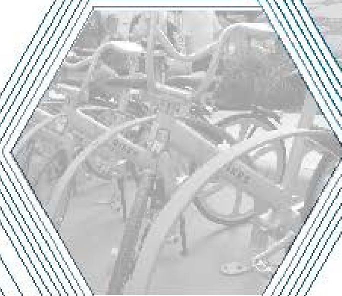

MULTI-CRITERIA DECISION-MAKING APPROACH FOR BUILDING RESILIENT AND SUSTAINABLE TRANSPORTATION INFRASTRUCTURE

ANAND J. PUPPALA
SURYA SARAT CHANDRA CONGRESS
TEJO V. BHEEMASETTI
JASASWEE T. DAS

FINAL REPORT

Center for Transportation Equity, Decisions & Dollars

MULTI-CRITERIA DECISION-MAKING APPROACH FOR BUILDING RESILIENT AND SUSTAINABLE TRANSPORTATION INFRASTRUCTURE

FINAL PROJECT REPORT

By:

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Sponsorship:
CTEDD

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16. Abstract

This project developed and validated a multi criteria decision making approach for enhancing the longevity of pavement infrastructure built on problematic expansive soils. Expansive soils swell and shrink with changes in moisture content, causing pavements to crack or heave. As of current state of practice, more than 25 state transportation agencies have either started recognizing or identifying this heave induced stress in their highway projects. These states are predominantly in Western, Midwestern and Southwestern United States. A recent study found that the annual cost of damage to constructed facilities owing to expansive clays in the United States was approximately $13 billion, and a significant portion of this amount can be attributed to damages sustained by pavement infrastructure. With continuing pressure on transportation agencies across the nation, several treatment approaches were attempted to mitigate the damage induced due to swell-shrink of the expansive soils. Despite the efforts there are still failures happening in many places, and this can be mainly attributed to not accounting all the parameters in performance evaluation. This project will develop a multi criteria decision making approach in evaluating the pavement performance by accounting different variables including type of stabilizer, characterization of expansive soils, curing period, life cycle cost analyses including user costs and agency costs, environmental effects, and performance monitoring data. The developed comprehensive approach will provide the best stabilizer that can provide a long sustaining resilient pavement infrastructure. The developed approach will be validated by studying three different treatments to stabilize expansive soils in Texas. The proposed research is of significant importance to Federal and State Highway Agencies as well as the construction industry at large. Any reductions in maintenance costs will be considered as huge savings to transportation agencies and these savings could be invested in other transportation needs.

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Abstract

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Chapter I: Introduction

Transportation agencies including state, city, and local districts continue to experience pavement failures on problematic soil subgrades that include high sulfate soils, collapsible soils, and frost-susceptible soils (Puppala and Hanchanloet, 1999). In Texas, the transportation agencies experience pavement distresses which are particularly evident in sites where there is presence of sulfate soils of 8000 ppm or higher (Puppala et al., 2018 & 2019a; Talluri et al., 2020). Many of the recent pavement failures are attributed to sulfate-induced soil heave where an expansive mineral called Ettringite is formed from calcium-based stabilizers reacting with water, clay, and sulfates in the soil (Puppala, 2016). Current chemical stabilization practices for high sulfate soils have resulted in high maintenance costs and safety concerns due to the increasing roughness and distress that these pavements have experienced. Many districts have to partially or completely rehabilitate these structures built on problematic soils within a few months to three to four years after original construction (Puppala et al., 2019b). In many cases, the repairs will include a complete restoration of the entire structure that can result in huge losses to agencies.

The main objective of this research is to develop a multi-criteria decision making approach that can facilitate transportation agencies to overcome financial obstacles related to repeated rehabilitation measures and systemic inefficiencies for treating poor subsoil conditions. This is achieved by evaluating the transportation infrastructure performance at two test sites by accounting type of stabilizer, characterization of soils, curing period, life cycle cost analyses including user costs and agency costs, environmental effects, and performance monitoring data. The developed decision-making approach is an attempt to provide a low-maintenance, cost-effective, eco-friendly and resilient transportation infrastructure. Any reductions in maintenance costs by implementing a solution that is sustainable and resilient will be considered as huge savings to transportation agencies and these savings could be invested for other transportation needs.

The proposed multi-criteria decision-making approach research effort accounts for different factors including economic costs, efficiency, and environmental aspects that affect the performance of a transportation infrastructure. The developed approach is illustrated and validated for two transportation infrastructure facilities located in North Texas. The technologies proposed in this research can be extended to develop reliable transportation infrastructure asset management framework, which will immediately benefit the transportation agencies.

The primary focus of this research study is to develop a comprehensive multi-criteria-decision-making analysis-based framework that can enable transportation agencies to choose the best solution that can be adopted to build resilient and sustainable transportation infrastructure. This research placed emphasis on the subgrade soil components of transportation infrastructure such as pavements, embankments, and bridges as the sustainability and resilience of these components have a significant impact on the overall quality of the infrastructure. To demonstrate the framework and how it can be implemented, two different field studies – subgrade stabilization for a high-volume road, and repair of bridge approach slabs and adjoining roadway – were used as example case studies. For each case study, appropriate metrics that can be used to assess the sustainability and resilience of the infrastructure were identified.

The rudiments of the sustainability evaluation lie in the life cycle assessment (LCA) that is comprised of life cycle inventory analysis (LCI), and environmental impact assessment (EIA), socio-economic impact of the infrastructure, which is gauged through a cost-benefit analysis of the project. A life cycle cost analysis (LCCA) is required to quantify the costs that are discounted to the net present value, and may include the initial costs involved in purchase, acquisition, and/or construction, besides the operation, maintenance, rehabilitation, and residual costs.

As with the LCA, scoping is an essential requirement for a proper LCCA. However, the study attaches more importance to the initial costs as they often govern decisions pertaining to fund allocation for many infrastructure projects. The benefits are in the form of tangible gains such as increased per capita income, reduced congestion, and better connectivity.

