>
<td>LOWER ENDWALL (SOUTH)</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>3-00</td>
<td>3-00</td>
</tr>
<tr>
<td>LOWER ENDWALL (NORTH)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>3-00</td>
<td>3-00</td>
</tr>
<tr>
<td>JAMESWAY LAB.</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>6-00</td>
<td>6-00</td>
</tr>
<tr>
<td>EMERGENCY EXIT</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>6-00</td>
<td>6-00</td>
</tr>
<tr>
<td>ROLLING DOORS (NORTH &amp; SOUTH)</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>5-00</td>
<td>6-00</td>
</tr>
</tbody>
</table>

**Legend**

- **ONE SHIFT (DAYS)**
- **NUMBER OF LABORERS**
- **TWO SHIFTS (DAY & NIGHT)**
- **NUMBER OF HOURS AND MINUTES WORKED**

Figure 8. Construction summary.
Time-motion studies were carried on during the construction of the trench. Included with the construction procedure in the following discussion are productivity rates measured during the excavation and fabrication of the facility. The results of the time-motion studies are presented in Tables I and II.

Table I. Excavation productivity.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Cutting time (hr:min)</th>
<th>Cutting speed (ft/ min)</th>
<th>Volume (yd³)</th>
<th>Weight (tons)</th>
<th>Output (yd³/hr)</th>
<th>Output (tons/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>East and west abutment cuts</td>
<td>3:45</td>
<td>8.2</td>
<td>1908</td>
<td>628</td>
<td>509</td>
<td>168</td>
</tr>
<tr>
<td>Abutment backfill</td>
<td>1:15</td>
<td>15.3</td>
<td>1465</td>
<td>433</td>
<td>1172</td>
<td>347</td>
</tr>
<tr>
<td>Grade cuts</td>
<td>0:35</td>
<td>13.1</td>
<td>437</td>
<td>184</td>
<td>749</td>
<td>315</td>
</tr>
<tr>
<td>South ramp and trench</td>
<td>12:51</td>
<td>11.0</td>
<td>8311</td>
<td>3326</td>
<td>647</td>
<td>259</td>
</tr>
<tr>
<td>North ramp</td>
<td>3:55</td>
<td>11.9</td>
<td>2455</td>
<td>975</td>
<td>627</td>
<td>249</td>
</tr>
<tr>
<td>Total or average</td>
<td>22:21</td>
<td>11.0</td>
<td>14576</td>
<td>5546</td>
<td>652</td>
<td>248</td>
</tr>
</tbody>
</table>

Table II. Construction productivity.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Quantity</th>
<th>Total time (hr:min)</th>
<th>Avg size (men)</th>
<th>Production rate (units/hr)</th>
<th>Labor productivity (man-hr/unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavation</td>
<td>14,576 yd³</td>
<td>22:21</td>
<td>2.0</td>
<td>652 yd³</td>
<td>0.003/yd³</td>
</tr>
<tr>
<td>Arch seats</td>
<td>400 ft</td>
<td>1:30</td>
<td>6.0</td>
<td>267 ft</td>
<td>0.022/ft</td>
</tr>
<tr>
<td>Timber scaffold</td>
<td>1 each</td>
<td>7:00</td>
<td>8.0</td>
<td>0.14 scaffold</td>
<td>56/scaffold</td>
</tr>
<tr>
<td>Metal arch</td>
<td>194 ft</td>
<td>84:00</td>
<td>8.0</td>
<td>2.31 ft</td>
<td>3.46/ft</td>
</tr>
<tr>
<td>Header beam systems</td>
<td>2 each</td>
<td>26:55</td>
<td>6.9</td>
<td>0.074 system</td>
<td>93.2/system</td>
</tr>
<tr>
<td>South upper endwall</td>
<td>1 each</td>
<td>8:05</td>
<td>5.8</td>
<td>0.124 endwall</td>
<td>46.9/endwall</td>
</tr>
<tr>
<td>North upper endwall</td>
<td>1 each</td>
<td>12:00</td>
<td>8.0</td>
<td>0.083 endwall</td>
<td>96.0/endwall</td>
</tr>
<tr>
<td>South lower endwall</td>
<td>1 each</td>
<td>24:00</td>
<td>5.9</td>
<td>0.042 endwall</td>
<td>141.0/endwall</td>
</tr>
<tr>
<td>North lower endwall</td>
<td>1 each</td>
<td>24:30</td>
<td>5.9</td>
<td>0.041 endwall</td>
<td>145.0/endwall</td>
</tr>
<tr>
<td>Rolling doors</td>
<td>2 each</td>
<td>43:30</td>
<td>7.0</td>
<td>0.046 door</td>
<td>151.5/door</td>
</tr>
<tr>
<td>Emergency exit</td>
<td>1 each</td>
<td>12:30</td>
<td>7.0</td>
<td>0.080 exit</td>
<td>88.0/exit</td>
</tr>
<tr>
<td>Jamesway office</td>
<td>1 each</td>
<td>12:00</td>
<td>3.0</td>
<td>0.083 office</td>
<td>36.0/office</td>
</tr>
</tbody>
</table>

Preparation of abutments

The first step of the Project 33 trench construction was the preparation of the processed snow abutments. Two 200-ft-long string lines were placed parallel to and 15 ft on either side of the trench centerline to guide the Peter snow miller. The miller then excavated approximately 1900 yd³ of in situ snow from the east and west abutment areas at a rate of 508.8 yd³, or 168 tons, per hour. The average forward speed of cut was 8.2 ft/min and the excavation was completed in 3 hr and 45 min of cutting time. Each of the excavations was well over 200 ft in length and
A STRAIGHT-WALL CUT-AND-COVER SNOW TRENCH

7 x 16 ft in cross-section. Figure 9 shows the sequence of the first six passes through the in situ snow. The milled snow was thrown on the natural snow surface away from the trench centerline. The snow from passes 7 and 8 (Fig. 10) was thrown into the west abutment excavation, forming a 2-ft-thick lift of processed snow. One compactive pass of a D-8 LGP tractor was made across the surface of the 2-ft-thick lift, but the risk of damaging the tractor tracks, because of the unevenness of the surface, prohibited this practice during the remaining backfill operation. An additional 1470 yd$^3$ of in situ snow was excavated, processed, and backfilled into the east and west abutment excavations as shown in Figure 10. The backfilling operation required 1 hr and 15 min at an average forward speed of 15.3 ft/min while processing at the rate of 1172.1 yd$^3$, or 347 tons, per hour.

