

Applications of Deep Soil Mixing for Soft Soil Improvement in East and Southeast Asia: A Scoping Review

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Applications of Deep Soil Mixing for Soft Soil Improvement in East and Southeast Asia: A Scoping Review

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ABSTRACT: Studies on deep soil mixing (DSM) are often highly site-specific, which focuses on specific in-situ soil conditions and desired project specifications. Although hundreds of studies have already been published, there is no consolidated body of knowledge that will serve as a reference for future DSM projects. This study presents a scoping review of the applications of deep soil mixing (DSM) for soft soil improvement in East and Southeast Asia. A total of 30 peer-reviewed studies published from 2010-2025 were analyzed following the PRISMA-ScR framework. Data were extracted according to the inclusion and exclusion criteria and were systematically organized into different classifications. The results show that DSM is commonly applied in soft and marine clay, with ordinary Portland cement as the primary binder. Wet-mixing techniques and column-based configurations were the most widely used approaches. Documented improvements show an increase in unconfined compressive strength from approximately 200 kPa to 3000 kPa, a decrease in settlement of up to 97.45%, and increases in bearing capacity of up to 169%, depending on the column arrangement and soil conditions. However, test methods in the majority of the studies focus more on laboratory experiments and software simulations, which reflect a consistent discrepancy between the field and laboratory performance of soils, with field strengths reported to be 15–55% lower. Minimal resources were gathered from countries such as the Philippines, and the overall trend in the type of soil studied leans toward clay-based soils rather than organic soils such as peat. Overall, this study concluded that DSM is an effective method in improving the qualities of soft soil. Further studies regarding DSM must focus on field-based investigations, develop a standardised design manual, and assess its long-term quality performance.

KEYWORDS: Deep Soil Mixing, Soft Clay, Ground Improvement, East Asia, and South East Asia.

1. INTRODUCTION

Soft soils, commonly scattered among the regions of East and Southeast Asia, impose major challenges to infrastructure development due to their high compressibility, weak shear strength, high water content, and long-term settlement (Bergado et al., 2010; Shen & Wang, 2020). In countries where rapid urbanization occurs, such as China, Thailand, Vietnam, Malaysia, and Singapore, there is a need for effective ground improvement techniques to make the construction of highways, embankments, ports, and underground structures on weak subsoil conditions feasible.

Deep soil mixing (DSM) is a widely used method among various ground improvement techniques for soft soil stabilization. DSM involves the in-situ mixing of soil with cementitious binders to form soil–cement columns or panels, thereby increasing strength, reducing compressibility, and improving overall ground stability (Kitazume & Terashi, 2013). Wet mixing, dry mixing, and jet grouting are some of the techniques used to implement DSM, depending on the project specifications and in-situ soil characteristics. Different studies reported that DSM can significantly enhance the engineering properties of soft soils, such as the unconfined compressive strength and settlement reductions under different loading conditions (Jamsawang et al., 2016; Voottipruex et al., 2011).

DSM applications in East and Southeast Asia are mostly focused on geotechnical engineering projects such as foundation support, embankment stabilization, tunnel construction, and land reclamation (Kang & Cheung, 2023). For example, Jamsawang et al. (2016) studied how DSM showed significant improvement in stiffness and load-bearing capacity and has been used to minimize the settlement in highway embankments on soft marine clay. Furthermore, DSM has been applied in tunnel construction on reclaimed land, where it has demonstrated effectiveness in

mitigating settlement associated with construction-induced ground movements. Different studies on DSM also presented the effects of the variation of cement binders and alternative additives. Fly ash and rice hull ash were used as additives on the cement binders, and studies show that soft soils manifested an increase in the unit weight and a decrease in moisture content (Daarol et al., 2023).

Although the implementation of DSM is rapidly increasing over the years and the presence of studies on the effectiveness of DSM is broader, particularly in East and Southeast Asia, the results vary and cannot be applied to all geotechnical engineering projects due to a significant difference in terms of site conditions, project specifications, binder characteristics, and testing methods. Consequently, there is an absence of a collection of general understanding on the behavior, performance, and limitations of DSM across varying soil conditions. Furthermore, there were also issues that were reported in relation to the discrepancy of laboratory and field performance in terms of strength development and quality control, which remain a recurring issue reported in several studies (Zuo & Wang, 2023).

Therefore, this study aims to collect and organise the existing literature on deep soil mixing applications for soft soil improvement in East and Southeast Asia, and group them according to different data classifications. Specifically, the study seeks to (1) identify the types of soils and DSM techniques used in the region, (2) examine the reported improvements in engineering properties such as strength and settlement, and (3) highlight existing research gaps to guide future studies.

