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Review

Assessment of Soil–Structure Interaction Approaches in Mechanically Stabilized Earth Retaining Walls: A Review

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Abstract: Mechanically stabilized earth (MSE) walls are recognized for their cost-effectiveness and superior performance as earth-retaining structures. The integration of internally reinforced walls has transformed soil preservation practices, garnering significant attention from the global technical community. The construction method of MSE walls has recently gained widespread popularity, likely due to its cost efficiency and simplicity compared to traditional externally reinforced walls. This paper provides a comprehensive review of MSE walls, including their historical development, aesthetics, benefits, drawbacks, factors influencing lateral displacements and stress responses, and the concept of the MSE wall system. Key approaches for analyzing seismic soil–structure interaction (SSI) issues are emphasized, investigating the dynamic interaction between the structure and soil through various research methodologies. This study incorporates multiple publications, offering an in-depth review of the current state of dynamic SSI studies considering surrounding structures. The findings emphasize the significant sensitivity of the dynamic behavior of mechanically stabilized earth (MSE) walls to soil–structure interaction, highlighting the necessity for continuous research in this area. The paper identifies research gaps and proposes future directions to enhance MSE wall design and application, facilitating further advancements in earth-retaining structures.

Keywords: mechanically stabilized earth walls; soil–structure interaction; internally stabilized fill; lateral displacements; a review

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1. Introduction

The history of retaining walls dates back to ancient Egypt when they were constructed to protect against the flooding of the Nile River. To combat erosion caused by the flooding, gabion-style retaining structures were built using reeds. These walls served not only as conduits for waterways on the land but also functioned to redirect Nile floods into reservoirs, proving to be efficient flood control solutions. Throughout history, an array of materials including sizable rocks, barrels filled with smaller stones, treated timber, cast-in-place concrete, and concrete slabs were employed in the construction of these retention walls. Mechanically stabilized earth (MSE) walls, a composite framework integrating soil and strengthening methods, were pioneered by Henri Vidal in the 1960s and gained popularity in the US during the 1970s [1,2]. These walls present benefits like reduced costs, construction simplicity, inherent stability that withstands settlement without fracturing, and improved seismic resistance in contrast to alternative retaining wall systems. Owing to these advantages, MSE walls have emerged as the favored choice for diverse applications [3]. They have been effectively utilized as embankments, coastal defenses, stabilizing elements for bridges (abutments), towers, buildings, industrial storage enclosures, roads, railways, and various other construction undertakings [4], as well as for conventional soil and rock mass retention purposes [5]. AASHTO criteria [6] recommend high-quality, free-draining granular materials for backfill in the construction of MSE walls. Yu et al. [7] stated that the performance of MSE walls is complex, making it difficult to simulate these walls effectively with numerical modeling approaches (such as the finite element and finite difference approaches). The intricate interactions between the soil and the supporting components, the soil and the exterior panels, and the incremental building process all contribute to this difficulty. Damians et al. [8] described the latest case study in which they implemented the finite element technique to model the behavior of an instrumented, 17 m high steel strip wall built in the USA [9].

Soil frequently comes into direct contact with structures, and its behavior under external dynamic forces such as seismic events or vibrations can profoundly impact the way the construction responds. The concept of dynamic SSI encompasses the relationship between the soil and the structure. In engineering design, it is a common assumption that the base of the wall possesses fixed support when evaluating the earthquake resistance of structures. However, this assumption is overly simplified and holds true only if the wall is supported by exceptionally rigid soil or hard rock strata [10]. Among the most important topics in the field of seismic engineering, SSI has received extensive focus internationally in the past few years [11]. Construction projects built on the ground surface are examples of an interrelated system that is subject to SSI effects. Initial developments date back to the late 19th century, but they did not fully evolve and reach their peak until the following decades and the first half of the 20th century. In the second half of the century; however, they advanced quickly owing primarily to the demands of the offshore and nuclear power industries, the introduction of powerful computers and simulation tools like finite elements, and the requirement for increased earthquake safety. Studies related to the interaction between soil and structure have demonstrated that a structure available on a loose base may respond dynamically differently than the same structure available on rigid strata [12,13]. The difference in vibrational force absorption between a flexible structure and the supporting surface is primarily attributed to stress wave radiation and hysteretic action. Numerous well-established analytical methods are accessible for computing the impacts of dynamic interactions between soil and structures [14]. The issue of soil–structure interaction becomes intricate when multiple edifices coexist in close proximity, as their structural responses within the ground influence one another. Owing to spatial limitations in urban areas and swift urban development, the construction of tall buildings grouped together has been progressively surging, particularly in regions with soft soil layers, such as the urban zones in Kobe, Japan [11]. In such scenarios, the energy released from shaking structures is transmitted to the soil and neighboring structures, leading to dynamic interactions among the buildings. Consequently, the dynamic characteristics and earthquake responses of a structure cannot be studied in isolation from those of nearby buildings.

Numerous studies in the literature have focused on investigating the effects of soil–structure interaction (SSI) on different types of structures and have proposed various modeling methods with varying levels of accuracy. However, it is evident that engineers have not fully integrated SSI effects into the design process. One possible reason for this oversight is the absence of SSI considerations in many international standards, leading some to underestimate its significance. Nevertheless, recent research and past disasters highlight the potential risks of neglecting SSI, emphasizing the need for thorough consideration of SSI in construction practices [15]. This study emphasizes the significance of soil–structure interaction (SSI) and its impact on seismic response in structures. It conducts a comprehensive review of various evaluation approaches for SSI, employing widely accepted modeling techniques and computational tools. This article offers valuable recommendations and guidelines to assist researchers in defining input parameters and mitigating risks, particularly in linear modeling scenarios. Additionally, it explores the historical development of MSE retaining walls, highlighting essential design aspects, factors affecting lateral displacements and stress responses, as well as the failure mechanisms of

MSE walls. The thorough analysis presented in this study identifies research gaps and proposes future research directions for further advancements in this field.

