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# Major Developments and Improvements in Mechanically Stabilized Earth (MSE) Walls: Analysis and Design over the last three decades



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**ABSTRACT:** Mechanically stabilized earth (MSE) walls have emerged as a reliable and economical solution in geotechnical and transportation engineering. Over the past three decades, extensive research has been conducted on the analysis, design, and performance of MSE walls. This paper presents a comprehensive review of these developments, highlighting key advancements in construction techniques, material usage, and design philosophies. Special emphasis is placed on the growing trend toward sustainability, particularly the use of alternative and environmentally friendly backfill materials. Given that backfill occupies a major portion of MSE wall systems, several experimental and numerical studies have explored the effectiveness of various sustainable materials and their impact on structural stability. The review also covers soil stabilization techniques, including both mechanical reinforcement and chemical additives, as well as the influence of different wall facings. Additionally, foundation soil stability and its interaction with the wall system are discussed. This paper aims to provide insights into recent trends that emphasize performance, sustainability, and cost-efficiency in MSE wall construction. The findings will be valuable for designers and practicing engineers seeking to implement modern, environmentally conscious solutions in retaining wall systems.

**Keywords:** MSE wall stability, parametric studies, sustainable backfill materials, facing panels, foundation soil.

## 1. Introduction

Mechanically stabilized earth walls (MSE walls) are used for supporting the retained backfill soil using reinforcement, reinforced backfill and rigid wall facing. MSE walls are often called by other names such as reinforced earth walls (RE walls), reinforced soil walls (RSW) or geosynthetic reinforced soil (GRS) or reinforced soil structure (RSS). The RE wall and RSW may consist of either metal strips or geosynthetic material as reinforcing material. However, GRS consists of geosynthetic material. The geosynthetic material may consist of geogrids, geocells, geomembranes, geocomposites, geotextiles, etc. The design of reinforced earth retaining structures is typically carried out in accordance with the guidelines of FHWA, IRC-102 (Berg et al., 2009; Indian Roads Congress, 2014) which place the quality of backfill at the forefront of their recommendations. In the era of highway expansion, the demand of MSE walls for elevated highways is increasing day by day. As traffic keeps increasing, highways are adding more lanes to meet the growing demand. The MSE walls are being used worldwide on a large scale. In North America, almost 80% of Highways are elevated and MSE wall based. Annually, over 850,000 $m^2$ of MSE walls are constructed for the U.S transportation system, which is more than half of the existing MSE walls in the highway sector at present (Berg et al., 2009).

MSE walls are used in elevated highways, expressways and bridge abutments. They are also used for steep embankments on limited land and supporting slopes in artificial fills. MSE walls can support the backfill with an inclination of 70° - 90° from horizontal (Hossain et al., 2012). So, the MSE wall reduces the need for land acquisition for construction because of being steep. Sometimes, due to limited availability of land for the right of way, MSE walls are constructed to reduce the need for more land acquisition. MSE walls save almost half the expenditure required for the construction of retaining walls (Singh and Akhtar, 2015). So, MSE walls are economical too. MSE walls can be constructed on poor foundation soil with low bearing capacity. It requires less skilled workers with easy construction techniques. Also, the time required for constructing MSE walls is less than that of conventional RE walls. Conventionally, MSE walls have been constructed since they were first developed by Henry Vidal. The first MSE wall in the U.S was built in 1971 near Los Angeles. The developments in MSE walls have been going on for decades since their inception. Generally, MSE wall construction needs huge information based on data of backfill material, foundation soil, as well as properties of reinforcement materials and the material used for wall facing.

This paper aims to provide necessary information on the recent developments and advances in the MSE wall construction practices. The current study demonstrates a dedicated attempt to unify the research related to the stability analysis and design of MSE walls when using various types of backfill materials, foundation soil, facing panels, etc. The authors endeavored to compile relevant papers from a wide range of sources, including journal articles, specifications, reference codes, reports, and other materials pertaining to MSE walls. A comprehensive dataset of more than various design codes and over 50 research articles from the past has been taken, which were compiled during the preparation of this review paper. The critical reviews have been addressed. Figure 1 shows the flowchart that outlines the process followed in the literature selection, screening, and analysis.

