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Using geotextile tube units in the core of a marine causeway to improve its stability

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ABSTRACT

Over the past thirty years, there has been a lot of interest in using geotextile tubes in the geotechnical and coastal fields for temporary and permanent buildings. Generally, the present investigation employed finite element computer software ABAQUS V6.14 to examine the stability of a marine causeway. The study presents a geotechnical reinforcement system consisting of geotextile tubes in the core of the concerned causeway. An additional aim of this study is to provide a comprehensive understanding of the behavior of this system in diverse geotechnical environments, specifically in three distinct soils: dense sand, silty sand, and stiff clay. The concerned marine causeway has a 45-degree angle and a height of 4.00 m, subject to a surcharge load and the surrounding seawater pressure. Many configurations of geotextile tubes were located in the core of the causeway to conduct the parametric study for this proposal system. The effect of the filling pressure, size of units, the number of units, and the type of filling material have been investigated. The filling pressure was implemented under three different values of 0 kPa, 20 kPa, and 40 kPa; it is worth mentioning that several preliminary models have been created to simulate the filling process of the geotextile tubes to have the resulted deformed shape obtained at the end of that stage within the construction steps of the causeway, two different diameters are employed i.e., 2.00 m and 3.50 m, number of units was changed from 1 to 3, depending on the capacity of the core area. Three different filling materials were employed in the study, i.e., local soil, dense sand, and concrete. The results showed that filling pumping pressure does not significantly affect the stability of the marine causeway. The previous finding was opposite to the effect of the units' number, which has a high degree of influence on the causeway stability. Also, using larger sizes of geotubes is advised during the designing stage. Moreover, using concrete or even improved soil as a filling material obviously gives better performance for the causeway stability than using the same soil as a filling material.

Keywords: Numerical modeling, Marine causeway, Geotextile tubes, ABAQUS

1. INTRODUCTION

The performance of many marine structures has improved due to substantial advancements in using geotextiles as a reinforcing technology in recent years. Numerous studies, including [1], [2], and [3], have suggested utilizing geotextile as a reinforcing material for embankments; another application for this material is to use it as a retaining structure. Previous experiences proved that embankment structures could be supported by the side-stacked geotextile tubes on their foundation; this technique worldwide verified its effectiveness [4] and [5]. Geotextile tubes could be defined as encapsulated units that could be hydraulically filled. The tube has inlet apertures on its top side where a conduit may be attached to carry hydraulic fill into the tube. Figure 1 illustrates geotextile tubes that could be used in coastal protection projects. The stability of geotextile tubes and the movement of the sand filling in the tubes under wave assault were explored in reference [6]. They found that the filling ratio was a factor in the tubes' deformation and that sliding was the primary scenario for failure, that was opposed to sand migration inside the tube, which did not mainly affect the failure. They also came to the conclusion that while analyzing the stability of the concerned structure, friction should be taken into account since it was intended to be the most significant stabilizing component. That parameter depends on the friction between geotube units each other, and the friction coefficient between geotube units and the foundation at the same time. Additionally, it relies on the weight of overlapping elements, which may vary depending on the size of the contact regions and the movement of sand inside the units, which can alter depending on how each displacement is distributed.

Figure 1: geotextile tube in coastal application, [7]

In [8], the authors investigated the coastal stability of the Kadalur Periya kuppam (KPK) shoreline, a fishing community in Tamil Nadu 70 kilometers south of Chennai, India. The study displays the results of many storms with high-intensity waves that caused severe erosion of the coastline. The implemented protection system consists of sand-filled geosynthetic tubes forming a submerged breakwater in depths up to 3.5 meters. According to the research, the geotextile material for this protective system should have a tensile strength of 200 kN/m; that requirement is essential as the material's tensile strength will only be 75% of its real strength after 500 hours of UV exposure. Different techniques were used for the stability in this study, and the breakwater was found to be secure against overturning, sliding, and bearing capacity. The wave loading per meter of the breakwater was 45 kN. With a factor of safety values of 2.65, 18, and 5, the breakwater was secure against overturning, sliding, and bearing capacity, respectively. Maximum scour depths for a 2 m wave height are 75 cm offshore and 8 cm onshore, respectively.

[9] studied seven large-scale two-dimensional physical models to examine the hydraulic stability of geotextile tubes with a filling percentage of 80% of sand against wave assault. As the crest tube was exposed to the most severe stress, the author discovered that sliding was the primary failure mechanism for a structure made of stacked geotextile tubes. Additionally, he discovered that single-tube crest formations were less stable than double-tube crest structures.

Determining the deformed shape of geotextile tubes after the filling process is crucial, as it governs the number and configuration of geotextile tubes required for stability in such systems. While laboratory experiments are widely regarded as the standard and most exact technique for determining the deformed shape, they are often deemed arduous, costly, laborious, and time-intensive. In contrast, numerical methods are seen as a superior alternative for circumventing the hindrances mentioned above. In this context, a specialized software model named GEOCOPS is widely used to design geotextile tube units [10]. Its purpose is to solve nonlinear equations that dictate the tube's shape. The deformed shape of the geotextile tube obtained from this software was based on Timoshenko's method [11]. Considering the slurry's unit weight and the pumping pressure. The citation authors [12] proposed a methodology for establishing the correlation among tube dimensions, slurry unit weight, pumping pressures, and tension force.

[4] used the three-dimensional finite element software (ABAQUS) to model geotextile tubes. That study was mainly concerned with improving the embankment's stability under gravity and surcharge loads. The numerical models in this study have been divided into two main stages; the first is to simulate the filling process of the geotextile tubes, while the second is to examine the embankment's stability when using additional units of geotextile tubes to retain the embankment. The study determined that implementing a rigid wall adjacent to the lower tube of stacked geotextile tubes mitigates the lateral movement of the embankment.

[5] produced a similar study to [4] but for a marine causeway, considering the influence of submergence under the effect of tidal range. Moreover, the study investigates three different filling pressures for the geotextile tubes 0, 5.0, and 20.0 kPa. The conclusion was geotextile tubes subjected to pumping pressures of 0 and 5.0 kPa improved the deformation behavior of the causeway with water depths of 0.5 and 1.5 m. In comparison, the models ceased when applying a pumping pressure of 20.0 kPa with water depths of 0.50 and 1.50 m.

[13] recommended that the use of geotextile tubes is a viable option for the construction of breakwater cores

due to their commendable strength and long-lasting properties. The cost-effectiveness of this approach is superior when compared to that of a traditional rubble mound breakwater. Furthermore, the use of geotextile mattresses serves to mitigate excessive settlement, particularly in very unstable seabed circumstances due to low soil stiffness.

When creating a geotextile tube, it is essential to carefully evaluate the specifications of the geotextile tube fabric and the filler material since both aspects play a crucial role in the overall design. Choosing a High Strength Woven geotextile is necessary for constructing geotextile tubes of significant dimensions.

2. METHODOLOGY

The finite element modelling software, ABAQUS version 6.14, was utilized to examine the impact of incorporating various configurations of geotextile tube systems in the core of a marine causeway. The main objective is to enhance the causeway's lateral displacement and check the variation in the vertical stresses under the base of the causeway structure. The studied 45-degree causeway is subjected to a surcharge load and hydrostatic pressure from the surrounding seawater.

To complete that investigation, four main groups of models are studied. Before conducting the models of the main structure in the present study, the verification step is essential to determine to what extent the ABAQUS V 6.14 software could be used correctly. This step validates the simulation process for the laboratory-tested model by studying the deformation shape of a geotextile tube [14]. The second group of models serves as a reference scenario for investigating the stability of the marine causeway without implementing any geotextile tubes. This study segment examined three distinct soil types: dense sand, silty sand, and stiff clay. The obtained results for the structure were lateral displacement and vertical stresses. The third group of models was conducted to have the deformed shape of the in-core placed geotextile tubes after the filling process under three different pressures. The fourth group of models focused on assessing the effectiveness of using a geotextile tube reinforcement system (GTRS) in enhancing the stability of the causeway. In that last group, many configurations have been studied to evaluate the influence of many parameters on the designing of GTRS. i.e., the filling pressure, the diameter of geotube units, the number of geotube units, and the filling material.

3. MODEL SETUP

3.1. Verification model

In [14], W. Guo conducted a series of experimental and analytical studies on geosynthetic tubes to develop closed-form solutions for the design of geosynthetic tubes. This section involves the simulation of one experimental model in [14] by using ABAQUS V6.14 software to verify the accuracy of the numerical model. The validation process entails a comparison of the deformed shape of the simulated model with the experimental observations. In the experiment coded by T1 in [14], the perimeter of the geotextile tube was 2.00 m; that perimeter leads to a theoretical diameter of 0.64 m; the geosynthetic material of the tube is impermeable to being filled with water under pumping pressure of 6.86 kPa.