Since the trenches were almost completely full of snow, the D-8 LGP tractor could now compact without fear of track damage. Four passes were made above each abutment.

The compacted processed-snow backfill age-hardened for 3 days before arch seat grade was established. Grade stakes were located in the backfill for use as elevation reference for the miller's final two abutment cuts as shown in Figure 11. The elevations were set according to the designed abutment thickness of 3 ft, requiring removal of an average of 2.85 ft of processed snow. Removal of this snow completely nullified the effect of the tractor compaction, as illustrated by Figure 4. The effect was that the abutments consisted of processed snow, uncompacted except for the single pass made by the Peter miller during the grade cut. Since this compaction was made on processed snow age-hardened 3 days, only a moderate increase in hardness was gained.

The grade cuts were completed in 35 min with the cut surface accurate to within 0.1 ft of the specified arch seat elevation. The snow was excavated at a rate of 749.1 yd$^3$, or 315 tons, per hour while the miller averaged a forward cutting speed of 13.1 ft/min.

Immediately after the grade cuts were made, the 2 x 12-in. timber arch seats were placed parallel to and offset 20.5 ft from the trench centerline (Fig. 12). The task was completed in 1 hr and 30 min by a crew of six men at a labor productivity of 0.002 man-hours/ft of arch seat. The 200-ft-long seats distribute the load applied by the corrugated steel arch and transfer it to the processed snow abutments. Since the sharp edge of the arch might cut into the 2 x 12-in. timber, a steel channel was inserted between the two members to further distribute loads (Fig. 3, Abutment detail). To determine the effectiveness of the steel channel, it was used to protect...
A STRAIGHT-WALL CUT-AND-COVER SNOW TRENCH

...a portion of the arch seat only. Each 200-ft-long seat consisted of 12-ft-long sections of timber with steel channel alternating with 12-ft sections of timber alone.

Ram hardness of the east and west abutment processed snow was measured after 3, 6, 9 and 24 days of age-hardening and compared with the hardness of unprocessed snow at the same depth. The results are shown on Figure 13, each processed snow curve being the average of ram profiles taken at Stations 1+00, 0+50, 1+00, 1+50 and 2+00 along the abutment. The effect of the single compactive pass by the tractor on the first 2-ft lift of west abutment snow is quite noticeable when the ram hardness of 24-day-old east and west abutment snow is compared.

Depth-density profiles were obtained from the abutments after 4 weeks of age-hardening (Fig. 14). The increase in density of the west abutment snow below 1 ft is also due to the single compactive pass made on that snow by the D-8 LGP tractor.

Excavation of trench and ramps

Excavation of the south ramp and the trench began on 12 July. Six days were spent excavating the 175-ft-long, 30-ft-wide south ramp and the 210-ft-long, 30-ft-wide, 26-ft-deep trench. The cutting sequence is illustrated in Figure 15. Figures 16 and 17 show the Peter snow miller completing cut 13 and starting cut 14. During excavation of the trench, the discharge chutes of the miller were incapable of casting all of the processed snow beyond the west abutment. Some of the snow was deposited upon the abutment, thereby burying the timber and steel arch seat (Fig. 16) until it was uncovered by hand excavation.
Figure 13. Ram hardness of processed snow abutments.

Figure 14. Depth-density profiles of east and west processed snow abutments.

Four weeks of age-hardening.
A STRAIGHT-WALL CUT-AND-COVER SNOW TRENCH

Figure 15. Excavation pattern for trench and south ramp.

Figure 16. Peter snow miller completing cut 13.
The north ramp was excavated during 2 - 4 August. The excavation required removal of 2460 yd³ of in situ snow following the cut sequence used for the south ramp and main trench. The total cutting time was 3 hr and 55 min.

The cutting time spent excavating the trench and both ramps was 16 hr and 46 min. The average cutting speed of the miller was 11.2 ft/min at an excavation rate of 642 yd³, or 256 tons, per hour.

The total cutting time during the 12 days the Peter miller worked at the trench was 22 hr and 21 min. The overall forward cutting speed of the miller was 11.0 ft/min and the overall average output rate was 652.2 yd³, or 248 tons, per hour at a labor productivity of 0.003 man-hours/yd³.

Refer to Table I for a summary of the excavation operation.

Construction of timber scaffold

The ski-mounted timber scaffold (Fig. 18) was constructed to facilitate fastening of the 41-ft span arch sections. An eight-man crew constructed and positioned the scaffold in 56 man-hours at a production rate of 0.14 scaffold per hour. During erection of the arch, the scaffold was moved along the abutments with pry bars.

Erection of 41-ft span arch

One hundred and ninety-four ft of 41-ft span corrugated steel arch was fabricated and erected without incident. The remaining 6 ft was erected with the south upper endwall. Using day and night crews of eight men each, the production rate was 2.31 linear feet of arch per hour. A total of 672 man-hours were required to fabricate and erect the 194 ft of arch.