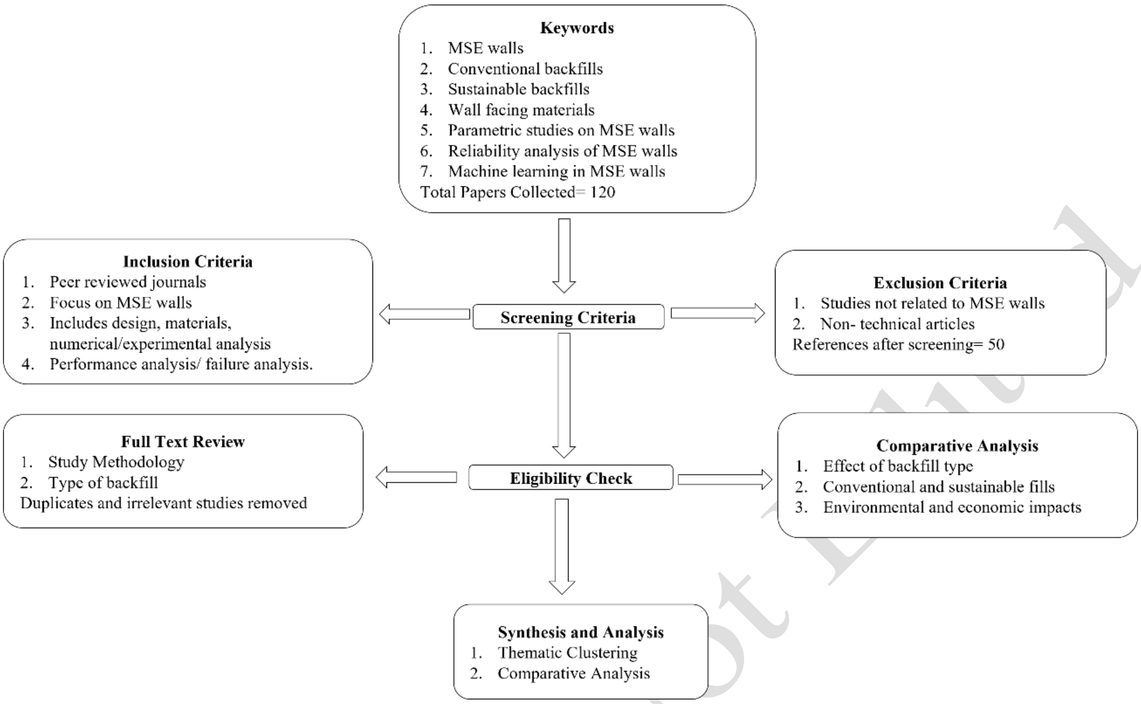


**Fig. 1.** Flowchart of the process followed in the literature selection, screening and analysis.

Despite significant advancements in the design and application of MSE walls, certain research gaps persist. Most existing studies have focused primarily on conventional backfill materials and standard construction practices, with limited exploration of alternative or sustainable fills and their long-term performance. Additionally, there is a lack of unified understanding regarding the interaction between various foundation soil types, reinforcement materials, and wall facings under diverse environmental and loading conditions. The integration of environmental considerations, modern instrumentation, and real-time monitoring techniques into MSE wall studies also remains underrepresented. The objective of this study is to compile and evaluate the recent advancements in MSE wall construction, with a focus on sustainability, performance, and cost-effectiveness. To investigate the influence of various backfill materials, especially alternative and sustainable fills, on the stability and environmental impact of MSE walls. To analyse the role of foundation soil conditions and wall facing types in the structural behaviour of MSE walls. Furthermore, various parametric studies are presented to analyze different aspects of MSE walls, providing insights into their behavior under diverse loading and environmental conditions.

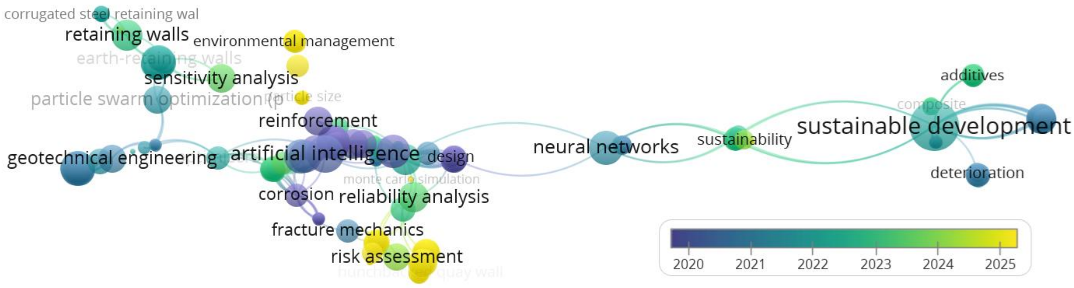


**Fig. 2.** Bibliometric analysis showing the current research trends in MSE wall.

A bibliometric analysis has been conducted to highlight the growing focus on Machine Learning (ML) and reliability analysis in the field of MSE walls (Figure 2). The findings indicate that researchers are increasingly emphasizing risk assessment, environmental management, sustainability, risk assessment/reliability analysis, ML and Sensitivity Analysis.

## 2. Conventional Backfill and Non-Conventional Backfill (Sustainable Fills)

Big projects like MSE wall construction require a large amount of material. Even a small change in the cost of any material can affect the entire project. Every project at present demands minimizing the expenses that are incurred during its development. On the other hand, there are many materials which are generated in industries as waste products for which proper dumping space is needed. The MSE wall can provide a space for storing materials by stabilizing them, which can then be used as backfill. Instead of placing a burden on dumping spaces like municipal solid waste (MSW) landfills, these backfill materials can be used as non-conventional backfills for MSE walls, known as sustainable fills. The cost of backfilling an MSE wall with traditional materials conforming to FHWA guidelines is very high. It is more expensive if the dredging area is far from the construction site. In such cases, researchers looked forward to alternative backfill materials like construction and demolition waste, bottom ash, crushed concrete, marginal soil, hybrid walls, etc. However, most of the non-conventional backfill materials are easily available, and their cost is very low compared to conventional traditional fills. In India, there are different varieties of soil which vary in size, texture, colour and properties from place to place.

### 2.1. Economic Considerations

The type of filling material to be decided is based on several factors like availability of backfill material, distance of mucking and hauling, cost of material, cost of transportation, and environmental impacts. When conventional backfill materials are scarce near the proposed MSE wall construction site, the project becomes economically unviable due to the high cost of fill materials and significant transportation expenses. The economic analysis of MSE walls has been performed with various combinations of reinforcing material, backfill material and facing panels by varying the height of the wall from 4 m to 9 m (Singh and Akhtar, 2015). The observations revealed that using local earth as backfill material costs about 62% of the total expenditure as compared to when cohesionless backfill soil is used.

**2.2. Performance Studies on Sustainable Fills**

There is a difference between backfilling with cohesionless soil and backfilling with non-conventional backfill material. Cohesionless soil conforming to a plasticity index ($I_p$) < 6 and a percentage of fines passing 75 micron sieve is less than 15% is classified as conventional cohesionless fills (Berg et al., 2009). Apart from cohesionless fills, some soils are used to minimize the expenses occurring during backfilling. There is a serious limitation that the mining of sand in many countries is illegal, and more specifically, the mining of cohesionless soil is impacting rivers on a large scale. Every small to big river/stream is still being mined, and the widening of banks occurs. The current research is shifting towards the use of various sustainable fills and marginal soils so that the river/ stream mining could be reduced on a large scale. In such soils, the percentage of fines is usually more than 15%. The potential of construction and demolition (C&D) waste as backfill material has been evaluated instead of the conventional costly materials using experimental analysis (Santos et al., 2013). It has been observed that the compressibility of the foundation occurs under the cumulative rainfall along with drying and wetting cycles seasonally. These variations influence the horizontal earth pressure, wall deformations, strains in reinforcement and wall deformation. C&D waste has low hydraulic conductivity, which needs improvement and is a subject for further research. The pullout performance of ribbed metallic strips in typical fill soils, such as natural sands and different recycled aggregates, is examined (Corrales et al., 2023). The results demonstrate that different sands had comparable pullout behavior, with particle size determining resistance. However, recycled sand performed poorly despite its interparticle bonding, and recycled sand showed reduced efficiency due to particle crushing. A study on the compaction of C&D waste has been conducted (Vieira and Pereira, 2016). It has been observed that an increase in compaction imparts more shear strength to C&D waste, and the increase in water content in C&D waste leads to a decline in interfacial shear strength. However, the leaching test did not show any hazard on the groundwater table.