For the numerical modelling, "ABAQUS" is the FE software employed for this task. A cylinder part was created to simulate the segment cut out of the tube; the cylinder was 2.00 m perimeter, and 0.60 mm thickness to represent the same experimented geotextile tube. The tube was placed on an analytical rigid surface representing the ground surface. The numerical model is similar to the models used in [4], [5], and [15]. To reduce the mesh sensitivity, several meshing sizes were tried, and the meshes were refined up to 0.02 m x 0.02 m, employing squared finite elements, were utilized. A linear reduced integration shell element was employed to reduce computational time. Typical values for isotropic linear elastic material properties for the shell elements were defined as having a mass density of 1700 kg/m^3, a Young's Modulus of elasticity of 1.7 GPa, and a Poisson's ratio of 0.40.

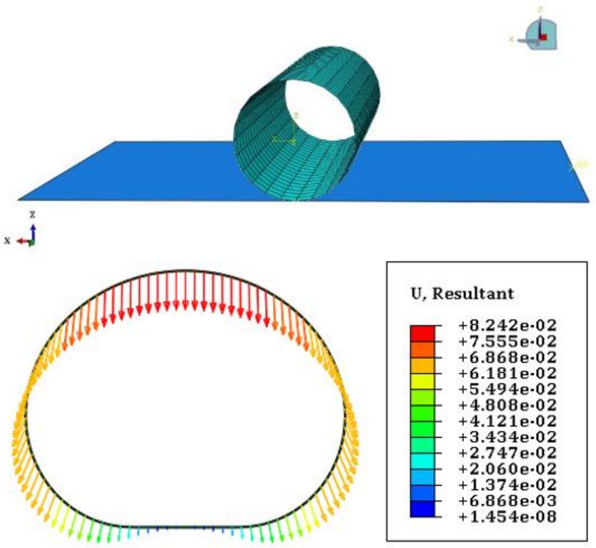

Figure 2: verification model and its results “U in meters”

The x, y, and z axes were oriented in a manner that was horizontally perpendicular to the length of the tubes, parallel to the length of the tubes, and vertically directed toward the top of the structure, respectively. Various boundary conditions were defined in the model; it was restrained along its vertical centerlines. The centerlines were oriented parallel to the vertical planes of symmetry on the z-axis. Their movements were allowed only in the Z-direction. The implementation of an x restraint will prevent the potential occurrence of crinkling in the shell elements. Implementing a y restraint is necessary to allow perpendicular stability to the tube during the filling process. During the simulation, a contact interaction was designated between the rigid surface and the tube with a sufficient value of friction coefficient of 0.6. the same pumping pressure as in the experimental procedure was applied by hydrostatic pressure on the inner surface of the shell. Before applying the hydrostatic pressure, a gravity load was applied for the tube to represent the own weight of the geotextile tube. Figure 2 shows the FE model for the experimented geotextile tube and the U results.

Results of the FE model showed that the deformed shape is acceptable and matched with the measuring of the experimental procedure in [14]. Dimensions of the experimental and FE models and the difference ratio are shown in Table 1, while the results of the deformed shape for the two models are shown in Figure 3.

Table 1. Comparison between experimental and numerical models.

Model	Height (m)	Width (m)
Experimental	0.526	0.699
Numerical	0.556	0.689
Different ratio	+ 5.70 %	- 1.43 %

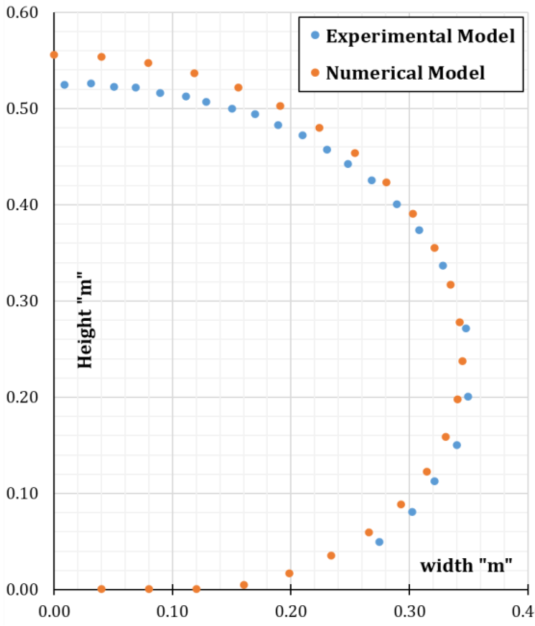

Figure 3: comparison between the half of the deformed shape obtained from the FM and EM.

3.2. Reference models

Before including any reinforcement by using any geotextile tubes, the models in this section were examined to get reference values for the study. The concerned marine causeway in this study is 4.00 m in height, 8.00 m in width at the level of its crest, and has a 1:1 side slope. The length is 6.00 m to represent part of the causeway's longitudinal direction. A representative cross-section of the structure is shown in Figure 4.

The causeway's soil was chosen to be consistently homogeneous and to fall into one of three categories: dense sand, silty sand, or stiff clay. The Mohr-Coulomb is the constitutive model that had been chosen to model the soil. For dense sand soil, the unit weight is γ_{dry} = 16.5 KN/m^3 and γ_{sub} = 9.50 KN/m^3 for the dry and submerged zones, respectively. The modulus of elasticity "E" and Poisson's ratio "υ" are 75E6 Pa. and 0.35, respectively. While 38 and 8 degrees are chosen for friction angle "Ø" and dilation angle "Ψ". A minimum value of 1E3 Pa. for cohesion "C" was input to avoid competitional errors, as advised in many previous works [16]. For silty sand soil, the dry and submerged unit weights are 17.8 and 10.8 KN/m^3, E = 19.6E6 Pa, υ = 0.3, Ø = 25^0, and C = 24E3 Pa [17], for the last studied type; stiff clay the input parameters are γ_{dry} = 18.67 KN/m^3 and γ_{sub} = 11.67 KN/m^3, E = 60E6 Pa, υ = 0.45, and C = 150E3 Pa [16]. The previous three types of soils were particularly suggested to have a wide investigation for three different classifications of soils, i.e., mainly high friction soil, high cohesion soil, and moderate friction and cohesion soil.

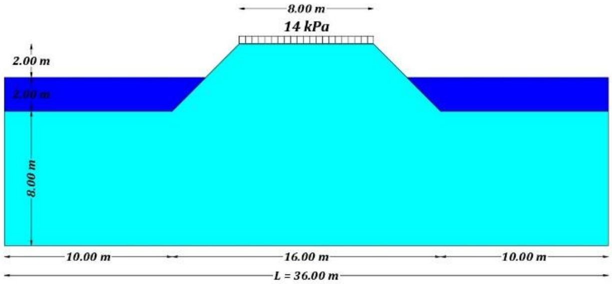

Figure 4: cross-sectional of the studied marine causeway "reference scenario"

The defined boundary conditions stipulate that the base of the foundation was immobilized in all directions. At the same time, the ends of the faces and the sides of the modelled causeway were constrained from movement within their respective plane. The three-dimensional finite element mesh utilized in the study comprised 4-node linear tetrahedron finite elements (C3D4).

In addition to the self-weight of the causeway, a surcharge pressure of 14 kPa was imposed on the crest surface of the causeway. The aforementioned live load denotes traffic loads of two-lane roadways in accordance with the Standard Specifications for Highway Bridges [18]. A hydrostatic pressure corresponding to a water depth of 2.00 m was exerted on both sides of the causeway.

The conclusions for the horizontal deformation "U1" on the right sloped surface of the concerning causeway in the three soil scenarios are presented in Figure 5. The results indicate that the high-density sand causeway exhibits minimal lateral deformation, measuring a value smaller than 0.5 mm at the toe of the causeway's inclined surface. Conversely, the silty sand causeway demonstrates the greatest potential for lateral deformation, surpassing 2.5 mm at the point of the highest level on the inclined surface; the negative sign refers to the inward direction.

Conversely, Figure 6 displays the results of normal stresses in the vertical direction "S33" along the baseline of the marine causeway. Values show that the maximum normal stresses correspond to the stiff clay model, contrary to the dense sand model, leading to the minimum stress values. Results of the S33 increase to reach the maximum direct under the center line of the causeway.