This study identified four metrics of resilience - (i) robustness, or the capacity of an infrastructure to withstand a certain level of stress without loss of function; (ii) redundancy, dictated by the extent to which a component can be replaced in the event of damage; (iii) resourcefulness, or the ability to identify distress in the infrastructure; and (iv) rapidity with which the distress is addressed and the losses are contained. Based on the output of the multi-criteria analysis, the study comments on the quality of an infrastructure resulting from the adoption of a particular design or construction alternative.

Chapter II: Literature Review (Task 1)

The main objective of this research task is to review and compile the current practices adopted by transportation agencies for increasing the longevity of the transportation infrastructure. Since, the condition assessments and strategies vary from each agency to agency and site conditions, attempts were made to identify all the metrics associated during planning, design, construction and maintenance phase of the transportation infrastructure. The literature review was provided in the below sections based on the sustainability studies followed by the resilience metrics that are adopted in transportation infrastructure.

A vast majority of transportation infrastructure invariably involves geotechnical engineering as one of the components. As Pantelidou et al. (2012) noted, initial stages of a project offer higher scope to introduce sustainability than the later stages between planning and implementation stages of the project (Figure 1). Geotechnical engineering, being positioned at the incipient stages of a project, provides ample opportunities for sustainable development. Incorporating sustainable geotechnical alternatives and practices at the initial stages can contribute towards the sustainability of the project at subsequent stages (Abreu et al., 2008; Basu et al., 2014). Some sustainable, geotechnical solutions involving alternate materials and sustainable construction processes include innovative ground improvement methods, use of recycled and alternate materials in construction, biotechnical and nature-inspired slope stabilization, use of geosynthetics and natural fibers for soil reinforcement, foundation reuse and retrofitting, geothermal pile foundations, and reuse of natural geomaterials for rehabilitation and maintenance of infrastructure.

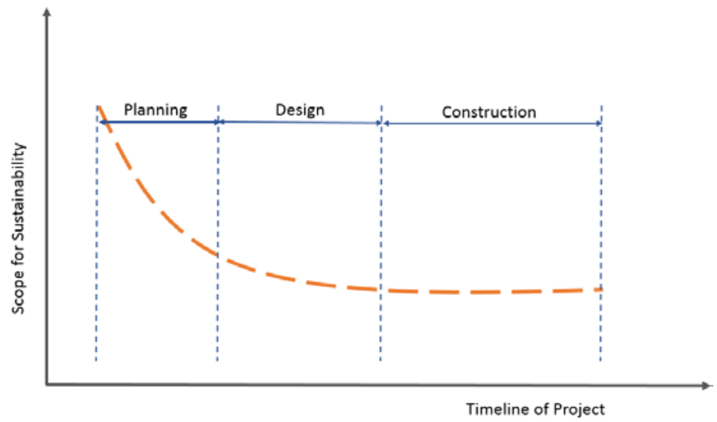

Figure 1. *Decrease in scope of sustainability with time (Pantelidou et al., 2012)*

Ground improvement methods focus on altering the engineering properties of the ground to satisfy design specifications and construction requirements. Present-day improvement techniques involve different levels of soil treatments – shallow, medium and deep – and employ a range of mechanisms such as compaction, dewatering, reinforcement, and the addition of admixtures to amend the soil. For example, a project in Haltom City, Texas, involved applying the deep-soil mixing (DSM) technique for stabilizing expansive subsoils along the I-820 corridor north of Fort Worth. As part of another project for the U.S. Army Corps of Engineers, researchers at UTA attempted sustainable biopolymer treatments to arrest surficial cracking on the slopes at Joe Pool Dam and Grapevine Dam in Fort Worth, Texas. For a state highway extension project involving SH 360 in Arlington, Texas, recycled materials such as reclaimed asphalt pavement and cement-stabilized quarry fines were successfully used as pavement base materials.

Sustainability of transport infrastructure can also be enhanced by the reuse of natural geomaterials and recycled aggregates in their construction and rehabilitation (Figure 2). Asphalt pavements can be recycled and reused as reclaimed asphalt pavement (RAP) material that is a beneficial substitute to virgin aggregate materials. They cut down the need to use virgin aggregates in roadway construction. For a highway extension project in Arlington, Texas, recycled materials such as reclaimed asphalt pavement and cement-stabilized quarry fines were successfully used as a pavement base material (Saride et al., 2010a & 2010b). Studies suggest that concrete used in construction can be recycled and reused as earthwork material; it was observed that crushed concrete aggregates have comparable modulus values with natural aggregates (Detterborn and Korkiala-Tanttu, 2017).

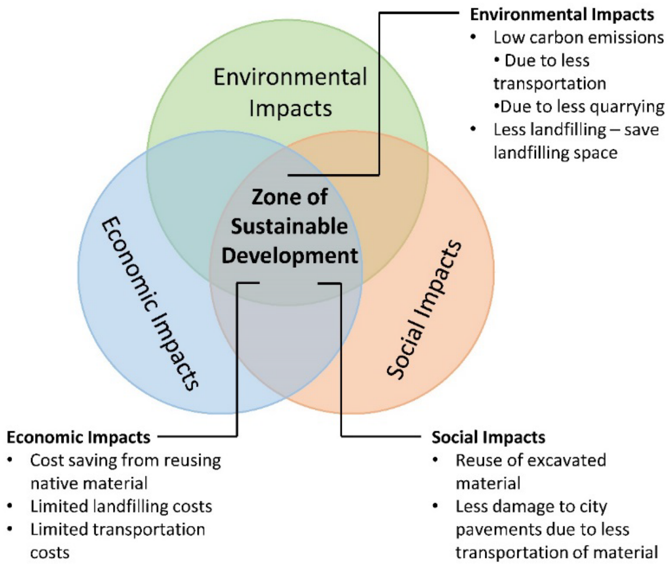

Figure 2. *Effect of soil reuse on sustainability factors*

Transportation geostructures such as embankments, bridges, and tunnels are considered as critical infrastructure (O'Rourke, 2007), and any loss of functionality due to internal or external disturbances can be catastrophic. The resulting consequences can have serious socio-economic implications for the community served by such infrastructure. Thus, a lack of resilience against unanticipated forces is not acceptable in transportation geotechnics. Reliability-based infrastructure designs ensure that a structure maintains functional integrity under normal operating loads and establish a sufficient degree of safety against the identifiable states of failure. However, the variability in soil properties and inherent uncertainty involved in geotechnics complicate the process of determination of reliable parameters for design purposes.

