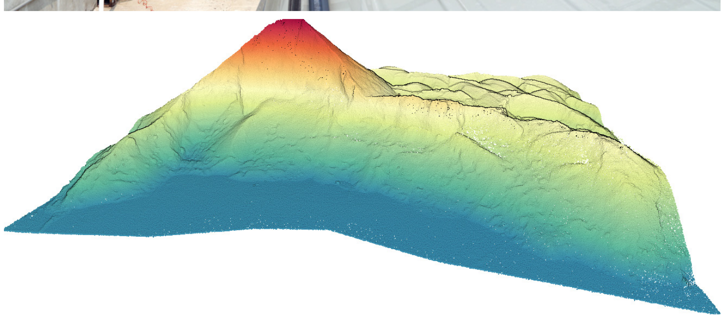
JOINT TRANSPORTATION
RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

Salt Monitoring and Reporting Technology (SMART) for Salt Stockpile Inventory Reporting



Justin Anthony Mahlberg, Raja Manish, Yerassyl Koshan,
Mina Joseph, Jidong Liu, Haydn A. Malackowski, Zechariah DeLoach,
Timothy Wells, Jeremy McGuffey, Ayman Habib, Darcy M. Bullock

SPR-4549 • Report Number: FHWA/IN/JTRP-2023/19 • DOI: 10.5703/1288284317650

RECOMMENDED CITATION

Mahlberg, J. A., Manish R., Koshan, Y., Joseph, M., Liu, J., Malackowski, H. A., DeLoach, Z., Wells, T., McGuffey, J., Habib, A., & Bullock, D. M. (2023). *Salt monitoring and reporting technology (SMART) for salt stockpile inventory reporting* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2023/19). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284317650

AUTHORS

Justin A. Mahlberg
Raja Manish
Yerassyl Koshan
Mina Joseph
Jidong Liu
Haydn A. Malackowski
Graduate Research Assistants
Lyles School of Civil Engineering
Purdue University

Zechariah DeLoach
Statewide Operations Assistant & Director
INDOT

Timothy Wells, PE
Research Section Manager
Indiana Department of Transportation

Jeremy McGuffey
Winter Operations Manager
Indiana Department of Transportation

Ayman Habib, PhD
Thomas A. Page Professor in Civil Engineering
Lyles School of Civil Engineering

Darcy M. Bullock, PhD, PE
Lyles Family Professor of Civil Engineering
Lyles School of Civil Engineering
Purdue University
(765) 494-2226
darcy@purdue.edu
Corresponding Author

JOINT TRANSPORTATION RESEARCH PROGRAM

The Joint Transportation Research Program serves as a vehicle for INDOT collaboration with higher education institutions and industry in Indiana to facilitate innovation that results in continuous improvement in the planning, design, construction, operation, management and economic efficiency of the Indiana transportation infrastructure. https://engineering.purdue.edu/JTRP/index_html

Published reports of the Joint Transportation Research Program are available at http://docs.lib.purdue.edu/jtrp/.

NOTICE

Technical Report Documentation Page

1. Report No. FHWA/IN/JTRP-2023/19	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Salt Monitoring and Reporting Technology (SMART): Development of a Photogrammetric System for Salt Inventory Reporting		**5. Report Date** July 2023 **6. Performing Organization Code**
7. Author(s) Justin A. Mahlberg, Raja Manish, Yerassyl Koshan, Mina Joseph, Jidong Liu, Haydn A. Malackowski, Zechariah DeLoach, Timothy Wells, Jeremy McGuffey, Ayman Habib, and Darcy M. Bullock		**8. Performing Organization Report No.** FHWA/IN/JTRP-2023/19
9. Performing Organization Name and Address Joint Transportation Research Program Hall for Discovery and Learning Research (DLR), Suite 204 207 S. Martin Jischke Drive West Lafayette, IN 47907		**10. Work Unit No.** **11. Contract or Grant No.** SPR-4549
12. Sponsoring Agency Name and Address Indiana Department of Transportation (SPR) State Office Building 100 North Senate Avenue Indianapolis, IN 46204		**13. Type of Report and Period Covered** Final Report **14. Sponsoring Agency Code**
15. Supplementary Notes Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.		

16. Abstract

Transportation agencies in northern environments spend a considerable amount of their budget on salt for winter operations. For example, in the state of Indiana, there are approximately 120 salt storage facilities distributed throughout the state and the state expends between 30 M USD and 60 M USD on inventory and delivery each year. Historical techniques of relying on visual estimates of salt stockpiles can be inaccurate and unhelpful for managing the supply chain during the winter or planning for re-supply during the summer months. This project report describes the implementation of a portable and permanent LiDAR system that can be used to inventory indoor stockpiles of salt in under 15 minutes and describes how this system has been deployed over 300 times at over 120 facilities. A quick and easy accuracy test, based on the conservation of volume, was used to provide an independent check on the system performance by repositioning portions of the salt pile. Those tests indicated stockpile volumes can be estimated with an accuracy of 1%–3% of indicated stockpile volumes. The report concludes by discussing how this technology can be permanently installed for systematic monitoring throughout the year.

17. Key Words winter operations, salt, management, stockpile, weather, LiDAR	**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (Of this report) Unclassified	**20. Security Classif. (Of this page)** Unclassified	**21. No. of Pages** 38 including appendices	**22. Price**

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

EXECUTIVE SUMMARY

Motivation

The Indiana Department of Transportation (INDOT) manages and maintains over 29,000 lane miles of roads statewide. INDOT spends a considerable amount of their annual budget on salt for winter operations. Annual spending ranges from 30 million USD to 60 million USD for salt material and delivery. Roadway salt is stockpiled statewide across approximately 120 facilities. (Figure 1.1 shows the location of salt storage and maintenance facilities statewide). An accurate inventory of the amount of salt available in each storage facility is important to ensure that an adequate volume is available for each winter weather event.

One of the challenges the agency faces is that each facility has different building sizes and types, causing unique storage capacities that preclude developing systematic visual inventory techniques, such as observing stockpile size to determine its volume. This estimation can also vary due to different visual perceptions and human error (Dargie Chekole, 2014). An example of four different salt storage facilities can be observed in Figure 1.2. Figure 1.2a shows the facility in Sellersburg, Indiana, which is a salt dome attached to a salt barn. Figure 1.2b is the Bloomington, Indiana facility, which consists of a rectangular wooden structure with an open end on one side and a complementing salt dome adjacent to the wooden structure. Figure 1.2c is the Gary, Indiana facility, which is a rectangular concrete and steel barn structure. Lastly, Figure 1.2d is a rectangular concrete and tension fabric structure in Rensselaer, Indiana. These four unique structures are only representative of a few configurations of over 120 INDOT facilities. The capacity and inventory in each facility becomes especially crucial for managing the supply chain during the winter season to ensure that facilities do not run out of salt or receive excess deliveries.

Traditional methods for determining the salt inventory per facility includes counting the number of truck loads using/delivering salt, estimating the percent of full capacity, and camera-based photogrammetry. Tracking material by truck load and even manual field surveys does not provide sufficient accuracy for season-long inventory management data. Visual observations to estimate the percent of full capacity vary widely and are dependent upon accurate facility capacity numbers. Photogrammetric systems can be expensive and can also be problematic due to low-lighting conditions and occlusions or areas that are not visible to the camera.

Study

The objective of this study was to develop and deploy a LiDAR-based Stockpile Management and Reporting Technology (SMART) system. This report describes the data and visualization tools that were employed for two winter seasons. These were tested using two portable systems and two roof-mounted systems. During this study, the INDOT/Purdue team collected data at over 120 INDOT salt storage facilities statewide. There have been over 300 unique data collections processed over two winter seasons, using all of the prototype systems, and the results were found to be repeatable with an accuracy of between 1%–3%. The roof-mounted permanent installation accounted for over 40 data collections between the two locations. The main body of this report describes the equipment, modelling, visualizations, and selected case studies. The appendix describes the implementation activities. The video at https://doi.org/10.4231/4MAG-JN90 provides a quick qualitative overview of how the SMART system models stockpiles and the resulting quantitative estimates of stockpile volume over several days with varying periods of salt usage (Malackowski, 2023).

Implementation

In March 2023, the INDOT/Purdue team used the portable SMART system to scan 123 salt storage facilities that have an approximate capacity of 350,000 tons. Between March 6th to 22nd, two INDOT staff members conducted scans of the facilities to plan the locations that INDOT would strategically allocate late season salt purchases. The 123 scanned salt storage facilities were found to have approximately 225,000 tons of salt. The remaining capacity identified in each facility was used to allocate locations to store the 53,000 tons of post-season salt purchases.

CONTENTS

1. PROJECT OVERVIEW . . . 1
1.1 Introduction . . . 1
1.2 Dissemination of Research Results . . . 1

2. SMART SYSTEM . . . 2
2.1 System Components . . . 2
2.2 Data Collection and Processing Methodology . . . 2

3. STUDY LOCATIONS . . . 4
3.1 Preliminary Scans . . . 4
3.2 Field Deployment . . . 4
3.3 2021–2022 Winter Monitoring Results . . . 5

4. FIELD VALIDATION OF VOLUMES . . . 9

5. CONCLUSIONS . . . 10

REFERENCES . . . 11

APPENDICES
Appendix A. Implementation Activities . . . 13
Appendix B. Permanent Install User Guide . . . 13
Appendix C. January 25th Winter Event Visuals . . . 13

LIST OF TABLES

Table 3.1 Summary of 2021–2022 data collections at each facility 7

Table 3.2 Salt pile inventory in cubic yards over the 2021–2022 winter season 8

LIST OF FIGURES

Figure 1.1 INDOT salt storage facilities and maintenance units 1

Figure 1.2 Example of INDOT salt storage facilities 2

Figure 2.1 The SMART system for data acquisition 3

Figure 2.2 SMART data acquisition and processing methodology 4

Figure 3.1 Locations of 2021–2022 data collections across Indiana 5

Figure 3.2 Testing locations for optimal permanent installation 6

Figure 3.3 Permanent installation of the SMART system 6

Figure 3.4 Total salt over the 2021–2022 winter season in the Lebanon, Indiana salt facility 8

Figure 3.5 Digital surface models of Lebanon salt over the 2021–2022 winter season 8

Figure 3.6 GoPro images of corresponding Lebanon salt piles for the 2021–2022 winter season 9

Figure 4.1 Data validation through salt repositioning 10

1. PROJECT OVERVIEW

1.1 Introduction

Winter maintenance operations typically include the use of de-icing materials with a heavy reliance on road salt. Across the United States, over 70% of the population live in a region that experience winter weather conditions (FHWA, 2023; Hintz et al., 2022). The use of road salt reduces and mitigates winter weather impacts and has increased over the decades with about 20 million tons of road salt used in the US per year (Bagenstose, 2019; Breining, 2017; TRB, 1991). Recent studies have shown that the use of de-icing salts have been impacting the biodiversity and fresh-water ecosystems due to a rise in salinity (Hintz et al., 2022; Kaushal et al., 2005; Kelly et al., 2018). This environmental impact merged with the fiscal accountability and necessity to ensure proper mobility standards paves the way for future roadway de-icing measures (FHWA, 2023; Hintz et al., 2022; Knapp et al., 2000; Mahlberg et al., 2021).

Many agencies have moved away from traditional salt storage methods which were uncovered, outdoor facilities due to the loss of material and environmental impacts during precipitation events, some states even enforce the use of covered salt stockpiles (Kasich & Tayler, 2013; MassDEP, 1997; Ohno, 1990; Salt Institute, 2015). Covered facilities for stockpiles make it difficult for evaluation of stockpiles through field surveys in an efficient manner due to limited access, poor lighting, and Global Navigation Satellite Signal (GNSS) accessibility is limited for Real-Time Kinematic (RTK) surveys (He et al., 2019; Yilmaz, 2010). The use of unmanned aerial vehicles (UAVs) has been commonly used for stockpile estimation in open environments as they are a quick and safe method to acquire stockpile data (Ajayi & Ajulo, 2021; Alsayed, Yunusa, et al., 2021; He et al., 2019; Hugenholtz et al., 2015; Liu et al., 2020; Mora et al., 2020; Zhu et al., 2018). The use of UAVs in indoor facilities is restricted due to minimal GNSS signal and obstacles in the flight path. All the limitations in volume estimation of salt stockpiles cause inaccuracies and do not scale well for managing the supply chain during the winter or planning for re-supply during summer months.