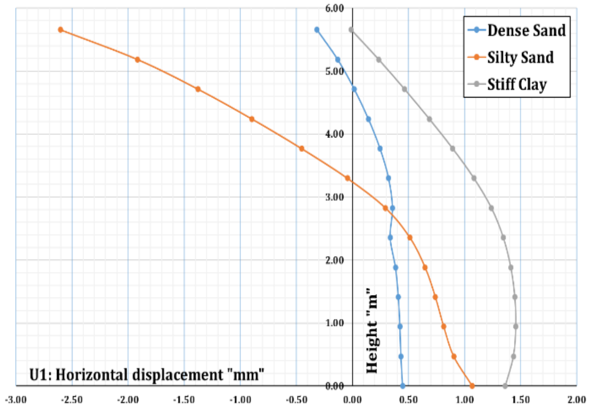

Figure 5: horizontal displacement of the marine causeway for the three cases of soils

3.1. Geotextile tube filling process models

These models were done to get the deformed shapes of the embedded geotextile tubes, which are supposed to be placed in the core of the marine causeway. Two different sizes of geotubes are employed in this investigation: a small geotube with a diameter of 2.00 m and a larger geotube with a diameter of 3.50 m. For each size, three different filling pressures are applied, i.e., 0 kPa, 20 kPa, and 40 kPa. Several individual sub-models were created to simulate the filling stage for each size and each filling pressure to obtain the deformed shape for each tube.

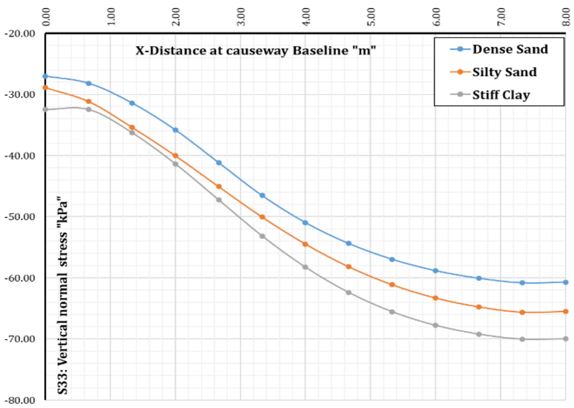

Figure 6: vertical normal stresses along the baseline of the marine causeway for the three cases of soils

Many filling materials have been experimented with in the present investigation, the same soil type as the causeway: local soil, dense sand soil, and concrete. It is worth mentioning that for the same size and pumping pressure, the obtained deformed shape of the geotextile tube stays the same, regardless of the filling material. The difference is about the input values for hydrostatic pressure applied on the inner surface of the shell representing the geotube during numerical modeling. The same model described in section 3.1 is recreated again. However, the input values for geotextile parameters are listed in Table 2 [4], [5], while Figure 7 illustrates the personification of the applied hydrostatic pressure inputs. Where P_0 is always zero pressure, P_1 is the indicated filling pressure; in this study, it is chosen to be 0 kPa, 20 kPa, and 40 kPa; in addition to, P_2 is the required hydrostatic pressure to be input ($P_2 = P_1 + \gamma D$). However, h_1 represents the height of zero pressure, which could be calculated by $h_1 = (D/2)\,(P_2+P_1)/(P_2-P_1)$. At the same time, h_2 is the radius of the geotube diameter for that case. All the previous input values depending on the same original point coincided with the location that appears in Figure 7.

Table 2. input parameters for geotextile material

Density (Kg/m^3)	75
Modulus of elasticity (KPa)	7.035×10^6
Poisson's ratio	0.45
Thickness (mm)	3

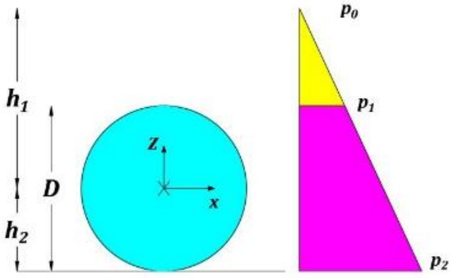

Figure 7: Inputs for hydrostatic pressure of filling process models

Figure 8 shows the obtained deformed shapes of the 2.00 m and 3.50 m diameter geotextile tubes from the filling stage under the three pressures mentioned above. The same behavior of the tube is observed at the same pressure, regardless of tube size; results revealed that higher pumping pressure leads to a higher height and smaller width for the geotextile tube and Vice versa for the smaller pumping pressure.

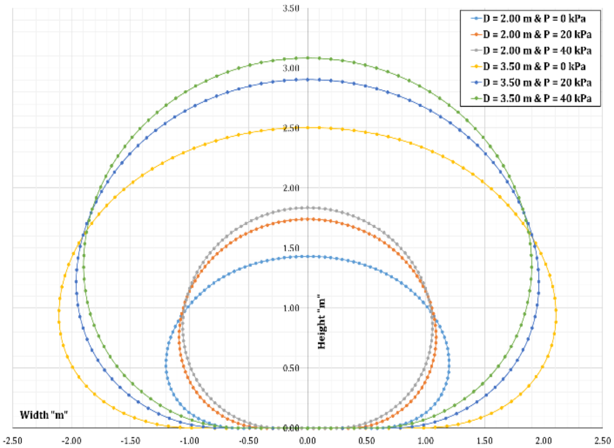

Figure 8: deformed shapes obtained from filling process models

3.2. GTRS models

These models aim to investigate the impact of the proposed reinforcement system on the marine causeway in question by incorporating geotextile tubes within the core layer. This study explores a novel application of geotextile tubes while mitigating the drawbacks associated with the penetration of the geotextile in the case of excessive loads, which leads to infilling material migration, particularly in soil materials. On the other hand, the proposed approach involves embedding the geotextile tubes within the core to prevent exposure to ultraviolet light or other direct detrimental factors. The models have been simulated under identical loads, boundary conditions, soil materials, and analysis procedures as the reference models outlined in section 3.2. However, the new component, geotextile tubes, has been incorporated as an embedded element within the soil in the interaction module in "ABAQUS V6.14". The proposed Geotextile Tubes Reinforcement System abbreviated as "GTRS", is depicted in Figure 9 for the case of zero filling pressure for 3.50 m of one unit configuration, as one of the six studied configurations.

The geotextile tubes consist of two parts: the geotextile skin part and the infilling material. The filling process modeled in the previous section obtains the geotextile skin. Therefore, for the linear elastic material of the geotextile material, linear integration shell elements were assigned. The mesh size was selected based on a 1:1 aspect ratio. Utilizing linear geometry shell elements (S4R) featuring reduced integration elements is a viable approach to economize computational time; material parameters of the geotextile skin of the tube are as listed in Table 2. The second part is the infilling material created to fill the geotube skin. For soil filling materials, the input parameters are as indicated in section 3.2.

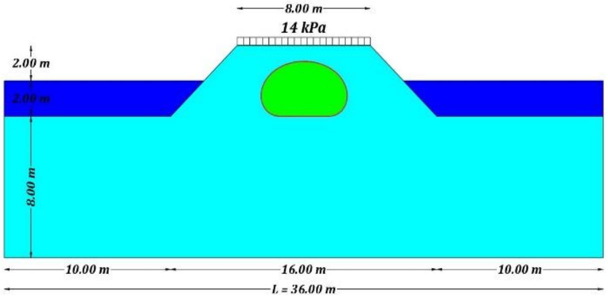

Figure 9: Purposed geotextile Tube Reinforcement System "GTRS" for the marine causeway

On the other hand, one of the proposed designs for "GTRS" is using concrete as a filling material. Concrete damage plasticity "CDM" is the constitutive model employed in numerical modeling. The proposed model is applicable for characterizing quasi-brittle substances, such as concrete, by replicating the phenomena of tensile cracking and compressive crushing. The model accounts for the material's isotropic elastic damage and plastic behavior. This constitutive model postulates that the deterioration of concrete material is primarily attributed to tensile cracking and compression crushing. The concrete used in the design is C40 grade concrete, which has allowable compressive strength "f_{ck} " =26.8 N/mm^2 and allowable tensile strength "f_{tk} " =2.39 N/mm^2, the density = 2400 kg/m^3, for the elastic stage; Elastic modulus "E" equals 30E9 Pa, and Poisson's ratio "ν" =0.2, for the plastic stage; Dilation angle "ψ" =30^0, Eccentricity "e" =0.1, Ratio of initial equi-biaxial compressive yield stress to initial uniaxial compressive yield stress is "f_{b0}/f_{c0}" = 1.16, ratio of the second stress invariant on the tensile meridian to that on the compressive meridian "K_c" = 0.6667, and viscosity parameter "μ" = 0.000. The input parameters for compressive and tensile behavior parameters are listed in Table 3 and Table 4, respectively [19]. The same type of finite elements is used for the concrete parts as for soil parts.