The viability of using C&D waste as an alternative backfill material in MSE walls has been evaluated, showcasing significant deformation reduction and sustainability benefits (Anita and Divya, 2024). Proper characterisation and processing of C&D waste can offer a sustainable solution to natural sand scarcity in urban construction. A recent study has investigated the dynamic response and stability of highway embankments incorporating 10% C&D waste comprising of dragged asphalt (DA), crushed brick (CB), and crushed concrete (CC) using FEM analysis (Gupta et al., 2025).

**2.3. Laboratory Investigations on Alternative Materials**

Numerous researchers have evaluated alternative materials to assess their performance as backfill and their compatibility when blended with other materials for use in MSE wall construction (Mandloi et al., 2022; Portelinha et al., 2021; Shiva Bhushan et al., 2019; Tehrani et al., 2019; Vieira and Pereira, 2016). Laboratory tests on steel slag and construction and demolition (C&D) waste have been conducted to evaluate their suitability as backfill materials for MSE walls (Mandloi et al., 2022). Results of the triaxial and California bearing ratio (CBR) strength tests highlighted the superior performance of the sustainable backfill materials as compared to the traditional backfill materials due to their drainage properties. Experimental analysis has been carried out to know the effectiveness of the use of crushed concrete as a backfill material for MSE walls (Shiva Bhushan et al., 2019). The following tests were performed to know the properties of soil, modified Proctor density, pH, crushability tests, specific gravity, hydraulic conductivity, water absorption, particle size distribution and x-ray fluorescence tests. Observations show that crushed concrete is suitable as an alternative backfill for the MSE wall, but it has a low draining property. A full scale experimental investigation on the use of lightweight expanded clay aggregates (LECA) of 10-25 mm size as an alternative backfill material for MSE wall has been presented and the horizontal as well as vertical deformations due to the applied static loads, impact loads and dynamic loads have been measured (Tehrani et al., 2019). It has been observed that the LECA can resist 10 $kN/m^2$ stresses with 12 mm settlement. Dynamic testing shows that it can tolerate 18 tons of axle load of a truck with deformation of 1 mm vertically and 1.7 mm horizontally. A study finds that the fibrous components in deeper MSW landfill layers give greater shear strength, while the inert waste and moisture in the top layers make them more prone to failure. Furthermore, older waste layers are more stable under seismic pressures because aging decreases total resistance while somewhat increasing friction (Shubham et al., 2022).

### 2.4. Drainage and Failure Mechanisms in MSE walls

Drainage is a serious concern, as it is a major cause of failure in many MSE walls that use fine-grained soil as backfill material. These soils have high shrinkage and swelling characteristics, which make them more prone to failure compared to soils with lower shrinkage and swelling potential. Mining on a large scale is not a viable solution; instead, alternative materials must be considered to offset the cost of mining cohesionless soil. The case studies on overall 320 failed MSE wall sites have been performed, out of which 221 cases were reported due to failure of any part of the MSE walls, and 99 cases were reported for excessive deformation (Koerner and Koerner, 2018). It has been revealed that the utilization of fine soil i.e., clay and silt as reinforced backfill material, location of drainage systems inside soil reinforcement zone, fine-grained soil with improper placement and poor compaction, design details not properly executed by the contractor and no good attempt to control beneath, and above water are the reasons of failure of these MSE walls. When collapse occurs, the facing falls first and leaving reinforced soil behind it and during global failure, the whole MSE wall fails. It incurs huge expenditure on repair and maintenance works due to the failure of any section or part of the MSE wall.

## 3. MSE Walls with Different Wall Facings

The MSE walls are built with facing panels as external support to retain the backfill soil. Behind the facing panels, the reinforcements and backfill material are confined by the facing. The facing panels are installed/constructed straight in two planes, i.e., planar, which may or may not have some inclination. These facing panels are of precast type and are available in many shapes like rectangular, cruciform, square, sloped, full height, integrated with traffic barrier, permanent wire mesh, temporary wire mesh, etc. There are variations in the dimensions of length, width and thickness of the facing panels. There are metallic connectors inserted within the panels during their pre-casting. The reinforcements are then connected to the facing panels with these connectors. The type of connector used depends on the type of reinforcement and facing panels. Nowadays, facing panels are manufactured by embedding geogrids in the panels. The geogrids are kept in rolled form for easy laying over the compacted backfill (Fig. 3 & 4).

**Fig. 3.** Facing panels (cruciform) with rolled attached geogrids (MSE wall site at Jamshedpur)

**Fig. 4.** Close view of rolled attached geogrids (MSE wall construction site at Jamshedpur)

On the other hand, there are wrapped walls in which backfills are confined with flexible reinforcements, but there are chances of escape of soil particles if there are no erosion control measures have been taken. The facing is on the verge of failure, partially or fully, depending on the deformations occurring within the backfill soil of the MSE wall. The properties used for modelling facing panels in various studies are summarized in Table 1.

**Table 1.** Properties of facing panels for modelling used in various studies.

| **References** | Baral et al. (2016) | Benmebarek et al. (2016) | Hossain et al. (2012) | Rabie (2014) | | Hulagabali et al. (2018) | Vibha and Divya (2021) |
|---|---|---|---|---|---|---|---|
| **Software** | PLAXIS 3D | PLAXIS 2D | PLAXIS 2D | PLAXIS 2D | | PLAXIS 2D | GEOSTUDIO |
| **Type of facing panels** | Concrete panels | Concrete panels | Concrete panels | Shotcrete wall | Concrete panels | Single facing | Modular Blocks |
| **Model Behavior** | Plate Elastic | Plate Elastic | Plate Elastic | Beam Elastic | Beam Elastic | Plate Elastic | Concrete Elastic |
| **Axial Stiffness EA (kN/m)** | 42 x $10^6$ | 3.5 x $10^6$ | 3.08x $10^6$ | 4.2x$10^6$ | 6x$10^6$ | 3625.950 | - |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Bending Stiffness EI (kN.m$^2$/m)** | 78500 | 5717 | 4017 | 1.4x10$^4$ | 4.5x10$^4$ | 6.799 | 15,000 |
| **Thickness of facing, t (m)** | 0.15 | 0.14 | 0.125 | 0.200 | 0.300 | 0.15 | - |
| **Poisson's ratio, υ** | 0.15 | 0.20 | - | 0.15 | 0.15 | 0.2 | - |
| **w [kN/m/m]** | 3.6 | 3.29 | - | 4.50 | 4.65 | 7.3 | - |

There is no available literature to compare the stability of faced panel walls and wrapped walls. These two walls serve their specific purpose. In facing panel walls, no escape of fines occurs, but in the case of wrapped walls, finer particles may escape to a certain extent. The wrapped facing walls are usually constructed for embankments. However, MSE walls are constructed for elevated highways, elevated railways, metros, etc. The purpose of the MSE wall with the faced panel is much different from wrapped walls. However, both provide stability to the structure.

