



US Army Corps
of Engineers®
Engineer Research and
Development Center



ERDC 6.2 Boreal Aspects of Ensured Maneuver (BAEM)

Using the Light Weight Deflectometer to Assess Groomed Snow and Ice Surfaces

Wendy L. Wieder, Sally A. Shoop, and Lynette Barna

May 2019



The U.S. Army Engineer Research and Development Center (ERDC) solves the nation's toughest engineering and environmental challenges. ERDC develops innovative solutions in civil and military engineering, geospatial sciences, water resources, and environmental sciences for the Army, the Department of Defense, civilian agencies, and our nation's public good. Find out more at www.erdcl.usace.army.mil.

To search for other technical reports published by ERDC, visit the ERDC online library at <http://acwc.sdp.sirsi.net/client/default>.

Using the Light Weight Deflectometer to Assess Snow and Ice Surfaces

Wendy L. Wieder, Sally A. Shoop, and Lynette Barna

*U.S. Army Engineer Research and Development Center (ERDC)
Cold Regions Research and Engineering Laboratory (CRREL)
72 Lyme Road
Hanover, NH 03755-1290*

Final Report

Approved for public release; distribution is unlimited.

Prepared for Assistant Secretary of the Army for Acquisition, Logistics, and Technology
103 Army Pentagon
Washington, DC 20314-1000

Under Project 465395, ERDC 6.2 “Boreal Aspects of Ensured Maneuver (BAEM),”
and Project 471941, “Remote Assessment of Snow Mechanical Properties”
and “Mobility in Peat and Northern Soils”

Abstract

The Light Weight Deflectometer (LWD) was designed to test the compaction or bearing capacity of in-place aggregate base-course materials. This study evaluated the potential of the LWD to also characterize groomed snow and ice surfaces as the ability to characterize the strength, or bearing capacity, of winter surfaces is crucial for evaluation of vehicle mobility in cold climates.

LWD tests were run on a variety of groomed snow and ice surfaces over asphalt pavement, gravel, and soil in the winter of 2018 in both Montana and Michigan. The LWD measures load and deflection, enabling calculation and backcalculation of stiffness parameters for the test surface layers. The initial results were reasonable for the snow layers analyzed. The Impulse Stiffness Modulus, calculated as the impact load divided by the deflection response, presents as a reasonable property for analysis, requiring no assumptions about other snow layer properties. However, the LWD components, specifically the rubber load buffers, may have issues with the effects of low temperature testing. These effects need to be considered when testing snow and ice surfaces. Additionally, the stress and compaction levels that most represent the conditions of interest for mobility purposes need to be determined. Specific and consistent LWD equipment configuration and test procedures need to be determined and implemented in further testing of winter surfaces.

Contents

Abstract	ii
Figures and Tables.....	iv
Preface	vi
Acronyms and Abbreviations	vii
Unit Conversion Factors	viii
1 Introduction.....	1
1.1 Background	1
1.2 Objectives.....	1
1.3 Approach	1
2 BAEM LWD Program.....	3
2.1 BAEM field campaigns.....	3
2.1.1 Montana	3
2.1.2 Michigan	5
2.2 LWD basic operation.....	7
3 Field Results and Observations.....	12
3.1 Montana	12
3.2 Michigan.....	19
4 Analysis and Discussion	20
4.1 Deflection data	20
4.2 Stress levels	26
4.3 Load data	27
4.4 Surface deflection modulus	29
4.5 LWDMOD backcalculation.....	32
4.5.1 Montana—bare asphalt concrete pavement	33
4.5.2 Montana—groomed snow over runway pavement	34
4.5.3 Michigan—groomed snow over natural subgrade	35
4.6 ISM.....	38
4.7 LWD depth of influence	40
5 Summary and Recommendations	41
References	45
Appendix A: Additional Site Imagery	48
Appendix B: Field Campaign Weather Conditions	54
Report Documentation Page	

Figures and Tables

Figures

1	Montana LWD test points plotted on summer imagery that shows pavement surfaces at West Yellowstone Airport, Montana	4
2	Montana test points plotted on winter imagery taken at the time of the field campaign	5
3	Schematic of the Michigan test site	6
4	Michigan test points plotted on summer imagery to show ground surfaces	6
5	Michigan test points plotted on winter imagery	7
6	LWD operation in Michigan. The LWD unit and the first operator are on the <i>right</i> , and the second operator with the PDA is to the <i>left</i>	9
7	Example of a normal data curve for an LWD test	10
8	Dynatest LWD with the center plug in (<i>left</i>) and out (<i>right</i>) with the center plate geophone extending through the loading plate annulus	11
9	Initial LWD tests on groomed snow over an unpaved ground surface	15
10	Center geophone divot and plate impression left by an LWD test using the 150 mm (5.9 in.) diameter loading plate	16
11	High offset from the first drop of an LWD heavy weight package on groomed snow over taxiway pavement	16
12	First drop deflection and load readings showing the deflection offset that indicates compaction or seating of the LWD into the snow	17
13	Irregular waveform readings from LWD testing of groomed snow over pavement	18
14	Example LWD data waveforms from Michigan—groomed snow over a grass-covered soil	19
15	Large deflections recorded for the first drop at a new load level for each level (<i>top</i>) of groomed snow over runway pavement in Montana and for only the second, third, and fourth level (<i>bottom</i>) of groomed snow over taxiway pavement in Montana	21
16	Impression left in the snow surface by an LWD test in Montana	22
17	Unedited LWD deflection data for groomed snow over runaway and taxiway asphalt concrete pavement in Montana (<i>top</i>) and various surfaces in Michigan (<i>bottom</i>)	23
18	Unedited LWD deflection data for Michigan ice surfaces	24
19	LWD deflections from Montana (<i>top</i>) and Michigan (<i>bottom</i>) with the first deflection at each load level removed. Note the deflection scale change for Michigan data	25
20	Load levels recorded by the LWD in Michigan, indicating a change in loading conditions between morning and afternoon tests	28
21	LWDMod Excel report	29
22	E_0 values calculated by LWDMod for example groomed snow surface data sets from Montana (<i>top</i>) and Michigan (<i>bottom</i>) data	31
23	Snow density test on groomed snow in Michigan	35

24	ISM values manually calculated for example groomed snow data sets from Montana (<i>top</i>) and Michigan (<i>bottom</i>) data	39
----	---	----

Tables

1	LWD testing stress level ranges	8
2	LWD drop heights for the light load package, 10 kg (22 lb).....	8
3	LWD drop heights for the heavy load package, 20 kg (44 lb).....	9
4	Montana LWD test-point details.....	13
5	Michigan LWD test point details	14
6	Comparison of contact pressures of U.S. military vehicles and aircraft to average contact pressures obtained with the LWD, highlighted in <i>green</i> , in Michigan (Michael Parker, CRREL, pers. comm., 7 November 2018).....	26
7	LWDMod backcalculated modulus results, in MPa, for groomed snow over grassed soil in Michigan	37
8	Backcalculated and calculated stiffness measures of groomed snow.....	42

Preface

This study was conducted for the Assistant Secretary of the Army for Acquisition, Logistics, and Technology under project number 465395, “Boreal Aspects of Ensured Maneuver (BAEM),” which is part of the U.S. Army Engineer Research and Development Center (ERDC) 6.2 Remote Assessment of Infrastructure for Ensured Maneuver (RAFTER) Program managed by Ms. Danielle Whitlow, ERDC Geotechnical and Structures Laboratory (GSL). This work is continuing under project number 471941, “Remote Assessment of Snow Mechanical Properties” and “Mobility in Peat and Northern Soils,” under the Entry and Sustainment in Complex Contested Environments Program managed by Dr. John Rushing, GSL.

The work was performed by Force Projection and Sustainment Branch (CEERD-RRH) of the Research and Engineering Division (CEERD-RR), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Dr. Harley Cudney was Acting Chief, CEERD-RRH, and Mr. Jared Oren was Acting Chief, CEERD-RR. The Deputy Director of ERDC-CRREL was Mr. David B. Ringelberg, and the Director was Dr. Joseph L. Corriveau.

The authors acknowledge the following people for field support: Mr. Bruce Elder, Mr. Charlie Smith, Mr. Mike Ekegren, Mr. Andrew Bernier, and Mr. Jason Olivier of CRREL and Dr. Russ Alger of the Michigan Technical University. Ms. Amelia Menke and Mr. Terry Melendy, Jr., CRREL, provided manuscript review comments.

COL Ivan P. Beckman was Commander of ERDC, and Dr. David W. Pittman was the Director.

Acronyms and Abbreviations

a	Loading Plate Radius
BAEM	Boreal Aspects of Ensured Maneuver
CBR	California Bearing Ratio
d_o	Deflection at the Center Geophone
E	Elastic (Young's) Modulus
E_o	Elastic Modulus from the Center Geophone
CRREL	Cold Regions Research and Engineering Laboratory
ERDC	U.S. Army Engineer Research and Development Center
f	Contact Stress Distribution Factor
FHWA	Federal Highways Administration
FWD	Falling Weight Deflectometer
GSL	Geotechnical and Structures Laboratory
ISM	Impulse Stiffness Modulus
KRC	Keweenaw Research Center
LWD	Light Weight Deflectometer
μm	Micrometer
NATC	Nevada Automotive Test Center
PDA	Personal Data Assistant
ν	Poisson's Ratio
σ_o	Stress under the Loading Plate

Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic inches	1.6387064 E-05	cubic meters
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
hectares	1.0 E+04	square meters
inches	0.0254	meters
kip	0.4536	tonnes
microns	1.0 E-06	meters
mils	0.0254	millimeters
pounds (force)	4.448222	newtons
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms

1 Introduction

1.1 Background

The Light Weight Deflectometer (LWD) is a portable version of the larger, typically trailer-mounted, falling weight deflectometer (FWD). The LWD was originally developed to estimate the in situ stiffness modulus of soils and is typically used for quality control and quality assurance and structural evaluation of mechanically compacted earthwork and pavement layers (Senseney and Mooney 2010). With its proprietary software, LWD-Mod, the LWD is used to backcalculate the soil elastic modulus for known one- and two-layer stratigraphy from the deflection data measured by up to three geophones (seismic transducers).

1.2 Objectives

As part of the U.S. Army Engineer Research and Development Center (ERDC) 6.2 Boreal Aspects of Ensured Maneuver (BAEM) Applied Research Program implemented by the ERDC Cold Regions Research and Engineering Laboratory (CRREL), the LWD was used in conjunction with several other test methods to evaluate various groomed snow and ice surfaces representative of what may be found in northern climates during winter. The other test methods included field California Bearing Ratio (CBR), 0.5 and 2.25 kg Clegg Impact Hammers, and several snow penetrometers. The goal was to establish a suite of tools to characterize snow surfaces when evaluating vehicle mobility in cold climates. The LWD is not usually operated on snow or ice surfaces as it is used more typically as a construction or pavement layer (i.e., base course, subbase, or subgrade) evaluation tool and, in cold climates, those activities are usually during the summer construction season.

1.3 Approach

This report documents the use of the LWD at the Nevada Automotive Test Center (NATC) in West Yellowstone, Montana, and at Michigan Tech University's Keweenaw Research Center (KRC) in Calumet, Michigan, during the BAEM winter 2018 field campaign. It also discusses our initial analysis of the LWD deflection and load data and the parameters that can be calculated from that data. These data will be used for statistical analyses to compare the LWD measurements with those of the other strength tests

performed under BAEM. Those tests were the field California Bearing Ratio, Rammsonde penetrometer, Russian Snow Penetrometer, and the Clegg Impact Hammer. That analysis is included in a forthcoming Shoop et al. report.*

* S. A. Shoop, W. L. Wieder, B. C. Elder, S. A. Beal, and E. J. Deeb, *Snow Mechanical and Spectral Characterization* (Hanover, NH: U.S. Army Engineer Research and Development Center, forthcoming).

2 BAEM LWD Program

The two BAEM field campaigns in January and February of 2018 used the LWD on snow and ice surfaces. The snow surfaces varied greatly both in the way they were groomed and compacted and in the variety of vehicles that traversed the surfaces daily. The same is true of the ice surfaces and their preparation and vehicle traffic.

Specifics of the history or evolution of the surfaces, with regard to specific grooming equipment, the dates operated, number of passes, etc., are not available. Most surfaces were groomed daily, and some were exposed to vehicle traffic prior to our measurements. However, in Michigan, a general description of their surface preparation protocol is as follows (Russ Alger, Michigan Technical University, pers. comm., 10 October 2018):

First, in early winter, we try to get the ground frozen as deep as possible before starting to compact the snow. This can involve plowing off any snowfall to eliminate insulation. For this we use a grader, end loader, plows on pickups, and road commission sized plow trucks. Once the ground is sufficiently frozen, we start to pack each snowfall with packers that are essentially snowmobile trail groomers. Once the road system is smooth, we start to pack with rubber tired rollers pulled behind pickups. If the snow gets deep from a single storm, some or all of it is plowed off using the grader and big plows and the packing resumes.

Both test sites have heavy usage by a variety of military and civilian commercial vehicles (i.e., tractor trailers) and standard cars and trucks as part of their respective winter test programs.

2.1 BAEM field campaigns

2.1.1 Montana

The first test program took place 24–31 January at NATC in West Yellowstone, Montana (Figure 1 and Figure 2). Appendix A provides additional views of the test areas. The West Yellowstone Airport property is leased from the Montana Department of Transportation Aeronautics Division for winter testing. The airport is closed to air traffic, with the exception of

emergency rescue helicopters, during the winter. The Montana site provided virgin snow, groomed snow, and trafficked snow surfaces over asphalt concrete pavements and natural subgrade.

In Montana, we, the BAEM team, ran the LWD on the following surfaces:

- Bare taxiway asphalt concrete pavement
- Cleared/groomed snow over natural subgrade
- Groomed snow over taxiway asphalt concrete pavement
- Groomed snow over runway asphalt concrete pavement
- Ice

The Montana testing included a variety of configurations and experimentation with the LWD as we determined the best way to operate the LWD on snow and ice and under the cold and dark conditions presented in the field. As testing proceeded, various aspects of the operations and equipment resulted in an evolution of the test procedure to optimize use in these conditions.

Figure 1. Montana LWD test points plotted on summer imagery that shows pavement surfaces at West Yellowstone Airport, Montana.



Figure 2. Montana test points plotted on winter imagery taken at the time of the field campaign.



2.1.2 Michigan

The second test program took place 19–23 February at KRC in Calumet, Michigan (Figures 3–5). Again, additional views of the test areas are provided in Appendix A. The site has an extensive set of snow and ice surfaces used for a variety of industry, private, and military vehicle and tire testing. The facility operates on 364 hectares (900 acres) near the Houghton/Hancock Airport.

In Michigan, the LWD was run on the following surfaces:

- Groomed snow over natural subgrade
- Groomed snow over gravel, both pads and roads
- Groomed snow over asphalt concrete pavement
- Ice over asphalt concrete
- Ice over gravel

The Michigan testing used the LWD configurations developed during the Montana testing.

Figure 3. Schematic of the Michigan test site.

