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Numerical Analysis of Bamboo Piles for Slope Stability

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Abstract. Uncontrolled population growth and disorderly urban development have witnessed severe human settlement damages worldwide. Extreme natural phenomena consequence of abrupt climate change such as intense rainfall index increment has provoked landslides incidents hardly to ignore over the last decades. Piles made of conventional materials such as timber, steel and concrete have traditionally been used for slope stabilization in order to prevent landslides incidents. The present paper studies the use of a non–conventional material, the bamboo of the Dendrocalamus Giganteus (DG) species as bamboo-pile for slope stability, to become a more environmental friendly pile material alternative. Its dimensions and more importantly its mechanical properties, besides its geographical availability and greenhouse gases absorbing capabilities make it suitable for an ecologic slope stabilizing pile element. Finite Element Method (FEM) analysis of bamboo-pile was developed on PLAXIS software for 2 and 3 dimensional tests. An unstable slope model condition was reinforced with bamboo-piles to observe the soil-pile interaction and evaluate the safety factor (SF). The results showed that the capabilities of the bamboo-piles are a promising effective alternative for slope stability.

Keywords. Slope stabilization, bamboo-pile, non-conventional materials, finite elements method.

1. Introduction

Unplanned human settlements that are mostly a product of population growth and uncontrolled urban development commonly becomes landslides vulnerable places (Figure 1) [3, 9]. Climate change and intense anthropogenic activities tend to increase the frequency and the magnitude of these events. Countries worldwide that suffer this type of event unfortunately experience economic issues due to damages on infrastructure, without to mention the hard time the victims have to face [5, 10, 12, 13].

Some slope stabilizing methods are rock-bolts, retaining walls, weight structures and piles among others. Piles are considered the oldest traditional method to overcome instability by reaching a stable layer strong enough to absorb the vertical and lateral loads. As time passed theories and practices have been developed to achieve more accurate pile design [8]. Currently high energy consumption and carbon emissions processed materials such as concrete and steel piles are mainly used in practice. The fabrication of these types of piles create high pollution of air and environmental degradation. Bamboo is an available ecological plant, its production releases oxygen in to the atmosphere and

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absorbs CO_2. When using bamboo, transport labor and cost could be reduced, as it is a slender element and it can be grown close to the worksites where it is needed. Rapid growth, low costs, renewable and simple material to produce are some other basic properties that make bamboo an appropriate material for contemporary development. Bamboo´s physical and mechanical properties match civil construction most updated and conventional materials. The energy necessary to produce $1m^3$ per unit stress projected in practice for materials commonly used in civil construction, such as steel, has been compared with that of bamboo. It was found that for steel it is necessary to spend 50 times more energy than for bamboo. The tensile strength of bamboo is relatively high and it can reach 370 MPa. This makes bamboo an attractive alternative material in tensile loading applications [7]. The objective of this paper is to apply a finite element program to analyze stabilization of a slope using Dendrocalamus giganteus (DG) bamboo. Variables such as position, diameter, inclination, pile row and triangular shaped pile row are analyzed in order to evaluate a safety factor (SF).

(a) Peru
(https://www.theguardian.com/global-development-professionals-network/2017/apr/13/peru-prevent-floods-landslides-climate-change (Dan Collins) 21th february 2018, Date revised.

(b) Swiss
https://bdnews24.com/world/2017/08/27/switzerland-halts-search-for-eight-hikers-likely-caught-in-landslide 21th february 2018, Date revised.

(c) Bangladesh
(https://abbtakk.tv/en/bangladesh-landslides-heavy-rains-kill-77/) 21th february 2018, Date revised.

(d) Sierra Leona
https://blogs.agu.org/landslideblog/2017/08/15/regent-landslide-1/ (Pettley., Image Switsalone)21th february 2018, Date revised.

Figure 1. Some examples of Landslide cases around world in 2017.

2. Bamboo-piles

Piles inserted in a soil mass can provide stability by adding the reactive portion to the resistant forces that act contrary to the ground. Slope stabilization by piles is known to be a passive technique in which soil displacements are required to activate pile forces. Thus pile shear strength is mainly the property defining pile capabilities to transfer forces from an unstable soil layer to a more stable soil layer. Stabilizing a slip soil layer with a single pile depends on its dimensions such as diameter and length, and to its ultimate bending moment, besides the soil properties [14]. A cane of bamboo DG could have diameters from 10 to 40 centimeters and the vertical length could reach 40 meters [6]. Bamboo is provided with a shear strength of 44MPa (Sartori e Cardoso Jr.1997) that make it suitable for slope stabilizing pile purpose (Figure 2).

