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Comparative review of Soil Reinforcements Types in Mechanically Stabilized Earth walls

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ABSTRACT

Mechanically Stabilized Earth (MSE) wall is one of the most common retaining wall systems used for roads and bridges because it is structurally efficient, cost-effective, and easy to implement. Soil resistance is enhanced by integrating it with reinforcement elements to increase load-bearing capacity and prevent collapse, resulting in a cohesive composite system. MSE walls are reinforced with different types of soil reinforcement, the most prevalent being metallic, i.e., steel strips; or geosynthetic, i.e., geogrid and geotextiles. These different types of reinforcement vary in tensile strength, interaction with soil, durability, corrosion resistance, and cost. These advantages have encouraged choosing the right reinforcement types to achieve both internal and external wall stability. The purpose of this work is to analyze the comparison of various soil reinforcement materials for MSE walls in respect to structural behavior, geotechnical efficiency, economic factors, and operational lifespan. Such studies work to determine the most appropriate reinforcement system that is suitable for infrastructure projects according to site conditions and design requirements.

1. Introduction

Mechanically Stabilized Earth (MSE) wall is a composite soil structure system consisting of foundation soil, facing elements, compacted backfill, and embedded reinforcements that collectively act to form a stable reinforced soil mass. The inclusion of tensile reinforcement improves the shear strength of the soil and restricts lateral deformation, enabling the reinforced zone to behave as a coherent structural block rather than as separate soil layers. Elements reinforcement may be metallic or polymeric and include steel strips, geogrids, geotextiles, and geosynthetic strips. Their performance depends primarily on soil reinforcement interaction mechanisms, where tensile loads are transferred through interface friction and in some cases, passive bearing resistance. Experimental observations indicate that interface resistance increases with normal stress, soil density, and improved interlocking between soil particles and reinforcement surfaces. [1] a fundamental design parameter reinforcement length is controlling internal stability and pullout resistance in mechanically stabilized earth walls. Current design guidelines consistently specify a minimum embedment length proportional to the wall height to ensure adequate anchorage beyond potential failure surfaces. [2] recommends that the preliminary reinforcement length be taken as the greater of 0.7H or 2.5 m, where H is the design wall height Similarly, the AASHTO LRFD Bridge Design Specifications (AASHTO, 2020) require that the soil reinforcement length for strip, sheet, and

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grid type reinforcements be not less than 70% of the wall height, unless justified by detailed site-specific analyses. These recommendations have been widely adopted in practice to provide sufficient pullout resistance and global stability .Addition to reinforcement length, the The choice of appropriate backfill material plays an important role in performance in MSE walls. Generally, it is recommended that granular soils are well graded and free draining, as frictional interaction with surface is increased and pore-water pressure buildup is reduced. More uniformity coefficients were found to increase pullout resistance in more well-graded aggregates compared with coarse aggregates, while lateral friction had also been found to influence the overall capacity by a small amount Herceg et al [3]. In addition, Corrales & Araújo [4] showed that recycled construction and demolition waste is able to achieve similar or better mechanical performance to natural sands because of better particle interlocking, providing a reason to use sustainable alternative backfills. Even though studies on MSE walls are numerous, few focus on any given reinforcement type and do not present direct, integrated comparisons under consistent conditions. Methods are varying and there is no integrated analyses of durability, economic and sustainability, which also restricts the objective evaluation. This paper fills the above mentioned gaps by publishing a short, multi-criteria overview of reinforcement types to guide the selection more informed and effective in engineering practice.

1.1 Historical and Concept MSE Walls

Reinforced earth is a building material for foundation and retaining structures, meaning soil with tensile strength increased by metal rods and geotextiles [5]. Thousands of years of soil reinforcement can be found at the Great Wall of China and the Mesopotamian ziggurat at Dur-kurigalza, which used natural inclusion and layered construction methods [6]. However, modern reinforced soil technology was introduced in the early 1960s through the pioneering work of the French engineer H.Vidal 1966 (see also Darbin and Schlosser). The first reinforced-earth retaining walls in the U.S. were constructed in 1972 incorporating metallic strips. This material improves the tensile strength and shear resistance [5], and the first geosynthetic-reinforced MSE wall was constructed in France in 1971, whereas geogrids became popular in the 1980s because of their enhanced load transfer properties [7].

