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Angel Mauricio Jaime Davila

Numerical Analysis of Bamboo Piles for Slope Stability

Dissertação de Mestrado

Dissertation presented to the Programa de Pós-Graduação em Engenharia Urbana e Ambiental of PUC-Rio in partial fulfillment of the requirements for the degree of Mestre em Engenharia Urbana e Ambiental.

Advisor: Prof. Celso Romanel

Co- Advisor: Prof. Khosrow Ghavami

Rio de Janeiro

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Pontifícia Universidade Católica do Rio de Janeiro

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To my beloved Family, my Mother Yolanda,
my Father Ismael, my Sister Alba, my
Brother Ismael and my Nephew and Godson
Jonas

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Abstract

Jaime Dávila, Angel Mauricio; Romanel, Celso (Advisor), Khosrow Ghavami (Co-Advisor). **Numerical Analysis of Bamboo Piles for Slope Stability**, Rio de Janeiro, 2018. 82p. Dissertação de Mestrado – Departamento de Engenharia Civil e Ambiental, Pontifica Universidade Católica do Rio de Janeiro.

Uncontrolled population growth and disorderly urban development had witnessed severe human settlement damages worldwide. Extreme natural phenomena consequence of abrupt climate change such as intense rainfall index increment had provoked landslides incidents hardly to ignore since 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 important its mechanical properties, besides its geographical availability and greenhouse gases absorbing capabilities totally matches 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 alternative for slope stability.

Keywords

Soil stabilization; bamboo-pile; non-conventional materials; finite element analyses.

Resumo

Jaime Dávila, Angel Mauricio; Romanel, Celso (Orientador), Khosrow Ghavami (Co-Orientador). **Uma Análise Numérica de Estacas de Bambu para Estabilização de Taludes**, Rio de Janeiro, 2018. 82p. Dissertação de Mestrado – Departamento de Engenharia Civil e Ambiental, Pontifica Universidade Católica do Rio de Janeiro.

O crescimento populacional descontrolado e o desenvolvimento urbano desordenado têm testemunhado danos severos em assentamentos humanos no mundo. Fenômenos naturais extremos, como consequência de uma mudança climática abrupta, como o intenso aumento do índice pluviométrico, provocaram incidentes de deslizamentos de taludes que dificilmente seriam ignorados desde as últimas décadas. Pilhas feitas de materiais convencionais como a madeira, aço e concreto têm sido tradicionalmente utilizados para a estabilização de taludes, com a finalidade de evitar incidentes de desabamentos de aterros. O presente trabalho estuda o uso de um material não convencional, o bambu da espécie *Dendrocalamus Giganteus* (DG) para estabilidade de taludes, como uma alternativa de material para pilha mais amigável ao ambiente graças a sua disponibilidade geográfica e capacidade de absorção de gases de efeito estufa. Suas dimensões e mais importantes suas propriedades mecânicas, são totalmente compatíveis com as de um elemento de estaca estabilizadora de taludes. Uma análise do Método dos Elementos Finitos (FEM) foi desenvolvida no software PLAXIS para testes em 2 e 3 dimensões. Usando um modelo de encosta instável reforçada com estacas de bambu para observar a interação do solo-estaca e avaliar o fator de segurança (FS). Os resultados mostraram que as capacidades das pilhas de bambu são uma alternativa promissora para a estabilidade de taludes.

Palavras-chave

Estabilização de Taludes; estacas de bambu; materiais não convencionais; analises de elementos finitos.

Table of contents

List of Figures

List of Tables

List of Symbols

u	Water presure
σ	Force resultant
σ_{xx}, σ_{yy}, σ_{zz}	Principal Forces 1, 2 and 3
σ'_{xx}, σ'_{yy}, σ'_{zz}	Efective stress component
E	Young Module
v	Poisson Module
c	Soil Coesion
φ	Shear strength Angle
$\mathbf{t}^{\mathbf{skin}}$	Force integration points
$\mathbf{K}^{\mathbf{skin}}$	Rigitity Matrix of material interface
$\Delta\boldsymbol{u}_{\boldsymbol{rel}}$	Vector of displacement between soil and pile
tn	Shear traction in the axial direction
ts e tt	The normal tension horizontal direction (keeps elastic)
Kn	Elastic Shear Rigidity
Ks e Kt	Normal and elastic rigidity in horizontal direction
up	Pile Displacement
us	Soil Displacement
T_{max}	Interface capacity for supporting the shear t_n along the pile (in axial direction of the pile)
$\mathbf{F}_{\mathbf{tip}}$	Forces at pile
$\mathbf{K}_{\mathbf{tip}}$	Matrix of spring element rigidity at the base of the pile
$\left(\boldsymbol{u}_{\boldsymbol{tip}}^{\boldsymbol{p}} - \boldsymbol{u}_{\boldsymbol{tip}}^{\boldsymbol{s}}\right)$	Relative Displacement of the vector between soil and the foot os the pile.

List of Equations

List of Abbreviations

GDP	Grow Domestic Products
UNHABITAT	United Nation Human Settlements Program
NOCMAT	Non Convectional Materials
INBAR	Indian Bamboo and Rattan
SF	Safety Factor
DG	Dendrocalamus Gitanteus

"There is no long term sovereignty if knowledge is not ours." José Mujica (Address Farewell, Mercosur Meeting, Argentina, 2014)

1 Introduction

Developed and developing countries updated urban challenges such as social shaping factors, environmental degradation and climate change events under an informal activity in a context of inequality and poverty tend to develop risk areas (United Nations Human Development Programme, 2009) Fig. 1.1 Severe environmental disasters caused by natural phenomena, such as floods, earthquakes, tsunamis, landslides, volcanic eruptions, cyclones, hurricanes, among others are frequently increased with abrupt climate change. The cities where these phenomena occur more frequently suffer deaths and economic issues. Action plans aiming to mitigate impacts of climate change had been the objective of different researchers and public institutions altogether. However, there are still difficulties that weaken these plans such as the disordered occupation without a safety criterion (Lemos, 2010). The increment on human settlements as a product of population growth and disorderly urban development had brought social vulnerability (Comission on Population and Development, 2008). Less favored people will bear the brunt due to the uneven distribution of politic and economic power over densely packed urban areas that face climate change extreme events. Despites these scenarios could be presented on any region of the world they are more often seen on developing countries where social distribution equity is more evident and as it seems to remain the same on the future certainly it could get worst according to documented data of the UNHABITAT Fig.1.1 (United Nations Human Settlement Programme, 2011).

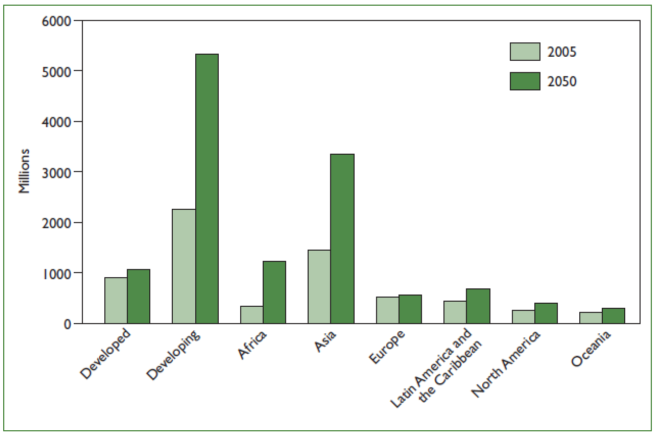


Figure 1.1 Urban population by region, 2005–2050 (United Nations Human Development Programme, 2009)

Unplanned settlements mostly irregular commonly becomes landslides vulnerable under climate change abrupt events such as hurricanes and increasing rain fall index Fig.1.2. Worldwide countries that suffer this type of issue unfortunately experienced great GDP [Gross Domestic Product] issues due to damages on infrastructure affecting its economy balance without to mention the hard time the victims face. Thus international institutions have recognize the needs to minimize this unwanted scenarios:

“ *Recognizing* that climate change represents an urgent and potentially irreversible threat to human societies and the planet and thus requires the widest possible cooperation by all countries, and their participation in an effective and appropriate international response, with a view to accelerating the reduction of global greenhouse gas emissions (COP21, 2015)”

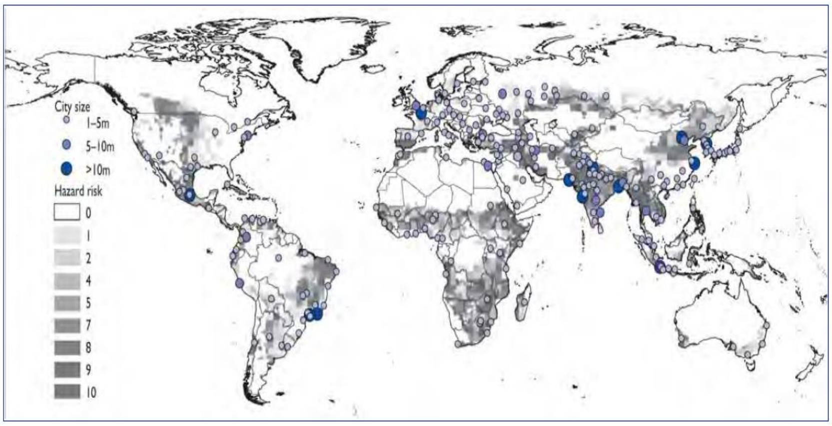


Figure 1.2 Cities in relation to current climate-related hazards (United Nations Human Settlement Programme, 2011).

Hence the use of non-conventional material with CO2 absorbing properties totally fills in the requirements to achieve reduction emission. In this context bamboo as a traditional and versatile material besides its absorbing CO2 capabilities totally catched the eyes of academic researchers around the world since last century.

The first chapter of this work briefly summarizes recent worldwide events caused by rainfall increases and related events around the world, their impacts mostly focused on Latino America’s regions, sums up some aspects of material selection, and shortly discusses non-conventional materials. The second chapter is mainly about bamboo characteristics, properties and treatments. The third chapter focuses on slope stability study, it briefly mentions techniques for stabilization and gives more in-depth information about pile stabilization techniques and methods for its analysis. Chapter four basically explains the modelling in finite element software PLAXIS, its characteristics and element capabilities to represent slopes and piles and its respective advantages and issues. The tests, its description and analysis are presented in Chapter 5. Finally conclusions and considerations are stated in Chapter 6.

1.1 Objectives

The objective of this work is to analyze the capabilities of bamboo-pile as an alternative non-conventional material that can be used in slope stabilization. Two and three dimensional analyses will evaluate bamboo-pile on PLAXIS software to simulate real situations. Pile position, length, diameter, spacing, pile row and triangular shaped row will be model to evaluate its influence on pile soil interaction by evaluating the safety factor. Conclusions and considerations based on the results of the tests will be given.

1.2 Documented Climate Events World Wide

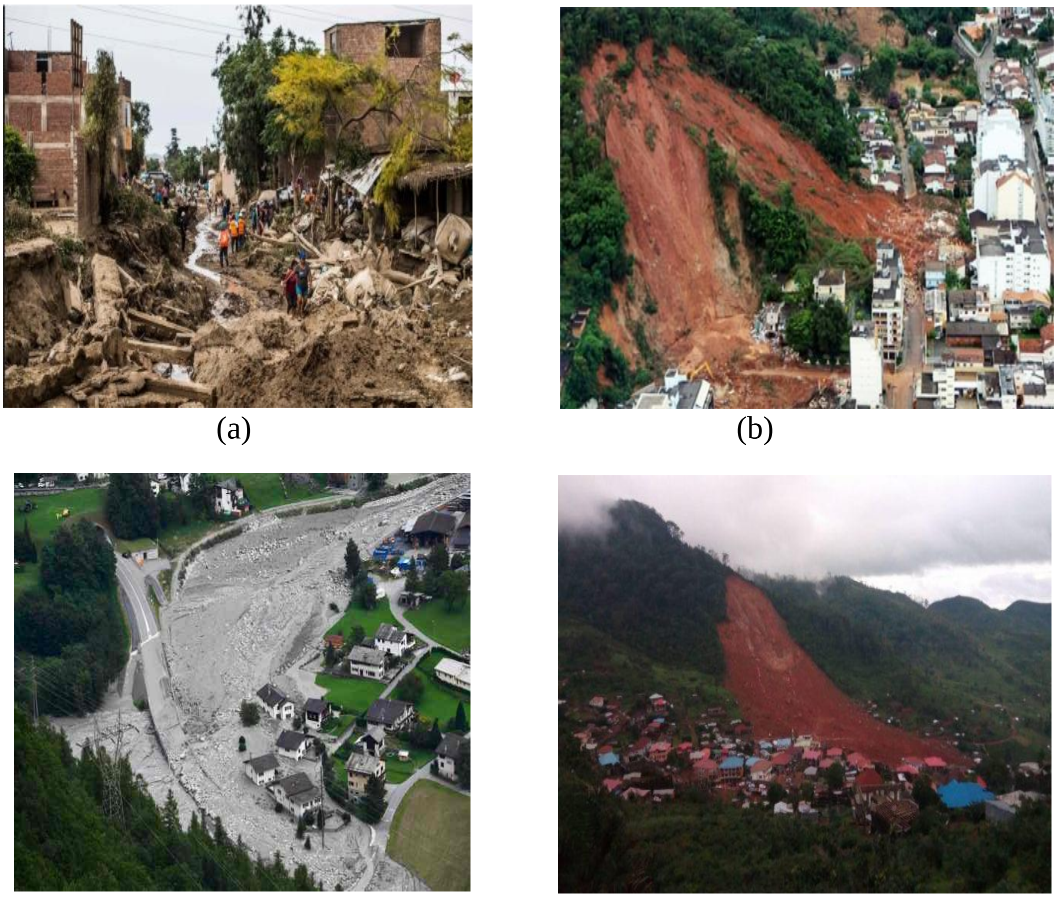
In 2005, the Katrina hurricane left material damages of more than 75 billion dollars, with deaths of 1,836 people. It was the most expensive environmental catastrophe of the United States of America.

In Central America, extreme climatic events such as droughts and floods are frequently experienced. In 2005, the Atlantic hurricane season in territories of southeastern Mexico, Guatemala and Salvador met the Stan phenomenon. On October 3, the Salvadoran president declared emergency alert, floods and widespread landslides left serious consequences for the population of that country, affecting half of Salvadoran territory.

In USA 2014, a landslide engulfed a rural neighborhood covering 2.6 km^2 areas in the state of Washington, near the North Fork of the Stillaguamish River; it left 43 deaths.

South America most recently events are the endless rainfalls in Peru that left 78 deaths and 643,216 people were affected so far in 2017 Fig. 1.3a

Also this year Mocoa, Colombia, had more than 250 deaths and 400 disappeared because of the overflowing of three rivers in Puntamayo Region, leaving 17 neighborhoods in sad conditions.



(a) (b) (c) (d)

Figure 1.3 Some landslides worldwide on 2017 (a) Peru (b) Bangladesh (c) Swiss (d) Sierra Leona

Landslides occurring present year:

On June 12 landslide in Bangladesh triggered by the heavy monsoon, estimated deaths were over 150 and communication infrastructure was so affected that the rescue had such a hard time that this landslide was called the worst of the country's history Fig.1.3b.

Later Freetown, Sierra Leona´s capital suffered torrential rainfalls taking account for 499 lives, leaving 3,000 people homeless and hundreds of buildings were damaged Fig.1.3c.

Swiss 200 villagers were not allowed to stay at home after Swiss Alpes presented landslides last August 23 in Bondo near Italian border, this landslide was categorized of a magnitude of 3 on Richter´s scale Fig. 1.3d.

1.2.1. Damage estimative due to climatological events

Maskrey (1993) describes a natural disaster as a product of the correlation between dangerous natural phenomena and certain vulnerable socioeconomic and physical conditions. According to documented data, the mortality rate for disasters is ten times higher in poor countries than in rich countries. Latin American countries are certainly vulnerable to these type of events; for example, Mexico has 71% of GDP, 15% of the territory and 68.2% of the population at risk due to climate change events (Olivera, 2013). Referring more specific to landslides economic issues, Colombia expends 4.4% of GPD by year and Costa Rica at Zona Azul reaches almost million dollars expenses per year (Carvalho & Galvao, 2006) (Decreto Ejecutivo N"33166. MP (Gaceta N"112), 2006). One comparative documentation on investment for slope contention works in Rio de Janeiro tripled in periods from 2001 to 2008 and from 2009 to 2012, this las period accounting almost for a million dollars average (d´Orsi, 2013).