In the direct aftermath of large disaster events such as hurricane, earthquake or snowstorm, the preservation and resilience of transportation infrastructure is extremely crucial for economic growth of the region and restoring daily mobility services. The quick restoration of transportation system post-disaster requires a smart, reliable, and efficient way of assessing the damages incurred due to the disaster events and then addressing and restoring the infrastructure to near functional state. Rogers et al. (2012) noted 8 categories of threats that could be encountered by transportation infrastructure: deterioration from aging and adverse ground conditions; damage due to abnormal loads; damage due to increased demand; terrorism; effects of climate change; effects of population growth; funding constraints; extreme hazard events.

Jimenez (2004) identified qualitative indicators based on social, natural resources, environmental, and economic factors and developed the Sustainability Geotechnical Evaluation Model (SGEM) to assess the sustainability of geotechnical techniques. The sustainable project appraisal routine (SPeAR) conceptualized by ARUP (2010) employs a color-coded rose diagram to indicate the sustainability of a project based on four criteria – economic, social, environmental, and natural resources – that are subdivided into 20 sub-criteria. The sub criteria such as transport, land use, air quality, stakeholder satisfaction, social responsibility, viability, water use, and others are arranged as sectors divided along the circumference of a circle. Holt et al. (2009) devised a color-coded indicator system called GeoSPeAR to estimate the sustainability of geotechnical projects. The model discarded 16 of the 122 indicators adopted by SPeAR that were considered less relevant to the geotechnical practice.

Praticò et al. (2011) formulated a life-cycle cost analysis tool (LCCA) to optimize and choose the best stabilizer and stabilization alternative for subgrade soils. The approach was demonstrated through two case studies involving low-volume roads in southern Italy and northern Texas, USA by considering agency costs, user costs, and externality costs in the LCCA.

A combination of life cycle costing (LCC) and life cycle assessment (LCA) was used by Zhang et al. (2008) to examine the sustainability of pavement systems having different overlays such as unbonded concrete, hot mix asphalt, and engineered cementitious composite (ECC). Lee et al. (2010a, 2010b) developed Building Environmentally and Economically Sustainable Transportation – infrastructure – highways (BE^2ST in-highways) – a LCA-based rating to assess sustainability of transportation infrastructure that primarily use recycled materials in their construction. Pittenger (2011) introduced Green Airport Pavement Index (GAPI) to compare the sustainability of different airport pavement treatments. GAPI measures the performance of pavement treatment methods based on resource use, life cycle costing, and project management by assigning weights to calculate the performance metric.

The New York State Department of Transportation (NYSDOT) developed GreenLITES (Green Leadership In Transportation and Environmental Sustainability) tool to measure performance, assess environmental sustainability, incorporate best practices, and identify collaborative initiatives for transportation projects (McVoy et al., 2010). Greenroads is another performance metric to quantify the sustainability of pavement infrastructure (Muench and Anderson, 2009). The Illinois Department of Transportation devised a sustainability rating system called I-LAST (Illinois - Livable and Sustainable Transportation) consisting of over 150 best practices for highway projects (Knuth and Fortmann, 2010). There are 17 sections and 8 categories of best practices related to design phase activities, design decisions, and construction specifications.

Chapter III: Development of framework (Task 2)

The main objective of this task is to develop a framework based on the metrics identified from the literature review and to overcome the limitations of the current practices. The framework placed particular emphasis on the geotechnical components of a transportation infrastructure as the sustainability and resilience of these components have a significant impact on the overall quality of the infrastructure. The proposed methodology evaluates the resource consumption, environmental ramifications, and socio-economic implications of transportation infrastructure, along with their reliability and robustness against unforeseen events. The developed framework broadly comprises of two major categories: resilience and sustainability. The resilient metric includes the factor of safety, sensitivity analysis, probability of failure, reliability index, field performance monitoring of a transportation infrastructure. The sustainability factors include socio-economic impacts, environmental impacts, life cycle inventory and life cycle cost analysis. The different steps of the proposed framework are illustrated in Figure 3.

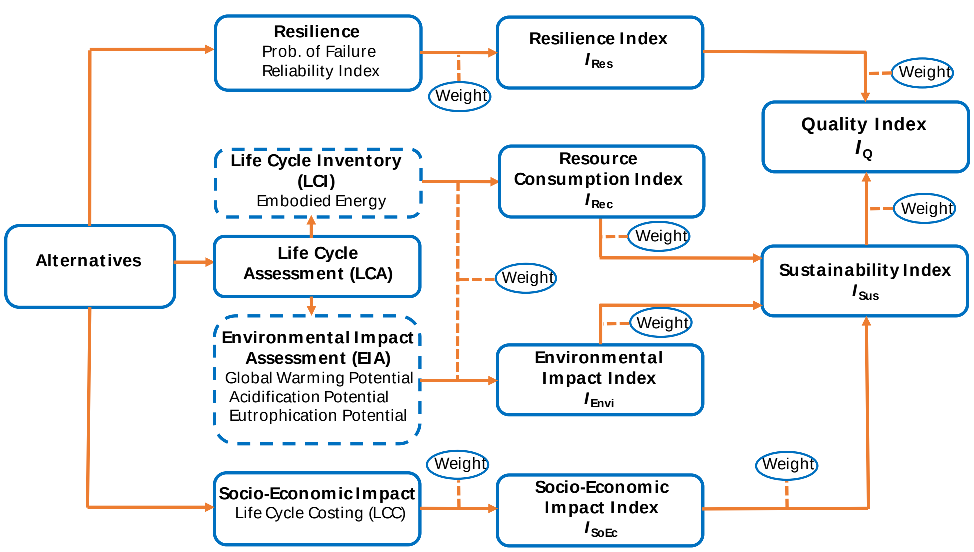

Figure 3. *Sustainability and Resilience Framework*

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In the above framework, the socio-economic impacts include different metrics including cost-benefit analysis, noise and vibrations and policy constraints. The environmental impact factor includes the global warming potential, acidification potential, eutrophication potential, and human toxicity potential. The life cycle inventory includes determination of embodied energy associated with different materials and rehabilitation techniques. The life cycle cost analyses include determining the present value of the different rehabilitation measures and resurfacing techniques that considers both the user costs and agency costs.