2. METHODS

2.1 Scoping review framework

This study uses a scoping review methodology following the PRISMA-ScR (Preferred Reporting Items for Systematic Reviews

and Meta-Analyses extension for Scoping Reviews) guidelines (Tricco et al., 2018). The goal of this study is to synthesize and categorize a structured presentation of the existing literature on the application of deep soil mixing (DSM) for soft soil improvement in East and Southeast Asia. This approach is well-suited for the current study since it involves in-depth research on relevant studies, identification of common trends, organization of underlying results, and establishment of knowledge gaps.

2.2 Research questions

This study is guided by the following research questions in accordance with the PRISMA-ScR framework:

1. Which soft soil types are commonly studied in DSM applications within East and Southeast Asia?
2. What DSM methods and binder materials are commonly used in the region?
3. What magnitudes of improvements in terms of strength and settlement are reported in the literature?
4. What research gaps exist in the current collection of literature?

2.3 Search strategy

Databases with a wide range of coverage of published and peer-reviewed geotechnical engineering literature, such as Google Scholar, Scopus, and Web of Science, were used for the study search. These databases provide a strong and well-balanced approach when it comes to pulling out literature that is relevant to the specifications issued by the researcher (Falagas et al., 2008). For each concept, multiple synonyms and related terms were included to ensure a broad coverage of studies. The keywords were grouped as follows:

- Technique-related terms: “deep soil mixing”, “DSM”, “deep mixing method”, “soil stabilization”, “ground improvement.”

- Soil-related terms: “soft soil”, “soft clay”, “cohesive soil”, “organic soil.”

- Location-related terms: “Southeast Asia”, “East Asia”, “Philippines”, “Vietnam”, “Thailand”, “Indonesia”, “Malaysia”, “Singapore”, “China”, “Japan”, “Korea”, “Hong Kong.”

The operator “OR” was applied within each group to include synonyms, while “AND” was used to combine different related texts. The search string was created based on key concepts related to DSM, soft soils, and geographic scope:

(“deep soil mixing” OR “deep mixing method” OR “DSM” OR “cement deep mixing”) AND (“soft soil” OR “soft clay” OR “cohesive” OR “organic soil”) AND (“ground improvement” OR “soil stabilization” OR “foundation improvement”) AND (“East Asia” OR “Southeast Asia” OR Philippines OR Vietnam OR Thailand OR Malaysia OR Singapore OR Indonesia OR China OR Japan OR Hongkong OR Korea)

2.4 Inclusion and exclusion criteria

Since the behaviour of a treated soil as well as the ruling geotechnical principles on DSM change very slowly over time, the literature search covers a fifteen-year time period, limiting the study to published papers between 2010–2025, and the application of DSM on these papers must be conducted within East Asia (China, Japan, Korea, or Hong Kong) or Southeast Asia (Indonesia, Malaysia, Philippines, Singapore, Thailand, or Vietnam). These studies must be focused on deep soil mixing (DSM), deep cement mixing (DCM), or deep mixing method (DMM), and their examples, and soft soils such as soft clay, marine clay, or organic soil. Engineering reports such as strength improvement (e.g., unconfined compressive strength), settlement reduction, stability, bearing capacity, and other improved soil properties (e.g., water content, void ratio, unit weight, etc.) must be presented by these studies and were tested through laboratory experiments, field case studies, or numerical and software simulations.

Studies were excluded if they were outside the defined geographic scope, did not involve DSM or related mixing techniques, focused on soils that are not classified as soft soils (e.g., sand, loam, etc.), or non-published sources such as editorials, opinion papers, and non-technical reports. Although limiting the review to peer-evaluated studies and articles downsizes the scope of the paper and disregards emerging ideas that are commonly presented in conference proceedings or technical report papers, this scoping review paper ensures quality control and data consistency, which are strengthened by multiple paper checking processes and a structured paper format.

2.5 Study selection process

The preliminary search using the search string yielded 378 records from the selected databases, which include books, technical design standards, theoretical studies, technical reports, etc. Paper titles were filtered for the initial screening using the keywords, and 112 studies were pulled out from the pool. 21 duplicate studies were identified, reducing the number of unique studies to 91.

Full-text articles were carefully reviewed to determine eligibility based on the inclusion and exclusion criteria. Most of the excluded papers were not included due to their outside-of-the-scope location, comprising 26 studies. 18 studies that do not include DSM or any of its examples were removed from the pool, 5 outdated papers were discarded, 9 studies that do not focus on soft soil were also eliminated, and finally, 3 unpublished papers were not included. A total of 30 studies were retained for the final data extraction. The overall selection process is summarized using a PRISMA flow diagram, which illustrates the number of records identified, screened, excluded, and included in the review.