In the disaster manual of The Economic Commission for Latin America and the Caribbean ECLAC, damage is empathized that it:

"... is those who suffer from immobilized assets, destroyed or damaged, and those inflicted on the existences (both of final goods and of goods in process, raw materials, materials and spare parts) ... it is, in essence, of the losses suffered by the assets during the claim. Among the main items in this category are total or partial destruction of the physical infrastructure, buildings, facilities, machinery, equipment, means of transport and storage, furniture: damage to farmland, risk works, reservoirs, etc."

The losses:

"...refer basically to the goods and services that are no longer produced during a period that began after the disaster was presented and which can be prolonged during the rehabilitation and reconstruction phase... the losses also include the exceeding costs required for the production of goods and the provision of services as a result of the disaster, as well as the lower inflows that have been received due to their impossibility or make it difficult to achieve them (which in turn are reflected in the macroeconomic indicators) (Bello O. D., 2012)."

ECLAC determines three sub-sectors for the estimation of climatological damage: the social sector, the infrastructure sector and the productive sector each one encompassing 26.7%, 17.3% and 54% respectively. Public Building, transport, electricity, water and sanitation correspond to infrastructure sector. The social sector comprises the subsectors of housing, education and health. supporting. Agriculture, industry, and commerce are the subsectors of the productive sector (Bello O. D., 2012).

Social vulnerability is a direct consequence of impoverishment, demographic increase, accelerated urbanization, industrialization without considering to protect their inhabitants from the environmental effects (Garcia Garcia, Bermúdez Jiménez, Perez Muñoz, & Crespo, 2013)

Thus the development of new technologies more accessible and with lower cost facilitates should be taking into account on the procedures to provide an economic resilience to cities in the regions that are likely to undergo environmental disaster events that jeopardize the well-being of its inhabitants.

1.3 Material Selection Criteria

When regarding selection of materials with sustainable patterns, the essential factor is to relate energy consumption as it is to document the information on the environmental impacts caused by an abuse of material consumption. Concrete as an example, one of the most related material for urban building is related to 5% of the anthropogenic CO2 emissions as its production mostly depends of fossil sources (Chennoufi, et al., 2010).

Conventional materials for construction purpose as concrete and steel depends on fossil sources. According to Diamond (2005) states that fossil sources perhaps may be ending by this century. Thus the increase of new energy alternatives provided by renewable or recyclable resources will be needed.

The life cycle analysis plays relevant role for material selection. It evaluates material extraction through the process until final disposal or reuse. Life cycle analysis is based on a procedure that measures the use of materials throughout its lifetime, depending on factors such as generation or reduction of waste, energy consumption or GHG emissions. These methods help to encourage the use of renewable, reusable or recycled materials by comparing them between materials of a given category related to the required energy impacts and raw resources needed for fabrication. When a database is finally created, it is possible to start identifying the options that meet the objectives and constraints of each project (Pouya Samani et al, 2015).Some well-known aspects for sustainable material selection are the following:

a) Energy Consume Reduction

Suitable material options on projects as accessibility conditions may help to avoid the excess of energy consume, hence regarding location is extremely relevant to attend this issue.

b) Use of renewable and recyclable resources

The use of renewable and recyclable materials helps preserve natural resources. Recycled materials incite a second or nth life, saving energy that would be required to produce new materials or products. In this way, both types of materials represent good alternatives to conventional materials. Besides, another advantage is that they help to reduce waste that should probably end up in landfills.

c) Environmental impact reduction

Selecting fabrication materials that do not have toxic and polluting substances in the process are convenient for water and soil conservation. The savings of the water and the avoidance of its pollution are indispensable to maintain this source needed for live in the planet (Lopez Lopez, 2008).

1.4 Non-Conventional Materials

Universities around the world have developed numerous research studies regarding non-conventional materials. But it is not only in academic practice that this preference can be found; currently there are several architectural projects that consider this kind of material more attractive Fig. 1.4. In recent years, the search for new materials and more eco-efficient techniques has managed to upgrade non-conventional materials functionality, proving them to be able to replace conventional materials. Limitations on the use of non-conventional materials created during the last century in the industry are gradually fading away. Bamboo and earth are the most popular non-conventional materials these days.

Figure 1.4 Centro Imagina in Leon Gto., Mexico more than half of material used on its construction are non-conventional catergory.

Notably steel and concrete are stated as the most suitable materials to consume for urban building purposes regarding its accessibility provided by their old and strong industry. Nevertheless non-conventional materials have the ability to promote environmentally friendly human activities (Ghavami, 2011).

Non-conventional materials have great significance in the following aspects:

- They have physical and mechanical properties capable of withstanding large structures.
- Low economic cost
- Low environmental impact
- Regulation advances
- Work diversification
- Durability

Studies for non-conventional materials for the construction were initiated by NOCMAT (Non-Conventional Materials), in 1970, with a continuous growth in this field and research. Organizations such as ABMTENC, INBAR, Rede Terra Brasil and Bambutec strive to achieve free polluted and segregated development by promoting the use of natural resources creating new hybrid techniques that call back ancient traditions.

2 Piles for Slope Stability

Some reasons for slope instability to be develop had to be with the cutting or filling of slopes and natural causes such pore pressure excess caused by high phreatic levels, sewage trajectory interruption, scouring provoked by superficially water erosion and soil layer resistance degradation by creeping process, besides increasing rainfall index. Soil stabilization is a resource born in the need to reinforce a soil structure making it more stable with the purpose of providing security and protecting a certain space and/or preventing invasion of other spaces by soil chain movements. Thus, several techniques to create slope stabilization have been developed, just to mention a few, but without deviating on the piles, other popular techniques could be: stabilization with rock-bolts (Fig. 2.1a), weigh structures (Fig. 2.1b), and retaining walls (Fig. 2.1c) or with vegetation (Fig. 2.1d). Some of existing techniques for slope stabilization are subdivided into "passive" and "active". The pile slope stabilization corresponds to a "passive" stabilization, this is attributed to the kind of effort required to activate forces on the pile that does not precisely need an extra force to be applied other than the soil displacement to activate the additional pile force. The rock-bolts (Fig. 2.1a), which require a pre-stress or post-stressed force, fall into active category.

(a) Rock-Bolts

(b) Weight Structures

(c) Retaining wall

(d) Vegetation

Fig. 2.1 Types of techniques for slope stability

Actually piles for soil stability are known to be an old engineering practiced technique, implemented in order to avoid soil mass slippage Fig.2.2. The piles are supposed to add a reactive portion to the resistant forces that are acting contrary to the ground. Spaced piles are inserted and embedded in the soil below the failure surface, where an enough stable soil layer is able to transfer forces along the piles.

Figure 2.2 Rudimentary wood piles for soil stability

This chapter presents a brief summary of fundamental considerations that have been related to this soil-pile stabilization technique. Guided by documented researches of many valuable experienced authors, taking into account different aspects they refer to achieve a proper pile design for slope stability. Thus, the soil and pile elements that are involved in the process and also their methods of analysis are described in this chapter.

2.1 Soil Behavior

Soil behavior depends mainly on its properties as the granulometry, water absorption and consolidation and creeping. These properties usually summarize soil mass capability to resist forces that might compromise its stability. Thus by knowing soil properties it is possible to determine a stable or unstable state and whether it is possibilities to change from one state to the other. It is also possible that a force externally applied as water weight or buildings construction can make the soil body loose stability. A brief analysis of the patterns presented in studies referring to soil slope developing forces is presented below.

Slope force development factors

The soil force development is recognized as the difference between the total forces and effective forces; the first one refers to the force of soil body and the pore pressure together, whereas the second only refers to the force of the soil body. While a force is being applied to the soil body, a normal force and the diverting force develop over time. In this interval of time, the forces that are transferred to the soil body draw a path. Thus these forces start behaving in different directions and efforts in the soil such as: vertical compression, horizontal compression and shear forces.

The soil forces under the load presents vertical compression ($\Delta\sigma_v > \Delta\sigma_h$). Following the direction towards the embankment toe, the shear force starts increasing until it reaches its greatest value under the toe($\Delta\sigma_v = \Delta\sigma_h$). . Moving away from the embankment shear strength change to horizontal compression ($\Delta\sigma_v < \Delta\sigma_h$). The different states of the forces are shown in Fig. 2.3.

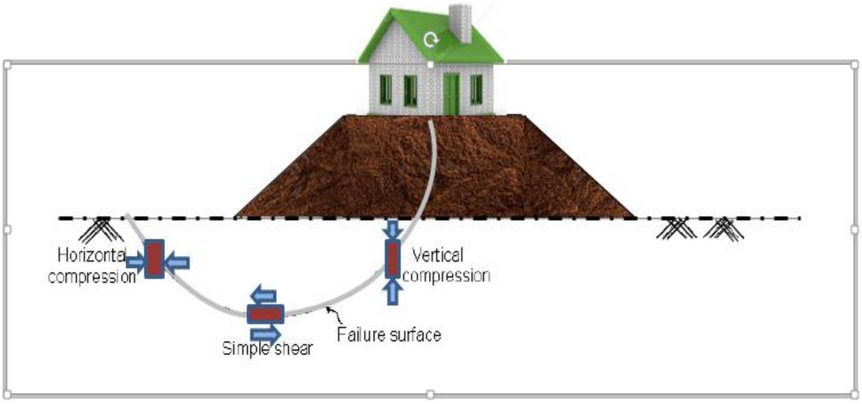


Figure 2.3 Stress Condition under embankment (Zdravkovic et al., 2002) Edited by Author

Coordinates

Coordinates method helps to analyze soil movements in two and three dimensions. State of stress can be expressed in Cartesian coordinates (x, y, and z). The resultant of the forces can be represented in the initial stresses σ_1, σ_2, σ_3 when the axis system is such that the forces that make up the shear force are equivalent to 0.

Water pore pressure

For engineering purposes, the soil is described at a macroscopic level. According to Terzaghi (1943 apud (Dao, 2011)), the description of the difference between the total stresses and the pore water pressures for saturated soils is shown in the matrix form of Eq. 2.1.

Equation 2.1 Water pore Pressure and total stresses

$$\begin{bmatrix} \sigma'_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma'_{xy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma'_{zz} \end{bmatrix} = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{xy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix} - \begin{bmatrix} u & 0 & 0 \\ 0 & u & 0 \\ 0 & 0 & u \end{bmatrix}$$

Where the total components σ' are the effective stress components, u is the water pressure component in the pore and σ is the initial stress. In formula 3.1 it can be recognized that the water pressure in the pore cannot withstand shear stress, consequently, the soil has particles that tend to resist all shear forces.

The determination of the total stresses pattern and the effective stress pattern are highly required to give a suitable stress prediction before and after linear slope starts gaining degrees. In addition, it should be taken into account that the interaction between the undrained deformation and the deformation due to the consolidation is actually very complicated. Thus, in a more convincing analysis, it is assumed that each type and deformation happens separately (Kourkoulis, Gelagoti, Anastasopoulos, & Gazetas, 2011).

Undrained Soil Pressure

Undrained soil pressure phenomenon happens when soil is subjected to external loads or forces, described as the state in which the pressure in the pore cannot dissipate in a given time span, this means that the dissipation coefficient is less than the soil pressure coefficient in the soil. As consequence, almost all external forces are transferred to the water pore leading to increase in the excessive pressure of the pore.

The factors that are involved in the undrained shear strength S_u are the soil granulometry (fine or coarse) and the load coefficient. Regarding the soil properties, the undrained shear strength depends solely on the void ratio and the water content. As much as angle of friction (ϕ) gives the impression to influence on slope, it is not fundamental for shear strength purposes. The shear strength value depends directly on the confining stresses and we may consider that an increase in shear effective strength results in an increase of the undrained shear strength (Fig. 2.4).

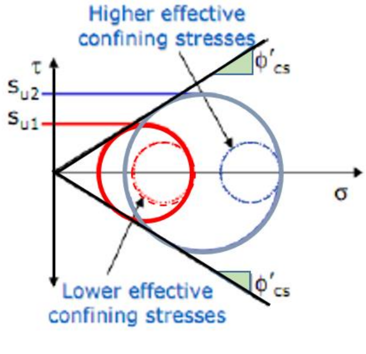


Figure 2.4 Relationship between effective confining stress and undrained shear strength (Whitman 1979)

Assuming a soft soil subjected to short-term landfill load, it is considered to be in an undrained state when the soil particles begin to slide one over the other, and this situation is defined as the maximum shear force in which the soil begins to fail.

Shear Strength

Laboratory tests or "*in situ*" tests help to determine soil shear strength. For fine-grained plastic soil undrained shear force, ranges are defined by the Atteberg limits (Fig. 2.5). With a liquid limit index IL = 1 the shear force will be 1Kpa and when it is equal to Plastic limit IL = 0 will be 150 Kpa, this means that knowing the water content in the soil, the undrained shear force can be predicted.

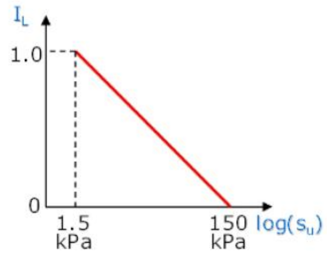


Figure 2.5 Atteberg Limits Diagram

Regarding stabilizing piles technique, the shear strength is essential and it must be considered when analyzing the horizontal stresses produced in a soil mass due to external loads (Dao, 2011). Other factors that influence shear strength could be slope inclination, speed of construction or natural slope creation.

Slope Instability

Instability could be naturally developed by the structure and dynamic evolution of the own slope. Some relevant conditionals of residual soils instability that progressively suffer modifications in their structures are weathering, mineral variation and the void index, which directly influence on its strength resistance, compressibility and permeability. Other causes can be produced by anthropogenic activities as engineering works such as pipelines and roadways construction in order to satisfy society's needs development. As in a soil mass, which is subjected to an initial stress depends on the load or unload action for strain to happen. In the meantime it is known that the soil movements are influenced by factors such as climatic, geomorphological, geotechnic, anisotropic, pedological, and hydraulic acting simultaneously.

A classification of soil mass movements could be the collapse, slip and creeping. Slips commonly happen in natural slopes and in the cut or creation of embankments, some of these characteristics are fast movements in short time lapse. The geometry of natural slope or embankment creeping condition and the drainages as well as the soil properties determines the shape of the slip surface (Pretto Ferronato, 2014).

There are normal four groups of slips: rotational, translational, block and debris falls. The first two accounts for are mainly defined by weak planes and disconnection or discontinuity between different types of soils or soil properties and its geometry. Rotational are smaller when compare to translational. For block flows erosion is the main cause of origin with the loss of support along the joints. In the case of debris flow dry and water saturation cases most provoke it.

There is two principal mechanism of instability: internal and external. Internal mechanism happen at the lithosphere and the commonly are provoked by earthquakes, tsunamis and volcanism activity. Volumetric variation create different scenarios, each one more vulnerable to fall than others. An external mechanism are related to the atmosphere its climatic variation such as rainfall index and temperate waves, the extremer they are the more influence they have. Anthropogenic activity also accounts for external mechanism, for example the creation of embankments and cuts. Geometric modification could end affecting not just the shape but the whole structure of the slopes. There are also intermediary mechanism such as hydraulic activity related to shear strength lost due to water trip carrying fine soil particles. This effect is sometimes hard to see at first sight because they act in long time period and for this reason monitoring water parameters such as rainfall index, retaining capacity and hydraulic conductivity is indispensable to prevent slope collapse incidents. Regarding slopes stability analysis, the safety factor SF is traditionally employed to evaluate the slope stability.

