Feasibility of SAA to Monitor Freeze-Thaw Performance of Pavement Foundations in Cold Regions

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ABSTRACT
Frost heave and thaw weakening have a significant impact on the performance of pavement foundations in cold regions, leading to structural damage. Road Agencies use different approaches, including seasonal load restrictions (SLR), to minimize the impact of this damage. Accurate and continuous measurement of displacements caused by frost action is crucial for agencies to assess the condition and behavior of pavement foundations. Existing methods, such as vehicle-mounted laser sensors and surveying equipment, have limitations in capturing the temporal distribution of displacement in roadways. Shape Array Accelerometers (SAA) can measure the ground's displacement in real-time and come with temperature sensors that provide temperature measurements at its location. This study discusses the installation procedure and evaluates the effectiveness of SAA in characterizing frost heave-thaw settlement of flexible pavements. SAA was installed along the cross-section of a flexible pavement within the Minnesota Road Research Facility (MnROAD) mainline on Westbound I-94 near Albertville, Minnesota. Minnesota falls in the wet-freeze climatic region, making it highly susceptible to freeze-thaw damage. The collected displacement and temperature dataset for the 2022-23 freeze-thaw season was analyzed, and maximum settlement of 3.5 mm and 10.3 mm were observed in the shoulder and passing lane, respectively. The temperature data indicated that the ground started to settle when thermocouple readings went below freezing, suggesting ice lens formation, resulting in the contraction of the soil structure. After the spring thaw, a maximum residual settlement of 6.6 mm remained along the wheel paths, but the ground eventually stabilized once the thawing was complete. The efficacy of SAA in capturing real-time displacement data indicates its potential for broader implementation in similar climatic conditions.

Keywords: Frost action, spring thaw, Shape Array Accelerometer (SAA), settlement, roadways

INTRODUCTION

The effects of seasonal frost action are one of the main influencing factors responsible for the rapid degradation of highways in cold climates (Nguyen et al., 2019; Rosa et al., 2017; Sadiq et al., 2023). The strength and stiffness of the base and subgrade increase during the winter (Rosa et al., 2016). As the soils thaw and the snow and ice melt, the base and subgrade become nearly saturated due to partial thaw conditions and trapped water, resulting in a decrease in strength and stiffness, often dropping below their pre-freezing levels (Naqvi et al., 2022; Simonsen & Isacsson, 1999). Consequently, the weakened pavement is no longer capable of withstanding the initially intended load, ultimately resulting in damage and a shorter useful lifespan (Rosa et al., 2016). The extent of pavement damage is directly influenced by the magnitude and frequency of the applied load, as well as the stiffness and strength characteristics of the pavement materials (Ovik et al., 2000).

To reduce the damage caused by truckloads during the spring thaw, agencies in cold climates typically implement spring load restrictions (SLR) between late February and May as a preservation strategy (Van Deusen et al., 1998). In Minnesota, where the present study was conducted, it was found that around 13 percent of the state network and 97 percent of the county state-aid highway (CSAH) are subjected to SLR (Ovik et al., 2000). The implementation of the SLR policy is predicted to extend the life of a typical low-volume asphalt road by about 10%, potentially saving more than $10,000,000 annually (Ovik et al., 2000). Rwebangira et al. (1987) recommended imposing SLR when the spring surface deflections of pavement exceed 45 to 50 percent of the summer deflections. However, Ovik et al. (2000) highlighted the disadvantages of applying load restrictions based on deflection, citing the challenges of frequent testing and the logistical complexities required for a large number of roads. Currently, subsurface monitoring, in-situ stiffness testing, average daily air temperature, and computational modeling are primarily used for determining the length and timing of spring load restrictions (Genc et al., 2022). Subsurface monitoring provides the benefit of continuous and site-specific observations, allowing for the detection of unanticipated changes during freeze-thaw cycles. Assessing subgrade stiffness and strength in the field typically involves using falling weight deflectometer (FWD) or lightweight deflectometer (LWD) test results (Genc et al., 2022). However, this approach yields data at specific points and necessitates repeated field visits for periodic assessments. The extent of pavement damage during spring thaw is influenced by various factors such as geographic location, solar radiation, drainage, air temperature, precipitation, moisture condition, and the soil's physical, thermal, and strength properties. Thus, imposing the SLR based on only daily air temperature may not be ideal and cannot ascertain the actual condition of the pavement. An alternative and promising approach to traditional monitoring methods involves using horizontal Shape Array Accelerometer (SAA) sensors, which enable continuous, real-time monitoring of subsurface roadway displacement. Shape Array (SAA) has been used in a variety of settings, including the monitoring of unstable slopes (Uhlemann et al., 2016; V. et al., 2012), ground movements associated with mining (Swarbrick & Clarke, 2015), ground movements due to soft ground tunneling (Hansmire et al., 2017), measuring retaining wall deflection (Lipscombe et al., 2014), and track settlement (Yan et al., 2021). However, its potential for monitoring subsurface displacement during frost heave and thaw settlement has not been investigated. In this study, the application of SAA has been investigated to track changes in the subsurface structure caused by freeze-thaw cycles in a flexible pavement located on the I-94 highway in Minnesota.

