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Transportation infrastructure settlement and heave distress: challenges and solutions

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Abstract: Transportation agencies spend millions of dollars annually to repair civil transportation infrastructure including pavements, earth structures and approach slabs distressed by soft compressible soils and expansive soils. Several research studies performed at the University of Texas at Arlington (UTA) focused on stabilizing these problematic soils so that they will provide better and more stable support to the transportation infrastructure. This paper focuses on a summary of two major distresses and mechanisms, and remedial measures for addressing these distress problems. A combined lime-cement stabilization method is fully evaluated in providing better support of pavement infrastructure, and these results are described here. Another major transportation infrastructure problem involving bridge approach slabs requires different treatment methods, and these results are briefly described. As a part of the recently completed research study assessments, both shallow and deep soil treatment methods for stabilizing soils are fully evaluated for their effectiveness in arresting the distress posed to the pavements and bridge approach slabs. These results along with a few future research needs are presented in this paper.

Key words: Ground improvement, Deep soil mixing, Settlements, Heaving, Instrumentation, Inclinometers
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1 Introduction

Expansive soils are commonly found in arid and semi-arid climate zones, which include countries like Australia, Canada, China, India, Israel, Iran, Italy, South Africa, United Kingdom and the United States. A number of control methods are extensively used in the field to stabilize these expansive soils. These methods include shallow stabilization treatment with calcium-based stabilizers and non-calcium-based stabilizers (Little *et al.*, 2000; Puppala *et al.*, 2003); and deep stabilization methods such as deep soil mixing (DSM) with calcium-based stabilizers. Both the techniques were proven to be effective in arresting volumetric movements in expansive soils that cause distress to the infrastructure built on them.

Two types of transportation infrastructure issues are the main focus of this paper. The first one deals with the pavements distressed by the subsoil heaving, and the second one deals with bridge approach slab bumps that are often attributed to settlements of soils. Both distresses result in large amounts of rehabilitation costs to transportation agencies, which often spend millions of dollars to address transportation infrastructure problems. The initial parts of the paper provide a summary of these distress patterns, which are then followed by a few research solutions that have been attempted in several research studies performed at The University of Texas at Arlington (UTA). Two studies in which the performances of shallow and deep stabilization techniques for the modification of subsoils were investigated are focused in this paper.

The shallow stabilization study was performed on a sulfate rich soil (expansive soil with soluble sulfates>2000 ppm), and design guidelines for selecting the stabilizer type were developed as a part of

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this study. Stabilizers selected and how they performed in both laboratory and research studies are covered here. A deep soil stabilization study using DSM columns was performed to mitigate bridge approach slab settlements, which is a major maintenance problem for several transportation departments nationwide. This uneven transition of approach slab to bridge deck often causes inconvenience to traveling passengers due to the sudden bump at the deck, eventually damaging the bridge infrastructure. The bridge then needs to be repaired, and thus increasing the cost of maintenance and repairs of the slabs.

In both shallow and deep soil stabilization studies explored for arresting the above distress problems, the performance of the structures with suggested stabilization methods was monitored with extensive field instrumentation, including inclinometers, pressure plates, extensometers, moisture probes and elevation surveys. These studies and the results are presented in the following sections.

2 Shallow treatment studies

2.1 Background

Expansive soils consist of both sulfate-rich soils and non-sulfate soils. Expansive soils containing soluble sulfates more than 2000 ppm are considered to be sulfate-rich (Mitchell and Dermatas, 1990). Several studies have shown that the use of calcium-based stabilizers for sulfate-rich soils can be counterproductive due to the formation of minerals such as Ettringite, which can cause more distress to the infrastructure (Mitchell, 1986; Hunter, 1988; Mitchell and Dermatas, 1990; Petry, 1994; Puppala *et al.*, 1999).

Each year, the local cities in North Texas spend considerable amounts of funds for annual maintenance and repairs of distressed pavements including those deteriorated by sulfate-rich and non-sulfate expansive soils. Therefore, it is necessary to explore new and alternate stabilization methods with the aim of constructing stronger and more stable subgrades with negligible heave problems in the future. In order to achieve this goal, extensive research was conducted at UTA and design guidelines were developed to assist in selection of stabilization for a better pavement design for different soil conditions.

