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TECHNICAL PAPER

Sustainable Characteristics of Reinforced Soil Structures – from Ancient Great Walls to Modern GRS Walls

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Abstract
This paper is dedicated to the memory of the Late Dr. Jonathan T.H. Wu in recognition of his outstanding contribution to the field of reinforced soil structures, especially for the geosynthetic-reinforced soil (GRS) structures with close reinforcement spacing. The objective of this paper is to introduce the sustainable characteristics of reinforced soil walls, including carbon emission, durability, ecology, vegetation, and landscape, which are less emphasized in the literature. In this paper, the sustainable/green characteristics of reinforced soil walls, using case examples from the ancient Great Wall to the modern GRS walls, are first discussed. The reasons for the extraordinary durability and stability of the ancient Great Wall, even though it was only reinforced by discontinuous (intermittent) natural materials, are investigated, and the reinforcing mechanism is discussed. A series of limit equilibrium analyses were performed to demonstrate the effect of closely spaced reinforcement on enhancing the system stability (i.e., the factor of safety). The results of this study reveal the reinforcements with close spacing could effectively confine the soil through the friction between the reinforcement and surrounding soil, and generate a moderate apparent cohesion to internally stabilize the soil mass, forming a stable soil-reinforcement composite. The findings above are supported by the pioneering works by Late Dr. Jonanthan Wu, who strongly advocated the superior merits of closely spaced GRS walls. In addition to the

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mechanical performance, several significant advantages of reinforced soil walls compared with traditional reinforced concrete retaining walls are discussed, with particular highlights in the aspects of the sustainable/green characteristics. The reinforced soil structure, especially with wrap-around facing on which vegetation can grow, is one of the vital green/sustainable geotechnology and is worth promoting and developing for the engineering practice worldwide.

Keywords Reinforced soil structure · Geosynthetics · Sustainable characteristics · Discontinuous reinforcement

1 Preface

This paper is written in memory of Professor Jonathan T.H. Wu, who has been an inspiration for our interests in GRS walls. The first author was one of the earliest Ph.D students of Professor Wu's long-term teaching career in CU-Denver. Considering Dr. Wu as a mentor, the first author continues his study and practices in GRS walls as well as other sustainable infrastructures in Taiwan, China, and the USA for almost 40 years. The second author had the privilege to co-author several papers with Professor Wu while Dr. Wu was the Visiting Professor of National Taiwan University, where he obtained his B.S. degree. The third author was Director of Geotechnical Research at Colorado DOT and a long-term friend of Jonathan. Quoted from the preface of Professor Wu's new textbook Geosynthetic Reinforced Soil Walls: "I must acknowledge Bob Barrett, a true innovator of reinforced soil technology, with whom I have had the privilege to work on many face-exploring projects over the past three decades". The fourth and fifth authors are the Ph.D students of second and first authors.

Dr. Jonathan Wu's contributions to GRS theory and practice over several decades are indeed substantial, and he will be fondly remembered and greatly missed by all of us.

2 Introduction: Sustainable/Green Engineering

To minimize or avoid severe problems due to climate change, the emphasis on sustainable elements such as durability, energy saving, ecology, and carbon reduction has become a crucial issue. While "green" architecture has been in vogue for more than 30 years, sustainability issues for civil infrastructure projects are rarely discussed. The so-called sustainable development refers to the development that meets the needs of contemporary people without compromising the needs of future generations (WCED 1987).

There seems to be no uniform definition of green engineering. The authors define it as an engineering project or system that is environmentally friendly, with minimal environmental damage over their life cycle (Chou 2019).

In most cases, green engineering and sustainable engineering have similar goals, ideas, methods, and even results, so the two terms are often mixed-used. Liu et al. (2019) elected to combine sustainable and green concepts in bridges, slope/retaining walls, tunnels, and building construction. The sustainable factors considered include safety, durability, efficiency, ecology, environmental protection, carbon reduction, landscape, energy saving, waste reduction, humanities, and creativity (Liu et al. 2019; Liu 2020).