The work performed as a result of this research project is the development of prototypes to validate the use case of LiDAR technology to manage stockpiles, specifically in the roadway salt storage applications. The contents of this report are organized as follows.

- Development of LiDAR technology system, data collection methods, and post processing methodologies (Section 2).
- Prototype testing through a case study of the 2021–2022 winter season using the portable prototypes (Section 3).
- Field validations of volumes found using SMART System (Section 4).
- Permanent installation solution exploration and implementation, INDOT staff training on system operations, and 2022–2023 case studies and winter results (Appendix A).
- Permanent installation of SMART system user guide (Appendix B).

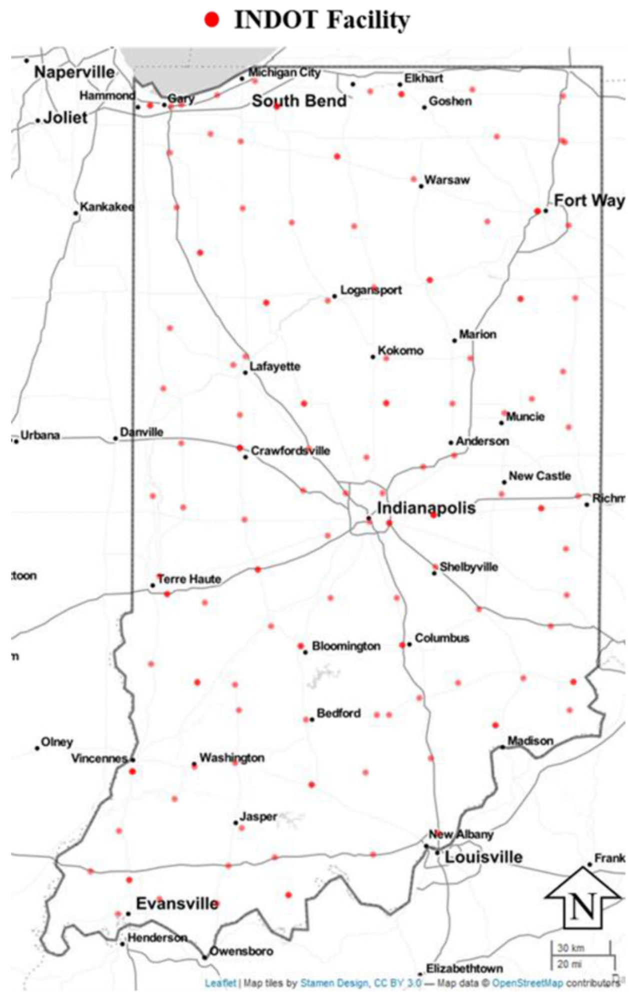


Figure 1.1 INDOT salt storage facilities and maintenance units.

Overall, the findings of this research and feasibility of the SMART system will be summarized in the conclusion section of the report.

1.2 Dissemination of Research Results

The technology developed in this study has been implemented statewide, for salt stockpile inventory and management. This includes data collection performed by INDOT employees, processing performed by Purdue, and dissemination of results with INDOT Material Management. In addition, the following is a list of papers that were prepared in part during this project.

- Mahlberg, J. A., Manish, R., Koshan, Y., Joseph, M., Liu, J., Wells, T., McGuffey, J., Habib, A., & Bullock, D. M. (2022). Salt stockpile inventory management using LiDAR volumetric measurements. *Remote Sensing*, *14*(19), 4802. https://doi.org/10.3390/rs14194802

(a) Sellersburg, Indiana Salt Facility

(b) Bloomington, Indiana Salt Facility

(c) Gary, Indiana Salt Facility

(d) Rensselaer, Indiana Salt Facility

Figure 1.2 Example of INDOT salt storage facilities.

- Manish, R., Hasheminasab, S. M., Liu, J., Koshan, Y., Mahlberg, J. A., Lin, Y.-C., Ravi, R., Zhou, T., McGuffey, J., Wells, T., Bullock, D., & Habib, A. (2022). Image-aided LiDAR mapping platform and data processing strategy for stockpile volume estimation. *Remote Sensing*, *14*(1). https://doi.org/10.3390/rs14010231
- Hasheminasab, S. M., Zhao, T., & Habib, A. (2023). Linear feature-based image/LiDAR integration for a stockpile monitoring and reporting technology. *Journal of Selected Topics in Applied Earth Observations and Remote Sensing* (JSTARS), *16*, 2605–2623. https://doi.org/10.1109/JSTARS.2023.3250392
- Liu, J., Hasheminasab, M., Zhou, T., Manish, R., & Habib, A. (2023). An image-aided sparse point cloud registration strategy for managing stockpiles in dome storage facilities. *Remote Sensing*, *15*(2), 504. https://doi.org/10.3390/rs15020504

These technical papers were prepared throughout the project and distributed to key INDOT stakeholders to facilitate early implementation of the new research findings.

2. SMART SYSTEM

2.1 System Components

There are several key components for the SMART System to be operational and portable. The system, outfitted with all its components, can be seen in Figure 2.1. The compact design makes the system easy to transport and convenient to collect data anywhere. The primary components of the system, as observed in Figure 2.1a, are a GoPro Hero 9 RGB camera (callout *i*), and two Velodyne VLP-16 LiDAR sensors (callout *ii*). The two LiDAR sensors, with different coverage areas, provide a greater point density, increased redundancy, and occlusion reduction compared to a single unit. Figure 2.1b shows the portable tripod that is used and the quick connect PVC/Polyvinyl chloride connection for fast and easy setup (callout *iii*). The remaining components can be observed in Figure 2.1c in the traveling case, which includes the power source, and the user interface tablet.

2.2 Data Collection and Processing Methodology

The SMART system's development, data acquisition procedure, and data processing strategy in this study are based on an early prototype system proposed by Manish et al., 2022. Figure 2.2 illustrates their proposed approach. When conducting an onsite data acquisition, the SMART system is placed on the tripod for scanning. Due to the limited field of view of LiDAR sensors, the system is rotated manually at a clockwise increment of 30 degrees (as illustrated in Figure 2.2a to capture enough data points to cover the stockpile. The orientation of the LiDAR units and camera requires the 30-degree rotation to be performed 7 times with LiDAR capturing 10-second-long scans. This results in LiDAR/RGB data collected over 180 degrees of rotation, the first scan being at degree 0 and the final scan 180 degrees from the first. With two LiDAR units, the procedure collectively obtains a complete 360-degree scan of the facility. Depending on the size of the stockpile, not all areas of the pile may be visible to the system at a given location which would motivate the use of multiple stations for data collection.

After the data collection, the team uses the techniques from Manish et al., 2022 to perform coarse and fine registrations of point clouds which are then used to determine the stockpile volume (Manish et al., 2022). As visualized in Figure 2.2b, at first, an image-assisted coarse registration of LiDAR scans is conducted wherein successive images are utilized to obtain scan-

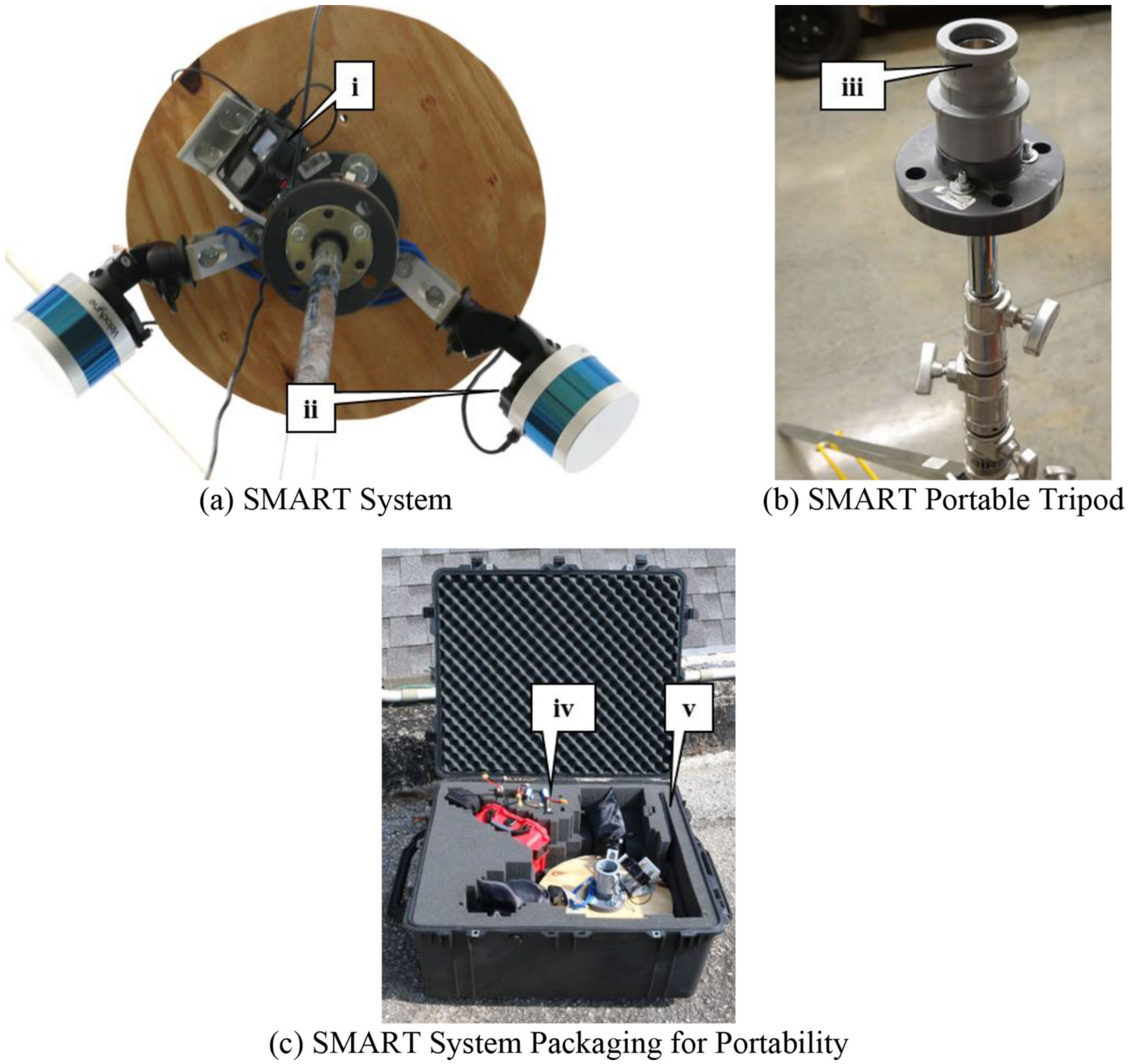
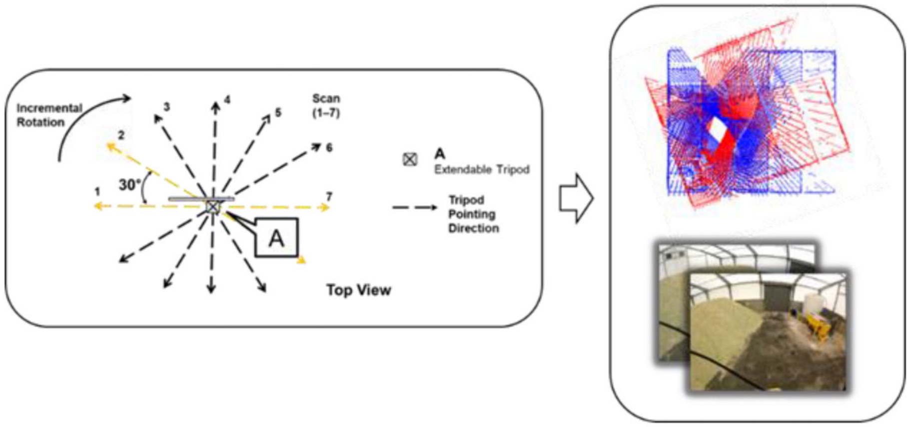