Many stabilizing agents have been proposed as primary soil stabilizing agents although ordinary Portland cement, lime and bitumen have been extensively used for ground treatments. By their nature, these stabilizing agents have to be used in varying amounts, which are typically more than 2% (Sherwood, 1995).

Sherwood (1995) recommended that the stabilizing agents should ideally have the following properties: (1) Be able to stabilize a wide range of soils; (2) Have a permanent stabilizing effect; (3) Be readily available at relatively low cost in large quantities; (4) Present no serious storage or transport problem; (5) Be relatively non-toxic and non-corrosive.

Stabilizers such as lime, cement, and bitumen meet these properties and therefore are commonly used in the field. However, when it comes to stabilizing sulfate soils, alternative additives are needed. Such additives include combinations of Type V cement with fly ash, ground granulated blast furnace slag, and lime with poly propylene fibers. Due to the scope of the paper size, authors provide shallow soil stabilization of non-sulfate soils using a combined lime-cement treatment method. Description of these studies is explained in the following sections.

2.2 Site details

The shallow stabilization study discussed here was conducted to develop stabilization methods for natural expansive soils that are prevalent in Arlington, Texas. Performance of stabilization methods considered here was evaluated in both laboratory and field conditions in order to select ideal stabilization method(s) for modifying expansive soils to minimize heave and shrinkage induced distresses. The combined lime-cement treatment method was considered for stabilization studies for natural expansive soils (Sirivitmaitrie *et al.*, 2008). The laboratory testing program was first conducted to assess the properties of expansive soils including basic soil property tests, chemical and mineralogy studies, and strength characteristics of the test site soils.

Monitoring studies were carried on the lime-cement stabilized soils in the field to assess the performance of the pavements, instrumentation included via elevation surveys, dynamic cone penetrometer tests (DCP) and visual field inspections. The field data was used to assess the performance of stabilized soils layers in providing adequate pavement support in real field conditions. A total of eight different sites from the city of Arlington were selected and studied in this research. In this study, test results from four sites are presented.

2.3 Results and discussion

Table 1 presents the ranges for basic soil properties, including specific gravity and Atterberg limits along with the Unified Soil Classification System (USCS) for all four sites studied in this research. All soils contain high plasticity index values and are considered as problematic, as they are expected to undergo large volumetric swell strains when subjected to inundation.

As a part of the mix design, the local city wanted to explore lime-cement treatment of the subsoils. Hence, the field soils of old pavement reconstruction or rehabilitation sections were stabilized with lime and then with cement. Field soil samples were collected immediately after the soil treatment and then they were subjected to Atterberg limits, unconfined compression strength tests, resilient modulus tests and swell and shrinkage tests.

Atterberg limits, including liquid limits (LLs) and plastic limits (PLs) of treated and untreated soils, are reported in Table 2. Test results from the International Parkway, Southmoore, Southeast Parkway and Commerce streets of Arlington, Texas, USA showed that the plasticity index (PI) values decreased considerably with lime, and further with cement treatment. The PI values were reduced from ‘28% to 39%’ range to ‘8% to 12%’ range.

Unconfined compression strength and swell, as well as linear shrinkage strain tests, were performed on the field mixed soil samples at field compaction conditions, which are closed to wet of optimum conditions. Test samples from all four sites were cured for 7 days, and then the engineering tests were performed.

Table 3 indicates that strengths were increased considerably (15 to 20 times the raw soil strength),

Table 1 Laboratory test results of test site soils and their ranges

Property	Untreated test soil property range
Passing #40 (%)	100
Passing #200 (%)	>80
Specific gravity	2.6–2.8
LL (%)	>50
PI (%)	25–40
USCS classification	Lean clay (CL) and fat clay (CH)

Table 2 Atterberg limits of treated and untreated clays

Location		Atterbertg limit (%)		
		LL	PL	PI
International Parkway	Untreated	58	21	37
	Lime	43	32	11
	Lime & cement	39	31	8
Southmoore	Untreated	60	21	39
	Lime	39	30	9
	Lime & cement	41	33	8
Southeast Parkway	Untreated	51	23	28
	Lime	51	36	15
	Lime & cement	48	36	12
Commerce	Untreated	61	24	37
	Lime	45	30	15
	Lime & cement	43	32	11

Table 3 Summary of test results for International Parkway, Southmoore, Southeast Parkway and Commerce