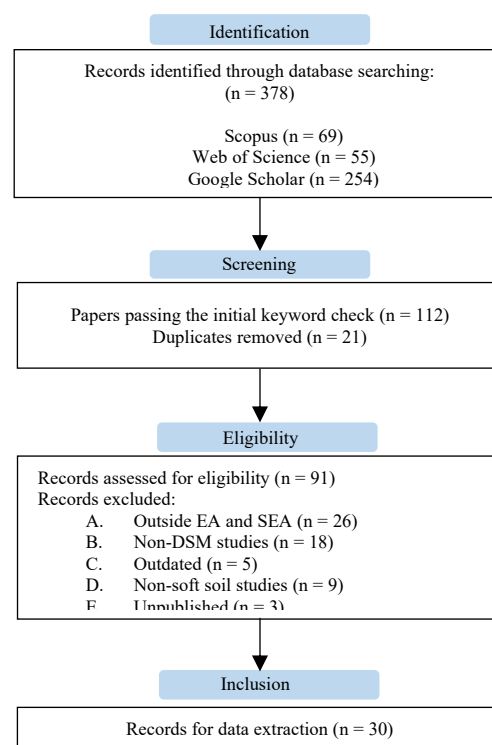


Figure 1. PRISMA 2020 flow diagram

2.6 Data charting and categorization

A data extraction table was developed to record important information from each selected study. The variables included in the charting process were as follows:

- Author(s) and year of publication
- Country or location of the study
- Soil type (e.g., soft clay, marine clay, organic soil)

- Type of deep soil mixing technique (e.g., DSM, DCM, DMM, jet grouting)
- Binder material used (e.g., ordinary Portland cement, fly ash, rice husk ash)
- Application of the technique (e.g., embankment, foundation, tunnel, reclamation)
- Reported engineering outcomes (e.g., unconfined compressive strength, settlement reduction, stability improvement)
- Methods for specimen preparation and implementation of the DSM application (e.g. in-situ demonstration, laboratory-mixed specimen evaluation, and computational modelling)

The extracted data were then categorized to identify patterns and trends across the studies. Categorization was performed based on the following groupings:

1. **Geographical distribution** – the studies were grouped based on the country where they were conducted to get a clearer picture of how research is spread across different regions.
2. **Soil type classification** – the studies were organized according to the type of soft soil being investigated, such as marine clay, soft clay, or organic soil.
3. **DSM technique and binder type** – the studies were grouped based on the type of mixing method used and the stabilizing materials applied during the process.
4. **Application type** – the studies were classified according to their engineering applications, including embankments, foundations, tunnels, and other underground structures.
5. **Performance outcomes** – the studies were also grouped based on the improvements reported, particularly in terms of strength, settlement, and overall stability.
6. **Implementations in DSM applications** – the studies were classified into types of methods and implementation and specimen preparation, which are: in-situ demonstration, laboratory-mixed specimen evaluation, and computational modelling.

This approach to organizing and grouping the data made it easier to get an overall view of the existing studies. It also helped in identifying common patterns, key trends, and areas where further research is still needed in the application of DSM for soft soil improvement.

3. RESULTS

3.1 Geographical distribution

Figure 2 presents the distribution of the included studies according to country. The studies were predominantly conducted in Southeast Asia, particularly in Thailand, Malaysia, and Vietnam. The widespread presence of Soft Bangkok clay across the region and the urgent need for infrastructure development led to the continuously increasing number of ground improvement studies. This study included 8 studies from this region.

Laboratory-based investigations as well as in-situ testing were common in countries with dominant soft soil conditions like Malaysia and Vietnam, which also contribute a significant number of studies focusing on the difficulties imposed by coastal and deltaic areas, each having 6 and 5 studies respectively.

Since conducting a full-scale field testing on DSM applications is costly and time-consuming, countries like Japan and China lean towards numerical modeling and theoretical analysis. This approach puts them at an advantage since these countries have strong research and computing capabilities, added to the presence of high-end universities and research institutions. Meanwhile, despite the presence of soft and problematic soils in many Philippine coastal and reclaimed areas (Dimalanta et al., 2024),

locally published studies on DSM remain relatively limited compared to the scale of geotechnical challenges in the country.

In general, the statistical count on the existence of studies on each region was mainly related to their soil types and their demand for ground improvement activities. This study shows that the existing literature between these regions is unbalanced, and it would be beneficial if further studies were concentrated more on countries with very limited research and implementation of DSM.