The reinforced soil walls, such as mechanically stabilized earth (MSE) wall and geosynthetic-reinforced soil (GRS) wall, fit the criteria of sustainable/green infrastructures. This paper discusses the sustainable characteristics of reinforced soil structures, from the ancient Great Wall in China to the modern GRS wall, especially with the wrap-around facing.

3 Bird Nest and The Great Wall—the Originators of Sustainable Reinforced Soil Structures

Interestingly, the reinforced soil concept was invented by the birds (Fig. 1). Smart birds not only know how to mix soil with tree branches, straw, etc. to build the nest structure but also know how to use its saliva in the soil to increase cohesion. Moreover, the birds probably understand structural mechanics; they know to build the nest in a spherical shape to take advantage of the arch effect.

The Great Wall, built in the Han Dynasty (202 BC–220 AC) near Yangguan Pass in northwestern China, is a typically reinforced embankment (Figs. 2 and 3). The reinforced soil structures were constructed by compacted yellow loess sandwiched by discontinuous (intermittent) natural reinforcing materials, such as reed, willow, and branch (Fig. 4). The spacing of the reinforcement is about 40 cm, and the wall/embankment is very steep with a slope angle of 70 degrees.

After 2000 years of weathering, some sections of the reinforced soil structures have remained with several meters high (Fig. 2). Another Great Wall, built in the Ming Dynasty (1368–1644 AC), in Black Mountain, Gansu Province, is shown in Figs. 5 and 6. This reinforced soil structure was built by losses sandwiched by rock pieces. This Great Wall is also called the cantilevered wall, and the layers of rock pieces are separated by about 40 cm, center to center.

From both sections of the Great Wall, we observed the fact that unlike the manmade reinforcement, the natural reinforced materials are discontinuous (intermittent) and are relatively weak in tensile strength. However, the backfill (loess) is somewhat cohesive and well compacted. These observations and findings indicate:

Fig. 1 Birds are the inventor of reinforced soil structures

Fig. 2 The Great Wall of the Han Dynasty in Yangguan Pass, China, an ancient reinforcing soil structure

(1) The conventional reinforced wall design assumes a potential failure wedge, and the reinforcement extending beyond the failure wedge acts as frictional quasi-tiebacks to help the potential failure wedge (Wu 2019). The quasi-tieback requires continuous reinforcement material, such as steel and geosynthetics, but the natural reinforcement is not continuous. Therefore, the quasi-tieback theory may not be applicable in reinforced Great Walls. Instead, the mechanism of apparent cohesion due to natural reinforcement

Fig. 3 A close look of a profile of the Reinforced Great Wall of the Han Dynasty in Yangguan Pass (spacing of reinforcement is about 40 cm)

Fig. 4 Natural reinforcing materials for Great Wall: reeds, willows, and branches

material is likely occurring. The spacing between the reinforcement is about 40 cm for both the Great Wall sections, and this narrow spacing does provide adequate interaction between the soil and the reinforcement. The reinforcement would increase the lateral confinement of soils and hence generate apparent cohesion, no matter what the soils are.

(2) The on-site loess, i.e., windblown silt with some cohesion, was compacted for building the wall. Due to the arid climate, the cohesion has been maintained for 2000 years, perhaps partially due to cohesive backfill in nature, partially due to matrix suction of unsaturated soil, and partially due to apparent cohesion caused by reinforced materials.