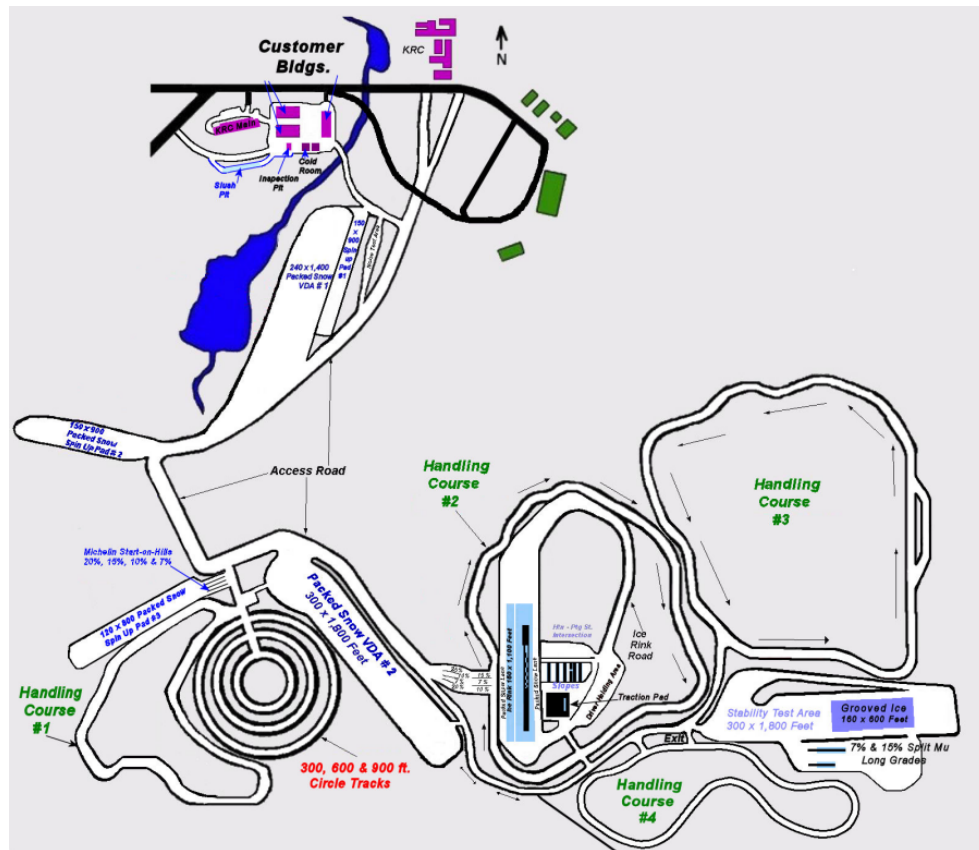
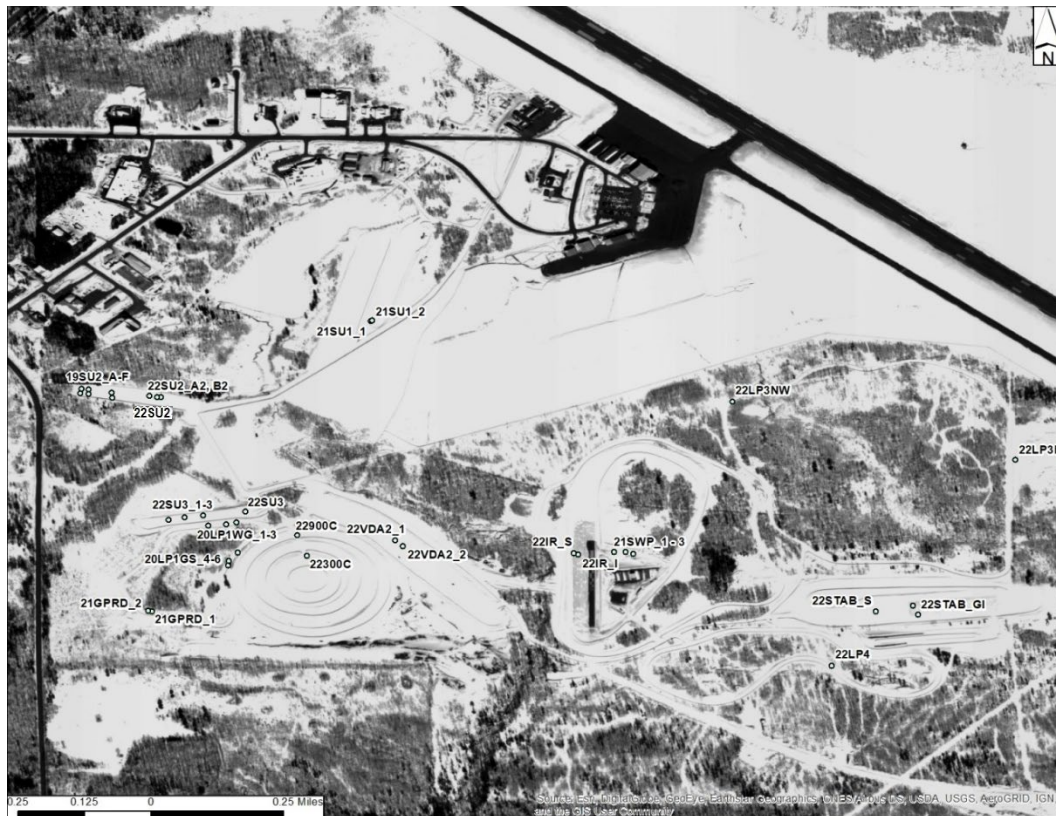


Figure 4. Michigan test points plotted on summer imagery to show ground surfaces.



Figure 5. Michigan test points plotted on winter imagery.



2.2 LWD basic operation

The Dynatest 3031 LWD consists of a weight package dropped from increasing heights along a guide rod. The weight makes contact with a rubber buffer, transferring the load to the soil surface via a 150 or 300 mm (5.9 or 11.8 in.) diameter loading plate. The surface response from the load impact generates a vertical deflection measured (through integration of velocity) by up to three geophones, one located at the center of the loading plate and two optional geophones that may be installed offset radially beyond the edge of the plate. Using the LWD to measure surface deflections is covered under ASTM E2583-07 (ASTM 2015).

The LWD weighs about 22 kg (48.5 lb) with the standard 10 kg (22 lb) drop weight installed. Two additional 5 kg (11 lb) weights may be added to produce higher loads. For the purposes of this report, the 10 kg (22 lb) load package will be referred to as light, 15 kg (22 lb) as medium, and the full 20 kg (44 lb) weight package as heavy.

Dynatest advises that “the LWD is best suited for use on unbound materials such as gravel or sand because of their typically low static pressure.”

Dynatest further advises that “the LWD is not suited to measure bound layers such as asphalt and Portland cement concrete because it cannot apply enough force to make accurate measurements” (Dynatest 2006a).

Dynatest suggests that the center deflections measured during testing soils and aggregate layers should be in the range from 300 to 2200 μm (11.8–86.6 mils), preferably in the range from 500 to 1500 μm (19.7–59.1 mils) (Dynatest 2006b). However, the LWD geophones have a range of 0–2200 μm (0–87 mils) (Dynatest 2006a); therefore, readings as low as 25 μm (1 mil) are valid for research applications such as the BAEM testing

Table 1 provides Dynatest’s recommended preferable range of average contact stress levels during testing (Dynatest 2006b).

Table 1. LWD testing stress level ranges.

Test Surface	Contact Stress Level
Granular base layers	200–300 kPa (29.0–43.5 psi)
Subbase layers	100–200 kPa (14.5–29.0 psi)
Soil subgrades	50–100 kPa (7.2–14.5 psi)
Soft subgrades	10–60 kPa (1.5–8.7 psi)

Senseney and Mooney (2010) explain further that the 100–200KPa (14.5–29.0 psi) stress level mimics the approximate stress level caused by ground vehicle loading on the pavement surface on a typical subgrade, subbase, or base course.

The BAEM standard LWD test sequence involves dropping the weight package four times at each of four different drop heights, producing four different load levels, for a total drop sequence of 16 drops. Tables 2 and 3 provide the drop heights typically used.

Table 2. LWD drop heights for the light load package, 10 kg (22 lb).

Load Level	Drop Height
1	15 cm (6 in.)
2	30 cm (12 in.)
3	46 cm (18 in.)
4	61 cm (24 in.)

Table 3. LWD drop heights for the heavy load package, 20 kg (44 lb).

Load Level	Drop Height
1	30 cm (12 in.)
2	46 cm (18 in.)
3	61 cm (24 in.)
4	76 cm (30 in.)

These heights can be adjusted during testing based on the load and deflection levels displayed on the LWD's personal data assistant (PDA). Drop height adjustment would most typically occur when there was a significant change in surfaces, such as from asphalt to groomed snow or groomed snow to ice.

The deflection and loading data recorded by the LWD is available in real time during testing from the LWD PDA (Figure 6). This allows the operators to make some subjective determinations about the quality of the load and deflection waveforms the LWD is reading. Things like magnitude of the signal, indicating appropriate loading levels; smoothness of the curve; offsets of the end of the signal, indicating compaction, may be assessed and evaluated on-site. When waveforms were irregular, additional drops were added to the sequence. Section 3.1 discusses irregular waveforms further.

Figure 6. LWD operation in Michigan. The LWD unit and the first operator are on the *right*, and the second operator with the PDA is to the *left*.

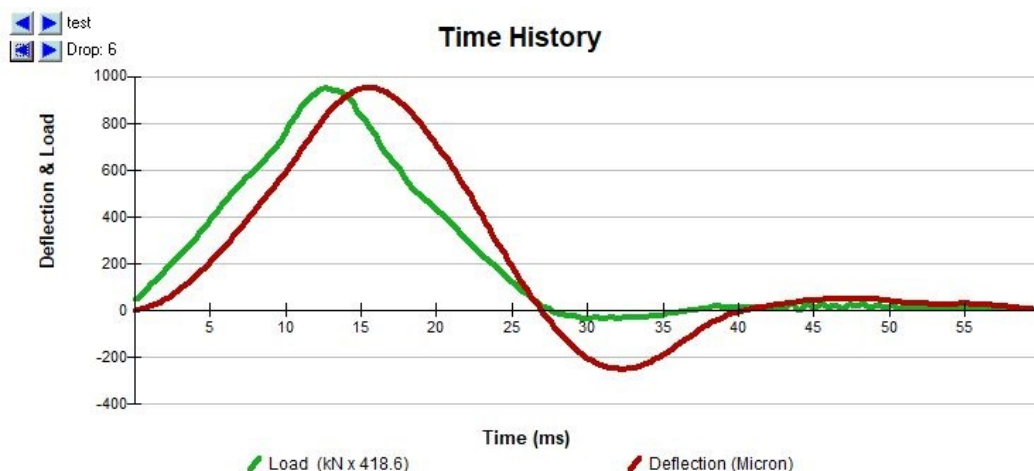


At the end of each test day, the raw data files from the LWD PDA were downloaded to a laptop computer.

Figure 7 illustrates an example of load and deflection data curves similar to those identified as ideal in the Dynatest LWDMOD manual (Dynatest 2006b): smooth bell curves that both return to zero after the load drop is complete. Figure 7 is similar to the display on the PDA. Identifying anomalous readings allows the operator to make additional test drops at a specific load level to ensure sufficient data for analysis.

The return of the deflection reading to zero after the load drop is important. The difference between the start and end level of the deflection curve is called the offset. Offset indicates either compaction of the material or transverse movement of the sensor due to impact. Dynatest recommends “Drops with negative Offset (the deflection curve settles below zero), and drops with significantly odd shapes should be removed” (Dynatest 2006b). Section 3.1 contains figures illustrating the deflection offsets measured during the BAEM LWD testing.

Figure 7. Example of a normal data curve for an LWD test.



The LWD may be run in several different configurations, with regard to the following:

- Plate size—The LWD has two plate sizes, 150 mm and 300 mm diameter (5.9 in. and 11.8 in.). Dynatest recommends the larger loading plate for softer soils (Dynatest 2006a).

- Weight package—Additional weights may be added to the LWD to provide additional loading. The three possible weight packages are light, 10 kg (22 lb); medium, 15 kg (33 lb); and heavy, 20 kg (44 lb).
- Geophones—One geophone is centered in the loading plate (mounted through an annulus in the center of the plate); the other two are external and, when used for this project, were located 305 and 610 mm (12 and 24 in.) from the center of the plate as recommended by Senseney and Mooney (2010) for unbound materials. The geophones reported deflection in mils. The LWD tests performed for the BAEM program had at least 16 drops per test point. When using the two external geophones, they were placed so that they made good contact with the test surface.
- Center plug—At the center of the loading plate is an annulus hole through which the center geophone makes contact with the testing surface. For softer soil materials, Dynatest (2006a) recommends using the screw-in plug provided. With the plug in, the center geophone reads the deflection of the plate as opposed to the ground surface (Figure 8).
- Rubber mat—Dynatest provides a 300 mm (11.8 in.) diameter rubber mat to help level and seal the LWD on the ground surface. The mat is used with both LWD plate sizes; a 150 mm (5.9 in.) mat is not provided. In some cases, the mat may be omitted, such as when testing soft soils with the center plug in place (Dynatest 2006a).

Figure 8. Dynatest LWD with the center plug in (*left*) and out (*right*) with the center plate geophone extending through the loading plate annulus.



3 Field Results and Observations

BAEM LWD test points, such as 19 RWY0, are labeled as follows. The first two numbers indicate the testing date, such as 19 January. The next three or four letters indicate the surface type or location, such as runway. The final numbers or letters are a descriptor of the point on the surface. During the actual testing, different names may have been given to test points. The naming convention was harmonized during the data transcription and preanalysis processing to ensure the correct data was attributed to the correct test point. (Note that images of the raw data from the equipment may still reflect the names given in the field [i.e., figures in section 3.1 and 3.2]). For the test points on the runway and taxiway in Montana, arbitrary point labels of 0, 50, and 100 were set in the field and paced off to be approximately 50 ft (15 m) from each other. Tables 4 and 5 list the test points with the date of testing; approximate local time; and a description of the test point, ground surface, and snow surface at the time of each test. Weather data for the field campaigns is provided in Appendix B.

In Montana, some testing days started at 22:00 and went into the morning of the next day. For these points, the two-digit date designator was the date that testing started. Therefore, some points with designator “25” were actually tested during the early morning hours of 26 January.

3.1 Montana

As discussed in section 2, on the first day of the field program in Montana, the LWD was tested in different configurations (i.e., different weight packages, loading plate sizes, and geophone configurations) on the surfaces of most interest: groomed snow over bare ground and groomed snow over asphalt concrete pavement (Figure 9). We also took an opportunity to test bare asphalt concrete pavement that was still available. After this first day, the bare pavement was covered by new snowfall.

Table 4. Montana LWD test-point details.

Test Point	Date	Approx. Local Time	Description	Ground Surface and Subgrade Soil	Snow Surface
24TWYS_AC	1/24/2018	15:40	Taxiway, south end	Asphalt concrete	None
24TWYS_G	1/24/2018	16:30	Taxiway, off pavement south end	Minimally maintained, leveled terrain over obsidian sand	Groomed snow
24TWYS	1/24/2018	16:45	Taxiway, south end	Asphalt concrete	Groomed snow
25RWY0	1/25/2018	22:00	Runway, north end—point 0	Asphalt concrete	Groomed snow
25RWY50	1/25/2018	22:15	Runway, north end—point 50	Asphalt concrete	Groomed snow
25RWY100	1/25/2018	22:30	Runway, north end—point 100	Asphalt concrete	Groomed snow
25RWY100_R1	1/25/2018	22:30	Runway, north end—adjacent to 25RW100	Asphalt concrete	Rutted groomed snow
25RWY100_R2	1/25/2018	22:30	Runway, north end—adjacent to 25RW100	Asphalt concrete	Rutted groomed snow
25TWY0	1/26/2018	3:10	Taxiway, north end—point 0	Asphalt concrete	Groomed snow
25TWY50	1/26/2018	3:00	Taxiway, north end—point 50	Asphalt concrete	Groomed snow
25TWY100	1/26/2018	2:45	Taxiway, north end—point 100	Asphalt concrete	Groomed snow
25TWY100_R1	1/26/2018		Taxiway, north end—adjacent to 25TWY100	Asphalt concrete	Rutted groomed snow
25TWY100_R2	1/26/2018		Taxiway, north end—adjacent to 25TWY100	Asphalt concrete	Rutted groomed snow
26IL0	1/26/2018	22:20	Ice lane	Asphalt concrete	Ice
26IL50	1/26/2018	22:30	Ice lane	Asphalt concrete	Ice
26IL100	1/26/2018	22:45	Ice lane	Asphalt concrete	Ice
29RWYC	1/29/2018	10:45	Runway, center	Minimally maintained, leveled terrain over obsidian sand	Groomed snow
31RWYC	1/31/2018	5:45	Runway, center	Minimally maintained, leveled terrain over obsidian sand	Groomed snow
22STAB_GI1-3	2/22/2018	15:00	Stability Test Area, grooved ice—points 1 through 3 (additional LWD tests with outer geophones)	Grass over Stability soil (well-graded sand/silty sand)	Grooved ice

Table 5. Michigan LWD test point details.

