Numerical Study of a Quay Wall Anchored by an Anchor Plate Backfilled with a Mixture of Sand and Recycled Waste

F. Z. Benamara[1], C. Kechkar[2], M. Feligha[3], M. Bencheikh[4], G. Nigri[5], and L. Louetri[6]
[1245]*Civil and Hydraulic Engineering Department, 8 mai 1945 Guelma University, Guelma, Algeria*
[1245]*Laboratory of Civil Engineering and Hydraulic (LGCH), 8 mai 1945 Guelma University, Guelma, Algeria*
[3]*Department of Civil and Hydraulic Engineering, University 20 August 1955, Skikda, Algeria*
[6]*Civil Engineering Department, Badji Mokhtar University, Annaba, Algeria*
E-mail: benamara_fati2003@yahoo.fr

ABSTRACT: Ideal backfill materials are granular stone, gravel, clean sand with a low percentage of fines. Such material is durable, strong and allows free circulation of water. Due to the depletion of available natural materials, recycled waste will be mixed with sand to form a reinforced fill which can be applied as contiguous fill for retaining walls, mechanically stabilized earth walls and bridge abutments. In this work, a numerical study is carried out by finite elements using PLAXIS 2D software on the Galay quay wall anchored by an anchor plate (sheet pile). In order to study the effect of adding recycled materials on the behavior of the anchored quay wall, three types of backfill based on sand and recycled materials (tire chips, fiberglass, plastic fiber) at different percentages were used as backfill behind the quay wall. The numerical results confirmed that recycled waste is an effective agent for improving the behavior of sandy soils used as backfill behind the anchored quay walls by reducing horizontal displacements and constraints and vertical overall (quay wall - backfill - anchor).

KEYWORDS: Backfill, Recycled materials, Anchor plates, Quay wall, and PLAXIS 2D.

1. INTRODUCTION

The finite element method is potentially a way to improve the calculation of structures because it allows the taking into account of complex phenomena or construction techniques. The finite element method requires us to specify how reality is represented and to develop simulation techniques that can help us understand how the structures operate. Finite elements make it possible to take into account three-dimensional effects that are very difficult to identify with traditional approaches. Numerical modeling by the finite element method has been used in the analysis of several geotechnical structures such as retaining structures, tunnels, road or railway embankments (Likitlersuang *et al.,* 2019; Pholkainuwatra, 2018). Several research studies on finite element modeling for geotechnical engineering analysis have been conducted. Simplified methods for ground settlement computation of tunnelling works using the PLAXIS finite-element programme were presented in (Likitlersuang *et al.,* 2014; Likitlersuang *et al.,* 2018). Many researchers have examined anchor retaining wall behavior over the years. For various retaining wall types and loading conditions, the soil-structure interaction has also been widely modeled using the finite element approach (Bilgin, 2010; Chen, 2023).

The anchor-plate walls are a common construction technique used to stabilize tile or support walls. These walls use anchor plates, also known as anchor trays, which are metal bars or steel cables anchored in the soil behind the wall. Anchored quay walls are structures used to stabilize quays and banks along waterways, ports and coastal areas (Chang *et al.,* 2022). These walls are designed to resist the forces exerted by water and the surrounding soil, with the aim of ensuring the stability and durability of the structure. Likitlersuang, (2019) and Hsiung, (2021) studied the effect of structural modelling on wall deformations of deep excavation. Retaining wall can be self-stabilizing or anchored in the massif and their operation can be governed by their embedded plug mobilizing a certain stop and/or by possible anchoring rods. Falling under this type of retaining wall, anchored retaining walls that are fixed with anchor plates (Adnan and Basm, 1991). A random finite-element method is employed to statistically assess a deep excavation are presented by Nguyen, (2021) The quay walls made up of a concrete diaphragm wall anchored at the back by sheet pile curtains are used because the natural ground offers insufficient bearing capacity to support a massive structure, but has geotechnical characteristics making it possible to offer a stop at the foot of the wall (submerged side) capable of balancing the thrust of the embankment. This is the case of sandy soils, marls or sufficiently compact clays (Das, 1995; Nguyen, 2022).

The French architect Vidal introduced the idea of reinforced soil for the first time in 1966 (Vidal, 1966). Since then, substantial improvements have been achieved in the planning and building of geotechnical constructions such pavements, embankments, retaining walls, and foundations. Randomly dispersed fiber reinforced soils show certain advantages when compacted with systematically reinforced soil (Amrutha, 2015).