4 Mechanism of Discontinuous Reinforcement of the Great Walls

Reinforced materials evolved from natural materials such as reeds, willow, branches of the ancient Han Great Wall, and rock blocks of the cantilevered Great Wall to artificial materials such as steel sheet, steel mesh, geotextile, and geogrid. Currently, geogrid is the prevalent

Fig. 5 The Great Wall of the Ming Dynasty in Black Mountain, Gansu Province

Fig. 6 A close look of Reinforced Great Wall in Black Mountain: the wall was built with loess sandwiched by rock pieces (spacings of reinforcement are about 40 cm)

reinforcing material. The evolution of materials keeps pace with times, but the principle and purpose are the same. The reinforcing mechanisms include (Wu 2019):

(1) Increase lateral confinement of soil
(2) Effect cohesion in granular fill
(3) Suppress dilation of soil
(4) Increase compaction-induced stress of soil
(5) Restrain lateral deformation of soil
(6) Stabilize potential failure wedge of a soil structure (i.e., serving as quasi-tiebacks)
(7) Preserve the integrity of soil by preventing loss of soil particles
(8) Accelerate dissipation of pore water pressure in low permeability fill
(9) Improve the ductility of soil

In addition to the above mechanisms, the authors would indicate that reinforcements also make up the lack of tensile strength in soil, and form a composite soil structure similar to reinforced concrete (RC). In the RC structure, the steel bar bears tension and the concrete sustains compression, while in the reinforced soil structure, the reinforcing material bears tension and the soil sustains compression. The friction between the soil and the reinforcing material is provided by the soil weight, which can resist the lateral earth pressure and reduce the lateral deformation of the soil. Although the reinforcing materials of the Han Great Wall and the cantilever Great Wall are not continuous (Figs. 2, 3, 4, 5, and 6), they do provide the friction force with the soil and avoid the lateral displacement of the soil. This mechanism is equivalent to provide an apparent confining pressure and increase the shear strength (Yang 1972) or create an apparent cohesion (Schlosser and Long 1974; Wu 2019).

Figure 7 shows the reinforcement mechanism and apparent cohesion of cohesive backfill by using the concept of Mohr circles/envelopes. If we perform triaxial tests for cohesive soil, the Mohr circles of the original (unreinforced), and the reinforced soil are represented by MC1 and MC2, respectively, in Fig. 7. The increased cohesion is called the apparent cohesion, c_a. Due to friction between the reinforcement and soil, the original soil is restrained

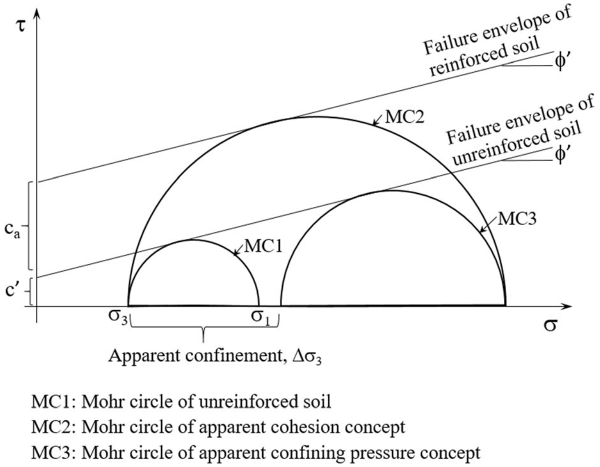

Fig. 7 Mechanism of the increase in shear strength of cohesive soil due to reinforcement

and therefore increases an apparent confining pressure, and hence reaches a more substantial bearing pressure, as indicated in MC3. Note that the apparent cohesion and the increased confining pressure mechanisms do not require continuous reinforcement; therefore, the intermittent reinforcements (such as reed, willow, branch, and rock pieces) are also applicable.

The mechanisms of apparent cohesion and apparent (increased) confining pressure are interrelated. By equating the shear strength of two mechanisms, the apparent cohesion of a reinforced soil structure can be determined as follow (Wu 2019):

$$c_a = \frac{T_{ult}}{2S_v}\sqrt{K_p} \tag{1}$$

where

c_a = apparent cohesion generated by reinforcement
T_{ult} = tensile strength of reinforcement
S_v = vertical spacing of reinforcement
K_p = coefficient of Rankine passive earth pressure