To investigate the efficiency of "GTRS" as a geotechnical reinforcement system and to obtain the optimum design and configuration for that system, three different parameters were considered: the pumping pressure "P", the size of the geotextile tube "D", the number of units "N", and the filling material's type. All the previous parameters are studied in three soil types, i.e., dense sand, silty sand, and stiff clay.

Table 3. Inputs for compressive behavior parameters "CDP" model

#	Yield stress	Inelastic Strain	Damage parameter	Inelastic Strain
	Pa	m	-	E-3 m
1	13.941E6	0	0	0
2	24.505E6	0.218E-3	0.103	0.218E-3
3	26.8E6	0.611E-3	0.215	0.611E-3
4	24.792E6	1.161E-3	0.338	1.161E-3
5	21.214E6	1.769E-3	0.448	1.769E-3
6	18.926E6	2.17E-3	0.509	2.17E-3
7	15.176E6	2.943E-3	0.602	2.943E-3
8	10.909E6	4.211E-3	0.706	4.211E-3
9	6.956E6	6.421E-3	0.805	6.421E-3
10	5.159E6	8.394E-3	0.852	8.394E-3
11	3.377E6	12.274E-3	0.9	12.274E-3
12	3.025E6	13.558E-3	0.91	13.558E-3
13	2.645E6	15.32E-3	0.921	15.32E-3
14	2.303E6	17.399E-3	0.931	17.399E-3
15	1.969E6	20.113E-3	0.94	20.113E-3
16	1.633E6	23.94E-3	0.95	23.94E-3
17	1.535E6	25.374E-3	0.953	25.374E-3

Table 4. inputs for tensile behavior parameters "CDP" model

#	Yield stress	Cracking Strain	Damage parameter	Cracking Strain
	Pa	m	-	m
1	2.39E6	0	0	0
2	2.18E6	0.025E-3	0.128	0.025E-3
3	1.885E6	0.053E-3	0.25	0.053E-3
4	1.75E6	0.067E-3	0.301	0.067E-3
5	1.425E6	0.105E-3	0.425	0.105E-3
6	1.196E6	0.14E-3	0.512	0.14E-3
7	0.947E6	0.192E-3	0.61	0.192E-3
8	0.719E6	0.27E-3	0.702	0.27E-3
9	0.485E6	0.436E-3	0.803	0.436E-3
10	0.376E6	0.597E-3	0.85	0.597E-3
11	0.262E6	0.95E-3	0.9	0.95E-3
12	0.239E6	1.073E-3	0.91	1.073E-3
13	0.216E6	1.231E-3	0.92	1.231E-3
14	0.197E6	1.389E-3	0.928	1.389E-3

In the process of GTRS modeling, several assumptions were taken into account. These include the sufficiency of geotextile skin strength to withstand the straining stresses generated on it, the exclusion of seams impact and their strength during simulation, and the impossibility of scouring in the surrounding soil.

4. RESULTS AND DISCUSSION

Several models were generated. A single alteration was made to each run to examine the impact of each parameter of "GTRS" on the stability of the marine causeway in question. To evaluate the change in the causeway's stability, outcomes of lateral displacement on the inclined surface of the causeway, as well as the normal vertical stress on the base of the causeway, will be displayed. The subsequent subsections present graphical representations and findings for every parameter on the lateral displacement in particular.

4.1. Effect of filling pressure of geotextile tube.

To study the effect of the filling pressure value on the efficiency of "GTRS", three different values of pumping pressure during the filling process are employed, i.e., zero pumping pressure, 20 kPa, and 40 kPa. The three pressures are applied to a single unit of geotextile tube with a diameter of 3.50 m; that unit was filled with concrete; however, as previously elucidated, the filling material type does not change the obtained deformed shape of the geotextile tube unit. This study aims to evaluate the stability of the concerned marine causeway under the same conditions in the form of lateral displacement of the inclined surface by comparing U1 values before and after using "GTRS". That procedure was repeated for the three types, as mentioned earlier, of soils for the causeway.

Figure 10, Figure 11, and Figure 12 show the lateral deformation of the right inclined surface along the height of the marine causeway. The figures represent the outcomes of the three soils: dense sand, silty sand, and stiff clay. As depicted in the figures, the change in filling pressure value during the filling process does not adequately affect the stability of the concerned structure in the three studied geotechnical cases.

Figure 10 shows that the maximum reached lateral displacement is located at the toe point of the inclination for the dense sand causeway. The value of 0.45 mm for the lateral displacement is obtained for the unreinforced causeway, while values are 0.39, 0.40, and 0.42 mm for the reinforced model during filling pressures of 0 kPa, 20 kPa, and 40 kPa, respectively. Irrespective of the results of the toe point, the stability of the causeway gained considerable impact at a level located approximately at half of the height when using "GTRS". The results at that level are shown in the form of enhancement percentage in Figure 13.

Figure 11 shows the results of the silty sand case; the maximum reached lateral displacement belongs to the unreinforced causeway located at the crest level with a value of 2.60 mm. That value changes to 1.78, 1.82, and 1.84 mm for the three filling pressures of 0 kPa, 20 kPa, and 40 kPa, respectively, when using "GTRS". Results in Figure 12 show that the maximum lateral displacement is located approximately at the first meter of the height. The U1 values are 1.46, 1.22, 1.23, and 1.26 mm for the unreinforced and those mentioned above three reinforced models, respectively.

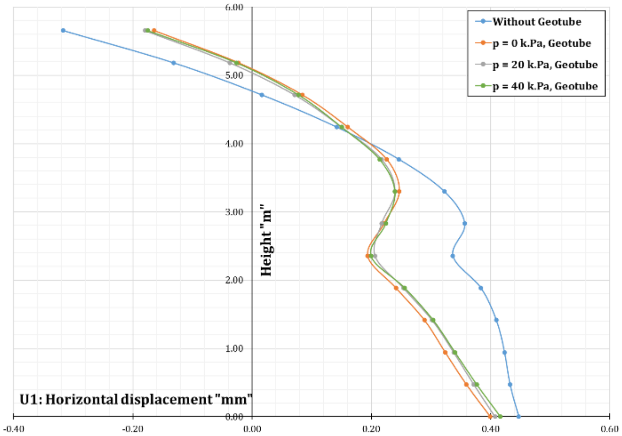

Figure 10: lateral displacement of the dense sand marine causeway for different filling pressures of geotextile tube

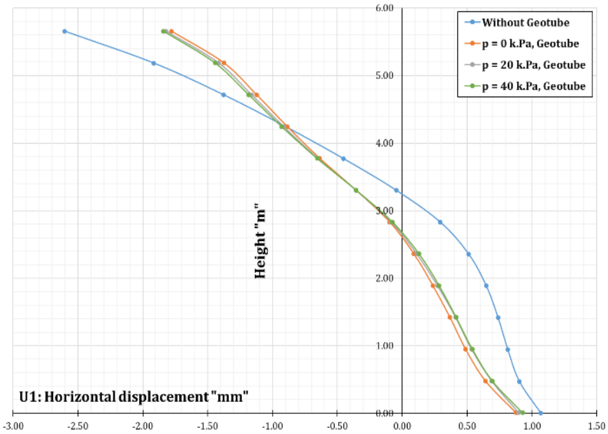

Figure 11: lateral displacement of the silty sand marine causeway for different filling pressures of geotextile tube

The same behavior in the lateral displacement is observed for the three studied filling pressures with very close results. However, a slight priority on the zero-filling pressure is observed in lower levels. Figure 13 confirms the previous finding, where the values of maximum enhancement in the lateral displacement percentage have a minor effect by the change in filling pressure values for the three studied soils. The relatively high values of enhancement percentage in the silty sand soil are basically due to the low rigidity of that type against the lateral displacement, as shown in Figure 5. Finally, a clear outcome could be ensured with a recommendation to avoid the use of high filling pressure during the installation process; zero pressure is recommended to avoid extra costs and any unnecessary difficulties for implementation on-site.

