Numerical modelling of geotextile tubes

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ABSTRACT
Geosynthetic tubes made of geotextiles and geomembranes have been applied since the 1960s for coastal protection, dike's construction, flooding control and dewatering materials with high water content. Several analytical methods were developed to simulate the behavior of these structures during the filling and dewatering processes. Also, numerical modelling has been carried out to represent and to predict the behavior of geosynthetic tubes. However, it is still necessary to develop simulations that are representative of the existing field conditions. In this paper, an analysis and a critical evaluation of existing numerical modellings were performed, considering the main aspects related to the filling process of geotextile tubes, with the goal of giving directions to future research. Results from the existing numerical models using finite element programs such as ABAQUS, FLAC, Plaxis and Phase 2 indicate their capacity to simulate the geosynthetic tube behavior, despite the limitations and premises presented.
Keywords: geotextiles, geotextile tube, numerical modelling, geosynthetic.

1. INTRODUCTION

Since the 1980s, geotextile tubes have been used in engineering projects around the world for different purposes—being the dewatering of mining tailings a more recent application. The possibility of using these structures as an alternative to the conventional disposal of the muddy tailings in dams and dikes has been widely discussed in Brazil due to recent failures in upstream dams in the state of Minas Gerais. However, the aspects related to the design of geotextile tubes, individually arranged or stacked, are still incipient.

The mechanical behavior of geotextile tubes during the filling, consolidation and stacking processes has been the object of research due to its importance as a new method of disposal of fine tailings and due to the complex manner in which these processes occur. For the study of the filling stage process, it's possible to apply the fluid characteristics to the material and to consider, during this particular process, the geotextile impermeable. However, this consideration is not possible for subsequent dewatering, consolidation and stacking processes due to the occurrence of water drainage.

After drainage, the filling materials cannot be treated as fluids but must be defined by their mechanical properties which are often too complex to describe analytically. Thus, it is necessary to use numerical methods such as finite elements and finite differences to help solve these problems involved and to allow the modelling of the tube behavior to be as close to field conditions as possible (Cantré, 2002).

The objective of this paper is to present and analyze some of the studies about numerical modelling of geotextile tubes that have already been carried out, briefly describing the methodology used and the results obtained by them. The works were subdivided by themes, initially presenting the research studies that addressed the modelling of the filing process and the stress analysis in a single geotextile tube; then the ones that simulated the consolidation process of the tube; and, lastly, the works that studied the stress-strain behavior of stacked tubes.

2. THEORETICAL FUNDAMENTATION

Geotextile tubes are closed tubular systems fabricated with geosynthetics. They may consist of woven, or non-woven geotextile, or geocomposite. Regarding tubes used for dewatering or containment, the filling is carried out by pumping the material into the tube. Figure 1 illustrates the geosynthetic filing process (Silva, 2017).

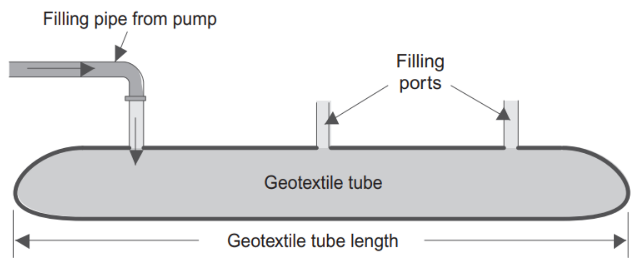


Figure 1. Schematic representation of the filling process (Lawson, 2008).

In order to design these structures, it is necessary to understand the main loads and critical conditions to which the tubes are submitted, such as the stresses on the material during the filing stage; the hydraulic behavior—including variations in transmissivity and permittivity during the dewatering process; deformations occurred during the consolidation stage; the material's durability; and the overall stability of the stacked tubes' structure.

Therefore, to perform a representative numerical simulation of the field conditions to which these structures are subjected, the properties involved in each of the mentioned processes must be correctly equated. The main parameters required for the characterization of geotextiles, constituents of geotextile tubes, can be divided into three groups:

- Physical properties: definition of weight, thickness, porosity, shape, structural arrangement of the wires and pore distribution (Silva, 2017);
- Mechanical properties: correspond mainly to the definition of tensile strength, creep, penetration resistance, tear strength and compressibility of the material (Palmeira, 1981);
- Hydraulic properties: definition of planar (transmissivity) and normal (permittivity) permeability, and filtration opening (Silva, 2017).