2. An Overview and Applications of MSE Retaining Walls

Soil, being a natural material, exhibits various characteristics depending on its type. The cohesion (C) and angle of internal friction (Ø) are key parameters that define its properties. Dry soil, when unrestrained, often results in sloping profiles rather than vertical surfaces. In certain applications, such as bridge abutments, underwater walls, submerged walls, wing walls, and stabilized slopes, it becomes necessary to maintain the soil in a perfectly vertical position, particularly on either side of a roadway. This vertical support is achieved through the use of ground-retaining structures. These structures play a crucial role in keeping the soil in a vertical and stable position. Retaining frames were previously made of reinforced concrete and designed as gravity or cantilever walls, resulting in rigid or flexible structures incapable of withstanding significant variations in settlement without the support of pile foundations. As the level of soil that must be kept vertically straight increases and the subsoil layers weaken, the cost of reinforced concrete retaining walls increases considerably. In response to earth pressure, the foundation is prone to collapse [16,17]. However, porous or unstable underlying soils need significant construction and design challenges. The vertical length of these walls usually ranges from 3 to 12 ft (about 0.9 to 3.70 m), and based on the wall design, stresses close to the wall face can range from 4000 to 7000 psf (about 192 to 335 kPa). The increasing extent of the walls presents a number of geotechnical issues, including insufficient safety factors for global stability, bearing capacity, differential settlement, and others. This problem can be resolved using the MSE technique (Figure 1). This configuration is referred to as an MSE wall, whereas the front sections work as a basis for support and the soil serves as a strengthening structure (as shown in Figure 1). The facing of MSE walls is commonly constructed using various thin components, including precast concrete tiles, dry cast modular boards, metal sheets and plates, welded metal mesh, bonded wire mesh panels, shotcrete, hardwood lagging and columns, and bundled sheets of geosynthetics [18]. The soil behind the facing is then compacted and supported by materials such as steel strips or bars, welded wire mats, polymer surfaces, or geotextile supports, which mechanically stabilize the entire structure [19]. A facing structure facilitates the creation of perpendicular and sloping mechanically stabilized earth (MSE) walls. Often, the soil is positioned as an unreinforced layer between the stable section and the existing ground surface, forming what is termed "retained backfill". In the construction of MSE walls, coarse soil is utilized as a foundational fill. These walls, classified as earth-retaining structures, comprise three main components: metallic or geosynthetic supports, facing elements, and soil-reinforced walls. As being developed in civil engineering over thirty years ago, MSE structures have gained popularity as a cost-effective alternative to traditional concrete-reinforced retention structures and started to spread to many nations and ended up being more widely used. MSE walls have emerged as the preferred method of earth retention filling due to their powerful load-bearing capacity, adaptability, and economy achieved by supplying granular fill and reinforcing components [20].

In addition to the previously mentioned applications, MSE retaining walls find use as temporary walls for road construction, soil preservation, filtration systems for oil storage containers, protection walls around gas storage facilities, extensions for levees, capacity enhancements for dams, and delineation of storage spaces in areas with unsuitable soil conditions for construction. The construction of MSE walls involves a diverse range of methods, tailored to meet specific project requirements and site conditions. Key steps include site preparation, excavation for a level foundation, installation of reinforcements such as geogrids or steel strips, backfilling with appropriate material, incorporation of facings for structural support and aesthetics, ensuring proper reinforcement and facing connections, implementation of drainage systems, and strict adherence to quality control measures. Construction techniques may vary based on design needs, wall type, and available resources. It is essential to follow the guidelines provided by project engineers to ensure the construction of a secure and durable MSE wall.

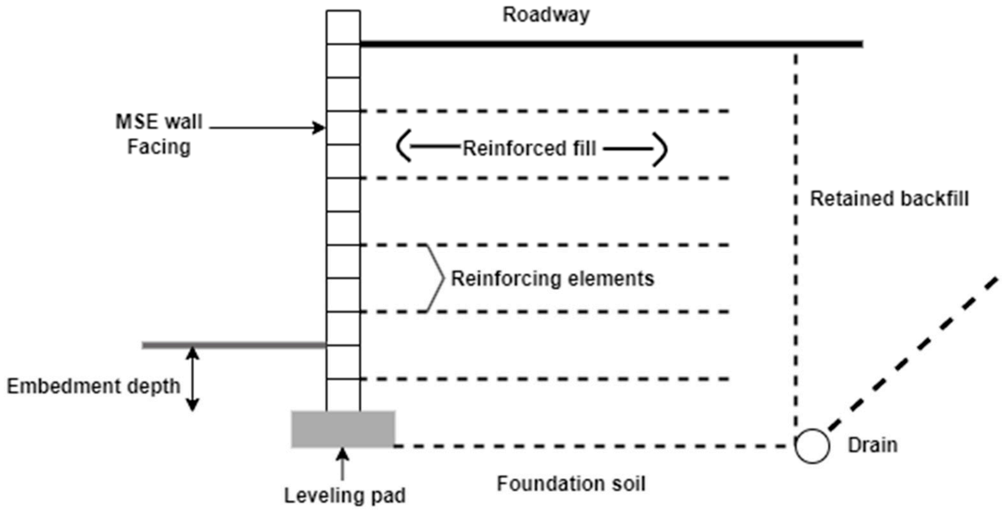

Figure 1. The essential parts of an MSE Wall.

Some previous studies focused on the numerical and experimental study of models for MSE walls. For instance, Burke et al. [21] used computational analyses on a complete geosynthetic soil reinforcement system by adopting the finite element technique. The model had a height of 2.8 m and a 20 cm thick earth foundation. It was subjected to Kobe earthquake vibrations with an amplitude of 0.4 g. The structure's borders and facings were designed as linearly elastic materials. The geosynthetic material was modeled using an ambling surface model of power reinforcing roles, and the backfill and foundation soil were modeled using an existing plasticity approach. The research was carried out assuming 2D plane strain settings using a modified DianaSwandyne-II program. The largest settlement in this study occurred below the reinforced line, even though the base of block movement at the shaking end tends to reach a higher value. The results of the study were highly comparable with the outcomes of the test results. Hossain et al. [22] studied how the backfill material affected the erroneous displacement of the MSE wall. It was found that high fine-grained backfill and poor drainage techniques may result in further displacement of walls or even failure.

3. Mechanisms of MSE Wall Failure

Although MSE walls are known for their reliability, ease of construction, and cost-effectiveness, the occurrence of MSE wall failures has become a concerning issue for various agencies that implement them. MSE walls exhibit two distinct forms of stability: internal stability and external stability. Consequently, addressing and discussing these two modes can be approached separately. Although the principle of soil reinforcement shares some resemblance to reinforced concrete, the interaction between soil and reinforcement differs significantly from the chemical bonding observed in steel-concrete structures. In the case of MSE walls, the interaction between soil and reinforcement relies on friction and interlocking of soil particles with the reinforcement aperture, creating a pseudo-cohesive effect, as depicted in Figure 2a [23]. The frictional characteristics and interlocking between materials depend on various factors, such as the crushability of soil particles and the surface roughness of reinforcement. For instance, the presence of water in the soil can act as a lubricant between particles, leading to a decrease in internal friction. The frictional and interlocking behavior is closely linked to the shear strength and the transfer of force in the reinforced materials. Additionally, the length and quality of reinforcement significantly impact the pullout resistance of the earth reinforcement [24]. For the MSE wall to resist external failures like overturning at its toe, sliding along the base, differential settlement, and loss of bearing capacity of the foundation, the earth reinforcement structure must function as an effective gravity retaining wall. Figure 2b illustrates a schematic representation of a typical reinforced soil retaining wall, indicating the forces involved in both internal and external stability analysis [25]. Despite making several assumptions, the behavior of MSE walls remains highly complex. As a result, engineers strive to develop standardized procedures and codes of practice for designing such walls. In general, the specifications AASHTO [6] and NCMA [24] provide the necessary criteria for earth reinforcement design to ensure it satisfies all failure modes. Table 1 provides a summary of the performance criteria utilized in the design of reinforced soil retaining walls based on AASHTO [6].