FIELD STUDY AREA

The study area was located in the Minnesota Road Research facility, known as MnROAD Mainline. The mainline is a 3.5-mile 2-lane interstate roadway carrying "live" traffic on westbound I-94, located in Albertville, 40 miles northwest of Twin Cities, Minnesota. Minnesota falls in the wet-freeze climatic zone. The region's elevated freezing index and relatively high precipitation make it especially vulnerable to freeze-thaw impacts (FHWA, 2015). The westbound lanes (Mainline) experience approximately 1,300,000 flexible and 2,000,000 rigid Equivalent Single Axle Loads (ESALs) per year with 23 percent trucks. For this study, a flexible pavement test section with measurements of 76.2 meters in length and 11.9 meters in width was reconstructed. The pavement has been designed as perpetual pavement, and the thickness of the subbase, base, and asphalt course was 30.5 cm, 24 cm, and 21 cm, respectively. The grain size distributions (ASTM D6913, 2014) of the materials are illustrated in Figure 1. Base and subbase have 82.8% and 41.8% gravel contents, respectively. The sand contents of the base and subbase are 15.7% and 56.4%, respectively. The subgrade has a fine content of 47.9%. Table 1 summarizes the index properties of all materials. According to the Unified Soil Classification System (USCS), base materials were classified as GW (well-graded gravel with sand), subbase materials were classified as GP (poorly graded gravel with sand), and subgrade soil was classified as SC (clayey sand). Both subbase and base materials were classified as A-1-a, while subgrade material was classified as A-6 based on the AASHTO classification. According to the US Army Corps of Engineers' frost susceptibility classification (US Army Corps of Engineers, 1965), the subgrade soil was classified as "medium-high frost-susceptible (F3)."

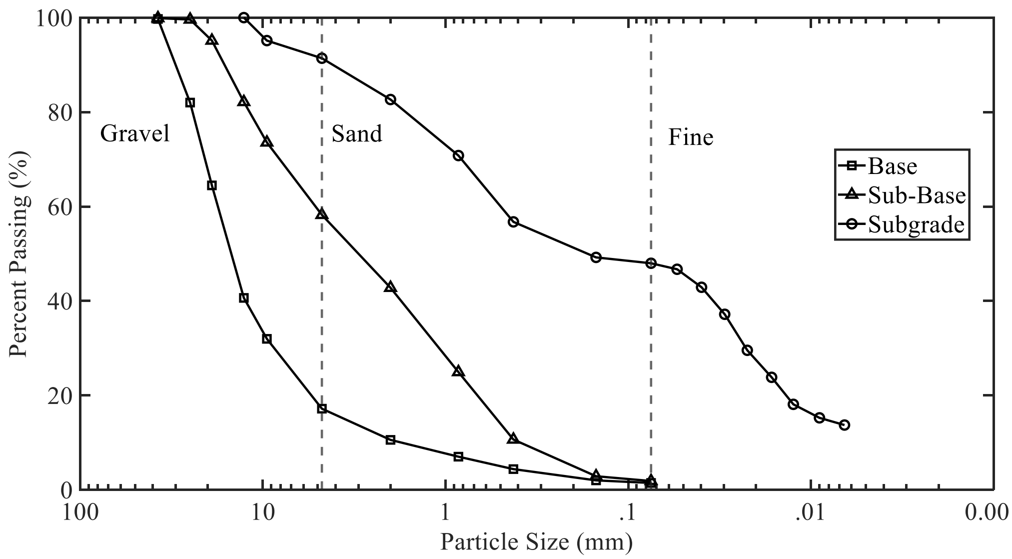

Figure 1. Grain size distribution of the geomaterials

SHAPE ARRAY ACCELEROMETERS (SAA)

The Shape Array Accelerometers (SAA) are composed of a sequence of thick-walled stainless-steel tube rigid segments. These segments are coupled by hydraulic hose couplings that possess flexibility specifically engineered to allow bending without inducing twisting. Every segment of the SAA is outfitted with three MEMS (Micro-Electro-Mechanical System) accelerometers and a digital temperature sensor. The utilization of MEMS accelerometers in the horizontal arrays facilitates the quantification of the X (vertical distances) and Z coordinates (distances along the array). Figure 2 depicts the measurement approach utilized by the MEMS sensors, determining the tilt of each segment, represented by the sine of the angle ϴ. The calculation of the relative movement of the segments involves the multiplication of the tilt angle by the length (L) of the respective segment. The displacement of the entire length of SAA can be calculated with an accuracy of 0.05 mm/m by fixing one point in the array (V. et al., 2012).