To perform numerical modelling, it is also necessary to define mathematical models that best represent: the stress-strain relations (constitutive model), the interactions between the different materials involved and the boundary conditions of the simulated problem.

3. MATERIALS AND METHODS

Initially, the major published articles on geotextile tubes were researched. Then, a study of the articles was performed and those that included numerical analyses were selected.

Since the objective of the article is related to computational modelling, works that used at least one modelling program were selected, regardless of the numerical method. Quantitatively, among the 10 studies evaluated, 5 used the finite element program ABAQUS, 3 used the finite difference program FLAC, 2 used the finite element program PLAXIS and 1 used the finite element program Phase 2.

Finally, regarding the conditions analyzed on tubes used for mining tailings dewatering, it should be noted that 5 of the studies evaluated the filling process and the maximum stresses in the geotextile, 2 articles covered the consolidation or dewatering simulation and 3 included stacked tubes' structures analysis. It is noteworthy that, to facilitate understanding and to improve the organization of this work, the articles described were subdivided into those three subgroups.

4. DESCRIPTION AND EVALUATION OF THE ARTICLES

4.1 Filling process modelling and stress evaluation on a single geotextile tube

Seay (1998) studied the three-dimensional behavior of geotextile tubes using finite element modelling. In her work, two distinct tube geometries on elastic foundations with different elastic modulus were modeled. The first geometry with a length/width ratio equal to 2:1 (length 3.0 m and width 1.5 m) and the second with a 5:1 ratio (length 7.5 m and width 1.5 m).

The main premises used for the geotextile were: a small amount of bending stiffness, thickness of 3 mm, impermeable material, linearly elastic behavior with Young's modulus equal to 7.0346 GPa, Poisson's ratio equal to 0.45, density of

75.0 kg/m³, specific weight of the slurry was 1.5 times the specific weight of the water, and the tube was symmetric on both XZ plane and YZ plane.

To perform nonlinear geometric analyses on geosynthetic tubes, Seay (1998) used the ABAQUS commercial finite element analysis program. The elements chosen for the modelling were the S4R (shell element) for the geotextile and the SPRING1 (spring element) for the elastic foundation. It is noteworthy that the use of membrane elements for geotextile modelling was also taken into account, although these elements act only when subjected to tensile stresses and it wouldn't be possible to adequately simulate the compressed regions due to wrinkling. The choice of the S4R element for the geotextile was based on the element's curvature, which is recommended when bending occurs and also based on its ability to change the thickness during the analysis, thus ensuring the nonlinearity of the model. As a limitation on the use of S4R finite elements, Seay (1998) mentions that they are elements of reduced integration and, therefore, may present hourglass mode shapes. It should be noted that the commercial program used, ABAQUS, contains a control for this limitation.

The tube filling simulation was modeled by the incremental application of hydrostatic pressure until the pressure reached the stress caused by the slurry's specified density. Figure 2 illustrates the model developed by Seay (1998).

The main results obtained were the three-dimensional shape of the tube, the contact between the tube and the elastic foundation, the stresses on the average geotextile surface, and the relationship between the final tube height and the applied pressure. In short:

- The contact region between the geotextile tube and the elastic foundation decreases as the hydrostatic pressure increases and increases as the foundation's stiffness decreases;
- There is an alternation between tension and compression regions on the tube's surface due to wrinkling in some geotextile parts;
- At a given hydrostatic pressure, the greater the length/width ratio, the greater the height reached by the tube (referring to the ground level).

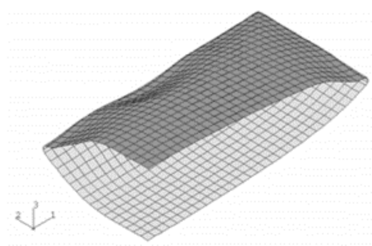


Figure 2. 3D example of the geotextile tube configuration obtained by Seay (1998).