The behavior of single-panel reinforced earth walls in different conditions, like the use of different soils (for foundation, reinforced soil and retained backfill soil), different reinforcements and various surcharge loads using PLAXIS 2D to compare the settlements and wall deformations have been analyzed (Hulagabali et al., 2018). Their observations showed that RE walls with gravel as backfill material, steel strips as reinforcing elements have the potential to perform good RE walls in terms of wall facing movement and settlement of ground behind the wall at a surcharge of 5 kN/m$^2$. However, the results were not satisfactory for clay as backfill material, polyethene terephthalate (PET) geogrid as reinforcement at a 20 kN/m$^2$ surcharge.

## 4. Stability of Foundation Soils

Any structure built on soft soil is prone to failure due to instabilities arising from seasonal fluctuations in the groundwater table. Another reason could be the type of soil available in the foundation layers of the MSE wall. Whenever the foundation soil has low bearing capacity, there might be risks of bulging, overturning, sliding, differential settlements, etc. If there is a combination of a high-water table and a low bearing capacity of soil, the chances of displacement of the MSE wall are high. Such soil needs soil stabilization, or suitable ground improvement is necessary to deal with such outstanding conditions. Also, the provision of proper drainage by means of sand drains, prefabricated vertical drains (PVDs) could be beneficial to dissipate the excess pore water pressure to improve stability. Several studies have tried to improve the stability of MSE walls by installing stone columns, piles, chemical methods of soil stabilization, etc.

Some authors did exceptionally well in stabilizing the foundation soil using prefabricated drains and stone columns (Bazazzadegan et al., 2024; Xue et al., 2014). A study has been conducted that demonstrates that geotextile-reinforced stone columns greatly increase bearing capability in sandy soils with soft clay lenses (Bazazzadegan et al., 2024). It draws attention to the ways that lens depth and thickness affect failure mechanisms, especially bulging behaviour. Sophisticated sensors have been used to provide detailed performance monitoring of an instrumented MSE bridge abutment wall (Sakleshpur et al., 2025). The results provide important information for confirming and improving MSE wall design techniques and show higher-than-expected vertical strains at the levelling pad.

Piles are used to give additional stability to MSE walls. Their effect has been studied by Jawad and Han (Jawad and Han, 2021), and more specifically, the effect of single free-headed laterally loaded piles on the MSE wall face displacements based on experimental and numerical analysis (FLAC 3D) were studied. It was observed that decreasing the pile offset and diameter of the pile leads to a linear reduction in the ultimate lateral load carrying capacity of the pile, whereas increasing the diameter of the pile and decreasing the pile offset leads to an increase in wall facing displacements. The observed lateral earth was found to have a non-linear passive earth pressure distribution, and its maximum value acts at a height of *0.78 H* to *0.82 H* from the foundation.

Soil stability can be achieved in the case of clayey soils by adding some foreign material (Bayat, 2025; Lee et al., 2001; Li et al., 2020) to clay to enhance its properties. Jahandari et al. (2017) analyzed the combined effect of mixing lime (3%, 5%, 8%) with clay, with adding geogrids and without adding geogrids on the modulus of elasticity, stress-strain behavior and unconfined compressive strength of clay. The optimal dosage was determined to be 8% based on improvements in UCS and modulus of elasticity. At this dosage, the UCS of the soil increased significantly from 407 kPa (untreated) to 1389.3 kPa (lime-only stabilized). Further UCS increased to 1499.62 kPa when reinforced with geogrids. Strain in soil generally decreases when lime is added, but when geogrids were also added, it increased strain, indicating that both deformability and plasticity increased. The modulus of elasticity of 8% lime added soil increased by 17.18 times, and when geogrid layers were also inserted, it reached 20.66 times the soil without reinforcement. The brittleness index increased with lime content but was moderated by the geogrid, decreasing from 2.95 (lime only) to 1.9 (lime and geogrid).

Similar studies related to mixing of in-situ soil can be found in using sand mixed with foundry waste (Lee et al., 2001) and fly ash with sand (Li et al., 2020). Figure 5 shows the flow chart of stabilization the foundation soils for MSE wall construction using suitable arrangements where the water table is high, and the foundation soil has low bearing capacity. A review emphasizes how nanoparticles can revolutionize soil stabilization by providing creative, sustainable solutions as well as in-depth understanding of their workings and benefits above conventional techniques (Bayat, 2025).

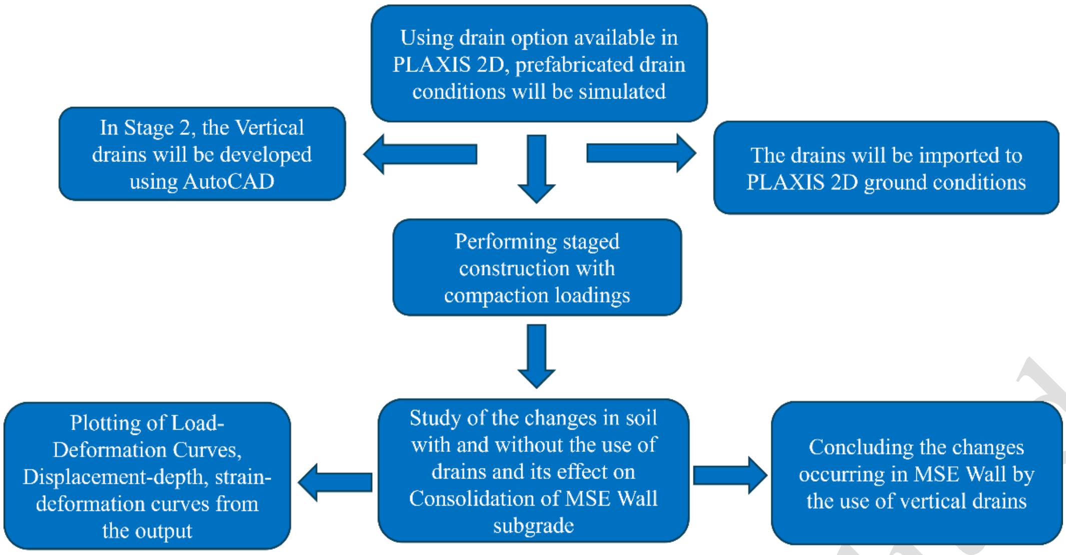


**Fig. 5.** The flow chart of stabilization the foundation soils for MSE wall construction using suitable arrangements where the water table is high and the foundation soil has low bearing capacity.