Table 1. Properties of the geomaterials

Properties		Base	Subbase	Subgrade
Gravel (%)		83	42	9
Sand (%)		16	56	44
Fine (%)		1.5	1.8	48
Compaction Characteristics	Maximum Dry Density (pcf)	120	118	111
	Optimum Moisture Content (%)	7	6	16
Liquid Limit (LL)		NP	NP	31.6
Plastic Limit (PL)		NP	NP	19.4
Plasticity Index (PI)		NP	NP	12.2
Specific Gravity (G_s)		2.23	2.25	2.68
USCS Classification$^+$		GW	SP	SC
AASHTO Classification		A-1-a	A-1-a	A-6

+ GW (well-graded gravel with sand), SP (Poorly graded sand with gravel), SC (Clayey Sand)
NP: Non-plastic

The SAAs were placed in the passing lane and the shoulder next to it (Figure 3), considering that the other side of the pavement beyond the centerline (CL) would display a similar deformation pattern. In this study, each SAA segment was 0.5 meters long, and a total of 10 sections were utilized, resulting in a combined length of 5 meters of roadway equipped with sensors (Figure 4). The SAA was positioned 12 cm below the top of the base layer (33 cm from the surface of the pavement). In accordance with the manufacturer's recommendation, the SAA was encased in schedule 80 PVC (Polyvinyl chloride) pipes with a 5 cm internal diameter (Figure 5a). Two PVC pipes were joined with PVC coupling, PVC primer, and cement were applied to secure the joint, and the pipes were then carefully placed in a trench (Figure 5b). The SAA was guided into the PVC by means of a fishing rope. The end nearest to the cable at the roadway's edge was designated as the near end, whereas the end embedded in the pavement was designated as the far end. The near end was secured by affixing it with a clamp that was connected to two steel bars embedded into the ground, each measuring 1.8 meters in length (as depicted in Figures 4 and 5c). The far end was kept free to accommodate any potential deformation. To ensure stability against heaving, considering the maximum frost penetration depth observed in MnROAD test cells from 2017 to 2019 is 1.7 meters (Cetin et al., 2021), two 1.8-meter steel bars were used. The holes for the steel rods were filled with a fast-setting concrete mix for the lower 0.3 meters and gap-graded aggregates for the upper 1.5 meters to minimize the adhesion between the steel bars and the surrounding materials, thus preventing any movement of the fixed end. The near end of the SAA was fitted with a horizontal installation kit, and the far end was fitted with a PVC cap to prevent water intrusion. After installing the SAA, the trench was backfilled with the base materials.