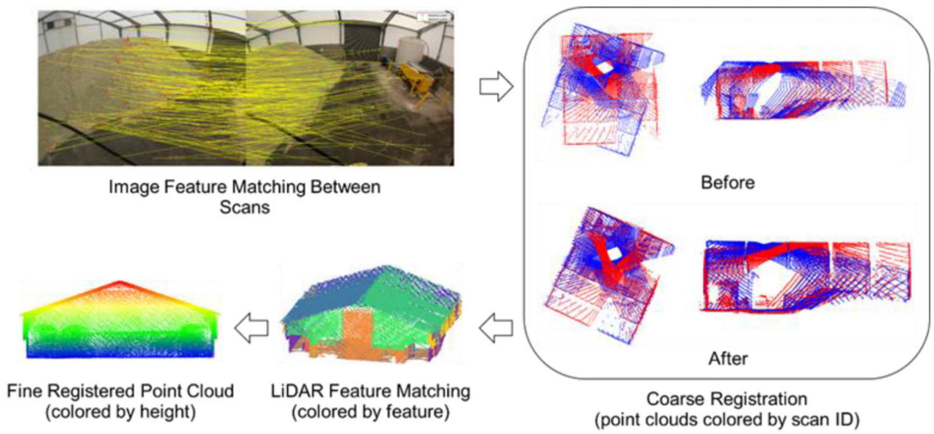
Figure 2.1 The SMART system for data acquisition.

to-scan transformation through constrained iterative matching of Scale Invariant Feature Transform (SIFT) features in two successive images at a time. The iterative matching avoids wrong matches due to the homogeneity of stockpile surface. Once the LiDAR scans are coarsely registered, all the individual scans are segmented to extract planar features, which are matched across the different scans. Then, a final optimization routine based on least squares adjustment is initiated for a feature-based fine registration of all scans (Lin et al., 2021). If more than one station was collected at a facility, then the fine registered scans from each location are used to perform a coarse registration of all stations using linear, and planar features derived from the registered scans at individual stations (Kwak & Habib, 2014; Mahlberg et al., 2022; Sampath & Shan, 2007). The multi-station coarse registration is then followed by a fine registration using matched planar features in the combined multi-station scans. Finally, to compute the stockpile volume, the multi-station fine registered point clouds are levelled until the ground of the facility aligns with the XY plane. Then, a digital surface model (DSM) is generated by defining grid cells of identical size (0.1 m $\times$ 0.1 m in this research) uniformly in the XY plane right over the stockpile area within the boundary of the facility, as shown in Figure 2.2c. Each cell is assigned a height at the center of the cell based on a bilinear interpolation of the LiDAR surface of the stockpile (this interpolation establishes stockpile surface in occluded areas).

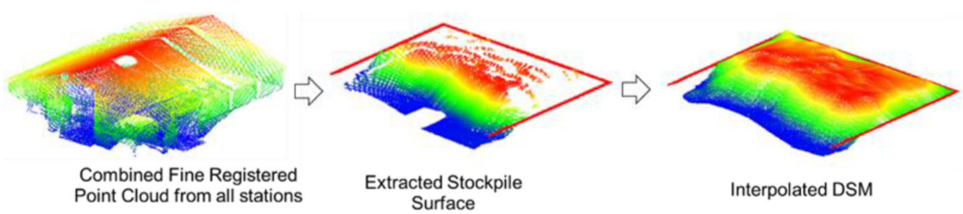
It is worth noting that when generating the DSM for a given facility, the number of grid cells will depend on the cell size, as mentioned above. The cell size will, in turn, affect data processing time—the smaller the cell, the more expensive it will be in terms of computation needed to generate the DSM. The selection of the cell size (0.1 m $\times$ 0.1 m) in this research did not result in a significant processing overhead. On a computer with an 8 core Intel i5 processor and 8 GB RAM, the DSM generation typically took about 30 seconds or less.



(a) Diagram of System Rotation for Data Collection



(b) Coarse Registration of Lidar Scans



(c) Digital Surface Model of Stockpile Area

Figure 2.2 SMART data acquisition and processing methodology.

3. STUDY LOCATIONS

3.1 Preliminary Scans

To capture a diverse portfolio of locations 26 INDOT facilities, and four local agency facilities were scanned for the 2021–2022 winter season. This diversity provided a magnitude of different challenges to ensure the system could accurately capture data in all facilities. Table 3.1 summarizes the facilities that were scanned and the number of times the data collection team visited to capture data for a given facility. It can be noted that 88 total surveys were collected and 12 of those facilities were frequently traveled to, for observing changes in salt inventory over the winter season. Figure 3.1 shows, spatially, the scanning coverage across the state of Indiana. Each representative callout on the map is the respective facility from Table 3.1.

3.2 Field Deployment

The success and learning opportunities of the portable system over the 2021–2022 winter season has generated interest in a permanent SMART system installation in facilities. This would enable the agency to observe salt amounts in near real-time from any location. Before mounting the system, a preliminary test was conducted to determine the optimal location for the SMART system. Figure 3.2a shows the

TABLE 3.1
Summary of 2021–2022 data collections at each facility

Map Ref.	Facility Name	# of Surveys	Map Ref.	Facility Name	# of Surveys
1	Crawfordsville	6	16	Rochester Unit	1
2	Lebanon	10	17	Greensburg Unit	1
3	Frankfort	6	18	Brookville Unit	1
4	Romney	6	19	Aurora Sub	1
5	West Lafayette River Road	4	20	Scottsburg Unit	1
6	Rensselaer	6	21	Sellersburg Unit-1	1
7	Chesterton	5	22	Sellersburg Unit-2	1
8	Michigan City	5	23	Corydon Unit	1
9	Miller	5	24	Salem Unit	1
10	Monticello	9	25	Bloomington Sub-1	1
11	US 231	8	26	Bloomington Sub-2	1
12	City of Lafayette Street Department	3	27	Columbus Sub	1
13	West Lafayette Street Department	1	28	Portland Unit	1
14	LaPorte Unit	1	29	Valparaiso Unit	2
15	Plymouth Unit	1	30	Valparaiso Unit 2	3

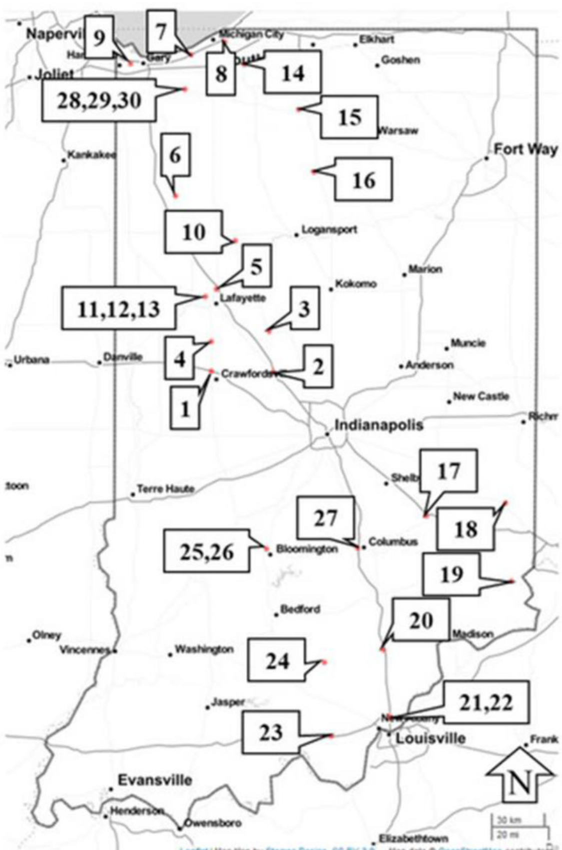


Figure 3.1 Locations of 2021–2022 data collections across Indiana.

temporary mounting of the unit on a mobile boom lift. Scans at three different mounting locations were performed to determine the optimal location. Figure 3.2b shows the three locations relative to the salt pile that were tested in the facility. The optimal location is shown as the red dot which provided the most coverage of the pile, while still capturing the front of the pile where most of the salt is removed. This position, at the time of the scan, was located towards the front of the pile but as the agency refills the barn, the system will be closer to the center of the pile. Additionally, this location provides visual to the LiDAR units and the camera of the back of the pile and an optimal view of the front of the pile where the amount of salt changes the most. The horizontal line in Figure 3.2b represents the center steel support in the salt barn and the three vertical lines represents the support truss to which the SMART system could be mounted. Additionally, the area in the front of the barn is an entryway used for storage, equipment, and loading, which is excluded from the salt pile estimation calculations.

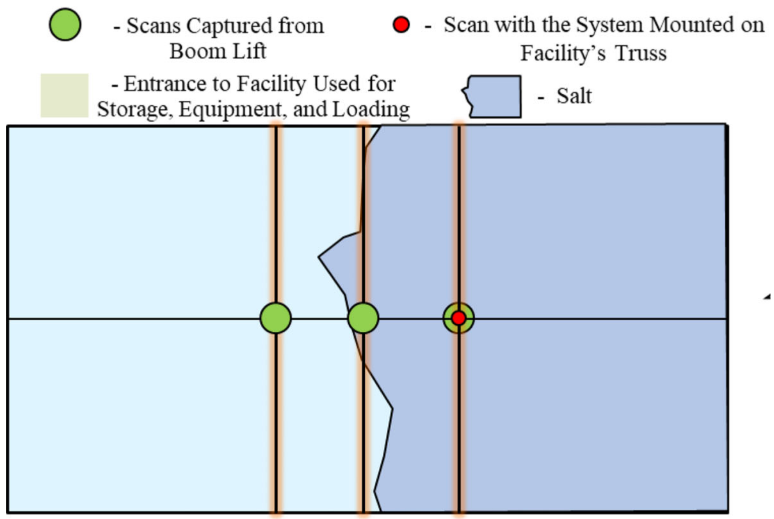
The system was mounted in the Lebanon salt barn in Figure 3.3a and salt dome in Figure 3.3b. The functionality still worked the same as the portable unit except now there is a rotating motor, seen as callout i in Figure 3.3, to perform a 270-degree rotation for scanning at 30-degree increments. This motor provided greater coverage of the storage facility, improved coarse registration quality, and reduced estimation errors, some of which were also observed in similar studies (Alsayed, Nabawy et al., 2021; EIP Enviro Controls, n.d.).

Volume estimation accuracy is influenced by the occlusions. Mounting the sensors at the peak of the structure increased visibility by 10%. In addition to careful sensor mounting, the occlusions can be minimized by pruning the peaks of salt while piling. The accuracy was also verified through terrestrial laser scanning (Manish et al., 2022).

3.3 2021–2022 Winter Monitoring Results

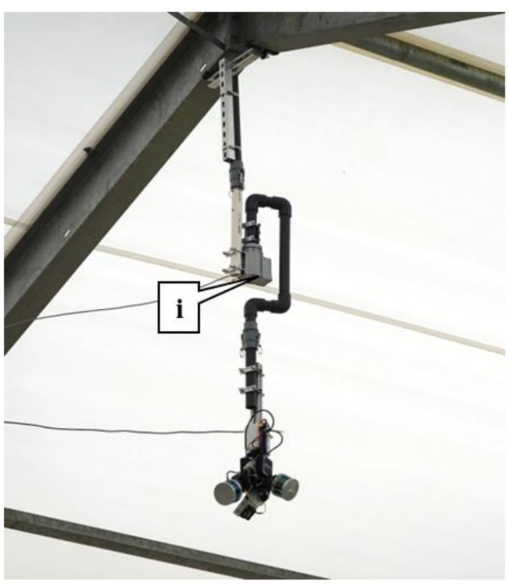
To monitor the salt stockpile inventory fluctuation during the 2021–2022 winter season, the data collection team visited 12 facilities multiple times after salt deliveries and before/after a winter storm event. These facilities were chosen due to their frequency of experiencing winter storm events, and they include some of the largest salt storage facilities in the state. Table 3.2

(a) Installation and Data Collection on Boom Lift

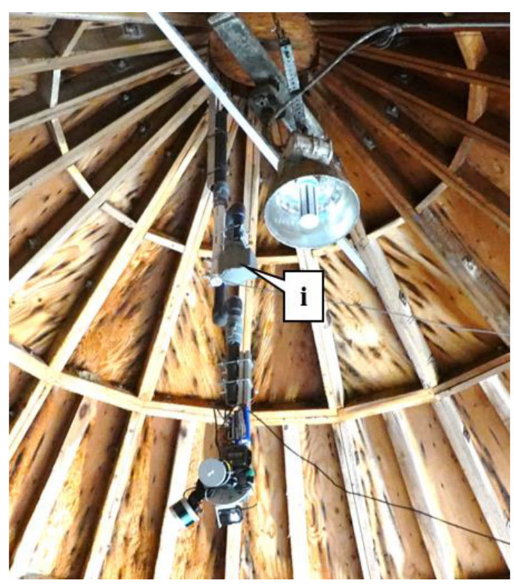


(b) Location of Scans Relative to Salt Pile

Figure 3.2 Testing locations for optimal permanent installation.



