Failure Mechanism and Behavior of Two-Tiered Bamboo Reinforced Mechanically Stabilized Earth Retaining Wall Subjected to Isolated Footing Load

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Abstract. Tiering of mechanically stabilized earth (MSE) retaining walls have several advantages over its single-tier counterpart, specifically reducing tensile stresses experienced by lower reinforcements. Bamboo reinforcements were investigated to determine if it was a viable economic and sustainable alternative. With the use of the finite element software RS2, a numerical analysis was conducted to verify the suitability of bamboo reinforcements in a two-tiered MSE wall subjected to an isolated footing load. A displacement-based approach on the footing was conducted to evaluate the wall's response at the serviceability limit state of the varied reinforcements. Moreover, the viability of bamboo reinforcements was determined by comparing how they performed at the allowable and ultimate settlement of the footing against commercially available reinforcements. In terms of serviceability, the bamboo reinforcements were at par with the chosen commercially available reinforcements since none of the bamboo reinforcements yielded from the 25 mm allowable settlement of the footing proving that it can be used as a support for resisting vertical loads from a footing in a two-tier MSE wall. The reinforcement properties, specifically the tensile modulus and ultimate tensile strength, did not affect the failure plane developed which was log-spiral, at least for the geometry and properties of the wall in this study. However, reinforcements with higher tensile moduli, including bamboo, exhibited a rapid failure after a small footing settlement from initial reinforcement yielding to wall failure.

Keywords: two-tier MSE wall · isolated footing · failure mechanism · bamboo reinforcement

1 Mechanically Stabilized Earth Retaining Wall

1.1 Tiered MSE Walls

MSE walls are widely used due to their advantages under static and dynamic loading, cost-effectiveness, ease of construction, and aesthetics. These are built with soil reinforcements which increase the load-bearing capacity and overall stability of the

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retaining structure [1]. It is also able to sustain large horizontal and vertical displacements. Increasing the wall height increases the tensile stresses experienced by the lower layers of reinforcements which requires decreasing the spacing between reinforcements to reduce tensile stresses at the bottom of the wall [2]. Consequently, this raises the cost of construction due to the necessity for more reinforcements. Tiering of walls addresses this issue as it is able to alleviate the tensile stresses on lower reinforcements.

1.2 Footing on Retaining Walls

Unlike conventional geosynthetic reinforced walls which are typically used for earth retention, geosynthetic reinforced soil retaining walls for bridge abutments or any other applied loading from an overlaying structure are subjected to higher surcharge loads. Thus, the allowable bearing pressure and resulting deformations are crucial considerations for design [3]. Producing a proper design for support of footings on walls, such as bridge abutment design, provides a cheaper alternative compared to conventional pile-supported design and is able to reduce differential settlements between bridge and approach embankments [4].

1.3 Bamboo Reinforcements

Bamboo is an abundant plant in the Philippines, which is easily accessible and versatile with numerous possible applications. It is considered to be a traditional source of construction materials, wherein five bamboo species in the Philippines have been documented for empirical use in construction [5]. Recently, sustainable and natural materials such as bamboo drew the attention of soil engineers since it is deemed to be very effective as a reinforcement because of its mechanical and engineering properties [6]. Due to its easy workability, it is simple for bamboo to be modified for a specific purpose such as soil reinforcements weaved as grids, meshes, and mats. Different geometries, configurations, and forms of bamboo reinforcements are possible as presented earlier in the aforementioned studies.

2 Model Simulation

2.1 Test Cases

The behavior and failure mechanism of a two-tiered bamboo reinforced mechanically stabilized earth retaining wall subjected to an isolated footing load was evaluated using a numerical approach by utilizing the 2D finite element program RS2 with respect to the Mohr-Coulomb constitutive model for the soil backfill. The viability of bamboo reinforcements was determined by analyzing their performance at allowable settlement (serviceability limits) and ultimate settlement against commercially available reinforcements offered in RS2 namely ACEGrid GG-40-I, Maccaferri Paragrid 30/5, and TenCate Miragrid GX 110/30. The bamboo reinforcement properties were taken from a study by Ahirwar and Mandal [7].

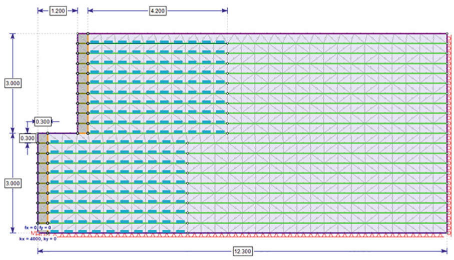

Fig. 1. RS2 base model

2.2 Model Creation

The main reference for the MSE wall construction procedures and material properties is from Huang et al. [8]. It investigated the influence of constitutive soil models on the predicted response of reinforced soil walls during construction and surcharge loading. The base model is a 6-m high MSE wall with a 3-m lower tier and upper tier height as shown in Fig. 1. It was constructed with 45 stages of bottom-up construction for the trials with a footing displacement of 1-inch. The first 20 stages were for the wall construction with an 8 kPa compaction load while the remaining 25 stages were for surcharge loading applied from the isolated footing placed on top of the MSE wall. Additional stages were included for surcharge loading for the model to fail depending on the maximum allowable footing load displacement until the reinforcements yield and show a clear failure surface. Lastly, the reinforcement length and spacing were designed to conform with FHWA [9] standards.