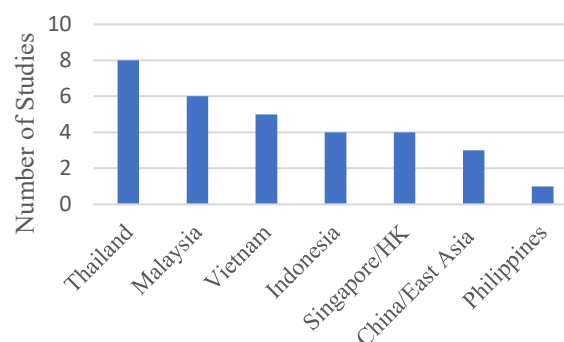


Figure 2. Distribution of studies by country

3.2 Soil types classification

Table 1 summarizes the classification of soil types considered in the reviewed studies. The majority of the reviewed studies are centred on the effects of DSM on soft clay and marine clay, which are typically found in coastal and deltaic regions. These types of soil are highly difficult to work with due to the inconsistency of their behavior and low shear strength. Most of the time, engineers proceeded with ground improvement methods such as DSM to make the construction of infrastructures on soft clay feasible.

The growing economy and industrialization of Southeast Asia, especially in regions like Thailand, Malaysia, and Vietnam, contribute to the developing demand in ground improvement projects (World Bank, 2023; United Nations, 2022). This trend is attributed to the increasing number of studies on soft clay, making it frequently investigated in DSM-related studies. In comparison, a smaller number of studies examine organic soils and peat, which behave differently from clay-based soils. These materials commonly show lower strength improvement after treatment, primarily because of their high organic and water content, which can affect the bonding process during stabilization.

The results of the reviewed studies show that treated peat soils have increased unconfined compressive strength from approximately 90 kPa to around 200–400 kPa. This notable improvement is still relatively lower than the strength increase usually achieved in cement-treated clay soils, which can reach much higher values.

These observations highlight the important role of soil type in determining the effectiveness of DSM. In particular, clay-based soils tend to respond more favorably to cement stabilization, whereas organic soils may require alternative treatment approaches or higher binder content to achieve comparable performance.

Table 1. Classification by soft soil type

Soil type	No. of studies	Description
Soft clay / Marine clay	28 (93.3%)	Most common soil: high compressibility and low strength
Organic soil / Peat	1 (3%)	High water content; limited strength improvement
Layered / Mixed soils	1 (3%)	Combination of clay, silt, and sand

3.3 DSM techniques and configuration

Table 2 presents the distribution of types of DSM techniques reported from the pool of studies, which are grouped into two categories: explicitly reported techniques and unspecified techniques. Only 3 studies have specified the DSM techniques used; 2 studies used the dry mixing method, while 1 study used the jet grouting method. The majority of the reviewed literature from the collection did not clearly state the technique used, and no assumptions were made to cope with the missing information.

Despite the lack of classification, many studies reported the use of cement slurry as their binding material, which implies that the study used a wet mixing technique. Since there was no direct statement from the reviewed studies that mentions this information, they were categorised as “not specified” to maintain transparency in methodology and avoid unsupported claims.

The inconsistency in reporting shows the current limitations in the current collection of literature. A clear comparison of technique performance, particularly in terms of strength improvement, mixing consistency, and field applicability, cannot be accurately established across different studies since the description of detailed DSM techniques was not included in most of the literature.

Overall, the results tell us that there is a lack of documentation regarding the specific techniques used, although the DSM is widely used in ground improvement projects in East and Southeast Asia. The choice of mixing method greatly affects the performance of a soil improvement method; hence, future studies should focus on reporting clear and complete DSM methodologies.

Table 2. DSM techniques and classification

Category	Type	No. of Studies
Explicitly reported techniques	Dry mixing	2 (6.7%)
	Jet grouting	1 (3.3%)
Not explicitly specified	(not specified)	27 (90%)

3.4 Binder materials

Table 3 presents the types of binders used in DSM applications. The compiled studies show that the widely used binder in the reviewed studies is the ordinary Portland cement (OPC), mainly because of its availability, and numerous studies have already confirmed its contribution in strengthening the geotechnical properties of soft soils. However, the huge global demand for cement production results in a substantial increase in carbon dioxide (CO₂) emissions, together with other pollutants, which account for approximately 7–8% of global CO₂ emissions (Andrew, 2018; International Energy Agency [IEA], 2022). This environmental degradation pushes several studies to explore alternative additives such as fly ash (FA), rice husk ash (RHA), and hydraulic cement (HC) as partial cement replacements.

While OPC generally provides higher strength even at relatively low percentages, results show that alternative binders

can contribute to improvements in specific soil properties. For example, a maximum replacement level of approximately 20% of cement by weight of RHA can improve strength performance. Further increase in the percentage of RHA resulted in the decline of its strength performance. On the other hand, FA was observed to improve shrinkage behavior and reduce cracking potential, although it may result in lower overall strength compared to OPC-treated soils.

These results show that a specific proportion of binder and additives must be used to achieve a balanced effect, maximizing strength and improving sustainability. Alternative binders provide possible benefits for environmental preservation and durability, depending on project requirements.