(a) Permanent Installation in a Salt Barn



(b) Permanent Installation in a Salt Dome

Figure 3.3 Permanent installation of the SMART system.

TABLE 3.2
Salt pile inventory in cubic yards over the 2021–2022 winter season

	Dates Collected																						
	2021									2022													
Name	**4/30**	**6/8**	**6/23**	**7/22**	**10/12**	**11/23**	**11/24**	**12/7**	**12/17**	**1/4**	**1/6**	**1/19**	**1/26**	**1/28**	**2/9**	**2/11**	**2/14**	**2/16**	**2/23**	**3/31**	**5/23**	**6/13**	**6/14**
Romney						715					1,137		1,099			417			519			1,216	
Crawfordsville						2,244					2,246		1,706			1,354			931			2,557	
Lebanon	1,995				1,882	1,897					1,788		1,305			1,053			2,408	2,156	3,276	3,255	
Frankfort						2,509					2,408		2,179			1,507			1,290			3,229	
Monticello								3,004				3,626						2,862	2,536			3,571	
WL River Rd						1,082						1,899				857						1,176	
WL 231	1,266	1,439		1,307					1,338			1,294			1,324	1,322			1,127			1,022	
City of Lafayette		1,789										1,729						1,495					
Rensselaer																910			1,010				
Miller			3,159				4,438	4,750		4,335							3,440						5,295
Chesterton			2,710					2,620		2,112							2,596						3,215
Michigan City			4,259					4,025		3,639							3,165						5,488

shows the 12 facilities that were monitored over the winter season and the amount of salt that was onsite at the time of the SMART salt scan.

A representation for salt over the course of a winter season at the salt barn in Lebanon, Indiana can be seen in Figure 3.4. The first scan of the winter season was taken November 23, 2021, and had 1,897 cubic yards (1,450 cubic m) of salt in the facility. The next scan was taken on January 6, 2022, after the first snow event in the area which occurred on January 2, 2022, providing the first opportunity to scan after a winter event with a volume of 1,788 cubic yards (1,367 cubic meters). The team continued to monitor the salt after snow events on January 26 (callout *iii*), February 11 (callout *iv*), February 23, March 31 (callout *v*), and at the end of the season on May 23 (callout *vi*) and June 13, 2022.

Monitoring the amount of salt over the winter season reveals trends during winter storm events, and when the facility received a salt delivery. This information is important to agencies as it will enable them to actively monitor their salt usage before and after a winter event. This information can also be used to determine the quantity of additional salt that should be ordered. Callouts i–vi illustrated in Figure 3.4 corresponds to the DSMs in Figure 3.5. These visuals are created in Cloud Compare from fine registered point clouds which are colorized by height (CloudCompare, n.d.; Kwak & Habib, 2014). Blue represents the ground surface and red represents the top of the salt pile which is approximately 4.4 yds high. Figure 3.5a corresponds to callout *i* in Figure 3.4, Figure 3.5b to callout *ii*, Figure 3.5c to *iii*, Figure 3.5d to *iv*, Figure 3.5e to *v*, and Figure 3.5f to *vi*. The largest difference in salt totals can be observed between Figure 3.5d where the salt total is at, 1,053 cubic yards, Figure 3.5e where the total is 2,408 cubic yards, and Figure 3.5f where the salt total is 3,276 cubic yards.

Figure 3.6 shows the representative camera images of the salt stockpiles. These images show the removal and refill of material over time-from the untampered "white" appearing salt in the early days to the green salt in the middle, and the refilled stockpile a mt the end. It should be noted that the salt may have varying color depending on added chemicals or fading of the top layer over time. Figure 3.5a aligns with Figure 3.6a, along with the remaining figures. Similar to Figure 3.5, the largest difference in salt totals can be observed between Figure 3.6d–f.

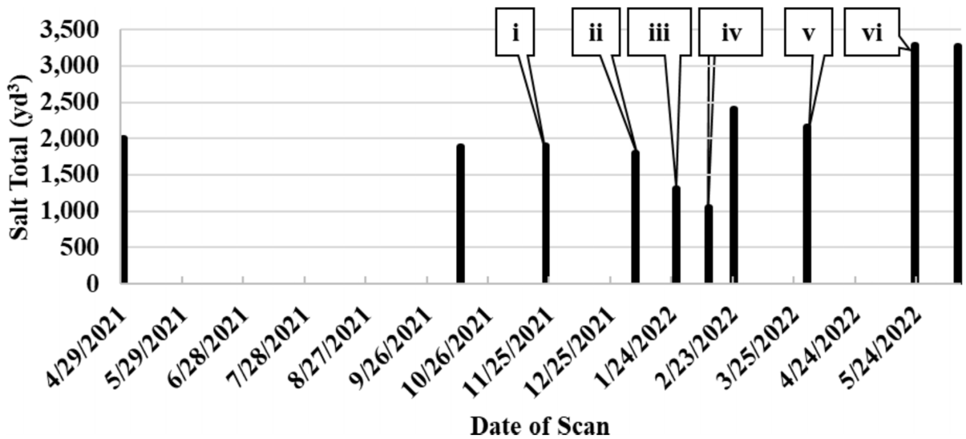


Figure 3.4 Total salt over the 2021–2022 winter season in the Lebanon, Indiana salt facility.

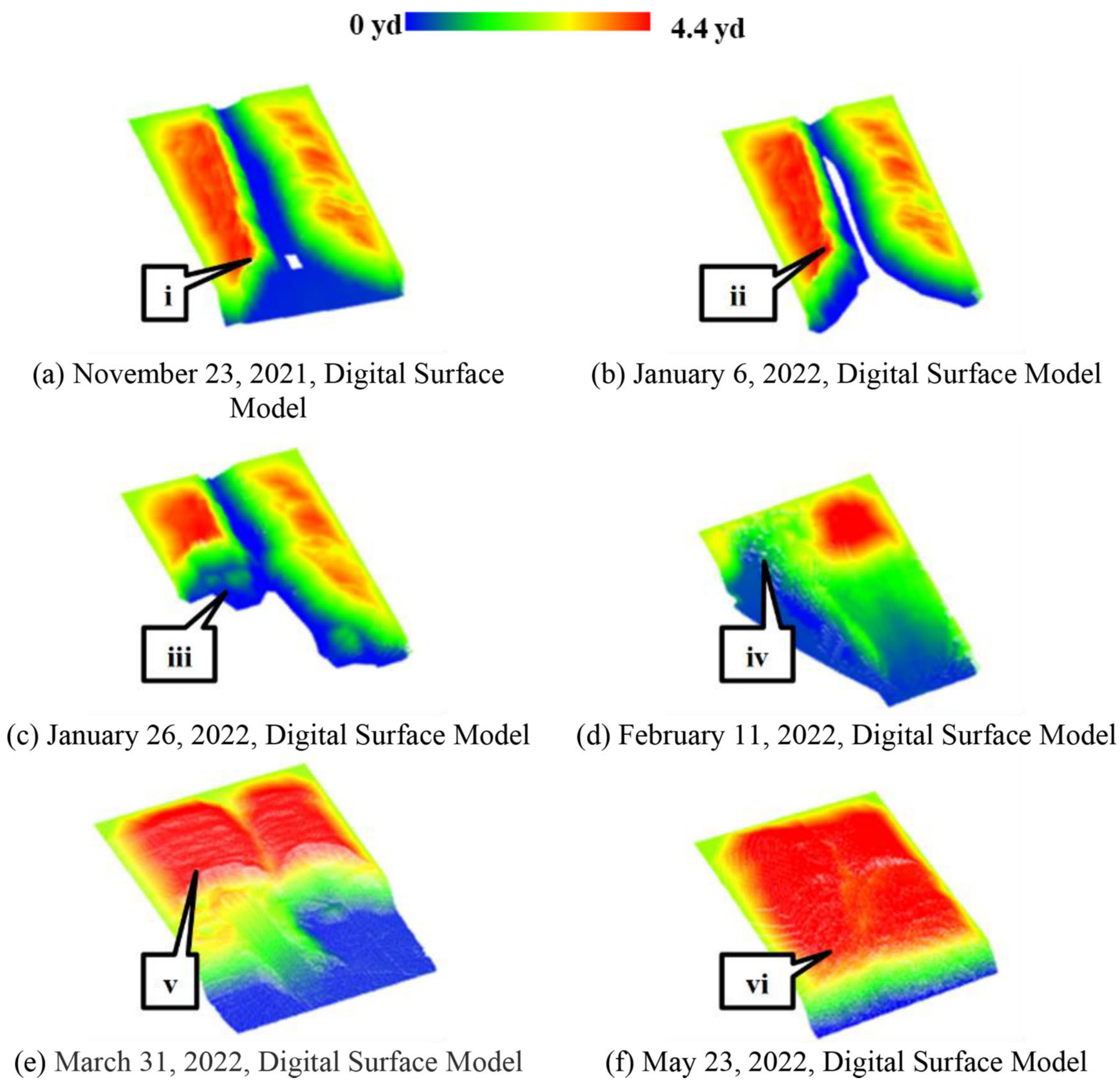
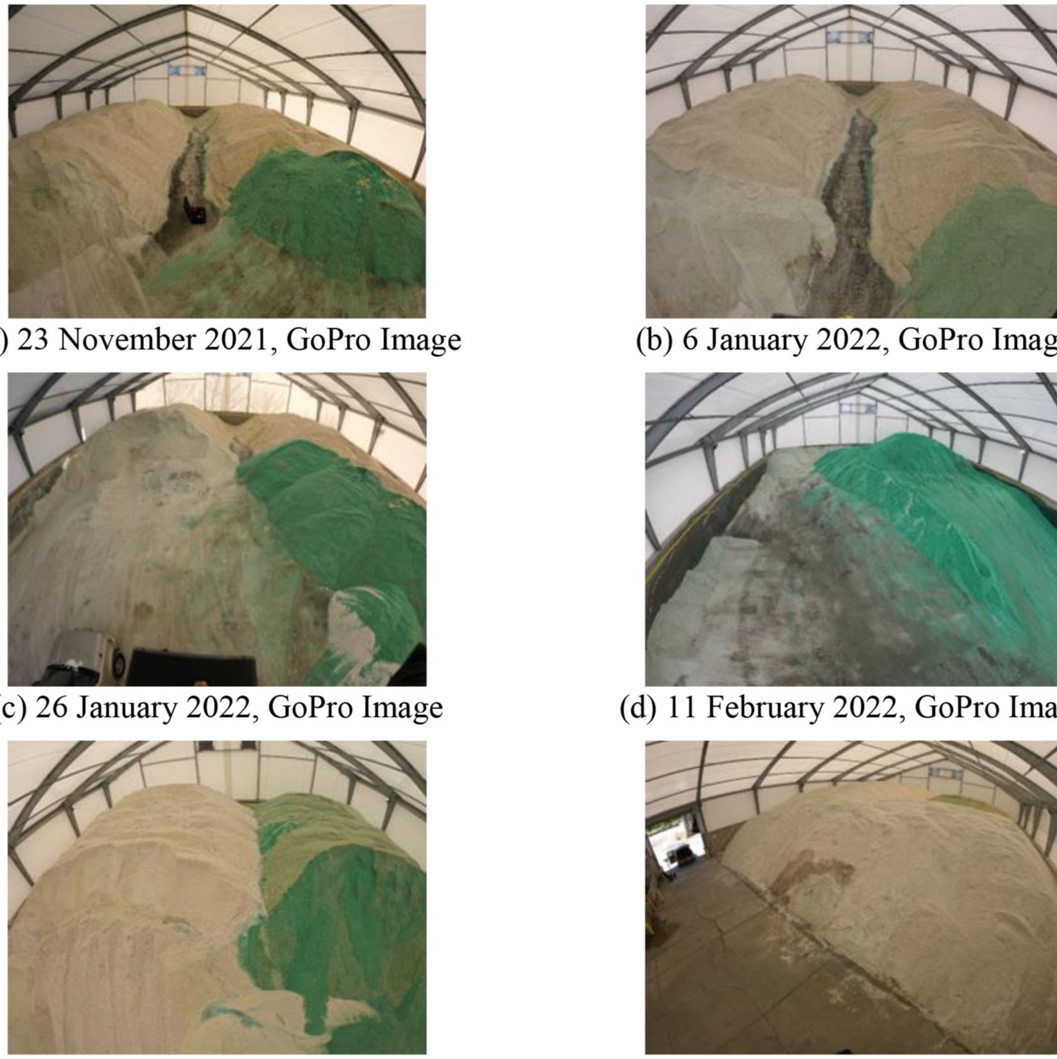


Figure 3.5 Digital surface models of Lebanon salt over the 2021–2022 winter season.