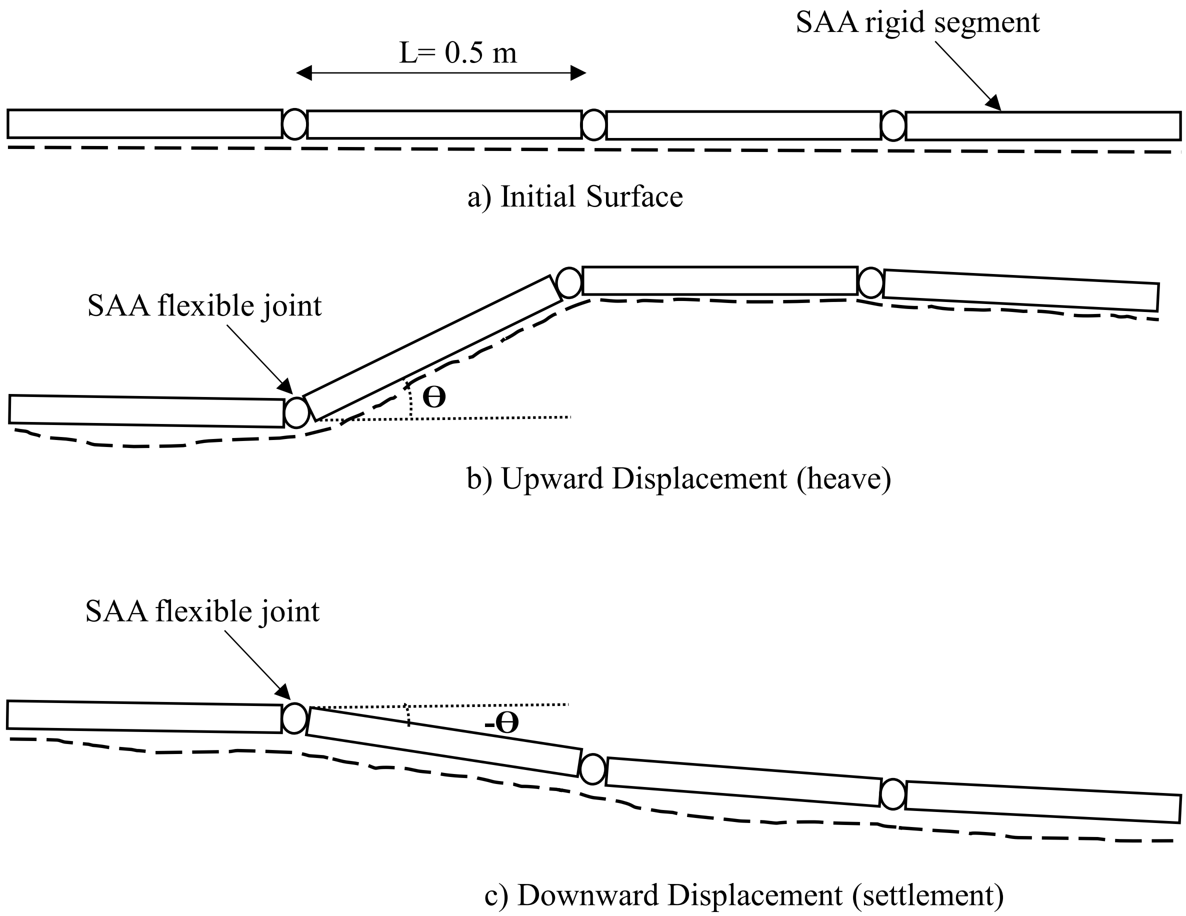

Figure 2. Working principle of SAA, a) initial surface, b) upward displacement, c) downward displacement

SAA data was collected using the Campbell Scientific CR300 data logger. To maintain sufficient voltage in the SAA segments and safeguard the sensors from power surges, an interface device (SAA-232) was connected between the logger and the Shape Array.

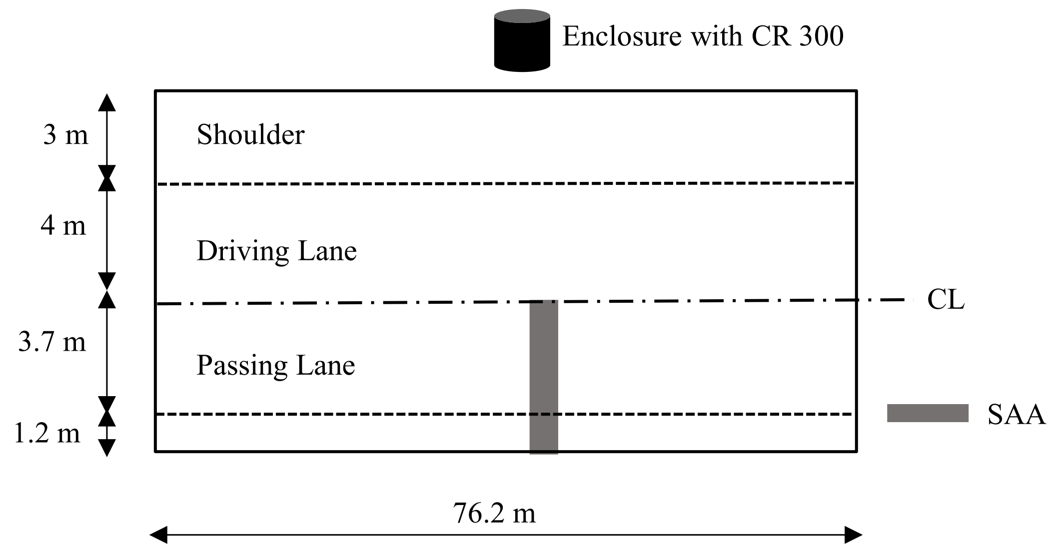

Figure 3. Plan view of the roadway with SAA

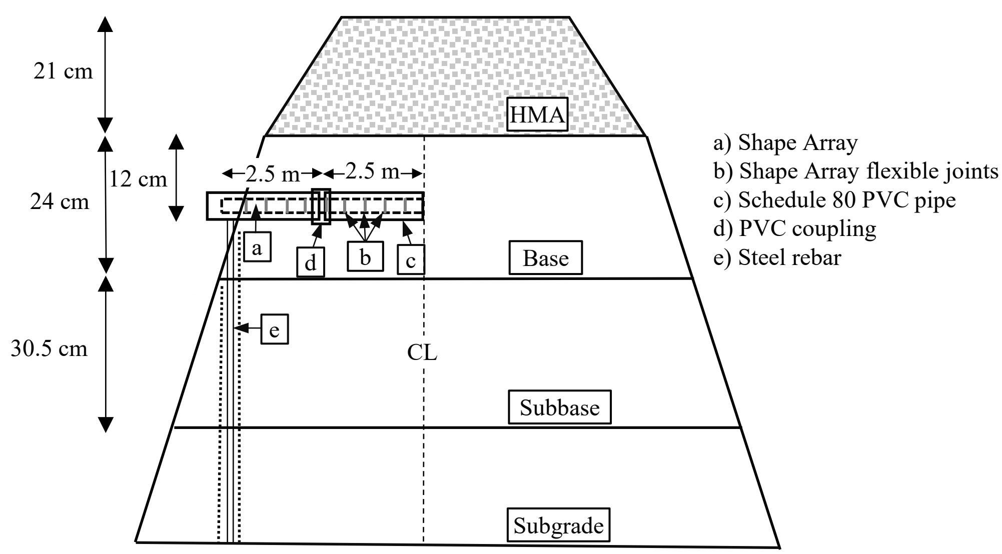

Figure 4. Schematic illustration of different elements of SAA installation (diagram is not to scale)