Table 3. Binder material used

Binder type	No. of studies	Observations
Ordinary Portland Cement (OPC)	22 (73.3%)	Provides the highest strength
Cement + Fly Ash (FA)	10 (33.3%)	Improves shrinkage, reduces strength
Cement + Rice Husk Ash (RHA)	4 (13.3%)	Optimal at ~20% replacement
Hydraulic Cement (HC)	3 (10%)	Comparable performance at high dosage
Cement + fiber	1 (3%)	Increased mixability

Note: Some studies are classified under multiple categories (e.g., multiple soil types, binders, or applications); therefore, the total number of entries may exceed the total number of reviewed studies.

3.5 Application of DSM

Table 4 summarizes the engineering applications of DSM in the reviewed studies. The presence of numerous coastal plains, river deltas, and low-lying areas in East and Southeast Asia, along with its soft soil composition, requires the installation of embankments that are essential for transportation infrastructure, including highways, railways, and flood control systems. The extracted data indicate a high proportion of published studies related to embankment construction. DSM is mainly used in embankment and foundation projects, where improvements in ground stability and load-bearing capacity are needed. In these applications, DSM has effectively enhanced the mechanical behavior of soft soils, making them more suitable for supporting structural loads.

Several studies report that soils treated with DSM show major reductions in settlement. For example, in highway embankment projects, settlement was reduced from approximately 1.26 m to about 0.38–0.58 m, showing a significant improvement in ground performance. The decrease in settlement is mainly due to the increased stiffness of the treated soil and the improved distribution of loads through the soil–cement columns.

Many studies also report the positive results of DSM application in foundations that are constructed on soft soils. Results show 169% increase in bearing capacity in comparison to untreated soil conditions, which means that DSM is effective in enhancing the load-carrying capability of weak ground, particularly in areas with soft clay deposits.

Aside from these conventional applications, DSM is also being used in more complicated engineering projects, such as tunnel protection, land reclamation, and excavation support systems. These applications are commonly situated in urban areas, wherein insufficient construction area and difficult ground conditions require more advanced and reliable ground improvement techniques.

Table 4. DSM application

Application	No. of studies	Observations
Embankments	20 (66.7%)	Significant settlement reduction
Foundations	15 (50%)	Increased bearing capacity (up to ~169%)
Land reclamation	8 (26.7%)	Used in coastal projects
Tunnel Protection	5 (16.7%)	Controls deformation
Excavation support	6 (20%)	Used with walls and reinforced columns
General ground improvement	18 (60%)	Broad application

3.6 Performance outcomes

Table 5 presents the key performance outcomes of DSM reported in the reviewed studies. The performance of DSM on various geotechnical parameters was reported to be satisfactory, as shown in Table 5. Most cases show improved soil performance after soft soil is improved using DSM. For example, studies by Jamsawang et al. (2016) reduced the settlement up to approximately 78% - 80% and Wang et al. (2019) showed that the soft soil improved with binder increased its unconfined compressive strength by

approximately 30% to 50% when compared to in-situ results. In some studies, the increase in UCS is commonly influenced by both binder composition and soil type. Teo et al. (2017) generated the relationships of fiber reinforcement and their mixability with OPC, signifying correlations with curing time and strength.

In general, more than half of the studies reported a significant increase in the UCS of the soils; two of the highest results were from Chompoorat et al. (2022) revealing a 12,400% increase in their laboratory-mixed specimen when compared to field results, and from Shiwakoti & Manai (2016), where there is an increase of 28,900% using a dry jet grouting method. Some of the studies also reported an increase in strength, however, the numbers were not indicated due to the fact that they only rely on the correlations with other soil behavior, such as soil bearing capacity (Ahmad et al., 2015; Uchiyama et al., 2024; Tanseng et al., 2025), consolidation time (Hamdhan et al., 2024), stiffness (Ho, 2022), decrease in permeability enhancement (Shiwakoti & Manai, 2016), and settlement reduction (Voottipruex et al., 2011; Ahmad et al., 2015; Jamsawang et al., 2016; Yao et al., 2016; Thinh et al., 2018; Nguyen & Nguyen, 2020; Ho, 2022; Pan et al., 2022; Zaika et al., 2023; Hamdhan et al., 2024; Uchiyama et al., 2024; Tanseng et al., 2025).

The addition of cement to soil through deep DSM changes its mechanical behavior and properties by forming a soil-cement composite (Kitazume & Terashi, 2013). Shen & Wang (2020) reported that the composition of the soil-cement column and the surrounding soil influenced the occurrence of internal and external failure modes.