Sample type	Curing period (d)	UCS (psi)*	Free swell strain (%)	Liner shrinkage strain (%)
International Parkway untreated	–	13.7 (94.46)	6.27	20.2
	7	202.3 (1394.81)	0	0
	7	250.9 (1729.89)	0	0
Southmoore untreated	–	22.1 (152.37)	5.08	18.3
	7	198.6 (1369.30)	0	0
	7	266.4 (1836.76)	0	0
Southeast Parkway untreated	–	47.35 (326.47)	5.30	19.2
	7	331.87 (511.59)	0	0
	7	520.25 (3587)	0	0
Commerce untreated	–	26.85 (184.99)	5.18	16.3
	7	150.36 (1035.98)	0	0
	7	204.58 (1409.55)	0	0

* Equivalent values with the unit of kPa are given in parentheses

and swell, as well as liner shrinkage strains, were also drastically reduced to 0%. Overall, both lime and lime-cement treatment tests results showed effective stabilization of the field treatment.

Due to the influence of the longitudinal profile on riding comfort and related indicators (e.g., international roughness index (IRI)), pavement sections built on the above mentioned four streets were subjected to elevation surveys periodically. These surveys were started from March 2006 for International Parkway, Southmoore and Commerce Street, and from November 2007 for Southeast Parkway site. The field surveys were conducted on the pavements using total station equipment. Results are shown in Fig. 1, in which each point represents the elevation of a treated section of the road.

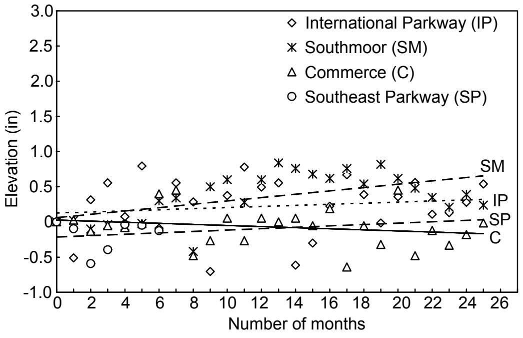

Fig. 1 Elevation surveys and best fit lines through the collected field survey data (1 in=2.5 cm)

As per the data shown in figure, no major rutting, permanent deformation, or shrink-related surface movements are noted. However, the monitoring time period is not sufficient to make final assessments. Nevertheless, the combined treatments used in the field treatment appear to provide stable and uniform support to the pavement infrastructure.

Results of the individual elevation surveys for one of the four test sites are shown in Fig. 2. The results are presented along with monthly average precipitation. For this site, the maximum monthly average precipitation is in May, and the minimum monthly average precipitation is in August. The maximum and minimum precipitation values from the monitoring period of March 2006 to September 2008 vary from approximately 2 to 5 in.

It is noticeable that in the early monitoring period (from March 2006 to May 2006), precipitation variations were more than 2 in (Fig. 2), which is considered to be high moisture content changes that could cause expansive subgrade soils to undergo swell and volume change movement within a short period of time. Accordingly, a differential elevation of 0.35 in was observed. However, this heave is considered to be low (<0.5 in), and it can be noted, from the elevation profile observed in a later monitoring period from May 2006 onwards, that the volume change in the test section diminished as compared to its initial high heaving pattern. Based on Fig. 2, heaving is attributed to the seasonal precipitation variations that the test sections experienced during the monitoring period.

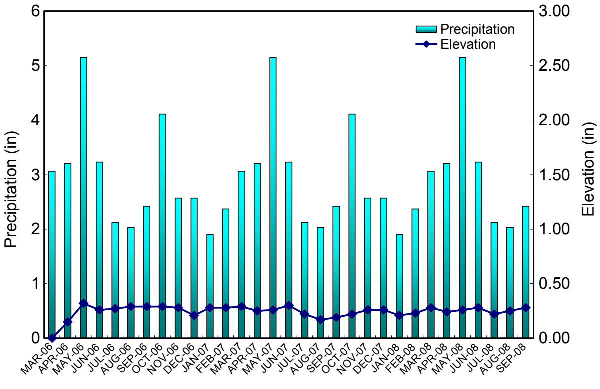

Fig. 2 Plots of pavement elevation changes and monthly rainfall data (www.ncdc.noaa.gov) at the International Parkway over a period for 30 months (1 in=2.5 cm)

Dynamic cone penetration tests were also conducted on all four test sites for three different time periods: 7 days, 12 months and 30 months. Fig. 3 shows typical DCP test results of IP site. Please note that tests were conducted in March 2006 (after 7 days curing), March 2007 (12 months after the construction) and September 2008 (30 months after the construction). The DPI values were taken at a slope between 10 cm and 15 cm of DCP data between those two depths.