The first step of the approach constitutes a life cycle assessment (LCA) to gauge the environmental impact analysis (EIA) and estimate the embodied energy (life cycle inventory). The socio-economic impact is quantified through a cost-benefit analysis that takes into account the initial costs involved in the purchase, acquisition, or construction, besides the operation, maintenance, rehabilitation, and residual costs. As resilience should be analyzed with a probabilistic perspective (Bocchini et al., 2014), the reliability index (β) and probability of failure (PF) are designated as indicators of infrastructure resilience. The aforementioned impact categories of sustainability and resilience are then assigned proper weights based on their relative importance.

The final step of the framework involves a multi criteria evaluation of the individual weighted indicators to determine a Quality Index (I_Q). The design alternative with the least I_Q is considered the most appropriate alternative. The tables below presents the spreadsheet set-up for the calculation of resource consumption, environmental impact assessment, socio-economic impact. Computation of sustainability index, computation of resilience index, and computation of quality index.

Table 1. *Calculation of resource consumption*

Resource category	Embodied energy consumed				Per cent consumption of embodied energy (%)				Weights	Weighted resource use			
	Alternative 1	Alternative 2	-	Alternative n	Alternative 1	Alternative 2	-	Alternative n		Alternative 1	Alternative 2	-	Alternative n
	(1)	(2)	-	(n)	(n+1) = [(1)/∑n] × 100	(n+2) = [(2)/∑n] × 100	-	(2n) = [(n)/∑n] × 100	(2n+1)	(2n+2) = (n+1)×(2n+1)	(2n+3) = (n+2)×(2n+1)	-	(3n+1) = (2n)×(2n+1)
Material 1	E_{11}	E_{12}	-	E_{1n}	P_{11}	P_{12}	-	P_{1n}	w_1	$P_{11}w_1$	$P_{12}w_1$	-	$P_{1n}w_1$
Material 2	E_{21}	E_{22}	-	E_{2n}	P_{21}	P_{22}	-	P_{2n}	w_2	$P_{21}w_2$	$P_{22}w_2$	-	$P_{2n}w_2$
Material 3	E_{31}	E_{32}	-	E_{3n}	P_{31}	P_{32}	-	P_{3n}	w_3	$P_{31}w_3$	$P_{32}w_3$	-	$P_{3n}w_3$
-	-	-	-	-	-	-	-	-	-	-	-	-	-
Transportation	E_{i1}	E_{i2}	-	E_{in}	P_{i1}	P_{i2}	-	P_{in}	w_i	$P_{i1}w_i$	$P_{i2}w_i$	-	$P_{in}w_i$
Resource Consumption Index (I_{Rec}) →										$\sum_{k=1}^{i} P_{k1}w_k = I_{Rec1}$	$\sum_{k=1}^{i} P_{k2}w_k = I_{Rec\,2}$	-	$\sum_{k=1}^{i} P_{kn}w_k = I_{Rec\,n}$

Table 2. *Environmental impact assessment*

Environmental impact category	Emission category contribution				Per cent contribution in emission category (%)				Weights	Weighted environmental impact			
	Alternative 1	Alternative 2	-	Alternative n	Alternative 1	Alternative 2	-	Alternative n		Alternative 1	Alternative 2	-	Alternative n
	(1)	(2)	-	(n)	(n+1) = [(1)/∑n] × 100	(n+2) = [(2)/∑n] × 100	-	(2n) = [(n)/∑n] × 100	(2n+1)	(2n+2) = (n+1)×(2n+1)	(2n+3) = (n+2)×(2n+1)	-	(3n+1) = (2n)×(2n+1)
Global warming	G_{11}	G_{12}	-	G_{1n}	P_{11}	P_{12}	-	P_{1n}	w_1	$P_{11}w_1$	$P_{12}w_1$	-	$P_{1n}w_1$
Acidification	A_{21}	A_{22}	-	A_{2n}	P_{21}	P_{22}	-	P_{2n}	w_2	$P_{21}w_2$	$P_{22}w_2$	-	$P_{2n}w_2$
Eutrophication	U_{31}	U_{32}	-	U_{3n}	P_{31}	P_{32}	-	P_{3n}	w_3	$P_{31}w_3$	$P_{32}w_3$	-	$P_{3n}w_3$
-	-	-	-	-	-	-	-	-	-	-	-	-	-
Human Toxicity	H_{i1}	H_{i2}	-	H_{in}	P_{i1}	P_{i2}	-	P_{in}	w_i	$P_{i1}w_i$	$P_{i2}w_i$	-	$P_{in}w_i$
Environmental Impact Index (I_{Env}) →										$\sum_{k=1}^{i} P_{k1}w_k = I_{Env\,1}$	$\sum_{k=1}^{i} P_{k2}w_k = I_{Env\,2}$	-	$\sum_{k=1}^{i} P_{kn}w_k = I_{Env\,n}$

Table 3. *Estimation of socio-economic impact*

Socio-Economic impact category	Cost category contribution				Per cent contribution in cost category (%)				Weights	Weighted socio-economic impact			
	Alternative 1	Alternative 2	-	Alternative n	Alternative 1	Alternative 2	-	Alternative n		Alternative 1	Alternative 2	-	Alternative n
	(1)	(2)	-	(n)	(n+1) = [(1)/∑n] × 100	(n+2) = [(2)/∑n] × 100	-	(2n) = [(n)/∑n] × 100	(2n+1)	(2n+2) = (n+1)×(2n+1)	(2n+3) = (n+2)×(2n+1)	-	(3n+1) = (2n)×(2n+1)
Agency costs	C_{11}	C_{12}	-	C_{1n}	P_{11}	P_{12}	-	P_{1n}	w_1	$P_{11}w_1$	$P_{12}w_1$	-	$P_{1n}w_1$
User costs	C_{21}	C_{22}	-	C_{2n}	P_{21}	P_{22}	-	P_{2n}	w_2	$P_{21}w_2$	$P_{22}w_2$	-	$P_{2n}w_2$
-	-	-	-	-	-	-	-	-	-	-	-	-	-
Externality costs	C_{i1}	C_{i2}	-	C_{in}	P_{i1}	P_{i2}	-	P_{in}	w_i	$P_{i1}w_i$	$P_{i2}w_i$	-	$P_{in}w_i$
Socio-Economic Impact Index (I_{SoEc}) →										$\sum_{k=1}^{i} P_{k1}w_k = I_{SoEc\,1}$	$\sum_{k=1}^{i} P_{k2}w_k = I_{SoEc\,2}$	-	$\sum_{k=1}^{i} P_{kn}w_k = I_{SoEc\,n}$