2.2 Piles for Slope Stability

Piles are consider the oldest traditional method used by man to overcome for foundations where is needed to reach a soil with sufficient stability capacities to absorb the vertical and lateral loads. Modern literature about piles documented that piles use started at the end of IXX century. Stabilizing piles had been used for natural unstable slopes on embankments or landfills, piers, offshore structures and on structures which are constructed in earthquakes areas (Poulos and Davis, 1980).

As time passed, many theories and practices had been developed, thus more accurate pile design methods are provided day by day. Along last decades the use of piles for landslides prevention has been a popular method for slope stabilization.

The pile purpose is to increase stability by adding the reactive portion to the resistant forces that are acting contrary to the ground. For these reason the acceptable deflection of the pile is essential for pile design. In slope stabilization by piles, soil displacements are required to activate pile forces, as it is a passive technique, hence pile stiffness is mainly the property that responds and mostly defines pile behavior. The stabilization given by a single pile with slip soil layer and slope angle depends on its properties such as; diameter, length and ultimate bending moment (Yi He, 2015).

The pile position on slope is commonly defined by a coefficient, which describes the relation between the length of the embedded pile and the slope height. Never the less the design should never be restricted to it, as many other aspects such the diameter, material of the pile and the spacing when using pile row are related to the force it transfer to the upper unstable soil layer (Kourkoulis, Gelagoti, Anastasopoulos, & Gazetas, 2011).

Regarding pile rows the spacing is expected to present proportional decrease on Safety Factor value, at any spacing increment. It is also expected a larger pile deflection when piles are closer. Also important to know that soil with less plasticity should experience poorer interaction with piles, this scenarios are presented on soils with high friction angle and low cohesion. Soil stability could be increase with a greater pile diameter but it also could decrease at some point in the interaction with the spacing in a pile row. Economic aspect should be taking into account when the spacing design is too short and determines too many elements to be use as the budget may limit project.

When it comes to have a good interpretation in situ simple and economic accessibly measurements as inclinometers have shown good response to get to know the contribution of pile rows as well to verify the soil displacement done by the piles implementation on site. Other methods as using pile with weak stiffness helps to show loads capacity that a pile would be subjected (Lirer, 2012).Several authors have classified pile types according to this factor in rigid or short, long or flexible and intermediate piles or root piles (Bello, 1997) (Poulos and Davis, 1980).

Rigid Piles or short piles

The use of these types of piles corresponds to big volumes of soil masses. Commonly, the diameter for these piles is found from one to 3 meters. They are mainly designed to withstand the shear forces.

Flexible Pile or Long Piles

Flexor moments are mainly involved in the displacement caused by movement of the soil mass in this type of pile-soil system. They provide stability based on the relation of maximum pile moment undergoing on the slope and the maximum moment that the pile resists (M_{max}/M_p) ratio. As flexible piles have a non-linear behavior they must need to reach the ultimate strength before they reach the maximum curvature.

Intermediate piles or Root Piles

These piles have a relatively smaller diameter compared to rigid piles in a range of 10 to 40 cm, but shear stresses and bending moments are also involved, the latter becomes the protagonist on the role in how much resistance is involved. This technique is studied in two ways: as an isolated pile, or group of piles. It is in this classification that the bamboo-stabilizing piles studied in this work are included.

2.3. Analysis Methods for soil-pile interaction

The three dimensional behavior between soil and pile is a complex phenomenon due to the strain characteristics and the resistance parameters of both elements. For these reason an accurate analyses should integrate the nonlinear behavior of the pile´s material and the soil flow around it. Determined by the magnitude of forces acting on the pile above the probable rupture surface to aim the stabilization condition of the slope (Mohamed Ashour, 2012).

When seeking for a slip surface, variational calculus, dynamic program, genetic algorithms, besides different developed techniques had been employed (Jianping, Jiachun, & Qingquan,, 2008). Some popular methods to solve calculus of lateral forces acting on piles are the limit equilibrium method LEM and the shear strength reduction methods SRM. Practical landslide engineering applies more commonly the LEM with slices methods for obtaining lateral force, never the less these methods aren't that enough sufficient for giving the lateral force distribution acting on the pile, which may affect the lateral deflection and shear strength of the pile. The called finite element model with the SRM are more used for more comprehensive analyses of slope stability and an advantage is that it does not precisely need a critic surface rupture (Chunmei Zhou, 2014). Among the several researches on methods of analysis of the forces provoked by landfill constructions, different perspectives to deal with the interpretation of the result have been studied.

a) Pressures

Pressure methods analyze the load distribution applied to the pile provided by the soil movement. In this method, the pile bending moment is the object of the analysis. Different authors identify aspects that influence the pile performance. Some of them affirmed that the fixation of the base pile edge has a relevant effect on the development of the moment of flexion.

b) Displacement

T.P.T. Dao 2011 points out two factors that affect the difference between the magnitudes of displacements when the piles are 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.

c) Uncoupled and coupled

Uncoupled methods consider pile response and slope stability separately with an equilibrium method analysis, whereas the coupled methods analyses both two ensemble. The Uncoupled analysis frequently have more conservative results than coupled methods (Jinoh Won, 2005). It is been found that loads on piles prediction with the available methods could vary significantly or could take to similar results based on the research of the problem (Ahmed Abdelaziz, 2015).

3 Bamboo-pile for slope stability

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 available ecological plant, its production releases oxygen in to the atmosphere and absorbs CO2. When using bamboo, transport labor and cost could be reduce, as it is a slender element and it can be planted close the worksites needed. Rapid growths, low costs, renewable and simple material to produce are some other basic properties that make bamboo a sophisticated material for the contemporary development. Bamboo´s physical and mechanical properties match the 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 or concrete, 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 can reach 370 MPa. This makes bamboo an attractive alternative to steel in tensile loading applications (Ghavami et al., 2004).

Different reports dated the earliest papers on the study of the properties of bamboo resistance exists since the beginning of the last century in Germany, Japan, and the United States during World War II (Lopez, 2003). The name bamboo is a popular term to refer from 60 to 90 genera of giant graminea comprising more than 1200 species of different types, of which there are growing mainly in the tropical regions of Asia, Latin America and Africa Fig. 3.1**.** In the American continent it can be founded from latitude 49° in southeastern USA to latitude 34° in south Uruguay and it can reach 5000 meters altitude.

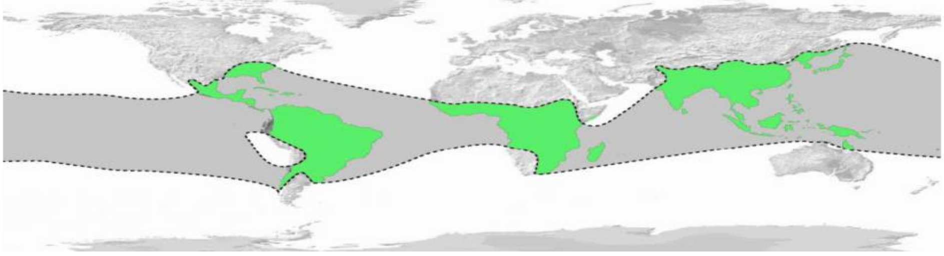


Figure 3.1 Natural Distribution of Bamboo Around The world (Source: Laroque, 2007

Bamboo has rapid growth, its properties complete its development at mature state when it reaches 3 years old. As it is renewable and simple material to produce, bamboo is naturally committed to the contemporary ecologic environmental development awareness, it represent wise innovative alternative to replace conventional materials. Its physical and mechanical properties match the civil construction most updated conventional materials.

For this work the bamboo-pile stabilization element will be represented by Bamboo´s of *Dendrocalamus Giganteus* species as its cane dimensions comprises diameters from 20 to 40 centimeters and its vertical length could reach 40 meters Fig. 3.2a and b. This dimensions properties makes them most suitable among other species for pile to be to overcome slopes instability.

(a) (b)

Figure 3.2 *Bamboo Dendrocalamus Giganteus* dimensions (a) Top view on bamboo´s DG cut (b) Lateral view of bamboo DG from Botanic Garden Rio de Janeiro.

Some of the most popular uses for bamboo are the following:

- Scaffoldings
- Composite elements
- Bridges
- Shelters
- Moving units (bikes and small cars)
- Handcraft

Regarding to slope stabilization with bamboo, it might come to mind in first place to use bamboo as vegetation layer for adding stability to a slope (Fig.3.3). However studies related to makino-bamboo forest in order to provide cohesion increment, stated that this technique is limited for a slope reinforcement and its success depends on factors such as the slope angle and height of roots breast (Der-Guey Lin, 2010).

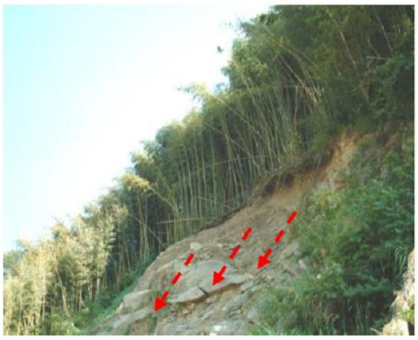


Figure. 3.3 Makino bamboo forest slope failure collapse Font Der-Guey Lin 2010

3.1 Bamboo Characteristics as Structural Material

When bamboo is studied as structural material some other perspectives are easy to remark. Its open space lay on the center of its longitudinal axis and its fibers require smaller mass volume than solid materials, such as wood or steel to support loads. When used as a beam, the tubular element has placement versatility, because its anatomy allows using the capabilities of element properties in 360 degrees with practically uniform performance. The distribution of high-density regions in the vascular bundles, which are composed of cellulose microfibers inside the parenchyma cell matrix of bamboo define it as a functionally graded material (Ghavami et al., 2015).

Comprehensive studies of topics that express and establish techniques, norms, guidelines as well as databases for a successful implementation of bamboo for building construction material are currently increasing day by day. Just to mention a few ISO 22156-2004 Design Standard, the Guidelines on the Design and Construction of Bamboo Scaffolds in India, regionally in Latin America, there is the E.100 Bamboo technical norms in Peru, Brazil and Mexico norms are on their way to be formally accepted (Esteban Flores Méndez, 2014) (Barbosa, Ghavami, & Moreira, 2016). Bamboo in fact resists 6 times more with respect to the specific weight compared to the steel. Fig. 3.4

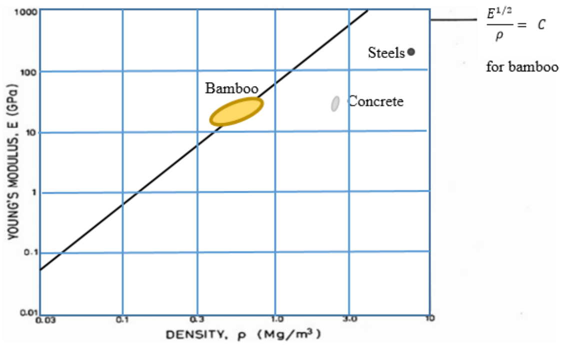


Figure 3.4 Bamboo performance Compared with other materials, in relation with Elastic module (E) vs ρ density (Ghavami K. , 2004) .

Conicity (δ) it's a propertie that has a relevant role for structural purposes and it is already introduced in Colombian and proposed for Brazilian norms. The values conicity are taken by the differences between dimensions of both top and bottom part of the cane divided on its height expressed in percentage value and it should not exceed 1%, this is intended to consider cross section geometrical properties to have no value far away from element. Conicity and dimension values are presented on Table 3.1 for element showed in Fig. 3.5.

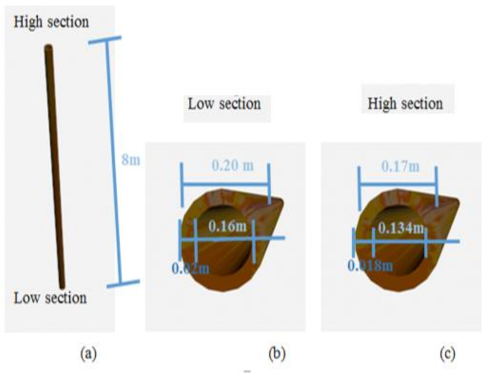


Figure 3.5 Bamboo Pile Dimensions (a) Side view of bamboo pile (b) Low section dimensions for Bamboo piles (c) High section dimensions for bamboo pile

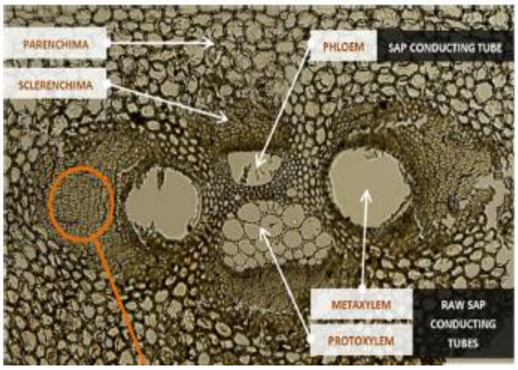
Bamboo geometric dimensions				
Length (L)	8	m		
High section				
Diameter (D)	20	cm		
Inner diameter (d)	16	cm		
Wall Thickness (Th)	2	cm		
Low Section				
Diameter (Di)	17	cm		
Inner Diameter (di)	13,40	cm		
Wall thickness (thi)	1,8	cm		
radio	10	cm		
Average Section				
Diameter (Da)	18,5	m		
Inner Diameter (da)	15	m		
Conicity (δ)	0,38	%		
Moment of de Inercia (I)	6,19	cm^4	0,000619	m^4
Area (A)	99,09	cm^2	0,009909	m^2
spinning ratio (i)	0,25			
slenderness (l)	0,031250			
Bamboo volume	0,07927	m^3		

Net Weight	0,63415	KN

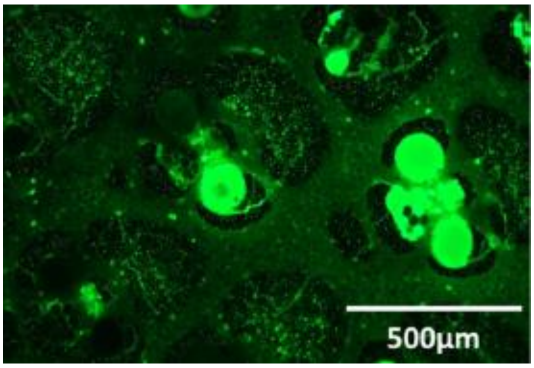
Table 3.1 Bamboo geometric dimensions

3.1.1 Bamboo´s Anatomy

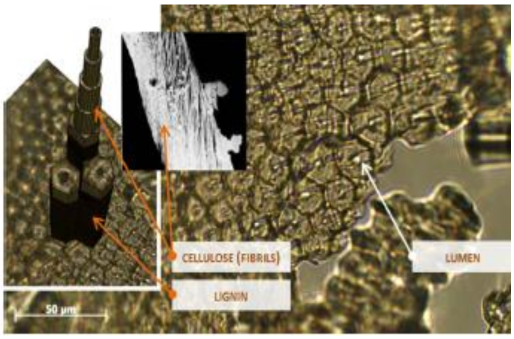
Bamboos are characterized by their hollowness cylindrical shape, their external wall is constituted by epidermis, hypodermis with a subjacent parenquima in a thin cortex. The internal layer is composed by vascular bundles formed by vessels, sieve tubes among others cells, fibers, and schlerenquima tissue with lignin content that along with silica give great strength to bamboo. Fig. 3.6a-d.



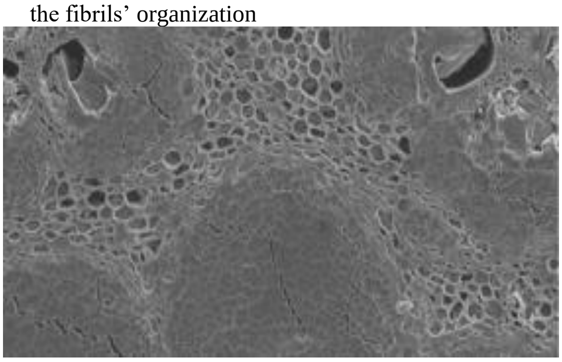
a) Transmission light microscopy image of a *Dendrocalamus giganteus'* transversal cut



b) Fiber bundle detail, 3D illustration of three single fibers and the fibrils' layers and fiber's microstructure, showing the fibrils' organization



c) Reflected light microscopy image carried out in fluorescence contrast mode



d) Scanning electron image

Figure 3.6 Bamboo micro-structural anatomy (a-d) (Queiroz Krause, de Andrade Silva, Ghavami, da Fonseca Martins Gomes, & Toledo Filho, 2016)

For a suitable use of bamboo, it is essential to understand the physical and mechanical properties. The following two sections briefly mention some skills for slope stability objective based on its physical and mechanical properties.