2. Fundamental Principal of Soil Reinforcement

Soil reinforcement is crucial for MSE walls, enhancing tensile resistance and shear strength and minimizing lateral deformation. Reinforcements come in various geometries, such as linear unidirectional elements(coated steel strips), composite systems (bar mats), and bidirectional geoynthetic sheets. They can be inextensible (e.g., steel strips) or extensible (e.g., geotextiles), and can be metallic or nonmetallic [8], [9]. According to [10] the behavior of soil-reinforced systems is affected by reinforcement type and distribution (uniform layers or random fiber). The interaction between soil and reinforcement is vital, as pull-out resistance relies on the surface and mechanical interactions between soil particles and the reinforcement [11]. Reinforced soils, using geogrid or fiber, enhance shear resistance by mobilizing tensile force and failure surfaces. Understanding soil properties and stress transfaer is key to interpreting their behavior [12]. Strength increases by altering the failure envelope and raising the apparent friction angle. [13] noted that these elements help prevent collapse by redirecting stresses to more stable areas, enhancing the safety and performance of structures such as retaining walls and solpes. The bonding between composite materials and soil are crucial for managing vertical deformations, as they significantly affect stress distribution and resistance in reinforced soil systems [14].

3. Classification of Soil Reinforcement Types

Soil reinforcement systems are classified by the material type used. [10] describe these systems as combinations of soil and reinforcement to enhance strength, categorizing them as metallic, geosynthetic, polymeric, or hybrid.

3.1 Metallic reinforcements

Metallic reinforcements have historically been used in reinforced soil structures due to their high tensile stiffness and strength. Their long-term performance is largely governed by corrosion resistance. Consequently, most metallic reinforcements are manufactured from galvanized mild steel, while protective coatings such as PVC or epoxy may be applied to enhance durability. However, these coatings may be susceptible to damage during construction, necessitating controlof backfill particle size should be limited (19 mm) or less to minimize abrasion. Common metallic reinforcement forms include steel strips, two wire strips, steel wire grids, and double twisted steel mesh , as shown in Fig 1 [8][9]. According, [15]studied a 12 meter- high earth- retaining wall found that passive force has minimal impact on anchoring length (0.25% at 0.6 m, 0.38% at 0.7 m, and 0.88% at 1.5m) they found that the PLAXIS modeling showed similar safety factors for geogrid and plate elements (differences of 0.7 to 3.4%), both exceeding 1.2. geogrid provided 13.7% to 31.4% greater safety, indicating a more secure structure.

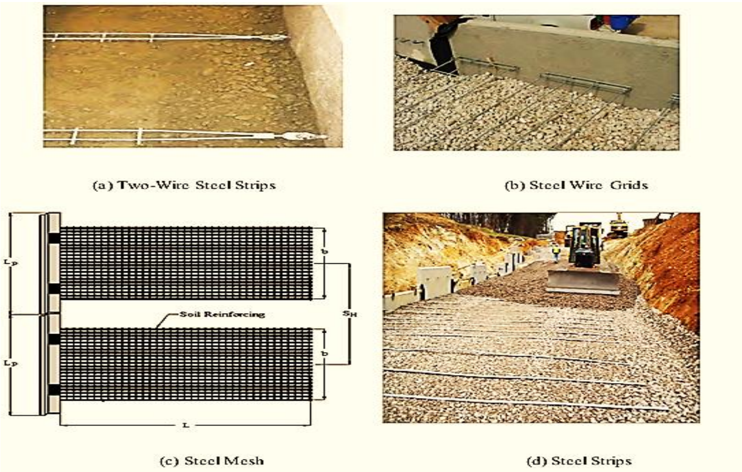

Figure 1: typesmetallic reinforcement [1].

3.2 Nonmetallic reinforcements

Nonmetallic reinforcements are generally referred to as geosynthetics, a broad class of polymer-based materials specifically engineered for geotechnical and civil engineering applications. The term “geosynthetic” is derived from the prefix geo, indicating association with earth, soil, and ground-related works, and the suffix synthetic, which denotes manufactured polymeric products. These materials are designed to enhance the mechanical and hydraulic performance of soil structures and infrastructure systems [16].

Geosynthetics of different types (planar products) including geotextiles, geogrids, geomembranes, geonets, geocomposites, etc., have various properties such as reinforcement, separation, filtration, drainage, and containment. Geosynthetics have advantages in comparison with older metal reinforcements—more corrosion resistant, lighter weight, easier to transport, easier to install, and cheaper. Therefore, their applications have markedly increased during the past few decades and have played a crucial role in creating more sustainable, economical, and environmentally friendly geotechnical engineering applications [17]. Multiple classification frameworks have been constructed for geosynthetics to standardize terminology and applications. Based on structural form and engineering function, a comprehensive system was proposed by [7] wherein they organized these materials into eight primary categories. Representative illustrations of these categories are shown in Fig 2.