The 2-ft-wide, 4 1/2-and 9-ft-long, 18-gage corrugated steel arch pieces were assembled on the snow surface adjacent to the trench by the eight-man night crew. Each 2-ft-wide 41-ft span section consisted of six 9-ft pieces and one 4 1/2-ft piece held together by 3/8-in. bolts. The short piece was always fastened at the bottom, or end, of the section and was alternately positioned at the east and west ends to stagger the roof splices (Fig. 7). Caulking was not used between pieces because of the increased time which the operation would entail.
Figure 18. Ski-mounted timber scaffold used for erection of the corrugated steel arch.

Three and sometimes four complete sections were bolted together and raised as a unit. Erection of the units was the task of the eight-man day crew. A military, Type 22b crane (Fig. 19) was used for lifting. Three-eighths-in. bolts were inserted from the outside by men on ladders and the nuts were placed and tightened from the inside by men on the timber scaffold. More than 12,500 bolts were used to fasten the 679 pieces of 18-gage corrugated steel arch.

Installation of snow fence

While the construction crew was erecting the corrugated steel arch, members of the pile test team fabricated and erected several hundred feet of aluminum-slat
snow fence. The fence was positioned parallel to and approximately 250 ft east south-east of the trench centerline (Fig. 20). At a later date, an additional 100 ft of fence was placed normal to the SSE winds, 300 ft upwind of the south endwall.

At the end of the "summer" construction season, all fence sections were dis­mantled and brought into the trench for winter storage.

Figure 20. Aluminum-slat snow fence placed upwind of trench.

Installation of header beams and door frames

The header beams were installed prior to erection of the sheet-steel endwalls. Each of the 34-ft-long beams was fabricated from two 15-in. wide steel channels laced together with 3-in. wide flat steel (Fig. 7). Recesses were excavated on opposite sides of the trench to accept the 2 x 6-ft footings upon which the beams rested. The footings consisted of three 8-in. x 8-in. 6-ft timbers tied together (Fig. 21).

After the crane positioned the header beam, it was carefully shimmed and leveled as shown in Figure 22.

Two 6-in. x 16-ft structural steel T-beam door jambs were fastened to each header beam using clip plates and 5/8-in. bolts. Built-up 3 x 2-in. steel angles were used as diagonal bracing between the header beam and the door jambs (Fig. 7).

The footing recesses were backfilled with processed snow at a later date.

The two header beam and door frame systems were completed in 186.3 man­hours, using a crew varying from one to eight men.

Erection of endwalls

The north and south upper endwalls consist of that portion of the endwall above the arch seats.

One three-section, 41-ft span arch unit was assembled on the snow surface near the south end of the trench. A five-man crew then fastened 4 x 4-in. curved sheet-steel angles to the lap joint between the last two sections of the unit. A platform consisting of 2 x 4-in. and 1 x 6-in. lumber was constructed within the perimeter of the arch to support the 20-gage "V"-notched sheet-steel endwall panels
during fabrication. These panels were fastened together and to the curved sheet steel angles with 3/8-in. bolts. The nearly fabricated south upper endwall is shown in Figure 23. Fabrication was completed in 30 man-hours.

Figure 21. 2 x 6-ft header beam footing in wall recess.

Figure 22. Positioning the south header beam.

Once the arch was rigged with wire rope and timber spreaders, the crane lifted and positioned the entire assembly (Fig. 24). The arch was then bolted to the erected roof and the endwall was fastened to the header beam with cane bolts as shown in Figure 6, Endwall-header beam slip-joint detail.
Installing the north upper endwall required more effort. The three-section arch unit had been erected previously and rigging, dismantling and moving it to the adjacent snow surface was required. The endwall was assembled on this arch unit and erected in the same fashion as the south endwall except that a total of 79.3 man-hours was required to complete the task, compared to 46.7 man-hours for the south endwall.
The lower endwalls were placed piece by piece rather than as an assembled unit. A scaffold was erected beneath the upper endwall to facilitate handling of the 20-gage "V"-notched sheet steel panels. Each panel was fastened with 3/8-in. bolts to adjacent panels, eventually forming a solid sheet-steel lower endwall. The 3/4-in. plywood sandwich grip connectors (Fig. 6) were fitted to the sheet-steel endwall panels and slush backfilled into 2-in.-wide, 6-in.-deep vertical wall slots. At the base of the lower endwall, a recess was cut into the trench floor and covered with plywood.

Completion of the south lower endwall required 141 man-hours, and the north, 145 man-hours.

**Installation of steel-slat rolling door**

An eight-man crew, working from a scaffold, drilled and tapped the jambs and mounted the rolling door track, chain, gear, and spindle hardware with bolts threaded into the tapped holes. Two chain hoists were used to lift and position the slat spindle (Fig. 25). The steel slats were lifted onto the scaffold and unrolled and guided over the slat spindle, then down through the tracks. The last slat was fastened to the slat spindle.

A sheet-steel cover was installed around the slat spindle to prevent blowing snow from clogging the door-raising mechanism. Strips of canvas tarpaulin were used to seal the edges of the door around the endwall-header beam and endwall-door jamb intersections. A 1/2-in.-thick piece of rubber, 2 x 14 ft, was attached to the bottom door slat. With the door closed, the rubber conformed to the unevenness of the trench floor and prevented blowing snow from entering the trench below the door. Figures 26 and 27 show the interior of the north endwall with the rolling door in place. The drift snow in the figures came through a hole near the top of the endwall and not from under the door. Shortly after the photos were taken an exhaust fan was installed in front of the hole.

A total of 303 man-hours were required for the installation of the rolling doors.