Several studies have been conducted on the use of recycled waste mixed with sand in embankments. A study evaluated the feasibility of using mixed construction and demolition recycled materials in geosynthetic reinforced embankments (Vieira and Pereira, 2018).

Deep soil mixing is a technique for improving ground that involves mechanically combining cementitious binders, including fly ash and cement, with the soil to improve the properties of soft soils. (Chompoorat *et al.,* 2022).

Por *et al.* (2015) studied the influence of the non-swelling clay content on physical and mechanical properties of the mixture by paying particular attention to its effect on shrinkage and swelling potential. The engineering properties of sedimentary soil using Portland cement improved for possible use in road construction. (Chompoorat *et al.,* 2019; Chompoorat *et al.,* 2021). Bacillus pasteurii bacterium in vegetative cell and bacterial spore forms were used to induce MICP in clay specimens and improved the engineering properties of soft clay. (Punnoi *et al.,* 2021) Chompoorat *et al.* (2021) examined the macro-mechanical and micro-structural behaviours of dredged natural expansive clay from coal mining treated with ordinary Portland cement or hydrated lime addition.

A numerical simulation revealed that the light-weight nature of tire chips is primarily responsible for the attainment of the active state in sandy backfill (Kaneda *et al.,* 2018).

An straightforward and affordable way to increase the engineering performance of existing soil is by randomly reinforcing it with recycled waste such as tire chips, fiber glass and plastic strips made from used plastic bottles. (Peddaiah *et al.,* 2018).

This numerical study is carried out to check the stability of the quay wall anchored by anchor plate (sheet piling) using the finite element analysis software PLAXIS 2D by varying the backfill behind the wall by different sand-based backfill and recycled waste such as tire chips, fiberglass plus polymers and plastic strips at different percentages. (Brinkgreve, 2003).

2. NUMERICAL MODELLING OF A QUAY WALL ANCHORED BY AN ANCHOR PLATE IN ORIGINAL BACKFILL

In this work, we studied the behaviour of a port-type retaining structure: the deep-water quay of the port of Calais. The backfill behind the retaining structure was replaced with a mixture of sand and recycled waste, with the aim of generalizing the use of recycled waste such as tire chips (TC), fiberglass and polymers such as backfill materials (Dutta and Mandal, 2013; Djadouni *et al.,* 2019).

2.1 Presentation of the Quay Wall of the Port of Calais

Built at the end of the 1980s, the structure consists of a reinforced concrete wall held at the top by two beds of tie rods. During its construction, it was instrumented to monitor deformations and displacements. The soils encountered on the Quay of Calais site were the subject of three surveys, which helped to clarify certain aspects of the soil characteristics. The soils encountered on the site were the subject of three reconnaissance campaigns, the detailed description of which can be found in Delattre, (1999). The site is initially made up of two formations: the Flandrian sands between the surface of the ground around + 5.00 Marine Rating (CM) and a depth from – 21.00 to – 22.50 CM. These sands are homometric fine sands, placed during sea level movements in the Quaternary, the clay of Flanders located below the level – 21.00 to – 22.50 CM, with an unrecognized thickness. It is a stiff clay, laid down in the Eocene. Table 1 brings together the values of the soil parameters taken from all the tests. Data relating to the deep water quays of the port of Calais were collected and analyzed (Delattre and Mespoulhe, 1999).

Based on the results of the tests carried out at the site such as the physical and mechanical properties of the different types of soils as shown in Table 1. The structure was modelled using the finite element method by using PLAXIS 2D software.

The work consists of a reinforced concrete retaining wall, made for the lower part by the technique of the wall moulded into the ground and for the upper part in coffered concrete. The wall is embedded in Flanders clay and anchored by two layers of passive tie rods connected to a curtain of sheet piles forming the anchor block as shown in Figure 1 (Delattre, 1999). The total free height of the structure is equal to 24 m and the load it receives (tools and excess weight on the medians) make it an important work in terms of civil engineering.