(a) 23 November 2021, GoPro Image

(b) 6 January 2022, GoPro Image

(c) 26 January 2022, GoPro Image

(d) 11 February 2022, GoPro Image

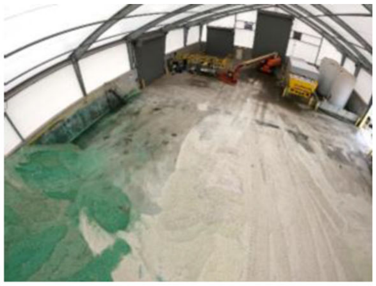
(e) 31 March 2022, GoPro Image

(f) 23 May 2022, GoPro Image

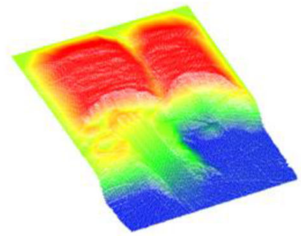
Figure 3.6 GoPro images of corresponding Lebanon salt piles for the 2021–2022 winter season.

4. FIELD VALIDATION OF VOLUMES

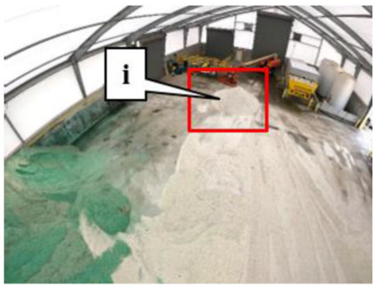
The principles of conservation of volume are used to provide a quick test of the system. To determine and validate the accuracy of the SMART salt system, a salt repositioning test was performed. This test collected data in a series of four scans with the permanent installation in the salt barn. The initial scan can be seen in a GoPro image collected directly from the system as Figure 4.1a and as a digital surface model from the processed point clouds in Cloud Compare as Figure 4.1b (CloudCompare, n.d.). This serves as the baseline volume for the following three scans. The total volume is 2,156 cubic yards (1,648 cubic meters). A payloader moved five buckets of salt from the initial stockpile to the front of the pile/facility (in the storage/loading area) to simulate the removal of salt for use on roadways, which can be seen as callout i in Figure 4.1c, d. After scanning, the initial stockpile has 2,149 cubic yards (1,643 cubic meters) and the moved salt is 9 cubic yards (6 cubic meters) bringing the total to 2,158 cubic yards (1,649 cubic meters). From the original scan, this is a 0.09% error. Five additional buckets were removed from the initial pile making a total of 10 removed buckets. The moved salt is referenced as callout *ii* in the GoPro image (Figure 4.1e) and in the digital surface model (Figure 4.1f). The initial stockpile now has a volume of 2,136 cubic yards (1,633 cubic meters), and the moved salt has a volume of 21 cubic yards (16 cubic meters) making a total of 2,157 cubic yards (1,649 cubic meters) and a 0.04% error. The moved salt was then returned to the initial stockpile and rescanned seen in Figure 4.1g,h. The total volume is 2,156 cubic yards (1,648 cubic meters) which was identical to the initial scan, meaning a 0.00% error. This validation test proved effective in determining the accuracy of the SMART salt system as the error observed was exceptionally low, depending on the occlusion percentage,



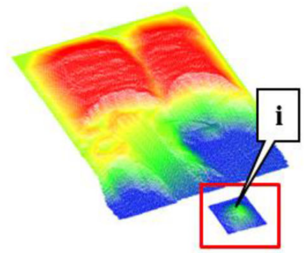
(a) GoPro Image Before Salt Repositioning



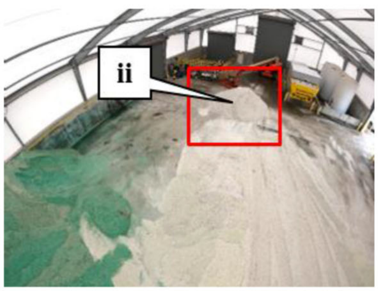
(b) Digital Surface Model Before Salt Repositioning



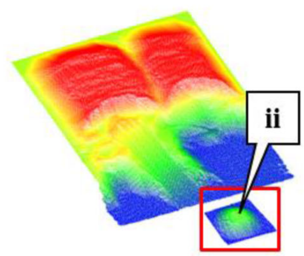
(c) GoPro Image with 5 Buckets Repositioned



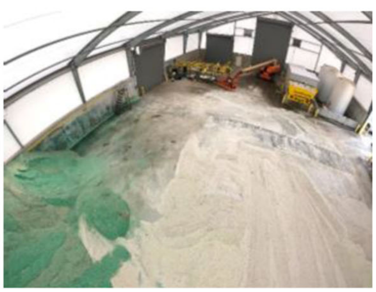
(d) Digital Surface Model with 5 Buckets Repositioned



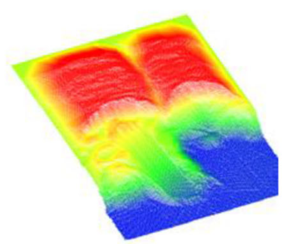
(e) GoPro Image with 10 Buckets Repositioned



(f) Digital Surface Model with 10 Buckets Repositioned



(g) GoPro Image After Salt Repositioning



(h) Digital Surface Model After Salt Repositioning

Figure 4.1 Data validation through salt repositioning.

vastly improving traditional methods of determining salt stockpile inventories, which inherently introduce a human interpretation/observation ambiguity/error.

5. CONCLUSIONS

This study showed the use and validation of the new Stockpile Monitoring and Reporting Technology (SMART) system that utilizes two LiDAR Sensors and a camera to determine accurate volume estimations of salt stockpiles. Using this system enables integrated visualizations of digital surface models and camera images to provide context to the accurate volume estimation. This portable or permanent system solves a large logistical problem of salt stockpile management for over 120 INDOT facilities across the state. The portable system was utilized during the 2021–2022 winter season for regular monitoring of 12 facilities and almost 100 scans. The 2022–2023 winter season monitored over 120 facilities and over 200 scans, outlined in Appendix A of the report. The volume estimate error is about 1%–3%, dependent on the occlusion percentage of the scan, providing the agency with a more concise and efficient method for determining stockpile quantities statewide.

The data this system delivers has the capability to provide the agency with a better understanding of salt usage during various parts of a winter storm and at all their facilities. The portable system provides versatility in not having a fixed asset in a barn. This system could be used to cover multiple facilities over the course of the winter and even be expanded for other stockpiles (e.g., asphalt, gravel, etc.) Another option with this system is a permanent installation, which would enable the agency to determine salt usage throughout a storm event and unit level usage. Additionally, this system could be integrated with the INDOT Management Information System (MIS) to provide notifications when stockpiles need replenishment or are at capacity to aid with stockpile delivery logistics. The system cost based on the current market rate of its components is about USD 10,000, and through various developmental phases, the data processing time to estimate volume has reduced from almost half day to under an hour. These costs currently only include the cost of the equipment. The computing time and process is still being improved, resulting in the annual cost of managing equipment and data to be reduced as well. Hence, with the increasing demand and reduction in the cost of LiDAR sensors, as well as further developments in hardware/software automation, the system is expected to become more cost-efficient and capable to provide end-users a near real-time volumetric assessment.

REFERENCES

Ajayi, O. G., & Ajulo, J. (2021). Investigating the applicability of unmanned aerial vehicles (UAV) photogrammetry for the estimation of the volume of stockpiles. *Quaestiones Geographicae*, *40*(1), 25–38. https://doi.org/10.2478/quageo-2021-0002

Alsayed, A., Nabawy, M. R. A., Yunusa-Kaltungo, A., Arvin, F., & Quinn, M. K. (2021). *Enhancing 1D LiDAR scanning for accurate stockpile volume estimation within drone-based mapping systems*. American Institute of Aeronautics and Astronautics.

Alsayed, A., Yunusa-Kaltungo, A., Quinn, M. K., Arvin, F., & Nabawy, M. R. A. (2021). Drone-assisted confined space inspection and stockpile volume estimation. *Remote Sensing*, *13*(17), 3356. https://doi.org/10.3390/rs13173356

Bagenstose, K. (2019, December 24). Heavy road salt use in winter is a growing problem, scientists say. *USA Today*. https://www.usatoday.com/story/news/nation/2019/12/24/winter-weather-road-salt-use-problems/2741286001/

Breining, G. (2017, November 6). We're pouring millions of tons of salt on roads each winter. Here's why that's a problem. *Ensia*. Retrieved July 6, 2022, from https://ensia.com/features/road-salt/

CloudCompare. (n.d.). *CloudCompare 3D point cloud and mesh processing software Open Source Project, Version 2.6.1* [Computer software]. Retrieved March 21, 2022, from http://www.cloudcompare.org/

Dargie Chekole, S. (2014). *Surveying with GPS, total station and terresterial laser scanner: a comparative study school of architecture and the built environment* [Master's thesis, Royal Institute of Technology]. https://doi.org/10.13140/RG.2.2.23262.92488

EIP Enviro Controls. (n.d.). *3D stockpile inventory pole mounted* [Webpage]. Retrieved August 24, 2023, from https://eipenviroindia.com/3d-stockpile-inventory-pole-mounted-or-inside-warehouse/

FHWA. (2023, February 1). *Snow and ice* [Webpage]. Federal Highway Administration. Retrieved July 6, 2022, from https://ops.fhwa.dot.gov/weather/weather_events/snow_ice.htm

He, H., Chen, T., Zeng, H., & Huang, S. (2019). Ground control point-free unmanned aerial vehicle-based photogrammetry for volume estimation of stockpiles carried on barges. *Sensors*, *19*(16), 3534. https://doi.org/10.3390/s19163534

Hintz, W. D., Fay, L., & Relyea, R. A. (2022). Road salts, human safety, and the rising salinity of our fresh waters. *Frontiers in Ecology and the Environment*, *20*(1), 22–30. https://doi.org/10.1002/fee.2433

Hugenholtz, C. H., Walker, J., Brown, O., & Myshak, S. (2015). Earthwork volumetrics with an unmanned aerial vehicle and softcopy photogrammetry. *Journal of Surveying Engineering*, *141*(1), https://doi.org/10.1061/(asce)su.1943-5428.0000138

Kasich, J. R., & Tayler, M. (2013, February). *Recommendations for salt storage*. Ohio's Water Resources Council.

Kaushal, S. S., Groffman, P. M., Likens, G. E., Belt, K. T., Stack, W. P., Kelly, V. R., Band, L. E., & Fisher, G. T. (2005). Increased salinization of fresh water in the northeastern United States. *Proceedings of the National Academy of Sciences of the United States of America*, *102*(38), 13517–13520. https://doi.org/10.1073/pnas.0506414102

Kelly, V. R., Cunningham, M. A., Curri, N., Findlay, S. E., & Carroll, S. M. (2018, May/June). The distribution of road salt in private drinking water wells in a southeastern New York suburban township. *Journal of Environmental Quality*, *47*(3), 445–451. https://doi.org/10.2134/jeq2017.03.0124

Knapp, K. K., Kroeger, D., & Giese, K. (2000, February 1). *Mobility and safety impacts of winter storm events in a freeway environment final report*. Center for Transportation Research and Education.