**Construction of emergency exit**

An emergency exit was designed, fabricated and erected in the field. It was placed on the outside face of the south endwall along the east arch seat. A 2 x 4-ft opening was cut through the sheet-steel upper endwall and framed with 2 x 4-in. lumber. The exit structure was fabricated from 2 x 4-in. lumber and 3/4-in. plywood in the form of a 4 x 5-ft box, 7 ft in height, having a hinged door on top.

To provide access to and from the trench floor when using the emergency exit, a permanent ladder was installed up the east wall of the trench at the south end. Eighty-eight man-hours were required to construct and erect the exit and ladder.

**Erection of the Jamesway office**

The office was erected in the southwest corner of the trench on a foundation of 2 x 12, 8 x 10, and 12 x 12-in. timbers (Fig. 28). It consisted of a two-section Jamesway building; a semi-circular structure with a plywood floor, wooden arch
Figure 26. Interior of north endwall showing header beam and rolling door system.

Figure 27. Drift snow behind the north rolling door.
frames, and insulated canvas skin. Thirty-six man-hours were required to complete erection.

INSTRUMENTATION

Thermocouples

A total of 25 copper-constantan thermocouples, arranged on the trench centerline in three vertical strings and at depths from 2 to 40 ft below the trench floor, were installed to monitor temperature (Fig. 29). The assemblies were lowered into 4-in.-diam holes cut with a CRREL auger and backfilled with processed snow. Rotary switches with silver contacts were used to select specific thermocouples during measurement of temperature with a precision potentiometer. Since the snow temperature did not vary with assembly location, the data from the three assemblies are combined and shown in Figure 30.

From the seven curves, one can conclude that: (a) seasonal effects are felt to a maximum depth of 25 ft and (b) continuous warming of the snow mass below 25 ft is not occurring, as evidenced by the convergence of the curves below that depth.

Vertical control

A permanent bench mark (BM-1) was established for vertical control within the trench, 27.5 ft in from the south endwall and 7.4 ft west of the trench centerline (Fig. 31). The bench mark was fabricated from a 23-ft-long, 2-in.-diam aluminum pipe having steel pipe caps at both ends. It was placed, free-standing, in a 22-ft-deep vertical hole cut with a CRREL snow auger. Snow fines produced while cutting the hole were removed prior to insertion of the pipe to eliminate all densification effects except those at the base of the bench mark.

Figure 28. Foundation for Jamesway office.

Figure 29. Location of thermocouples.

Figure 30. Temperature distribution in the snow mass below the trench floor.

Figure 31. Vertical control within the trench.
A STRAIGHT-WALL CUT-AND-COVER SNOW TRENCH

The snow temperature was a constant -24°C throughout the year prior to the excavation of the trench. (Benson, 1959)

Figure 30. Temperature profiles. Curves represent data averaged from assemblies TC-1 thru TC-3.

Figure 31. Location of BM-1 and arch seat points.

The bench mark was referenced to the "Camp Century Elevation Datum" established by Waterhouse in the summer of 1961. Relative to this datum, the elevation of the top of the BM-1 pipe is 113.18 ft.

Arch seat levels

Three points were established on each arch seat for vertical control (Fig. 31). The points consisted of 20d nails driven into the 2 x 12-in. timber seat and made conspicuous with orange cloth. Yearly surveys were run from BM-1 to each of these points (Table III).

The "Difference in elevation" figures of Table III represent changes in the vertical distance between the arch seat nails and the bench mark base. The natural densification occurring between two such layers can be obtained from Figure 32.
Figure 32. Vertical strain rate variations with depth.

using

$$\Delta h = \int_{h_1}^{h_2} \dot{\varepsilon} \, dh$$

(1)

where $\Delta h$ equals the annual decrease in height between layers $h_1$ and $h_2$, $h_1$ equals the arch seat elevation, $h_2$ equals the elevation of BM-1 and $\dot{\varepsilon}$ equals the vertical strain rate expressed in years$^{-1}$.

The total $\Delta h$ occurring in the 44 ft of snow between elevations $h_1$ (16.5 ft from Figure 40) and $h_2$ (60.5 ft) can be obtained by dividing the 44 ft into several depth increments and obtaining a $\Delta h$ for each increment. The total $\Delta h$ for the $h_2 - h_1$ interval then equals the sum of the $\Delta h$s and has the value 0.59 ft/yr.

Heat introduced into the trench has warmed the surrounding snow mass and increased the strain rate. The effect of temperature on strain rate can be represented by the equation:

$$\dot{\varepsilon}_2 = \dot{\varepsilon}_1 \frac{7000}{\frac{7000}{e^{\frac{T_1}{T_2}}}}$$

(2)

which is a simplified version of the exponential expression of Mellor (1964) where $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ are the strain rates at temperatures $T_1$ and $T_2$ which are expressed in degrees Kelvin.

Assuming that the -24.5°C mean annual temperature surrounding the trench has been increased to -21°C in the floor and walls of the trench, the 0.59 ft/year natural densification rate increases to 0.80 ft/year.
### Table III. Arch seat elevations.*