Figure 2. Bamboo DG Pontifica Universidade do Rio de Janeiro.

3. Slope stabilizing piles finite element method (FEM) model

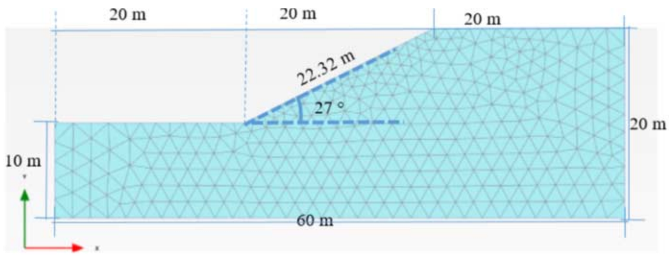
Some of the most used methods to analyze piles for slope stabilization employs soil pressure limit obtained from empirical or numerical analyses. Recently 2 and 3 dimensional software methods linked analyses are more frequently seen, since they became increasingly available [1]. Regarding pile modeling T.P.T. Dao 2011 points out two factors that affect the difference between the magnitudes of displacements on piles subjected to lateral forces. The first is the distance between the toe of the embankment to the pile or piles and the second is the stiffness of the layer or layers of the ground [4].

3.1. Definition of critical slope sliding surface

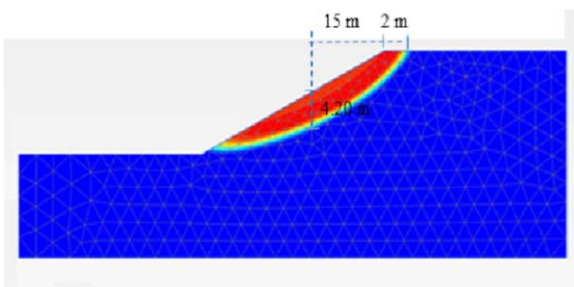
Some parameters of the present slope model data were extracted from previous work of Zou et al 1995 used to perform an equilibrium limit state that develops a critical sliding surface with a safety factor (SF) close to failure [2]. The creation of a critical sliding surface by numeric tools as finite elements is not a minor issue. It occurs by the resultants of stress distribution, associated to a lower SF for many idealized critical sliding surfaces in the domain. The analyses execution was based on two stages divided in two phases for each one. The first two phases correspond to the linear elastic stage. The gravitational activity takes place at initial phase and then the pile or piles are inserted at phase 1, which verifies the linear elastic behavior looking forward to obtain the initial stress state, this configures a certain slope accommodation or/and densification as a whole body. The second stage corresponds to a Mohr Coulomb Model plastic analysis in phase 2 and finally phase 3 attends for safety factor calculation in order to find a critical sliding surface. In the software the soil mass is set to the Mohr Coulomb analysis type, the soil model comprises a clay embankment with the following critical properties, 200 MPa for elastic module, specific weight of 8 KN/m^3, 20° for friction angle and 0.25 for Poisson´s ratio. The sliding surface starts developing below the 4.20 m depth induced by using cohesion of 3Kpa (Figure 3b).This same Zou´s slope model has been studied by different researchers such as Lobato 1997, who´s SF calculation had 0.96 value by means of a dynamic FE software DYNREL and Nguyen 1985 using Bishop method with a SF value of 0.98 [2].

3.2. Dimensional analyses

The representation on 2 dimensional software comprises 642 elements and 5325 nodes for a very fine mesh type. Slope dimensions are 60-meter horizontal length divided in three 20 meter sections, from left to right, the lower section flat with 10-meter height, followed by a 27°-degree slope section and finally the top section which is also a 20-meter height flat layer Figure 3a. The calculated safety factor for those parameters resulted in 1.022.



(a) Slope Mesh in PLAXIS 2D



(b) Slope Displacement 2D Image

Figure 3. Slope Definition in PLAXIS 2D.

Bamboo DG mechanical properties were obtained from previous work done by Lima 1995 [9]. As a linear elastic element 12 GPa for young´s modulus and 2.5 kN/m^3 for specific weigh were used for a circular tube pile with 2 cm thickness wall. Bamboo-pile analyzed variables were position, inclination, spacing and diameter for the 2 dimensional analysis.