A series of limit equilibrium (LE) analyses was performed to investigate the aforementioned reinforcing mechanism and to compare the reinforcing effect of continuous and discontinuous reinforcement quantitatively. The Great Wall, as discussed previously, is used as examples. In the LE analyses, the Great Wall is modeled as a reinforced embankment consisting of compacted loess sandwiched with layers of natural reinforcement. The soil has unit weight $\gamma = 20$ kN m^3, and shear strength properties of cohesion $c = 20$ kN/m^2, and friction angle $\phi = 20°$. The natural reinforcement has the tensile strength of $T_{ult} = 5$ kN/m and has a vertical spacing of $S_v = 40$ cm, and horizontal spacing of 10 cm when the discontinuous reinforcement is considered. According to Eq. 1, the apparent cohesion of the natural reinforcement (reed, willow, branch) can be obtained as 9 kN/m^2 by Eq. 1.

By using the simplified Bishop method with circular failure surfaces, with the apparent cohesion, we calculate the safety factor of the sliding for composite material as FS = 1.95 (Fig. 8). It is located somewhere between the unreinforced loess (FS = 1.36 in Fig. 9) and a

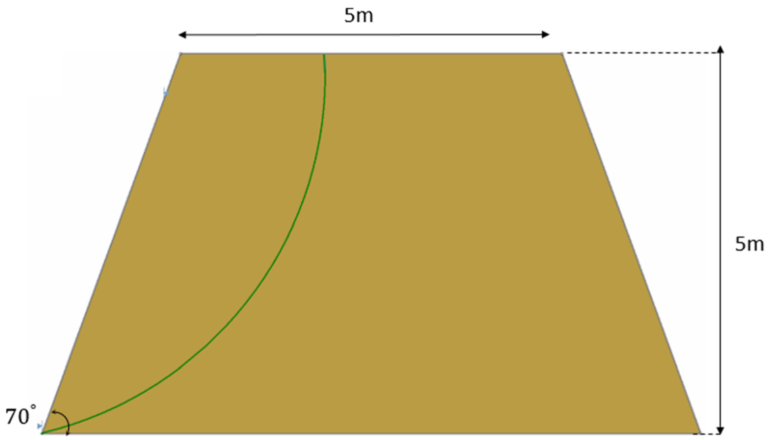

Fig. 8 Potential failure plane of the Han Great Wall, providing the reinforcements are taken into account as apparent cohesion (FS = 1.95)

pseudo condition that the natural reinforcement is continuous (FS = 2.07 in Fig. 10). The results indicate that the benefit of discontinuous reinforcement is not far away from that of continuous reinforcement, providing the apparent cohesion theory is reliable.

If we ignore the apparent cohesion and calculate the safety factor using the random search method (i.e., the failure plane avoids the natural reinforcement), a safety factor of FS = 1.48 (Fig. 11) is obtained. This finding indicates that if apparent cohesion is not taken into account, the benefit of discontinuous reinforcement is limited when using the traditional slope stability analysis approach.

The above analyses demonstrated that the role of discontinuous reinforcement is valid, although not substantial in tensile strength, providing the spacing of reinforcements are close. This apparent cohesion mechanism is evidenced by

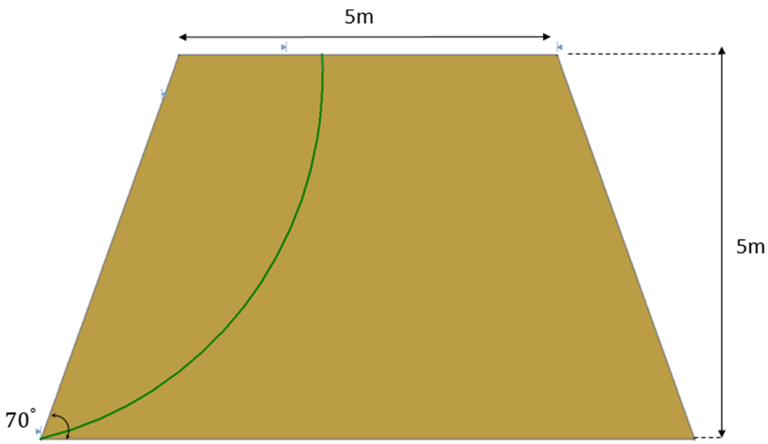

Fig. 9 Potential failure plane of the Han Great Wall, assuming the reinforcements were not installed (FS = 1.36)