Table 4. *Computation of Sustainability Index*

Sustainability indicator	Index value				Weights	Weighted index			
	Alternative 1	Alternative 2	-	Alternative n		Alternative 1	Alternative 2	-	Alternative n
	(1)	(2)	-	(n)	(n+1)	(n+2) = (1)×(n+1)	(n+3) = (2)×(n+1)	-	(2n+1) = (n)×(n+1)
Resource Consumption Index	I_{Rec1}	I_{Rec2}	-	I_{Recn}	W_1	$I_{Rec1}W_1$	$I_{Rec2}W_1$	-	$I_{Recn}W_1$
Environmental Impact Index	I_{Env1}	I_{Env2}	-	I_{Envn}	W_2	$I_{Env1}W_2$	$I_{Env2}W_2$	-	$I_{Envn}W_2$
Socio-Economic Impact Index	I_{SoEc1}	I_{SoEc2}	-	I_{SoEcn}	W_3	$I_{SoEc1}W_3$	$I_{SoEc2}W_3$	-	$I_{SoEcn}W_3$
Sustainability Index (I_{Sus}) →						$\sum = I_{Sus1}$	$\sum = I_{Sus2}$	-	$\sum = I_{Susn}$

Table 5. *Computation of Resilience Index*

Impact category for resilience	Impact category contribution				Per cent contribution in impact category (%)				Weights	Weighted impact			
	Alternative 1	Alternative 2	-	Alternative n	Alternative 1	Alternative 2	-	Alternative n		Alternative 1	Alternative 2	-	Alternative n
	(1)	(2)	-	(n)	(n+1) = [(1)/∑n] × 100	(n+2) = [(2)/∑n] × 100	-	(2n) = [(n)/∑n] × 100	(2n+1)	(2n+2) = (n+1)×(2n+1)	(2n+3) = (n+2)×(2n+1)	-	(3n+1) = (2n)×(2n+1)
Probability of Failure	F_{11}	F_{12}	-	F_{1n}	P_{11}	P_{12}	-	P_{1n}	W_1	$P_{11}W_1$	$P_{12}W_1$	-	$P_{1n}W_1$
Piezometer reading	Z_{21}	Z_{22}	-	Z_{2n}	P_{21}	P_{22}	-	P_{2n}	W_2	$P_{21}W_2$	$P_{22}W_2$	-	$P_{2n}W_2$
-	-	-	-	-	-	-	-	-	-	-	-	-	-
Inclinometer reading	R_{i1}	R_{i2}	-	R_{in}	P_{i1}	P_{i2}	-	P_{in}	W_i	$P_{i1}W_i$	$P_{i2}W_i$	-	$P_{in}W_i$
Resilience Index (I_{Res}) →										$\sum_{k=1}^{i} P_{k1}W_k = I_{Res\ 1}$	$\sum_{k=1}^{i} P_{k2}W_k = I_{Res\ 2}$	-	$\sum_{k=1}^{i} P_{kn}W_k = I_{Res\ n}$

Table 6. *Calculation of Quality Index*

Quality impact indicator	Index value				Weights	Weighted index			
	Alternative 1	Alternative 2	-	Alternative n		Alternative 1	Alternative 2	-	Alternative n
	(1)	(2)	-	(n)	(n+1)	(n+2) = (1)×(n+1)	(n+3) = (2)×(n+1)	-	(2n+1) = (n)×(n+1)
Sustainability Index	$I_{\text{Sus } 1}$	$I_{Sus\,2}$	-	$I_{\text{Sus n}}$	W_S	$I_{\text{Sus } 1} W_S$	$I_{\text{Sus } 2} W_S$	-	$I_{\text{Sus n}} W_S$
Resilience Index	$I_{Res\,1}$	$I_{Res\,2}$	-	$I_{\text{Res n}}$	W_R	$I_{Res\,1} W_R$	$I_{Res\,2} W_R$	-	$I_{Res\,n} W_R$
Quality Index (I_Q) ⟶						$\sum = I_{Q1}$	$\sum = I_{Q2}$	-	$\sum = I_{Q\,n}$

Chapter IV: Data Collection (Task 3)

The main intent of this research task is to select case studies and perform data collection for evaluating and validating the developed framework. Two different test sites within Texas were selected for performing the studies. The test sites are located at US67 and US82 where major rehabilitation works were performed by Texas Department of Transportation (TxDOT). Figure below presents the test site locations.

Figure 4. *Test Site Locations*

Field studies using LiDAR were performed at US 67 test site using FARO 3D scanner. Anchor bolts were installed at the bridge site for the scan registration process. LiDAR surveys were performed at different locations around the bridge infrastructure. The remote data collection analysis on the initial scans depicted that the pavement forensics including bridge approach slab settlement in comparison to the elevation of the bridge deck. The LiDAR surveys were also performed at US 82 test site to determine the pavement forensics. The 2D visualizations were developed for the test site at US 67 and US 82 test sites.

Chapter V: Validation Studies (Task 4)

This section demonstrates the application of the proposed combined assessment framework to a ground improvement project undertaken by researchers at The University of Texas at Arlington. As presented in the Chapter IV, two test sites where significant rehabilitation works were performed were selected. The details of the analyses are presented in the below sections:

Case Study 1 – Validation Studies for U.S 82 Test Site, Bells, Texas

The field study, sponsored by the Texas Department of Transportation (TxDOT), was aimed at stabilizing the sulfate-rich expansive subgrade soils for a high-volume road in North Texas. The test site is located at US 82 highway near Bells, TX. Novel construction techniques with two different stabilizers and extended mellowing periods are adopted at this site. Two treated pavement test sections and one control unpaved test section were constructed and monitored periodically during the course of two years and the details of the results are presented.