It can be observed from Fig. 3 that there is no considerable deterioration seen in DCP values in the treated layers over the last 30 months, which indicates that the stabilization still remains effective. These tests were conducted along the test section at random locations, and the near closeness of the DCP data at different depths indicates a uniform treatment of lime-cement additives with the native local soil.

Other studies, including visual photographic examinations of the test sites with lime-cement treated sections and those with control site using old traditional lime treatment methods, are made. The photographs shown in Fig. 4 indicate no ponding on the site built on combined lime-cement treated subgrades whereas pavement sections built on lime treated subgrade showed ponding problems. Similar observations are noted at other three test sites.

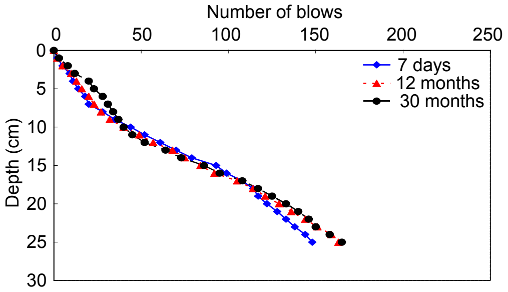

Fig. 3 Typical DCP test results on the International Parkway test site

Fig. 4 Photos of control site (ponding) (a) and test site (no ponding) (b) of Southeast Parkway after years of service

Overall, based on the analyses of both field studies and laboratory test results, the research team has recommended the combined lime-cement treatment method for field subgrade treatments for supporting pavement infrastructure in North Texas soil conditions.

3 Deep soil stabilization study

Bump on approach slab, due to differential settlement, causes extensive damage to bridge infrastructures, and this problem results in agencies spending millions of dollars on maintenance costs. This is a national problem, which usually comes from soil settlements arising from embankment fill and subgrade foundation materials, as well as erosion and desiccations of fills around the approach slab and bridge abutment.

Maintenance and repair of these bridge approach slab settlements cost millions of dollars annually, which absorbs almost all the available maintenance resources. Briaud *et al.* (1997) reported that 30% of bridges in Texas, i.e., 13 800 out of 46 000 bridges, were subjected to the bump problem, while another study cited that the annual cost for "bump" repairs in Texas is USD 7 million (Seo, 2003). This signifies that the bump is a major, if not a premier maintenance problem in Texas.

Several researchers studied the bridge approach settlement to determine both the causes of the bump and the techniques to mitigate the problem (Hopkins, 1985; Stewart, 1985; Kramer and Sajer, 1991; Jayawickrama *et al.*, 2005; White *et al.*, 2007). From the literature review, it was found that the causes of the bump are varied. The primary sources of the problem can be broadly divided into four categories: (1) material properties of foundation and embankment, (2) design criteria for bridge foundation, abutment and deck, (3) construction method, and (4) maintenance criteria. Note that not all the factors contribute to the formation of the bump or differential settlement concurrently, as one factor may be more problematic than the other.

One of the major contributors to settlements is weak subgrade conditions, and any mitigation technique attempted to reduce bridge approach settlements should address this foundation issue. Hence, an attempt was made to address the stabilization of weak subgrade foundation conditions in one of the bridge sites using deep soil mixing (DSM) columns. The evaluation of this technology was done as a part of Texas Department of Transportation (TxDOT) research.

3.1 Site details

A bridge along Interstate Highway 30, in the northern region of Arlington, Texas, was monitored to address the application of the DSM technique in real field conditions. A 19 ft (5.7 m) embankment on the south side of the bridge was constructed over the DSM treated test section, while other side of the bridge was constructed on a local soil without the DSM treatment, and this section is treated as a control section. DSM columns were 4 ft (1.2 m) in diameter and 25 ft (7.5 m) in length, or until the tip of the columns seated on a hard shale layer. The columns were constructed in a triangular arrangement with a center-to-center column spacing of 5.5 ft (1.65 m). Design details were provided to the research team, and these results are used to reconfirm the quality control/quality assurance (QC/QA) practices with respect to soil improvements with the DSM method. A perspective view of the DSM construction is shown in Fig. 5.