2.3 Footing Geometry and Load Application

The footing used that acted as the surcharge load on the MSE wall was a rigid isolated footing. The surcharge load was applied as displacement controlled with uniform settlement along the bottom of the footing. Its width was 1.5 m and was located 1.65 m from the facing of the upper tier measured until the leftmost edge of the footing for the base model. For the test cases simulated until allowable settlement, a set displacement of 1-inch was programmed for the footing as suggested by Terzaghi [10]. Therefore, the service state or only until the allowable settlement of these models is being tested and analyzed. For the test cases that ran until failure, additional stages were added with 10 mm footing displacement per stage to find the displacement of the footing that caused reinforcement yielding and formation of the failure surface.

3 Allowable Settlement

3.1 Facing Displacement

Bamboo reinforcements were observed to have the second least maximum facing displacement, which was due to the high tensile modulus of the bamboo reinforcements as seen in Fig. 2. A higher tensile modulus requires more force for the material to deform

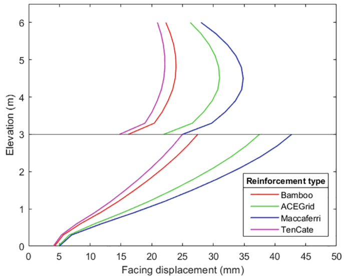

Fig. 2. Facing displacement at allowable settlement

since it is less flexible compared to those with a lower tensile modulus. For serviceability limits, the facing displacements were ranked according to their tensile moduli, with the highest tensile modulus garnering the least displacement. However, a higher tensile modulus does not automatically make the reinforcement stronger since the ultimate tensile strength will dictate the yielding point of the material. Additionally, not having a displacement greater than 50 mm which is the maximum allowable facing displacement prescribed by FHWA was satisfied by the bamboo reinforcements justifying that bamboo reinforcements can possibly be a viable alternative to their commercially available counterparts.

3.2 Shear Strain

Less strains were observed from the contour plots of the bamboo and TenCate reinforcements in Fig. 3 which was due again to their high tensile moduli. Consequently, greater strains developed for the ACEGrid and Maccaferri reinforcements because of their low tensile moduli. No yielding of reinforcements occurred for the allowable settlement of the footing. Moreover, no clear failure surface was defined which suggests the wall did not fail during the 1-inch settlement of the footing. Thus, bamboo reinforcements were considered to be at par with the tested commercially available reinforcements since they were able to withstand the 1-inch allowable settlement of the footing. From a serviceability standpoint, bamboo reinforcements are suitable to be used as a support in an MSE wall to resist vertical loading from an isolated footing.

3.3 Reinforcement Load

Bamboo garnered the second highest reinforcement load as observed in Fig. 4 which was due to its higher tensile modulus compared to ACEGrid and Maccaferri. Based on plots per layer of reinforcement, all cases had similar trends but just differ in the magnitude of load carried per reinforcement. Hence, changing the properties of the reinforcements (at least for the 4 cases tested in this study), specifically its tensile modulus and ultimate tensile strength, do not affect the propagation of the load carried by the reinforcement, just the magnitude of the load carried.

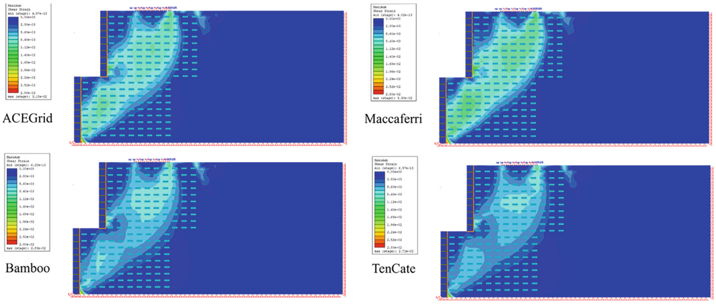

Fig. 3. Maximum shear strain contour plots

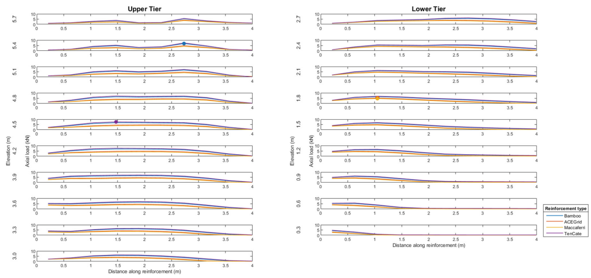

Fig. 4. Reinforcement loads

4 Ultimate Settlement

4.1 Initial Yielding of Reinforcements

The red portions in the reinforcements in Fig. 5 denote the reinforcement elements that yielded. Reinforcements with higher tensile moduli (bamboo and TenCate) tended to yield multiple layers simultaneously. During the first stage of the footing settlement which caused the reinforcement failure, the yielded reinforcements already reached the lower tier. Meanwhile, reinforcements with lower tensile moduli (ACEGrid and Maccaferri) only had yielded reinforcements at the top 3 layers of the wall. The strains were already concentrated where the reinforcements failed for bamboo and TenCate while the strains for ACEGrid and Maccaferri were still distributed throughout the wall.