3.1.2 Physical Properties

Variations in moisture content, density and resistance along the thickness of the bamboo are responsible for the adversities that bamboo behavior faces in its use. This behavior has a relation with possible collapses of the element.

Density

The density of the bamboo is measured taking an average of the most solid part and the weakest part of the cane. The anatomical structure determines the distribution of the fibers in a given dimension, in most of the cases it is the diameter or thickness of the vegetal wall. The density of bamboo is estimated between 0.5 and 0.9 g/cm^3. The density increases from the bottom towards the top. At the node it is greater due to smaller the parenchyma´s content. The fibers exist in greater quantity at the upper part where resistance to the flexion and compression tends to have better performance, but it is weaker for the shear efforts Fig.3.7. The upper part of the cane, with smaller vascular bundles, but with a superior number of fibers, causes the density percentage to be increased. Even the highest values of modulus of elasticity are obtained from the upper part.

Bamboo´s module of rupture varies linearly along with density, porosities of the element volume fraction are highly related to bamboo´s density. Recent studies on *Dendrocalamus Giganteus* laminae mechanical test have shown that this species have considerable voids volume fraction which are divided mainly in vessels and pores that influence the tensile and compression mechanical behavior (Queiroz Krause, de Andrade Silva, Ghavami, da Fonseca Martins Gomes, & Toledo Filho, 2016).

For these reason bamboo´s density turn to be a smart option in areas where it is difficult and expensive to transport material such as steel and concrete, and where the scatter space represents an issue to handle big and heavy elements.

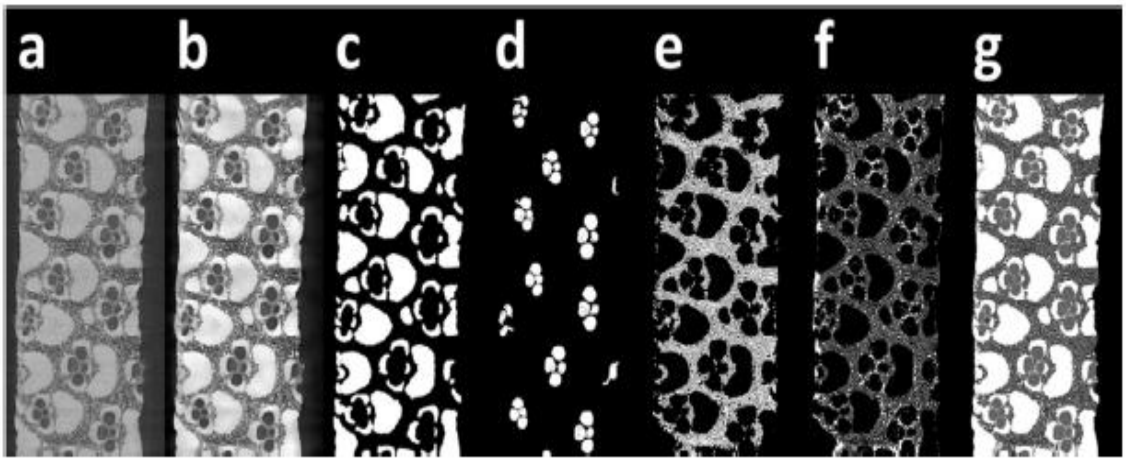


Figure 3.7 X-ray microtomography image analysis: (a) a typical slice image from ML sample; (b) filtered image; (c) sclerenchyma; (d) vessels; (e) pores; (f) parenchyma; (g) a pseudo-color composition showing segmented phases: pores (dark grey), vessels (grey), parenchyma (light grey), sclerenchyma (white). parenchyma (light grey), sclerenchyma (white) (Queiroz Krause, de Andrade Silva, Ghavami, da Fonseca Martins Gomes, & Toledo Filho, 2016).

Water Content

The water content is the amount of water contained in the wall and in a cell lumen of a particular section of the cane as a percentage of its own dry weight. Among the different species, water content in a bamboo may vary in different parts of the same cane. Water content is influenced by age and season. Green specimens without maturity present higher moisture content than the mature specimens. Under natural conditions, the moisture content of a cane can range from 40 to 150%.

Younger canes contain greater uniformity in moisture content in the longitudinal direction of the element. At one year of age, the cane has an approximate content of 120 to 130% of humidity in the upper and lower part. At 2 years of age, the water content mainly reduces at the top. Throughout its cultivation and before harvest, the bamboo cane remains moist and fresh. The moisture content is higher in the interior than in the exterior part of the cane, reported variations is 155% for the inner part and 70% for the parts close to its periphery. The variation of the moisture content has a relation with the amount of parenchyma cells present on the element and the amount of water drought. Water content influences resistance properties, in dry conditions the resistance of the cane is greater than in green state. Bamboo as a hygroscopic material has an active moisture content balance, which means that when it is completely wet, the bamboo discards excess water and transfers it to the atmosphere until the moisture content reaches a balance with the atmosphere. The moisture content balance depends entirely on the relative humidity of the atmospheric environment where the cane is found (Lopez O. H., 2003) (Qingfeng, Harries, Xiangmin, Liu, & Gottron, 2014).

Knowing that bamboo tends to lose resistance after being immersed in water, in the case of the stabilization with bamboo piles, a water proof treatment would be suitable and even indispensable to keep the resistances durability, especially to protect the rigidity of the element, which is fundamentally needed for forces interaction between the soil and pile.

Shrinkage

The bamboo as anisotropic material has moisture content in its axial, radial and tangential directions and when cell walls start losing it, the shrinkage begins to settle and at the same time the strength of the material increases (Ghavami K. , 2004). Shrinkage is not a fully continuous phenomenon, it can stop when the moisture content has decreased by 70-40% and then it can start over. Excessive and irreversible shrinkages, just above the fibers' saturation point can happen with only a partial recovery in intermediate stages. Bamboo´s drying process certainly influences on element performance, a quick drying process can lead to the emergence of cracks or separation of the surface due to a sudden shrinkage. Authors noted that shrinkage occurs from the bottom to the top due to the amount of parenchyma in the thickness of the wall along the cane. Bamboos of the *Dendrocalamus Giganteus* and *Bambusa Vulgaris Schard* have shown low absorption capacity among species tested. The water immersion of these species raised the water content by 6% in 7 days water immersion (Qingfeng, Harries, Xiangmin, Liu, & Gottron, 2014). For stabilizing pile element this is a great characteristic as stiffness is required to remain as less as possible affected.

Thermal Conductivity

Bamboo has an excellent thermal insulating capacity. The cellular structure cavities when dried become air-filled, which isolate them, resulting in minimum thermal conductivity. Factors such as density, moisture content and atmospheric temperature could modify inner structure properties, thus thermal behavior results favorable minimizing this inconvenient effects. This properties may not apply under the ground as air will be difficult to fill into the cavities, this another important reason to apply a good treatment to take care of the probable issues this property may represent (Lopez O. H., 2003).

Hardness

Wear and impact resistance represent the hardness of bamboo. As explained earlier, the hardest part of the cane wall is three thirds to the outside, which includes a large amount of fibrous bundles and the weakest part is three thirds of the inner wall where the amount of fibrous bundles is smaller, but it has a greater number of parenchyma cells. The outer sheath wall consists of two layers of epidemic cells with high silica content on which the epidermal layer lays on. The outer layer of the cortex covers in a cutinized of glazed layer known as cuticle and is composed of cellulose and pectin covered by a layer of paraffin. Between the epidermises, hypoderm lies, consisting of several layers of thin walls of *sclerenchumatous* cells. These two layers spread an extraordinary hardness to the outer surface of the cane, and they form a type of protective shield against insects, termites, and weather (Ghavami, 2011).
Hardness is mainly a property that piles for stabilizing slope base on their design.

3.1.3 Mechanical Properties

Bamboo culm structure is strategically provided with walls strong enough to have flexion and tensile resistance that could overcome lateral wind force, it also is provided with compression resistance to support its own weight. Along the culm mechanical properties have different meanings, but commonly it is taken an average between the low, medium and upper zone. The vascular bundles in the internodal part consist of metaxylem, phloem, and proxtoxylem vessels, which are founded around fiber bundles and they spread the resistance along bamboo cane (Gavhami, 2011).

Strength Values

To reach a specific resistance value of bamboo may result in a hard controversial labor. Worldwide researchers have obtained different values test. Different values from the same bamboo crop are commonly to happen, this issue is attributed to the different procedure on bamboo tests (Sharma, Harries, & Ghavami, 2015). The next table expresses some results found by different authors that have published their results for

Dendrocalamus Giganteus species on compression, flexural, traction and shear strength Tables 3.2 to 3.6.

Autores	especie	s_{mc} (MPa)	Ec (MPa)
Lima (1995)	DG	33-37,5	23.24-45.33
Sartori e Cardoso Jr.(1997)	DG	63,74	X
Gonçalves et al. (2000)	DG	55	X
Ghavami & Marino 2001	DG	77,96	X
Pereira e Beraldo (2007)	DG	65,5	X
Carbonari et al 2016	DG	x	X

Table 3.2 Compression strength values results by different authors

Autores	especie	s_{mf} (MPa)	Ef (MPa)
Lima (1995)	DG	37	12000
Sartori e Cardoso Jr.(1997)	DG	122,58	x
Gonçalves et al. (2000)	DG	166	x
Ghavami & Marino 2001	DG	x	x
Pereira e Beraldo (2007)	DG	98,9	x
Carbonari et al 2016	DG	x	x

Table 3.3 Flexural strength values results by different authors

Autores	especie	s_{mt} (MPa)	E_t (MPa)
Lima (1995)	DG	23-210	6300-16513
Sartori e Cardoso Jr.(1997)	DG	135,33	x
Gonçalves et al. (2000)	DG	195	x
Ghavami & Marino 2001	DG	157,1	18950
Pereira e Beraldo (2007)	DG	147,7	x
Carbonari et al 2016	DG	119	x

Table 3.4 Traction strength values results by different authors

Autores	especie	s_{mc} (Mpa)	Ec (Mpa)
Lima (1995)	DG	x	x
Sartori e Cardoso Jr.(1997)	DG	44,13	x

Gonçalves et al. (2000)	DG	10	x
Ghavami & Marino 2001	DG	x	x
Pereira e Beraldo (2007)	DG	x	x
Carbonari et al 2016	DG	x	x

Table 3.5 Shear strength values results by different authors

3.2 Bamboo Treatment

Bamboo treatment may have different approaches. Since it is a plant cultivation approach attend to give helpful information for prevent issues with the crop. Some aspects are present below:

Weather and temperature

Bamboo grows in temperatures between 9°C and 36°C. Several authors have proved that bamboo cultivated in drier regions tend to have better resistance.

Topography

One of bamboo´s advantage is that it can be cultivated in terrain with sloped topography. In fact, the bamboos grown in regions with pronounced slopes have greater resistance because of the gravitational forces to which they are subjected.

Bamboo´s Age

In general, bamboos at 3 years of age have reached their maximum resistance. Bamboos aged from one year to two years when being dried may obtain higher resistance values compared to the more mature ones.

Collection

To give a good bamboo treatment, at the time of being harvested, several authors have expressed different techniques, such as to collect bamboo in dry seasons because the amount of starch is smaller; others instead said that in in the rainy season insects are drown. And others related to moon phases.

Each project purpose defines the durability of bamboo wanted to be maintained, this is another aspect to take care of when choosing a way of treatment. The most commonly bamboo attended problems are micro-organism attack and shrinkage. The high starch content may attract insects to the bamboo as a food resource. An increase in the moisture content causes the increase of starch, provoking insects to become even more attracted to invade the bamboo element, consequently impairing its durability. Hygroscopic reaction on bamboo may affects its mechanical properties, thus in order to add durability to bamboos waterproof treatments are frequently a challenge.

Physical-Chemical Treatment

The called physical treatment starts after crop is collected. Anatomy plays relevant role when choosing a suitable treatment looking forward to obtain the objective functionality of the element. Besides keeping away insects, the physical-chemical treatment is mainly used to reduce the appearance of cracks in cases of a drastic change in temperature, it may cause cracks and fissures in the bamboo, which mostly leads to splits on specimen.

Drying can give bamboo a better conservation of its physical properties, it reduces insect attack and save transport costs making bamboo lighter. Authors suggest that a moisture content between 13 and 15% is sufficient to contribute to enhance durability (Ghavami, 2011). Some of the most popular methods for drying bamboo are: the natural method, in a temperature-controlled room, in an oven and with smoke or fire. Natural drying is the most economic method, drying in kiln can result faster method but it needs constant attention because carelessness can cause fractures in the element. Drying or curing with smoke is convenient to increase resistance to putrefaction and cracking, thus extending the lifetime. Another type of curing is immersion in brine or sludge it is favorable to degrade bacteria by reducing the attack of insects or larvae as the salinity of the waters and the sludge benefit in the process to exterminate the starch (Lopez, 2003).

Chemical Treatment

The chemical treatment is mainly based on the preservation of the mechanical properties of the bamboo, preventing the degradation of the durability by means of chemical solutions as soluble oil or simple oil obtained by the distillation of coal like creosote and tar are effective for buried stems. Some designed solutions based on additives are pentachlorophenol solutions and solvents, such as Impretox, Pentox, Xilophene and Xilotex. The disadvantage is its high toxic potential.

Water-soluble solution effective in preventing fungal and insect bites. They are combinations of salts, among others, such as:

- Chlorinated Zinc Chromate
- Or Chrome Copper Acid
- The Metarsenite of Zinc

- Chromium Copper Arsenate

As oil solution they are also substances with toxicity.

Synthetic Resins attend waterproofing agents that sometimes prevent insects and fungi attack (Culzoni, 1989).

Different inconveniences may risk the performance of chemical substance over bamboo such as raining, leaching resistance and a high evaporation capacity. Good penetration solutions with high diffusion capacities have more chances to achieve an improvement on the element (Bello L. A., 1997)

In order from the lowest to the highest energy consumption, the most popular methods for chemical treatment and some of their characteristics are mentioned to follow.

Container solution, needs bamboo to be impregnated quickly after collecting the elements this process is called Leaves Sweating, the immersion happens when the bamboo element is totally submerged in a water-soluble or oil derived solution. It can be done in cold or hot temperatures. The water-soluble solutions perform better with this method and economic advantages may be relevant.

Some products are externally applied on the outer layer of bamboo a few times; bamboo sometimes can repel the substance and this alternative may become deficient. Recommendation says that the element should have no more than 15% water content. Never the less effectiveness of this process is mostly appreciated with bamboo slats.

Culzoni (1989) recommended to use Boucherie method for a large amount of bamboos regarding it should be done shortly after collection to improve effectiveness of the method.

Day by day, researchers discover several methods to improve the structure of the bamboo for strengthening purpose. Pallav Saika, in 2015, created a formulation based on tobacco leaves, resin solution, vegetable oil removed from *Azadirachta indica* and an emulsifying agent to improve the flexural strength and compression in bamboo. It was developed showing the capabilities of the most ecological additives (Pallav Saikia, 2015).

Recently, PUC-Rio tested impregnation of silver Nano–particles. This chemical treatment showed a great performance increasing durability of the specimens that were treated in the study to conserve bamboo properties, avoiding microorganism attacks for longer than 150 days (O. Pandoli, R. D., 2016) documented and they still going with same performance updated.