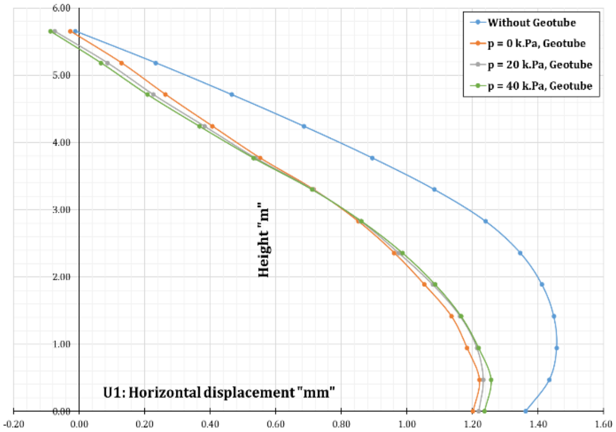

Figure 12: lateral displacement of the stiff clay marine causeway for different filling pressures of geotextile tube

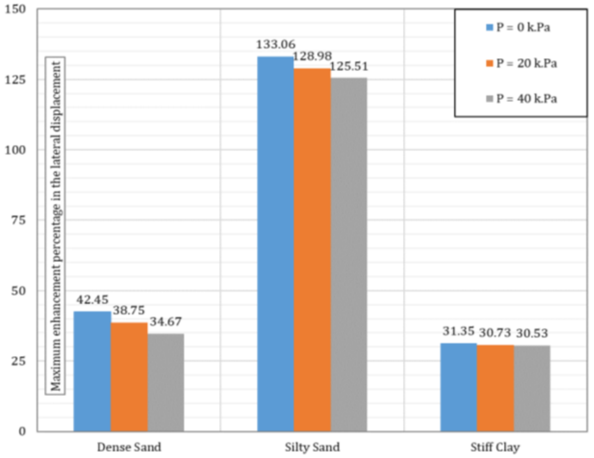

Figure 13: Percentage of maximum enhancement in the lateral displacement of the three types of soil for different geotextile tube filling pressures

4.2. Effect of the diameter of the geotextile tube.

This subsection displays results related to another design parameter that may have a significant impress during the design stage of this system, i.e., the diameters of the geotextile tubes. Increasing the diameter of the geotextile tube no doubt allows a larger volume of the filling concrete material to exist in the core of the causeway. At the same time, it decreases the surrounding soil area, which could change the rigidity of the remaining part of the soil.

For that purpose, Figure 14**,** Figure 16**,** and Figure 17 display the lateral displacement along the inclined surface of the marine causeway. All studied models in this subsection employed "GTRS" consisting of zero filling pressure for one geotextile tube unit. Only the diameter of this unit changed from 2.00 m to 3.50 m for the three studied soil cases.

Figure 14 shows the results of the dense sand causeway; as mentioned before, the U1 result at the toe point gives a value of 0.45 mm for the non-reinforced causeway, while the values of the GTRS at the same point are 0.42 mm and 0.39 mm for the 2.00 m and 3.50 m diameters, respectively. However, Figure 16 shows values of 2.60 mm, 2.25 mm, and 1.78 mm at the crest point of the silty sand causeway for the three simulated models in the same order. Also, Figure 17 shows that the maximum values of U1 are 1.24 mm, 1.09 mm, and 0.85 mm for the same models, respectively.

Examination of the effect of the diameter in GTRS at the three studied soils shows that the highest enhancement percentage related to the silty sand soil with a maximum value of 133.06 % for the 3.50 m diameter, while the same value changed to 42.45% and 31.35 % for the dense sand and stiff clay causeways respectively. At the same time, the values of the smaller diameter are 13.56, 58.67, and 12.16 % for the three soil types in order, respectively. See Figure 18.

As an assessment of that parameter, the results obtained in this subsection remove fears that are mentioned at the beginning, which are related to the rigidity of the remaining soil around the geotextile tube. Findings ensure that the procedure gives more rigidity against lateral displacement for the causeway inclined surface, presenting the chance for more stability of the whole structure.

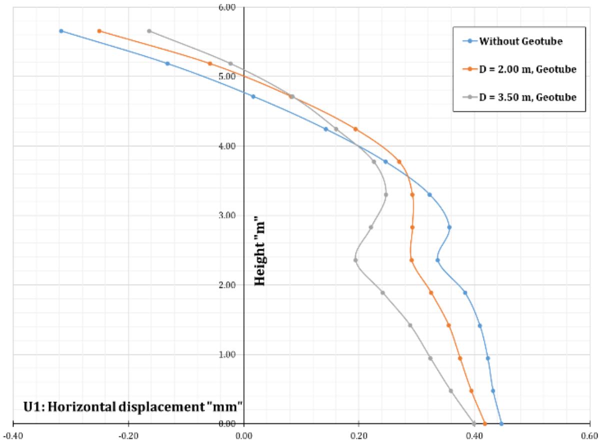

Figure 14: lateral displacement of the dense sand marine causeway for different geotextile tube diameters

4.3. Effect of units' number of the geotextile tube.

To have a broad answer to the question that was raised in the previous subsection, to know if the increasing of the occupied area by concrete in this structure increases the stability of the causeway or not. Three configurations are studied for each soil type. The number of units changed from one to three units, see Figure 15. Substantially, all geotextile tubes located in the core of the studied model in this subsection are zero pressure-filled with a diameter of 3.50 m.

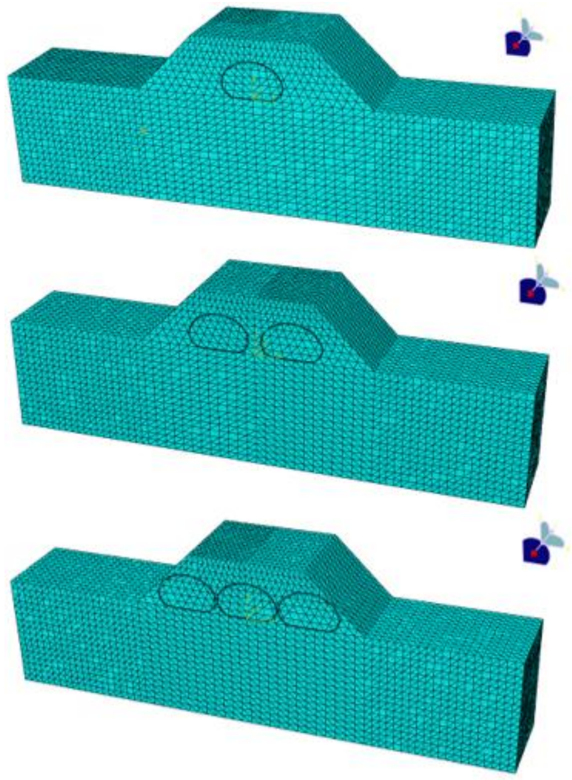

Figure 15: the configurations of 1-unit, 2-units, 3-units' models

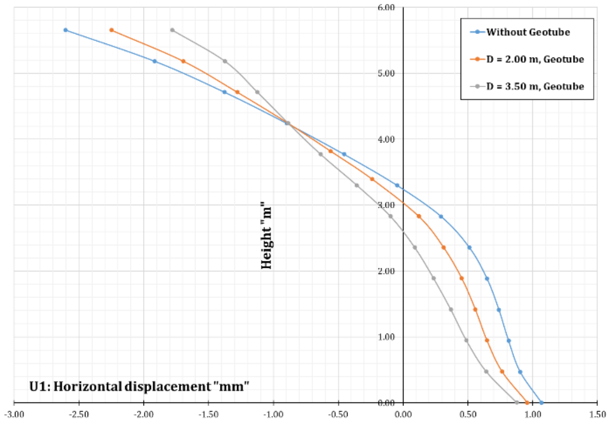

Figure 16: lateral displacement of the silty sand marine causeway for different geotextile tube diameters

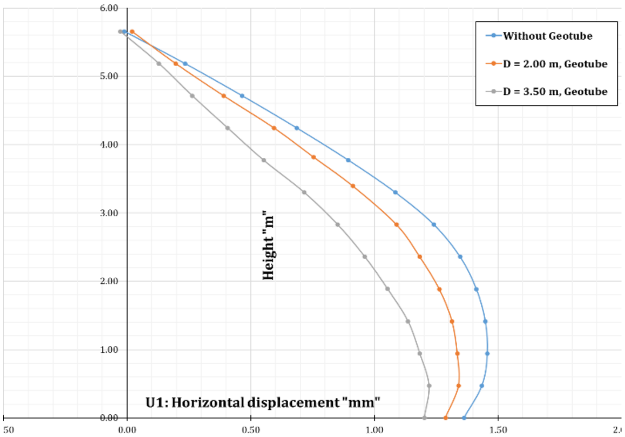

Figure 17: lateral displacement of the stiff clay marine causeway for different geotextile tube diameters