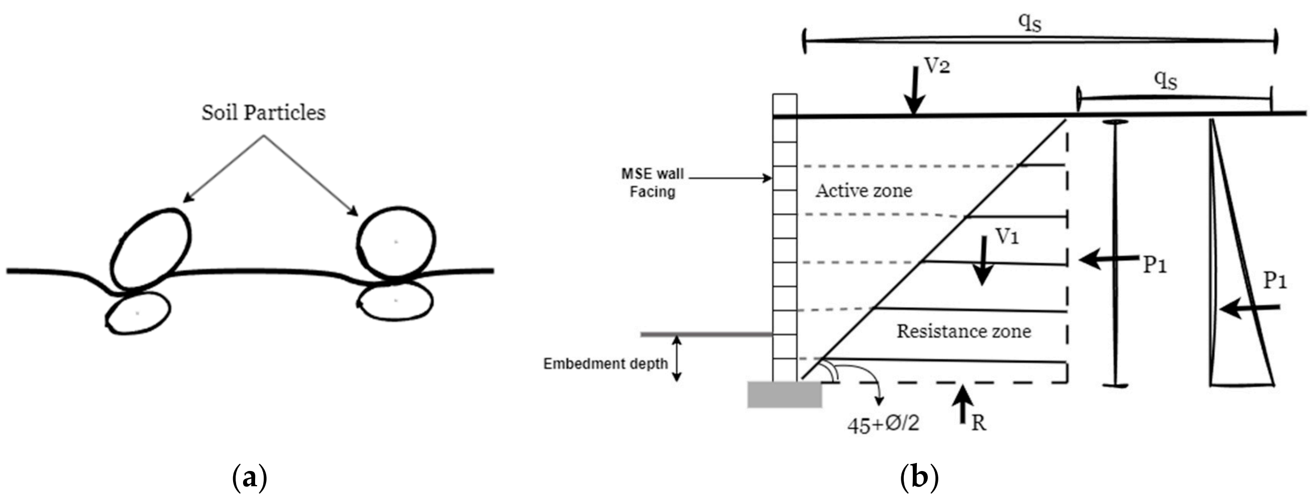

Figure 2. (**a**) The schematic of interaction between soil and (**b**) reinforcement and a reinforced soil retaining wall with the forces considered in the analysis of its external stability.

Table 1. The criteria for evaluating the performance applied in the design of reinforced soil retaining walls [6].

Type of Failure	Factor of Safety Used to Evaluate Performance
Sliding	≥1.5
Overturning	≥2
Bearing Capacity	≥2.5
Pullout	≥1.5

External stability in soil structures relies on their ability to withstand external forces based on their weight and stiffness. Earth reinforcement structures, when behaving like rigid bodies, exhibit external failure mechanisms similar to conventional gravity walls, including sliding failure, bearing failure, and overturning failure [26,27], as shown in Figure 3. Sliding failure primarily occurs at the base or foundation level. The numerical analysis shows that the backfill failure follows classical Rankine's or Coulomb's model, but the reinforced soil remains outside the failure envelope [24]. This supports treating reinforced soil as gravity walls. The key factors affecting sliding stability are the friction and interlocking between these zones, which depend on the weight of the reinforced soil, the contact surface between reinforcement and soil particles, and the area of reinforcement and foundation. The study on overturning stability [28] identifies key factors: wall height, unit weight of reinforced soil, friction angle of backfill, and surcharge load. Notably, there exists a close relationship between the failure modes of overturning and bearing capacity.

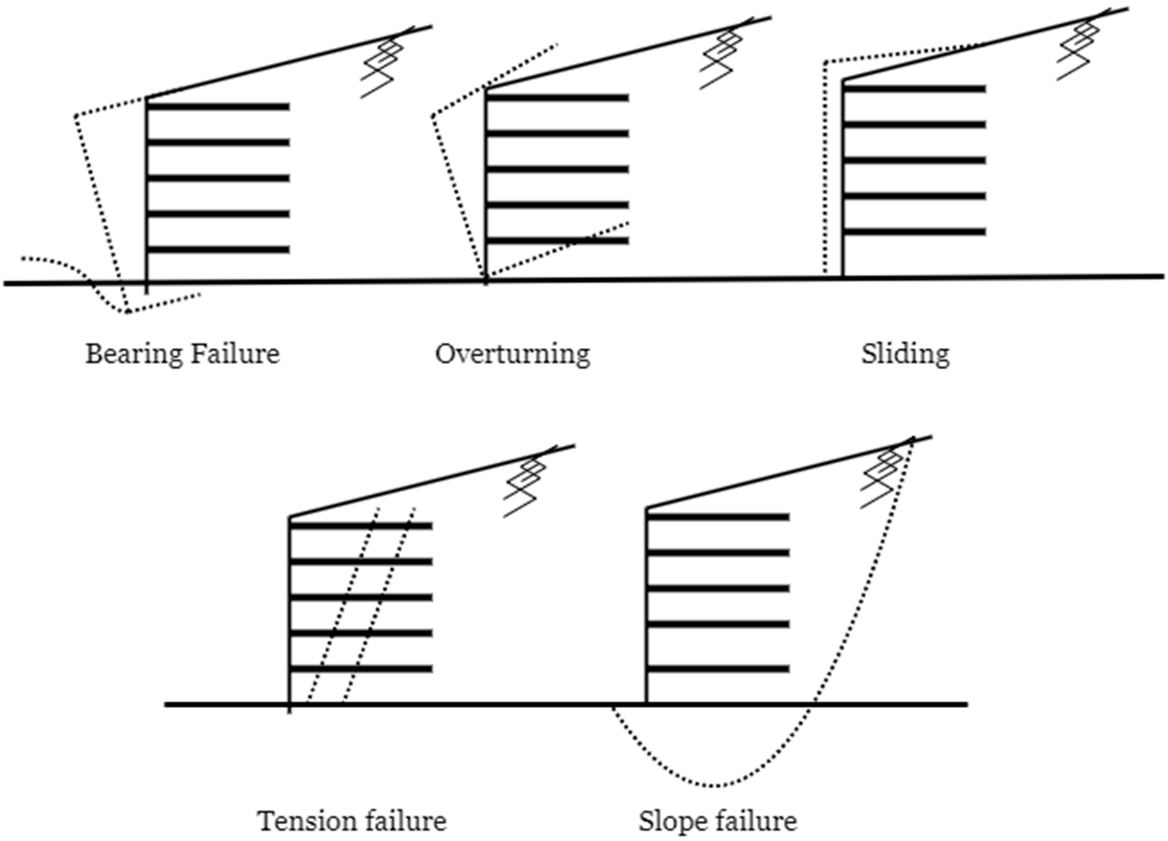

Figure 3. The primary way in which reinforced soil systems tend to fail is the principal mode of failure.