3.3. Position influence

Different positions for bamboo-pile with H/Ho coefficient (Figure 4) along the slope of the clay embankment were tested to evaluate SF. For position a vertical insertion and a 9-meter pile length with head value of 1 m was considered. Piles inserted from the middle of the slope to the top had collapsed. The greatest increments were observed for lower positions, highest value was calculated at H/Ho = 1.6, from that position on, the safety SF starts decreasing but no less than a unit as shown in Table 1.

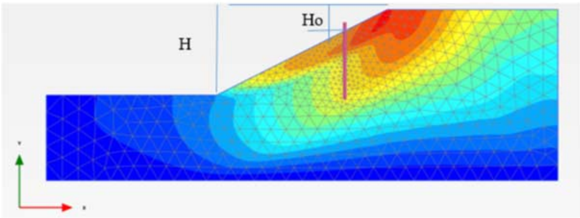


Figure 4. Position H/Ho Coefficient.

Table 1. Bamboo-pile Position influence on single pile analysis.

Position (H/Ho)	SF	Increment
8.00	1.056	3.33%
4.00	1.072	4.89%
2.67	1.073	4.99%
2.00	1.073	4.99%
1.60	1.062	3.91%
1.33	1.061	3.82%
1.14	1.046	2.35%

3.4. Inclination

Three inclinations at H/Ho=1.6 were compared to a vertical insertion. Normally inserted to slope, 45° degrees and inserted with twice the angle of the slope Table 2. Normal insertion showed to have the best performance by raising SF percentage in 2% compared to the vertical pile inserted (Figure 5).

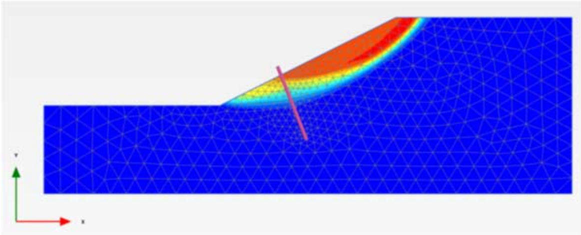


Figure 5. Normal inserted pile view on 2D PLAXIS.

Table 2. Bamboo-pile inclination influence on the slope SF model for PLAXIS 2D.

Inclination	SF
Vertical	1.043
Normal	1.062
54 Degrees	Collapsed
45 Degrees	1.028

3.5. Diameter influence

Diameter influence was evaluated each 5 cm from 10 to 40 cm. Results showed an average gain between 1 to 2% on each 5 cm increment of bamboo-pile diameter on SF. After 30 cm diameter safety factor starts decreasing Figure 6. This effect is a software issue perhaps, Lobato 1997 previously warned that a great transverse dimension for pile stabilizing effects acting on a relative small strip on mesh elements could scatter veracity results, then greater discretization mesh will be needed with potential possible error to happen [2].

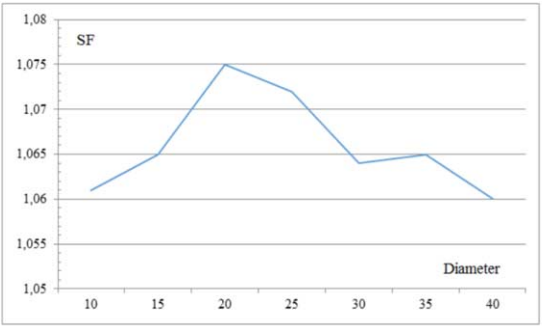


Figure 6. Diameter influence.

3.6. Spacing

Spacing tests were evaluated for a 20 cm diameter bamboo pile starting with spacings from 2 diameters (2D) to 5 diameter spacing (5D) center to center length spacing between piles. An increasing relative order did not existed for safety factor modifying spacing. The highest value appeared to be with 2D spacing reaching 14% increment followed by 4 diameters (4D) and 5D with 11% and 10% increment respectively. The lowest value resulted for 3 diameters (3D) spacing with only 6% increment on the SF Figure 7.