Houng (2001) performed a two-dimensional (2D) modelling of a single geomembrane tube resting on clays and sand foundations in order to evaluate the applicability of these structures for flood control. The research was conducted by using the finite difference computer program Fast Langrangian Analysis of Continuous (FLAC).

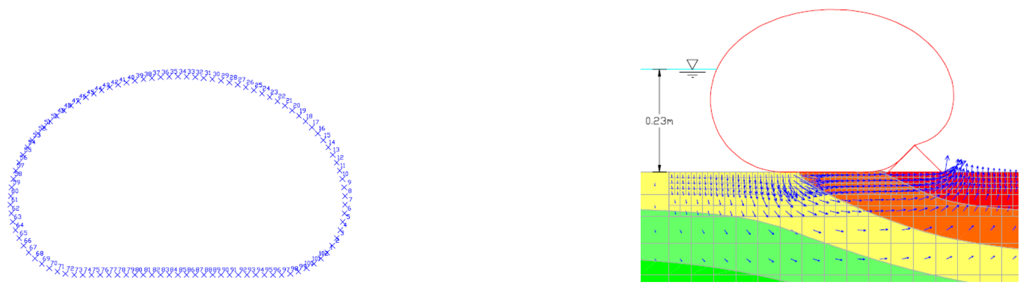
To justify the two-dimensional modelling, Houng (2001) assumed the tube was infinitely long. Beam elements with elastic behavior were used, that is, the behavior of the elements followed Hooke's stress-strain law and, consequently, the perimeter of the tube section varied with the applied pressure. The hydrostatic water pressure was considered constant and applied as point loads at the nodes of the beam elements. Figure 3 presents the models developed for the analysis.

Houng (2001) highlighted the importance of grid mesh refinement for modelling, since, in the finite difference method, the stresses are constant in the elements. As a result, deformations and displacements are represented by displacements of the grid as a whole. Therefore, if the number of grid zones is insufficient, strain localization or shear bonds (especially in the plastic region) may not be detected. The work also cites a limitation of the finite difference method in tube modelling, which would be the non-interpolation of stresses and deflections for a beam between two nodes. This particularity causes bent sharp transitions between the elements.

In the studies carried by Houng (2001), the tube was initially modeled on soft clays with different shear strength values. The foundation soil was considered saturated and in an undrained condition. For the interface between the tube and the soil, the Mohr-Coulomb failure criterion was chosen. To determine the thickness, the author simulated tubes with thicknesses ranging from 2 mm to 4 mm. The obtained results indicated that the final height reached was not highly sensitive to the thickness variation. Therefore, for the remaining analyses, a thickness of 3 mm was used. In addition, unit weight of 950 kg/m³ and a modulus of elasticity of 1 MPa were adopted (according to the author, a representative value for high-density polyethylene).

As the main result of the initial simulation, it stands out the fact that the higher the undrained foundation soil resistance, the lower the tube subsidence, the smaller the contact area between the tube and the foundation, the lower the geosynthetic stresses (due to the increase of the water pressure which was kept 1 m above ground level) and the greater the height and width reached by the tube. It is noteworthy that the largest variations were observed for the foundation's shear strength in the range of 0.096 kPa to 1.2 kPa.

Houng (2001) also modeled a tube supported on triangular wooden blocks of different geometries on one side and subjected to water levels on the opposite side, as illustrated in Figure 3b. Analyses were performed with and without the pore pressure, considering the instabilities by rolling, sliding and piping. The foundation was modeled as being composed of sands. For validation, a comparison was made with the results obtained experimentally.



a) Model developed for the initial analysis

b) Model developed for the stability analysis

Figure 3. Representation of the geometry modeled (adapted from Houng (2001)).

Guo (2012) used the finite difference program FLAC for modelling the geotextile tubes' behavior under different initial conditions and filling pressures, which were resting on a deformable foundation. The obtained results were used to validate two analytical methods evaluated in the work.

For the foundation soil, Guo (2012) used a Poisson's ratio equal to 0.35, compression ratio 0.35, unit weight 18 kN/m³ and the shear and bulk modulus of elasticity varied between 9 layers, as shown in Table 1.

Table 1. Properties of soil layers.