<table>
<thead>
<tr>
<th>Point</th>
<th>27 Sept 1962 elevation (ft)</th>
<th>1 Aug 1963 elevation (ft)</th>
<th>Difference in elevation † (ft)</th>
<th>6 Aug 1964 elevation (ft)</th>
<th>Difference in elevation † (ft)</th>
<th>17 July 1965 elevation (ft)</th>
<th>Difference in elevation † (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>134.50</td>
<td>133.55</td>
<td>-0.95</td>
<td>132.14</td>
<td>-2.36</td>
<td>130.13</td>
<td>-4.37</td>
</tr>
<tr>
<td>B</td>
<td>134.39</td>
<td>133.33</td>
<td>-1.06</td>
<td>132.13</td>
<td>-2.26</td>
<td>131.18</td>
<td>-3.21</td>
</tr>
<tr>
<td>C</td>
<td>134.58</td>
<td>133.68</td>
<td>-0.90</td>
<td>132.52</td>
<td>-2.06</td>
<td>131.63</td>
<td>-2.95</td>
</tr>
<tr>
<td>D</td>
<td>134.32</td>
<td>133.19</td>
<td>-1.13</td>
<td>131.58</td>
<td>-2.74</td>
<td>130.45</td>
<td>-3.87</td>
</tr>
<tr>
<td>E</td>
<td>134.43</td>
<td>133.27</td>
<td>-1.16</td>
<td>132.07</td>
<td>-2.36</td>
<td>131.10</td>
<td>-3.33</td>
</tr>
<tr>
<td>F</td>
<td>134.45</td>
<td>133.31</td>
<td>-1.14</td>
<td>132.12</td>
<td>-2.33</td>
<td>131.23</td>
<td>-3.22</td>
</tr>
</tbody>
</table>

* With reference to BM-1 (elev = 113.18 ft).

† With reference to 27 Sept. 1962 elevation.
A STRAIGHT-WALL CUT-AND-COVER SNOW TRENCH

From footing tests conducted in the trench by Mr. S. C. Reed of USA CRREL, it is estimated that the arch seats, which place an additional 2380 psf load on the wall, would settle into the wall at a rate of about 0.16 ft/year. Adding the corrected natural densification rate of 0.80 ft/yr to this value a total yearly downward movement of the arch seat relative to the reference layer is obtained. The difference between the computed value of 0.96 ft/year and the measured value of 1.05 ft/year can be attributed to lack of lateral restraint on the trench walls, a factor not considered in the theoretical approach.

Floor arching study

On 27 June 1963, six 5-ft-long, 2-in.-diam piles were driven 3 ft into the trench floor at Station 1+00 by Kovacs (1964). The first was placed on the trench centerline, the second through fifth at 3-ft intervals along the left side of the cross section and the sixth, 14 ft from the centerline, 1 ft from the wall. Elevations were periodically obtained of the six points to the nearest 0.001 ft with reference to BM-1. During the period from July 1963 to July 1964, the centerline point did not change in elevation while the elevation of point 6 decreased by 0.15 ft, indicating the relative draw-down of the trench floor near the walls. From July 1964 to July 1965, the centerline point rose 0.01 ft while point six dropped 0.15 ft.

On Figure 33 the theoretical natural densification rate of 0.24 ft/yr between the trench floor layer and the bench mark reference layer as computed from eq 1 is shown along with the 1964-1965 floor deformation measurements.

Figure 33. Deformation rates relative to the deep bench mark.
Excavation of the trench removed a stress of approximately 350 gm/cm² from the trench floor layer. Because snow is visco-elastic there is an immediate elastic recovery, or rebound, upon stress removal followed by a delayed recovery, or elasto-viscous aftereffect. The elastic recovery corresponds to relaxation of the Maxwell spring while the delayed recovery is represented by relaxation of the Voigt unit of Maxwell and Voigt rheological models in series, a system commonly used to describe the time dependent deformation characteristics of visco-elastic materials such as snow.

Since the floor arching instrumentation was installed a year after excavation of the trench, the elastic recovery would not enter into measurements obtained but if the delayed recovery rate was significant after a year, it would raise the elevation of the floor relative to the deep bench mark.

A second action, plastic flow of snow up into the trench, would also tend to raise the floor elevation. The floor layer under the walls carries a surcharge due to the weight of the snow located above. The load on each side of the trench causes upward movements, or heave, of the floor. Similar occurrences exist in open cuts in soft clay and, on occasion, sheet piles are required to retain the material.

Present knowledge will not permit isolation of the delayed recovery and plastic flow deformations and it can only be stated that any upward motion of the floor relative to the deep bench mark is caused by a combination of the two actions which are a maximum at the trench centerline and zero at the walls.

Relative to the deep bench mark, the snow surrounding the trench at the elevation of the floor moves downward due to the natural densification of the material between the floor and the deep bench mark. Within the trench the floor elevation does not decrease at the same rate due to the lack of surcharge on it. Consequently large shear stresses develop at the wall - floor intersection and are relieved by a downward flow of the trench floor in that area. These localized displacements, termed "draw-down" displacements, can effect structures or tests whose foundations are placed close to the floor-wall intersection. From Figure 33 it is evident that the major downward floor displacements because of wall surcharge occur within 5 ft of the wall and that the floor is not drawn down along the trench centerline.

The 22 ft of snow between the floor and deep bench mark experiences some densification because of its own weight. The strain rates are less than those at the same depth under natural densification because of removal of the 350 gm/cm² surcharge and the absence of snow accumulation on the floor.

The Newtonian viscous shear equation:

\[ \dot{\varepsilon} = \frac{\sigma}{\eta_c} \quad \text{or} \quad \eta_c = \frac{\sigma}{\dot{\varepsilon}} \quad (3) \]

states that the coefficient of compressive viscosity (\(\eta_c\)) equals the snow load pressure (\(\sigma\)) divided by the vertical strain rate (\(\dot{\varepsilon}\)). The coefficient of compressive viscosity is also a function of temperature and density. Construction of the trench has not affected the density of the snow below the excavation but from a comparison of Figures 1 and 30, it is evident that the temperature of that material has been changed. Figure 30 shows that summer warming is greater than winter cooling, indicating an increased average temperature which would decrease \(\eta_c\) and cause accelerated strain rates. The effect of temperature on strain rate is represented by eq 2.