Kwak, E., & Habib, A. (2014). Automatic representation and reconstruction of DBM from LiDAR data using recursive minimum bounding rectangle. *ISPRS Journal of Photogrammetry and Remote Sensing*, *93*, 171–191. https://doi.org/10.1016/j.isprsjprs.2013.10.003

Lin, Y. C., Liu, J., Cheng, Y. T., Hasheminasab, S. M., Wells, T., Bullock, D., & Habib, A. (2021). Processing strategy and comparative performance of different mobile LiDAR system grades for bridge monitoring: A case study. *Sensors*, *21*(22), https://doi.org/10.3390/s21227550

Liu, S., Yu, J., Ke, Z., Dai, F., & Chen, Y. (2020). Aerial–ground collaborative 3D reconstruction for fast pile volume estimation with unexplored surroundings. *International Journal of Advanced Robotic Systems*, *17*(2). https://doi.org/10.1177/1729881420919948

Mahlberg, J. A., Desai, J., Li, H., Sakhare, R. S., Wells, T., & Bullock, D. M. (2022). Calibration and confidence in snowplow fleet operations and fleet telematics. *Journal of Transportation Technologies*, *12*(4), 696–710. https://doi.org/10.4236/jtts.2022.124040

Mahlberg, J., Zhang, Y., Jha, S., Mathew, J. K., Li, H., Desai, J., Kim, W., McGuffey, J., Wells, T., Krogmeier, J. V., & Bullock, D. M. (2021). *Development of an intelligent snowplow truck that integrates telematics technology, roadway sensors, and connected vehicle*. https://doi.org/10.5703/1288284317355

Malackowski, H. A., Joseph, M., Brinster, G., Mahlberg, J., Manish, R., Koshan, Y., Habib, A. F., & Bullock, D. M. (2023). *Salt stockpile inventory - January 24 to 27, 2023-INDOT Lebanon salt facility* [Dataset]. https://purr.purdue.edu/publications/4266/1

Manish, R., Hasheminasab, S. M., Liu, J., Koshan, Y., Mahlberg, J. A., Lin, Y. C., Ravi, R., Zhou, T., McGuffey, J., Wells, T., Bullock, D., & Habib, A. (2022). Image-aided LiDAR mapping platform and data processing strategy for stockpile volume estimation. *Remote Sensing*, *14*(1), 231. https://doi.org/10.3390/rs14010231

MassDEP. (1997). *Guidelines on road salt storage*. Massachusetts Department of Environmental Protection. Retrieved July 6, 2022, from https://www.mass.gov/guides/guidelines-on-road-salt-storage

Mora, O. E., Chen, J., Stoiber, P., Koppanyi, Z., Pluta, D., Josenhans, R., & Okubo, M. (2020). Accuracy of stockpile estimates using low-cost sUAS photogrammetry. *International Journal of Remote Sensing*, *41*(12), 4512–4529. https://doi.org/10.1080/01431161.2020.1723167

Ohno, T. (1990). Levels of total cyanide and NaCl in surface waters adjacent to road salt storage facilities. *Environmental Pollution*, *67*(2), 123–132. https://doi.org/10.1016/0269-7491(90)90077-P

Salt Institute. (2015). *Salt storage handbook: Safe and sustainable salt storage*. http://www.nwpa.us/uploads/1/2/9/8/129889926/salt-institute-salt-storage-handbook.pdf

Sampath, A., & Shan, J. (2007). Building boundary tracing and regularization from airborne lidar point clouds. *Photogrammetric Engineering & Remote Sensing*, *73*, 805–812.

TRB. (1991). Highway deicing comparing salt and calcium magnesium acetate. *Highway Deicing: Special Report 235*, 16–30. Transportation Research Board.

Yilmaz, H. M. (2010). Close range photogrammetry in volume computing. *Experimental Techniques*, *34*(1), 48–54. https://doi.org/10.1111/j.1747-1567.2009.00476.x

Zhu, J., Yang, J., Fan, J., Danni, A., Jiang, Y., Song, H., & Wang, Y. (2018). Accurate measurement of granary stockpile volume based on fast registration of multi-station scans. *Remote Sensing Letters*, *9*(6), 569–577. https://doi.org/10.1080/2150704X.2018.1452060

APPENDICES

Appendix A. Implementation Activities

Appendix B. Permanent Install User Guide

Appendix C. January 25th Winter Event Visuals

APPENDIX A. IMPLEMENTATION ACTIVITIES

A.1 Permanent Installation

A.1.1 Prototype Fixed Installations

INDOT identified two candidate locations for the installation of a permanent system due to the size of the barn, frequent changes in stockpiled amount, and relative proximity to stakeholders involved. A SMART permanent solution was installed in the salt barn at the Lebanon unit in November of 2022 and Indianapolis Subdistrict in January of 2023. These systems are shown in Figure A.1a, b below. The permanent installations are denoted by callout *i* and *ii* in the below figure. The fixed SMART permanent installation simplifies the data collection process, and data is recorded with higher precision. The rotating motor on the permanent installation makes the process repeatable, and the post processing time is significantly reduced as consistent rotations help streamline the coarse registration between scans. Between the two systems, there were over 40 data collections performed during the 2022–2023 winter season. Appendix B shows a step-by-step user guide on how to operate the prototyped permanent installed system. A video showing the results obtained from the permanent installation in Lebanon is shown here: https://doi.org/10.4231/4MAG-JN90 (Malackowski et al., 2023).

(a) Lebanon Unit Permanent Install

(b) Indianapolis Subdistrict Permanent Install

Figure A.1 SMART permanent install locations.

Figure A.2 represents the salt usage out of the Lebanon Unit through the 2022–2023 winter season. Scans range from November 16, 2022, to February 28, 2023. The first major event occurred on December 22nd, followed by three major winter events in January. The first occurred around January 24th, then on the 27th and the 29th. Figure A.2 shows the steady decrease of salt in storage due to the winter events. After the third snow event, salt was delivered to refill the facility to prepare for the remainder of the winter. The first storm occurred on January 25th and required the facility to use 443 tons of salt during the first day of the storm and an additional 143 tons by January 27th to fully clear the roads from the event. The next event occurred on the 29th and observed 294 tons leave the facility based on the January 30th scan. The team returned to the facility on February 1st to scan the restock of salt the unit received and accounted for an increase of 300 tons. There were several other scans performed through February with no major changes observed.

A Digital Surface Model (DSM) of the salt pile along with collecting images for confirmation provides context to the data collections. The DSM for each scan from callout a–e from Figure A.2 can be visualized in Figure A.3. Figure A.4 is the supporting images for the scans. It can be noted that between callouts b and c, a multiday winter storm occurred and during that first day of the storm, where there was 443 tons of salt used, and callout d is after the entire storm cleanup is complete. In total, 577 tons of salt were used by that single unit during the storm cleanup operation. During this storm, scans were performed each time salt left the facility. The results of these scans are summarized in Table A.1. Manual recording methods would assume each truck used the same amount of salt, but the SMART system shows how each truck refill varies. This illustrates how discrepancies can form over many truckloads. A video with photos, digital models and the changing stockpile volume estimates is available through the following link https://doi.org/10.4231/4MAG-JN90 (Malackowski et al., 2023).

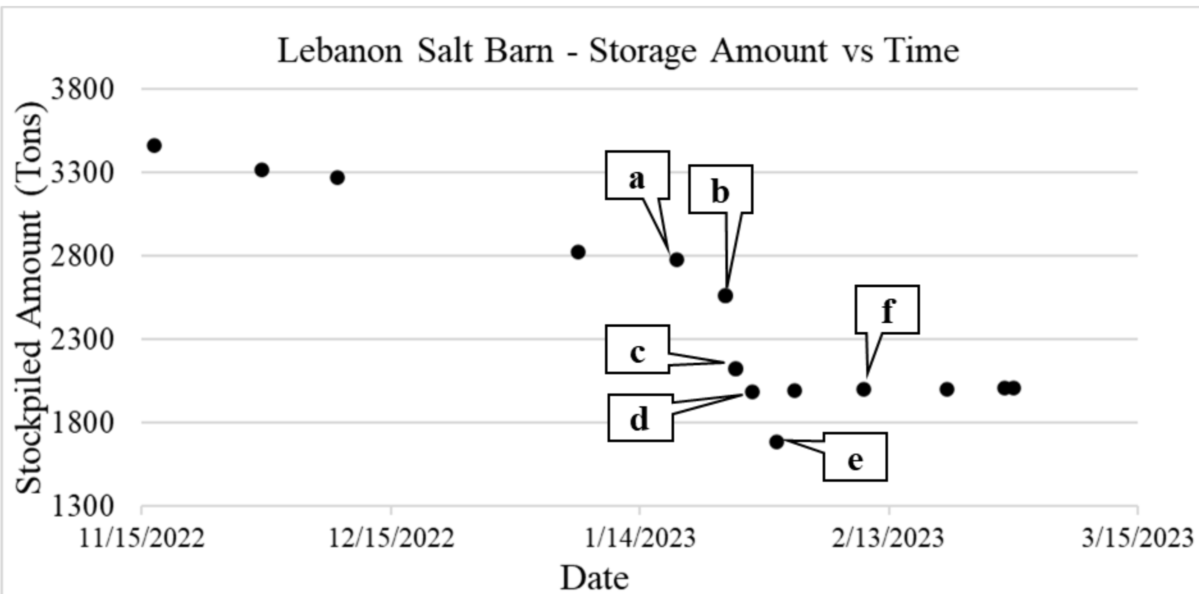
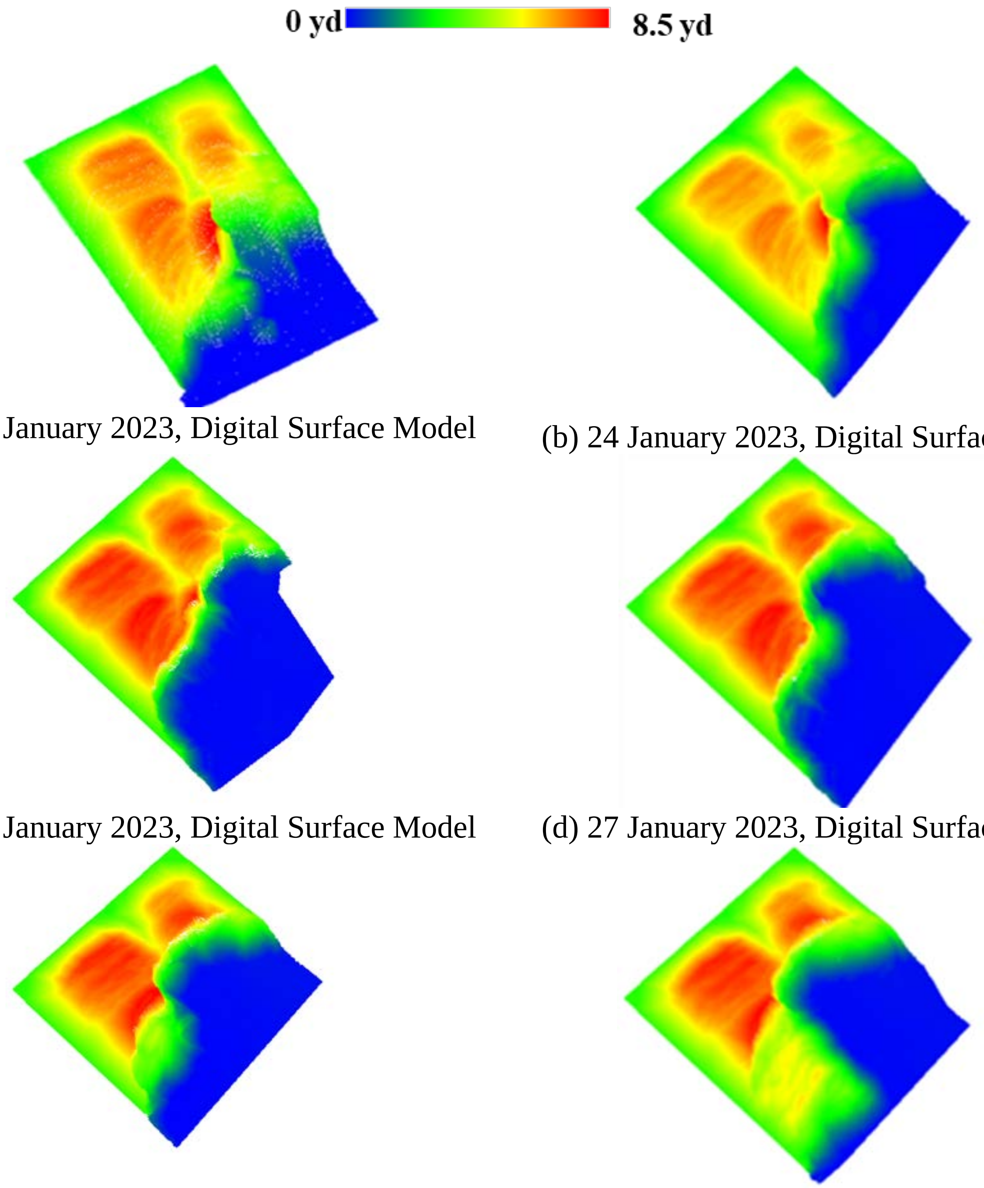


Figure A.2 Current salt usage over the 2022–2023 winter season in the Lebanon, Indiana salt facility.