Test Point	Date	Approx. Local Time	Description	Ground Surface and Subgrade Soil	Snow Surface
19SU2_A-F	2/19/2018	10:45–11:40	Spin Up Pad 2—points A through F	Grass over Rink natural soil (silty sand)	Fresh over groomed snow
20LP1WG_1-3	2/20/2018	10:00	Loop 1* (washed gravel subgrade—points 1 through 3)	Compacted road gravel	Freezing rain and fresh snow over groomed snow
20LP1GS_4-6	2/20/2018	13:00	Loop 1 grass subgrade—points 4 through 6	Grass over Rink natural soil (silty sand)	Freezing rain and fresh snow over groomed snow
21SWP_1-3	2/21/2018	8:00	Sweeper parking pad—points 1 through 3	Grass over Rink natural soil (silty sand)	Fresh over groomed snow
21SU1_1, 2	2/21/2018	13:00	Spin Up Pad 1—points 1 and 2	Compacted road gravel	Groomed snow
21GPRD_1, 2	2/21/2018	14:00	Loop 1 road adjacent to gravel pad—points 1 and 2	Compacted road gravel	Groomed snow
21SU2_A2, B2	2/21/2018	15:00	Spin Up Pad 2—points A2 and B2 (farther west of original 2/19 point A)	Grass over Rink natural soil (silty sand)	Groomed snow
22SU3_1-3	2/22/2018	8:00	Spin Up Pad 3—points 1 through 3	Compacted road gravel	Groomed snow
22SU2	2/22/2018	11:45	Spin Up Pad 2—near 21SU2_B2 (farthest west)	Grass over Rink natural soil (silty sand)	Groomed snow
22SU3	2/22/2018		Spin Up Pad 3 at the top of the sloped roads	Compacted road gravel	Groomed snow
22LP3E	2/22/2018	12:10	Loop 3 east	Compacted road gravel	Groomed snow
22IR_I	2/22/2018	12:25	Ice Rink, ice surface	Grass over Rink natural soil (silty sand)	Ice
22IR_S	2/22/2018		Ice Rink, snow surface	Grass over Rink natural soil (silty sand)	Groomed snow
22STAB_S	2/22/2018	12:35	Stability Test Area, snow—points 1 and 2	Grass over Stability soil (well-graded sand/silty sand)	Groomed snow
22STAB_GI	2/22/2018		Stability Test Area—grooved ice	Grass over Stability soil(well-graded sand/silty sand)	Grooved ice
22VDA2_1, 2	2/22/2018	12:50	Vehicle Dynamics Area 2—points 1 and 2	Grass over Rink natural soil (silty sand)	Groomed snow
22900C	2/22/2018		900 ft circle—points 1 and 2	Compacted road gravel	Groomed snow
22300C	2/22/2018	13:00	300 ft circle—points 1 and 2	Compacted road gravel	Groomed snow
22LP4	2/22/2018	14:30	Loop 4—points 1 and 2	Stability soil (well-graded sand/silty sand)	Groomed snow
22LP3NW	2/22/2018	14:50	Loop 3 northwest—points 1 and 2	Compacted road gravel	Groomed snow
22STAB_GI1-3	2/22/2018	15:00	Stability Test Area, grooved ice—points 1 through 3 (additional LWD tests with outer geophones)	Grass over Stability soil (well-graded sand/silty sand)	Grooved ice

*Loop 1, 2, 3, and 4 are the BAEM designations for the Handling Courses depicted in Figure 3.

Figure 9. Initial LWD tests on groomed snow over an unpaved ground surface.



We made the following observations during these preliminary LWD tests:

- The smaller plate (150 mm [5.9 in.] diameter) produced a deeper impression (Figure 10) in the snow after testing than the larger plate (300 mm diameter [11.8 in.]), indicating larger plastic deformation of the snow surface under the higher contact stress delivered by the smaller-area plate.
- The heavier weight package, which was added when we began testing on the bare asphalt pavement surface, was too heavy for groomed snow (loads of 8.1, 11.0, 14.2, and 17.1 kN [1820, 2472, 3192, and 3844 lb-f]). In groomed Montana snow, the heavy weight pack seated the plate deeper into the surface and produced deflection waveforms that indicated significant plastic deformation, in the form of compaction of the snow surface, as shown by the offset in the deflection waveform (Figure 11). The light weight package (loads of 3.0, 5.3, 6.8, and 8.2 kN [674, 1191, 1529, and 1843 lb-f]) produced more regular deflection waveforms and less permanent deformation in the snow.
- For groomed snow over either pavement or ground, the outer two geophones provided no readings.

Figure 10. Center geophone divot and plate impression left by an LWD test using the 150 mm (5.9 in.) diameter loading plate.

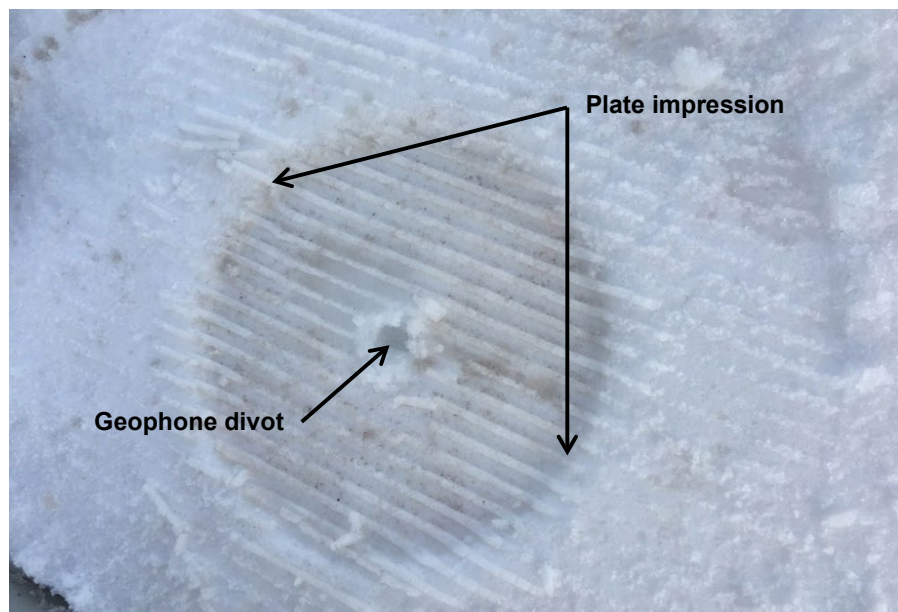
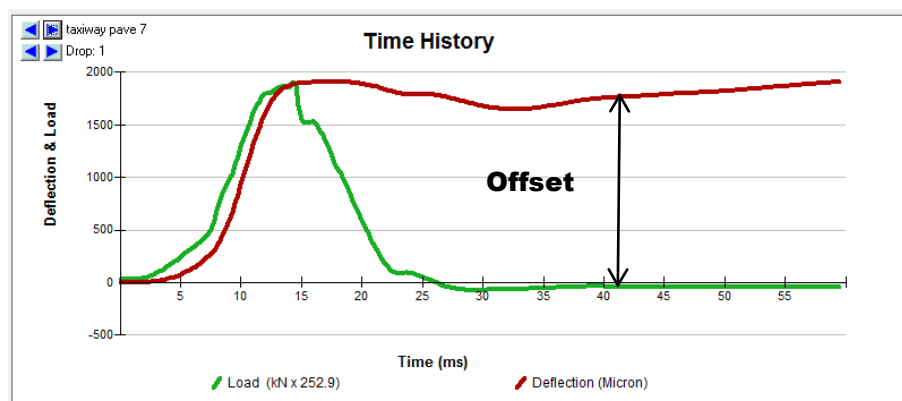
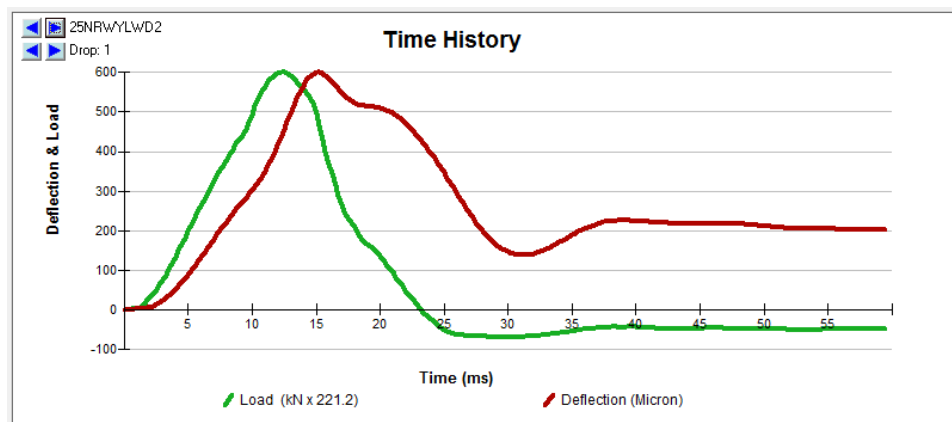


Figure 11. High offset from the first drop of an LWD heavy weight package on groomed snow over taxiway pavement.



- The first drop at the lowest drop height (load level), even with the light weight package, caused the LWD to noticeably seat into the snow (Figure 12); and on each successive first drop at a higher load level, the LWD would seat farther into the snow, indicating further compaction of the snow under the LWD test action.
- If the LWD was run with the plug out of the center of the plate, the geophone would produce a divot in the snow surface (Figure 10).
- We used the rubber matt for most testing as the LWD tended to slide on the groomed snow and ice surfaces.

Figure 12. First drop deflection and load readings showing the deflection offset that indicates compaction or seating of the LWD into the snow.



- During several tests, the LWD PDA recorded very irregular loading and deflection waveforms (Figure 13). There was no obvious cause for these irregularities observed at the time of the testing.
- As the testing progressed, the Teflon ring from the basic drop weight package came loose and would fall as the weight package was lifted back into place. This required the operator to lift the ring and replace it before the next drop.

These observations lead to the selection of the following configuration for operating the LWD on groomed snow surfaces:

- Center plate annular plug in
- 300 mm (11.8 in.) diameter plate
- Rubber mat
- Light weight package
- Center geophone only

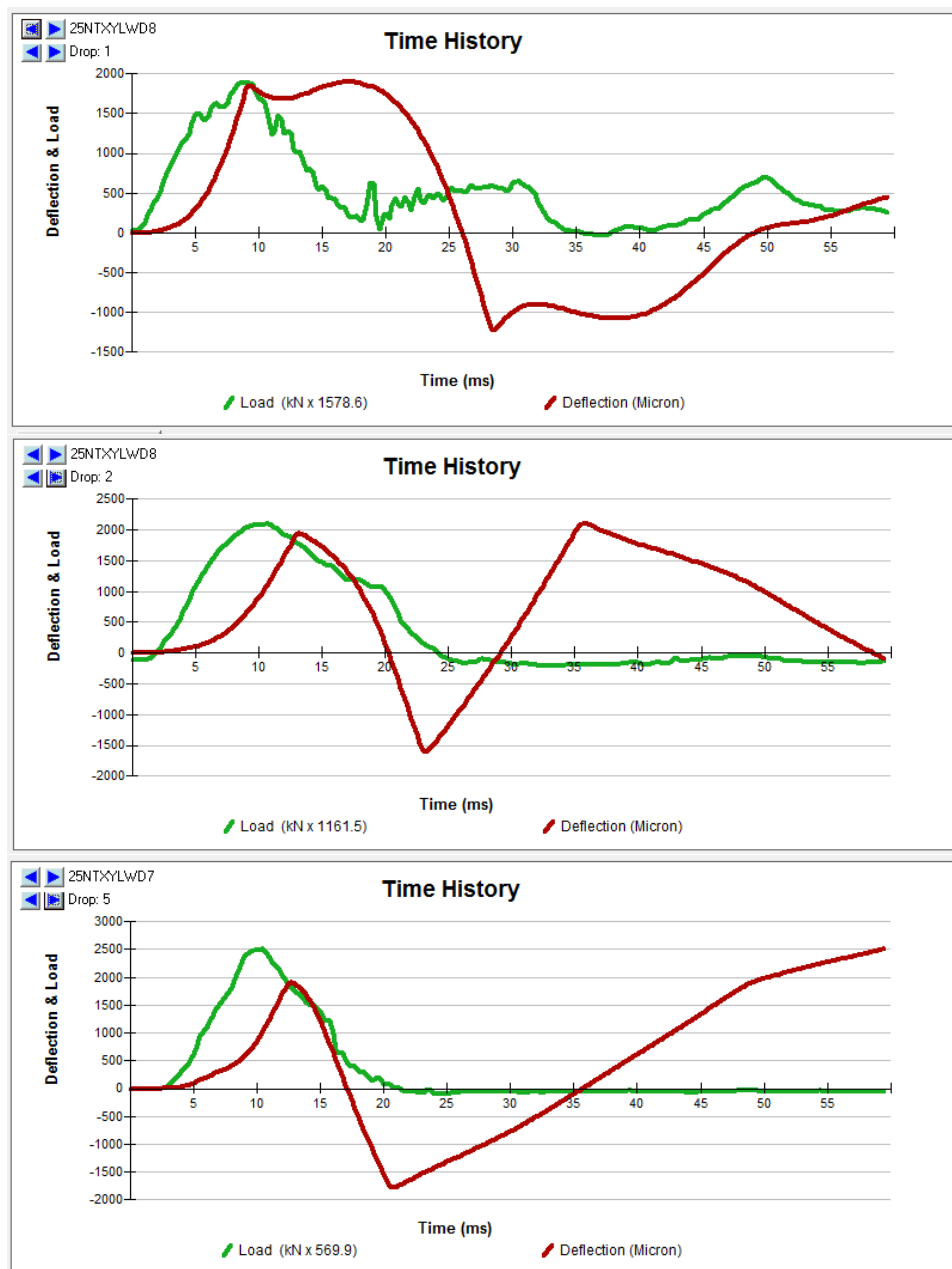
This configuration gave loading levels of around 3.0, 5.7, 7.2, and 9.0 kN (674, 1281, 1619, and 2023 lb-f) at the four drop heights both in Montana and Michigan and was used for the remainder of the testing.

Later in the Montana testing, we used the LWD on an ice lane surface. For this testing, which was more analogous to an asphalt concrete surface, we used the following configuration:

- Center plate annular plug out
- 300 mm (11.8 in.) diameter plate

- Rubber mat
- Light weight package (one point) then the heavy weight package
- All three geophones attached, center geophone as well as the two external geophones

Figure 13. Irregular waveform readings from LWD testing of groomed snow over pavement.