If, at any depth, \(h\), the temperature and density are held constant:

\[ \dot{\varepsilon}_1 = \frac{\sigma_1}{\eta_c} \quad \text{and} \quad \dot{\varepsilon}_2 = \frac{\sigma_2}{\eta_c} \quad (4) \]

where \(\dot{\varepsilon}_1\) and \(\dot{\varepsilon}_2\) are the strain rates at depth \(h\) before and after excavation of the
trench and \( \sigma_1 \) and \( \sigma_2 \) are the vertical snow loads at the trench and bench mark before and after excavation. Solving for \( \eta_c \) in the first equation and substituting in the second equation, it is found that

\[
\xi_2 = \frac{\sigma_2}{\sigma_1} \xi_1
\]

or

\[
\xi_2 = \xi_1 - \xi_1 \frac{\sigma_R}{\sigma_1}
\]

where \( \sigma_R \) is the stress removed which equals \( \sigma_1 - \sigma_2 \). If the strain rates obtained are then corrected for temperature according to eq 2, the curve in the lower left of Figure 32 is obtained. By applying eq 1 to this curve, the densification occurring between the floor and the bench mark is found to equal 0.08 ft/yr. If the strain rates were not corrected for temperature changes, the densification would be 0.06 ft/yr, indicating a strain increase in excess of 30% due to warming.

The net floor deformation rate as shown on Figure 33 is the algebraic sum of the displacements produced by densification, draw-down, rebound and heave. From the figure, it is evident that only slight relative elevation changes exist along the cross section to within 5 ft of the trench walls and tests or structures founded within the center two-thirds of the section would be free from differential movement difficulties. Floor arching studies performed on narrower trenches indicate that significant relative deformations occur over a greater portion of the cross section.

Cross sections

During August 1962, points were established in the trench at stations 0+25, 0+75, 1+25 and 1+75 (Fig. 34). Several types of measurement points were tried, including wood dowels, steel rods, welding rods, and lag screws. Eight and one-half inch lag screws proved far superior to the other types.

![Figure 34. Cross-section locations.](image)

Just prior to installation, each screw was removed from the 70F temperature of the office Jamesway and pounded half way into the wall. Each was then rotated into the wall with a wrench until the face stood 1 in. out from the snow. Where the snow was quite hard or an ice lens was present, a 3/8-in. diam pilot hole was drilled with bit and brace before insertion of the lag screw. When the snow was very soft or coarse, the screw was twisted into position by hand; if it had not set in a day, it was removed and relocated in firmer snow.

In addition to the instrumentation described above, seven points were installed on the corrugated steel arch at station 0+75 (Fig. 35). Steel tapes were permanently fastened to points C, D, and E, because of their location high above the trench floor. A detail of these points is shown in Figure 36. Between measurements, the tapes were secured to the arch 4 ft above the arch seat; C and D above the east seat and E above the west seat.
The relative elevations of the east and west wall lower points for each cross section were established by leveling. The four sections were tied together by referencing the survey to BM-1. All other points in each of the four sections were located by triangulation from the two lower points as shown in Figure 37. Additional measurements were also taken as a check.

All distances were measured in feet to the nearest 0.01 ft with a 50-ft steel tape. A special holding device designed by Tobiasson was attached to the tape to facilitate measurement in the arctic cold. Mittens or gloves could be worn during taping which was accomplished more accurately when the "Tobiasson Cold Grip" was used (Fig. 38).

To reduce errors in the method of observation and to provide continuity, a standard data collection procedure was adopted. A form, which was taken into the field, contained spaces for recording dimensions as they were measured.

The change in shape of the station 0+75 cross section is shown on Figure 39. The section area equalled 1182 ft$^2$ on 2 September 1962, 1130 ft$^2$ on 30 September
Figure 38. Obtaining cross-section measurements with the "Tobiasson Cold Grip".

Figure 39. Cross-section closure at station 0+75.

1963, 1099 ft² on 7 September 1964, and 1074 ft² on 17 July 1965, which indicates yearly area reductions of 4.2%, 3.3% and 2.7% during 1962-1963, 1963-1964 and 1964-1965 respectively. The trench appears quite stable when compared to the undercut side trenches of Camp Century which are closing at rates as high as 16% per year. A small portion of the 16% is due to the undercut nature of the trench. Much more heat has been introduced into the Century trenches and most of the
A STRAIGHT-WALL CUT-AND-COVER SNOW TRENCH

Additional deformation can be attributed to heating, and subsequent weakening of the snow.

The decrease in area reduction rate from 4.2 to 2.7% yr is associated with apex buckling of the steel arch, and a decreasing vertical closure rate attributable in considerable degree to the gradual increase in density of the surrounding snow and colder temperatures in the trench, the result of shorter periods of summer occupancy in recent years.

Snow accumulation

The amount of snow accumulating on the corrugated steel arch and on the snow surface adjacent to the trench affects the closure rate of the trench. Surface elevations obtained from topographic maps and photographs are shown on Figure 40. The figure illustrates that an above-surface obstruction will create excessive snow accumulation in the area close to the obstruction and that snow will not accumulate above the obstruction until the surrounding area has been elevated to the top of the obstruction.

![Figure 40. Snow accumulation at the trench.](image)

The arch apex was 13.5 ft above the snow surface when erected in 1962. At a snow accumulation rate of 4 ft per year, which has been determined from measurement of accumulation stakes placed nearby, the surrounding area will reach the arch apex elevation late in 1965. Until that time, no snow will accumulate above the apex. Once the apex elevation is reached, the natural accumulation rate of 2.8 ft per year (Mock, 1965) can be expected throughout the area. The increase in present accumulation rate from 2.8 ft to 4 ft in the area surrounding the trench is due to the obstruction created by the trench and, in fact, by the entire Camp Century complex. With time, the obstruction will disappear and the natural accumulation rate as measured by Mock away from the influence of camp will prevail.
PERFORMANCE

General

At this writing three years have elapsed since construction of the facility. During that time the extensive pile testing program for which the trench was constructed was carried on successfully. The high roof of the trench provided ample room for positioning and driving piles and the endwalls effectively sealed the interior of the trench from drifting snow. Generally, the concept has proven itself and can be classified as a feasible undersnow facility design. However, problems have occurred and certain aspects of the design should be modified if future trenches are constructed. In the remaining sections of this report, the major problems encountered are discussed.