## 5. Various Parametric Studies on Different Aspects of MSE Wall

Soil exhibits numerous properties which change at different stages with location and time. Varying such parameters often shows some significant changes to the performance of MSE walls. These parameters play a vital role in the MSE wall construction stages and for the service life of MSE walls. Various methodologies have been developed and implemented by several researchers to understand the impact of various parameters on MSE walls. These parameters can be in any number, but sometimes their combinations and sometimes individual parameters affect stability most. These parameters are important for spatial stability as well as for probabilistic studies.

### 5.1. Studies on Different Parameters of MSE Wall

The parametric studies on MSE wall has been conducted for different studies on MSE wall (Bathurst et al., 2006; Chalermyanont and Benson, 2005; Javankhoshdel et al., 2019; Mathew and Katti, 2014; Ozturk, 2014; Pramanik and Babu, 2022; Vlček, 2014; Zhang et al., 2022). A summary of the constitutive model considered for different components of MSE wall analysis is shown in Table 2.

**Table 2.** Summary of the constitutive model considered for various components of the MSE wall analysis.

| Components | Constitutive Material Model Assumed | References |
|---|---|---|
| Backfill Soil | Mohr-Coulomb | Xue et al. (2014), Vibha and Divya (2021), Vlček (2014), Hossain et al. (2012), Won and Langcuyan (2020), Abdelouhab et al. (2011), Baral et al. (2016) |
| | Elastic Perfectly Plastic | Benmebarek et al. (2016) |
| | Hardening Model | Rabie (2014) |
| | Hardening Soil | Xue et al. (2014), Rabie (2014), Baral et al. (2016) |

| | | |
|---|---|---|
| Foundation Soil | Jointed Rock | Won and Langcuyan (2020) |
| | Mohr-Coulomb | Vibha and Divya (2021), Benmebarek et al. (2016), Vlček (2014), Hossain et al. (2012) |
| Reinforcement | Linear Elastic | Abdelouhab et al. (2011) |
| | Beam Elements | Vibha and Divya (2021) |
| | Geogrid Elements | Xue et al. (2014), Rabie (2014), Vlček (2014), Benmebarek et al. (2016), Hossain et al. (2012), Won and Langcuyan (2020), Baral et al. (2016) |
| | Strip Elements | Abdelouhab et al. (2011) |
| Facing of wall | Plate Elements | Rabie (2014), Hossain et al. (2012), Baral et al. (2016) |
| | Linear Elastic material | Benmebarek et al. (2016), Abdelouhab et al. (2011) |
| Leveling Pad | Plate Elements | Hossain et al. (2012) |
| Bearing Pad | Beam | Won and Langcuyan (2020) |
| PVDs (if used) | Drain Elements | Xue et al. (2014), Rabie (2014) |

Some authors performed various parametric studies on reinforcement of MSE walls. Javankhoshdel et al. (2019) considered the spatial variability of reinforcement and foundation soil properties. They assumed that the reinforced soil is purely frictional, while the foundation soil is cohesive-frictional. It has been reported that the cross-correlation between soil parameters with spatial variability is used to calculate the FS and to obtain good results of designs with the least probability of failure using the Limit Equilibrium (LE) Method and Cuckoo search. Bathurst et al. (2006) studied the effect of flexible and stiff facing on the reinforcement load using tie-back analysis (Simplified Method) of two 3.6 m high GRS, both inclined at 8° from the vertical. The observations showed that flexible facing had 3.5 times more peak load than stiffer facing at the construction completion and two times more at the surcharge ending period. The stiffer face using the Simplified Method provided a maximum reinforcement load which was 1.5 times greater than that observed at the end of construction loading. The surcharge stress in the stiff facing case required for reinforcement creep failure will be 2 times more than the predicted value.

### 5.2. Studies on Numerical Modelling and Analysis

Generally, two numerical analysis methods, Finite Element Method (FEM) and finite difference method (FDM) have been carried out by researchers depending upon the applicability and accuracy of the methods. The FEM divides complex geometries into elements and uses interpolation, making it suitable for irregular domains. In contrast, the FDM uses grid-based approximations, best suited for simple, regular geometries. FEM offers greater flexibility and accuracy for complex boundary conditions, while FDM is easier to implement for basic problems. Belabed et al. (2011) analyzed the internal stability of MSE walls by varying the heights and angle of internal friction in 5 different cases and compared the outputs from LE analysis with FLAC 2D based on FDM to validate the results. It was observed that the elliptic earth pressure at the back of a vertical surface with a mixed surface of failure is the critical one. The wall height and angle of internal friction influence the failure surface slope geometry and tension development in reinforcement. However, the study of inclination is an important aspect which has also been studied.

The properties of backfill play an important role in achieving the stability of the MSE wall. The properties of backfill soil used in various numerical modelling are shown in Table 3. Abdelouhab et al. (2011) observed that the modulus of elasticity values between 1.5 - 60 GPa have a good impact on the deformation of the wall and little influence on FS. Hossain et al. (2012) presented a case study of excessive displacement of the MSE wall facing with a displacement of 300- 450 mm in 5 years. The field tests like resistivity imaging and field boring were carried out at the failed section and PLAXIS 2D based on FEM has been used to assess the failure causes. The observations showed that fines were more than 15% in the backfill soil, and the formation of a perched zone of water resulted in bulging at the MSE Wall facing. Improper length of reinforcement is also a cause of excess displacement. Xue et al. (2014) studied a case of instability in a wrapped face wall using PLAXIS 2D. It has been observed that due to pore water pressure increment, general sliding failure occurred covering from the front of the toe to the foundation soils with bulging and rotation of the wall face. The maximum bulging was observed at 3.7 meters near to mid-height of the wall. Rabie (2014) evaluated the performance of hybrid soil-nail walls and MSE walls using PLAXIS 2D and the LE Method, highlighting limitations of traditional LE failure surfaces in global stability analysis. The study found that the FS from finite element (FE) analysis was lower than that from LE methods, emphasizing the need for careful modelling of composite systems.