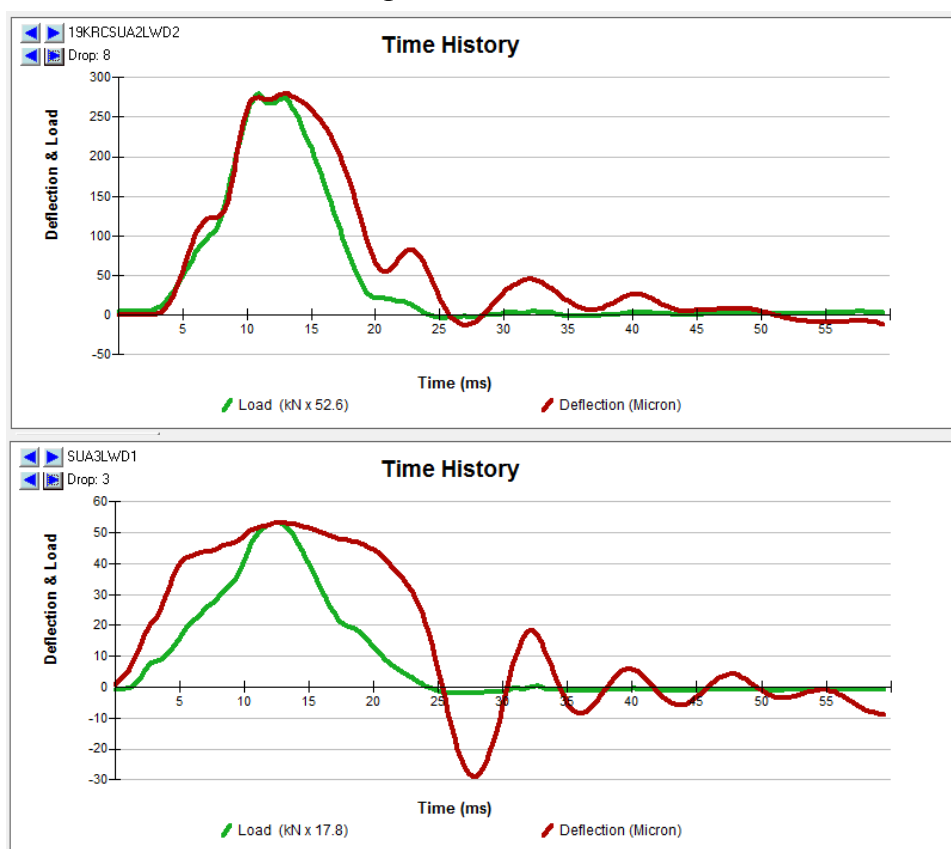


3.2 Michigan

The Michigan testing used the configurations determined earlier in Montana. Various existing prepared snow and ice surfaces at the site were tested. Test points were underlain by natural subgrade, gravel, and pavement, depending on the specific test location (Table 5). In Michigan, the snow surfaces were groomed daily, and traffic was limited on most of the surfaces to preserve surface integrity.

For the Michigan data, in addition to the first drop at each drop height often producing an impression and associated deflection offset, waveforms of subsequent drops indicated stiffer surfaces than those tested in Montana and a tendency for the LWD weight package to bounce because of these stiffer surfaces (Figure 14). At many points, the deflection readings were in the lower range of the LWD geophone, less than the 300 μm (12 mils) lower end testing value suggested by Dynatest (Dynatest 2006b).

Figure 14. Example LWD data waveforms from Michigan—groomed snow over a grass-covered soil.



4 Analysis and Discussion

The Dynatest LWD has a proprietary software package, LWDMOD. With LWDMOD, users may view data files; export the data to other formats; and backcalculate soil stiffness, in terms of elastic modulus, from the LWD deflection data. The LWDMOD software is based on the Dynatest ELMOD program used by the larger FWD for layered-pavement strength analysis. The program backcalculates soil-layer moduli (elastic moduli, E), and can confirm layer thickness (Dynatest 2006b).

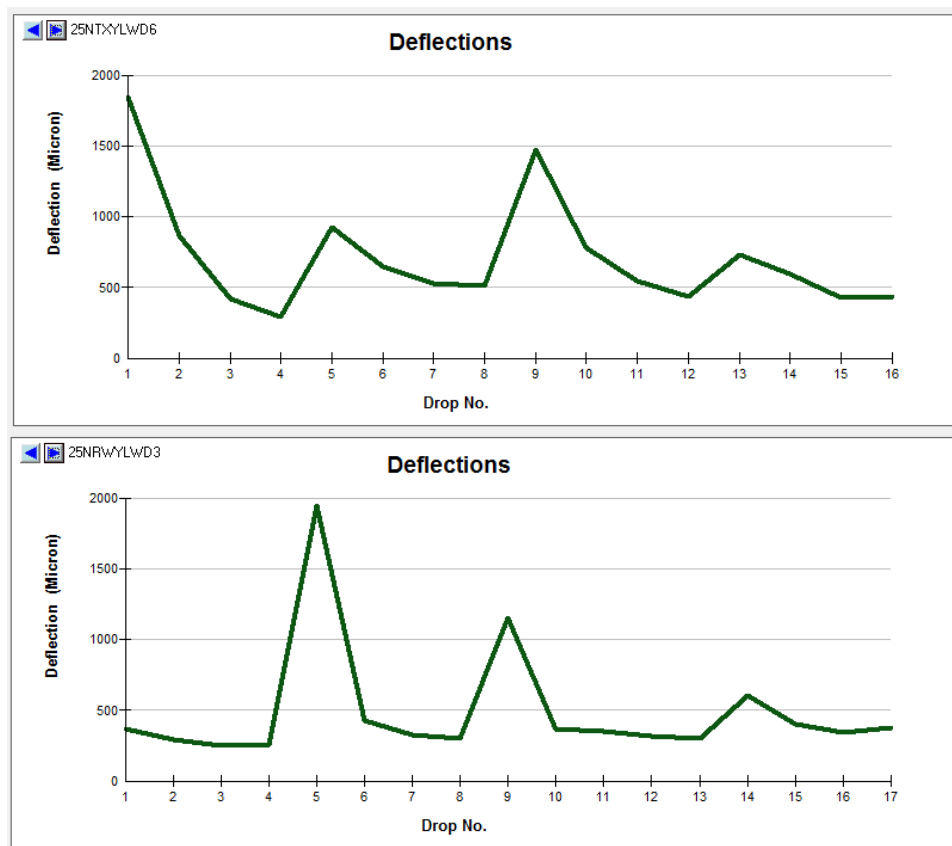
Raw data files from the PDA are imported into LWDMOD for generating reports and backcalculation layer analysis. Importing data from the Montana and Michigan test program generated the following error message multiple times per test file: “Invalid deflection at location: XXXX. Drop: X.” This LWDMOD error message indicates an abnormality of the snow data from standard LWD soil/aggregate test data. The data, however, still transferred into LWDMOD and was available for editing and analysis.

4.1 Deflection data

At some test points, the first drop of the entire testing sequence, drop 1, produced a large deflection (Figure 15, top). In other cases, this was not observed (Figure 15, bottom). The large drop 1 deflection indicates the action of the LWD compacted the snow under the first drop at those points. The lack of a high initial deflection is likely due to one of two possibilities: (1) the snow surface was compacted sufficiently that the first load level of LWD testing imparted no additional compaction, or (2) the operator placed the LWD firmly enough to additionally compact the snow surface.

The first measurement at each additional drop height, drops 5, 9, and 13 in a 16-drop series, also frequently produced an excessive deflection, both at Montana and Michigan, as shown in Figure 15. In both cases, these large deflections at the beginning of the test and at the first drop at each higher load level indicate further compaction of the snow layer under the loading of the LWD.

Figure 15. Large deflections recorded for the first drop at a new load level for each level (*top*) of groomed snow over runway pavement in Montana and for only the second, third, and fourth level (*bottom*) of groomed snow over taxiway pavement in Montana.



After the LWD test sequence was completed and the LWD was picked up and removed from the test point, plate impressions up to 5 cm (2 in.) in depth (i.e., Montana test point 25TWY100) remained at several points (Figure 16). These impressions are additional evidence of the compaction of the snow layer under the LWD test loading.

Figure 17 provides examples of deflection data. The testing in Montana was on groomed snow over asphalt concrete pavement. In Michigan, the data is for groomed and compacted snow surfaces over a variety of ground surfaces. Both sites had a variety of vehicles trafficking the snow surfaces. Note that the deflections from Michigan were significantly lower than the deflections measured at Montana, and the LWD did not show as high initial deflections at each new drop height as seen in Montana. Both of these indicate that the snow surfaces, or the composite snow/aggregate/ground systems, at Michigan were stiffer, in terms of LWD response, than those tested at Montana.

Again, note the higher deflections at drops 1, 5, 9, and 13, indicating compaction of the snow layer under the action of the LWD test.

For the testing on the ice surfaces at Michigan, the resulting deflections were very low as shown in Figure 18. The LWD was in the same configuration as for the groomed snow testing, specifically with the light weight package and the center plate plug in. The first drop at each height did not produce larger deflections.

The magnitude of the ice surface deflections is similar to those of several of the Michigan snow surfaces. This is unexpected as ice surfaces intuitively should be much stiffer than groomed snow. One possible explanation is that the LWD was not in as good a contact with the ice surfaces as with the snow. It should also be noted that, on the ice surfaces, the higher weight package may be more appropriate. The heavy weight package was used on an ice surface in Montana; however, those tests were conducted with the center plug removed from the LWD plate. Review of that data indicates that either the center geophone was stuck or not in good contact with the ice surface, resulting in poorly shaped deflection waveforms and unreasonably low values for those deflections. Because of these issues with the data from the ice surfaces, this report will not discuss these data further.

Figure 16. Impression left in the snow surface by an LWD test in Montana.



Figure 17. Unedited LWD deflection data for groomed snow over runaway and taxiway asphalt concrete pavement in Montana (*top*) and various surfaces in Michigan (*bottom*).

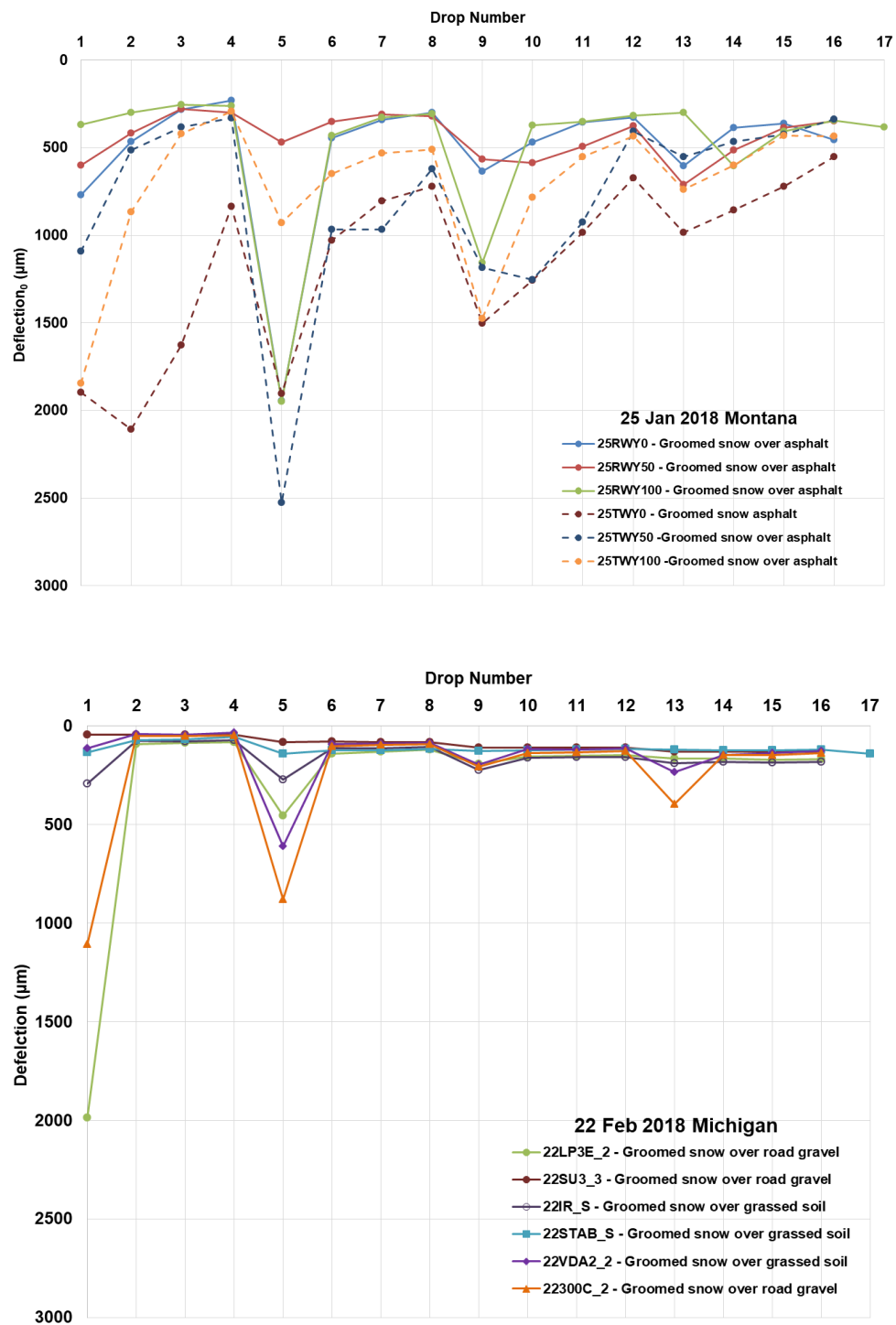
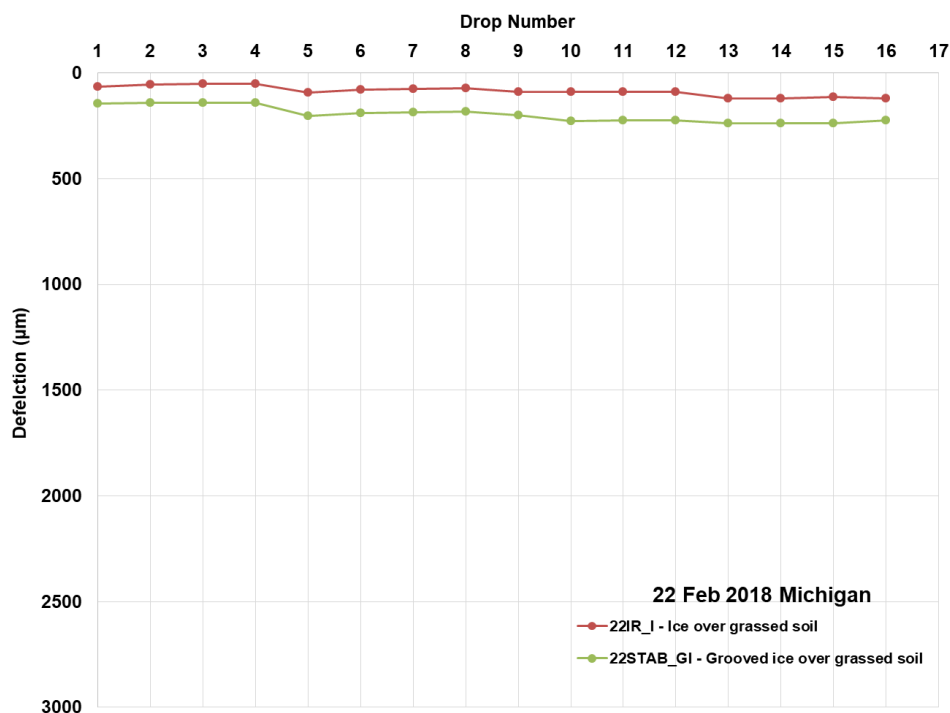


Figure 18. Unedited LWD deflection data for Michigan ice surfaces.