Table 5. Performance outcomes

Author	Country	Soil type	Strength parameter change	Observations
Ahmad et al. (2015)	Malaysia	Soft clay	Bearing capacity: +80% - +168%, settlement: -20% to -70%	DM columns improved bearing capacity and reduced settlement compared to untreated soil
Bergado et al. (2010)	Thailand	Soft Bangkok clay	UCS: +1100% to +5900%	Deep mixing effectively reduced embankment settlement
Chompoorat et al. (2022)	Thailand	Soft clay	Strength increase (qu): +500% to +12,400%	Strength increases with OPC; FA reduces shrinkage
Daarol et al. (2023)	Philippines	CL clay	Strength increase (deviator stress / shear strength): +15% to +340%	RHA significantly improves strength; optimal at 20% replacement
Duong & Nu (2020)	Vietnam	Soft soil	Strength increase (UCS, E50): +50% to 80%	Clear quantified strength improvement using RHA
Hai & Fellenius (2013)	Vietnam	Soft clay	0% improvement (failure case)	Column system failed due to inadequate strength gain
Hamdhan et al. (2024)	Indonesia	Soft soil	Settlement: - 97.45%, Consolidation time: +89.60%	Lattice pattern most effective among DCM configurations
Ho (2022)	Hong Kong	Contaminated soft marine clay	UCS: +1400% to +7400%; stiffness: +1400% to +7400%; shear strength (CU): +100% to +200%; settlement: -30% to -60%; permeability: -50% to -90%	Strength and stiffness strongly governed by water/cement ratio; long-term curing increases strength; DCM improves load transfer and reduces settlement while controlling contaminant migration
Thinh et al. (2018)	Vietnam	Soft soil	Settlement: -81% to -96.6%	CDM improves stability and reduces displacement
Jamsawang et al. (2016)	Thailand	Soft clay	Settlement: -78% to -80%	Improved load sharing and reduced deformation
Meepon et al. (2016)	Thailand	Soft Bangkok clay	UCS increase: +191%	Increase due to higher cement content
Nguyen & Nguyen (2020)	Vietnam	Soft soil	Settlement: -76%	DCM columns + geotextile significantly reduce settlement (0.508 m → 0.120 m)
Pan et al. (2022)	China	Soft soil	Tunnel displacement: 66% of allowable limit, settlement: 55% – 60% of allowable limit.	Proper DSM parameters minimize tunnel deformation
Petchgate et al. (2025)	Thailand	Clay & sand	UCS: +840% to +21,800%; E50: +47.04% to +77.65%	HC and OPC significantly improved strength and stiffness; field values exceeded laboratory predictions due to higher cement content

Shiwakoti & Manai (2016)	Vietnam	Soft soil	SUCS: +7,400% to +28,900%; Permeability: -573,000%;	Significant improvement in multiple engineering properties
Sukpunya et al. (2016)	Thailand	Soft clay	Shear strength: ↑ +8% to +310%	Strength improvement depends on column pattern
Tang et al. (2011)	Malaysia	Peat & organic soil	UCS: +20% to +1400%	Significant strength and stiffness improvement due to formation of CSH and ettringite; microstructure becomes denser
Tanseng et al. (2025)	Thailand	Soft clay	Bearing capacity: +2900%; lateral displacement: -63%; settlement: -67%; F.S.: +100% to +130%	SCC-W with SCC-CW significantly reduces soil movement and improves basal stability; allows bracing-free excavation and long-term performance stability
Uchiyama et al. (2024)	Indonesia	Multi-layered soft soil	UCS: +3300% to +8500%; bearing capacity: +3300% to +8500%; settlement: -50% to -80%; strength vs design: +92%	Field UCS (1724 kPa) significantly exceeded target (900 kPa); strength gain attributed to curing temperature and sampling bias; DCM effective in complex layered soils.
Voottipruex et al. (2011)	Thailand	Soft clay	Axial bearing capacity: +75% to +129%; lateral bearing capacity: +1400%; settlement: -40% (vs DCM), -60% (vs unimproved); lateral movement: -60%	SDCM piles significantly improved performance due to concrete core; major gain in lateral resistance ($\approx 15\times$); improved stiffness and load transfer efficiency
Wang et al. (2019)	Hong Kong	Soft marine clay	UCS (field vs lab): -30% to -55%;	Strength strongly influenced by W:C, dosage, and curing age; field strength significantly lower than laboratory due to mixing variability
Xue et al. (2024)	Malaysia	Soft soil (clay, peat)	UCS: +116%	Fly ash cement effective; strength strongly reduced by organic content and poor soil
Yao et al. (2016)	China	Soft soil	Settlement (column length increase): -50%	Settlement strongly controlled by column length and replacement ratio; higher surcharge amplifies difference
Yoshida et al. (2018)	Singapore	Marine clay (reclaimed land)	Lateral pressure: -41% to -50% (actual vs assumed); S-Wall deflection: -30%	DSM induces significant lateral pressure; actual field response differs from prediction; pressure relief holes reduce deformation; design must consider lateral effects
Zaika et al. (2023)	Indonesia	Soft soil	UCS: +248%; Settlement: -74.5%	DCM significantly reduces settlement and increases strength; overlapping columns improve internal stability; area ratio strongly influences performance
Zuo & Wang (2023)	China	Soft soil	UCS: -15% to -55% (field vs lab); UCS: +31% (bidirectional mixing);	Field strength lower than the lab due to variability in mixing

Note: Strength parameters reported in the reviewed studies include unconfined compressive strength (UCS), compressive strength (qu), and shear strength, depending on the methodology and testing conditions of each study. "Soft Bangkok clay" is a site-specific subtype of soft clay commonly reported in Thailand, and is categorized under soft clay in this review for consistency.