Internal stability is determined by the strength and stiffness of the reinforced soil mass. Experimental data demonstrate that reducing the spacing between reinforcements increases the soil's stiffness and reduces tension within the reinforcement [29]. Accordingly, AASHTO requires the spacing of vertical soil reinforcement to be limited to 0.80 m. The design of reinforced soil retaining walls considers two critical factors: the bond rupture strength between the reinforcement and soil, and the strength of the reinforcement itself. The occurrence of failure in such walls is determined by the rupture of reinforcement and pullout strength (Figure 3). If the tensile force in the reinforcement exceeds the friction force between the reinforcement and soil, the reinforcement may be pulled out from the soil mass, leading to local failure. Pullout failure typically arises when the reinforcement length is insufficient to resist tension or when the soil's strength is inadequate to handle the tension force [24]. Additionally, another potential failure mode occurs when the tensile force in the reinforcement surpasses the rupture strength of the reinforcement itself, resulting in elongation or breakage and causing rupture failure [30]. Currently, panel elements are widely utilized on the front face of earth reinforcement structures to enhance the strength and stability of the reinforced soil zone and mitigate surface erosion. The stiffness of the earth reinforcement facing has a significant impact on the tension failure of the reinforcement [29]. Reducing the reinforcement length in the reinforced soil zone moves the maximum stress position closer to the facing due to limited surface area for tension force distribution. Shorter reinforcement selection forces the maximum reinforcement load towards the facing blocks to ensure sufficient anchorage. However, the maximum tension force in the reinforcement is independent of reinforcement length [29]. The result indicates that the rupture failure surface of the reinforced soil is closer to the facing blocks than Rankine's rupture failure surface. This rupture surface is another scenario that may lead to tension failure.

Friction between the soil and reinforcement plays a crucial role in determining the pullout force, acting as a pseudo-cohesion for the earth reinforcement. If the reinforcement length is too short to mobilize sufficient friction force against the prevailing tensile force, pullout failure often occurs at the end of the reinforcement, particularly at the top of the wall. AASHTO recommends a safety factor of 1.5 for the pullout failure mode and requires a minimum reinforcement length of 0.9 m [6].

It is important to consider that the Ultimate Limit State (ULS) of MSE walls involves evaluating the wall's structural integrity under severe loading conditions to ensure it can withstand the forces without failure. Important considerations at the ULS include the wall's bearing capacity, resistance to sliding and overturning, pullout resistance of reinforcement, and overall stability, including seismic factors and interactions with adjacent structures. For instance, an MSE wall supporting a highway embankment is designed to withstand the maximum traffic loads and seismic forces. The wall's facing is engineered to provide adequate friction with the underlying soil, preventing sliding or overturning during extreme loading. On the other hand, the Serviceability Limit State (SLS) of MSE walls focuses on their performance under normal conditions to maintain functionality and aesthetics. Key aspects at the SLS are deflection control, cracking prevention in the facing and reinforcement, settlement avoidance, and proper water drainage to prevent hydrostatic pressure and maintain serviceability. For example, an MSE wall used for residential landscaping is designed to meet specific deflection limits for a smooth appearance. The facing material is chosen to resist cracking, and an effective drainage system is installed to avoid water accumulation and potential damage.

4. Advantages and Disadvantages of MSE Retaining Walls

The application of mechanically stabilized earth (MSE) walls, which come in diverse dimensions and arrangements, hinges on their designated function and particular surroundings. These walls capitalize on their intrinsic gravitational forces to resist external factors like lateral earth pressures, water pressures, and seismic occurrences. This allows for the efficient dispersion of bearing pressure across a substantial area. When contrasted with concrete walls, MSE retaining walls present advantages in terms of cost efficiency and their capacity to withstand greater overall settlements and differential movements without experiencing failure. Their construction is also simpler and quicker, as they do not require external structures like scaffoldings or curing time. MSE walls are often capable of withstanding complex dynamic loads, including earthquakes, as well as static loads [23]. Due to their cost-effectiveness and strength, MSE structures are highly favored by contractors and architects. These walls present numerous advantages, including ease of construction, limited reliance on heavy equipment, swifter assembly in comparison to traditional concrete walls, and the potential to utilize more land area for construction purposes. Furthermore, MSE walls eradicate the necessity for specialized labor, wall finishing, and extensive site preparation. They can be installed in tight spaces or areas where building a concrete wall would be challenging. However, this approach may reduce the amount of land required. While MSE walls exhibit high resilience to earthquake forces, they are susceptible to elastomeric distortion. Combined with additional reinforcing components, MSE walls can reach heights of 60 ft (about 18 m) and could be compared to other tall retaining structures. Since MSE walls might be available in a variety of dimensions and forms, their use can eliminate the requirement for drilling foundations, enabling their use in areas with shallow ground [24]. The design of MSE walls comes with certain drawbacks, such as the need for a minimum diameter to achieve stability. Moreover, the availability of coarse-grained soil for the reinforced soil mass can be costly, making the construction process less profitable in regions with a scarcity of granular material. Proper drainage systems must also be incorporated. Additionally, the reinforced components must be designed to withstand weathering and deterioration, which could potentially diminish the mechanical advantages of the composite framework.