**Table 3.** Properties of backfill soil used in various numerical analyses.

| **References** | Abdelouhab et al. (2011) | Hossain et al. (2012) | Xue et al. (2014) | Rabie (2014) | Baral et al. (2016) | Benmebarek et al. (2016) | Hulagabali et al. (2018) | Vibha and Divya (2021) |
|---|---|---|---|---|---|---|---|---|
| **Software** | FLAC 2D | PLAXIS 2D | PLAXIS 2D | PLAXIS 2D | PLAXIS 3D | PLAXIS 2D | PLAXIS 2D | GEOSTUDIO |
| **Model** | Mohr-Coulomb | Mohr-Coulomb | Mohr-Coulomb | Mohr-Coulomb | Mohr-Coulomb | Elastic perfectly plastic | Mohr-Coulomb | Mohr-Coulomb |
| **Unit Weight, $\gamma_{unsat}$ (kN/m$^3$)** | 15.5 | 18.8 | 19 | 19 | 21 | 18 | 18 | 15.53 |
| **Unit Weight, $\gamma_{sat}$ (kN/m$^3$)** | 15.5 | 22 | 19 | 19 | 22.7 | 18 | 18 | 15.53 |
| **Poisson's ratio, ν** | 0.3 | 0.32 | 0.33 | 0.35 | 0.3 | 0.3 | 0.3 | - |
| **Elasticity Modulus, E (kPa)** | 50000 | 12500 | 5000 | 25000 | 20000 | 30000 | 15500 | 13300 |
| **Angle of Internal friction, ϕ** | 36° | 34° | 30° | 34° | 37° | 30°, 35°, 40° | 34° | 24° |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Cohesion , c (kPa)** | 0 | 1 | 16 | 5 | 10 | 0 | 0 | 7 |
| **Dilatancy Angle, ψ** | 6° | 4° | - | - | - | 5° | 4° | - |

Baral et al. (2016) observed that inextensible reinforcements had less displacement as compared to extensible reinforcements. Decreasing order of stiffness in reinforcing elements was found as Metallic Strips > steel welded grids > Polypropylene> High-density polyethylene > Polyethylene Terephthalate. Examining the quality of the backfill material reveals that even a slight improvement in embankment cohesion can result in substantial decreases in both lateral earth pressure and the maximum tensile force experienced by the geosynthetic (Benmebarek et al., 2016). Hulagabali et al. (2018) observed that the RE walls with gravel as backfill material, steel strips as reinforcing elements show good performance of the RE wall in terms of wall facing movement and settlement of ground behind the wall at a surcharge load of 5 $KN/m^2$. However, the results were not satisfactory for clay as backfill material, Polyethylene Terephthalate (PET) geogrid as reinforcement at a surcharge of 20 $kN/m^2$. Investigations on the effects of rainwater infiltration with time on marginal backfill have been done (Vibha and Divya, 2021). Two types of geogrids- conventional geogrids and composite geogrids have been used. It has been observed that the FS declined below 1.5 in 2 days, 3 hours when using a conventional geogrid. However, the FS was constant at 1.88 during these 3 days in the case of composite geogrids, which shows that the overall performance of the MSE wall has been improved. Critical parameters and failure mechanisms in shored MSE walls are revealed by a thorough FE analysis, emphasizing the necessity of better reinforcement-facing connections and external stability concerns (Vairamani et al., 2024).

### 5.3. Studies on Machine Learning

Machine learning (ML) is a specific subset of Artificial Intelligence (AI) that plays an important role in the analysis and design of MSE walls by enhancing prediction accuracy, optimizing design, and managing complex datasets. ML can model highly nonlinear behavior in MSE wall systems more efficiently than traditional analytical methods. Once trained, ML models can quickly estimate outcomes without repeated costly numerical simulations (e.g., in FLAC or PLAXIS). A study has been developed that compared AI-ML models for predicting reinforcement tensile forces in MSE walls under train loading, with the ANFIS-GA model achieving the highest accuracy ($R^2$=0.9876) and lowest errors (Vadavadagi et al., 2024). Emotional Neural Network, Multivariate Adaptive Regression Spline (MARS), and Symbiotic Organism Search-Least Squares Support Vector Machine (SOS-LSSVM) artificial intelligence (AI) models have been applied for predicting the factor of safety and reliability index of retaining walls (Mishra et al., 2021). SOS-LSSVM outperformed others with high accuracy, showing the potential of AI in simplifying and improving geotechnical reliability analysis. The Adaptive Dimensional Search algorithm has been applied for the cost-optimized design of MSE walls using discrete variables and standard design codes (Kazemzadeh and Akiş, 2020). Results highlighted the method's efficiency and robustness and concluded that enhancing foundation properties can further reduce overall construction costs in practical applications. Ozturk (2014) analysed the deformations in back-to-back MSE (BBMSE) walls for bridge approach embankments. Artificial neural network (ANN) has been applied to predict the permanent displacements caused by earthquakes in the retaining walls under the dynamic loads. The reinforcement length, reinforcement spacing, wall height, and facing type were the factors considered while simulating the wall geometry. The seismic excitation employed in the investigation exhibited peak ground accelerations at three distinct levels: 0.2g, 0.4g, and 0.6g. The results demonstrated encouraging agreement between the finite element analysis findings and the neural network's predicted displacements. Pramanik and Babu (2022) forecasted the maximum tensile loads in the reinforcement layers of the MSE wall and found notable discrepancies between the measured and expected tensile loads. The authors established a load bias that measures the disparities as the ratio of measured to predicted maximum tensile loads. The authors suggested a novel method that makes use of an ANN-based response surface method (RSM) to enhance the prediction of maximum tensile stresses. This technique tries to simulate the connection between numerous variables, determining the maximum tensile load in steel-strip reinforcement. The outcome shows that the ANN load model performed satisfactorily in estimating the stability of the MSE walls.