Soil Layer	Elastic Modulus E (kPa)	Bulk Modulus K (kPa)	Shear Modulus G (kPa)
1	65,59	72,87	24,29
2	163,96	182,18	60,73
3	229,55	255,06	85,02
4	295,14	327,93	109,31
5	360,72	400,80	133,60
6	426,31	473,67	157,89
7	491,89	546,55	182,18
8	557,48	619,42	206,47
9	623,06	692,29	230,76

The geosynthetic tube was considered impermeable, with a perimeter of 9 m, thickness of 0.3 mm, modulus of elasticity of 7.032 x 10^3 GPa and moment of inertia of the beam element of 2.025 x 10^{-12} m^4. The filling material was seen as having unit weight of 12 kN/m³.

The tubes were modeled with 100 beam elements and the foundation with grids of dimensions 0.1 m x 0.1 m and 0.2 m x 0.2 m. Friction between the tube and the foundation was not considered. Hydrostatic pressure was converted to point loads and applied to the geosynthetic beam element nodes. Figure 4 illustrates the model developed.

As expected, the results indicated that the higher the applied pressure, the greater the observed subsidence and the more rounded was the final tube configuration. We must observe that an uplifting effect of the ground occurred on the tube sides. In addition, Guo (2012) mentions that the moments observed in the beam elements were very small and, therefore, can be neglected.

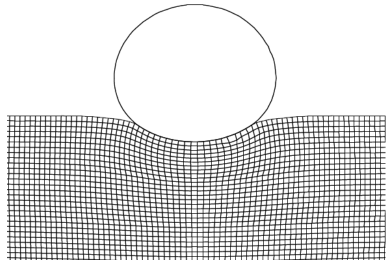


Figure 4. Representation of the geometry modeled (adapted from Guo (2012)).

Mendonça (2016) used the finite element computer program Phase2 to evaluate the behavior of a single geotextile tube used for the confinement of tailings subjected to different filling pressures and with different mechanical properties. The foundation was considered flexible, the tube's weight was considered negligible and the tube's length was assumed much greater than the cross section, thus allowing the two-dimensional (2D) analysis.

From the evaluation of the properties of iron mining tailings from various references, Mendonça (2016) adopted the following parameters for the filling material: a friction angle of 30º, cohesion equal to 0 kPa and unit weight equal to 18 kN/m³.

Shape analysis for each filling pressure and geotextile tube design was performed based on the method proposed by Plaut & Suherman (1998). To perform the calculations, the program MathLab was used.

Mendonça (2016) performed parametric analyses by varying the stiffness of woven and nonwoven geotextiles. For woven geotextiles, the elastic modulus varied between 200 and 800 kN/m, whereas, for nonwoven geotextiles, the elastic modulus ranged between 20 and 50 kN/m. It is important to point out that the tube was taken as having elastic behavior.

The types of materials, properties, and initial loading conditions of the foundation and tailings are shown in Table 2. The finite element mesh was established with 8.000 6-node triangular elements as shown in Figure 5.

Table 2. Properties of the foundation soil and filling material

	Foundation	Mining tailing
Initial condition	Field Stress & Body Force	Field Stress & Body Force
Constitutive model	Elastic	Elastic
Unit weight (kN/m³)	27	18
Yield criterion	Mohr-Coulomb	Mohr-Coulomb

The main conclusions, regarding the numerical modelling, obtained by Mendonça (2016) were:

- The geotextile tube tends to have a circular shape when the filling pressure is considerably greater than the hydrostatic pressure caused by the filling material so that the tube's width in contact with the base decreases as the fill pressures increase;
- The foundation's influence on mechanical stresses on geotextile is small. Still, verifying the foundation is important for assessing the stability of the system as a whole;
- The properties of the filling material (tailings in the specific case of the related work) have a great influence on the numerical analysis;
- Stresses along the perimeter of the tube tend to be more uniform for more circularly shaped tubes.