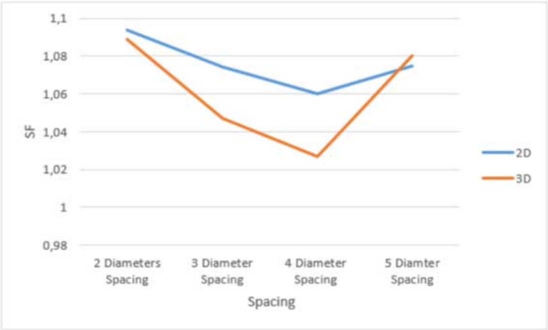
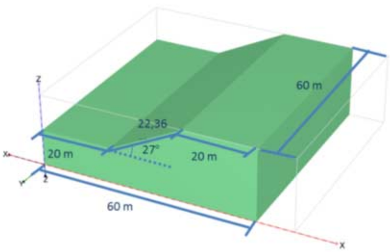


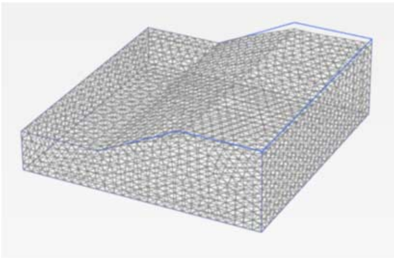
Figure 7. PLAXIS 2D VS PLAXIS 3D Spacing.

4. 3D analyses

For 3 dimensional analyses, slope dimension remains the same as 2 dimensional analyses just adding a slope width of 60 m. Model is shown in Figure 8a for PLAXIS 3D. The 3 dimensional model comprises 55809 elements and 81309 nodes shown in Figure 8b for a very fine mesh type. PLAXIS 3 dimensional analyses reached 1.034 for Safety factor close to failure. In Figure 9b incremental displacements are shown, it can be noticed in lateral view Figure 9a that it is very similar to 2 dimensional analyses and the sliding surface also started to develop after 4.20 m depth. Now in the top view Figure 9b it is possible to appreciate that greatest displacements in a darker color occurring near the center area on 30 meters width distance approximately and 15 meters from the top section to the lower section. For 3 dimensional analyses, a single pile, the spacing, the pile row and the diameter equivalence of bamboo bundles on triangular shaped row influence were analyzed.

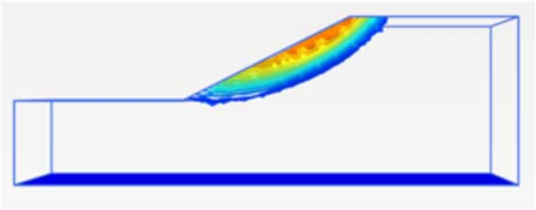


(a) Slope 3D PLAXIS model

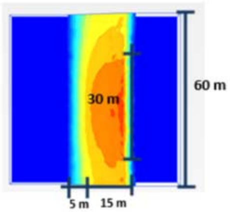


(b) Slope Mesh 3D

Figure 8. Slope definition for 3Dimensional analysis.



(a) Lateral view 3D critic surface rupture



(b) Top view critic surface rupture

Figure 9. Critic surface rupture.

4.1. Single pile influence

Results in a single pile for 3 dimensional analyses did not show a big increment in SF as it did happen on 2 dimensional analyses, nevertheless it did show an influence. However, this is the consequence of the different behavior of the pile element used in each dimensional software. In PLAXIS 2D an idealized superimposed position in the mesh on the out-plane direction is simulated, whereas soil displacements are supposed on an average in the interaction with the beam row element used, differently from PLAXIS 3D the embedded pile element used does form part of the mesh, instead of being superimposed [11]. For this same single pile situation, steel and concrete materials were also tested. Steel did have the greatest SF, although less than 1% difference was appreciable among the three materials.

Table 3. Single pile analyses for different materials on PLAXIS 3D.

Material	SF
Bamboo	1.05
Steel	1.054
Concrete	1.051

4.2. Pile row spacing influence

Spacing pile row test results showed to be in a little better agreement to those obtained with 2 dimensional analysis Figure 7. The SF did show the same decrease in 3 diameters spacing and raising again on 4D. However, any overall displacements reduction is easy to observe from the top view (Figure 11a-d).