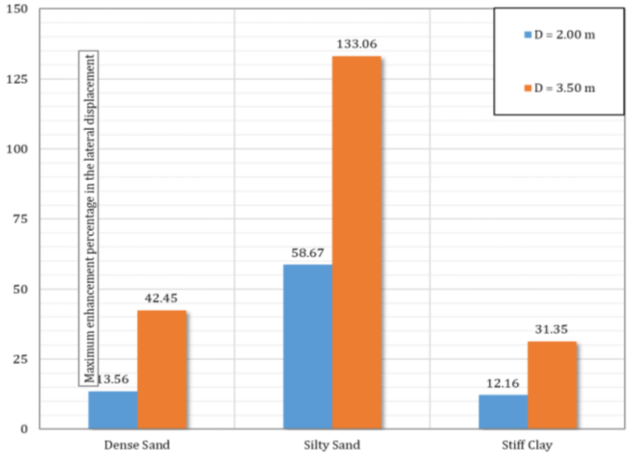

Figure 18: Percentage of maximum enhancement in the lateral displacement of the three types of soil for different geotextile tube diameters

The outcomes of the dense sand causeway are depicted in Figure 19. The lateral displacement findings at the toe point indicate a measurement of 0.45 mm for the non-reinforced causeway. In contrast, the lateral displacement values at the same location are 0.39 mm, 0.36 mm, and 0.40 mm for the 1, 2, and 3-unit configurations in "GTRS", respectively. It is remarkable to notice that lateral displacement, which occurs at the toe point from the 3-unit configuration, is more than the other two configurations. An explanation for that result is deduced from the large area of the concrete occupied near the toe level in the cross-section, which makes the medium in that level more rigid in the inner core, leading to a smaller remaining area of soil at sides to resist the stresses, so it gives more lateral displacement. To prevent the lengthening of the discussion about the outcomes. A similar behavior for the silty sand causeway is noticed in Figure 20; the friction soil of both causeways could explain this. Another note could be recorded by screening the results along the whole height of the causeway; for the lower half height, the results of the 2-unit and 3-unit models are close to each other. For the upper half, their results are different enough and do not lead to a priority for a specific model.

Figure 21 shows deformations of the stiff clay causeway. Again, the same finding is obtained, which means increasing the unit number is an advised requirement. Screening of the figure shows that at a height of 3.30 m, the value of U1 is about - 0.36 mm for the 3-unit GTRS; at the same time, that value was about + 1.10 mm for the un-reinforced model. The negative sign represents the displacement to the inner direction, while the positive sign represents the displacement to the outer direction. This change in direction, not only in the values, explains the high values displayed in the results of the percentage of maximum enhancement in the lateral displacement in Figure 22. The results of U1 at the toe level were 1.36, 1.20, 0.95, and 0.68 mm for the reference model, 1-unit GTRS, 2-unit GTRS, and 3-unit GTRS models, respectively, which means that the remaining cohesion soil has the sufficient rigidity to resist the applied stresses.

Among all the studied parameters, the maximum reached stability for the causeway belongs to the 3-unit configuration of GTRS. The previous finding could be ensured by screening the bar charts in Figure 22. The maximum enhancement percentage of the lateral displacement for the dense sand, silty sand, and stiff clay are 116.76 %, 491.85 %, and 123.49 %, respectively. Again, the high values obtained in the silty sand causeway reflected from its low rigidity against lateral displacement, as shown in Figure 5. Finally, the results of this subsection show that increasing the number of geotextile tube units as possible increases the stability of the marine causeway.

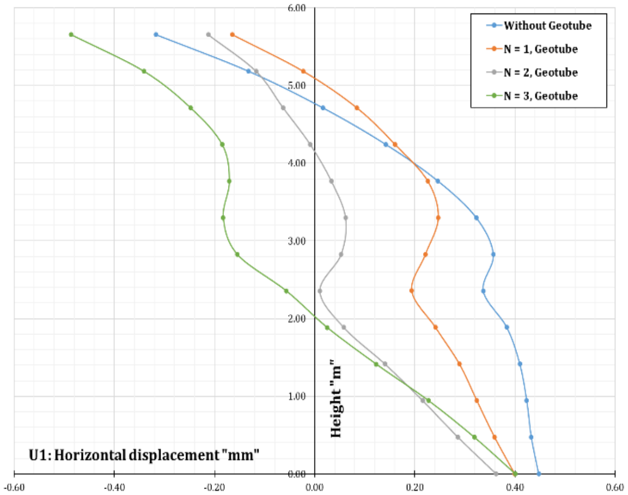

Figure 19: lateral displacement of the dense sand marine causeway for different numbers of units of geotextile tube

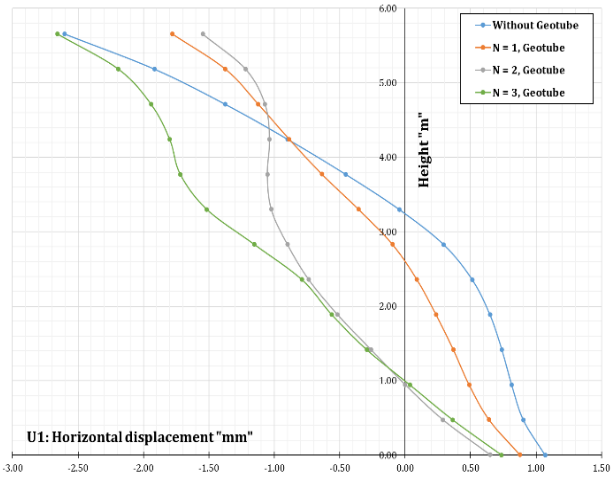

Figure 20: lateral displacement of the silty sand marine causeway for different numbers of units of geotextile tube

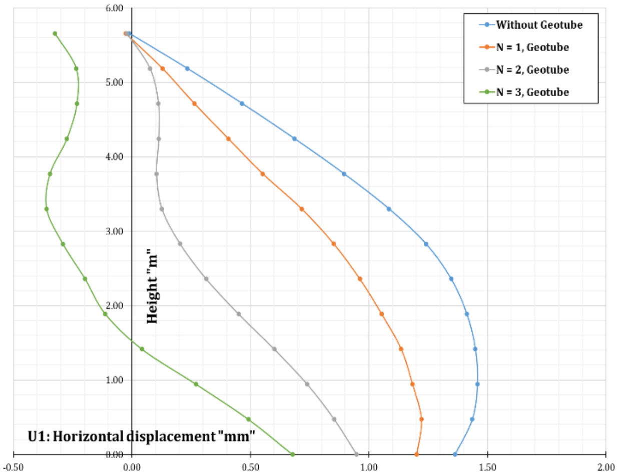

Figure 21: lateral displacement of the stiff clay marine causeway for different numbers of units of geotextile tube

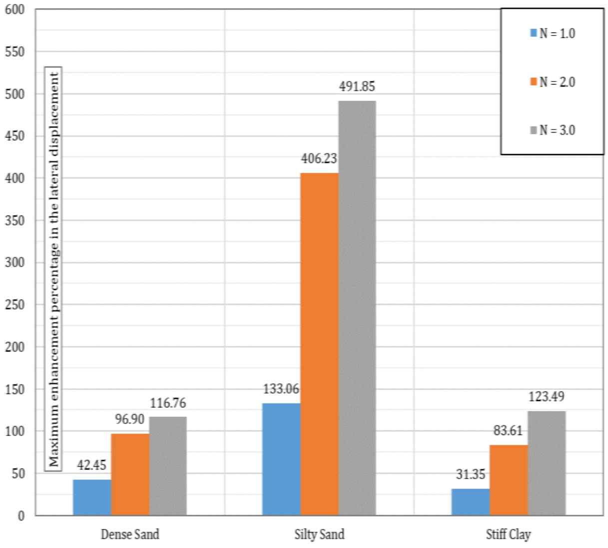

Figure 22: Percentage of maximum enhancement in the lateral displacement of the three types of soil for different numbers of units of geotextile tube

4.4. Effect of filling material for geotextile tube

In the previous parametric studies, the concrete material has always been the filling material; numerous previous studies have discussed this type of geotextile tube as a breakwater [20], [21], and [22]. It must be mentioned here that using a geotextile tube gives feature ease of construction without the need for forming shuttering works, regardless of the economic cost of the concrete material. To have a general view of the "GTRS" efficiency and to study the possibility of using other filling materials having an economic priority. The present subsection discusses the results of using three types of filling materials, i.e., local soil, dense sand soil, and concrete material. The expression of local soil means using the same soil existing at the construction site, which could be used after being extracted from any other excavation works. Therefore, the local soil and dense sand are the same for the first studied causeway. The purpose of using the local soil as filling material leads to results only depending on adding geotextile material in a closed shape in the core of the causeway as reinforced material. On the other hand, the aim of using a foreign material such as concrete or dense sand soil is to take advantage of the previous concept and inject the core of the causeway with a stiffer material.