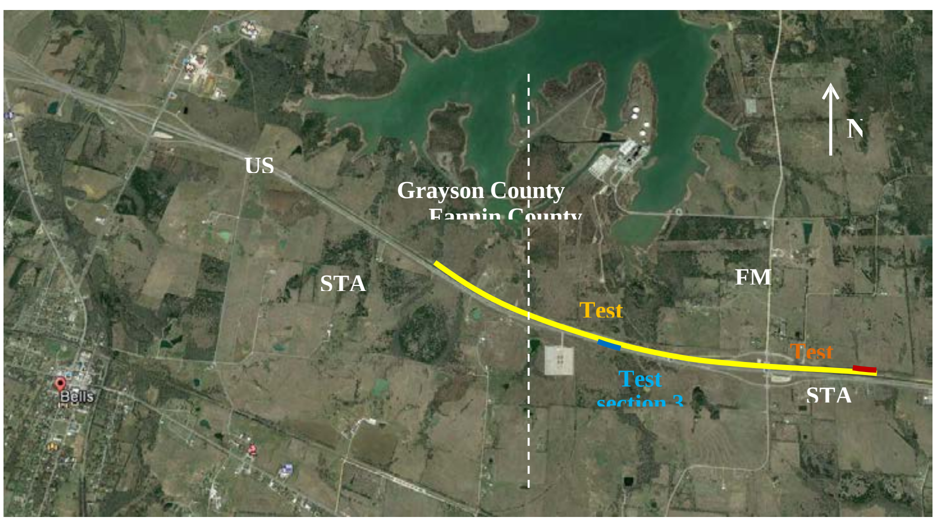

Figure 5. *Layout of test sections at US 82, Bells, TX*

Field monitoring studies include monitoring of these test sections were conducted using elevation surveys, surface profiler studies and Falling Weight Deflectometer investigations. An overview of each test section along with the construction steps followed in the field is presented in Table 7. Test sections 1 and 2 were constructed with extended mellowing periods of 10 and 7 days, respectively. Test section 1 is 2.1 miles long and is part of the east bound US 82 pavement lanes in STA 89+00 Fannin County to STA 1715+00 in Grayson County. Test section 2 is in the north bound shoulder from STA 88+00 to 89+00, extending to 100 feet. Test section 3 was constructed in the median and away from both pavement lanes of US 82 highway. The following sections present the field monitoring studies and the analyses of field monitoring results.

Table 7. *Construction phase followed for different test sections*

Days	Treatment		
	Lime + Fly Ash Extended mellowing (Test Section 1)	**Lime Extended mellowing (Test Section 2)**	**Lime 3 day mellowing (Test Section 3)**
1	Lime Treated subgrade (6%) light compact	Lime Treated subgrade (6%) light compact	Lime Treated subgrade (6%) light compact
2-3	Mellowing period	Mellowing period	Mellowing & Final Compact
4	Recut & Light Compact	Recut & Light Compact	-
5	Mellowing period	Mellowing period	-
6	Recut & Light Compact	Recut & Light Compact	-
7	Mellowing period	Remix & Final Compaction	-
8	Fly ash treatment (3%) & Light Compact	-	-
9	Mellowing period	-	-
10	Remix & Final Compaction	-	-

The developed framework was used to evaluate the sustainability and resiliency metrics for the data collected on test sections 1 and 2. The tables below provide the summary of the test results.

Table 8. *Calculation of resource consumption*

Resource category	Embodied energy consumed (MJ)		Per cent consumption of embodied energy (%)		Weights	Weighted resource use	
	Test Section I	Test Section II	Test Section I	Test Section II		Test Section I	Test Section II
	(1)	(2)	(3)=[(1)/((1)+(2))] × 100	(4)=[(2)/((1)+(2))] × 100	(5)	(6)=(5)×(3)	(7)=(5)×(4)
Lime	8268	8268	50.00	50.00	0.33	16.67	16.67
Fly Ash	78	0	100.00	0.00	0.33	33.33	0.00
Transportation	112	346	24.45	75.55	0.33	8.15	25.18
Resource Consumption Index (I_{Rec})						58.15	41.85

Table 9. *Environmental impact assessment*

Environmental impact category	Emission category contribution		Percent contribution in emission category (%)		Weights	Weighted environmental impact	
	Test Section	Test Section	Test Section I	Test Section II		Test Section I	Test Section II
	(1)	(2)	(3)=[(1)/((1)+(2))] × 100	(4)=[(2)/((1)+(2))] × 100	(5)	(6)=(5)×(3)	(7)=(5)×(4)
Global Warming Potential	1566240	1560000	50.10	49.90	0.33	16.70	16.63
Acidification Potential (gSO_2 eq.)	968.37	965.64	50.07	49.93	0.33	16.69	16.64
Eutrophication Potential (gPO_4^{3-} eq.)	161.61	124.64	56.46	43.54	0.33	18.82	14.51
Environmental Impact Index (I_{Env})						52.21	47.79

Table 10. *Computation of socio-economic impact*

Socio-Economic impact category	Cost category contribution		Per cent contribution in cost category (%)		Weights	Weighted socio-economic impact	
	Test Section I	Test Section II	Test Section I	Test Section II		Test Section I	Test Section II
	(1)	(2)	(3)=[(1)/((1)+(2))] × 100	(4)=[(2)/((1)+(2))] × 100	(5)	(6)=(5)×(3)	(7)=(5)×(4)
Cost of treatment (US$)	338.52	312.00	52.04	47.96	1.0	52.04	47.96
Socio-Economic Impact Index (I_{SoEc})						52.04	47.96