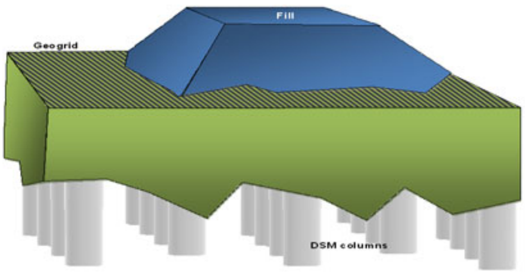

Fig. 5 A typical perspective view of DSM treated test section (figure not drawn to scale)

As a part of the research, laboratory investigations were conducted to study the properties of DSM treated soil samples prepared in the laboratory setting. The test results show that the foundation soil has gained more strength and exhibited less compressibility with the DSM technique. The test site with DSM treatment was instrumented with various sensors including vertical inclinometer, horizontal inclinometer, sondex, and rod extensometers. Elevation surveys were performed to monitor soil movements in the vertical direction.

3.2 Analysis of monitoring data

Elevation surveys were performed at a location close to a highway pavement both in treated and untreated sections by using a total station (TS) device, which has a resolution of 0.1 in (0.25 cm). Generally, the data obtained from the surveys are the elevation data compared to a preset Benchmark (BM) value, which was fixed and located far from the area of the study to avoid any influencing circumstances affecting the BM elevation. The collected elevation data are presented in Fig. 6. For example, the movement in a treated section on Mar. 20, 2009 is equal to 0.12 ft (0.036 m). The positive value shows that the selected point is settled.

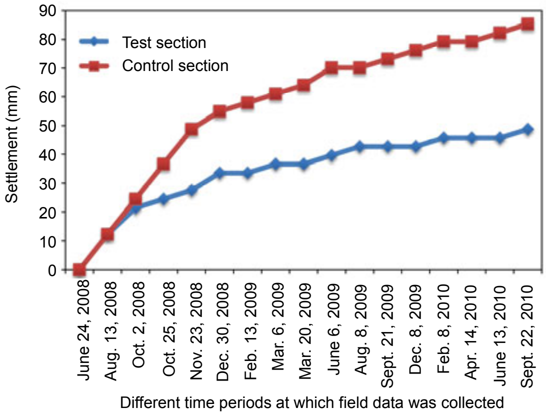

Fig. 6 Elevation survey data comparison between control and test sections

The elevation survey results for the control section are presented in Fig. 6. It can be observed from the figure that the control embankment settled about 3.44 in (8.6 cm), within 3 years.

The data collected in the field is used not only for the mitigation settlement efficiency evaluation, but also for development of design charts for settlement analysis. In this study, two numerical models using the finite element model and the hyperbolic model for long-term assessments are used. For the FEM, the data collected from the field instrumentation was employed to validate the model. The hyperbolic model formulated by Lin and Wong (1999) used the observed field data to establish the time-settlement equation for each embankment. Once validations were done, the models were used for further modeling of hypothetical embankment sections for design chart development. A brief overview of the finite element modeling performed for this study is explained in the following sections.

3.3 Finite element modeling

Both test and control sections are simulated in the FEM models with the embankment geometry and surcharge loading from traffic with different DSM sections, and these results are used to develop design charts for DSM selection. Plaxis software was used for the modeling analysis.

A cross-section and subsurface profile of the test embankment section modeled in FEM analysis is shown in Fig. 7. The embankment has a total height of 19 ft (6 m) from an existing ground surface and has a side slope of 1V:4H. This section was used in the model to analyze the soil movements occurring within and underneath the embankment. The embankment was constructed on soft clay with a thickness of 26 ft (8 m) underlain by 10 ft (3 m) of thick hard shale (green). The soil cement columns have a diameter of 4.0 ft (1.2 m) with a center-to-center spacing of 5.5 ft (1.67 m). However, in numerical analysis, instead of using the diameter of the DSM columns, the area-ratio (a_r) between the DSM and natural soil was used.