The behavior of lateral displacement of the inclined surface of the three studied causeways is shown in Figure 23, Figure 24, and Figure 25. Results reveal that using local soil-filled geotextile tubes needs to be reconsidered as it has not shown a clear improvement in the stability of the structure. The percentage of maximum enhancement in lateral displacement shown in Figure 26 shows that local soil filling does not provide values that reach 5.0% for any of the three types of soils.

The underlying principle of using dense sand as a filling material is to present an alternative economic solution to the concrete-filled one. Results in Figure 24 and Figure 25 show that using dense sand as a filling material for the other causeways gives a moderate enhancement to the stability of the structure. Substantially, an adequate solution for a lower cost; Figure 24 displays results obtained from silty sand causeway; the reached U1 values at the crest level are 2.60 mm, 2.32 mm, 1.62 mm, and 1.78 mm for the un-reinforced model, local filling, dense sand filling, and concrete filling GTRS models, respectively. In Figure 25, the results of U1 of stiff clay causeway reach the maximum values at the first meter high; the obtained values are 1.46 mm, 1.43 mm, 1.30 mm, and 1.20 mm for the same four models.

Depending on the same approach to have a general view of the effect of GTRS on the stability of the causeway for the three studied soils, Figure 26 is displayed. For all the studied cases, using concrete as a filling material gives the best strength for the marine causeway, especially for the silty sand causeway. On the other hand, filling of a geotextile tube with dense sand soil shows an adequate ability to deliver high stability for the silty sand and stiff clay causeways, where the percentage enhancement changed from 133.06 % in the case of using concrete GTRS to 44.12 % in the case of dense sand GTRS for the silty sand causeway. At the same time, these values are 31.35 % and 15.36 % for the same order of the models, respectively.

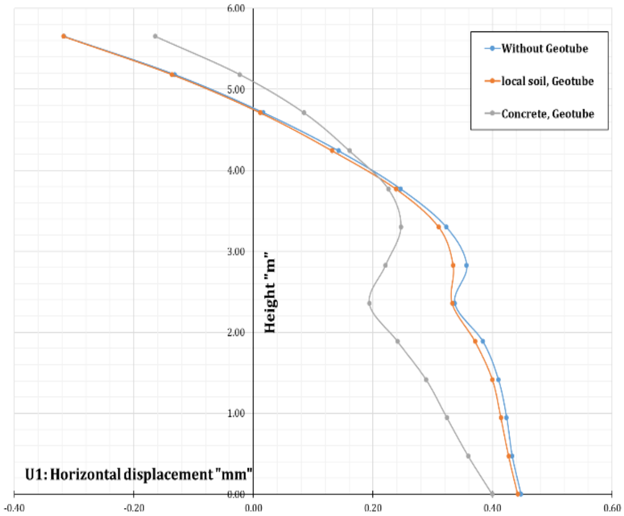

Figure 23: lateral displacement of the Dense sand marine causeway for different filling materials in units of geotextile tube

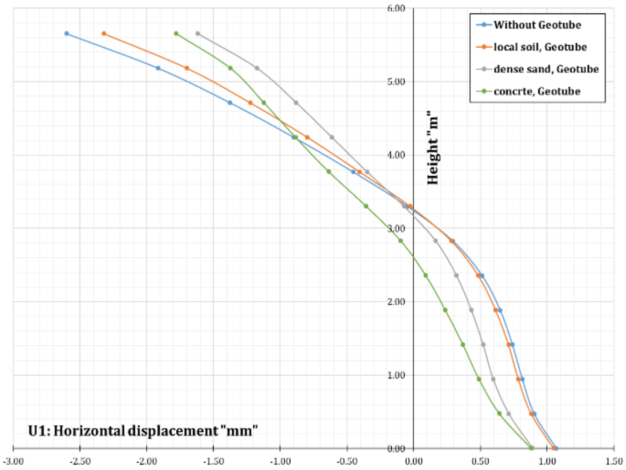

Figure 24: lateral displacement of the Silty sand marine causeway for different filling materials in units of geotextile tube

4.5. Changing of soil stresses as a result of GTRS.

Irrespective of the lateral displacement, it is considered a sufficient pointer to the stability of the causeway according to many previous works [4],[23],[5], and [24]. It is of significance to investigate the vertical stresses at the base of the marine causeway, especially when using concrete-filled units. The results displayed in this subsection belong to the same models displayed in the previous subsection. All models are 1-unit configuration, zero pressure-filled, and 3.50 m diameter. The filling material is changed as previously.

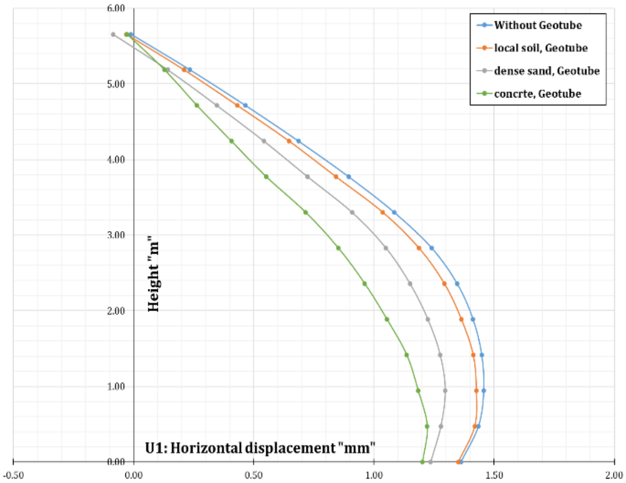

Figure 25: lateral displacement of the Stiff clay marine causeway for different filling materials in units of geotextile tube

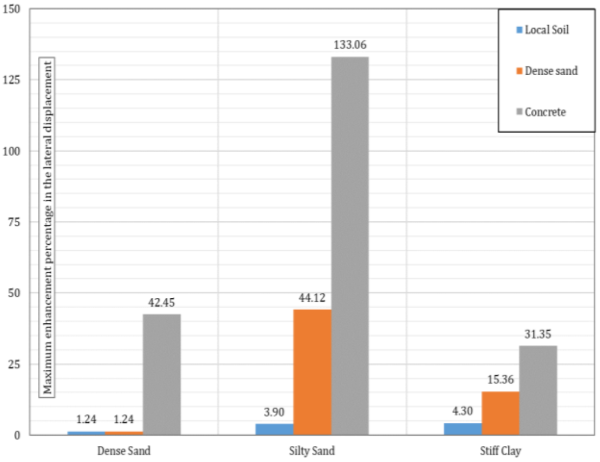

Figure 26: Percentage of maximum enhancement in the lateral displacement of the three types of soil for different filling materials in units of geotextile tube

The effect of the "GTRS" on the normal vertical stress "S33" under the half base of the three studied causeways is displayed in Figure 27, Figure 28, and Figure 29. Results of the un-reinforced causeway and three different filling materials for "GTRS" show that using that system reduces the vertical stresses by a considerable proportion, especially directly under the base of the geotextile tube, which is located at the middle third of the base. The values of the vertical stresses under the location of the geotextile tube have a high reduction in the case of a concrete-filled geotextile tube; the same location shows that using geotextile tubes filled with local soil has smaller vertical stresses than the dense sand-filled geotubes, the same behavior is noticed for the three studied types of soil.

For more examination, Figure 27 shows that values of S33 at the center line of the causeway are 60.70, 46.90, and 32.90 kPa for the reference model, dense sand-filled and concrete-filled GTRS, respectively. Instead, Figure 28 shows that these values at the same location are 65.50, 41.80, 40.40, and 34.0 kPa for the reference model, dense sand-filled, local soil-filled GTRS, and concrete-filled GTRS, respectively. Otherwise, the results in Figure 29 are 69.9, 62.50, 58.70, and 38.60 kPa for the same models, respectively.