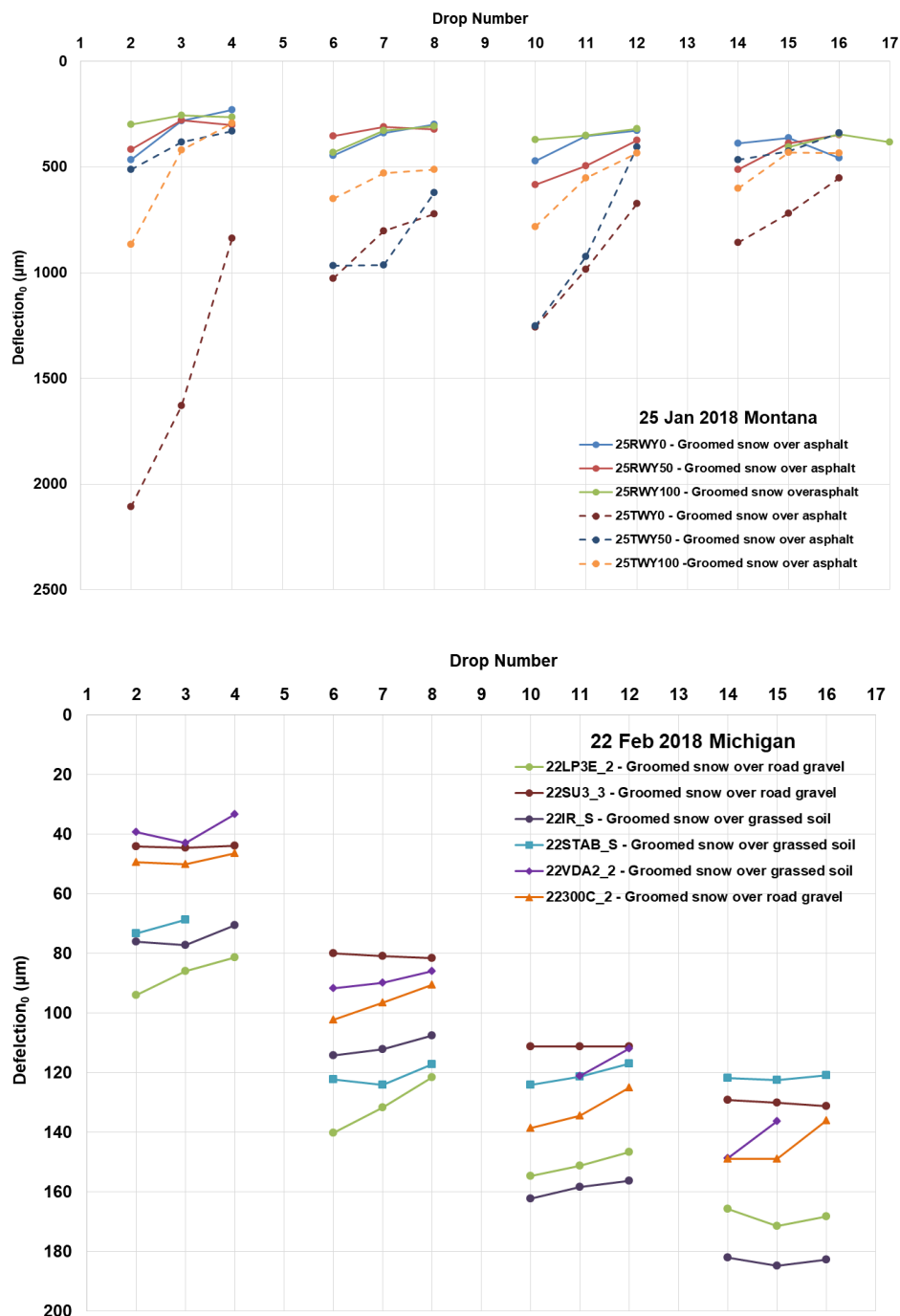
Removing the large deflection values for the first drop at each height, and several other deflection values with anomalous waveforms as defined by Dynatest and recommended in the LWDMOD Program Guide (Dynatest 2006b), provides a clearer picture. The edited data would also most likely produce better results in the LWDMOD backcalculation analysis. Figure 19 shows examples of the edited data. These graphs make it very clear that the deflections measured in Michigan were about 80% lower than those measured in Montana.

A different approach to the data from the first drop of the LWD test sequence is that it may best represent the condition of the snow that a vehicle or aircraft might encounter for mobility purposes. That the properties of the snow surface captured by the first drop of the LWD best characterize the surface is something to consider but is a very transitive state as the surfaces we tested had already been groomed, and many had received vehicle traffic. A consideration of what compaction state we want to evaluate is needed.

Finally, we should note that ASTM E2583-07 includes the following estimates for single operator, single equipment coefficient of variation in deflection measurements for typical field conditions: 10% to 20% for gravels, 15% to 35% for sands, and 40% to 60% for silts and clays with liquid limits less

than 50% (ASTM 2015). It follows that these variations would affect any other parameter calculated from the deflection data (i.e., modulus and ISM). Mazari et al (2013) and McLain et al. (2018) discuss further the LWD's variability. Therefore, future use of the LWD needs to consider if the variation in measurements on these snow surfaces is from the snow or the LWD itself.

Figure 19. LWD deflections from Montana (*top*) and Michigan (*bottom*) with the first deflection at each load level removed. Note the deflection scale change for Michigan data.



4.2 Stress levels

Table 6 gives the contact pressure, or contact stress, levels of military vehicles and aircraft of interest in the BAEM study. Table 6 also shows the average stress levels achieved by the LWD for the Montana and Michigan field-testing. From the table, it is obvious that the LWD is capable of delivering comparable contact stress levels to several of the vehicles listed. Lower drop heights would enable the LWD to deliver lower stress levels than those obtained here. The LWD values also fall within the ranges for testing subbase layers, soil subgrades, and soft subgrades suggested by Dynatest as discussed in section 2.2 (Dynatest 2006b).

For aircraft of interest in BAEM, the C-130 and C-17 have contact pressures that are above those obtained with the LWD during this testing. Using the higher weight package could produce this stress level but would probably result in significant compaction of the snow, especially in the less groomed snow surfaces like those in Montana.

Table 6. Comparison of contact pressures of U.S. military vehicles and aircraft to average contact pressures obtained with the LWD, highlighted in *green*, in Michigan (Michael Parker, CRREL, pers. comm., 7 November 2018).

Vehicle	Aircraft	LWD Drop Height	Contact Pressure kPa (psi)
SUSV			13 (1.9)
BVS 10			19 (2.75)
	LC 130 (ski)		34 (5)
		1	41 (6)
AAV RAM			53 (7.7)
		2	82 (12)
M1A1			97 (14)
M88A2			97 (14)
		3	109 (16)
		4	133 (19)
LAV25A2			179 (26)
MTVR-MK23			193 (28)
MTVR-MK31			200 (29)
LVSF			317 (46)
	C-130		724 (105)
	C-17		1069 (155)

4.3 Load data

During both field campaigns, the LWD was stored in either a heated office trailer or garage. At the start of testing, the LWD was loaded into the back of an open truck to transport it around the site and then transferred to a plastic sled to move between test points.

Sometimes in Michigan, this meant that some LWD tests would take place in the morning within an hour of the LWD coming out of the heated garage and then several hours later after the LWD had been sitting at ambient outside temperature. While in Montana, the LWD testing spanned a much shorter period.

During the processing of LWD data, we noticed that the LWD load varied between the morning and afternoon tests (Figure 20) even though the weight package and the drop heights were not changed. The air temperature on this day of testing increased only slightly from -1.1°C (30°F) in the morning to -0.4°C (31.2°F) in the afternoon.

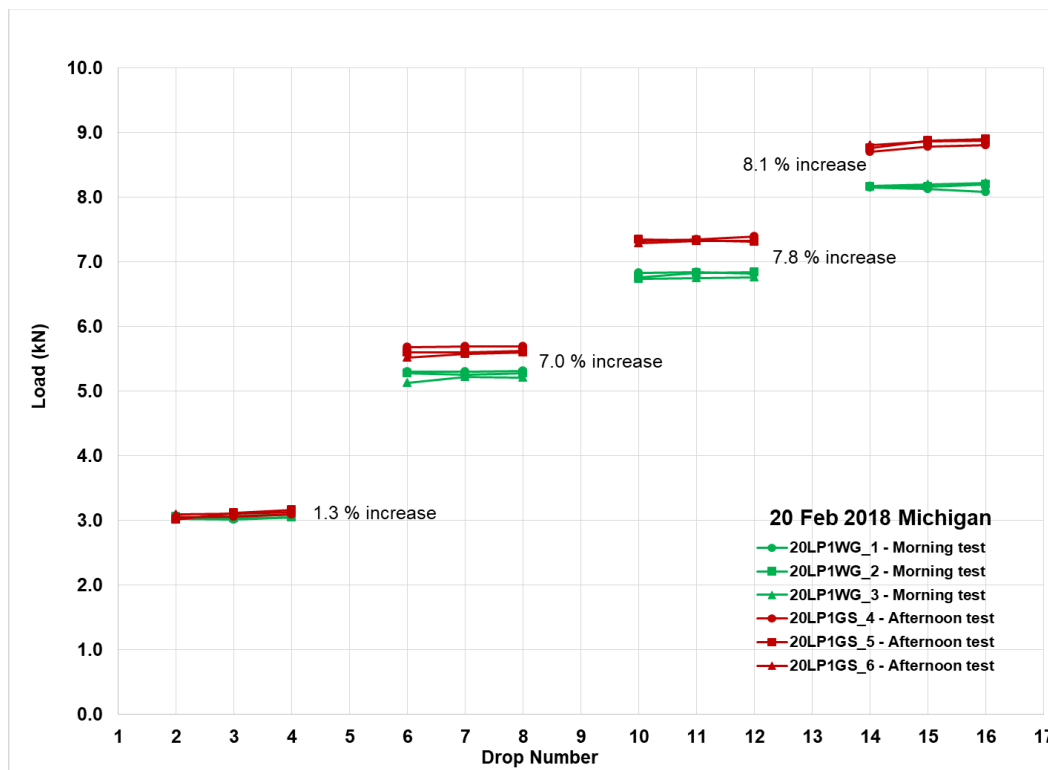
The cause of this load change is a temperature sensitivity in the LWD electronics or a change in the mechanical properties of the LWD components, such as the rubber buffers on the LWD. Other researchers have reported on the change in load associated with a change in stiffness of the LWD's buffers (Vennapusa and White 2009; Adam and Kopf 2004; and Siekmeier et al. 2009).

The Minnesota Department of Transportation addresses this issue as follows: "LWD devices should not be used when the temperature falls below 5 degrees Celsius (41 degrees Fahrenheit) to ensure the device's components, particularly the rubber buffers, work as intended" (Siekmeier et al. 2009).

For the larger FWD the Federal Highways Administration's (FHWA) FWD manuals indicate that

changes in the temperature of the rubber buffers on the FWD cause the measured load to change over the test period even though the distance the weight falls is the same. Typically, the rubber buffers increase in temperature when testing, which results in a decreased applied load, because the buffers are less stiff (FHWA 2000).

Figure 20. Load levels recorded by the LWD in Michigan, indicating a change in loading conditions between morning and afternoon tests.



The FHWA recommends that FWD operators need to minimize these variations by conditioning as follows the buffers prior to testing (Schmalzer 2006):

- Standard buffer warm-up sequence (in ambient temperatures above 10°C [50°F]): One drop at each of the first three drop heights, and then four drops at height 4; repeated eight times (a total of 56 drops).
- Cold-weather buffer warm-up sequence (in ambient temperatures below 10°C [50°F]): drop height 1 repeated 32 times, followed by the standard buffer warm-up sequence (a total of 88 drops).

The procedure suggested by the FHWA is not likely to be applicable to testing with the LWD in below-freezing temperatures. It seems more logical that the buffers would need to be kept at a constant cold temperature, or in a range of cold temperatures, to ensure they had the same stiffness and thus were delivering the same load throughout a given test program.

4.4 Surface deflection modulus

Once the data from the LWD PDA is downloaded to a computer, the data may be imported into LWDMOD. From there, the data may either be edited and analyzed with LWDMOD or exported into Excel or Word. Figure 21 shows the Excel version of the data from one test point at Montana. It is interesting to note that, for this test point, geophones 2 and 3 were not connected to the LWD, and yet a value for “Def. 2” (the deflection measured by the second geophone) is given. This could be misleading if the data is analyzed by someone who did not know that outer two geophones were not in use.

Figure 21. LWDMOD Excel report.

File:	25NATC v2																
Date:	26. January 2018																
Point	Location	Drop	Time	Radius	Load	Stress	Pulse W.	Dist. 1	Dist. 2	Dist. 3	Def. 1	Def. 2	Def. 3	Eo	Offset	Energy	
No.				mm	kN	kPa	ms	mm	mm	mm	Micron	Micron	Micron	MPa	Micron	Joule	
2	25NRWYLWD2	1	22:14:00	150	2.7	38	21.5	0	305	610	600	4		17	202	1.066	
		2	22:14:23	150	2.8	39	21.75	0	305	610	417	4		25	105	0.665	
		3	22:14:30	150	2.5	36	21.75	0	305	610	278	4		34	78	0.329	
		4	22:14:39	150	2.9	41	22	0	305	610	300	5		36	53	0.406	
		5	22:15:16	150	5.7	81	18	0	305	610	470	4		45	105	1.191	
		6	22:15:26	150	5.6	80	17.75	0	305	610	352	6		60	50	0.756	
		7	22:15:35	150	5.7	81	18	0	305	610	309	4		69	21	0.636	
		8	22:15:50	150	5.7	80	18	0	305	610	321	4		66	61	0.657	
		9	22:16:14	150	7.2	102	15.75	0	305	610	566	4		48	227	2.524	
		10	22:16:24	150	7.2	101	15.25	0	305	610	585	4		46	218	1.872	
		11	22:16:33	150	7.3	104	16.25	0	305	610	494	4		55	180	1.426	
		12	22:16:42	150	7.3	104	16	0	305	610	374	5		73	70	1.028	
		13	22:17:09	150	8.6	122	14.25	0	305	610	709	5		45	340	3.973	
		14	22:17:19	150	8.6	122	14.25	0	305	610	513	6		63	153	1.772	
		15	22:17:29	150	8.9	125	14.75	0	305	610	387	5		85	64	1.276	
		16	22:17:40	150	8.9	126	15	0	305	610	348	4		95	39	0.973	

LWDMOD calculates a surface deflection modulus value, E_0 . E_0 is defined as the weighted mean modulus of the equivalent half-space calculated from the deflection measured at the center geophone using Boussinesq equations (Ullidtz 1987 as cited by Horak 2007). A value is calculated for each drop in the test sequence. The Boussinesq solution determines stresses, strains, and deformations at any location in a homogenous, isotropic, elastic half-space due to a surface point force.