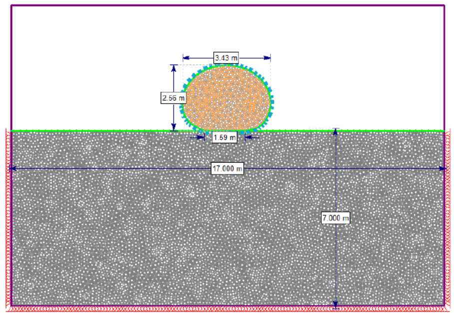


Figure 5. Geometric model and finite element mesh defined by Mendonça (2016).

Silva (2019) performed a back analysis of the work presented by Silva (2017) in which a geotextile tube was used for the confinement of gold mine tailings. The objective was to match the dimensions measured in the field—height and width—using tridimensional numerical modelling. The author also aimed to find out the acting stresses on the filled geotextile.

Silva (2019) used the computer's finite element program ABAQUS version 6.14. The tube geometry adopted was the same used in the field experiment, however, representing only ¼ of the tube for saving time on the numerical modelling.

The main properties and assumptions assumed for the geotextile were: a polypropylene material with an elastic modulus of 0.30 GPa, Poisson's ratio of 0.40, geotextile thickness of 1.80 mm and geotextile density of 900 kg/m³. Silva (2019) mentions that these characteristics are compatible with those found in the field experiment. The geotextile constitutive model was the elastic linear, and the woven geotextile was modeled using membrane elements (M3D4R).

The filling material was considered as fluid and then, a hydrostatic loading was applied with the magnitude dependent on the specific weight of the tailing defined as 1.45 g/cm³. Figure 6 illustrates the results obtained by Silva (2019).

From the results, Silva (2019) found dimensions similar to the field ones: height of 1.00 m and width of 1.63 m in the modelling, while in the experiment height of 1.00 m and width of 1.67 m was obtained. It was also possible to define the circumferential tension that was acting in the field that was approximately 7.28 kN/m.

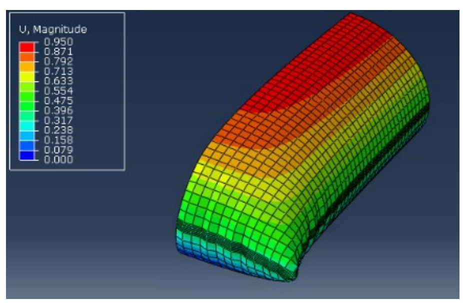


Figure 6. Filled tube modeled by Silva (2019).

4.2 Modelling of the consolidation and dewatering processes after the filling of the geotextile tube

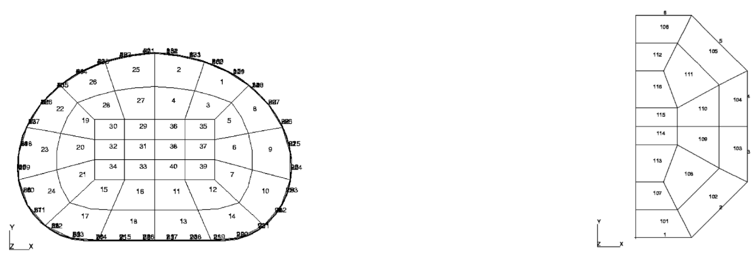
Cantré (2002) used the computer's finite element program ABAQUS to simulate the 2D behavior of geotextile tubes under loading and drainage conditions. Two models were presented in the paper: the first evaluated the maximum stresses on a 3-2-1 stacked structure of tubes and the second simulated dewatering and consolidation after the initial loading.

The main premises adopted in this work were: plane strain, that is, the tube was considered very long compared to its cross section, the geotextile self-weight was neglected, the friction between the geotextile and the filling material and between the geotextile and foundation was included. For the load model, only the mechanical properties of the material were assumed. Linear loading was adopted, and for the drainage model, it was considered one-directional flow out of the tube.

For the stacked model (3-2-1), only the mechanical properties of the filler material were considered, which means that the drainage of the tube had already occurred. The initial model's geometry corresponding to the moment after the filling process was defined from the formulations proposed by Plaut and Suherman (1998). The filling soil yield's criterion was the Mohr-Coulomb. For both the geotextile shell and the fill material, CPE8 solid elements (plane strain, eight nodes) were used, and in order to calculate the circumferential tension forces, B22 beam elements (10^{-4} m^4 moment of inertia) were used. For the geotextile tube, the following properties were considered: 3.5 mm thickness, elastic modulus equal to 7 GPa, Poisson's ratio 0.4 and density of 400 kg/m³. The foundation was considered rigid.