The design of MSE walls has traditionally relied on classical methods that follow a deterministic approach, using predefined safety factors to ensure stability under assumed conditions. These methods, such as limit equilibrium theories and empirical formulas (e.g., Rankine, Coulomb), depend on known soil parameters and tend to be conservative, prioritising safety over efficiency. They are generally easy to implement and computationally efficient but are limited in adaptability and may not accurately capture complex or nonlinear behaviours. In contrast, modern ML-based design methods offer a probabilistic and data-driven approach, utilising large datasets to identify patterns and predict outcomes with high accuracy. Techniques such as ANNs, Support Vector Machines (SVMs), Adaptive Neuro-Fuzzy Inference Systems (ANFIS), and metaheuristics are increasingly being integrated with traditional tools like FEM to improve prediction and design quality. While ML methods require more computational effort during the training phase and demand technical expertise, they excel in handling uncertainties directly and are highly adaptable to varying conditions. These modern approaches enable performance optimisation and cost-efficiency, making them especially useful for complex, large-scale, or data-rich geotechnical problems (Phoon and Zhang, 2023; Shubham et al., 2022, 2024).

### 5.4. Studies on Reliability Analysis

A reliability-based study is necessary because it guarantees consistency, dependability, and credibility in performance or results throughout time and under many circumstances. Because real-world systems and materials frequently entail uncertainty, unpredictability, and partial knowledge, probabilistic studies are necessary. There are internal and external modes of failure of MSE walls. It becomes necessary to predict these failure modes using a probabilistic approach. There are various probabilistic methods like Mean Value First Order Second Moment (MVFOSM), Monte Carlo Simulation (MCS), First Order Reliability Method (FORM), and Second Order Reliability Method (SORM), which have been used for reliability analysis of MSE wall. The timeline of studies based on ML and reliability approaches for MSE walls has been shown in Figure 6. Chalermyanont and Benson (2005) performed parametric studies to determine how the probability of external failure is affected by uncertainties associated with design parameters using MCS and Bishop's Simplified Method. Zevgolis and Bourdeau (2010) considered system reliability analysis of RSS with three external modes of failure: sliding, eccentricity and bearing capacity and assumed that different failure modes are independent and mutually exclusive events. It has been observed that bearing capacity has a higher degree of uncertainty (COV=0.4145) as compared to sliding (COV=0.2861) and eccentricity (COV=0.1110), where COV is the coefficient of variation. The observations showed that there is an impact on the computed system failure probability when cross-correlation between shear strength properties was neglected. Hamrouni et al. (2020) carried out research work to find out how the statistical characteristics affect the wall facing in terms of maximum horizontal displacement with the help of six parameters using FLAC-2D, Karhunen-Loève expansion method (K-L method) and MCS. The findings include that the internal friction angle of soil has a significant impact on the wall displacement, whereas the facing displacement increases with the COV.

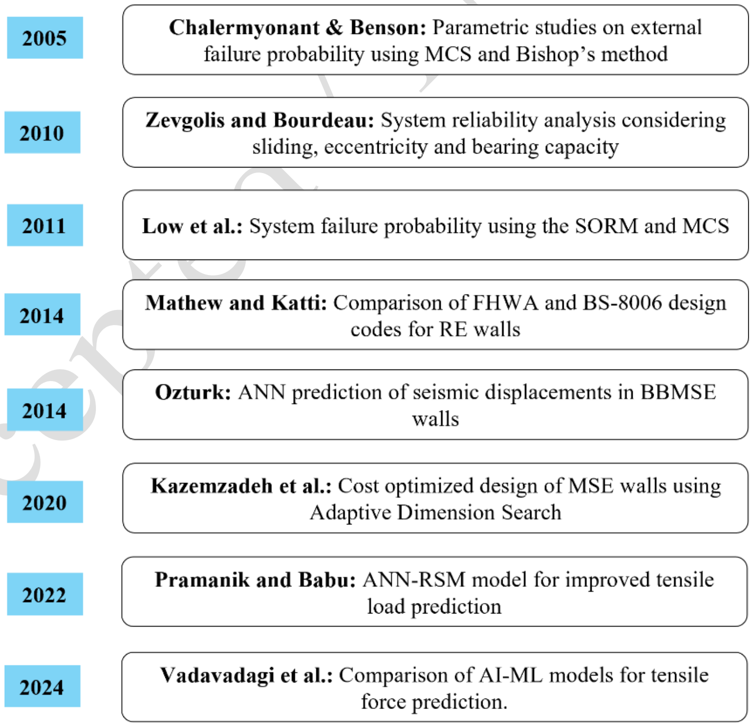


**Fig. 6.** Timeline of ML and reliability approaches for MSE walls

Vlček (2014) tried to establish the differences between assumed and measured values in terms of geosynthetic axial forces and wall deformations by analytical and numerical analysis using PLAXIS 2D. The reason for differences in measured and assumed values is due to overestimation of axial reinforcement forces, which is a result of a conservative vertical stress calculation approach. It was observed that the maximum lateral displacements occur at a height of 0.2 H to 0.4 H. When there is an increase in the eccentricity of surcharge load, then Meyerhof's theory becomes conservative for stress distribution. Tie-back method is good for extensible reinforcements, but the Coherent gravity method proved satisfactory for inextensible reinforcements. Mathew and Katti (2014) compared the two reinforced earth wall design codes namely FHWA Vol. 1 (Federal Highway Administration) and BS 8006:1995 (British Standards) by using 16 combinations of 3 dimensional variables namely: vertical spacing between steel strip reinforcements, height of wall and length of reinforcement with a fixed value of 0.75 m for horizontal spacing with the help of coherent gravity method. FHWA and British Standard codes were compared to determine the quantity of reinforcement required in design. It has been observed that the estimation of the amount of reinforcement for 9m, 7m, 5m, 3m and intermediate heights will now become easier for the designer as per the British Standard and FHWA. A table has been provided for ease in estimation of reinforcement in FHWA, even if the design has already been done by the British Standard.

A study presents the combined deterministic and probabilistic approach to estimate maximum deformation in MSE modular block walls using numerical modelling, RSM and MCS (Lin et al., 2016). The research effectively links deformation predictions to reliability-based performance criteria. The CDF is then used to produce a reliable design for a range of serviceability criteria under working conditions. The authors presented a fitted normal distribution curve for relative frequency percentage against Error (Fig. 7).