Entrances

The entrance ramps proved to be the most troublesome part of the facility. Although the aluminum-slat snow fences placed upwind of the trench during 1962 precipitated large quantities of snow before it reached the ramps, the ramp cuts rapidly accumulated drifting snow. Figure 41 shows the north ramp after a day of bad weather. Soon, the time and equipment required to keep both ramps open could not be justified and the north ramp was allowed to fill with drifting snow. To prevent the force of the snow on the rolling door from buckling the steel slats, the 4 x 4-in. timber anchors fastened to the bottom of the door jambs were cut. The jambs and rolling door were allowed to swing back free of the snow and the door was raised so that only the bottom 2 ft remained suspended below the slat spindle. A plywood wall (Fig. 42) was built under the raised door to seal off the trench and was mistakenly fastened to the jambs and the rolling door. Forces which developed on it pushed it, the door, and the jambs inward, severely buckling the lower slats of the door.

Figure 41. North ramp after a storm.
The north ramp soon filled with drift snow, a material which densifies rapidly, causing a rapid transmittal of force to objects retaining it. Lateral forces built up on the endwall and soon buckling of the sheet steel was apparent. Pressure on the lower endwall pushed the sheet steel and the jambs inward rapidly since the bottom of each jamb was now unattached to the trench floor. In a year the 14-ft-long jambs were pushed approximately 8-in. out of plumb. The only forces resisting the lateral pressure were developed: (1) at the endwall-arch connection, (2) by the header beam, and (3) by the plywood sandwich grip connectors.

The rate of densification and consequently the rate of load build-up on the endwall is slowing down. However, buckling continues and will do so until the snow is cut away from the sheet-steel endwall, creating a free-standing snow wall just outside the north end of the trench. If the endwall is not freed, the snow will continue to apply force to the corrugated steel arch, the header beam and the plywood grip connectors. Buckling of the arch will continue, the header beam will move inward on its foundations, and the plywood grip connectors will yield continuously.

To prevent similar damage to the south endwall during the winter of 1962-1963, a wall consisting of 55-gal drums and plywood was built just outside the south end of the trench. Processed snow was blown over the wall, sealing the trench for the winter as shown on Figure 43a. The rolling door remained in the up position during the winter so that any unforeseen forces developing on the endwall would not buckle the steel slats.

The south ramp filled with drift snow rapidly and remained closed until June 1963. At that time the Peter miller opened the trench for the summer season. The blowing snow had deposited loosely and the miller sank into weak spots, at times so deep that heavy equipment was required to pull it free. A second problem occurred when the miller tried to cut through the processed snow which it had deposited on the floor of the ramp when sealing the trench the previous year. Because of the material's hardness, slope and irregularity, it could not be cut. A D-8 LGP tractor with blade was also incapable of removing the year-old processed snow and it remains in the ramp as a passable but troublesome area. Snow accumulated on the south endwall above the 55-gal drum and plywood wall as shown on Figure 44 and buckled the upper endwall as shown on Figure 45.46.

The escape hatch built during the summer of 1962 was extended 8 ft in the winter of 1962-1963 and 4 ft in the summer of 1964. The top of the hatch was 4 ft below the snow surface prior to the first extension. The extended hatch as shown on Figure 44 provided the only winter entrance and exit for personnel obtaining measurements in the trench.
Figure 43. Two methods used to seal the trench.

Figure 44. South end of trench in February 1963.
During the summer of 1963 the south ramp was kept open by a D-4 tractor with bucket. At the end of the season, a plywood lean-to was used to seal the trench for the winter as shown on Figure 43b. The top of the lean-to rests against the header beam for lateral support. Rather than using processed snow to seal the trench, the ramp was bulldozed full of snow by a D-8 LGP tractor. To insure that the miller would not sink into weak spots next time the ramp was opened, the tractor compacted the snow in lifts during the backfilling operation.

In 1964 a covered entrance ramp was constructed to eliminate the costly maintenance task of removing drift snow from the deep open ramp of years past. The Peter snow miller cut a 250 ft long inclined slot from the snow surface to the door in the south endwall of the trench. The bottom 12 ft of the ramp cut were milled 9 ft wide enabling that area to be roofed with 14-ft span corrugated steel arch used previously in the trenches of Camp Century. Processed snow was blown above the steel arch to create a structural roof element capable of withstanding stresses imposed by future snow accumulation. The covered ramp reduced the effort required to keep the trench open but its small entrance, just below the surface, rapidly choked with drift snow.

During September 1964 a 50-ft-long above-surface extension was erected at the end of the trench. The extension consisted of processed snow walls and a 14-ft span corrugated steel arch roof covered with 8 in. of processed snow. The walls were erected by dumping processed snow between plywood forms which remained in place for 18 hours, then were re-erected elsewhere. At the upper end of the extension, a timber frame supported a three piece plywood door which provided access for personnel and equipment and sealed the ramp during bad weather (Fig. 46). After a storm a tractor cleaned drift snow from in front of the doors by cutting a series of swales perpendicular to the trench centerline, a procedure much easier than that required to remove drift from inside an open ramp.