ANALYSIS OF TEST RESULTS AND DISCUSSIONS

Subsurface Displacement from SAA

Figure 6 illustrates the temporal profiles of vertical displacement and temperature as recorded by the SAA at a depth of 33 cm beneath the pavement surface. Initially, as the pavement was designed as a perpetual pavement, it exhibited minimal settlement of just 0.3 mm until December 20th due to consolidation and compaction from traffic loads. When the temperature dropped below freezing (0˚C), an atypical phenomenon occurred whereby the ground underwent settlement. This observation is significant as freezing temperatures are commonly linked to heaving, principally resulting from the development of ice through the freezing of pore water and consequent volume expansion (Genc et al., 2022; Naqvi et al., 2023). On March 3rd, 2023, a maximum settlement of 8.2 mm and 9.8 mm was observed along the outer and inner wheel paths, respectively. This can be attributed to the contraction of soil structure. The overlying load from the thick asphalt layer (21 cm), overlying material of the base layer (12 cm) above SAA, and heavy traffic were large, and the ice lenses formed during freezing were not strong enough to lift the overlying structure/profile. Thus, the freezing of water within the soil caused the soil structure to contract, filling the void spaces and resulting in a net decrease in volume and subsequent settlement. Besides, the water ingression during freezing in the unfrozen zone can result in consolidation (Zhang et al., 2016), and the net displacement of the pavement structure is a combination of all these factors. As freeze-thaw action involves a multiphase process with thermo-hydro-mechanical (THM) interactions, a coupled THM model (Luo et al., 2017) is recommended in a future study for better understanding and explaining the observed behavior in the pavement structure. This model considers the combined effects of temperature, moisture, and mechanical properties and can provide insights into how these factors contribute to pavement behavior in similar scenarios.

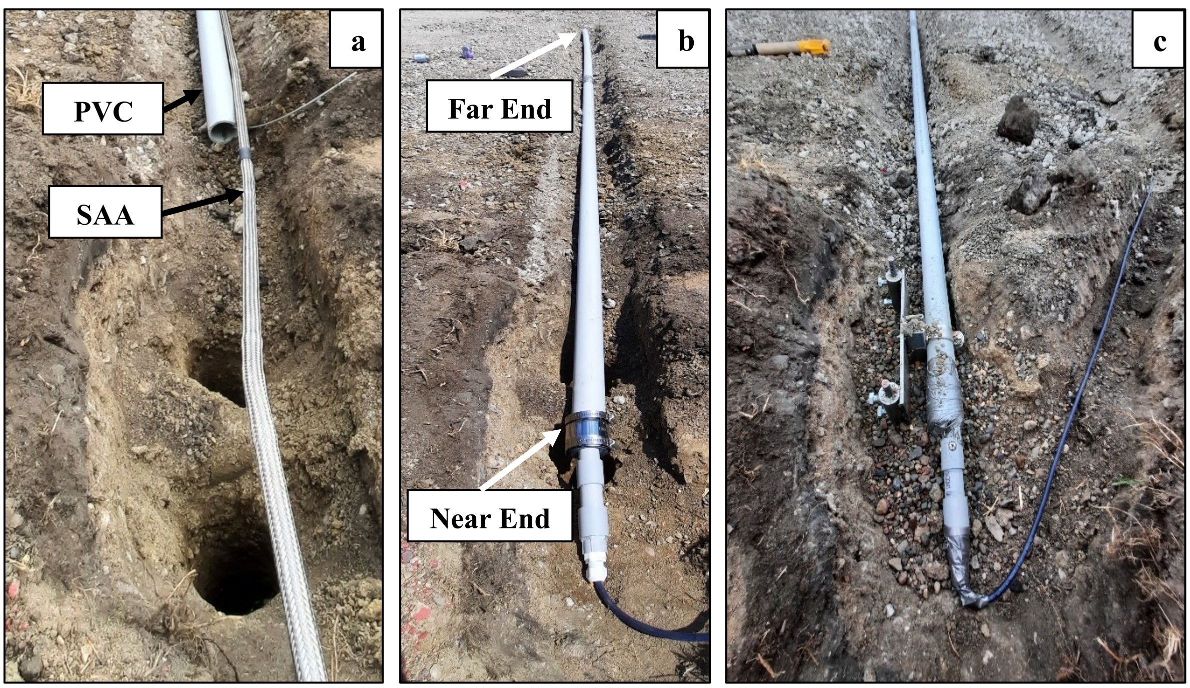

Figure 5. SAA installation a) SAA segments and PVC pipe b) Near end with installation kit and far end of SAA c) Securing the near end using a clamp

Subsequently, with rising temperatures, the ground started to return to its original state as the ice turned back to water, allowing the soil structure to expand. The ground became fairly stable on March 25th, with a residual settlement of 5.4 mm and 6.6 mm along the outer and inner wheel paths, respectively.