5. Factors Affecting Horizontal Displacement of MSE Walls

MSE walls serve as an alternative to traditional gravity walls, offering simplified construction methods, aesthetic design, and cost-effective options. To ensure satisfactory performance, thorough investigation of building and design is necessary. During MSE wall construction, reinforcements are layered into the backfill soil. This reinforced material utilizes the relative movement between the reinforcement and soil to withstand soil stress induced by the retained soil. As a result, the interaction that occurs between an MSE wall's elements, particularly the interaction between soil and reinforcement, determines the wall's effectiveness [25]. Additionally, the structure should give careful consideration to the ground stress brought on by preserved soil [24]. Federal Highway Administration [24] and AASHTO [6] proposed a factor of 0.7 of the height of the wall (H) with a minimum of 2.4 m for the length of reinforced soil in current construction methods. Even so, a minimum reinforcing length of 0.6 H was mandated by the National Concrete Masonry Association [26]. The implementation of the required reinforcing length could be limited in cases when natural formations of stones, artificial shoring infrastructure, or similar retaining walls are evidently associated with an MSE wall [31]. Stability problems and excessive lateral movement may arise in these circumstances. The choice of backfill soil is crucial along with reinforcing length, since Soong and Koerner [32] documented 20 cases of geosynthetic-reinforced wall collapses brought by the poor functioning of restricted backfill. Such unacceptable horizontal movement or possibly the failure of an MSE wall can result from an insufficient amount of strengthened soil. Therefore, since in many situations there is not much space back the wall, lateral movement brings a significant risk [33].

Kibria et al. [30] studied how strengthening the soil affected the MSE wall's instability. The researchers used two inclinometers, which were set up on the scene as a component of the forensic examination to track the future movement of the MSE wall. The inclinometer readings revealed that throughout the examination time, the wall maintained moving at a regular rate of 4.5 mm/month. To analyze the impacts of soil strengthening on horizontal displacement at various wall heights and backfill conditions, a parametric approach was carried out. Findings from the FE simulations were employed in a statistical evaluation software for evaluating sensitivity. Depending on the assessments, it was shown that reinforcement length and stiffness had a significant impact on how much MSE walls would move horizontally at a given height. According to the analysis, it was determined that one of the reasons impacting the durability of the wall may be insufficient reinforcing length. At a fixed wall height, horizontal movement reduced when reinforcement strength, length, and backfill soil friction angle increased. For a wall height of 4 m, it was found that the influence of reinforcement stiffness was insignificant. On the other hand, with an 8 m wall elevation, the horizontal displacement expanded to 389 mm at reinforcement stiffness and length (L) of 250 kN/m and 0.6 H, respectively. According to the fluctuations in movement with reinforcement length, displacement significantly decreased with an increase in the L/H ratio from 0.5 to 0.7.

Abdelouhab et al. [31] built a 2D computer model of an MSE wall in the finite difference program FLAC 2D. From this study, it could be found that the MSE walls' durability and deformations are most significantly impacted by the soil shear strength factors, and the capability of adhesion is increased by using composite strips that are two times larger than metallic strips. When employing high-adherence synthetic strips, the stability is considerably higher. Additionally, the parametric analysis of the strip modulus of elasticity reveals, for the longitudinal stiffness, a value less than 3500 kN/m^2 for the wall face. This factor has a considerable influence on wall durability and displacement. Moreover, the analysis of interface characteristics reveals that variations in interface shear stiffness significantly affect wall displacement fluctuations. For an accurate assessment of structural movements, the authors recommend obtaining an appropriate estimate of this variable, such as through laboratory pullout tests, for each type of reinforcement. Wang et al. [33] used field investigations to assess the load distribution features of MSE walls during cyclical load conditions, and implemented computational models to assess the influence of the length of reinforcement, the friction factor of the reinforcement–soil interface, as well as the strength of reinforcement regarding the stress-distribution attributes of MSE wall. The findings of this study indicated that a vertical dynamic soil pressure exhibits a discernible diminishing pattern ranging from high to low throughout the wall height while the number of load cycles increases. Throughout the length of reinforcement, the vertical dynamic soil pressure goes up first before decreasing. Additionally, the stress-distribution angle of the MSE wall does not alter significantly as the load cycles reach beyond 100,000; the upper section maintains at 35~79°, and the central part maintains at 47~68°. In MSE walls, the depth of stress distribution has a significant impact, approximately 1.13 times the overall wall height. The dimension and modulus of the reinforcement also influence the stress distribution in the MSE wall, with their effects ranking second and third, respectively.

6. Soil–Structure Interaction

Seismic vibrations transmitted from the bedrock through soil strata can cause damage to buildings on the ground during earthquakes. Understanding the ground acceleration effects is crucial for earthquake-resistant building designs and mitigating natural disasters. Lamb [34] studied the ground's elasticity, which marks the beginning of soil dynamics. Jacobson [35] analyzed the elastic resisting moment of a cantilever model to assess the impact of ground motion on structures during earthquakes. Bycroft [36] introduced rotation, torsion, and vibration analysis methods for circular and rectangular bases. These investigations contribute to a better understanding of earthquake response and aid in developing resilient structures. Bycroft's [36] remarks served as the foundation for Parmelee's interpretation of the fundamental SSI formulae. Due to advances in computer technology, numerical techniques of SSI quickly advanced after the 1970s. The investigation of SSI was then accelerated for the design and building of massive structures like nuclear power facilities.

In their research, Liao et al. [37] addressed the practical implementation of SSI and highlighted two main challenges for computational approaches: incorporating non-linear dynamic soil constitutive theories and establishing appropriate soil boundary conditions. This study presents a case analysis with a hyperbolic soil constitutive model and viscous boundary conditions to investigate the impact of SSI on ground acceleration and the acceleration spectrum. Using the non-linear finite element modeling program MSC.Marc, the researchers studied SSI in loess soils and examined the interaction between the incorporated columns and the surrounding soil. Their findings indicate that SSI leads to a reduction in surface peak accelerations, with a smaller decline scale as soil thickness increases. Additionally, SSI results in decreasing surface peak acceleration spectra, with an increase in decline scale as soil thickness increases. These insights shed light on the behavior of SSI in loess soils and have implications for seismic design and analysis of structures.

In contrast to the ground vibrations recorded in the deep soil layer, seismic waves propagating near the soil surface can induce ground movements that are considerably more pronounced and exhibit distinct characteristics compared to those documented on the soil surface. The effects observed in the field are the combined outcome of seismic events and site-specific features. A number of seismic events, where field impacts were recorded, are available. As an illustration, site amplification following the seismic event in 1985-Mexico City resulted in significant destruction and the downfall of many structures [38]. Seed [39] presented thorough research on the connection between damage to structures and soil state. Several investigations have also demonstrated a connection between destruction, geographic regions, and ground conditions [40,41]. Numerous researchers have investigated the relationship between soil and several types of constructions, such as bridges, minarets, and others, using earthquake data analysis [42]. According to Rahgozar [43], there are typically two approaches used to analyze the results of SSI throughout seismic events: (a) an extensive interaction evaluation that takes into account the fluctuation of the movements in both the building itself and the surrounding soil; or (b) an internal investigation where the movements in the surrounding soil are considered to be uniform above the foundation surface. Investigators have looked into various parts of seismic SSI evaluation, and their findings have been reported in the literature, i.e., Gazetas [44].