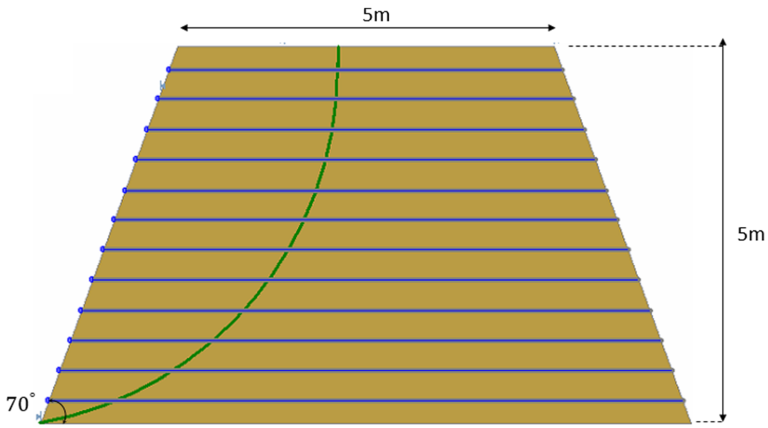

Fig. 10 Potential failure plane of the Han Great Wall, assuming the reinforcements were continuous (FS = 2.07)

the fact that ancient Great Walls have maintained their original geometry in the arid area for 2000 years.

5 Comparison of the Conventional Reinforced Concrete Wall and Reinforced Soil Wall

The reinforced concrete wall dominated the wall market for several decades until the appearance of reinforced soil (MSE, GRS) wall. We compare the reinforced soil wall with the conventional reinforced concrete wall and summarize it in Table 1.

The above characteristics may explain why the reinforced soil walls, no matter the ancient Great Wall or modern GRS wall, are more sustainable than the conventional concrete wall.

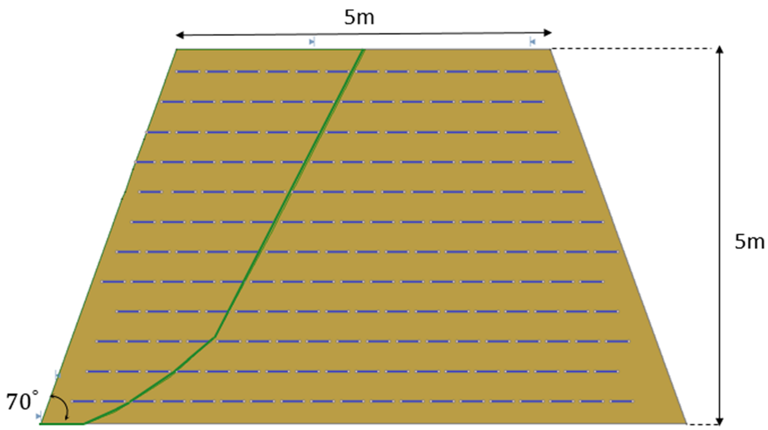

Fig. 11 Potential failure plane of the Han Great Wall, the reinforcements are discontinuous, and the apparent cohesion is not taken into account (FS = 1.48)