4.2 Wall Failure

Development of the log spiral shape which indicated the failure of the model occurred at a footing displacement of 130 mm and 210 mm for bamboo and TenCate, respectively, as seen in Fig. 6. This gave a 20 mm footing settlement difference only for both reinforcements from initial yielding to development of the failure surface which somewhat exhibits a brittle failure of the reinforcements with higher tensile modulus due to the sudden failure of the model after a small footing settlement. Failure occurred at a footing displacement of 200 mm for both ACEGrid and Maccaferri. This resulted in a 60 mm

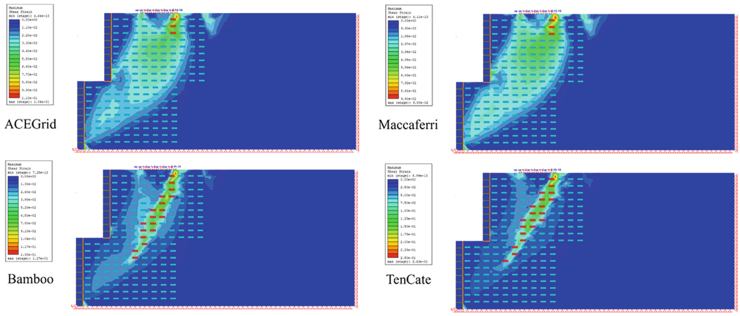

Fig. 5. Maximum shear strain contour plots and yielded reinforcements

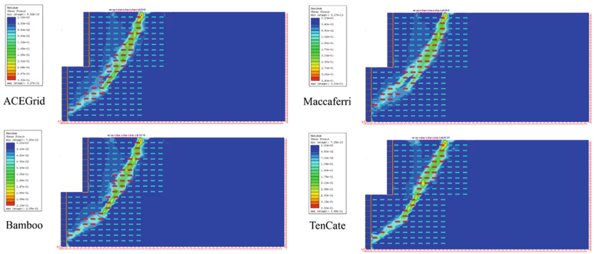

Fig. 6. Failure surfaces and yielded reinforcements

and 70 mm settlement difference from initial yielding to the development of the failure surface.

4.3 Performance of Bamboo Reinforcements

Initial bamboo reinforcements yielded at the lowest reported footing displacement and reached the ultimate settlement at the lowest reported footing displacement as seen in Table 1. Bamboo reinforcements may have the lowest gap between the values but when comparing the difference of the ultimate settlement to the allowable settlement of 1 inch, the bamboo generated more than a 100 mm difference which is four times the displacement compared to the allowable settlement.

The average difference of footing displacement at initial yielding to ultimate settlement for high tensile modulus (bamboo and TenCate) was about 14% while for low tensile modulus (ACEGrid and Maccaferri) was about 48%. Reinforcements with lower tensile modulus almost had 1.5 times greater of a difference compared to reinforcements with lower tensile modulus. Hence, reinforcements with lower tensile modulus are generally safer since there is more allowance before the structure fails. Larger footing settlement must first occur after initial reinforcement yielding before failure.

Table 1. Reinforcement yielding at footing settlements

Reinforcement	Tensile Modulus (kN/m)	Ultimate Tensile Strength (kN/m)	Footing Settlement at 1st Reinforcement Yielding (mm)	Ultimate Settlement (mm)
Bamboo	865	28	100	130
ACEGrid GG-40	1049.52	51.853	140	200
Maccaferri Paragrid 30/5	444.44	25.429	130	200
TenCate Miragrid GX 110/30	333.33	20.025	190	210

5 Conclusions

Reinforcements with higher tensile modulus (bamboo and TenCate) exhibited somewhat of a brittle failure due to its sudden failure after a small footing settlement from initial reinforcement yielding. The opposite was true for reinforcements with smaller tensile modulus (ACEGrid and Maccaferri) which yielded slower as footing settlement depth increased. Generally, reinforcements with lower tensile modulus are safer since there is more allowance before the wall fails. All reinforcement types developed a log-spiral shape of the failure plane. Reinforcement properties, specifically the tensile modulus and ultimate tensile strength, did not affect the failure mechanism that occurred, at least for the geometry and properties of the wall in this study.

Initial bamboo reinforcements yielded and reached ultimate settlement at the lowest reported footing displacement. Nonetheless, bamboo reinforcements were able to withstand the allowable settlement without any yielding and no development of failure surface. From a serviceability standpoint, bamboo reinforcements are viable to be used as a support for resisting footing loads since the bamboo garnered more than a 100 mm difference from allowable settlement to ultimate settlement.

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