3.7 Implementation in DSM applications

Table 6 presents the implementations of DSM applications reported in the reviewed studies. This paper categorized the reviewed studies in terms of the methods of preparation for validating the DSM specimen. One of these implementation methods is the in-situ demonstration, where the specimen was directly evaluated for its structural and foundational support. The study by Meepon et al. (2016) reports the improved stability of a soft Bangkok Clay with a soil profile consisting of highly plastic clay (CH), underlain by stiff clay layers by jet grouting a column that supports the shallow foundation. Another implementation is using a specimen mixed in the laboratory to improve the engineering properties of a soft soil; Daarol et al. (2023) emphasized the use such as rice hull ash as a partial replacement of OPC and revealed an increase of 20% in shear strength compared to cement. The last of the implementation is the computational analyses by specimen representation, in which constitutive models are used to generate meshes for soil matrices with varying soil characteristics. Yao et al. (2016) highlighted the tendency of the soft soils found in the Yellow River Alluvial Plain, Shandong Province, China to be highly compressible and low shear strength; through a series of physical modelling, the overall characterizations of silt, silty sand, and silty clays improved that

follows the trend of reduction in foundation settlement with the decrease in surcharge load.

From the consolidation of the reviewed studies, Wang et al. (2019) emphasizes the importance of trial mixing of binders before applying DSM techniques in the field as the study presents the comparison between the preparations of specimens in laboratory and in-situ, where laboratory-mixed samples demonstrate lower shear strength mainly due to the lack of variabilities increasing shear strength in the field. Moreover, Teo et al. (2017) also compared the mixability of binders and their Scale of Fluctuations (SOF) when centrifuge models were used when mixing binders for soil improvement and reinforcement. Jamsawang et al. (2016) also compared field analysis of soft marine clays mixed with OPC to the three-dimensional numerical analysis with coupled hydro-mechanical model, which revealed that the computational model outperforms the field results as it demonstrated evidence for significant difference. The last addition to the combination of validating specimen preparation is the study by Ni et al. (2019) where they used both laboratory model tests and numerical simulations to investigate the bearing capacity of composite ground with soil-cement columns under earth fills.

Table 6. Implementation in DSM applications

Implementations	No. of studies	Observations
In-situ Demonstration	14 (46.7%)	Evaluated for proper structural and foundational support
Laboratory-mixed Specimen Evaluation	12 (40%)	Significant increase in strength for slope stabilization
Computational Modelling	9 (30%)	Used for geotechnical characterizations

3.8 Research gaps

In the applications of deep soil mixing in East and Southeast Asia, this study identified areas for further research based on the reviewed literature for improving soil conditions, particularly for soft soils. First, the number of studies for the other types of soft soils (e.g. organic soils, peat) is very limited. Countries in Southeast Asia, such as Malaysia, Indonesia, Vietnam, and parts of the Philippines, contain significant deposits of peat and organic soils that are typically found on their coastal plain, wetlands, and low-lying areas. Despite the fact that the mentioned types of soft soils behave differently, especially mixed with cement binders during DSM application, these soils found in the involved regions can often be encountered in infrastructure development projects (Huat et al., 2011; Kazemian et al., 2011). In addition, there should also be studies including how climate interacts with the applicability: freezing-thawing and drying-wetting cycles for East Asia and Southeast Asia, respectively. Therefore, studying how their mechanical properties interact with different soil improvement techniques, especially DSM, would be beneficial for future engineering projects.

Second, this paper is solely focused on scoping studies from published articles and journals; conference proceedings, gray literature, and non-English studies have not come up during the keyword filtering process, thus, did not get included in the review. A study by Park et al. (2023), an investigation of the applicability of DMM for coastal structure foundation, was not included during the filtering of search results using keywords due to its Korean title. These reasons have limited the included studies during the keyword filtering process.