Table 1 Comparison of the reinforced soil wall with reinforced concrete wall

Comparison item	Reinforced concrete (RC) wall	Reinforced soil (MSE, GRS) wall
Cost	The cost is higher if the wall is taller than 5 m. Unit price increases significantly with height	The cost is competitive if the wall height is lower than 5 m. If the wall is taller than 5 m, the price would be lower than the RC wall.
Appearance	Concrete surface	Vegetated (wrap-around surface) or unique blocks (segmental facing)
Design concept	External stability, and need a facing to resist bending moment.	Internal stability, part of the lateral earth pressure are balanced by friction between the reinforcement and soil.
Earthquake (EQ) resistance	Low EQ resistance. The concrete facing and soil have different periods and frequencies and may cause separation between them during the earthquake.	High EQ resistance. The reinforced material has strong tensile resistance; therefore, it can avoid tensile and shear cracks in backfill. The soil and reinforcement composite has excellent seismic resistance, and the friction resistance may prevent the separation between reinforcement and surrounding soil. When using the wrap-around facing wall, because there is no concrete facade, the earthquake would not cause separation between the wall facade, connection, and backfill.
Ability to tolerate settlement	Generally, 5.0 cm is the maximum allowable settlement. Since the facade is rigid, only little differential settlement is allowed.	A settlement of less than 30 cm is acceptable. Although the foundation soil may settle a substantial amount, the differential settlement can be reduced significantly due to the leveling effect of reinforcement (Fig. 12). Besides, the preloading method may eliminate the possibility of subsidence after construction.
Drainage system	The drainage layer and pipes are usually installed immediately behind the wall,	The drainage layer is placed between the backfill and the undisturbed soil and connected to the bottom, to avoid softening of the backfill caused by seepage due to rainwater infiltration.
Carbon emission	Carbon dioxide emission is relatively large due to concrete/steel production, transportation, and wall construction.	Carbon dioxide emission is about 1/5 of the counterpart of the RC wall in the life cycle of the wall. Additionally, if the wrap-around facing is used, the plant photosynthesis can balance the carbon dioxide emitted during the material production and construction process. It may achieve carbon-neutral or even negative carbon emissions.

6 Sustainable Characteristics of Modern GRS Walls

Similar to ancient Great Walls, the performances of modern GRS walls are much better than predicted by conventional analytical models. The late Professor Jonathan Wu and

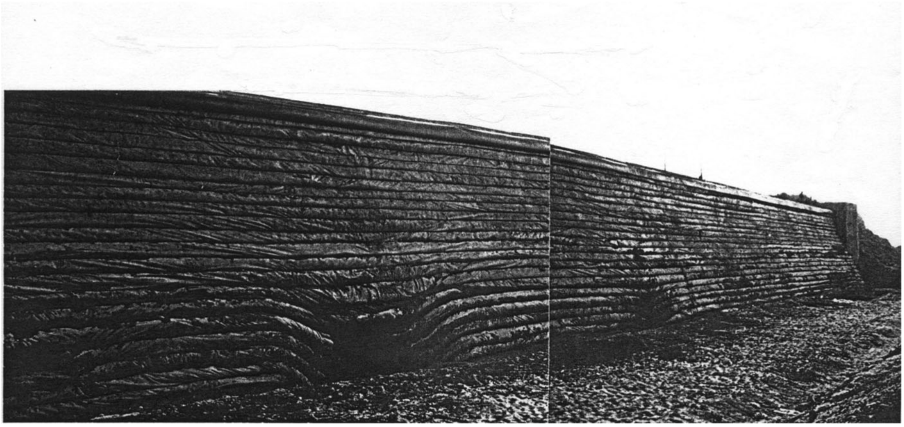

Fig. 12 A significant differential settlement does not affect the performance of a geotextile-reinforced soil wall in southern Taiwan (courtesy of Shannon H. Lee)

the first author of this paper were principals in the famous Denver test walls. The test results of the Denver walls demonstrated that the bearing pressure (failure surcharge) of the geotextile-reinforced walls, i.e., 29 psi (= 200 kPa), is much higher than the predicted values from 0 to 7.3 psi (= 0~50 kPa) by various design methods (Chou 1992; Claybourn and Wu 1992; Wu 2019).

Curiously, the performance of the Denver test wall with clayey backfill is better than its counterpart with sandy backfill (Chou 1992). This finding seems to contradict most of the design guidelines; i.e., granular material is required or preferable for backfill of reinforced soil walls. The authors believe that, if we can prevent water infiltration, cohesive backfill could be beneficial for bearing pressure and slope stability, which is agreeable with the fact that the Great Wall backfill is cohesive. In fact, cohesion does increase the safety factor in our calculation, as discussed above.