That portion of the ramp extension structure above the surface acted as an obstruction and a long drift was created downwind of the structure. The entrance ramp was constructed along the centerline of the trench and in that position, perpendicular to the prevailing wind, the area in front of the doors was scoured clear of drift snow even after severe storms.
The three piece door was sealed in September 1964 and remained closed until May 1965 when the trench was again opened for the summer. Vehicular passage into the trench was possible after 15 minutes of bulldozing, a vast improvement over the many days spent opening the trench during previous years.

**Roof system**

By referring to Figure 39, it is apparent that the arch is moving both downward and inward. The inward motion changes the shape of the arch, reducing the span and increasing the rise. The corrugated steel arch has not been designed for such deformations and eventually buckling occurs. Two years after erection, the arch covering the pile test trench had buckled slightly at its apex. Continued buckling there during 1964 and 1965 has effectively added another hinge to the arch, creating a three-hinged structure. The new hinge introduces little immediate danger to the roof system, except that another line of buckling will eventually develop at the center of the haunch as evidenced by similar arches installed over the reactor area trenches at Camp Century. Once this line becomes noticeable, remedial measures must be initiated if use of the trench is to continue safely.

To prolong the life of long span corrugated steel arch the structure could be erected with the span one to two feet longer than normal. Pre-straining the arch in the direction opposite to expected horizontal deformations would result in an initially weaker arch but one that would reach its maximum strength a few years after erection. An arch installed in the conventional manner is initially stronger but loses its load carrying capacity as the snow around it deforms. Since the snow loads on arches increase with time it is advantageous to utilize arches whose strength also increases.

A second method of prolonging the life of the roof would be to place processed snow on the steel arch. Given sufficient time to age-harden, the processed snow develops substantial strength and resistance to deformation. Recent tests conducted at Camp Century have shown that processed snow arches 3 ft thick at the crown, can, after 21 days of age-hardening, support themselves in free spans up to 50 ft without collapse or drastic deformation. In addition to strengthening the roof system, a processed snow cover over the corrugated steel arch would prevent drift snow from filtering into the trench through openings developed in buckled areas.

The endwalls have suffered gross deformations due to the snow load imposed on them (Fig. 46). Since they are firmly connected to the arch, it has also deformed in that area. Localized deformation at each end of the trench triggered the line of buckling at the arch apex along the entire length of trench. Had deformation of the endwalls not affected the arch, apex buckling would not have occurred as soon. In the future, the endwall and roof structures should be isolated to prevent such interaction.

Visual observation of the arch seats indicates little difference in performance between the bare timber seat and the timber seat protected with a steel channel. Elimination of the channel from future arch seats would simplify construction without affecting the strength of the roof structure.

Comparison of the performance of the corrugated steel arch covering the trench with that of arches installed during 1960 over the reactor area trenches of Camp Century indicates that the pile test trench arch will have a maintenance-free life of from 4 to 6 years. By applying the new techniques mentioned to future facilities, it is felt that similar trenches can be constructed with a design life as long as 10 years.
CONCLUSIONS

In a high polar environment such as Camp Century, Greenland, it is feasible to create subsurface facilities by cutting wide trenches in snow with the Peter snow miller and covering them with corrugated steel arches. Although the arch erection for such a facility is time-consuming, it can be accomplished by engineer construction troops, unaccustomed to the environment, without previous experience in the erection procedure. A small crane and timber scaffold greatly simplify the arch erection.

Sheet steel endwalls can be used to seal the facility from the harsh ice cap environment but the large deformations experienced by such structural components necessitate elimination of unyielding connections between roof and wall elements. Where connections are made, deformation of one element can cause localized failures within adjacent elements. Since deformation of the surrounding snow mass is continuous, such problems are rapidly magnified. The failure of a structural system due to progressive failure of its components is an important and often inadequately thought-out factor in design of facilities in a material capable of deforming with the rapidity of the uppermost layers of the Greenland Ice Cap.

Instrumentation installed in the area has shown the following:

1. The presence of the facility affected the temperature of the snow to a maximum depth of 25 ft below the trench floor.
2. The initial cross-sectional area reduction rate of 4.2% decreased to 2.7% after three years due to increased density of the surrounding snow and lower temperatures, the result of less frequent occupancy.

3. Trench floor arching displacements are greatest at the wall-floor intersection and, to eliminate differential settlements caused by these displacements, structures should be founded as far from the wall as possible on two rows of footings equidistant from and on opposite sides of the trench centerline.

4. The corrugated steel arch which covers the trench initially protrudes above the snow surface and, acting as an obstruction, creates excessive drift snow accumulation in the area. However, until the adjacent undisturbed surface reaches the elevation of the arch apex at the natural accumulation rate of 2.8 ft per year, snow will not accumulate above the apex.

Access to and from the facility, a major problem because of drifting snow, was compounded by the 2.8 ft of annual accumulation at the site. To relieve the maintenance problem, a covered entrance ramp of formed processed snow was constructed and a three-piece door erected at the upper end of the processed section to seal the ramp from the surface environment. The above-surface covered entrance ramp greatly reduced the maintenance required to keep the trench open to personnel and vehicular traffic.

LITERATURE CITED


Kovacs, Austin (1964) Project 33 trench floor arching phenomenon, USA CRREL Technical Note (unpublished).


A straight-wall cut-and-cover snow trench was constructed at Camp Century, Greenland, during the 1962 summer, to house tests performed by USA CRREL Project 33, Feasibility Study of Pile Foundations in Snow. In this report, the parameters used to design the trench and the equipment and methods used in the construction are presented and evaluated. Time-motion studies covering all phases of construction are included as a guide for the planning and evaluation of similar construction. Performance is discussed and documented by instrumentation installed in the trench. (Authors' abstract)
Construction--Greenland
Snow trenches--Construction
Snow (Construction material)--Test results
Snow--Mechanical properties--Testing equipment
Foundation construction--Greenland
Camp Century
Shelters--Instruments