As mentioned earlier treatment becomes part the project when using bamboo no matter it is to preserve appearance, increase durability, tensile strength, adhesion, compression, splitting or any other physical-mechanical property. When addressing sustainable issues to bamboo uses it is important to have in mind that durability treatment may take away ecological aspects when using chemical solutions. To foresee the scenarios that bamboo will be subjected and a correctly applied treatments highly increases the chances of a successful project. However it is not feasible to determine a general method for treating bamboo, since the objectives or circumstances of its use are not always the same. Different situations can help to save on the cost, or to provide treatment whenever and wherever the budget allows and the treatment completes the desired purpose.

3.3 Bamboo Durability

Bamboo is a material that could be degraded under environmental conditions, it is normally attacked by insects and moulds. Its durability is determined on factors such as: type of species, age, conservation conditions, treatment and curing. The two main durability issues are the insect attack and the moister content. Between this two issues is an existence relation cause humidity content may produce starch on the bamboo which turns out to be an insect's food resource making it attractive for them to invade.

Durability of natural bamboo varies from 1 to 36 months depending on the species and the climatic conditions. Documented research in India say that on storage bamboo receives from 20 to 40% of damage on the culm. Tribal housing made of structural bamboo deteriorates in 2 years period when replacements requirements are needed (Muthukrishnan, Remadevi, & Sundararaj, 2009). Muthurishnan et al. (2009) did tests for different chemical and botanical solutions treatments on bamboo specimens of 60 cm length culms buried in a termite test yard for the species for *Bambusa* bamboo and *Dendrocalamus Strictus* for a 36 months period. Bifenthrin treated bamboos completed the test with 100% protection against termites. Dr.Shailesh Kr.Agrawal xecutive Director, Building Materials & Technology Promotion Council, stated on his research on Bamboo as a Material for Housing and Buildings that untreated bamboo has a service life time between 4 to 6 years in exposed conditions.

When it comes to the bamboo treatment its fibers are indispensable to be kept unchanged any moment. The most common methods used are leaves transpiration, impregnation, immersion and Boucherie Method.

An experience with bamboo treated against insects and for enhancing bonding capabilities has been documented. It was use as a concrete reinforcement on a beam at PUC-Rio, the specimen resulted in satisfactory condition after a lapse of time of 15 years with just slight deterioration on the tensile strength when was compared to a untreated bamboo specimen, it was also compared with a structure of concrete reinforced with steel which was part of the subway of Rio and with 30 years aged the element of steel presented great corrosion. In this same research water absorb capacities among several species of bamboo is presented Fig. 3.8 where Bamboo DG and Bamboo from the species *Bambusa Vulgaris Schard* showed the lowest capacity to absorb water with also dimensional variation of the transversal section beneath the other species tested. (Ghavami K. , 2004).

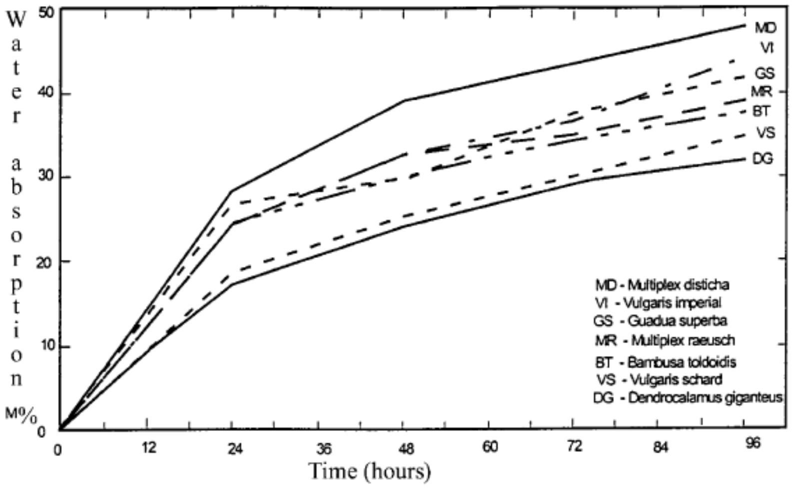


Figure 3.8 Water absorption of different species of bamboo (Ghavami K. , 2004)

Updated research with silver nanoparticles impregnations, demonstrated a great improvement, leaving bamboo free of fungal colonies for documented time of 5 months documented, never the less the bamboo up today stay still the same.

Some other structures of bamboo such as the bamboo Amphitheater also in PUC-Rio that was raised up in 2014 and it still up without any degradation appreciable up today.

4 Pile modeling by Finite Elements FE- Method

Some of the most used methods for slope stabilization with piles employs soil pressure limit obtained in empirical or numerical analyses. Currently the finite element method is one of the most recurrent analysis methods, since it facilitates the labor and offers precision. Recently FEM in 2D and 3D couple analyses are more frequently seen as they became increasingly available (Ahmed Abdelaziz, 2015). Kourkolis et al. 2011 propose in one of his publications a hybrid method based on two steps stabilizing piles modeling by means of the finite element technique, which hold wide analytical acceptance. The first step is to develop a slope in which the safety factor is increased by means of strength provided by one single pile. In the second case, with the configuration of set of piles, it is sought to provide the strength prescribed in step one. 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.

4.1 PLAXIS

PLAXIS (Finite Element Code for Soil and Rock Analysis) is a finite element package developed for applications to geotechnical problems by the Technical University of Delft, in The Netherlands since 1987, and succeeded in 1993 by the commercial company PLAXIS. It was developed with the purpose of being a practical numerical tool for the use of geotechnical engineers who are not necessarily specialists in numerical procedures. This software development philosophy has resulted in a quite simple user-engineer interaction (pre- and post-processing routines are very easy to manipulate). Soil strain, stability and ground water analyses are some geotechnical engineering issue PLAXIS was develop to analyze.

When modelling pile design for slope stability the next factors are takin into account:

a) The pile material

Pile material stiffness capabilities to absorb loads and transfer forces from a stable layer to the less stable layers is mainly given by the elastic module provided for E parameter.

b) Pile Dimensions

The greater the diameter, the greater the capacity to absorb forces. The pile diameter directly influences on the ultimate strength of the pile, depending on the properties of the pile material. Regardless of the pile´s behavior linear or non-linear, both are able to provide force by this technique. For the non-linear behavior piles need to reach the ultimate strength before they reach the maximum curvature, which will depend in part on the pile length.

c) The pile bedding

Seeking to generate the appropriate acting forces in the pile, the bedding size must provide enough resistance for the pile to remains unchanged to the same level of deformations. Conclusions based on soil homogeneity are that the longer and deeper the bedding in the zone of stable soil, the greater the moment of flexion required to reach the resistant force needed.

d) Soil properties

The bearing capacity of the pile under soil load pressure will be tested, hence soil properties play a relevant role in this interaction between both elements on whether the soil properties will help to provide stability together with the pile or whether the soil will flow around it.

e) Spacing

Decreasing space between piles increases the force per unit width, but the effectiveness decreases the soil pile iteration. The spacing directly influences the displacements required to generate the last effort. For this reason, not all configurations can provide the necessary conditions to generate an effective acting force. The sliding soil volume can generate certain bending force acting on the piles. In this situation the spacing is governed by the depth where the slip occurs.

Thus when it comes to a real situation pile modeling can affect the project economically when it is needed to increase the pile dimensions, the depth of excavation, or the requirement of more piles depending on spacing determined by soil composition properties on the slope.

4.2 Pile Structural Element on PLAXIS 2D and 3D

PLAXIS 2D

Although strength forces on the soil and strains have three-dimensional behavior 2D may seems unrealistic to use for analyses, 2D also may result in a simplified representation of a plan strain model in order to preview a global behavior of structure and even obtain some preliminary results on deformations or structural forces. Idealizing a superimposed position in the mesh on the out-plane direction, whereas soil displacements are supposed on an average in the interaction with other structural elements influenced by interfaces stiffness. (Mortier, 2014). In PLAXIS 2D provide 3 main elements to represent a pile or pile rows with different specific characteristics mention below:

Plate elements

- Advantages
    - Possibility to enter an axial stiffness;
    - Possibility to enter a bending stiffness and to obtain structural forces in piles;
- Limitations
    - When using interfaces unrealistic shear planes may be introduced.
    - Interaction with soil due to interfaces, but soil cannot flow through the plates (Discontinuous mesh);

Node to node anchors

- Advantages
    - Possibility to enter an axial stiffness;
- Limitations
    - No interaction with soil, soil can flow through the n2n anchors (continuous mesh);
    - No possibility to enter a bending stiffness and to obtain structural forces in piles.

Embedded Pile Row

- Advantages
    - Possibility to enter an axial stiffness;

- Interaction with soil due to line to line interfaces and soil can “flow through” the embedded pile row (continuous mesh);
- Possibility to enter a bending stiffness and to obtain structural forces in piles;
- No unrealistic shear planes are introduced.

Embedded Beam Row or Embedded Pile Row

Thus embedded pile row or beam row combine the best properties of the plate element and the node to node anchor making of it the most reliable pile representation among the three options. The “embedded pile row” element can be used to simulate a row of piles with a certain spacing perpendicular to the model area. The stiffness properties are entered per pile, the program calculates the smeared properties per meter width. Special feature of this structural element is that it is not directly coupled to the mesh. It is indirectly coupled via a line to line interface (consisting of spring elements and sliders) Fig. 4.1. This separation between the pile and the soil mesh is the main characteristic of this element. The embedded beam row is assumed as an average of the soil displacements on the out plane. The distribution of the embedded beam row shear force calculates the soil lateral mobilization to evaluate whether it is exceeded or not. This last assessment is made by depth meter unit, over total pile length (J.J.M. Sluis, 2014).

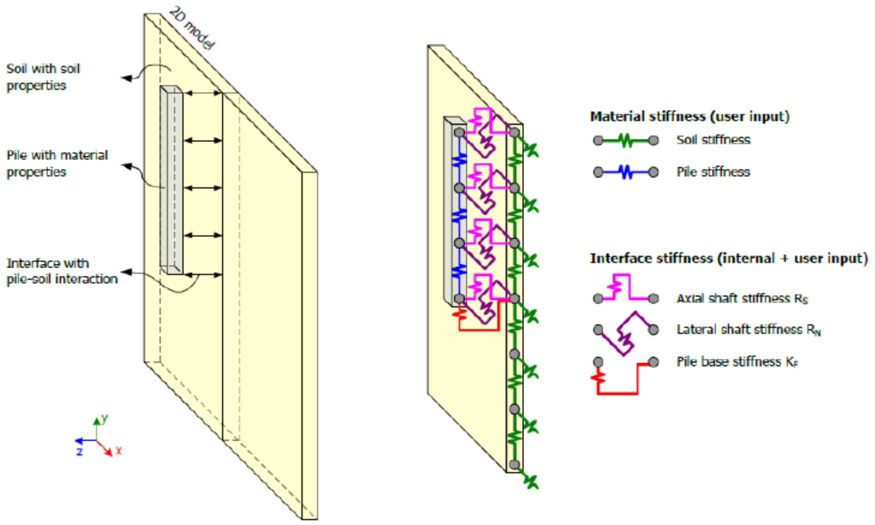


Figure 4.1 Principles of Embedded Pile Row or Beam row

PLAXIS 3D

In PLAXIS 3D software embedded pile beam is used to represent the pile. Dao 2011 performed an analysis on the pile model prior to the implementation of the embedded pile in the PLAXIS 3D software. He concluded that the embedded pile in general is able to represent a real pile, even with a margin of over estimation of forces with the respecting displacements in order to simulate the realistic situation for pile stabilizing slope (Dao, 2011).

Embedded Pile

The embedded pile in PLAXIS 3D has been developed to describe the interaction of the pile and the soil around it. The interaction in the pile skin and the foot resistance is described below: by means of lined interface elements, the pile is considered as a beam that can traverse a tetrahedral element of 10 nodes with arbitrary orientation (Fig. 4.2). This is due to the existence of a beam element of 3 extra nodes that are introduced inside the tetrahedral element of 10 nodes.

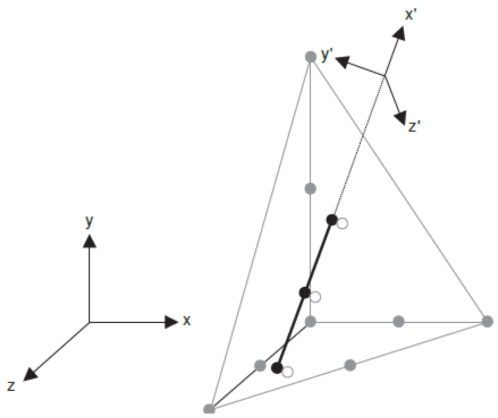


Figure 4.2 Embedded pile element illustration, the black line is the embedded beam. Gray balls represent virtual nodes of the soil element.

Embedded pile can be used to model different types of slender structures that interact with soil and / or rocks as a pile, soil anchor or rock-bolt. The embedded pile is assumed with an elastic region around the pile having a dimension equivalent to the pile diameter, this makes it almost behave like a volume pile. However, installation effects of piles are not taken into account and the pile-soil interaction is modelled at the center rather than at the circumference. Once the mesh is created, new nodes in the pile are created as well. Thus, special interfaces of the pile-soil interaction are made by the connection of new pile nodes and existing soil nodes. An elastoplastic model is used to describe the behavior of interfaces. The interaction may involve the strength of the skin (in units of force per length) and the resistance of base tip (in units of force), the sum of which is considered the carrying capacity that each embedded pile has. For both resistance forces, a critical fault is applied to distinguish between the behavior of the elastic interface and that of the plastic interface.

The skin resistance of the interface is represented by the following constitutive Eq. 4.1:

Equation 4.1 Skin Resistance of the interface

$$t^{skin} = K^{skin}.\Delta u_{rel}$$

Where t^{skin} is the force at the points of integration; K^{skin} is the stiffness matrix of the interface material; Δu_{rel}= $\boldsymbol{u^p - u^s}$ is the relative displacement of the vector between the ground and the pile. In addition, the above equation can be represented in coordinates of the 3D system (n, s, t) as in Eq. 4.2.

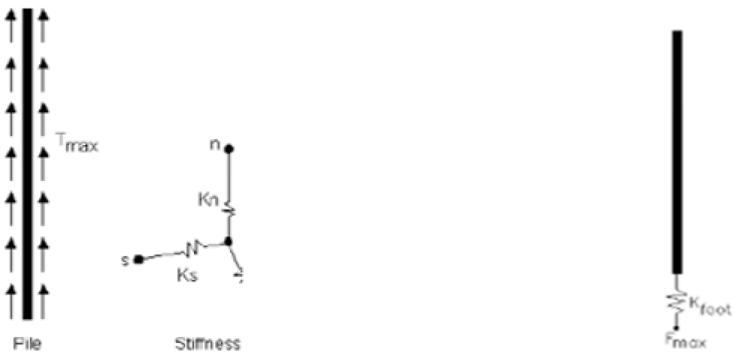
Equation 4.2 Skin Resistance Coordinates Matrix

$$\begin{bmatrix} t_n \\ t_s \\ t_t \end{bmatrix} = \begin{bmatrix} K_n & 0 & 0 \\ 0 & K_s & 0 \\ 0 & 0 & K_t \end{bmatrix} \begin{bmatrix} u_n^p - u_n^s \\ u_s^p - u_s^s \\ u_t^p - u_t^s \end{bmatrix}$$

Where:

t_n	traction stress in axial direction
t_s e t_t	The normal traction in the horizontal direction (remains elastic)
K_n	Shear elastic Stiffness
K_s e K_t	Normal elastic Stiffness in horizontal direction
u^p	Pile Displacement
u^s	Soil Displacement

Fig. 4.3a gives a view of Eq. (4.2). It should be considered that the skin resistance T_{max} is defined as the interface ability to withstand the shear force t_n along the pile (in the axial direction of the pile). For the elastic behavior of the shaft, the shear force t_n at the particular point has to be less than the local skin strength at the point T_{max} ($/t_n/ < T_{max}$). In the same way, the plastic behavior happens when shear strength is greater than the skin resistance ($/t_n/ \geq T_{max}$)



(a) Shear Resistance Tmax along the pile (b) Maximum Force at the base of the pile

Figure 4.3 Shear Resistance at the base of the pile (a) and (b)

In addition to skin resistance, at the tip it is governed by a non-linear spring at the base (Fig. 4.3b). The resistant tip is represented by the following Eq. 4.3:

Equation 4.3 The tip resistance

$$0 \leq F_{tip} = K_{tip} \cdot \left(u^{p}_{tip} - u^{s}_{tip}\right) \leq F_{max}$$

The force at the tip of the $F_{tip\ pile}$ is zero in the case of pullout (tension behavior). The failure occurs when the force at the F_{tip} pile is equal to the maximum strength at the pile edge in the case of compression. Figure 4.4shows the normal force, shear force and traction force acting on the sliding of the element.