Unlike the traditional unreinforced wall, lateral earth pressures inside the GRS wall vary from the facing to the section beyond the reinforced zone. Chou and Wu (1993) conducted a study to investigate the behavior of a GRS wall on a 0.3-m reinforcement spacing by the finite element analyses. The lateral pressures along the three sections of a GRS wall were examined: (1) lateral earth pressure/stress against the wall facing; (2) lateral earth pressure behind a reinforced soil mass; and (3) lateral stresses within the reinforced soil mass along the plane of maximum reinforcement.

Figure 13 indicates that the earth pressure against the wall facing, the smallest of the three, is nearly constant with depth except near the base of the ground, where it is constrained to deformation due to friction at the ground base. The earth pressure behind the reinforced soil mass, the largest among the three, is rather close to the Rankine active earth pressure. The earth pressure along the plane of maximum reinforcement tensile loads is somewhere between the other extreme situations (Chou 1992; Chou and Wu 1993). This study supports the merits of reinforced soil structure since the earth pressure inside the reinforced zone is smaller than the earth pressure of the traditional concrete wall, because of the friction between the reinforcement and soil balances part of the Rankine earth pressure.

As shown in the Glenwood Canyon, Colorado geotextile test wall (Fig. 14), the front-facing of the wall was removed but the wall remained stable for 5 years due to

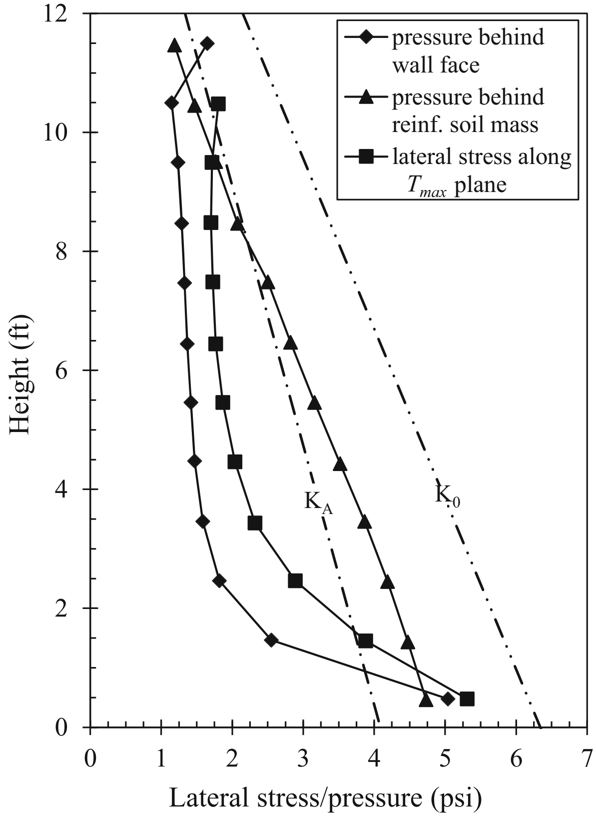

Fig. 13 Lateral earth pressure along three different sections of the Denver Test Wall, based on finite element analyses (redrawn from Chou 1992; Chou and Wu1993)

near-zero earth pressure at the front face. The sidewall (longitudinal direction) also stood for years without collapse because of reduced earth pressure due to reinforcement. The wall was taken out of service with no evidence of distress.

Fig. 14 A cut of the Glenwood Canyon geotextile test wall along I-70 (the front-facing was removed, but the wall has been stable for many years before demolition)

Currently, geogrid is the most popular reinforcement material for any MSE or GRS structures. Geogrid is a plastic material, which at first sight is not green material. However, due to the high tensile strength and durability of geogrid and its unique characteristics, i.e., allowing grass to grow in the grid, if the wrap-around facade is used, it can form a green and sustainable structure (Fig. 15). In Taiwan, as well as some other humid countries, the wrap-around GRS wall (or slope if the slope is less than 70 degrees) is the standard hillside retaining structures. Voids between the geogrids and the sandbags behind the geogrids offer a perfect habitat for small animals and vegetation, and therefore enhance biological diversity (Chou et al. 2018), as shown in Fig. 16.