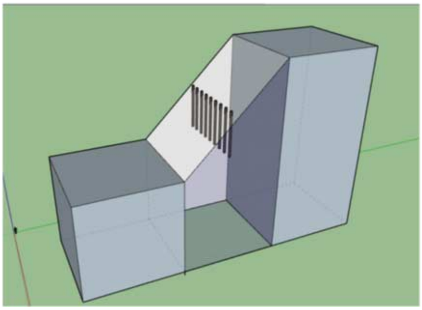
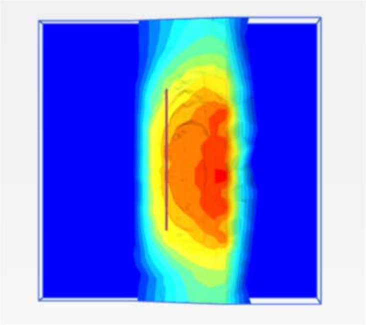
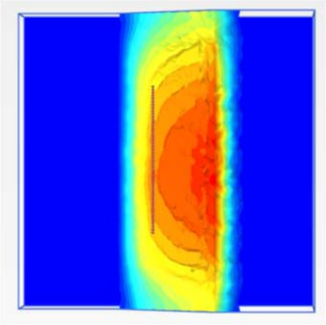


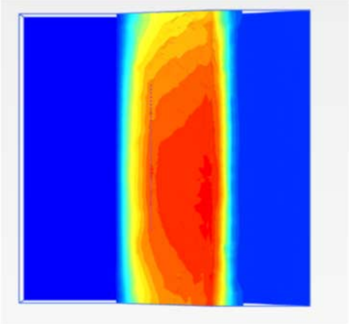
Figure 10. Pile Row.



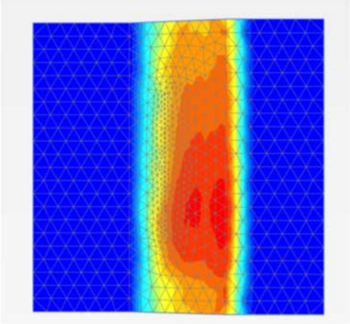
(a) 2Diameter Spacing



(b) 3 Diameters Spacing



(c) 4 Diameters Spacing



(d) 5 Diameter Spacing

Figure 11. Pile Row Spacing in PLAXIS 3D top view.

4.3. Bundle of bamboo diameter equivalence for pile row triangular shape analyses

Increasing bamboo-pile stiffness to increase influence on slope stabilization without modifying its natural properties was done by representing a bundle of bamboos Figure

12 and testing them in a triangular shaped row Figure 11. Giving diameter equivalence for pile properties parameters in the software obtained by means of iteration of inertia values (I) by means of diameter (d) and thickness (e) dimensions (Eq. (1)) Table 4.

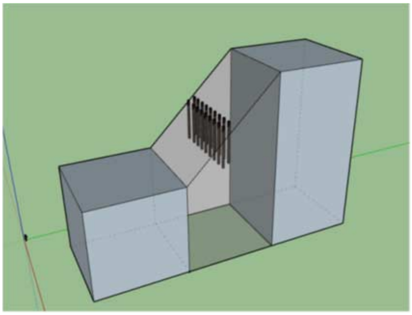


Figure 12. Triangular pile shaped row.

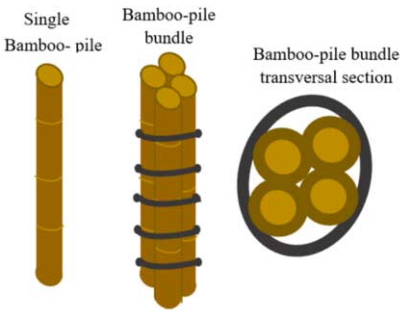


Figure 13. Single Bamboo-pile and Bamboo pile Bundle.

$$I = \pi/64\,[d^4 - (4 - 2e)^4] \quad (1)$$

Table 4. Diameter bamboo bundle equivalences.

D(m) Equivalence	I (m^4)	No. Bamboos
0,295	1,85E-04	4
0,349	3,71E-04	8
0,389	5,56E-04	12
0,422	7,42E-04	16
0,452	9,27E-04	20

Results showed a big influence on diameter equivalence with a great improvement for safety factor. Tests increasing the triangular shaped row distance from 30 m to 50 m width were performed. Unexpectedly a regular 20 cm diameter bamboo-pile used in 50 m triangular shaped row did perform with the highest safety factor. Improving SF two other alternatives for triangular shaped row were tested. A reduction in triangle size was done from 2 meters to 1 meter to a proportion 1 to 0.5 meter (base and height), however an improvement did not show up. Adding one more triangular shaped row, did only increase 2% for 50 m width triangular shaped row compared with a single triangular shaped row with a regular 20 cm diameter bamboo pile, whose final SF increment reaches the highest value above 14% of the slope SF without any pile Table 5.