Matinmanesha and Asheghabadi [45] performed a study to investigate the SSI under earthquakes by adopting Abaqus software. The researchers observed that there is a significant amplification within the soil–foundation surface with respect to grounds and structures after a seismic event. Additionally, the damaging effect of the seismic at the soil–foundation contact is increased by this intensification. Thus, the bedrock vibrations are amplified to some extent through all ground materials. Numerous elements, such as the nature and features of the ground, the degree of frequency of earthquakes, and the characteristics of the underlying structure, have all an impact on the quantity of the intensification.

The impacts of the SSI are typically not considered in assessments of the shaking risk of structures. It was successfully established that they may still significantly influence their performance during earthquakes. In reality, European earthquake codes mandate their inclusion in assessments of specific constructions, such as tall buildings or those with significant non-linear or second-order (p-Δ) responses.

Clemente et al. [46] conducted a study on the interaction between MSE walls and soil under earthquake loads to understand the effects of seismic activity on retaining walls. The research focused on seismic-resistant building construction in the Philippines, a region prone to frequent shaking due to its location in the Pacific Ring of Fire, where several tectonic plates converge. The Philippine archipelago experiences frequent seismic and volcanic activity, leading to significant seismic hazards. For instance, a 6.9-magnitude earthquake that struck Davao del Sur on 15 December 2019 resulted in numerous casualties and extensive damage to infrastructure and homes in Region XI (Davao) and Region XII (Soccsksargen). Over 60 health institutions, 400 schools, and nearly 26,000 homes were destroyed, with a majority of the damages occurring in the state of Davao del Sur [47]. The study also considers the possibility of higher magnitude earthquakes, with the largest possible magnitude and potential for a seismic event in the Philippines estimated to be around 8.0 Mw over 50 years based on research into the likelihood of such events [47]. Understanding the impact of earthquakes on MSE walls is critical for enhancing seismic resilience in this earthquake-prone region.

Bapir et al. [15] reported that while a structure is placed on considerably soft soil and is exposed to a seismic motion, the soil beneath it may have a double impact within the structure. The variation in rigidity within the structure and the ground beneath causes the first impact, referred to as kinematic interaction, to occur. Due to the presence of a robust foundation, when a seismic ground movement propagates through the free field, the waves undergo alterations and dispersion. The primary effects of kinematic interactions are observed in pile foundations. Another scenario referred to as inertial interaction takes place when the accumulated inertia of the shaking structure augments the shear forces and bending moments at the ground level, consequently leading to increased soil deflection. The structural–soil interaction (SSI) system exhibits greater flexibility in response to distortions in the underlying subsurface, intensifying the impact on the foundation's movement [48,49]. Many years ago, there were a wide range of studies and analyses on SSI, including a number of assessment studies on advancements in modeling approach and application scenarios. The effects of SSI on constructions are still up for debate among the international technical community due to the absence of a common understanding.

It was previously reported how static and dynamic SSI have evolved historically by Roesset [50]. The advantages and drawbacks of previous models were addressed, while Dutta and Roy [51] provided a thorough analysis of several simplified approaches for describing the structure and the soil interaction. The past history and current status of SSI analyses on structures were then reviewed by Lou et al. [11], with an emphasis on the theoretical and numerical techniques used to address SSI problems. In order to discretize the soil domains, earlier efforts to create and apply the finite element method (FEM) and boundary element methods (BEM) approaches were reviewed.

Dhadse et al. [52] reported the benefits and challenges of finite element modeling in SSI issues. In order to address non-linear challenges, particularly the interface between the foundation and the ground, the research studied the mathematical modeling of FEM using proper soil constitutive models. In an earlier study, different methods and modeling techniques were presented and contrasted in order to assess the impacts of SSI on walls [53]. Numerous examples of how SSI leads to additional damage to structures during earthquakes are used to highlight the importance of taking these effects into account throughout the process of designing. Additionally, a summary of the developments and current status of the SSI study of various structures was provided.

7. Techniques for Evaluating Dynamic SSI

7.1. Substructure Approach

The substructure approach is a method that considers the soil and structure as separate entities, solving them individually, and then combines their effects through superposition concepts to evaluate the ultimate earthquake resistance of the structure [48]. This approach uses resistance and transfer functions to address inertial and kinematic interactions independently. Initially, the substructure method required a linear assumption for soil and structural behavior due to its reliance on superposition concepts. However, this limitation has been overcome by employing equivalent-linear and non-linear computational models for soil fields, including non-linear beam structures for pile foundations [54] and the beam on the non-linear Winkler foundation model for weak foundations [55]. These advanced models enable more accurate assessments of seismic behavior and provide valuable insights into the performance of structures under earthquake loads. The non-linear behavior of the superstructures might be modeled through simplified constitutive models without considering the style of the foundation and the material model [56]. As shown in Figure 4, there are three primary steps for solving SSI issues using the substructure technique [15,57]:

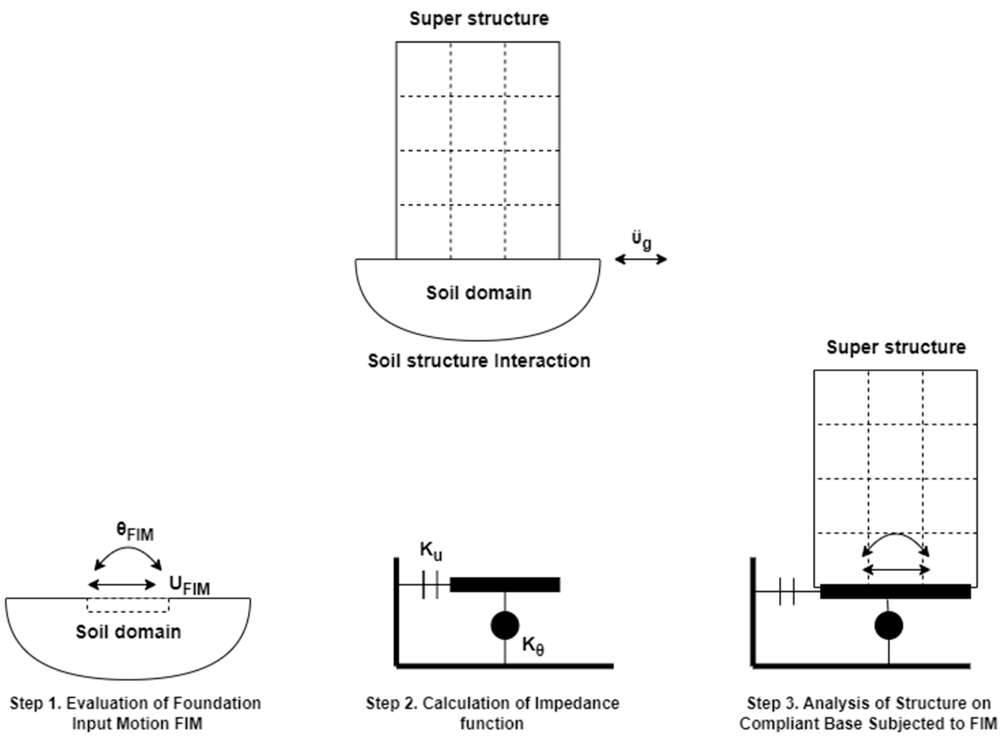

Figure 4. Applying the substructure technique to analyze the SSI issue.

- Assessment of the foundation input motion (FIM), which at first is dependent on the stiffness and geometry of the supporting structure and the soil, as well as assessment of the transfer functions used to transform the free-field motion (FFM) to FIM. The structure and foundation must be free of mass in order to assess FIM. Rotational (θ_{FIM}) and translational (U_{FIM}) elements of the imposed earthquake load to the foundation are depicted. A transfer function that just represents the consequences of the kinematic interaction and ignores the inertial interaction is known as the ratio of FIM to FFM.
- Assessment of the resistance functions of the foundation, which describe the rigidity and damping properties of the interactions between the ground and the foundation. A number of springs and dashpots that are determined by the horizontal (K_u) and rotational (K_θ) stiffness of the foundation soil are typically used to simulate this. The connection between the ground and the foundation is modeled by frequency-dependent dynamic resistance coefficients.
- The structure is represented with springs and dashpots as a foundation for support and the FIM as a source of motion in order to calculate the earthquake response of the construction. Subsequently, either a reaction spectrum assessment or a time history analysis is used to determine the structure's seismic behavior. The consequences of the inertial interaction are represented in this stage.

7.2. Direct Approach

7.2.1. Motion Formula

The direct technique is considered the most efficient method for addressing SSI challenges, particularly when dealing with complex structural design and non-linear soil modeling. A simplified representation of the direct technique is shown in Figure 5, wherein the governing equations for movement are solved to study the soil and the structure as one unit [58]. The underlying structure is connected to the soil through interface components, represented as a continuous surface. Proper boundary conditions are applied to prevent wave reflection as they pass through the interface. With this approach, the entire system is analyzed in the time domain, using input data from free-field movement. This comprehensive analysis allows for a detailed understanding of the dynamic interactions between the soil and the structure, making it a valuable tool in earthquake engineering.

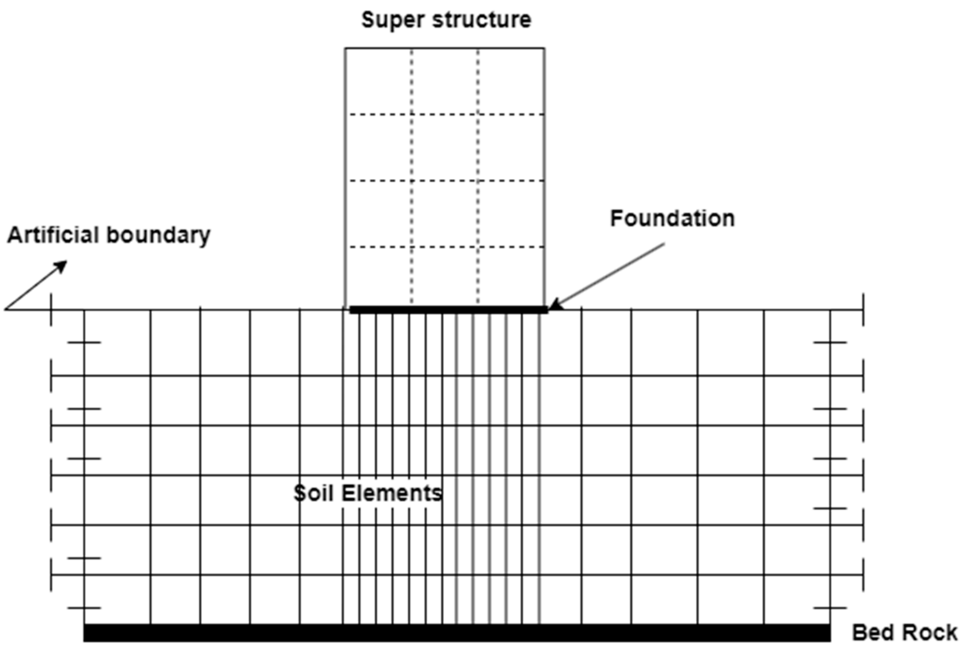

Figure 5. Illustration of the direct approach of the soil–structure relationship employing continuum modeling with finite elements.

The linear and non-linear soil models for various types of GREEK foundations can be solved using the direct technique, which is an efficient technique for solving a wide variety of SSI challenges. However, due to the difficulties and high computation cost, the direct technique is rarely employed in the field of engineering, particularly for issues involving complicated design and non-linear equations. A ground-based structure method's governing equation that describes motion could be expressed in the following form:

$$[M]\{\ddot{u}(t)\} + [C]\{\acute{u}(t)\} + [K]\{u(t)\} = -[M]\{\ddot{u}_g(t)\} = \{F(t)\} \quad (1)$$

In which [M], [C], and [K] stand for the mass, damping, and stiffness matrices, respectively; $\{\ddot{u}(t)\}$, $\{\acute{u}(t)\}$, and $\{u(t)\}$ represent the soil's acceleration, velocity, and movement, respectively; $\{\ddot{u}_g(t)\}$ represents the bedrock's source acceleration; and {F(t)} represents the source of seismic loads. When the previous formula of motion is solved numerically, it is simple to derive the dynamical response solutions for the entire structure.