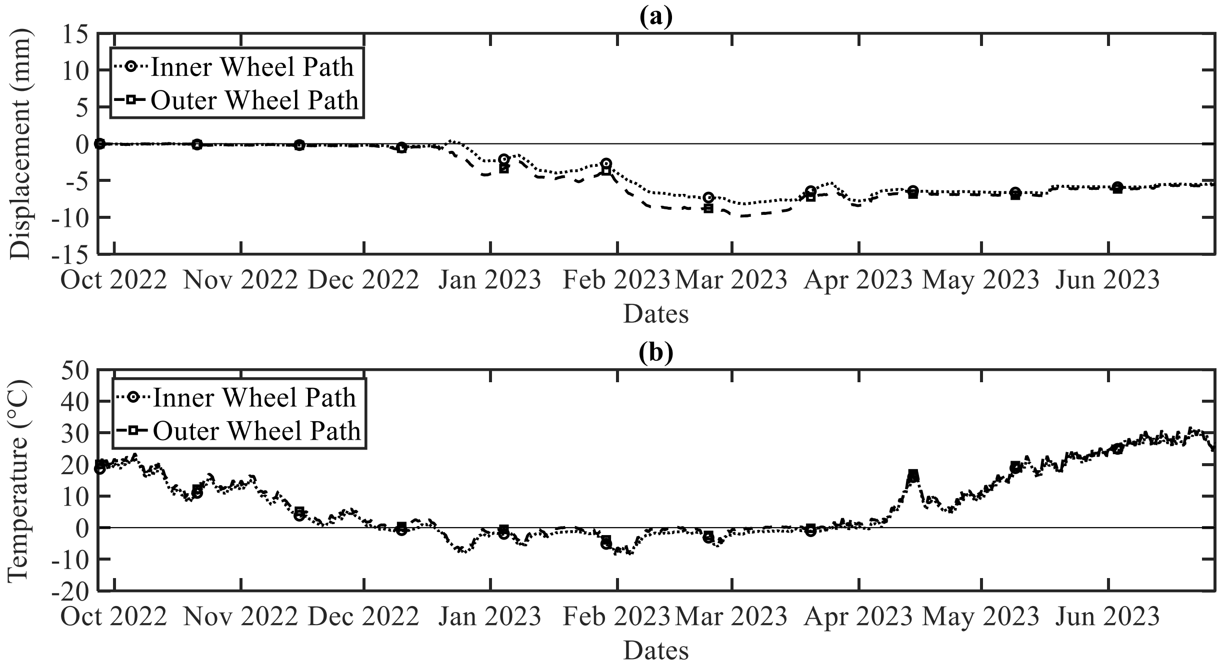

Figure 6. Displacement and temperature values obtained from SAA

Figure 7 presents the displacement data along the length (5 m) of the Shape Array (SAA) sensors at different time points during the freeze-thaw season. The initial 1.5 m length of the SAA is in the shoulder, and the rest 3.5 m is in the passing lane. All segments of the SAA in the passing lane experienced settlement on December 27th, 2022, and March 3rd, 2023. As discussed earlier, this settlement can be attributed to the lower subzero temperatures and the phase shift of pore water to ice, which caused the contraction of the soil structure as the growing ice was not strong enough to lift the substantial surcharge load above the SAA. Consequently, there was a net drop in volume, resulting in settlement. Notably, maximum settlement, measuring 10.3 mm, occurred at a distance of 3.5 meters from the road's edge. The segments within the shoulder area exhibited less settlement in comparison to those in the passing lane, with a maximum settlement of 3.5 mm.

Subsequently, as temperatures rose above freezing after March 3rd, the ground gradually began to revert to its original state. Between March 25th and May 25th, no significant movement was observed in any of the SAA segments, indicating that the ground had reached a stable condition following the thawing process.

While the pavement examined in this study, an interstate highway, exhibited small displacement due to its robust design for heavy loads and perpetual pavement, the findings hold significant implications for low-volume roads. Spring Load Restrictions (SLR) are typically enforced on such roads as they are more susceptible to damage during freeze-thaw cycles (Rwebangira et al., 1987). Implementing load restrictions early imposes costs on the trucking industry in terms of time and expenses. Delaying these restrictions imposes costs on taxpayers by leading to increased road damage. The key to cost-effective management lies in the timely application of SLR. With real-time pavement displacement and underground temperature data, the SAA can be a useful tool for determining the optimal timing for implementing and lifting SLR. Additionally, it can function as a performance indicator for evaluating the pavement's condition throughout its lifespan.

Since the SAA is made of stainless steel and enclosed inside Schedule 80 PVC pipe, capable of withstanding high pressure, the equipped SAA system is expected to have negligible effect on the road structures. Field tests like the Falling Weight Deflectometer (FWD) are recommended in future studies to verify the structural integrity of the roadway at the SAA location. It's important to note that while this technology serves a critical role in structural monitoring and stability assurance, its design isn't specifically tailored toward temperature adjustment within pipe systems.