Figure 7a illustrates the finite element mesh used by Cantré (2002) for the stress analysis on the lower left tube of the stacked structure. It stands out that the main results were the reduction in the stresses and deformations observed on the tube with the increase of the elastic modulus of the foundation.

With respect to the drainage model, the octahedral geometry presented in Figure 7b was used for the tube cross section. As initial conditions, a constant void ratio equal to 0.5 and an initial saturation of 1 were adopted. For the beam elements of the tube, an elastic modulus of 5 MPa was used (according to the author, a small value was used to enable deformations of the soil body). It is noteworthy that the elasticity modulus of the filler material was defined as a function of pore pressure in order to increase with its decrease.



a) Finite element mesh for the stacked structure

b) Finite element mesh for the drainage model

Figure 7. Finite element meshes modeled (adapted from Cantré (2002)).

Brink (2014) used the finite element programs ABAQUS (Dassault Systems, 2013) and PLAXIS (2013) to perform two-dimensional modelling of the consolidation process of hydraulically deposited soils. To do so, initially, one-dimensional analyses were performed, and after the validation of the results, the complexity of the models was increased for a two-dimensional geotextile tube filled with fine soil and a tailings storage facility.

The main premises considered in the analysis were that the filling material (slurry) acted as a Newtonian fluid with zero shear strength, and the filling process would occur instantaneously, which means without consolidation during the filling. The geosynthetic was assumed to be weightless and to have no ability to carry moments or to interact frictionally with the slurry fill.

To determine the initial tube geometry after the filling process, Brink (2014) used an analytical formulation. The following parameters were determined as input: a circumference perimeter of 15 m and a filling pressure of 0.1 kPa.

In the program ABAQUS, the geotextile was meshed using T2D3 truss elements with a section area of 0.001 m²/m, elastic modulus of 1,100 MPa and Poisson's ratio of 0.49 (elastic properties correlated with polyethylene).

For the filling soil, the Modified Cam Clay constitutive model and the CPE6MP triangular finite element mesh were utilized. The foundation was considered rigid and it was modeled with R2D2 type rigid elements.

Brink (2014) realized that the main limitation of the programs used for the analysis of the consolidation of hydraulically deposited soils is the relation between the initial effective stress and the preconsolidation stresses of the soil—parameters which should be initially defined in the development of the model. When the preconsolidation stresses are significantly lower than the initial effective stress, the results obtained are too inaccurate to be used in engineering projects because the programs underestimate the deformations that occur at stresses below the initial effective stress. Brink (2014) points out that, if using PLAXIS, it is possible to circumvent this limitation by changing the preconsolidation stress fixed in the program code.

4.3 Modelling of the stacked structure of geotextile tubes

Kim (2003) performed a two-dimensional (2D) analysis of four types of water-filled geomembrane tube dams to evaluate the applicability of these structures for flood control. The analyses were performed using the explicit finite difference program FLAC and, due to the nonlinear geometric characteristics of the deformations, the large-strain mode was used in the simulations.

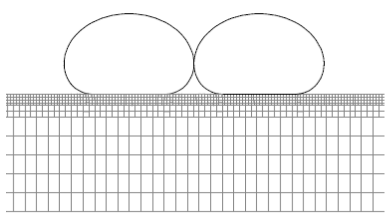
Kim (2003) mentions that one of the characteristics of ground tube modelling is that there are no typical boundary conditions, such as restraints or degrees of freedom. The tube can, therefore, deform wherever the equilibrium of the structures leads it to and, if the system becomes unstable, the structure may slide or roll on the ground. In addition, the contact region between two components changes constantly, making modelling without the use of interface elements very difficult.

In the numerical modelling, Kim (2003) used beam elements for the structural components such as tubes, straps and aprons, grids for the soil and drain, interface elements in the contact regions, and hydrostatic pressure to model water inside the tube. The hydrostatic pressure was converted to point loads and applied to each node of the beam elements.