Additionally, the use of geosynthetics to reinforce structures instead of traditional RC structures can reduce carbon emissions. Photosynthesis creates plant matter out of carbon dioxide and water. In the life cycle of the wall, the plant photosynthesis can balance the carbon dioxide emitted during the material production and construction process. It can achieve the goal of zero emissions (that is, carbon neutral), or even negative carbon emission. Hence, the reinforcement soil wall with vegetation is a sustainable and green engineering approach.

As shown in Table 2, a significant feature of the geogrid wall is its low carbon emission. Compared with the RC retaining wall, its carbon emission is only about 1/5 during the project life, including material manufacturing, transportation, construction, and operation (Heerten (2009); Heerten (2012); NCKU (2009) Tsai et al. (2014); Chan (2010); Chou and Cheng (2015); Chan, T.J (2010).

Compared with conventional reinforced concrete walls, reinforced soil structures, especially geogrid-reinforced soil structures with wrap-around facing,

Fig. 15 Typical geogrid-reinforced walls with the wrap-around facings in Taiwan. The geogrids allow grass to grow through the grid

Fig. 16 Geogrid-reinforced wall with wrap-around facing provides an excellent habitat for small animals and encourages biological diversity

have shown sustainable advantages in safety, cost efficiency, reliability, ecology, landscape, and carbon emission reduction. Many examples in Taiwan and other countries have been proved to be sustainable and green projects (Chou and Cheng 2015; Chou 2019).

7 Conclusions

To face severe problems due to climate change, the emphasis on sustainable elements such as durability, energy saving, ecology, and carbon reduction has become a new trend of global civil engineering, and retaining structures are no exception. The reinforced soil structure, especially for wrap-around facing on which vegetation can grow, is one of the vital technologies in green/sustainable civil engineering and is especially adaptable to humid areas of the world.

This paper discusses the green characteristics of reinforced soil walls, including the ancient Great Wall and modern GRS wall. The discontinuous (intermittent) natural reinforcements of the Great Wall also confine the soil through the friction between the reinforcement and surrounding soil. This

Table 2 Comparison of carbon emission of gravity type, cantilever type RC wall, and wrap-around facing GRS wall in the life cycle (unit: ton). *source:* Chan, T.J (2010)

Type	Gravity concrete wall	RC cantilever wall	Geogrid-reinforced soil wall
Carbon emission during production, transportation and construction	322,196	147,830	43,429
Carbon emission during service	-	-	− 53,500* (surface vegetation)
Total	322,196	147,830	− 10,071

*The carbon emission reduction period was assumed to be 10 years confinement can generate moderate apparent cohesion, which increases the safety factor against the sliding failure. Comparison between the reinforced soil wall and the traditional RC retaining walls indicates that the former offers several significant advantages over the latter. The merits not only related to safety and economy but also include sustainability factors such as carbon emission, durability, ecology, and landscape.

The reinforced soil structure has been widely proved, from the ancient Great Wall to modern geosynthetics-reinforced soil wall, to be green/sustainable geotechnology, which is worth promoting as the technology of choice.

Authors' Contributions The first three authors conceived of the presented idea. The last two authors performed the computations. The first author supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

Data Availability The datasets presented in this study are available from the corresponding author on reasonable request.

Compliance with Ethical Standards

Competing Interests The authors declare that they have no competing interests.

Ethical Approval and Consent to Participate Not applicable.

Consent for Publication Not applicable.

Code Availability Not applicable.

Notation

Basic SI units are given in parentheses c, cohesion (Pa); c_a, apparent cohesion (Pa); K_p, coefficient of Rankine passive earth pressure (dimensionless); S_v, vertical spacing of reinforcement (m); T_{ult}, tensile strength of reinforcement (N/m); ϕ, friction angle (°); γ, unit weight (N/m^3)

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