Table 11. *Sustainability assessment*

Sustainability indicator	Index value		Weights	Weighted index	
	Test Section I	Test Section		Test Section I	Test Section II
	(1)	(2)	(3)	(4)=(1)×(3)	(5)=(2)×(3)
Resource Consumption (I_{Rec})	69.98	30.02	0.33	23.33	10.01
Environmental Impact (I_{Env})	52.21	47.79	0.33	17.40	15.93
Socio-Economic Impact (I_{SoEc})	52.04	47.96	0.33	17.35	15.99
Sustainability Index (I_{Sus})				58.08	41.92

Table 12. *Metrics of resilience*

Resilience indicator		Control Section	Test Section I	Test Section II
Fatigue (Cracking)	FoS_f	1.188	1.455	1.454
	β_f	0.307	1.052	0.894
	P_{Ff}	0.379	0.146	0.186
Rutting	FoSr	2.582	2.986	2.754
	βr	0.579	0.958	0.897
	P_{Fr}	0.281	0.169	0.185
Present Serviceability Index (PSI) recorded	10/1/2014	-	4.80	4.77
	9/1/2015	-	4.76	4.72
	3/29/2016	-	4.15	4.04

Table 13. *Resilience assessment*

Resilience indicator	Impact category		Per cent contribution in impact category		Weights	Weighted impact	
	Test Secti	Test Secti	Test Section I	Test Section		Test Section	Test Section
	(1)	(2)	(3)=[(1)/((1) +	(4)=[(2)/((1) +	(5)	(6)=(5)×(3)	(7)=(5)×(4)
Present Serviceability Index	4.57	4.51	50.33	49.67	0.33	16.78	16.56
Probability of Fatigue	0.146	0.186	43.98	56.02	0.33	14.66	18.67
Probability of Rutting	0.169	0.185	47.74	52.26	0.33	15.91	17.42
Resilience Index (I_{Res})						47.35	52.65

Table 14. *Estimation of Quality*

Quality indicator	Index value		Weights	Weighted index	
	Test Section I	Test Section II		Test Section I	Test Section II
	(1)	(2)	(3)	(4)=(1) × (3)	(5)=(2) × (3)
Sustainability Index (I_{Sus})	58.08	41.92	0.5	29.04	20.96
Resilience Index (I_{Res})	47.35	52.65	0.5	23.68	26.33
Quality Index (I_Q)				52.72	47.29

As per the framework, test section II stabilized with 6% lime, has a lower I_{Sus} of 41.92 and is considered more sustainable. This is also corroborated by the calculation of the threshold sustainability value. However, test section I stabilized with 6% lime and 3% fly ash, is ranked higher in resilience (I_{Res} = 47.35). Upon combined assessment and from the pictographic representations, it is found that test section II is most suitable for field implementation when the weightage accorded to sustainability and resilience is the same. An interesting trend may be observed if the weight attached to the sustainability index (W_S) is less than 0.25. In such a scenario, the test section I would have a lower I_Q, and would be preferable for field implementation.

<u>Case Study 2 – Bridge Approach Slab at U.S. 67, Cleburne, Texas</u>

This section demonstrates the application of the proposed combined assessment framework to a bridge study. This field study, supported by TxDOT, chronicles the use of an alternate, lightweight, polymeric geofoam material to mitigate the settlement of bridge approach slabs and adjoining roadway for a state highway in Texas. The specifics of the field study such as location, layout, construction details, and monitoring protocol are provided. During 1995 and 1996, the US 67 bypass was constructed in Cleburne, Texas to divert US Highway 67 traffic around the downtown district. One of the four bridges constructed in the project was a 40-ft high overpass bridge situated at the intersection between US 67 and State Highway 174 as illustrated in Figure 6.

Figure 6. *Location of test site in Cleburne, Texas*

The bridge was designed for two-lane traffic conditions. Both ends of the bridge structure were placed on the abutments supported by drilled-shaft foundations. Adjacent to the bridge abutments, approach embankments were built to support the interfacing bridge approach slabs and roadways. Within approximately 16 years after the initial construction, the approach slab of the bridge had experienced approximately 17 inches of settlements, as shown in Figure 7. During that period, several treatment methods including hot mix overlays, grout injections, soil nailings, and others were attempted; however, those methods were proven to be ineffective in mitigating the settlements.