Using the center geophone data, the E_0 (MPa) equation is

$$E_0 = \frac{f(1-\nu^2)\sigma_0 a}{d_0}, \quad (1)$$

where

- f = contact stress distribution factor (2 is used for a uniform stress distribution [default] and $\pi/2$ is used for the rigid case, which may be more correct for cohesive materials),
- ν = Poisson's ratio of the soil (0.35, software default value),
- σ_o = stress under the plate (MPa),
- a = loading plate radius (mm), and
- d_o = the deflection at the center geophone (mm) (Dynatest 2006b).

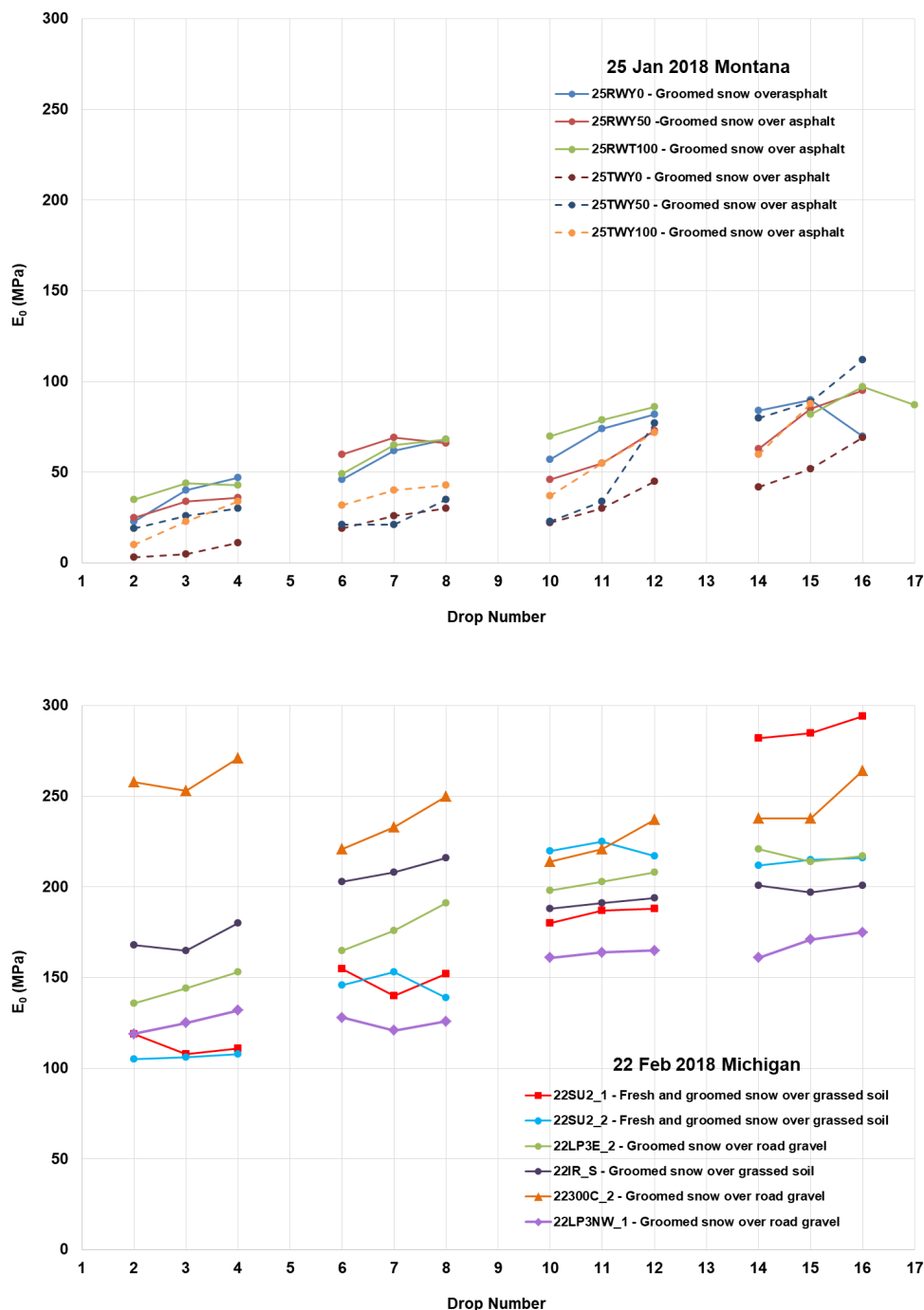
Figure 22 presents two sets of groomed snow E_o values from Montana and Michigan. In each case, data from the first test at each drop height has been deleted. In the case of the Michigan data, there are several other points that have very irregularly shaped waveforms and meet the criteria for deletion as suggested in the LWDMod Program Guide, as shown in Figure 14. They have been left in this data set for this comparison. The E_o data does confirm the relative stiffness of the Michigan packed (or groomed) snow surfaces compared to those at Montana, the calculated E_o being in many cases twice that of the value calculated for the Montana surfaces. This is likely because of differences in grooming needs and methodology.

Figure 22 again indicates that the snow layers are being further compacted by the LWD. The Minnesota Department of Transportation (Siekmeier et al. 2009) notes that the operator may notice that the LWD modulus values increase slightly during successive test drops for a fixed height. They suggest that, if the increase is greater than 10%, it is probable the material is not adequately compacted, or in other words is continuing to be compacted by the LWD. In Figure 22, the E_o value calculated for point 25TWY10 increases 240% during the three measurements at the drop height 1. Point 22LP3E-2 increases 12.55% and 15.8% at drop heights 1 and 2, respectively. These increases indicate the snow is continuing to compact under each additional load drop, and therefore the LWD is measuring a higher modulus value as the test proceeds.

The use of E_o for further comparison of the surface strength, or bearing capacity, of groomed snow over asphalt or soil subgrades is not ideal. The LWDMod software assumes typical pavement structures with stiff layers over soft. Layered systems of snow over asphalt or snow over soil do not fit this assumption. Also, the impressions left behind in the snow after LWD testing indicate that many of the groomed snow surfaces tested

were exhibiting plastic, not elastic, behavior at the compaction levels encountered. Therefore, E_0 , calculated using Boussinesq theory, when analyzed with other measures of snow surface strength, may not provide an accurate comparison.

Figure 22. E_0 values calculated by LWDMod for example groomed snow surface data sets from Montana (*top*) and Michigan (*bottom*) data.



4.5 LWDMod backcalculation

LWDMod may be run for a one-, two-, or three-layer system. Its most typical application is to determine required thickness of overlay material of a given modulus value (i.e., the specified strength of the actual construction asphalt concrete) to restore a pavement system to a required overall strength.

The data from Montana and Michigan were run using the two-layer case to see if LWDMod could refine the modulus values for the different groomed snow layers, given an initial seed modulus value for snow. It is also possible to enter three layers, but backcalculation is only performed on the top layer and the subgrade. In the three-layer case, the entered seed E value of the second layer will be regarded as a fixed value (Dynatest 2006b).

Prior to running LWDMod, data was screened using the LWDMod plot function to remove from the analysis drops with abnormal deflection values, such as the first drop at each load level, and other drops with poor deflection and load waveforms as suggested by Dynatest (2006b) (see Figure 13 and Figure 15). We anticipated that the cleanest data would present the best chance for analysis in the LWDMod program.

For the backcalculation analysis, LWDMod requires that each layer be defined by thickness, modulus, and Poisson's ratio. The thickness and the modulus values of a layer may with be fixed, or set to their actual values, allowing the program to iterate other parameters until a set of values can be found that allows the modulus equation to calculate deflections that most closely fit measured deflection data. In our case, the thickness of the layers, snow, asphalt, and soil were known and therefore fixed. LWDMod was run to see if it could better refine the modulus values from the seed values taken from the literature.

LWDMod was run on selected points where the load and deflection versus time and where the deflection versus drop data indicate the best quality data taken. Three sets of data were used as follows:

- Montana—bare asphalt concrete pavement
- Montana—groomed snow over runway pavement
- Michigan—groomed snow over natural subgrade

4.5.1 Montana—bare asphalt concrete pavement

The bare pavement at the south end of the taxiway was tested in several configurations when investigating the protocol for the LWD on the first day of testing (test point 24TWYSAC). Two configurations gave more typical LWD load and deflection waveforms with time. These were using each plate size with the annular plug removed. All three geophones were attached for this test.

The pavement system was 5.5 in. (140 mm) of asphalt concrete over 180 mm (7 in.) of base course; the subgrade is obsidian sand (Montana Department of Transportation 2015; Morrison Maierle Inc. 2015). Seed modulus values for the asphalt concrete and base course were 24,250 MPa and 600 MPa (3517 ksi and 87 ksi), respectively. A Poisson's ratio value of 0.25 for the asphalt concrete was used in the LWDMOD file settings for the Poisson's ratio (program default value of 0.35).

These values were selected to represent asphalt concrete at or just below 0°C (32°F) and a value of a clean, well-drained gravel (the base course). Modulus values vary widely for asphalt concrete depending on the grade of the asphalt binder, aggregate gradation, and temperature. Values for the base course materials vary depending on the gradation, water content, and whether the base-course material was frozen or unfrozen. Poisson's ratio for asphalt concrete is also variable with temperature. We consulted several sources to select these values (Janoo and Grestorex 2002; Masada et al. 2004; Tayebali et al. 1994).

Importing the raw data file into LWDMOD resulted in multiple, repeated messages, "Invalid deflection at Location: XXXXXX Drop:X," for every test-point name and drop number. The software gave no indication as to the basis for this invalidity. However, the data were imported and available for analysis with no other indication as to any problems with the data, other than the deflection and load waveforms were not regular, bell-shaped curves, and frequently the deflection offsets were significant.

The first attempt at backcalculation using the data from all three geophones and a two-layer system calculated modulus values for the asphalt concrete and base course of 64,587 MPa and 548 MPa (9368 ksi and 79 ksi), respectively. This value for asphalt concrete is extremely high and not considered realistic. The data was run again with only the data from the center geophone used. LWDMOD calculated modulus values for the asphalt

concrete and base course of 24,782 MPa and 823 MPa (3594 ksi and 119 ksi), respectively, which are more realistic values.

4.5.2 Montana—groomed snow over runway pavement

At the time of testing, the groomed snow layer over the asphalt concrete on the runway was 11.4 cm (4.5 in.). Sampling the groomed snow over the runway and taxiway in Montana was problematic given that the box-cutter snow tools available were designed for virgin snow sampling and were not strong enough to drive into the groomed snow. Therefore, the density of the groomed snow over the asphalt surfaces in Montana was given an estimated value of 0.42 g/cm³ (0.015 lb/in³) (Bruce Elder, CRREL, pers. comm., April 2018).

Using this density, a seed value of 21 MPa (3.0 ksi) for the modulus of elasticity for the snow was determined using the graph by Shapiro et al. (1997), which is a modified version of Mellor's work (Mellor 1975). A Poisson's ratio of 0.3 for snow was also taken from this source.

The pavement system was 14.0 cm (5.5 in.) of asphalt concrete over 17.58 cm (7 in.) of base course; the subgrade is obsidian sand (Montana Department of Transportation 2015; Morrison Maierle Inc. 2015). The seed modulus and Poisson's ratio values for asphalt concrete were the same as those used in section 4.5.1.

Using the center geophone deflections, a two-layer analysis for the snow over the asphalt concrete was performed for the data from point 25RWY50. For the first run, with all the data from the entire drop sequence, LWDMOD calculated a value of 19 MPa (2.8 ksi) for the snow layer and 2396 MPa (348 ksi) for the asphalt layer. Deleting the first drops at each load level and rerunning the program gave a snow layer modulus of 20 MPa (2.9 ksi) and a value of 5270 MPa (764 ksi) for the asphalt layer. The value for the snow modulus is very similar to the seed value, but the backcalculated asphalt modulus is very low considering the asphalt is at freezing or below.

In this case, it appears that the program is working more with the modulus value of the bottom layer of the system, the asphalt, to reach a solution that matches the deflection data rather than with the modulus value of the top snow layer.

4.5.3 Michigan—groomed snow over natural subgrade

The Michigan test-point data used to check the LWDMod backcalculation program was groomed snow over natural subgrade at Spin Up Pad 2. Data from two points were used: 19SU2_A with 350 mm (13.8 in.) of groomed snow and SU2_C with 220 mm (8.7 in.) of groomed snow.

Equipment was available in Michigan to measure groomed snow density (Figure 23). A 5.8 cm (2.28 in.) diameter aluminum cylinder was driven into the surface of the snow down to a depth of 2.5, 5.0, or 7.6 cm (1, 2, or 3 in.). The bottom of the cylinder was sheared off with a sharp stainless steel plate. This sample was weighed, the volume calculated, and the resultant density recorded.

Figure 23. Snow density test on groomed snow in Michigan.



At Spin Up Pad 2, the groomed snow had a density of 0.59 g/cm^3 (0.2 lb/in^3). Two snow seed modulus values, 100 and 1100 MPa (14.5 and 160 ksi), were tried corresponding to the lower and upper ends of the range of modulus values given for snow density of 0.59 g/cm^3 from Shapiro et al. (1997). Two values were also tried for the frozen subgrade seed modulus, 3000 and 6000 MPa (435 and 870 ksi), from a study by Janoo et al. (1999) on New Hampshire road subgrade soils.

Again, importing the raw data file into LWDMOD resulted in multiple, repeated messages, “Invalid deflection at Location: XXXXXX Drop:X,” for every test point name and drop number. And again, the data were imported and available for analysis with no discernable issues or errors.

We ran LWDMOD both with the full data set for two representative points (19SU2_A and 19SU2_C) and then repeated the analysis using edited data sets with anomalous drops removed. For each of those two cases, the use of a several seed modulus values required four additional runs of LWDMOD. A final fifth run used the edited data and seed values suggested by the results of the previous runs. Table 7 presents the results of these LWDMOD program runs.

For point 22SU2_A, with the thicker (350 mm [13.8 in.]) groomed snow layer, the runs with the lower seed modulus value for the snow layer returned values for the soil layer that were unrealistic, being greater than 10^{16} MPa (1.4×10^{15} ksi). But both the full data set and the edited data set for this point finally returned modulus values of near the 100 MPa seed value for the snow and 478 MPa (69.3 ksi) for the soil layer. Even the runs with the higher seed modulus for snow returned snow modulus values around 100 MPa (14.5 ksi).

For point 22SU2_C, the 220 mm (8.7 in.) layer, the problem with unrealistic values of the soil layer did not repeat. The fifth run results gave a snow modulus value of 157 MPa (22.8 ksi) and a soil modulus of 587 MPa (85.1 ksi). It is interesting to note that, for the case of the 100 MPa (14.5 ksi) snow layer, both seed modulus values for the soil layer returned the same backcalculated modulus values.

The runs of LWDMOD with the Montana and Michigan data raised another question. Since LWDMOD was designed for pavements and to help determine overlay thickness, it is uncertain if the Poisson’s ratio is being attributed to the correct layers. When the Poisson’s ratio is reset in the program, it seems to indicate that is a value for the new overlay material; however, the software and manual are not clear on that point. Therefore, it is unclear what values of Poisson’s ratio are being applied; and, with groomed snow especially, that may be an issue.

Table 7. LWDMOD backcalculated modulus results, in MPa, for groomed snow over grassed soil in Michigan.