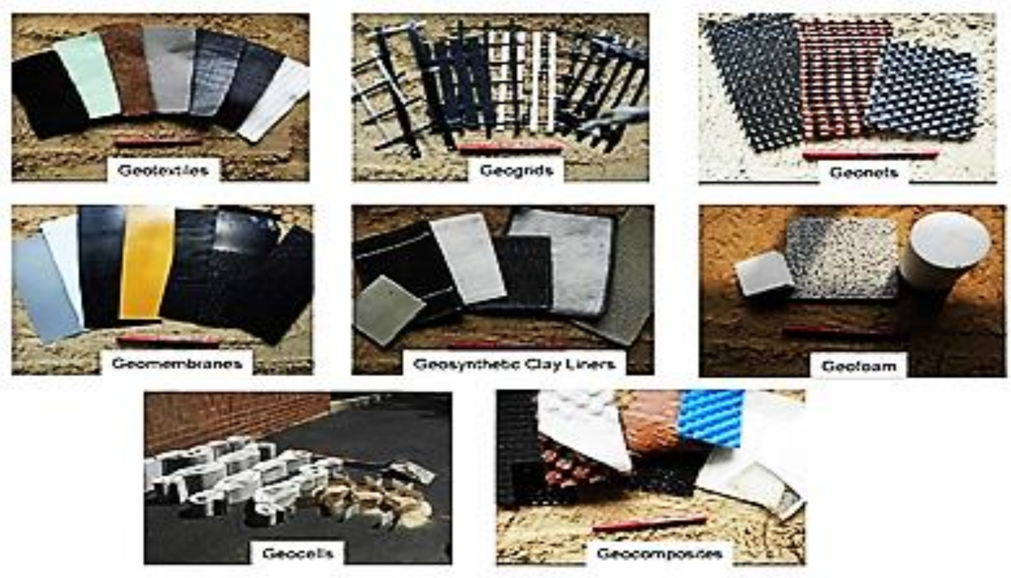

Figure 2: Types of geosynthetics [4].

3.3 Geotextiles

Conventional soil reinforcing technology includes geosynthetic inclusions such as geogrid and geotextiles, appreciated for the appearance, stability, easy construction, seismic effect, and deformation resistance of the earth [18]. The performance of geotextile depends on the depth of placement, and attributes of the soil, and woven geotextiles have been proven to increase the mechanical strength more than non-woven geotextiles [19]. Geotextiles have many applications like separation, reinforcement, drainage, filtration, which makes them of great importance in civil engineering and pavement design [20]. Geotextiles' tensile strength will increase the total soil load resistance and improve the performance of the soil when subjected to load [21]. Several studies have shown the significant effect of geotextile reinforcement in increasing CBR values, especially in clay and sandy soils [22]. Geotextile layers formation and number is important for reducing settlement of the footings and also to increase the load capacity. Geotextiles provide eco-sustainable development and stabilize poor soils thus decreasing energy-intensive excavation and fill materials [23]. Geotextiles have been studied by systematic characterization of types by their manufacturing techniques that determine their design and structural and engineering behavior. The principal taxonomies are woven, nonwoven, knitted and stitched geotextiles, each showing as shown in Fig 3[16].

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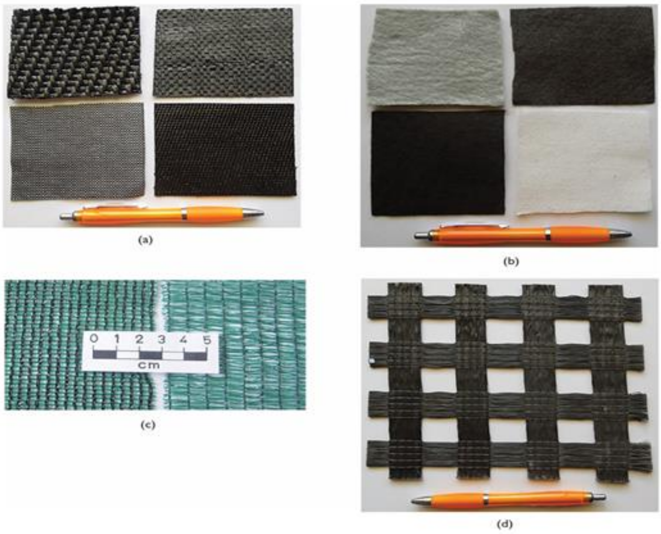

Figure 3: Typical geotextiles: (a) woven geotextile; (b) nonwoven geotextile; (c) knitted geotextile; (d) stitched geotextile.[11] .