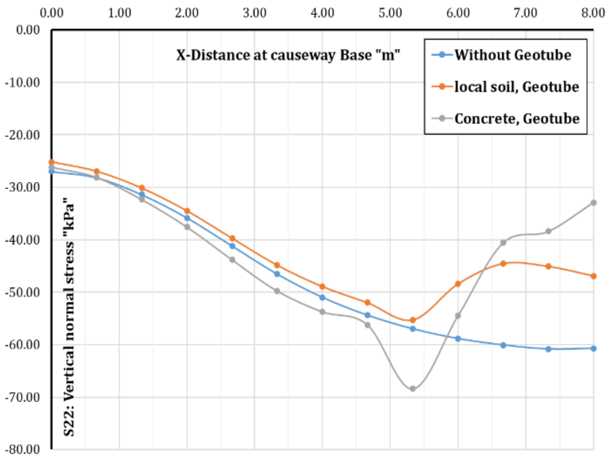

Figure 27: vertical normal stress "S33" along the half base of the dense sand causeway for different filling materials in geotextile tubes

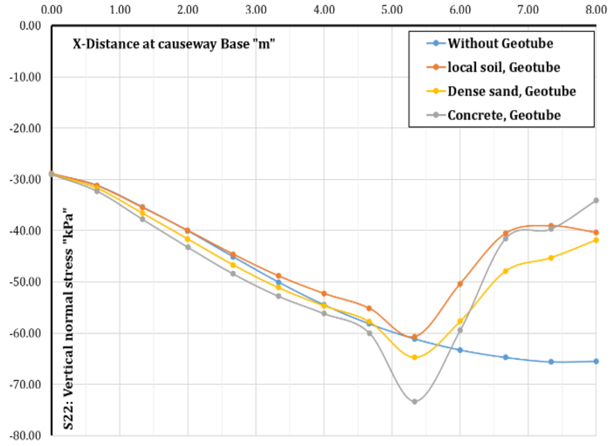

Figure 28: vertical normal stress "S33" along the half base of the silty sand causeway for different filling materials in geotextile tubes

Also, as depicted in the figures, concrete-filled units increase the vertical stresses near the position of the geotextile tube's side borders. The increase in these values does not exceed 13% of the maximum stresses reached in the unreinforced model. Aside from this increase, it must be emphasized that the maximum values reached by vertical stresses for this system are within the bearing capacity value of all studied soil types.

Hence, another feature of using "GTRS" that appears from the examination of these charts is decreasing the vertical stresses under the causeway body, even in the case of using local soil, in the three studied causeways by 22.75%, 38.36%, and 16.01% for dense sand, silty sand, and stiff clay causeways, respectively. However, For the concrete-filled GTRS, the values of vertical stress at the center line have more decreased values, with some increase at the sides of the geotextile tube units.

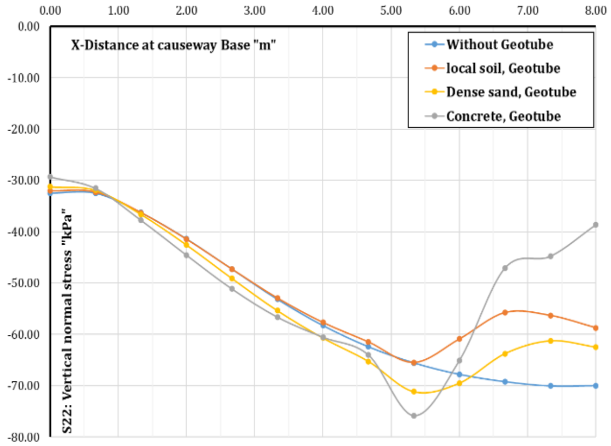

Figure 29: vertical normal stress "S33" along the half base of the stiff clay causeway for different filling materials in geotextile tubes

5.CONCLUSION

A revolutionary geotechnical technique, "GTRS," that adds geotextile tube units to the marine causeway's core layer is used to evaluate the enhancement in the causeway's stability. This technique must first determine the deformed shape of geotextile tube units after installation process during the causeway construction.

Therefore, many numerical models were carried out using ABAQUS V6.14 software to simulate the filling process of multiple sizes of geotextile tubes under different groups of filling pressure, filling materials, and numbers of units. Before performing these Numerical models, a verification model had been created to simulate a small-scaled experimental model that had been studied by W. Guo [14]. Comparing results between the two models shows sufficient matching for the deformed shape, whereas only 5.0 % and 7.0 % differences were found in the extracted height and width of the malformed geotextile tube.

After that, "GTRS" performance in the causeway was studied in two portions. First, three large-scale reference models for the marine causeway were simulated to analyze the behavior of three soils: dense sand, silty sand, and stiff clay. Second, investigating the marine causeway's stability using the "GTRS" reinforcing system. The second primary component of the GTRS system was a parametric analysis that varied one parameter in each model to measure the lateral displacement of the inclined surface and vertical stresses under the causeway foundation. The study concluded that:

- The system presented "GTRS" herein serves as a viable method for achieving geotechnical reinforcement in marine causeways while adhering to recommended construction and design criteria focusing on sustainability.

- Regarding analyzing the reference models, the location of maximum lateral displacement on the inclined surface of a causeway is contingent upon the soil type, specifically, the toe level of the dense sand causeway, the crest level of the silty sand causeway, and the lower third of the stiff clay causeway. The results indicate that the silty sand exhibits the greatest degree of lateral deformation, whereas the dense sand demonstrated a comparatively more rigid behavior among the three models; in addition, screening the vertical stresses on the baseline shows that the stiff clay causeway has the largest S33, while the dense sand causeway leads to the lighter stresses, as already indicated in Figure 5 and Figure 6.

- Studying the filling pressure parameter does not show a powerful effect on the stability of the structure, as the results converged for the three applied pressures: 0 Kpa, 20 Kpa, and 40 Kpa. That result is useful, especially for the construction process, to avoid extra efforts during the filling process, which could save on pumping costs, where zero pressure is recommended for the presented "GTRS".

- Examining the effect of geotextile tube sizes on the performance of "GTRS" shows that using larger sizes of geotube units in the configuration of the system is required to achieve high stability for the causeway; the percentage of enhancement for 3.50 m diameter units reached 42.45%, 133.06%, and 31.35% for the dense sand, silty sand, and stiff clay causeways, respectively. In comparison, these values only reached 13.56 %, 58.67%, and 12.16% for the 2.00 m diameter; the results of the small diameter do not reach even half of the large unit's percentage.

- Of all studied models, it could be ensured that the largest stability for the marine causeway was achieved by increasing the number of geotextile units. Three configurations for each kind of soil were studied. The number of units had been changed from one to three. The 3-unit "GTRS" models obtain the maximum enhancement percentage values of 116.76%, 491.86%, and 123.49% for dense sand, silty sand, and stiff clay causeway, respectively.

- The last studied parameter was the effect of filling material on the performance of the "GTRS"; three various materials were tried, i.e., the concrete material, which already had been employed in the previous models, local soil, which may exploit the extracted native soil from other dredging works to be used in geotubes filling process, in addition to, using dense sand soil for the same purpose. The main intention of trying the last two materials rather than the concrete is to reduce the cost of the presented system. As was expected, the concrete units show the best version in the stability of the studied structure, especially for the silty sand causeway, where the maximum enhancement percentage reaches 133.06% at the silty sand causeway. On the other hand, the results of the dense sand-filled units reveal a moderate influence on the stability of the studied causeways, where the maximum percentage enhancement was 44.12% and 15.36% for the silty sand and stiff clay causeways, respectively. Realistically, it could be confirmed that using the same soil of the causeway as a filling material does not change the results of causeway stability, at least in the form of lateral displacement.

- Examination of the stresses under the marine causeway shows that using "GTRS" with any studied filling materials decreases vertical stresses at the center of the causeway, especially for concrete and dense sand-filled units. Whatever, the behavior of the vertical stresses shows a slight increase at the location below the side of the geotextile tube before a decline in the middle of the baseline of the causeway for the types above. The results of vertical stresses show that using local soil in "GTRS", which does not affect the lateral deformation, decreases the vertical stresses along the base of the causeway.

6.RECOMMENDATIONS FOR FUTURE WORKS

- Study the internal stresses in the geotechnical skin of the geotubes and the effectiveness of seams.

- Investigate additional geotechnical phenomena, such as consolidation and compaction, and their effect on the stability of the causeway.

- Studying the stability of the marine causeway against other hydrodynamic phenomena, such as wave attack, which may occur in open coastal areas.

- Despite the effectiveness and features of the numerical investigations, conducting large-scale physical models in the laboratory or in-site is a more accurate analysis of those types of structures.

- Study individually potential failure models, such as sliding, overturning, and stress, that may occur under aggressive loading situations.

- **Credit Authorship Contribution Statement:**

Ahmed Abou Seedah: Literature review, Methodology, Software, Formal analysis, original draft preparation, and Investigation; **Ehab Tolba**: Visualization, Conceptualization, Supervision, Investigation, and Reviewing; **Elsayed Galal**: Visualization, Conceptualization, Methodology, Original draft preparation, Supervision, Editing, and Reviewing.

- **Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

- **Declaration of Funding**

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