(a) 18 January 2023, Digital Surface Model

(b) 24 January 2023, Digital Surface Model

(c) 25 January 2023, Digital Surface Model

(d) 27 January 2023, Digital Surface Model

(e) 30 January 2023, Digital Surface Model

(f) 10 February 2023, Digital Surface Model

Figure A.3 Digital surface models of Lebanon salt over the 2022–2023 winter season.

(a) 18 January 2023, GoPro Image

(b) 24 January 2023, GoPro Image

(c) 25 January 2023, GoPro Image

(d) 27 January 2023, GoPro Image

(e) 30 January 2023, GoPro Image

(f) 10 February 2023, GoPro Image

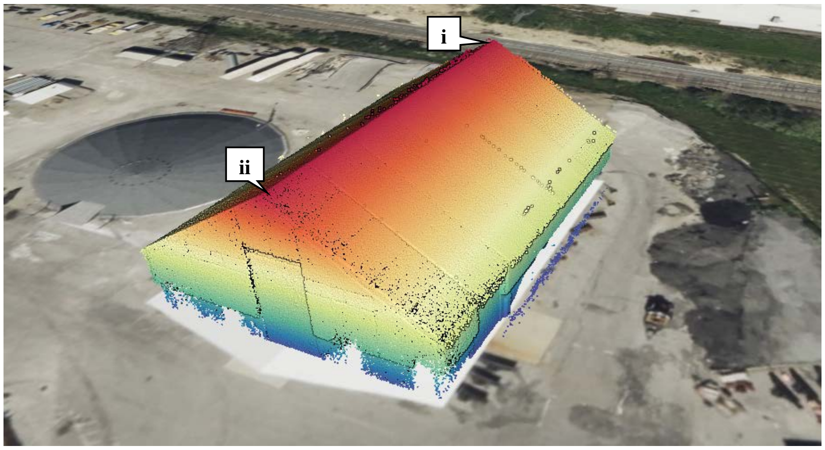
Figure A.4 GoPro Images of corresponding Lebanon salt piles for the 2022–2023 winter season.

Table A.1 Lebanon Salt Usage–Jan 25th Winter Storm

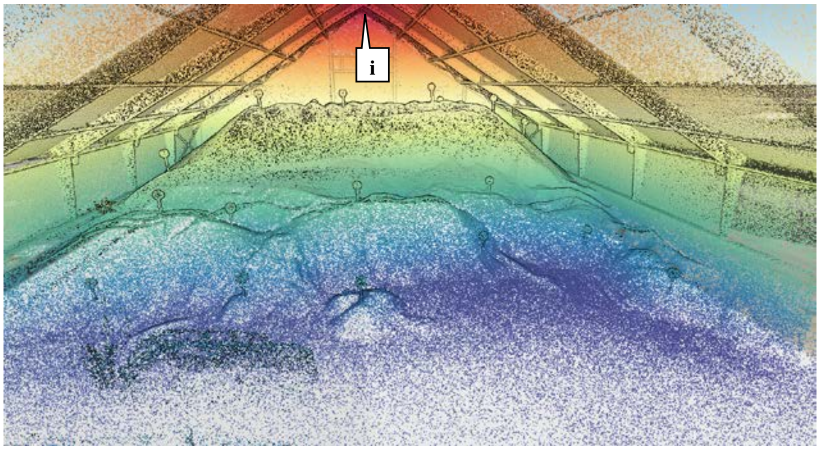
#	TIME	Amount (tons)
0	01/24/2023–09:41	2,561
1	01/25/2023–08.36	2,289
2	01/25/2023–08:47	2,285
3	01/25/2023–09:01	2,273
4	01/25/2023–09:12	2,268
5	01/25/2023–09:59	2,222
6	01/25/2023–10:22	2,220
7	01/25/2023–10:41	2,209
8	01/25/2023–11:06	2,196
9	01/25/2023–11:12	2,190
10	01/25/2023–11:22	2,184
11	01/25/2023–11:30	2,178
12	01/25/2023–11:39	2,169
13	01/25/2023–11:44	2,154
14	01/25/2023–12:30	2,148
15	01/25/2023–12:39	2,142
16	01/25/2023–13:34	2,137
17	01/25/2023–13:49	2,125
18	01/25/2023–14:49	2,116
19	01/25/2023–15:27	2,118
20	01/27/2023–1:00	1,984

A.1.2 Future Implementation

The results from the prototypes have resulted in an expanded effort for further fixed installations statewide. Recent development in LiDAR sensors have greatly improved sensors by eliminating moving parts, providing a larger field of view, and more scan lines. Testing indicates that the new sensor location should be at the peak of the facilities (as tall as possible) and located at the ends of each building peak. Figure A.5a shows a point cloud from a lidar scan conducted in the INDOT salt barn at the Fort Wayne District. Callouts *i* and *ii* show the approximate locations anticipated for permanent sensor mounting locations. Figure A.5b shows the interior of the building and the salt pile. Callout *i* shows the same location as callout *i* in Figure A.5a but the interior suggested mounting location at the peak of the building. Power and internet would be needed in a NEMA enclosure in the building with conduits run to each of the sensor locations (*i*, and *ii*) to provide power over ethernet connection to the sensors. The NEMA box should be easily accessible and all installed equipment will be required to be rated IPX6 or better to protect against the corrosive salt environment. Additional field testing will be conducted in August 2023 to validate these mounting locations.



(a) LiDAR Scan of Exterior of Salt Facility

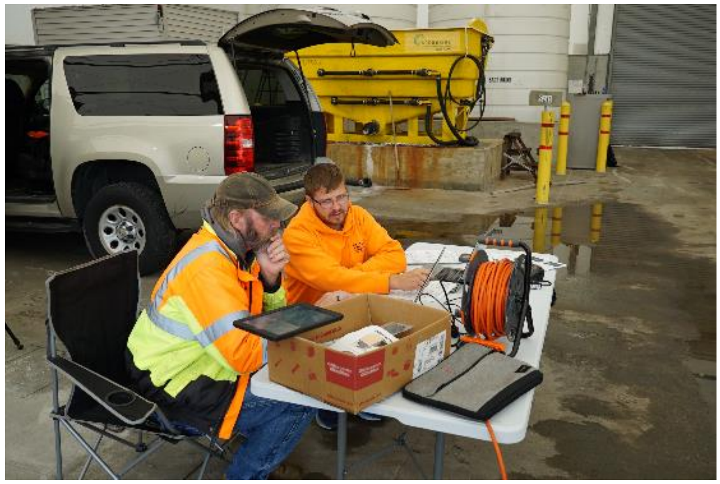


(b) LiDAR Scan of Interior of Salt Facility

Figure A.5 Approximate permanent LiDAR sensor mounting locations for the Ft Wayne salt barn.

A.2 INDOT Data Collection Training

Including INDOT in data collection was critical in refining the sensor design and obtaining statewide data collection from over 120 facilities. INDOT staff were trained on two portable units. The training workshops covered system set up, tear down, operation, and file management. By the end of the workshop, the data collection team was able to perform test scans with the system before they scanned all the facilities statewide. Figure A.6 show examples of the hands-on training for the INDOT colleagues.



(a) Fall 2022 SMART Training Workshop – File Management Training

(b) Fall 2022 SMART Training Workshop – System Operation Training

Figure A.6 INDOT training workshop on SMART portable units.

A similar training was held in February 2023 to demonstrate operation of the permanent solution (Figure A.7). A handout was distributed during the training, and a hands-on demo was performed to show how to operate the system. The operating manual can be found in Appendix B.

Figure A.7 Winter 2023–permanent install operation training.

A.3 2022–2023 Winter Monitoring Results

In March 2023, the INDOT/Purdue team used the portable SMART system to scan 123 salt storage facilities that have an approximate capacity of 350,000 tons. From March 6 to March 22, 2023, two INDOT staff members conducted scans of all facilities. This data would help plan the locations they would strategically allocate their late season salt purchases. Those 123 salt storage facilities were found to have approximately 225,000 tons of salt. The remaining capacity identified in each facility was used to allocate locations to store 53,000 tons of post season salt purchases.

Table A.2 shows a summary of the pre-season and post-season scans for all the facilities compared to their designed capacity. This statewide effort was valuable to show the scalability of the system and helped continue development as feedback came in from both the field team and the processing team.