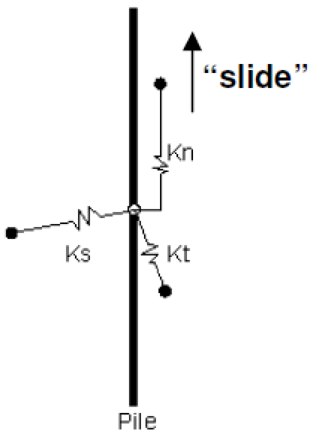


Figure 4.4 Node Model for soil pile Interaction

Embedded Beam Row VS Embedded Pile

The embedded pile row or beam row in 2D basically behave in the same manner as the 3D embedded piles: a structural line element coupled via springs and sliders to the mesh. Hence piles deformation are elastoplastic strains of the soil and/or from the line to line interface. The biggest difference, which also accounts for the 2D vs. 3D behavior, is the stiffness of the line to line interface. In difference the embedded pile does form part of the mesh, instead of being superimposed on it, as embedded beam row does in 2 dimensions as it can be seen in Fig. 4.5. Both two elements interactions are showed:

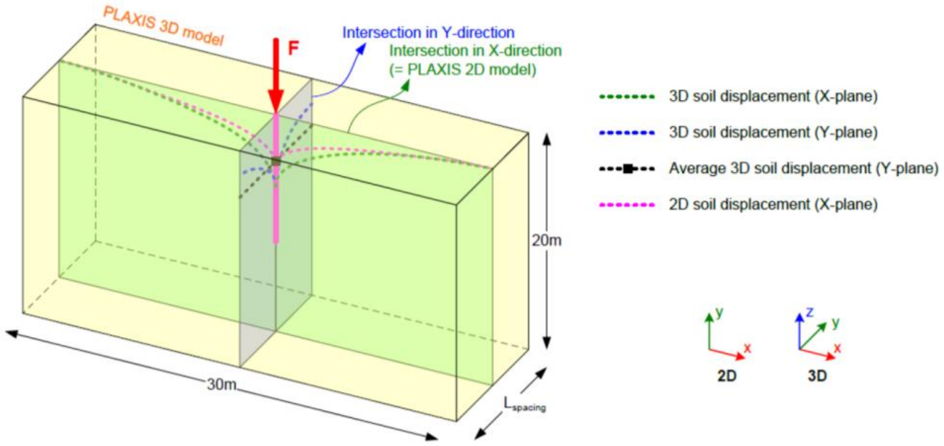


Figure 4.5 2D beam row and 3D embedded pile behavior

The stiffness of the springs in the 3D line to line interface is set to a high value such that elastic deformations are negligible but not so stiff that numerical problems arise. As a result of this choice all deformations of the pile are a result of elastic/plastic deformations of the soil itself and/or from plastic deformations in the line to line interface. a 2D model however this principle no longer works since the soil displacements are no longer a representation of reality but rather an average of the out of plane soil displacement (J.J.M. Sluis, 2014).

However, in comparison with a real situation, it is desirable that the bearing capacity of the beam should be established on the basis of the actual load tests of the pile testing element.

4.3 Pile Soil Interaction in PLAXIS

The soil-pile interaction is mostly done in the centrality and the embedded beam is assumed to be an elastic region which is equivalent to the diameter of the embedded pile as mention before. The displacement produced in this zone of the piles is expected to occur at the same time in the surrounding soil. In the interaction, only the compression, tensile and flexural stresses in different directions can be represented, and all of them may have some significance for each application of pile in order to analyze the behavior of the soil-pile interaction.

The pile location regarding the slope or landfill construction has a certain influence on the pile edge displacement and the bending moment. It is important to stress out that the flexion of the pile depends greatly on the proximity and magnitude of the stresses caused by the soil movement. The same effect can be attributed to the displacements. R_{inter} reduction factor influences the tensile force. After the tensile force occurs, the pile is subjected to a lateral effort against the ground, pressing the front part of the pile and tensioning at the back. R_{inter} parameter has significance in the existing soil displacements around the pile over the soil-shear iteration through the tensile stress of the element.

R_{inter} interface acts through a layer-dependent traction model that directly relates the force around the pile with the resistance of the skin. The R_{inter} interface can also be used to control sliding between the pile and the ground in the axial direction, which means that there is an influence on the relative displacements of the soil-pile, whenever it is in the axial direction. Plaxis manual offers some options for R_{inter} values relate to materials and soil interactions Table. 4.1.

Interface Tipe	R_{inter}
Sand / steel	2/3
Clay / steel	1/2
Sand / concrete	0,8 – 1,0
Soil / geogrid	0,8 – 1,0
Soil / geotêxtil	1.0

Table 4.1 – Some typical values for R_{inter}.

Other parameters that have a certain influence when considering the displacements caused by the movements of the soils in vertical and horizontal directions in the soil model are the parameter M that determines the coefficient of vertical and / or horizontal tension and the parameter OCR, which is the inverse of the consolidation coefficient.

Modeling satisfying situations of a pile subjected to lateral forces caused by soil movements tends to create the interaction where the soil activates the compression, tensile bending and shear forces of the pile. These efforts can be generated by establishing the soil parameters in the PLAXIS software in order to obtain the required conditions to prove the pile capabilities to stabilize a soil mass.

The safety factor SF analysis is a popular method to evaluate slope stability. In order to model a slope in critic failure situations, soil properties are inserted with parameters that decrease the SF until it leads to failure or close to it. From that moment on, it is possible to begin pile design for increasing slope stability raising the safety factor values.

5 Study Case

The creation of a critique surface rupture by numerical tools, especially finite elements, it is not a minor issue. It occurs by the resultants of stress distribution obtained by this method, associated to a lower safety factor for many idealized critique rupture surfaces in the domain. By this means, sloped was forced to slip with a cohesive soil parameter variation. This chapter presents the performed tests to evaluate the bamboo-pile capacities for slope stabilization by finite element couple method in 2 and 3 dimensions using numerical software PLAXIS. The study test description is based on the information discussed in the previous chapters.

5.1 Critic Slope Definition

Parameters of tested soil model data were abstracted from previous model studied by Zou et al 1995 used to perform equilibrium limit state to develop a critical rupture surface, also used for bamboo pile stabilization analysis by Lobato in 1997. The analyses executed were based on two stages divided in two phases each one. The analyses execution were based on two stages divided in two phases each one. The first two phases corresponds to the linear elastic stage. First the gravitational activity takes place at initial phase and then the pile or piles are included 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. 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, a clay embankment with next properties, 200 MPa for elastic module, specific weight of 8 KN/m^3, 20° for friction angle, 0.25 for Poisson´s ratio and cohesion of 4 KPa. The sliding surface stars developing below 4.20 m dept induced by reducing the cohesion to 3KPa Fig. 3b.This same Zou´s slope model was studied by different researchers such some calculations of SF are presented below on Table 5.1.

Autor	Method	SF
Lobato 1997	Limit Equilibrium Method (Janbu)	0,9600
Zou et al. 1995	Finite element program coupled with an improved dynamic method	1,0000
Nguyen 1985	Bishop Method	0,9800
Angel Jaime 2017	Finite Element Method with PLAXIS 2D software	0,9638
Angel Jaime 2017	Finite Element Method with PLAXIS 3D software	1,034

Table 5.1 Some Safety Factor Zou´s Model from different Researchers appling different methods

5.2 2D 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 27° degrees slope section and finally the top section also flat with 20-meter height (Fig.5.1). Calculated safety factor for those parameters resulted on 1.022 (Fig.5.2).

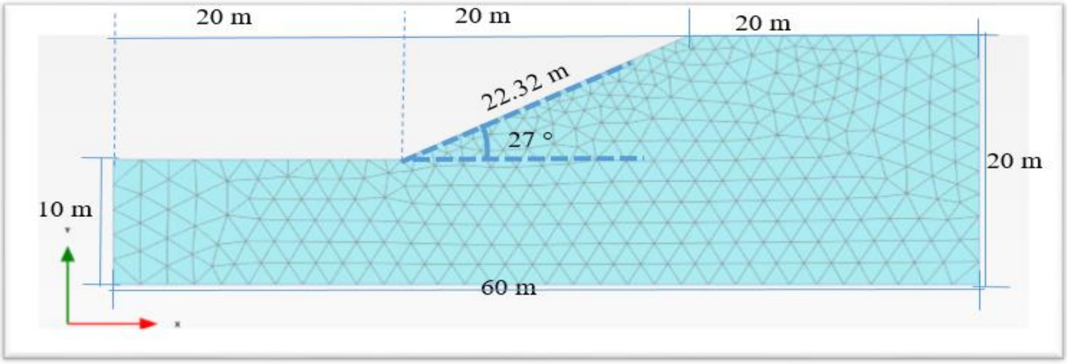


Figure 5.1 Slope Mesh in PLAXIS 2D

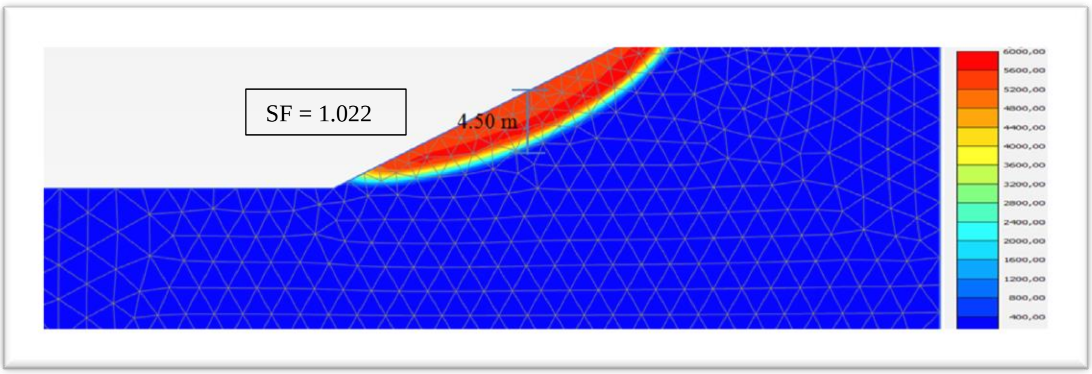


Figure 5.2 Safety factor calculation and critic rupture or sliding surface

Bamboo pile analysis

Bamboo´s properties were taken from a previous work of Lima 1995, who did essays bamboo DG to provide mechanical resistance values. He did also use it for slope analysis objectives. Pile element properties for FE analyses are 12 MPa for young´s module, 8 KN/m^3 for specific weigh for a circular tube pile type with thickness of 2 cm. Bamboo-pile position, inclination, spacing and diameter where aspects for 2D analysis in this work.

Position Influence

Different H/Ho coefficient bamboo-pile positions (Fig. 5.3) along 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 at H/Ho = 2 (Fig. 5.4), from that position on, the safety SF starts decreasing but no less than unity. Table 5.2

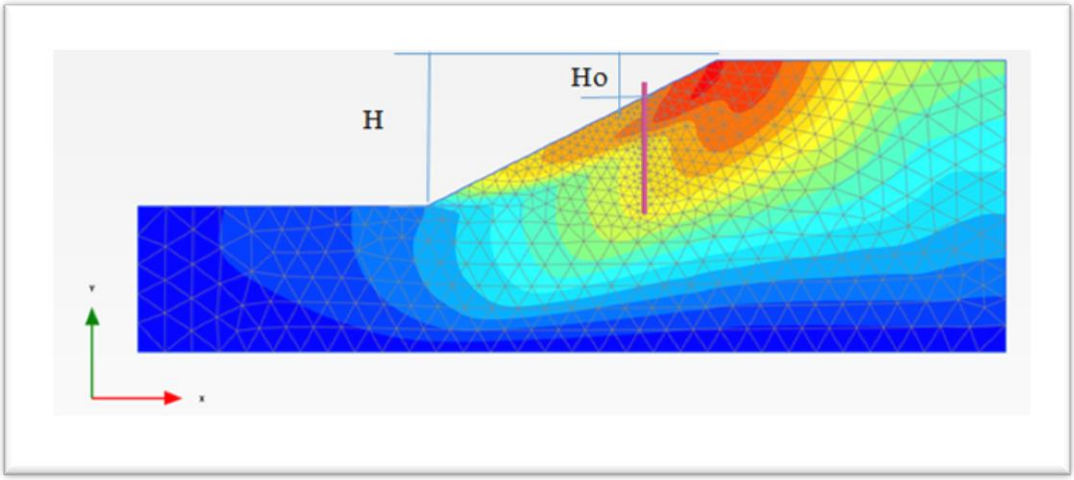


Figure 5.3 Pile inserted near top of the slope

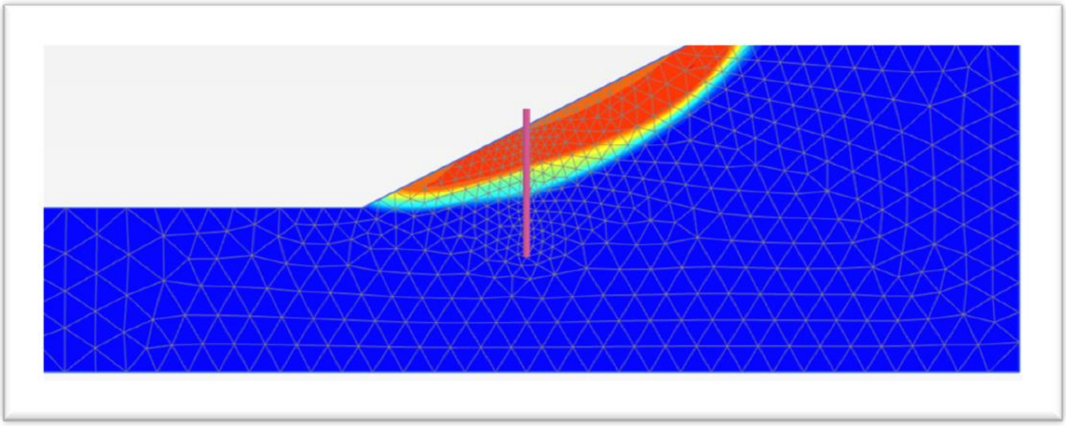


Figure 5.4 Pile vertically inserted position H/Ho = 2.00

Bamboo-pile Position Influence		
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%

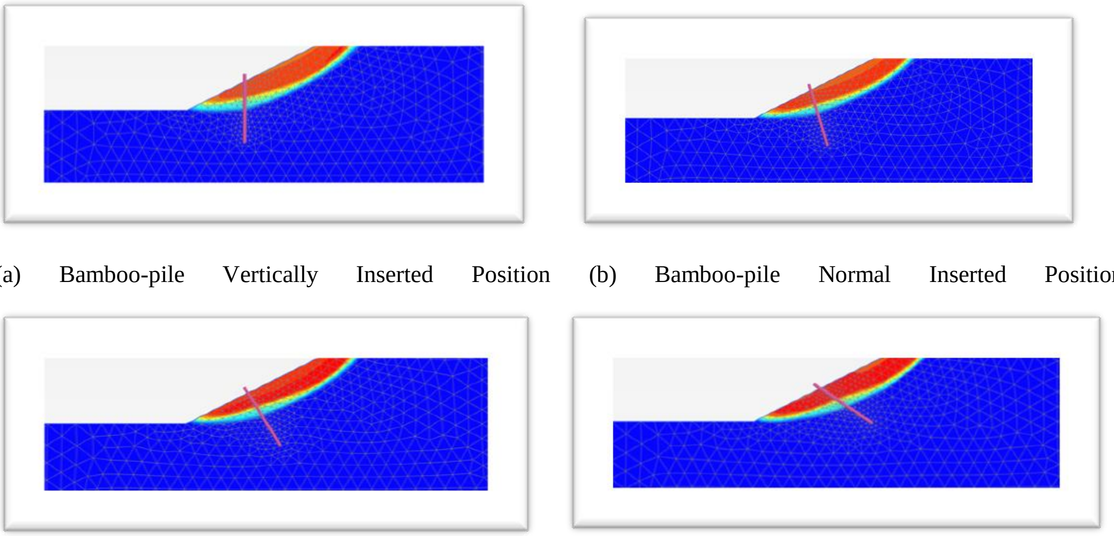
Table 5.2 Bamboo-pile Position influence on the slope model for PLAXIS 2D