3.4 Geogrids

Geogrids are geogrids with interconnected segments in an open grid form and are used primarily for soil reinforcement by means of mechanical interlocking. This means that, according to research, multiple geogrid layers significantly increase tunnel stability by giving better load distribution under axial loads [24]. Geogrids have been shown in experimental setups to significantly improve the unconfined compressive strength (UCS) and California Bearing Ratio (CBR) values of reinforced soil, illustrating its improved load-bearing capability [13]. Geogrids improve soil stability as they allow confinement for reduction in lateral deformations and increase in peak strength. This is notably true on granular soils in which geogrids enable better particle interlocking and friction at the soil geogrid interface [25]. The geometry of the geogrid apertures is also a factor as smaller apertures can provide better interaction of the soil reinforcement, therefore better performance can be achieved [13]. Geogrid shows a better performance of soil stabilization when compared to geotextile [26]. Also ductile, absorbing the energy generated by earthquake activity it captures and dissipates energy which is particularly strong with dynamic loads [27]. Extruded geogrids are described according to the direction of stretching during fabrication which conditions their tensile properties. Uniaxial geogrids and biaxial geogrids that offer similar strengths in both the two principal directions, and triaxial geogrids that give almost identical tensile strength in multiple directions [17] .

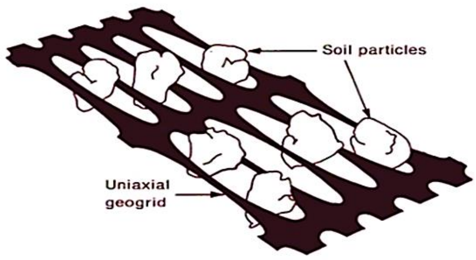

Figure 3: The interlocking mechanism in geogrid-reinforced soil [3] .

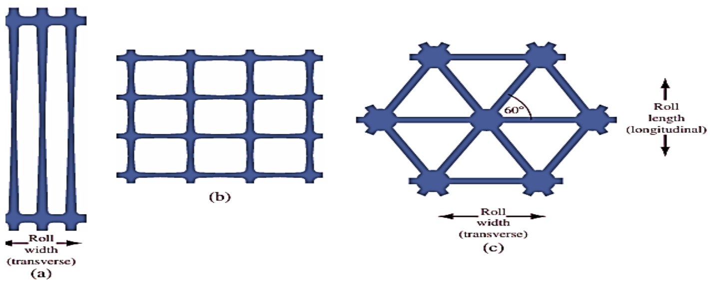

Figure 4: Extruded geogrid: (a) Uniaxial; (b) Biaxial; (c) Triaxial [29].

3.5 Polymeric Geostrip

Polymeric strips (Geostrips) are modern reinforcement elements embedded within soil to create mechanically stabilized systems capable of increasing shear strength, reducing settlement, and improving long-term structural stability. Their use has grown significantly due to both technical and economic advantages over traditional reinforcements.[28]. Polymeric strips typically consist of high-strength polyester tendons encased in a polyethylene sheath, as shown in Fig 5, where the polyester acts as the primary load-bearing component while the sheath provides protection and dimensional stability [29]. Shaking table test reveal that dynamic tensile force along polymeric geostrip are affected by peak ground acceleration and the stiffness of the reinforcement[30]. Research identifies multiple grades such as M25, M37.5, M50, and M65, each providing different tensile capacities that directly influence pullout resistance and reinforced soil performance. [31]. Commercial products are commonly supplied with tensile strengths ranging from approximately 20 to 100 KN as this study, tensile forces of 75KN were used.

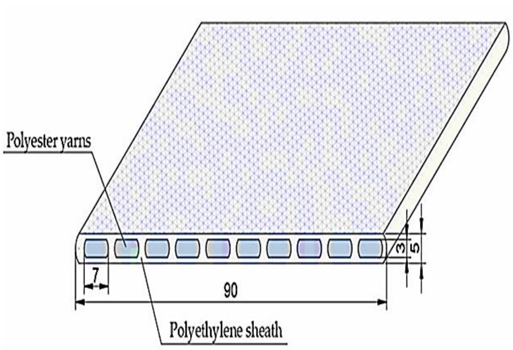

Figure 5. Polymeric geostrip reinforcement strip Herceg et al. (2023).

4. Literature Review

The table 1provides on overview of past research on soil reinforcement types, focusing on the contributions made by researchers regarding their responses.