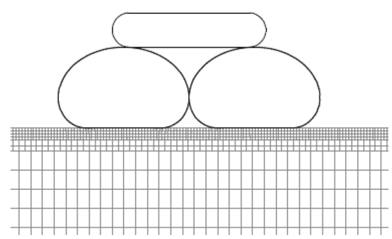
Young's modulus of the PVC (polyvinyl chloride) geomembrane was 0.12 GPa. The thickness and inertia modulus of the tube used in the analyses were 0.508×10^{-3} m and 1.09×10^{-11} m^4, respectively. For the soil (silty sand) foundation, the Mohr-Coulomb yield criterion and the following properties were used: dry density of 1600 kg/m³, internal friction angle of 36°, dilatation angle of 7°, Poisson's ratio of 0.292, bulk modulus of 16 MPa, shear modulus of 7.7 MPa, porosity of 0.4 and permeability of 0.02 mm/s. It was expected that the interfaces would be defined by both normal and shear resistances and by the friction angle. Thus, the cohesion between the geomembrane and the ground was ignored.

Initially, Kim (2003) verified the effect of Young's modulus variation in the analyses simulating the tube with values ranging from 1.0 GPa to 0.12 GPa. It was assumed linear stress-strain behavior for the geomembrane and rigid foundation. Numerical results indicated that Young's modulus did not significantly affect the deformation of the cross section of the tube. The stresses on the material also did not vary considerably with Young’s modules tested. It is also noteworthy that the small magnitude of the moments obtained was due to the reduced thickness and the small moment of inertia of the tube.

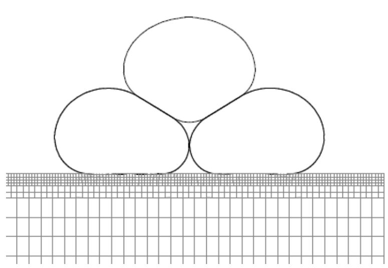
In addition, Kim (2003) also modeled a stacked tube dam in the 2-1 configuration (two tubes at the base and one at the top). The methodology used by the author was subdivided into 4 steps, as indicated in Figure 8, the first being the installation of the base tubes, which include the filling of the tubes and relocation so that both had only one lateral point of contact; in the second stage straps were inserted into the base tubes and the top tube was added; in the third stage the top tube was inflated; in the last step straps were placed over the top tube. After obtaining the model, the stresses on the tubes and their deformations for different water levels outside the structure were evaluated.



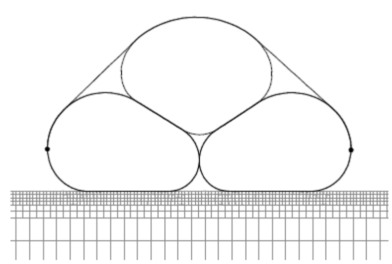
a) After inflation of the two bottom tubes



b) After bottom strapping and setup of top tube



c) Inflation of the top tube



d) Final shape of the stacked tube dam with top strap

Figure 8. Representation of the geometry modeled (adapted from Kim (2003)).

Zhang et al. (2006) used the finite element analysis computer program ABAQUS to extend the two-dimensional model of a stacked geotextile tube structure created by Cantré (2002), including the foundation properties. The aim of the study was to explore the maximum circumferential tension of geotextile tubes for foundations with varied properties and to analyze the hydraulic and geotechnical stability of the tubes. It is important to notice that the author adopted a stacking of formation 3-2-1 in which three tubes are arranged at the base, two at the intermediate level and one at the top. For stress assessment, only the left tube at the lower level was analyzed. The loading for the other tubes was performed by applying a 12 kN linear load acting on the upper right region of the modeled geotextile.

The finite element modelling was divided into two static steps; the first aimed to achieve a state of equilibrium caused by the gravity of the soils, and in the second step the load referent to the other stacking tubes was applied. Figure 9 illustrates the deformations obtained from the modelling.