Test Point and Layers	Run 1		Run 2		Run 3		Run 4		Run 5	
	Seed Modulus	Back- calculated	Seed Modulus	Back- calculated	Seed Modulus	Back- calculated	Seed Modulus	Back- calculated	Seed Modulus	Back- calculated
19SU2_A*										
Snow	100	85	100	85	1100	98	1100	98		
Soil	3000	3×10^{20}	6000	1×10^{16}	3000	525	6000	525		
19SU2_A**										
Snow	100	87	100	87	1100	108	1100	104	100	102
Soil	3000	3×10^{20}	6000	3×10^{20}	3000	330	6000	416	450	478
19SU2_C*										
Snow	100	129	100	129	1100	140	1100	133		
Soil	3000	1452	6000	1452	3000	857	6000	1156		
19SU2_C**										
Snow	100	120	100	120	1100	184	1100	160	170	157
Soil	3000	5926	6000	5926	3000	376	6000	553	450	589

* All data

** Anomalous data deleted: For 19SU2_A, these were drops 1, 5, 9, and 13. For 19SU2_C, they were drops 1, 5, 6, 9, 10, 13, and 16.

This initial look at LWDMod indicates that without further research and consideration of elastic theory and equations used, LWDMod may not be predicting “better” or more refined values for moduli from the deflection data gathered in Montana and Michigan than those taken from the literature and used for the seed modulus values in the backcalculation.

4.6 ISM

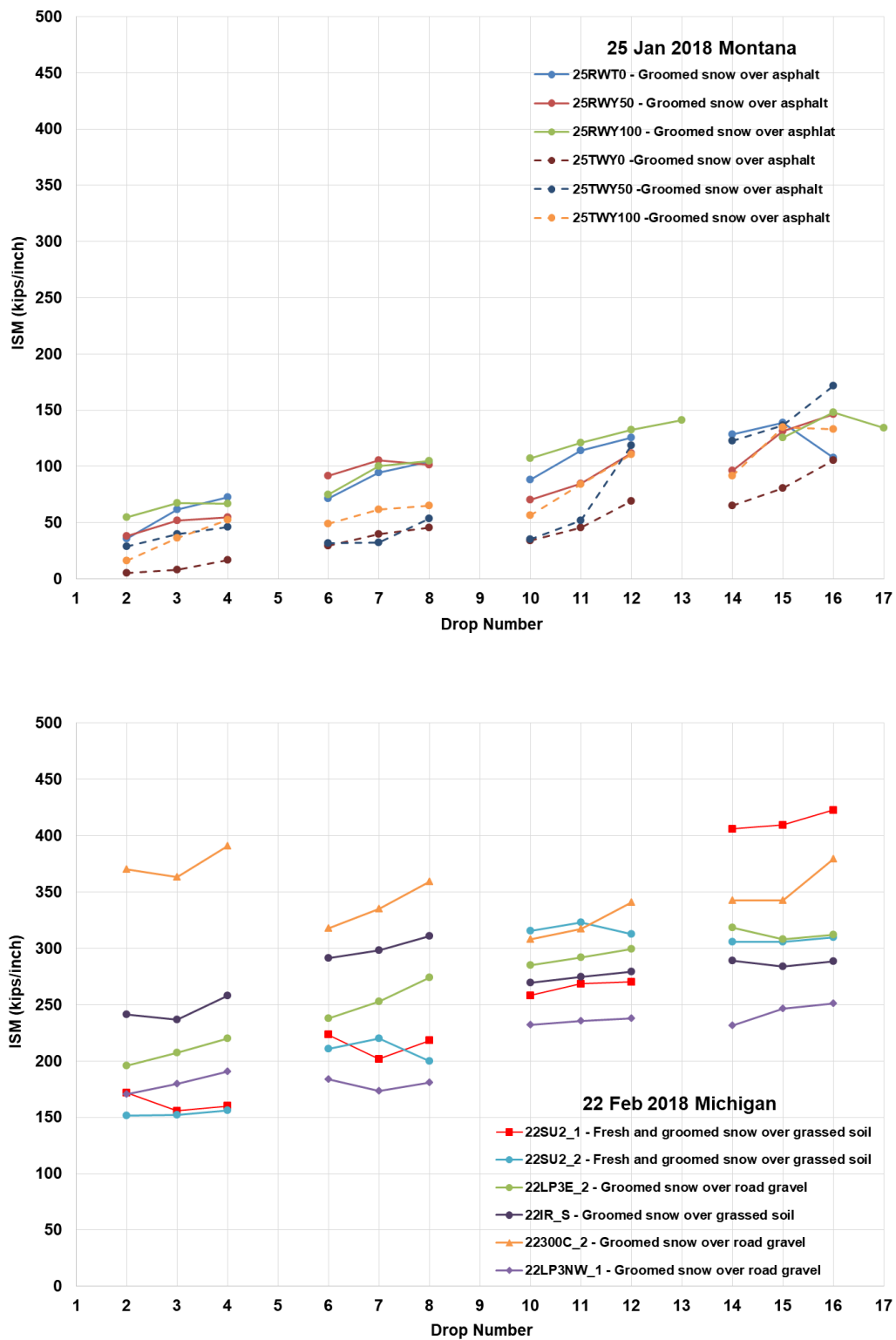
The Army and the Air Force use the Impulse Stiffness Modulus (ISM) as a pavement evaluation parameter (USACE 2001). It provides a qualitative stiffness comparison between test points and pavement sections and is calculated as follows:

$$\text{ISM} = \text{load/deflection (kips/inch)}$$

Figure 24 plots the ISM values calculated from representative data for snow surfaces in Montana and Michigan. Data from the first test at each drop height has been deleted. In the future, data from other drops may also warrant deletion based on poor waveforms if this data is to be analyzed further.

Again, the snow surfaces in Michigan are stiffer than those in Montana, by approximately five times, even when underlain by natural subgrades and gravel as opposed to asphalt concrete pavement.

Figure 24. ISM values manually calculated for example groomed snow data sets from Montana (*top*) and Michigan (*bottom*) data.



4.7 LWD depth of influence

One final topic of concern with regard to the LWD and what characteristics it may be measuring on these winter surfaces is the depth of influence, or measurement, of the LWD. The depth of measurement for the LWD is a matter of significant research (Tirado et al. 2015). Both (1) how deep into the soil or other material the LWD load is penetrating and (2) how the center geophone and the configuration of the outer radial geophones, which measure vertical surface deflections caused almost entirely by strains deeper in the material (Senseney and Mooney 2010), are capturing that response are topics of ongoing discussion. Dynatest states: “There is no theoretical penetration depth for the LWD. The penetration depth depends entirely on the stiffness of the material, the force applied and the load plate radius” (Dynatest 2006a).

For the LWD with the single center geophone in place, Senseney and Mooney (2010) suggest for unbound soils materials that the depth through which the LWD is measuring is 1.0 to 1.5 times the diameter of the loading plate used. Mooney and Miller (2009) suggest 0.9 to 1.1 times the plate diameter, based on in situ stress-strain responses measured (for a specific soil), and Adam and Kopf (2009) report 2 times the plate diameter.

This means that the LWD measurements, and the E_o , ISM, and backcalculated modulus values derived from those measurements, may be for anywhere from the top 27 to 105 cm (11 to 41 in.) of material using the 300 mm plate (11.8 in.). In the tests from Montana, this would include both the snow and the ground or pavement layer. But in the tests in Michigan, the depth of the snow surfaces varied from 17 to 35 cm (6.6 to 14 in.). For the deeper snow, the LWD may be providing insight into only the snow layer.

Attaching the outer geophones increases the depth of the response measured, again because the radial geophones measure vertical surface deflections caused almost entirely by strains in deeper material, up to 1.8 times the load plate diameter (Senseney and Mooney 2010). However, for the snow surfaces encountered in the BAEM testing, when the outer geophones were attached, they did not register any surface response, thus precluding any analysis that data could provide.

5 Summary and Recommendations

The LWD test measures load and deflection data from a series of drops of a weight package intended to simulate the contact stress vehicles impart to unbound pavement layers. From that data, several parameters that describe the total pavement system, or the individual pavement layers, may be calculated. Using the LWD to assess groomed snow surfaces overlaying pavement, aggregate, and soil surfaces is a new application for the equipment.

Under winter conditions in Montana and Michigan, we tested groomed snow surfaces. We looked at the deflection and load waveforms the LWD produced and also the magnitudes of deflection, load, stress, and two stiffness measures, E_o and ISM. For selected test points, we used LWDMOD, the analysis software for the LWD, to backcalculate layer modulus specifically for the groomed snow layers.

Table 8 summarizes the stiffness values calculated from the LWD data, with the values of ISM converted to metric units. The values for the snow layer modulus are for that material alone as the LWDMOD backcalculation fits the data onto a two-layer system, with separate modulus values for the each layer. The modulus values backcalculated for groomed snow were reasonable for snow within the density range of 0.40 to 0.55 g/cm³ (0.014 to 0.020 lb/in.³) (Mellor 1975). To provide a frame of reference to materials used in pavement construction, snow modulus values range from less than those of clayey soils, 35–100 MPa (5 to 14.5 ksi), to values stiffer than asphalt concrete, 3500 MPa (508 ksi) at 21°C (70°F) (Newcomb et al. 2002).

E_o and ISM calculations treat the material under the LWD test point as a composite or whole and give a range of values that corresponds to the calculated values from the first through the fourth drop heights, or load levels, of the test. Unfortunately, there are not comparable values for E_o and ISM from the literature; however, the three calculated parameters all trend the same between the points.

Table 8. Backcalculated and calculated stiffness measures of groomed snow.

Test Point	Backcalculated Snow Layer Modulus (MPa)	E_o (MPa)	ISM (KN/mm)*
25RWY50—Montana	20	32–81	9–24
19SU2_A—Michigan	102	122–140	31–36
19SU2_C—Michigan	157	202–260	52–65

*1 KN/mm = 5.71 kips/in.

The ISM may be the most meaningful for our purposes and needs the least number of assumptions to calculate. Backcalculation of layer modulus values with LWDMod requires input of seed modulus values, Poisson's ratio, and layer thickness. In addition, both backcalculated modulus and direct calculation of the surface modulus value, E_o , are dependent on assumptions about the elastic nature of the combined layers of snow, pavement, and soil surface. We know these assumptions may not be true, especially for the snow layer, due to high deflections seen at the first drop of each higher load level and to the impression the LWD makes in the less-compacted snow surfaces.

To advance the use of the LWD for cold regions applications, further investigation is required for testing with the LWD on ice surfaces. Ice surfaces are stiffer; therefore, the heavy weight package, as opposed to the weight package selected for this study, may be more appropriate. A smooth surface that allows even contact pressure between the LWD plate and the surface is critical but may be more difficult to achieve on an uneven ice surface. In addition, the center plate plug was used in this study; but for further work on ice, which is more analogous with a pavement surface, the plug could be removed and the outer two geophones attached. Care would need to be taken to ensure the geophones are moving freely and in good contact with the ice surface. We noted the center annulus through the load plate can trap loose snow, which impedes the ability of the center geophone to move freely.

To compare the LWD data to other strength tests, we need to decide which load-level data should be used. It is obvious that, for lower-density snow, the LWD itself continues to compact the snow throughout the test drop sequence. The LWD is able to deliver loading at stress levels equal to a variety of the vehicles with contact pressures ranging from 41 kPa to 133 kPa (6 to 19 psi). However, for the purposes of assessing vehicle mobility, the first deflection measurement from the test sequence could be of interest as

it is a measure of the surface prior to additional compacting under the actions of the LWD test, and this could be further explored.

Discrepancies in the load level between morning and afternoon testing in Michigan indicate that the LWD would benefit from a cold soak test to analyze the temperature sensitivity and develop a test protocol to reduce any temperature-induced variability. A procedure such as suggested by the FHWA where the buffers are warmed up before testing is probably not appropriate for tests in winter environments.

Temperature sensitivity may influence not only the buffers but also other components, such as the rubber mat. The LWD should be used to test a surface with a modulus value in the middle of the equipment's intended range and then cold soaked and operated at a range of temperatures to define the temperature range in which the LWD performs accurately.

To further explore the use of the LWD on winter surfaces, a controlled test on uniform areas is needed (i.e., uniform snow depth, underlying surface, shade, or other changes that might affect the snow strength). Concurrent snow and air temperature readings and physical sampling to provide snow depth and density would help determine the variables of the snow surface that impact the LWD measurements and to determine how then to use the LWD to quantify the variability of winter surfaces. These types of tests may also help to resolve the depth-of-influence or measurement issue.

Additionally, a method to quantify the depth of the impression left by the LWD would be useful. This information, especially on thinner snow layers over pavements, may provide insight into the elastic or plastic nature of groomed snow under the LWD's repeated loadings and the amount of compaction the LWD is imparting to the snow surface.

Finally, the variability of the LWD itself is of concern. Again, snow surfaces are highly variable, and the ability of the LWD to capture that is still uncertain. A controlled program with a significantly greater number of points on uniform snow surfaces could be used to assess both the variability of the LWD and the difference between snow surfaces. Such snow surfaces would need to be carefully prepared over uniform pavement or soil surfaces.

The LWD testing under the BAEM program used the equipment in a way that it is not typically used with regard to both temperature and the surface material tested. The LWD is used for road construction quality control, typically on unbound aggregate or soil layers used in pavement construction, at above freezing temperatures. Agencies such as Minnesota Department of Transportation (Siekmeier et al. 2009) indicate that LWD tests resulting in additional compaction of the material should be discontinued and that material be “corrected” prior to retesting. That is part of the quality control function of the device.

For the purposes of characterizing snow and ice surfaces for vehicle mobility in cold climate, the LWD needs to be carefully assessed at those temperatures. A consistent procedure is also needed to ensure testing at the contact stress levels that will provide the information needed to make mobility assessments. This may allow the LWD to become a useful tool in predicting vehicle mobility in winter climates.

References

- Adam, D., and F. Kopf. 2004. Operational Devices for Compaction Optimization and Quality Control. In *Proceedings, International Seminar on Geotechnics in Pavement and Railway Design and Construction*, 16–17 December, Athens, Greece, 97–106.
- ASTM. 2015. *Standard Test Method for Measuring Deflections with a Light Weight Deflectometer (LWD)*. ASTM E2583-07. Conshohocken, PA: ASTM International.
- Dynatest. 2006a. *DYNATEST 3031 LWD Light Weight Deflectometer: Owner's Manual Version 1.0.1*. Søborg, Denmark: Dynatest International.
- . 2006b. *LWDMOD Program Guide for DYNATEST 3031 LWD Light Weight Deflectometer: Owner's Manual Version 1.0.0*. Søborg, Denmark: Dynatest International.
- FHWA (Federal Highways Administration). 2000. *Long-Term Pavement Performance Program (LTPP) Manual for FWD Measurements Operational Field Guidelines, Version 3.1*. McLean, VA: U.S. Department of Transportation, Federal Highway Administration.
- Horak, E. 2007. Surface Moduli Determined with the Falling Weight Deflectometer Used as Benchmarking Tool. In *Proceedings of the 26th Southern African Transportation Conference*, 9–12 July, Pretoria, South Africa, 284–293.
- Janoo, V. C., and A. Greator. 2002. *Performance of Montana Highway Pavements During Spring Thaw*. FHWA/MT-02-066/8155. Springfield, VA: National Technical Information Service.
- Janoo, V. C., J. J. Bayer Jr., G. D. Durell, and C. E. Smith. 1999. *Resilient Modulus for New Hampshire Subgrade Soils for Use in Mechanistic AASHTO Design*. Special Report 99-14. Hanover, NH: U.S. Army Cold Regions Research and Engineering Laboratory.
- Masada, T., S. M. Sargand, B. Abdalla, and J. L. Figueroa. 2004. *Mechanical Properties for Implementation of Mechanistic-Empirical (M-E) Pavement Design Procedures*. Athens, OH: Ohio Research Institute for Transportation and the Environment. Ohio University.
- Mazari, M., G. Garcia, J. Garibay, I. Abdallah, and S. Nazarin. 2013. "Impact of Modulus Based Device Variability on Quality Control of Compacted Geomaterials Using Measurement System Analysis." Paper presented at the TRB 92nd Annual Meeting, 13–17 January, Washington, DC.
- McLain, K. W., D. P. Bumblauskas, D. J. White, and D. D. Gransberg. 2018. Comparative Analysis of Repeatability and Reproducibility of Compaction Testing. *Journal of Structural Integrity and Maintenance* 3 (2): 106–113.
<https://doi.org/10.1080/24705314.2018.1461545>.