Table 1 . Historical researches on soil reinforcement types

References	Material	Used
[32]	**Geotextile**	Geotextile layers increase soil shear strength and stiffness modulus
[33]	**Geogrids**	Improves stress redistribution and stability
[34]	**Geotextiles**	have been successfully used to reinforce soft foundation soil
[35]	**Geotextile**	Optimize bearing capacity and increasing plate size decreases the bearing capacity ratio (BCR)
[36]	**Geosynthetics**	Cost-effective, enhance performance, reduce maintenance, and carbon footprint
[37]	**Geotextile**	Soil nets have better reinforcement effects compared to traditional methods
[38]	**Geotextile**	Bio- based geotextile can effectively improve the bearing capacity of weak soil foundations under vertical static loads
[39]	**Geotextile**	Shear strength and deformation resistance increased with geotextile layers
[40]	**Geotextile**	Geotextile reinforcement increases frictional resistance in peat soil
[41]	**Polymeric Geogrids**	Provide actionable information about structural health
[42]	**Geogrids**	Geogrids reinforcement improves soil cohesion while decreasing the internal friction angle.
[43]	**Polymeric Geostrip**	Synthetic polymer can enhance the geotechnical properties of soils
[44]	**Geogrids**	Desirable and effective for sustainable development
[26]	**Geotextile& geogrids**	Geosynthetic layers reduce settlement by 20% and increase bearing capacity.
[45]	**Geotextile**	Woven geotextile significantly enhances the bearing capacity of clay compared to unreinforced soil
[46]	**Geotextile**	Improves soil strength and bearing capacity
[24]	**Geogrids**	Enhances tunnel stability and load distribution and reduces stress concentrations, minimizing collapse risks
[47]	**Geogrids**	Reinforcement significantly enhances the strength of gravelly soils by generating inward friction resistance, which increases surrounding pressure and improves soil strength
[48]	**Geotextile& geogrids**	Enhancing the strength of reinforced soil retaining walls by increasing cohesion
[49]	**Geotextile**	Increases the bearing capacity of reinforced sand significantly
[50]	**Polymeric Geostrip**	Increasing the stiffness of the polymeric strap reinforcement material resulted in decreased horizontal displacement of the reinforced earth wall while increasing dynamic earth pressure
[51]	**Geotextile**	Fibers play a significant role in enhancing soil stability and addressing various geotechnical engineering challenges
[52]	**Geogrids**	Emphasizes the importance of material selection in the design of geogrids for effective soil reinforcement application
[53]	**Geogrids**	Significantly enhance peak strength and reduce lateral deformation in reinforced soil due improved particle confinement

5. Conclusion

Based on the results of this comparative review, it is shown the effectiveness of Mechanical Stabilization Earth (MSE) walls is essentially determined by the mechanical compatibility between soil and reinforcement, the durability of the reinforcement material, and the quality of design implementation. All the reinforcement types such as metallic, geotextiles, geogrids and polymeric geostrips provide a progressive improvement in shear strength, tensile resistance, decrease in lateral deformation and more bearing capacity. Nevertheless, their performance also varies by the stiffness, interaction mechanism and long-term durability characteristics.

Although metallic reinforcements have strong tensile characteristics and are adapted to a high load for large walls, they must be corrosion-resistant and comply with backfill quality control in the long term.

• Geosynthetic construction such as geogrids and geotextiles is effective for high deformation tolerances, particle confinement and good performance for the pullout resistance, providing efficient solutions for static and dynamic loading.

• Geostrips with polymeric form show the property of controlled tensile behaviour and show better performance under cyclic and seismic loading owing their ductility and resistance to environmental degradation.

• Geosynthetic reinforcements provide sustainable benefits such as reduced material consumption, minimizing excavation of weak soils, energy saving in transportation and construction, and recycling of material.Studies show they help decrease carbon footprint and maintenance need over the infrastructure project's lifecycle, making them compatible with sustainable geotechnical design principles. Geotechnically, the review confirm that optimal performance of MSE walls depends on:

1. Adequate reinforcement length (generally ≥0,7 H) to ensure pullout resistance and global stability.
2. Selection of well-graded, free-draining granular backfill to maximize frictional interaction.
3. Proper evaluation of reinforcement stiffness relative to soil stiffness to control deformation.

Consideration of long-term creep approaches rather than purely prescriptive methods.

A multi-criteria analysis considering structural behavior, soil reinforcement interaction, durability, constructability, cost, and sustainability should be the best selection criteria for selecting the right system. Future research projects are to work on long-term monitoring methodologies, life-cycle assessment, and performance based seismic design in order to further optimize reinforcement selection for future infrastructure design.

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