Inclination

For inclination position H/Ho = 1.60 was taken to perform the analysis. To observe the influence three situations with different angle of insertion had been compared to vertical insertion on safety factor value. Normally inserted to slope, 45 degrees inserted and inserted with twice the angle of the slope (54° degrees) (Fig. 5.5 a-d). The results are shown in Table 5.3

Bamboo-pile inclination influence		
Inclination	SF	Increment
Vertical	1,062	3,91%
Normal	1,075	5,19%
45°	1,075	5,19%
54°	1,098	7,44%

Table 5.3 Inclination results for bamboo-pile influence on slope test analyses



(a) Bamboo-pile Vertically Inserted Position (b) Bamboo-pile Normal Inserted Position

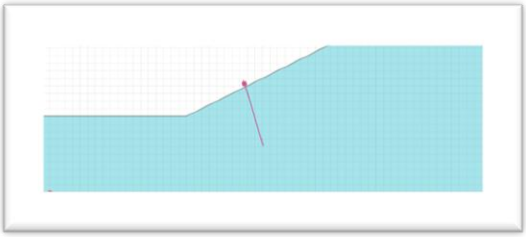
(c) bamboo-pile Inserted 45° angle (d) Bamboo-pile Inserted 54° angle

Figure 5.5 Bamboo-pile inclination analyses position H/Ho=2.67 (a-d)

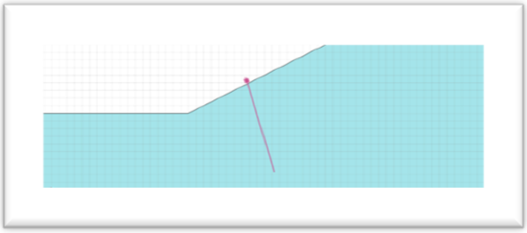
For this analysis 54°had the best performance of all three option tested by raising safety factor percentage in 7.44% compared to the slope without any reinforcement.

Bamboo-pile Length

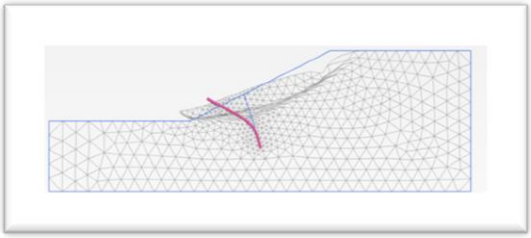
For position test position H/Ho = 1.60 was also taken and two lengths were compared 9 meters length and 13 meters length. Results are shown on Fig. 5.6a-0.



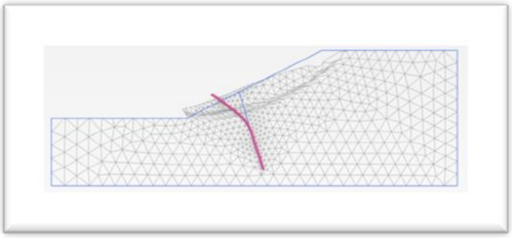
(a) Bamboo-pile 9 m length



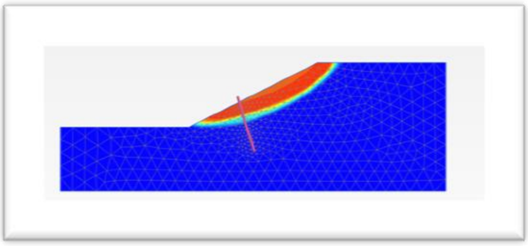
(b) Bamboo-pile 13 m length



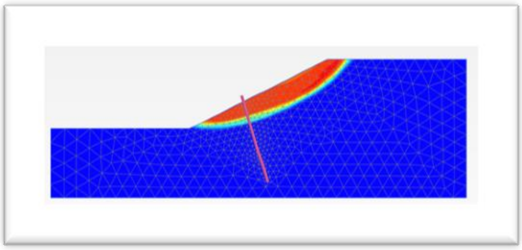
(c) Bamboo-pile 9 m length deformation



(d)Bamboo-pile 13 m length deformation



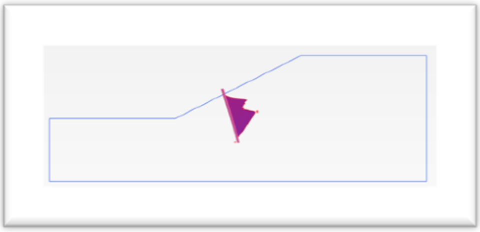
(e) Bamboo-pile 9 m length SF calculation



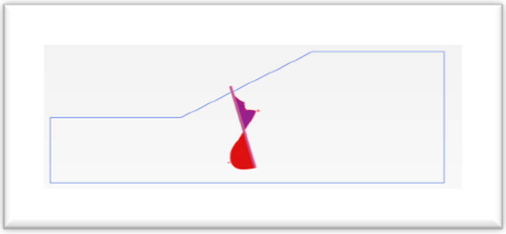
(f) Bamboo-pile 13 m length SF calculation

(g) Bamboo-pile 9 m length displacements

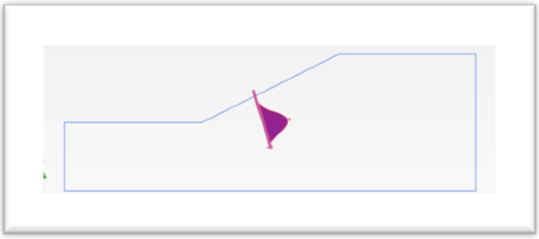
(h) Bamboo-pile 13 m length displacements



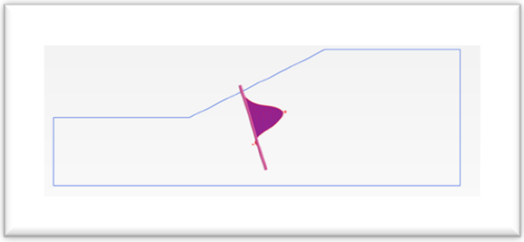
(i) Bamboo-pile 9 m length axial forces



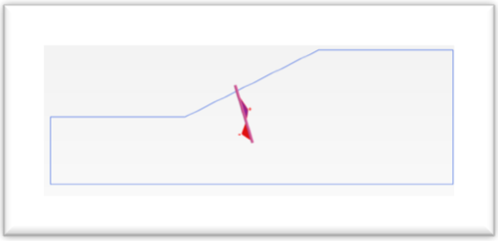
(k) Bamboo-pile 13 m length axial forces



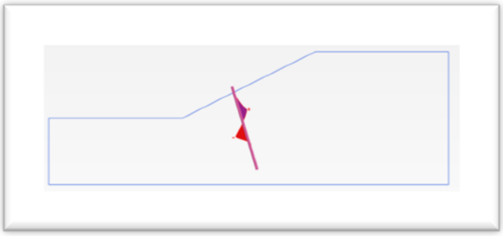
(l) Bamboo-pile 9 m length bending forces



(m) Bamboo-pile 13 m length bending forces



(n) Bamboo-pile 9 m length bending forces



(o) Bamboo-pile 13 m length bending forces

Figure 5.6 Bamboo-pile length analyses position H/Ho=2.67 (a-o)

Bamboo-pile Length Influence		
Length (m)	9	13
SF	1,075	1,052
Max. Displacement (m)	1,114	0,806
Max. Axial Force (KN/m)	7,78	5,248
Max. Bending Force (KN.m/m)	34,38	24,45
Max. Shear Force (KN/m)	15,44	11,31

Table 5.4 Bamboo-pile length analyses position H/Ho=2.67

The behavior for pile length showed that for greater sized pile length, it will add more flexibility to the bamboo-pile leading to have a greater deformation on the element and failing to increment the stability. Thus the effectiveness of the bamboo pile added forces is lower with a greater length Table 5.4.

Diameter Influence

As bamboo of *Dendrocalamus Giganteus* species diameter is known to be founded from 10 to 40 cm diameter influence was evaluated on this range each 5 cm.

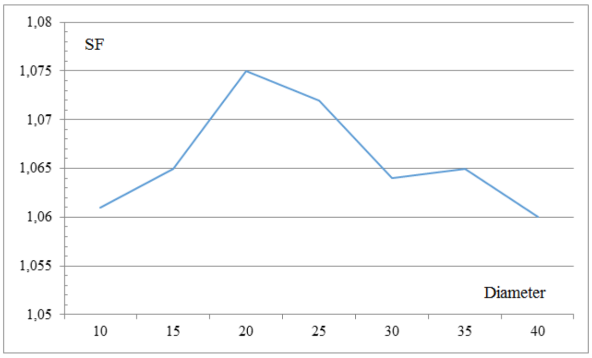


Figure 5.7 Influence for bamboo-pile diameter

In Fig 5.7 is noticeable that from diameters 10 to 20 a proportional increment is appreciable, then the SF decreases on 25 cm diameter, the decrease kept on going with a recovery gain on 35 cm diameter and finally reaching the lowest value at 40 cm diameter. 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.

5.3 3D Analyses

For 3 dimensional analysis slope dimension remains the same as 2D analyses just adding a slope width of 60 m (Fig. 5.8).

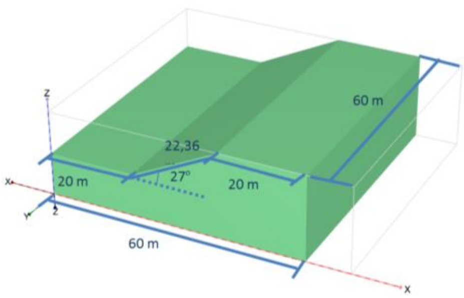


Figure 5.8 Slope 3D PLAXIS model

The model representation on 3D software comprises 55809 elements and 81309 nodes shown in Fig. 5.9 below for a very fine mesh type.

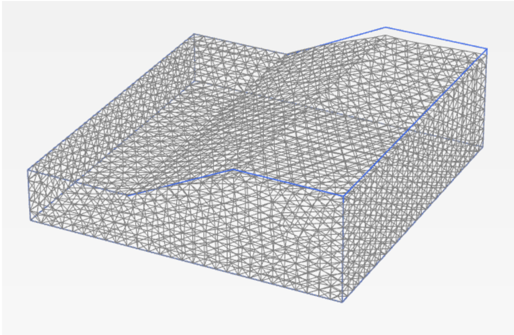
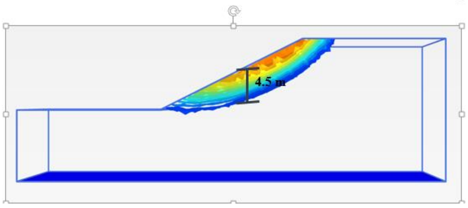
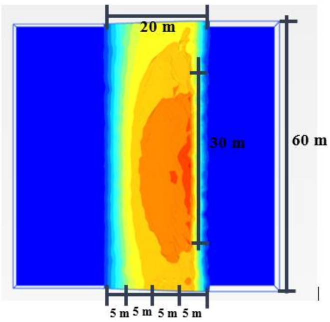


Figure 5.9 Slope 3D Mesh

The potential critic surface rupture is shown in Fig. 5.10(a) starting at 4.20 meters depth. From top view it is possible to appreciate that greater displacements (dark orange) occur on center area over 30 meters distance approximately Fig. 5.10(b). By 3D PLAXIS safety factor value with the same soil parameters was 1.034.



(a)



(b)

Figure 5.10 Displacement with 3 Kpa cohesion
(a) Side view critic Surface Rupture (b) Top view of Slope displacement

Single Pile Influence

For Single pile analyses pile was taken from 2D analysis position with the best improvement which was for H/Ho = 1.60. To compare bamboo-pile behavior other pile materials as steel and concrete were tested.

Material	SF	Increment %
Bamboo	1.05	1.55%
Steel	1.054	1.93%
Concrete	1.051	1.64%

Table 5.5 Single Pile Influence analysis

Results on single pile for 3D analyses show that there is not a big increment in SF as did happen on 2D analyses, never the less it did show it influence. Regarding materials steel did had the greatest SF, concrete did not probe to have better performance than bamboo for the same dimension characteristics Table5.5.

Pile Row spacing influence

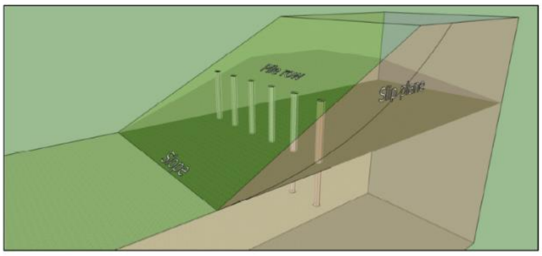


Figure 5.11 Pile (Mortier, 2014)

Three dimensional spacing pile row Fig. 5.11 test results showed to be in little better agreement to those obtained with 2 dimensional analysis Fig.5.12. The SF presented the greatest value with 2 diameter spacing decreasing for 3 diameter and 4 diameter spacing the last one with lowest, unexpected increment SF for 5 diameters spacing was presented with the second greatest factor. However any overall displacements reduction is easy to observe from top view (Fig. 5.13a-d).