- Mellor, M. 1975. A Review of Basic Snow Mechanics. In *The International Symposium on Snow Mechanics*, 1–5 April 1974, Grindelwald, Switzerland. IAHS-AISH Publication 114:251–291.
- Montana Department of Transportation. 2015. *West Yellowstone Airport: 2015 Update—Pavement Condition Indexes*. Bozeman, MT: Robert Peccia and Associates, Inc.
- Mooney, M. A., and P. K. Miller. 2009. Analysis of Lightweight Deflectometer Test Based on In-Situ Stress and Strain Response. *ASCE Journal of Geotechnical and Geoenvironmental Engineering* 135 (2): 199–208.
- Morrison Maierle, Inc. 2015. *Yellowstone Airport 2015 Pavement Reconstruction Plans*. Bozeman, MT: Morrison Maierle, Inc.
- National Oceanic and Atmospheric Administration. 2019a. Local Climatological Data Station Details, West Yellowstone, MT US, WBAN:94163, January 2018. <https://www.ncdc.noaa.gov/cdo-web/datasets/LCD/stations/WBAN:94163/detail>.
- . 2019b. Local Climatological Data Station Details, Hancock Houghton Co Airport, MI US, WBAN:14858, February 2018. <https://www.ncdc.noaa.gov/cdo-web/datasets/LCD/stations/WBAN:14858/detail>.
- Newcomb, D., D. Timm, and J. Mahoney. 2002. It's Still Dirt, Rocks and Asphalt—Right? *Hot Mix Asphalt Technology* 7 (4): 16–22.
- Schmalzer, P. N. 2006. *LTPP Manual for FWD Measurements, Version 4.1*. Publication No. FHWA-HRT-06-132. McLean, VA: U.S. Department of Transportation, Federal Highway Administration.
- Senseney, C. T., and M. A. Mooney. 2010. Characterization of Two-Layer Soil System Using a Lightweight Deflectometer with Radial Sensors. *Transportation Research Record: Journal of the Transportation Research Board* 2186 (1): 21–28. Washington, DC: Transportation Research Board of the National Academies. <https://doi.org/10.3141/2186-03>.
- Shapiro, L. H., J. B. Johnson, M. Strum, and G. L. Blaisdel. 1997. *Snow Mechanics: Review of the State of Knowledge and Applications*. CRREL Report 97-3. <http://hdl.handle.net/11681/9238>.
- Siekmeier, J., C. Pinta, S. Merth, J. Jensen, P. Davich, F. Camargo, and M. Beyer. 2009. *Using the Dynamic Cone Penetrometer and Light Weight Deflectometer for Construction Quality Assurance*. MN/RC 2009-12. Maplewood, MN: Minnesota Department of Transportation.
- Tayebali, A. A., B. Tsai, and C. L. Monismith. 1994. *Stiffness of Asphalt-Aggregate Mixes*. Strategic Highway Research Program-A-388. Berkley, CA: Institute of Transportation Studies, University of California–Berkeley.
- Tirado, C., M. Mazari, C. Carrasco and S. Nazarain. 2015. Evaluating Influence Depth of Light Weight Deflectometer through Finite Element Modeling. In *Airfield and Highway Pavements 2015*, 789–800. Reston, VA: American Society of Civil Engineers. <http://dx.doi.org/10.1061/9780784479216.070>.
- Ullidtz, O. 1987. *Pavement Analysis*. New York: Elsevier.

USACE (U.S. Army Corps of Engineers). 2001. *Airfield Pavement Evaluation*. United Facilities Criteria (UFC) 3-260-03. Washington, DC: USACE, Naval Facilities Engineering Command, and Air Force Civil Engineer Support Agency.

Vennapusa, P. K. R., and D. J. White. 2009. Comparison of Light Weight Deflectometer Measurements for Pavement Foundation Materials. *Geotechnical Testing Journal* 32 (3). West Conshohocken, PA: ASTM.

Appendix A: Additional Site Imagery

Figure A-1. West Yellowstone Airport central runway, taxiway, and ice lane LWD test points as they relate to the airport pavement surfaces.

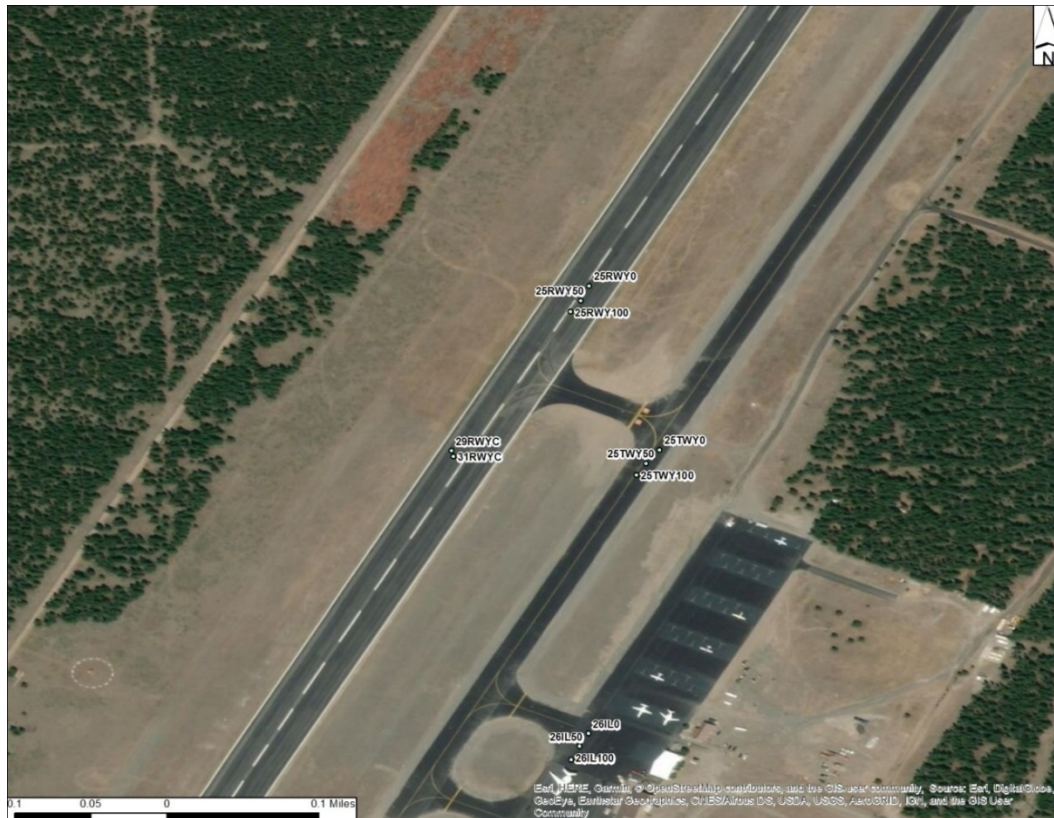


Figure A-2. West Yellowstone Airport south taxiway LWD test points as they relate to the airport pavement surfaces.



Figure A-3. Michigan Spin Up Pads 1 and 2 LWD test points.



Figure A-4. Michigan Spin Up Pad 2 LWD test-points winter imagery.



Figure A-5. Michigan Spin Up Pad 3, Loop 1, Vehicle Dynamics Area 2, and the 900 and 300 ft circles LWD test points.



Figure A-6. Michigan Spin Up Pad 3, Loop 1, Vehicle Dynamics Area 2, and the 900 and 300 ft circles LWD test-points winter imagery.

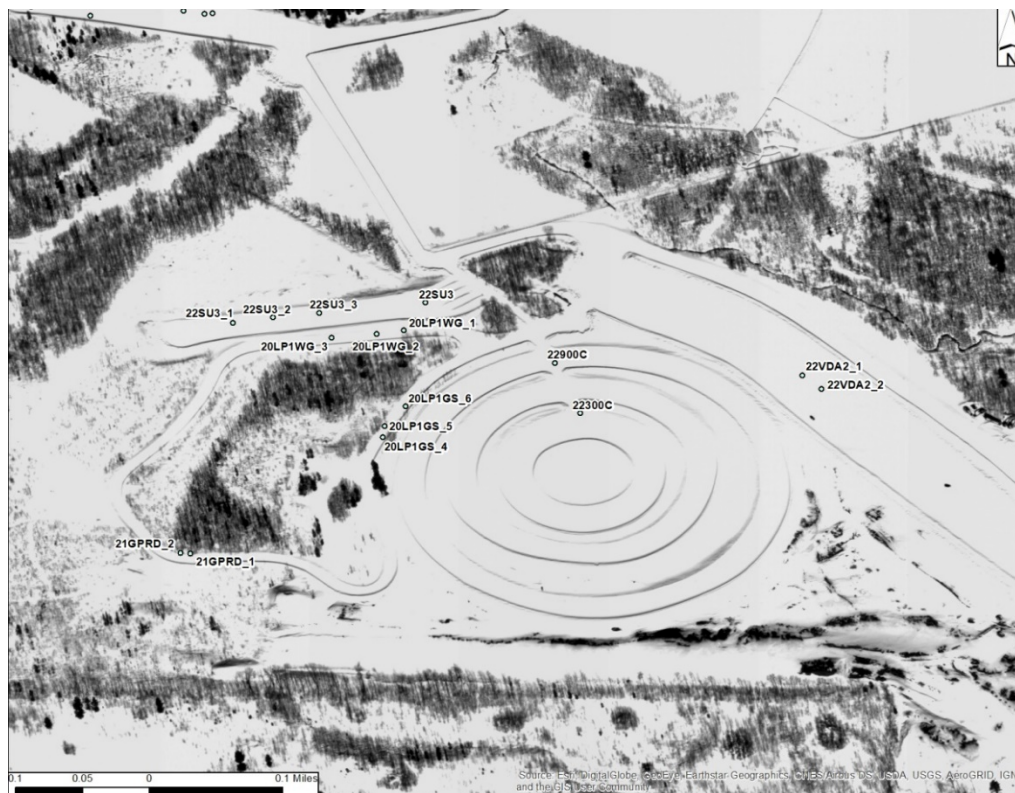


Figure A-7. Michigan Ice Rink and Sweeper parking pad LWD test points.



Figure A-8. Michigan Ice Rink and Sweeper parking pad LWD test-points winter imagery.



Figure A-9. Michigan Loop 3, Stability Test Area, and Loop 4 LWD test points.



Figure A-10. Michigan Loop 3, Stability Test Area, and Loop 4 LWD test-points winter imagery.



Appendix B: Field Campaign Weather Conditions

Table B-1. Montana.

Date	Daily Temp		Snow Data			Weather Description
	Max (°C)	Min (°C)	Daily (cm)	On Ground (cm)	Melt (cm)	
22-Jan	-8	-25	14	0	NA	Overcast to scattered clouds, snow
23-Jan	-5	-18	5	76	NA	Overcast to scattered clouds, snow
24-Jan	-6	-9	3	76	NA	Overcast and snow, then sunny
25-Jan	1	-14	0	76	NA	Sunny, some overcast and broken clouds
26-Jan	-3	-13	8	84	NA	Overcast and snow, then clear
27-Jan	-6	-13	5	89	NA	Over cast and snow, then broken clouds, partly sunny
28-Jan	-4	-9	5	94	NA	Over cast and snow, then broken clouds, partly sunny
29-Jan	-1	-5	0	89	5.08	Overcast then scattered clouds
30-Jan	-1	-2	0	84	NA	Broken clouds
31-Jan	0	-14	0	84	NA	Overcast, then broken clouds, partly sunny
1-Feb	-6	-22	0	84	NA	Clear
2-Feb	-4	-23	4	89	NA	Clear

Source: Data from National Oceanic and Atmospheric Administration (2019a).

Table B-2. Michigan.

Date	Daily Temp		Snow Data			Weather Description
	Max (C)	Min (c)	Daily (cm)	On Ground (cm)	Melt (cm)	
16-Feb	-7	-17	6	74	NA	Overcast and snow, then clear
17-Feb	-3	-11	0	74	NA	Overcast, then clear
18-Feb	-2	-9	0	74	NA	Clear, then overcast
19-Feb	-2	-9	3	76	NA	Overcast and snow, then broken clouds
20-Feb	-2	-9	12	81	NA	Freezing rain and snow in morning, overcast
21-Feb	-8	-17	6	84	NA	Overcast and snow, then scattered clouds
22-Feb	-3	-19	1	84	NA	Overcast then clear
23-Feb	-2	-5	18	74	NA	Over cast and snow heavy at times, then mostly cloudy
24-Feb	1	-13	0	71	3	Mostly sunny

Source: Data from National Oceanic and Atmospheric Administration (2019b).

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE (DD-MM-YYYY) May 2019			2. REPORT TYPE Technical Report/Final		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Using the Light Weight Deflectometer to Assess Groomed Snow and Ice Surfaces					5a. CONTRACT NUMBER	
					5b. GRANT NUMBER	
					5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Wendy L. Wieder, Sally A. Shoop, and Lynette Barna					5d. PROJECT NUMBER 465395 & 471941	
					5e. TASK NUMBER	
					5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Army Engineer Research and Development Center (ERDC) Cold Regions Research and Engineering Laboratory (CRREL) 72 Lyme Road Hanover, NH 03755-1290					8. PERFORMING ORGANIZATION REPORT NUMBER ERDC/CRREL TR-19-5	
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Assistant Secretary of the Army for Acquisition, Logistics, and Technology 103 Army Pentagon Washington, DC 20314-1000					10. SPONSOR/MONITOR'S ACRONYM(S) ASA(ALT)	
					11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.						
13. SUPPLEMENTARY NOTES ERDC 6.2 Boreal Aspects of Ensured Maneuver (BAEM)						
14. ABSTRACT The Light Weight Deflectometer (LWD) was designed to test the compaction or bearing capacity of in-place aggregate base-course materials. This study evaluated the potential of the LWD to also characterize groomed snow and ice surfaces as the ability to characterize the strength, or bearing capacity, of winter surfaces is crucial for evaluation of vehicle mobility in cold climates. LWD tests were run on a variety of groomed snow and ice surfaces over asphalt pavement, gravel, and soil in the winter of 2018 in both Montana and Michigan. The LWD measures load and deflection, enabling calculation and backcalculation of stiffness parameters for the test surface layers. The initial results were reasonable for the snow layers analyzed. The Impulse Stiffness Modulus, calculated as the impact load divided by the deflection response, presents as a reasonable property for analysis, requiring no assumptions about other snow layer properties. However, the LWD components, specifically the rubber load buffers, may have issues with the effects of low temperature testing. These effects need to be considered when testing snow and ice surfaces. Additionally, the stress and compaction levels that most represent the conditions of interest for mobility purposes need to be determined. Specific and consistent LWD equipment configuration and test procedures need to be determined and implemented in further testing of winter surfaces.						
15. SUBJECT TERMS Compaction, Deflection, Ice mechanics, Ice--Bearing capacity, Light weight deflectometer, Loads (Mechanics), Mobility, Snow mechanics, Snow--Bearing capacity, Testing						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON	
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (include area code)	