Table A.2 Winter 2022–2023 Statewide Salt Inventory

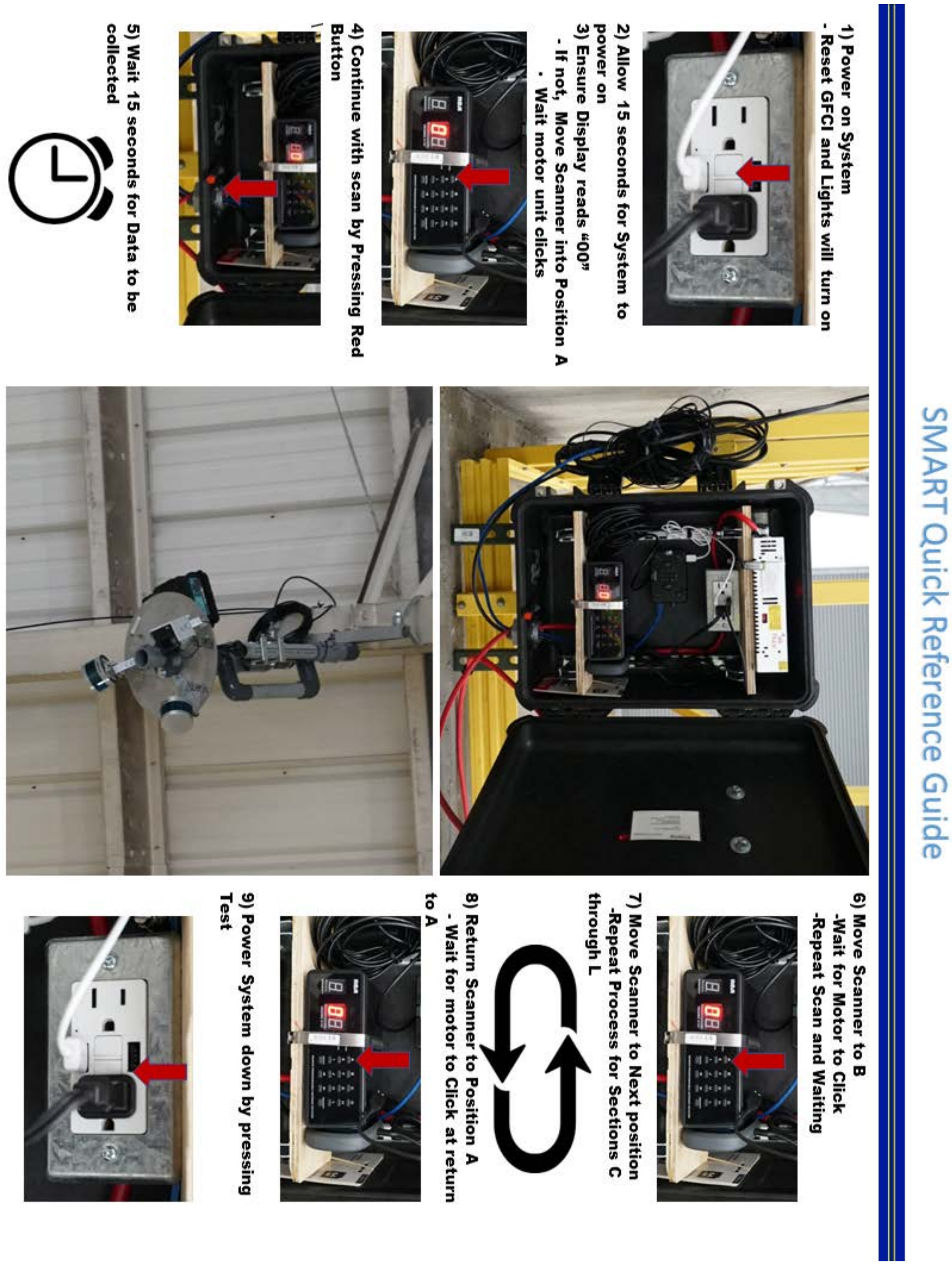
Unit Name	Unit Type	Preseason Scan Date	Pre-season Tons	Post-season Scan Date	Total Salt (tons)	Conveyed Capacity (80%)
71st	Dome	11/2/2022	1,835	3/13/2023	2,090	3,293
Aberdeen	Dome	1/17/2023	715	3/7/2023	642	1,070
Albany	Barn	11/15/2022	3,943	3/15/2023	3,833	4,333
Albany Portland	Dome	N/A	N/A	3/15/2023	499	714
Alexandria	Barn	11/21/2022	2,387	3/13/2023	2,349	3,134
Amity	Dome	12/12/2022	339	3/6/2023	747	1,242
Anderson	Dome	11/21/2022	2,704	3/15/2023	3,121	3,322
Angola	Dome	1/31/2023	1,717	3/21/2023	1,979	3,518
Ashboro	Dome	1/12/2023	1,319	3/14/2023	1,163	1,295
Aurora	Barn	11/3/2023	4,791	3/7/2023	5,701	5,765
Bainbridge	Dome	1/19/2023	3,844	3/13/2023	3,796	3,496
Beanblossom	Barn	11/18/2022	2,064	3/8/2023	1,017	1,766
Bedford	Dome	2/2/2023	1,964	3/8/2023	1,890	3,301
Birdseye	Dome	1/30/2023	1,901	3/7/2023	2,364	3,713
Bloomingdale	Barn	N/A	N/A	3/13/2023	176	1,513
Bloomingdale	Dome	N/A	N/A	3/13/2023	1,065	1,513
Bloomington	Dome	2/7/2023	602	3/8/2023	,563	1,068
Bloomington	Barn	2/7/2023	1,809	3/8/2023	1,815	1,068
Bluffton	Barn	11/3/2023	4,628	3/20/2023	3,499	6,402
Boyle	Dome	2/1/2023	949	3/7/2023	949	1,573
Brimfield	Dome	1/4/2023	2,871	3/21/2023	3,091	3,264
Brookville	Barn	10/28/2022	3,634	3/7/2023	2,466	3,020
Brownstown	Dome	N/A	N/A	3/15/2023	617	1,408
Brownstown	Barn	N/A	N/A	3/6/2023	977	1,408
Cambridge City	Barn	11/15/2022	4,743	3/14/2023	2,908	4,116
Carbondale	Dome	1/9/2023	1,236	3/14/2023	1,271	1,333
Chandler	Dome	1/19/2023	574	3/7/2023	481	1,054
Chesterton	Barn	11/14/2023	5,173	3/21/2023	4,770	11,165
Chrisney	Dome	1/18/2023	1,040	3/7/2023	661	3,090
Cloverdale	Dome	11/16/2022	863	3/13/2023	566	1,283
Columbus	Dome	2/13/2023	2,395	3/8/2023	1,989	3,905
Corydon	Dome	2/1/2023	723	3/9/2023	1,012	1,598
Crane	Barn	2/2/2023	2,097	3/8/2023	1,221	3,109
Crawfordsville	Barn	12/21/2022	3,243	3/13/2023	2,162	3,020
Crown Point	Dome	11/7/2022	2,741	3/22/2023	2,844	3,319

Unit Name	Unit Type	Preseason Scan Date	Preseason Tons	postseason Scan Date	Total Salt (tons)	Conveyed Capacity (80%)
Dale	Barn	1/18/2023	2,165	3/7/2023	1,851	4,770
Derby	Dome	1/24/2023	1,006	3/7/2023	896	1,399
Elkhart	Dome	12/13/2022	2,943	3/21/2023	2,829	4,873
Elkhart - New Paris	Dome	N/A	N/A	3/21/2023	136	4,873
Evansville	Barn	1/19/2023	1,171	3/7/2023	1,184	1,405
Flora	Dome	2/7/2023	1,139	3/20/2023	1,144	1,336
Fort Wayne	Barn	11/7/2022	4,715	3/20/2023	3,311	6,602
Fort Wayne	Dome	11/7/2022	2,958	3/20/2023	TOO FULL	
Fortville	Dome	11/21/2022	1,838	3/15/2023	2,578	2,907
Fowler	Dome	1/9/2023	2,965	3/15/2023	2,875	3,625
Frankfort	Dome	1/9/2023	3,474	3/15/2023	3,144	3,530
Ft Harrison	Dome	1/12/2023	1,366	3/14/2023	1,209	1,314
Gary	Dome	1/20/2023	4,249	3/22/2023	1,905	3,082
Gas City	Dome	11/3/2022	3,182	3/22/2023	2,389	3,318
Grantsburg	Dome	1/18/2023	589	3/7/2023	500	933
Greenfield	Dome	12/12/2022	2,574	3/14/2023	2,552	2,599
Greensburg	Barn	1/17/2023	2,797	3/7/2023	2,454	3,218
Indy Sub	Barn	1/5/2023	2,763	3/23/2023	4,819	4,222
Jasper	Dome	1/18/2023	697	3/7/2023	850	1,216
Kentland	Dome	11/21/2022	1,629	3/20/2023	1,628	1,942
Kokomo	Dome	1/9/2023	893	3/13/2023	702	708
Lafayette - Lafayette	Dome	1/9/2023	2,480	3/15/2023	2,357	4,064
Lafayette - Remington	Dome	N/A	N/A	3/15/2023	1,449	4,064
LaPorte Sub	Barn	12/13/2022	2,515	3/21/2023	2,431	2,238
LaPorte Unit	Dome	N/A	N/A	3/21/2023	1,830	3,750
Laud	Dome	1/30/2023	868	3/22/2023	1,425	1,786
Lebanon	Dome	N/A	N/A	3/15/2023	294	4,661
Lebanon	Barn	N/A	N/A	3/23/2023	1,789	4,661
Liberty	Dome	1/5/2023	704	3/14/2023	726	742
Linton	Barn	2/2/2023	3406	3/8/2023	2,222	4,770
Lizton	Dome	1/19/2023	1,366	3/13/2023	TOO FULL	1,395
Logansport	Barn	11/9/2022	3,623	3/20/2023	2,569	2,889
Loogootee	Barn	1/24/2023	1,968	3/6/2023	1,851	3,109
Madison	Barn	11/3/2023	1,779	3/6/2023	1,429	1,766
Madison St	Dome	11/2/2023	2,412	3/13/2023	2,703	3,327

Unit Name	Unit Type	Preseason Scan Date	Preseason Tons	Postseason Scan Date	Total Salt (tons)	Conveyed Capacity (80%)
Markle Bluffton	Barn	11/7/2022	2,831	3/20/2023	1,977	6,402
Martinsville	Barn	11/17/2022	696	3/8/2023	711	664
Martinsville	Dome	11/17/2022	502	3/8/2023	591	664
Medaryville	Dome	12/13/2022	1,115	3/21/2023	597	1,420
Michigan City	Barn	11/14/2022	2,626	3/21/2023	3,160	4,445
Miller- Gary	Barn	11/7/2023	2,311	3/22/2023	3,138	5,538
Mishawaka	Dome	11/14/2022	2,315	3/21/2023	2,601	3,274
Monroe	Dome	11/7/2022	2,736	3/20/2023	2,362	2,029
Monticello	Barn	9/29/2022	3,600	3/20/2023	3,732	2,677
Muncie	Dome	1/3/2023	1,662	3/15/2023	2,197	2,401
New Castle	Dome	11/15/2022	965	3/14/2023	1,362	1,421
New Haven	Barn	11/7/2022	3,056	3/20/2023	2,264	6,148
Newport	Dome	2/8/2023	1,068	3/14/2023	1,132	1,330
North Vernon	Dome	12/14/2022	870	3/6/2023	811	853
Oakland City	Barn	1/24/2023	1,253	3/6/2023	1,220	2,339
Orland	Dome	1/4/2023	2,075	3/21/2023	1,846	3,518
Paoli	Dome	1/18/2023	2,847	3/8/2023	2,549	5,362
Penntown	Dome	N/A	N/A	3/7/2023	666	939
Peru	Dome	11/9/2022	2,325	3/22/2023	2,610	3,243
Plymouth	Barn	11/9/2022	4,477	3/21/2023	4,648	5,490
Poseyville	Dome	1/19/2023	782	3/6/2023	TOO FULL	1,066
Princeton	Dome	1/24/2023	470	3/6/2023	327	2,339
Rensselaer	Barn	11/9/2022	5,489	3/20/2023	6,200	11,812
Richmond	Dome	11/15/2022	2,307	3/14/2023	2,186	2,052
Rochester	Dome	11/9/2022	1,480	3/21/2023	976	1,942
Romney	Dome	2/8/2023	1,069	3/14/2023	818	1,311
Roselawn	Dome	11/9/2022	2,142	3/21/2023	2,166	1,883
Rushville	Dome	1/5/2023	979	3/14/2023	1,077	1,385
Salem	Dome	2/2/2023	730	3/9/2023	908	1,082
Scottsburg	Dome	2/2/2023	525	3/8/2023	TOO FULL	896
Sellersburg	Barn	N/A	N/A	3/9/2023	1,589	1,458
Sellersburg	Dome	N/A	N/A	3/9/2023	1,019	1,458
Seymour	Dome	11/15/2023	587	3/6/2023	711	3,082
Shelbyville	Barn	12/12/2022	329	3/14/2023	330	780
Shelbyville	Dome	12/12/2022	688	3/14/2023	660	780
Shipshewana	Dome	12/19/2022	1,349	3/21/2023	1,110	1,583

Unit Name	Unit Type	Preseason Scan Date	Preseason Tons	Postseason Scan Date	Total Salt (tons)	Conveyed Capacity (80%)
South New Haven	Dome	2/1/2023	2,271	3/20/2023	2,448	6,148
Spencer	Dome	2/7/2023	3,130	3/8/2023	3,009	3,903
Sullivan	Barn	1/24/2023	1,071	3/6/2023	1,117	3,118
TerreHaute	Dome	2/8/2023	2,472	3/14/2023	2,247	3,244
Tipton	Dome	11/21/2022	2,094	3/13/2023	2,303	3,271
Veedersburg	Dome	1/9/2023	2,029	3/13/2023	1,700	1,942
Versailles	Dome	1/17/2023	702	3/7/2023	637	896
Vincennes	Dome	1/24/2023	1,745	3/6/2023	1,910	3,456
Wabash	Barn	11/14/2022	3,139	3/22/2023	2,318	6,203
Wanatah	Dome	11/9/2022	4,387	3/21/2023	5,356	5,766
Warsaw	Dome	12/19/2022	1,852	3/21/2023	1,133	1,786
Washington	Dome	2/1/2023	1,596	3/6/2023	1,604	3,431
Waterloo	Dome	12/15/2022	1,241	3/21/2023	1,061	1,202
West Lafayette	Barn	11/1/2022	1,674	3/14/2023	1,317	
Westfield	Barn	11/21/2022	3,515	3/13/2023	3,266	3,063
Winamac	Dome	N/A	N/A	3/21/2023	2,906	3,319
Winchester	Barn	11/15/2022	3,080	3/15/2023	2,841	3,228

APPENDIX B. PERMANENT INSTALL USER GUIDE



APPENDIX C. JANUARY 25TH WINTER EVENT VISUALS

https://doi.org/10.4231/4MAG-JN90

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

About This Report

An open access version of this publication is available online. See the URL in the citation below.

Mahlberg, J. A., Manish R., Koshan, Y., Joseph, M., Liu, J., Malackowski, H. A., DeLoach, Z., Wells, T., McGuffey, J., Habib, A., & Bullock, D. M. (2023). *Salt monitoring and reporting technology (SMART) for salt stockpile inventory reporting* (Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2023/19). West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284317650