Third, this study revealed that there is an absence of studies in the complete validation using all three (3) implementations of the DSM application for soft soils in the East Asia and Southeast Asia regions. The validations of methods that are consolidated in this study include in-situ demonstration, laboratory-mixed specimen evaluation, and computation modelling. The combination of these three (3) implementations ensures that the geotechnical parameters, as well as mechanical properties, of the samples obtained from laboratory testing are simulated and modeled using numerical analyses that correctly replicated the in-situ conditions. The availability of the said topic could have provided this study, and future studies, a comprehensive analysis of the peak efficiency of DSM applications.

Fourth, following the scoping review of the literature on the applications of DSM in soft soils, a systematic reference mapping should be undertaken. However, this also faced the limitation that there is not enough study to distribute the values, thus, employing geospatial and geostatistical interpolation methods may be challenging but not impossible.

Finally, most of the reviewed studies focus on the short-term strength and settlement performance of DSM in soft soils. This approach does not capture the behavior of treated soils over extended periods when being subjected to continuous external loading and environmental factors. Although, this calls for a large-scale project as it would involve determining the tendency of the soils to swell or consolidate when deep soil mixing is employed.

4. CONCLUSIONS

This study systematically reviewed the application of deep soil mixing (DSM) for soft soil improvement in East and Southeast Asia using a scoping review approach. Based on the analysis of the selected studies, several important results were identified regarding the current state of research, practical applications, and existing limitations of DSM in the region.

First, DSM has been widely applied as an effective ground improvement techniques for areas where soft marine clays are commonly found (Al-Bared & Marto, 2017), especially since most of the specimens from the reviewed studies were from countries with peninsula (Thailand, Malaysia, Vietnam, Cambodia, Japan, Korea), archipelagos (Indonesia, Philippines, Singapore, Hongkong, parts of Malaysia), and coastal parts of China. Soft marine clays as specimens used by 90% of the studies reported to have significant improvements in shear strength and stability, and reduction in settlement and compressibility. Reports also showed an observable increase in unconfined compressive strength and reduced deformation under loads, both of which are important for embankments, foundations, land reclamation, and underground tunnel constructions. Other types of soft soils reviewed in the study (e.g. organic soils and peat) also reported a significant increase in shear strength proportionate to a higher binder content and longer curing time.

Second, the review reveals that 26 studies, all of which have soft marine clay as a specimen, opted to use OPC as a binder to improve the soil characteristics. However, it is consistent with the three (3) studies that used rice husk ash (RHA) as a combination, temporary, or substitute to OPC that RHA demonstrated higher shear strength, better reactivity, and surface cracking. Due to the lower specific gravity of RHA compared to OPC, it can also absorb moisture faster than cement alone (Daarol et al., 2023), thus, better in shrinkage reduction (Chompoorat et al., 2022) and higher in shear strength (Xue et al., 2024) without compromising its economic viability. This goes to show that there are a lot of similar studies using the combination of having the same DSM type with a soft soil specimen and binder (Chompoorat et al., 2022; Daarol et al., 2023); thus, having the same effective results (Ishikura et al., 2016; Ho, 2022; Hamdhan et al., 2024), only differing in countries and regions.

Third, the reviewed studies revealed the problematic characteristics of marine clays and soft soils in general to be weak and highly compressible; exhibiting high moisture content and low shear strength which can result in swelling and settlement. With this, only two (2) studies opted for dry deep mixing method despite its advantages in improving wet, soft soils. With this conclusion, this goes to show that implementing wet mixing methods on soft marine clays are implemented with careful consideration to the water-cement ratio as an increase in hydration can cause excess water to come out of the sample during the cementing process (Daarol et al., 2023); this could increase pore water pressure and reduces effective stress, which results to a decrease in shear strength.

Fourth, the reviewed studies demonstrated a fair distribution for the implementation of DSM applications as 46.7% used in-situ demonstration, 40% employed mixing in the laboratory for specimen evaluation, and 30% analyzed the samples using numerical simulation and computational modelling. Out of these percentages, there are also seven (7) studies that used two (2) implementations of DSM application, in which they consistently reported that either laboratory-mixed or the soil model samples showed better performance than the field results. The findings concluded that there are variabilities, such as schedule setbacks and other construction practices, present in the field that affect the geotechnical characteristics. Although there is no comparison between laboratory-mixed and soil models, the combination of these two implementations demonstrated that the bearing capacity is proportional to the soil strength of composite grounds.

Finally, as discussed in section 3.8, the research gaps in the current collection of literature includes: (1) assessing the applicability of DSM in other soft soils (organic soils and peat) while acknowledging seasonal changes (freezing-thawing and drying-wetting); (2) extending from journals into other types of literatures (gray literature, conference proceedings), as well as better screening and keyword filtering methods for the inclusion of non-English articles; (3) validating the implementations of DSM applications through employing all in-situ demonstration, laboratory mixing for sample evaluation, and computational analysis; and (4) generating reference maps for the involved regions, in terms of observed improvement, soil types, seasonal changes, and DSM types.

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