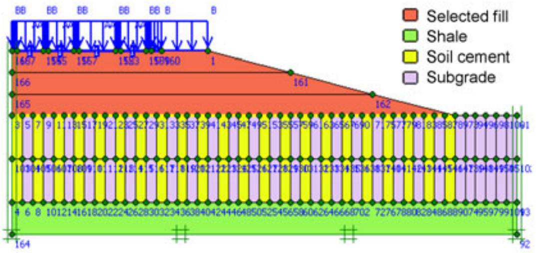

Fig. 7 Geometry and boundary conditions of the DSM columns model

Note: for interpretation of the references to color in this figure, the reader is referred to the web version of this article

The deep mix columns were constructed with their bases placed on top of the hard shale layer. Therefore, the lengths of the columns used in this numerical analysis were equal to the thickness of the soft clay layer at 26 ft (8 m). The geometry of the embankment, modeled together with the boundary conditions, is shown in Fig. 7.

The analytical predictions of soil movements in the DSM treated section are in good agreement with the field observations data monitored from all instruments, including horizontal inclinometer and elevation surveys. Also, hyperbolic modeling was used on the initial settlements to interpret the long-term consolidation settlements. Overall, these analyses showed that the model used here was effective not only for calculating the settlements in the present field conditions, but also for predicting the settlements over a long-term time frame.

Analyses are attempted using (1) DSM area-ratios, (2) embankment heights, and (3) slopes to develop design charts for different case scenarios. The results from these studies reveal that the most effective method in reducing the embankment settlement is by using a suitable area-ratio, which has a value between 0.5–0.6. Lowering the embankment height is another effective method, as it reduces gravity loads exerting on the subgrade. Hence, lesser settlement due to consolidation of the soft clay layer has occurred. Therefore, by lowering the height of embankment, this approach slab can also experience less embankment settlement. However, traffic and embankment weight-related variables may increase the settlements, as stress transfer in the subsoils will be high. Though traffic weight is transient, it was modeled as dead load acting on the embankment system. Because of all the variables, this approach is sometimes difficult or impossible to implement.

A typical design chart for selecting the area-ratio for DSM columns is presented in Fig. 8. This chart presents the final settlement of the embankment settlement coming from weak foundation settlements. The subgrade foundation thickness was kept as a constant at 25 ft (7.5 m). As the height of embankment increased, the overall settlement increased. In order to mitigate the settlements, the foundation subgrade needs to be strengthened with deep soil mixing columns. This can be seen in the form of area-ratio which defines the planar area of the treated soils with the total areas of the embankment system. As area-ratio increases, the treated and composite soil system will have enhanced soil compressibility properties, which in turn reduce the final settlements.

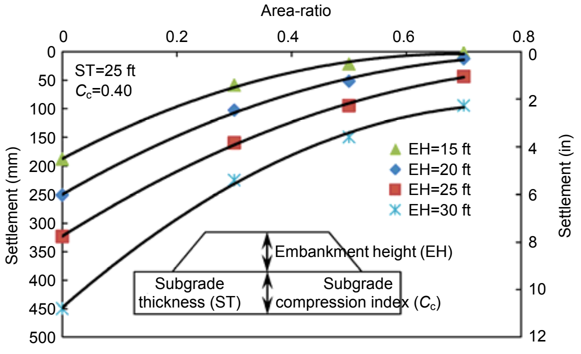

Fig. 8 Design chart for DSM columns with various area-ratios and heights of embankments for a subgrade thickness of 25 ft (7.5 m)

4 Summary

Two different stabilization studies were conducted to reduce distresses caused to pavements and approach slab infrastructure in Texas. These stabilization studies, along with field case study details, are discussed in this paper. The first stabilization method described was a shallow stabilization method using a combination of lime and cement additives for enhancing the long-term performance of stabilization and providing better support to pavements. Based on the field monitoring, the combined treatment provided stable support without any major distress.

In the second research study, a deep soil stabilization technique, DSM, was used to mitigate bridge approach settlement problems. Based on laboratory and field monitoring studies, the DSM methods have resulted in lesser settlements underneath the approach slabs. As a part of this research, design charts were prepared to determine the area-ratio for the DSM columns for an effective reduction in settlements of different soft subsoils. Overall, this paper highlights the key points of both research studies that looked at the soil stabilization solutions for mitigating pavement and bridge infrastructure problems. In both projects, the solutions suggested are implemented in the field; hence, these methods can be considered as viable solutions for future construction projects.

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