Table 5. Triangular shaped pile row analyses for bamboo bundle diameter equivalences.

No. of Bamboos diameter equivalence	No. Rows	Triangular base-height dimensions (m)	30 meter distance triangular line row Increment %	50 meter distance triangular line row Increment %
1	1	2_1	4,26%	12,28%
4	1	2_1	4,06%	5,80%
8	1	2_1	3,87%	6,67%
12	1	2_1	3,97%	12,19%
16	1	2_1	3,77%	8,32%
20	1	2_1	1,16%	11,90%
1	1	1 _0.5	4,35%	10,06%
1	2	2_1	3,87%	14,31%

5. Conclusion

The main objective of this work was to study a numerical methodology of bamboo DG piles as a stabilizing pile element for soil slope. PLAXIS software was use to reach this objective. The analytical study of the use of bamboo as a pile for soil slope stability was done by evaluating its capabilities over different factor such as position, inclination, spacing, diameter, pile rows, and pile row triangular shaped with diameter equivalences of bamboo bundles. Safety Factor value was used as reference to analyze each influence of the different variables tested on this research on a finite element method (FEM).

Chapter 5 showed the tests results. For a single pile there is a notable difference between the Safety factors values of 2D and 3D analyses. As explained in chapter 4 the elements provided by PLAXIS in 2 and 3 dimensions, embedded beam row and embedded pile respectively, behaves differently. For 2 dimensional analysis single bamboo-pile SF increased 8% with embedded beam row element. However, for single bamboo-pile as an embedded pile for 3 dimensional analysis, the safety factor did increase but less than 2%. Regarding position the inclusion of the pile at lower section had greater performance on improving SF. In inclined tests, normal insertion resulted in better performance than any other inclination tested. For diameter influence, a proportional increment did appear but it also showed that with a greater diameter, results may scatter veracity, for this reason, slender diameters would be more suitable when aiming realistic responses. When it came to pile row results the analysis did not show a proportional increment for spacing order. The greatest spacing performances in both two and three dimensional analyses were presented for 2 and 5 diameter spacing. Although a regular 20 cm bamboo diameter on triangular shaped row was able to raise up the SF over 4% more than any bamboo bundle diameter equivalence, triangular shaped row tests with diameter equivalence of bamboo bundles on a triangular size for 2 to 1 meter (base to height) developed a greater SF increment than a single line row on 3 dimensional tests. The greatest increase of SF among all the analyses done was obtained for two triangular shaped row on a 50 meter distance along the width of the slope, the percentage radically increased up to 14%.

To finally conclude it must be said that from this FEM analysis bamboo-pile result in a limited element for slope stabilization and performance, for this reason it should be added another possible solution to improve it. Never the less bamboo´s potential as stabilizing element for geotechnics purpose is still stated as a non-conventional suitable material, when it comes to its economic, geographical, physical and mechanical properties being an ecofriendly alternative to replace conventional materials in order to reduce the vulnerability of risk areas without disregarding ecological and economical aspects.

In this experience, due to the mechanical properties that bamboo DG has, the results were expected to be better in the effectiveness of this method, at the end the increment of the safety factor was minimum. Other configurations to enhance the SF were applied such as increasing the number of embedded pile elements in more triangular shaped rows. Trying to run the calculation for SF with this new configurations, suddenly unattached pile element nodes to the mesh appeared to be attach requested in order to complete the calculation, and as this issue actually appeared when tests for 1 and 2 triangular shaped rows where done it was easy to solve for that number of three noded embedded beam piles, but when it comes to more than two triangular shaped rows, the process became extensively laborious that it seems to be an endless job when it comes to try different coordinates for each requested node of the three noded embedded pile elements used when the number is raised up to 30 embedded piles or more.

However here are some suggestions for future research:

- New configuration design of pile implementation and an increment in the number of piles on mesh.
- To use a head pile support beams to try create a stronger interaction of the elements with it in a group of piles.
- Test bamboo-piles on slopes with different dimensions and soil characteristics
- Add a mechanical improvement to the bamboo-pile element to test its use as a composite element.
- A deeper study on bamboo-pile treatment to increase its durability.

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