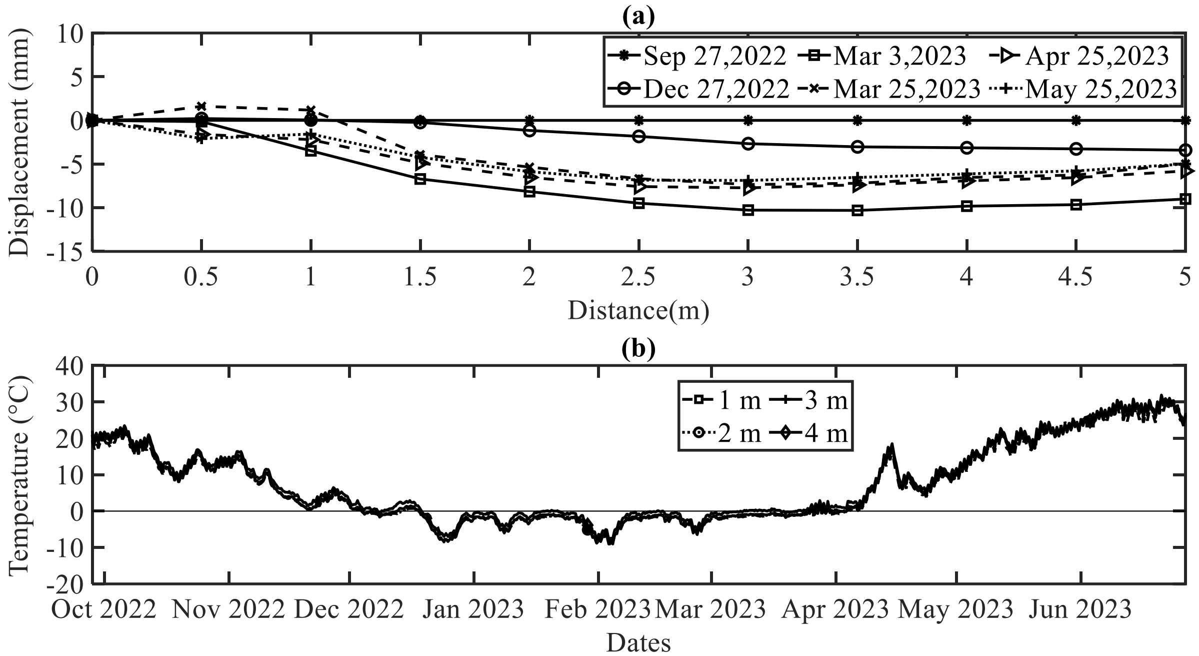

Figure 7. Displacement and temperature variation along the width of pavement

CONCLUSIONS

In this study, Shape Array Accelerometers (SAA) were utilized for comprehensive monitoring of freeze-thaw behavior and subsurface displacement within a flexible pavement on the I-94 highway. The primary findings are summarized below.

- Settlement profiles closely aligned with temperature measurements, the ground underwent noticeable displacement at the onset of freezing, affirming the reliability of SAA data.
- The roadway did not fully recover after the thaw and had residual settlement, measuring 5.4 mm and 6.6 mm along the outer and inner wheel paths in the passing lane.
- The SAA can be a valuable tool for precisely determining the timing of spring load limit implementations. The study identified that the ground reached stability on March 25th by analyzing settlement profiles and subsurface movement post-thaw, indicating an appropriate period for lifting spring load restrictions. Although the studied pavement is designed for heavy traffic and does not require spring load restrictions, the observed settlement trend indicates potential efficiency in applying such restrictions for cost-effective roadway management with SLR requirements. The magnitude of displacement from SAA in a specific roadway can also be used to assess SLR necessity.

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REFERENCES

ASTM D6913. (2014). *Standard Test Methods for Particle Size Distribution (Gradation) of Soils Using Sieve Analysis* (Vol. 04, Issue 200). ASTM International. https://doi.org/10.1520/D6913-04R09E01.2

Cetin, B., Coban, H. S., Edil, T. B., Ceylan, H., Likos, W., Zheng, J., & Buss, A. (2021). *Determining Pavement Design Criteria for Recycled Aggregate Base and Large Stone Subbase*.

FHWA. (2015). *Long-Term Pavement Performance (LTPP) Program*.

Genc, D., Ashlock, J. C., Cetin, B., Ceylan, H., Cetin, K., & Horton, R. (2022). Comprehensive in-situ freeze-thaw monitoring under a granular-surfaced road system. *Transportation Geotechnics*, *34*(March), 100758. https://doi.org/10.1016/j.trgeo.2022.100758

Hansmire, W. H., McLane, R. A., Frank, G., & Bragard, C. Y. (2017). Challenges for Tunneling in Downtown Los Angeles for the Regional Connector Project. *Proceedings of the World Tunnel Congress 2017*.