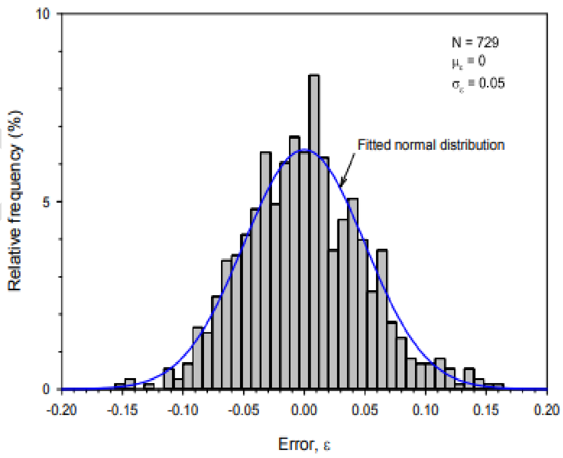


**Fig. 7.** Error analysis using logarithm values of the maximum normalized horizontal facing displacements from the numerical model and RSM Equation (Lin et al., 2016).

### 5.5. Comparison of the Present Study with Classical Studies

The present work is built upon prior studies by leveraging machine learning (ML) techniques to enhance the prediction and design of MSE walls. Compared to previous research, Vadavadagi et al. (2024) achieved high accuracy in predicting reinforcement tensile forces using an ANFIS-GA model

($R^2$ = 0.9876). The current study further refines these prediction models, aiming to improve both the precision and computational efficiency of MSE wall design under varying load conditions. Mishra et al. (2021) demonstrated the utility of various AI models, including SOS-LSSVM, in predicting factors of safety for retaining walls, where SOS-LSSVM outperformed others in accuracy, suggesting the potential for AI in simplifying complex geotechnical reliability assessments. In contrast, the present work introduces new ML techniques that build on these methods while focusing on minimizing prediction errors and enhancing the optimization of wall designs for various geotechnical scenarios.

Furthermore, the probabilistic reliability studies focused on assessing failure modes in MSE walls using methods like Monte Carlo Simulation (MCS) and First Order Reliability Method (FORM) (Chalermyanont and Benson, 2005; Zevgolis and Bourdeau, 2010). These studies set a foundation for understanding the uncertainty in design parameters and external failure modes. The present study similarly addresses these uncertainties but with a focus on integrating more advanced ML models, allowing faster and more accurate predictions of wall behavior under dynamic loading conditions. This approach not only aligns with but also extends the methods employed by previous studies, offering a more streamlined and efficient solution to MSE wall design and reliability assessment. Over the decades, key analytical models have relied on several assumptions that come with certain limitations. Table 4 shows the various assumptions with limitations in analytical models.

**Table 4.** Assumptions and limitations in key analytical models.

| S.No. | Assumption | Limitation | References |
|---|---|---|---|
| 1. | Homogeneous soil | Causes uneven settlement, stress | Hamrouni et al. (2020) |
| 2. | Elastic reinforcement | Deformation affects stability | Chalermyanont and Benson (2005) |
| 3. | Ignore long term effects | Weakens performance over time | Vibha and Divya (2021) |
| 4. | Simple loads | Misses seismic/dynamic impact | Won and Langcuyan (2020) |
| 5. | Ideal boundaries | Affects wall-soil interaction | Xue et al. (2014) |
| 6. | Ignore environment | Material/soil degradation | Zhang et al. (2008) |
| 7. | Pseudo-static seismic | Underestimates demand | Basha and Babu (2009) |

## 6. Conclusion

Over the past three decades, extensive research has significantly advanced the understanding of materials, design methodologies, and stability analyses related to Mechanically Stabilized Earth (MSE) walls. These structures have emerged as reliable and cost-effective solutions in geotechnical engineering, owing to their simplicity in design, ease of construction, and time efficiency. This review highlights the progression in MSE wall technology, aiming to support engineers and researchers in making informed decisions for future applications. A notable shift has been observed in recent research trends- from the exclusive use of conventional cohesionless fill soils to the exploration of non-conventional and sustainable alternatives. This transition is largely driven by the increasing scarcity of high-quality cohesionless soils and the need to utilize locally available resources. While guidelines from agencies such as FHWA recommend cohesionless soils for backfilling due to their superior performance, the practical limitations related to their availability have prompted the investigation of alternative materials. However, many of these alternatives, though sustainable and locally sourced, pose challenges due to their variable geotechnical properties. As such, soil stabilization- either through mechanical modification or the inclusion of foreign or waste materials-remains a critical area for further exploration. Continued research in this direction is essential to enhance the performance and reliability of MSE walls constructed with non-conventional backfills. The key outcomes of the review are as follows:

- There are several ongoing studies on the sustainable backfill soils to reduce the burden of waste generated from several industries like thermal power plants, slag from steel plants, soil-like material from municipal solid waste landfills, construction and demolition waste, etc. Sustainable fills are economical and reduce the hazards of mining sand from rivers and estuaries.
- There are marginal soils available which can also be used as alternate materials for backfilling, but due to their higher fine content, there are problems of drainage, rainfall infiltration, volumetric changes, etc., and these must be addressed for long-term stability. Such soils need stabilisation during in-situ backfilling of MSE walls through the addition of stabilising agents like lime or by mechanical means in the form of sand drains, stone columns, sand piles, etc. The type of reinforcement and its distribution horizontally and vertically in the MSE wall also play a crucial role in enhancing stability, which needs further research in the case of marginal soils.
- The reliability analysis of MSE walls has been performed for cohesionless backfilled soils for both geosynthetic and metallic reinforcement. On the other hand, the reliability of sustainable fills is yet another area of research that ensures whether the MSE wall is reliable or not.
- Several numerical and computational, analytical and experimental testing methods have emerged over time. Several parametric studies are needed for sustainable backfill materials as well as for marginal soils, considering both the panel facing wall and wrapped walls.

While MSE walls are designed for a service life of 75 to 100 years, most existing structures have only been in place for approximately 40 to 45 years since the concept was first introduced. As a result, additional time is needed before the long-term performance and durability of the earliest MSE walls can be fully assessed. Under such circumstances, reliability-based analyses of MSE walls will be helpful, especially in the case of marginal soil backfilled MSE walls.

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### Conflicts of interest/Competing interests

No potential conflict of interest in the subject matter discussed in this manuscript.

### Authors' contributions

Consent to submit has been received explicitly from all co-authors. Authors whose names appear on the submission have contributed significantly to the work submitted.

### Use of Artificial Intelligence

No Artificial Intelligence tool has been used in writing the manuscript.

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