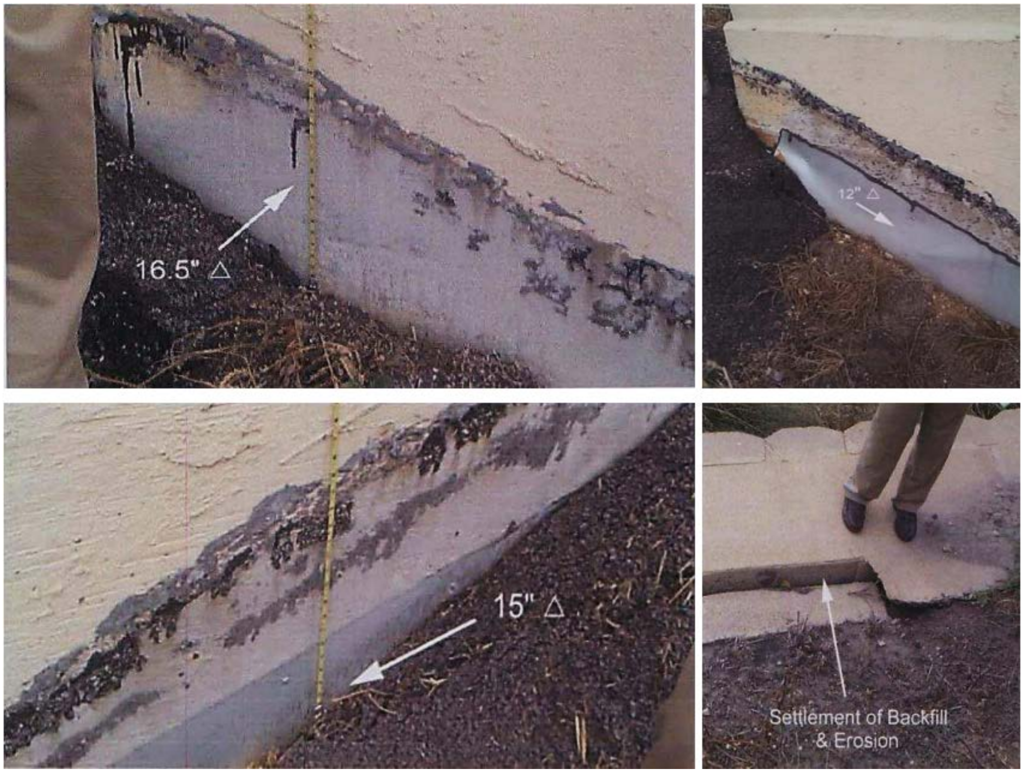

Figure 7. *Bridge approach settlement (Courtesy: TxDOT)*

In order to alleviate the settlement problems that occurred on the approach embankments of the overpass bridge situated on US 67 over SH 174 in Johnson County, Cleburne, Texas, the research team worked with TxDOT's Fort Worth district to study the potential of using the Geofoam embankment system to mitigate settlements. Geofoam can reduce the loads acting on existing soils by replacing parts of the embankment as a lightweight fill material. For this reason, EPS 22 geofoam blocks were recommended to be used as the fill material. This material was used to replace a 6 ft. depth of the top part of the embankment on the east end of the bridge for the present test section. The details of the analyses are summarized in the tables provided below:

Table 15. *Calculation of resource use*

Resource Category	Embodied energy consumed (MJ)		Percent consumption of embodied energy (%)		Weights	Weighted resource use	
	Test Section I	Test Section II	Test Section I	Test Section II		Test Section I	Test Section II
Soil	0.01	0.01	50.00	50.00	0.33	16.67	16.67
Geofoam	159480	0	100.00	0.00	0.33	33.33	0.00
Transportation	250	150	62.50	37.50	0.33	20.83	12.50
Resource Consumption Index (I_{Rec})						70.83	29.17

Table 16. *Environmental impact assessment*

Environmental impact category	Emission category contribution		Percent contribution in emission category (%)		Weights	Weighted environmental impact	
	Test Section I	Test Section II	Test Section I	Test Section II		Test Section I	Test Section II
Global Warming Potential (gCO_2 eq.)	5922000	0.0	100.0.00	0.00	0.33	33.33	0.00
Acidification Potential (gSO_2 eq.)	828.0	0.0	100.00	o.00	0.33	33.33	0.00
Eutrophication Potential (gPO_4^{3-} eq.)	0.65	0.0	100.00	0l.00	0.33	33.33	0.00
Environmental Impact Index (I_{Env})						100.00	0.00

Table 17. *Computation of Socio-Economic Impact*

Socio-Economic impact category	Cost category contribution		Percent contribution in impact category (%)		Weights	Weighted socio-economic impact	
	Test Section I	Test Section II	Test Section I	Test Section II		Test Section I	Test Section II
(1)	(2)	(3)	(4)=[(2)/((2) + (3))] × 100	(5)=[(3)/((2) + (3))] × 100	(6)	(7)=(6)×(4)	(8)=(6)×(5)
Cost of repair (US$)	7920.00	980.00	88.99	11.01	1.0	88.99	11.01
Socio-Economic Impact Index (I_{SoEc})						88.99	11.01

Table 18. *Sustainability assessment*

Sustainability indicator	Index value		Weights	Weighted index	
	Test Section I	Test Section II		Test Section I	Test Section II
Resource Consumption (I_{Rec})	70.83	29.17	0.33	23.61	9.72
Environmental Impact (I_{Env})	100.00	0.00	0.33	33.33	0.00
Socio-Economic Impact (I_{SoEc})	88.99	11.01	0.33	29.66	3.67
Sustainability Index (I_{Sus})				86.61	13.39

Table 19. *Resilience assessment*

Resilience indicator	Impact category contribution		Per cent contribution in impact category (%)		Weights	Weighted impact	
	Test Section I	Test Section II	Test Section I	Test Section II		Test Section I	Test Section II
Max. vertical movements (in.)	1.50	17.0	8.11	91.89	0.50	4.05	45.95
Probability of Failure	0.12	0.82	12.77	87.23	0.50	6.38	43.62
Resilience Index (I_{Res})						10.44	89.56

Table 20. *Calculation of Quality Index*

Quality indicator	Index value		Weights	Weighted index	
	Test Section I	Test Section II		Test Section I	Test Section II
Sustainability Index (I_{Sus})	86.61	13.39	0.5	43.31	6.70
Resilience Index (I_{Res})	10.44	89.56	0.5	5.22	44.78
Quality Index (I_Q)				48.53	51.48

Various details on how the framework can be used is explained using the bridge repair. The focus is on using lightweight, polymeric EPS geofoam to mitigate the settlement of bridge approach slabs. Both the methods are fully assessed with the proposed framework in terms of enhancing both sustainability and resilience characteristics.

Chapter VI: Conclusions

Through this research, a holistic sustainability and resiliency framework to evaluate two or more alternatives to stabilize the problematic subgrade soils has been developed. A multi-criteria approach was developed considering the both sustainability and resiliency metrics or measures. The framework enables comparison among any number of competing alternatives across any number of metrics. It also allows some flexibility in assigning weights to the impact categories and metrics. The developed approach accounted for different variables including treatment techniques, type of stabilizer, curing period, life cycle cost analyses including user costs and agency costs, environmental effects, and performance monitoring data.

Two test sites were selected based on the past history and rehabilitation works performed at those sites. The test site 1 (Case Study 1) presented the evaluation of two different treatments at the test site. Field monitoring was performed at the test sites using different approaches. The performance metrics were used for the resiliency analyses and for the sustainability different environment, cost-best analysis, and socio-economic impact analyses were performed. Both sustainability and resiliency metrics were used to reach a rationale conclusion to choose the best performing stabilizer. The test site 2 (case study 2) presented the evaluation of the performance of the geofoam as a solution to mitigate the bridge approach settlement. The performance data collected over the years using LiDAR, inclinometers were used for the analyses.

The proposed research is of significant importance to Federal and State Highway Agencies as well as the construction industry at large. Selection, based on sustainability and resilience, among the two different alternatives would support in the reduction of maintenance costs.

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