Geosynthetic materials are known to exhibit thermo-visco-elastic-plastic behavior (Perkins, 2000) and direction-dependent and normal stress-dependent behaviors. However, in the work of Zhang et al. (2006), the tube was modeled with two-node beam elements (B22) and linear elastic behavior. The main properties used for the tubes were: density of 400 kg/m³, modulus of elasticity equal to 7 GPa, Poisson's ratio of 0.4, beam element section area of 10^{-3} m² and moment of inertia equal to 10^{-10} m^4. For the filling and foundation soils, elastic-plastic behavior and Mohr-Coulomb failure criterion were adopted. In the modelling, four-node flat plane strain elements (CPE4) were used.

From the comparison of the modelling performed with the results obtained by Cantré (2002), the authors concluded that the elasticity modulus of the foundation soil is directly related to the maximum stresses observed on the geotextile. Therefore, the foundation's influence on modelling should not be neglected.

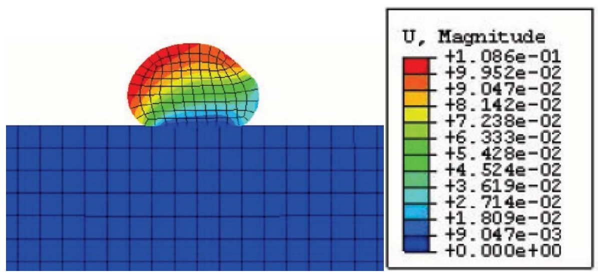


Figure 9. Representation of the deformations on the modeled geometry (adapted from Zhang et. al. (2006)).

Kim et al. (2014) used the PLAXIS 2D 8.2 finite element computer program to evaluate the behavior of geotextile tube stacking under different loading conditions. The focus of the study was to evaluate the stability of structures subjected to scouring.

The constitutive model used for the filling material of the tube, dam and foundation soils was the linearly elastic, perfectly plastic one with the Mohr-Coulomb yield criterion. The geotextile was modeled as an elastic material having a thickness of 3 mm and a modulus of elasticity of 7 x 10^9 Pa. The properties of the tubes used in the simulations are shown in Table 3.

All materials were modeled with triangular elements of fifteen nodes. Interface elements were used to simulate the slip between the ground and the geotextile. It is noteworthy that the horizontal displacements of the foundation were disregarded.

Table 3. Properties of the geotextile tubes

Tube	Material model	Theoretical diameter (m)	Final tube height (m)	Normal stiffness (EA) (kN/m)	Tensile strength (kN/m)	Permeability (cm/s)
Tube 1	Linear elastic	4.0	2.20	$21,10^4$	200	1×10^{-4}
Tube 2	Linear elastic	4.0	2.20	$21,10^4$	200	1×10^{-4}
Tube 3	Linear elastic	2.0	1.10	$21,10^4$	200	1×10^{-4}

5. CONCLUSIONS

Analyzing the works described in this article made it possible to observe a high heterogeneity in the various aspects of numerical modelling. The authors used programs with different numerical methods, such as finite differences and finite elements. In addition, different types of elements were used for the geosynthetic, such as shell elements, membrane elements, truss elements, and beam elements. The boundary conditions and premises in the analyses were also diverse. This is due to the inherent complexity of the hydraulic deposition in geotextile tubes and due to the lack of programs capable of modelling geosynthetics in general, obliging the authors to make adjustments in the models.

Despite this diversification of methodologies, there is a greater number of two-dimensional modellings compared to three-dimensional ones. This is mainly due to the simplification of the model, although, the results obtained are representative only in the intermediate sections of the tube when the ratio between the length and width of the tube is high.

Another premise considered in most of the evaluated works is the use of hydrostatic pressure inside the geotextile tube. This condition allows the simplification of models by avoiding the need for geomechanical characterization of the filling materials. However, among the main applications of geotextile tubes, this condition is only observed when the tube is used for flood protection when the filling material is water.

In addition, there is a predominance of choice of elastic linear behavior for the geosynthetic. This constitutive model should be used with caution for this type of material because it is representative only for a certain range of stresses that depends on the properties of the geotextile. Therefore, their indiscriminate use can lead to models that do not faithfully represent field conditions.

Finally, it is evident that there are still many gaps in which research can be conducted, showing the need for further work to enable a simulation of the various failure modes associated with structures composed of geotextile tubes. Publications that analyzed the numerical modelling of the filling, stacking, and consolidation of the structures were studied. However, no studies that addressed these processes together were identified.

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