7.2.2. Reliability of Computations for the Direct Approach

Rulin and Menglin [59] discussed that if the vertical modeled border is placed far enough from a numerical domain of soil as practicable, the effect of the constructed boundary on the numerical near field could be disregarded while studying the seismic effect of the ground at the site and the damping characteristics of the soil material. The horizontal span between the vertical modeled border and the near field is supposed to be no less than five times longer than the thickness of the soil stratum. The mesh distribution should adhere to specific conditions to avoid the individual elements' filtering effect on the effective components of earthquake waves. In general, the vertical mesh dimension should be greater than one-eighth of the shortest wavelength of functional harmonic elements composing the earthquake waves propagating through the ground. It is widely recognized that soils demonstrate pronounced non-linear hysteretic behaviors when subjected to loading and unloading cycles, particularly in the face of severe seismic events. The extent of soil displacement is primarily governed by the intensity of soil non-linearity. Consequently, the inclusion of soil non-linearity in analyses of soil–structure interactions becomes imperative to attain solutions that align with real-world scenarios. In sophisticated seismic design practices, the central approach to evaluating soil non-linearity is the associated linear method. This technique employs diverse iterative procedures to transform non-linear problems into linear approximations [59,60]. This approach allows for a more accurate evaluation of soil behavior and its impact on the overall seismic response of structures, leading to improved design outcomes.

Based on the stated meshing specifications, the number of nodes and elements in the 3D model used for earthquake response assessment could be extremely high for the soil particles in a deeper layer. Subsequently, it is obvious that the computational accuracy of the typically applied evaluation approach will be significantly constrained for the motion response examination of various large-scale and sophisticated 3D models for the construction project during multiple earthquake instances. Jingbo and Yandong [61] stated that viscous-spring boundaries could be used to model the response of unbounded soil to the scattered wave in the scenario of the dynamic soil–structure interface. In contrast with alternatively constructed borders, this type of boundary could replicate both the elastic rebound capacity of its surroundings as well as the infinite soil's ability to absorb scattering waves.

To summarize this, a number of variations within both methodologies, particularly with respect to efficiency and precision, are discussed above. In comparison to the direct technique, the substructure technique offers better computational efficiency and requires less time to address SSI issues, as it does not require discretization of the semi-infinite soil media. Consequently, the substructure technique finds more practical applications, with many investigators using it for SSI assessment [62–64]. Moreover, it allows for the separate and independent calculation of the implications of inertial and kinematic interaction. However, recent research [65] raised concerns about the substructure technique's reliability, indicating that it may lead to overestimation of top movement and design foundation forces. Additionally, it has been found that the substructure technique results in a higher interstory drift requirement in the structure than the direct method [66]. The substructure technique, as highlighted by Jahromi et al. [67], may not adequately handle materials and geometric non-linearity. Therefore, when dealing with complex and significant structures, soil models (direct method) that consider both structural and soil non-linearity should be used. However, additional research is needed to better understand how well substructure theories function in different SSI situations, particularly when considering structure non-linearity.

8. Case Studies

The design of earthquake-resistant structures is also required for building MSE walls in areas where there is a high risk of earthquakes. In this section, a number of case studies are summarized briefly.

Alimohammadi and Memon [68] analyzed and reported the collapse of an MSE retaining wall in Tennessee, USA. The authors performed an extensive site inspection, field data gathering, lab testing, and numerical modeling (using the SLOPE/W software). It was reported that poor building methods were the reason for the retaining wall's failure. More specifically, the backfill material utilized was not correctly compacted, and the wall was not built in line with the design standards. The wall collapsed as a result of the differential settlement which in turn caused structural problems. Thus, this study demonstrated that the retaining wall was properly constructed to withstand the vertical loads from the roadway above and the lateral earth pressure; nonetheless, the breakdown of the retaining wall was caused by the use of inadequate construction materials.

Li et al. [69] used the finite element strength reduction approach to study the failure process of MSE walls. It was observed that the length of the reinforcement and the height of the wall are key factors in failure mode change. The authors summarized design recommendations, generated a failure surface trend, and evaluated the critical reinforcement length to provide the results of the parametric analysis. It was found that an increase in height could mitigate the strengthening impact of the reinforcement, requiring a longer reinforcement length to preserve a favorable failure mode.

Damians et al. [8] performed a sustainability evaluation technique and provided cases to choose the most sustainable choice among various traditional gravity and cantilever wall types, steel, and MSE walls of 5 m height. For the analyses of this study, the authors used the MIVES technique, which is based on value theory and multi-attribute hypotheses. The reported results showed that MSE wall solutions are frequently the best choice for each sustainability pillar category (environmental, economic, and societal/functional) in comparison to conventional gravity and cantilever wall responses. The authors stated that the MSE wall methods are, by a wide measure, the best option if environmental concerns are the stakeholders' top priority. Depending on the MIVES approach, it was determined that the MSE wall solutions were the best type of structure as a significant portion of the structure is made of soil rather than concrete and steel reinforcement.

Rajoo et al. [70] used a reinforcement technique to investigate the effect of seismic excitation on the MSE wall stability. For this, they modeled and analyzed a 44 m high MSE wall by adopting finite element techniques (Plaxis 2D software, 8.1). The authors used a number of dynamic scenarios to determine the failure modes of these walls. It was demonstrated how different levels of MS walls are affected by earthquake severity. It was found that wall deformations increased along with earthquake magnitude, and the recorded data of earthquakes with a higher magnitude and closer epicentral distance exhibit greater deformations. Additionally, the deformations detected on higher walls were getting worse when reinforcement was maintained at a consistent level.

Mehta and Shah [71] studied different design methods of MSE walls, i.e., pseudo-dynamic approach [72–74], pseudo-static approach [75], and tieback wedge method [76]. The authors stated that the modified M-O equation (pseudo-static technique) is the most effective one for designing reinforced earth walls.

9. Summary and Future Research Needs

This article provides a comprehensive review of the background, aesthetics, failure mechanisms, advantages, disadvantages, and factors influencing the lateral displacements and stress responses of MSE walls. It also summarizes the literature on the effects of SSI on the seismic response of MSE walls, encompassing both computational and analytical investigations. The main concept of dynamic SSI is thoroughly presented, and several methodologies are discussed.

MSE walls find widespread application in various construction projects. The stability analysis of soil structures is typically divided into two categories: external stability and internal stability. These two aspects are closely interconnected, as external stability addresses the overall deformation resistance of the reinforced retaining wall, while internal stability is concerned with the bond between the reinforcement and soil, directly influencing the shape deformation.

The substructure technique proves to be more computationally efficient and faster in addressing dynamic SSI compared to the direct technique. However, technological difficulties must be overcome, and cost-effectiveness and construction schedule implications should be considered when implementing solutions to enhance deficient underlying soils and improve wall lateral displacement behavior.

MSE walls offer a cost-effective and highly potent solution, but careful evaluation of the project's site, soil conditions, and drainage requirements is essential for a successful wall structure. Additionally, further research is needed to better understand how substructure theories function in various SSI situations, particularly when considering structure non-linearity. Such research can enhance the overall understanding and performance of MSE walls in seismic conditions.

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