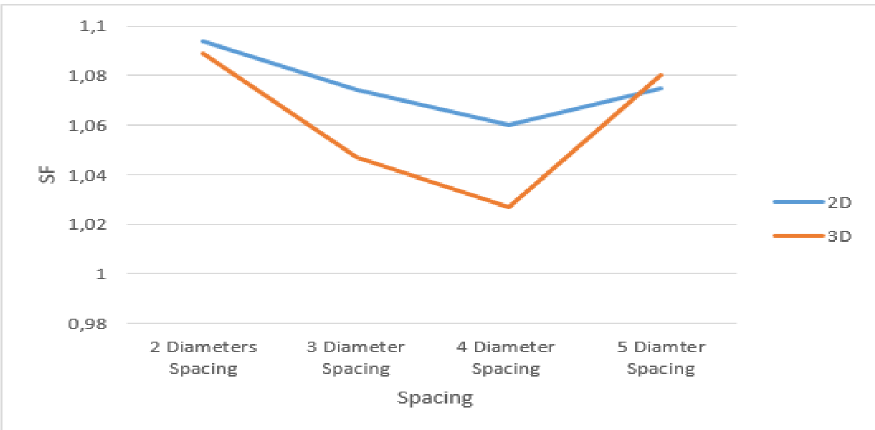
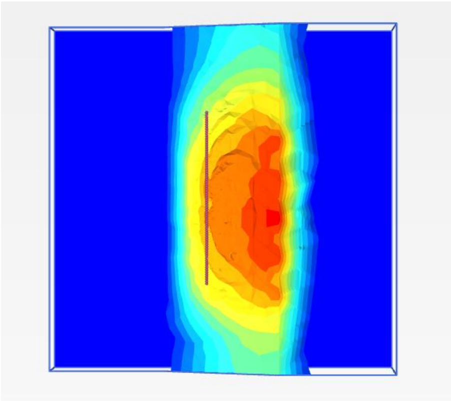
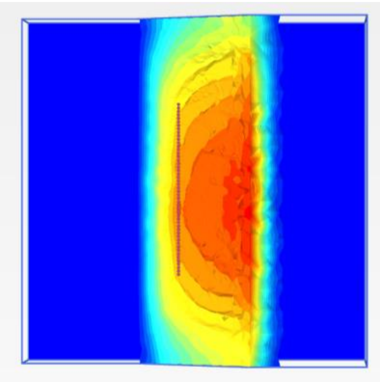


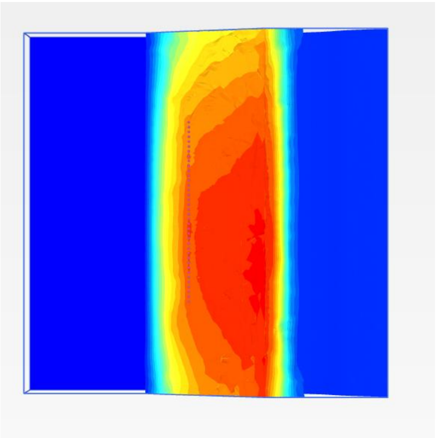
Figure 5.12 PLAXIS 2D VS PLAXIS 3D Spacing



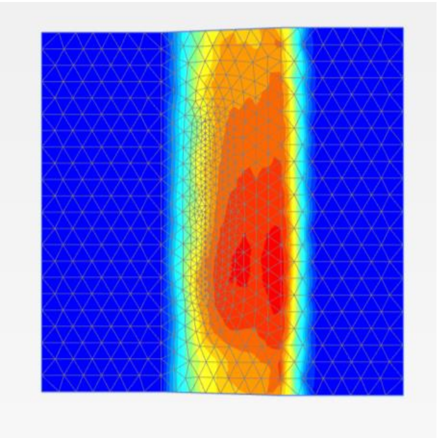
(a) 2 Diameters spacing



(b) 3 Diameters spacing



(c) 4 Diameter spacing



(d) 5 Diameter spacing

Figure 5.13 Top view spacings for (a-d)

Bundle of Bamboo Diameter Equivalence for Pile Row Triangular Shape Analyses

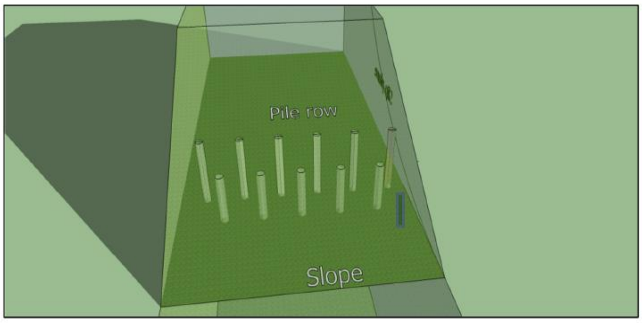


Figure 5.14 Triangular pile shaped row (Mortier, 2014)

Increasing bamboo-pile stiffness to influence on slope stabilization without modifying its natural properties was done by representing a bundle of bamboos Fig. 5.15 and testing them on a triangular shaped row Fig. 5.14. Giving diameter equivalence for pile properties parameters on the software obtained by means of iteration of inertia values (I) by means of diameter (d) and thickness (e) dimensions (Eq. 5.1) Table 5.6.

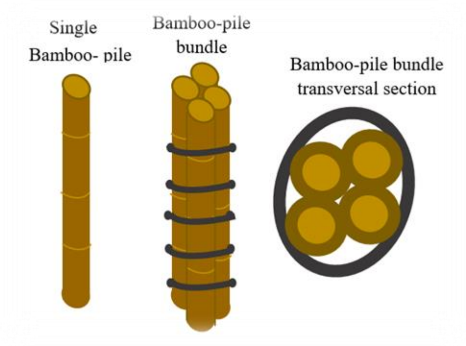


Figure 5.15 Single Bamboo-pile and Bamboo-pile Bundle

Equation 5.1 Inertia

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

D(m) equivalent	I (m^4)	No. Bamboos
0,2955	1,85E-04	4
0,3499	3,71E-04	8
0,3892	5,56E-04	12
0,4225	7,42E-04	16
0,4527	9,27E-04	20

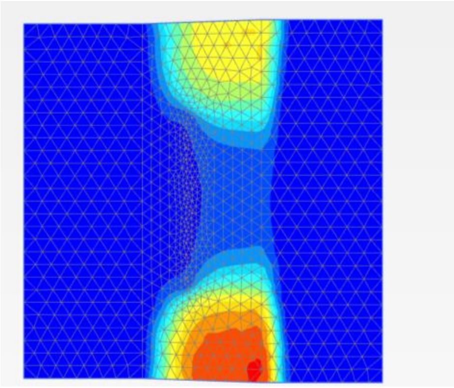
Table 5.6 Diameter bamboo bundle equivalence

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 were performed. Unexpectedly a regular 20 cm diameter bamboo-pile used in 50 m triangular shaped row did perform with the highest safety factor. To improve SF two other alternatives for triangular shaped row were tested. A reduction on triangle size for a proportion 2 to 1 for 1 to 0.5 meter (base and height), where a better improvement did not showed up. And adding one more triangular shaped row, only for 50 m triangular shaped row did increase 2% compared with a single triangular shaped row on a regular 20 cm diameter bamboo pile, which final SF increment reaches the highest value above 14% of the slope SF without any pile Table 5.7.

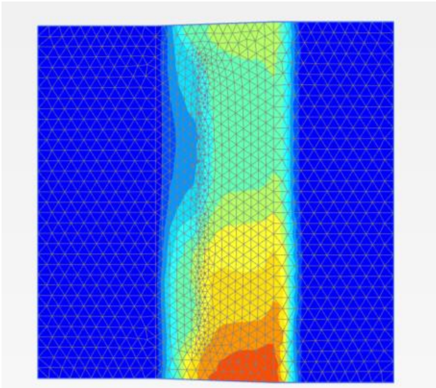
No. Bamboos	Number of	Triangular base-height	30 meter distance triangular line	50 meter distance triangular line

	rows	dimensions (m)	row Increment %	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%

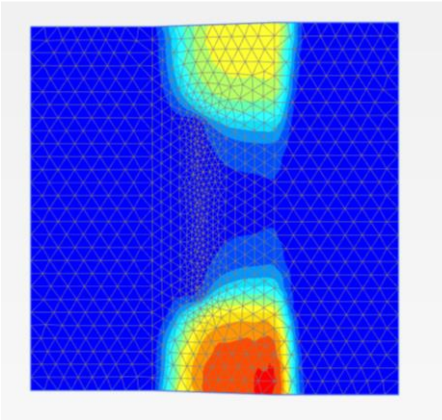
Table 5.7 Triangular shaped pile row analyses for bamboo bundle diameter equivalences



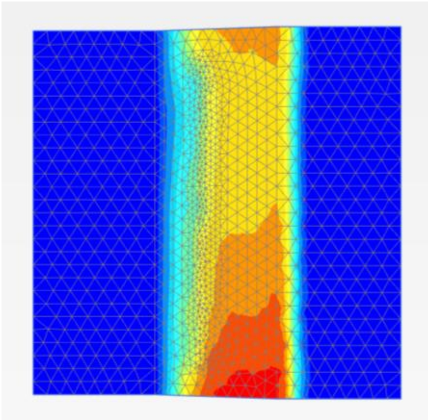
(a) 30 m triangular shaped row
for 4 bamboos diameter equivalence



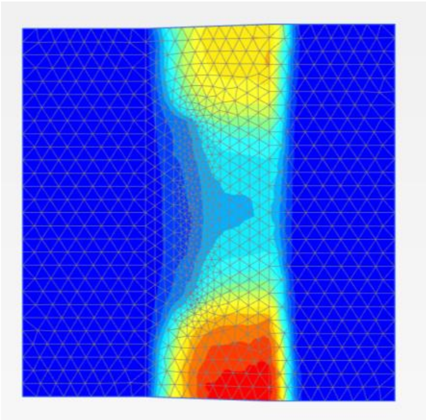
(b) 50 m triangular shaped row
for 4 bamboos diameter equivalence



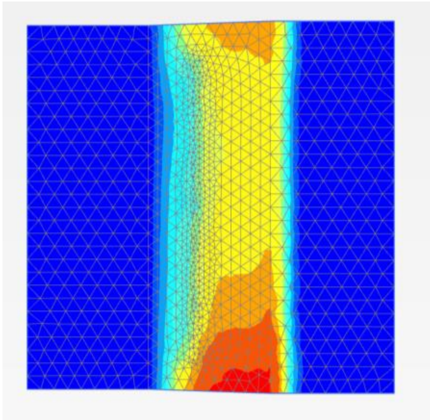
(c) 30 m triangular shaped row
for 8 bamboos diameter equivalence



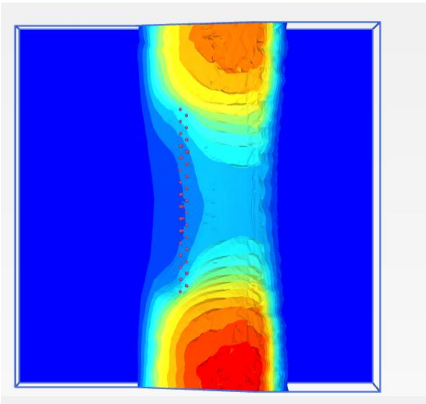
(d) 50 m triangular shaped row
for 8 bamboos diameter equivalence



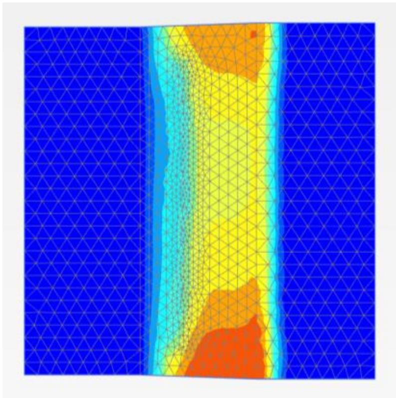
(e) 30 m triangular shaped row
for 12 bamboos diameter equivalence



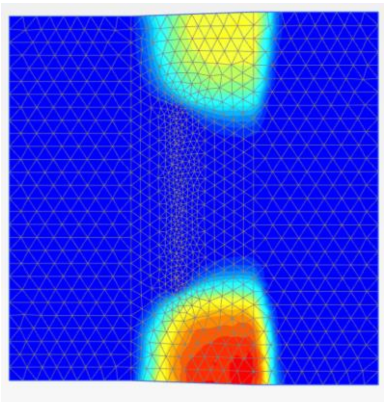
(f) 50 m triangular shaped row
for 12 bamboos diameter equivalence



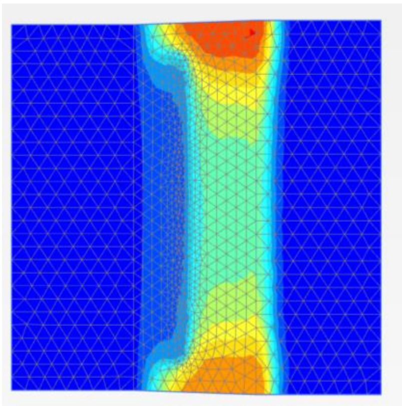
(g) 30 m triangular shaped row
for 16 bamboos diameter equivalence



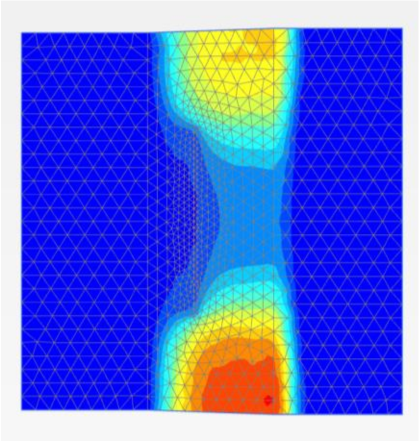
(h) 50 m triangular shaped row
for 16 bamboos diameter equivalence



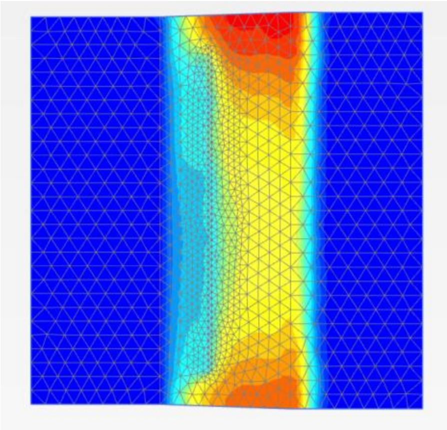
(i) 30 m triangular shaped row
for 20 bamboos diameter equivalence



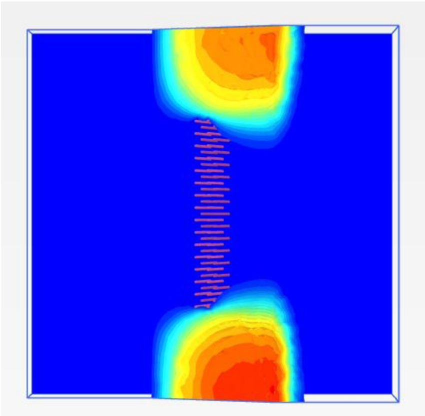
(j) 50 m triangular shaped row
for 20 bamboos diameter equivalence



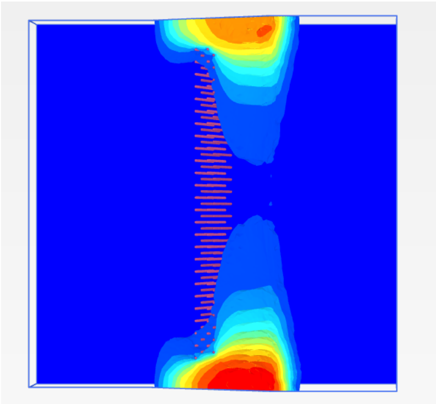
(k) 30 m triangular shaped row
for 20 cm bamboo diameter
in 1 m to 0.5 m base high relation
triangular shaped row



(l) 50 m triangular shaped row
for 20 cm bamboos diameter
in 1 m to 0.5 m base high relation
triangular shaped row



(m) 30 m triangular shaped row
for 20 cm bamboo diameter
in 2 row triangular shape (2 m to 1m)



(n) 50 m triangular shaped row
for 20 cm bamboos diameter
in 2 row triangular shape (2 m to 1m)

Figure 5.16 Top view for different pile configurations (a-n)

On top view for the different tests on triangular shaped row of bamboo bundles on 30 m and 50 meters distance along the width of the slope for 4 bamboos Fig.5.16a-b, 8 bamboos Fig.5.16c-d, 12 bamboos Fig. 5.16e-f, 16 bamboos Fig.5.16g-h, 20 bamboos Fig. 5.16i—j, for regular 20 cm diameter bamboo DG on a reduced triangular relation base high Fig. 5.16k-l and for two triangular shaped rows with regular 20 cm bamboo Fig.5.16m-n displacements fading away are appreciable but SF increment still relatively low regarding that a much greater SF value was expected..

6 Conclusions, Experiences and Suggestions for future Researches

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 it, was explain in chapter 4 the elements provided by PLAXIS in 2 and 3 dimensions, embedded beam row and embedded pile respectively, behaves different. For 2 dimensional analysis single bamboo-pile SF increased 8% with embedded beam row element. However, for single bamboo-pile as 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 great 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 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. Despites that with 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 tests 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 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 economic aspects.

On the experience, due to the mechanical properties that bamboo DG has the results were expected to be better on the effectiveness of this method, at the end the increment of the safety factor resulted was minimum. Other configuration to enhance the SF were applied such as increasing the number of embedded pile elements on 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 requested for attach them to the mesh 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 be solved for that quantity of three noded embedded beam piles with a little patience, but when it comes to more than two triangular shaped rows, this makes the process so extensively laborious that seems to be an endless work when it comes to try different coordinates for each requested node of the three noded of the multiple embedded pile elements used.

However here are some suggestions for future research:

- New configurations design of piles implementation and achieve to increment the number of piles on mesh.
- To use a head pile support beam to try create a stronger interaction of the elements with it on 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 use it as a composite element.
- Give a deeper study on bamboo-pile treatment to increase its durability.

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