Lipscombe, R., Carter, C., Perkins, O., Thurlow, P., & Guerrer, S. (2014). The Use of Shape Accel Arrays (SAAs) for Measuring Retaining Wall Deflection. *Proceedings of the 39th Annual Conference on Deep Foundations.*

Luo, B., Ishikawa, T., Tokoro, T., & Lai, H. (2017). Coupled thermo-hydro-mechanical analysis of freeze–thaw behavior of pavement structure over a box culvert. *Transportation Research Record*, *2656*(1), 12–22. https://doi.org/10.3141/2656-02

Naqvi, M. W., Sadiq, M. F., Cetin, B., Uduebor, M., & Daniels, J. (2023). Frost Susceptibility Evaluation of Clay and Sandy Soils (1). *Geo-Congress 2023 GSP 340*, *April*. https://doi.org/10.1061/9780784484678.046

Nguyen, T. T. H., Cui, Y. J., Ferber, V., Herrier, G., Ozturk, T., Plier, F., Puiatti, D., Salager, S., & Tang, A. M. (2019). Effect of freeze-thaw cycles on mechanical strength of lime-treated fine-grained soils. *Transportation Geotechnics*, *21*(April), 100281. https://doi.org/10.1016/j.trgeo.2019.100281

Ovik, J. M., Siekmeier, J. A., & Deusen, D. A. Van. (2000). *Improved spring load restriction guidelines using mechanistic analysis*.

Rosa, M. G., Cetin, B., Edil, T. B., & Benson, C. H. (2016). Development of a test procedure for freeze-thaw durability of geomaterials stabilized with fly ash. *Geotechnical Testing Journal*, *39*(6), 938–953. https://doi.org/10.1520/GTJ20150126

Rosa, M. G., Cetin, B., Edil, T. B., & Benson, C. H. (2017). Freeze–Thaw Performance of Fly Ash–Stabilized Materials and Recycled Pavement Materials. *Journal of Materials in Civil Engineering*, *29*(6), 04017015. https://doi.org/10.1061/(asce)mt.1943-5533.0001844

Rwebangira, T., Rutherford, M. S., Mahoney, J. P., & Hicks, R. G. (1987). Development of Spring Load Restrictions for Local Roads. *Transportation Research Record*, *1128*, 42–52.

Sadiq, M. F., Naqvi, M. W., Cetin, B., & Daniels, J. (2023). Role of Temperature Gradient and Soil Thermal Properties on Frost Heave. *Transportation Research Record: Journal of the Transportation Research Board*, 036119812211472. https://doi.org/10.1177/03611981221147261

Simonsen, E., & Isacsson, U. (1999). Thaw weakening of pavement structures in cold regions. *Cold Regions Science and Technology*, *29*(2), 135–151. https://doi.org/10.1016/S0165-232X(99)00020-8

Swarbrick, G., & Clarke, S. (2015). *Shape Accel Arrays — comparative performance in a mining application*. *2001*, 195–206. https://doi.org/10.36487/acg_rep/1508_10_swarbrick

Uhlemann, S., Smith, A., Chambers, J., Dixon, N., Dijkstra, T., Haslam, E., Meldrum, P., Merritt, A., Gunn, D., & Mackay, J. (2016). Assessment of ground-based monitoring techniques applied to landslide investigations. *Geomorphology*, *253*, 438–451. https://doi.org/10.1016/j.geomorph.2015.10.027

US Army Corps of Engineers. (1965). *Soils and geology – pavement design for frost conditions.*

V., B., T., A., L., D., T., S., & D., J. (2012). Unstable Slope Monitoring with a Wireless Shape-Acceleration Array System. In *FMGM 2007* (pp. 1–12). https://doi.org/doi:10.1061/40940(307)38

Van Deusen, D., Schrader, C., Bullock, D., & Worel, B. (1998). Springtime thaw weakening and load restrictions in Minnesota. *Transportation Research Record*, *1615*, 21–28. https://doi.org/10.3141/1615-03

Naqvi, M. W., Sadiq, M. F., Cetin, B., Uduebor, M., & Daniels, J. (2022). Investigating the Frost Action in Soils. *Geo-Congress 2022 GSP 336*, 257–267. https://doi.org/10.1061/9780784484067.027

Yan, R., Take, W. A., Hoult, N. A., Meehan, J., & Levesque, C. (2021). Evaluation of Shape Array sensors to quantify the spatial distribution and seasonal rate of track settlement. *Transportation Geotechnics*, *27*, 100487. https://doi.org/10.1016/j.trgeo.2020.100487

Zhang, L., Ma, W., Yang, C., Wen, Z., & Dong, S. (2016). An investigation of pore water pressure and consolidation phenomenon in the unfrozen zone during soil freezing. *Cold Regions Science and Technology*, *130*, 21–32. https://doi.org/10.1016/j.coldregions.2016.07.007