Table 1 Geotechnical characteristics of soil layers (Nguyen *et al.*, 2005)

Soil Layers	γ_{sat} (kN/m³)	γ_d (kN/m³)	c'(kPa)	φ'(°)	E (MPa)
Backfill	20.25	16.50	3	39	32
Sand Flandriens	20.25	16.50	4	38	36
Flanders clay	20	15.5	25	20	35

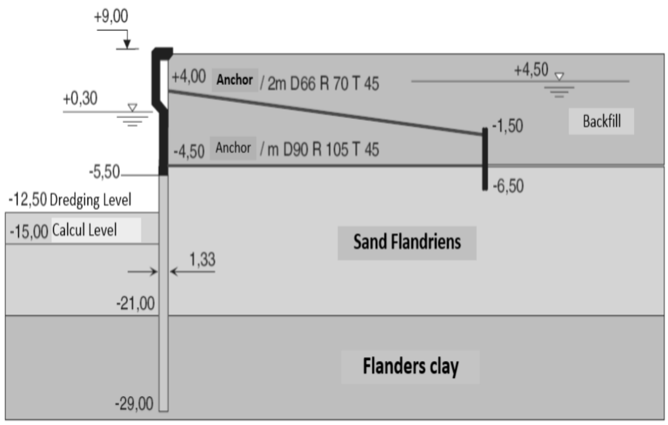


Figure 1 Typical section of the quay wall (Delattre, 1999)

2.2 Quay wall Model with the Original Embankment

The quay wall was modelled using the properties of the materials, soils and backfill presented in Table 1. The model is modelled by 15-node linear elements as shown in Figure 2. The soil was modelled using the elastoplastic Mohr-Coulomb model. The dimension of model is (80 x 80) m as shown in Figure 2. The diaphragm wall and the sheet pile are modeled by plate elements whose behavior is assumed to be linear elastic, The diaphragm wall and the sheet pile curtain are modeled by plate elements whose behavior is assumed to be linear elastic, the same for the anchor rods. Regarding the boundary conditions: On the lateral edges, the normal displacement is zero and the shear is zero (smooth contact) while, for the lower edge, the two components of the displacement are imposed and zero. The hydraulic boundary conditions impose the load on the roof of the water table and on part of the vertical boundaries. They vary from one calculation to another depending on whether the tablecloth is lowered or raised. The number of elements are 161 and the number of nodes are 1411. Figure 3a shows the initial mesh of the model and initial hydraulic conditions.
The quay wall with original embankment was studied by varying the water level between 30.6 m to 40 m as shown in Figure 3b.

The characteristics of the quay wall, the anchoring and the anchor rods are presented in Tables 1, 2 and 3.

Table 2 Quay Wall properties (Delattre, 1999)

Parameters	Symbol	Value
Elastic Plate Element		
Normal stiffness	EA [kN/m]	4.400×10^7
Bending stiffness	EI [kNm²/m]	5.950×10^6
Specific weight	w [kNm/m]	44.220
Poisson coefficient	ϑ	0.20

Table 3 Anchor properties (sheet pile) (Delattre, 1999)

Parameters	Symbol	Value
Elastic Plate Element		
Normal stiffness	EA [kN/m]	8000×10^4
Bending stiffness	EI [kNm²/m]	2.660
Specific weight	w [kNm/m]	3.120×10^{-3}
Poisson coefficient	ϑ	0.20

a) Elastic upper anchor

Parameters	Symbol	Value	Unit
Normal stiffness	EA	4.749×10^5	[kN/m]
spacing	Ls	2	m

b) Elastic lower anchor

Parameters	Symbol	Value	Unit
Normal stiffness	EA	1.272×10^{6}	[kN/m]
spacing	Ls	2	m

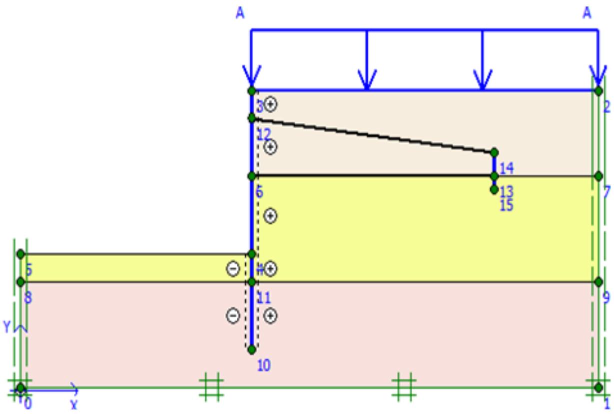
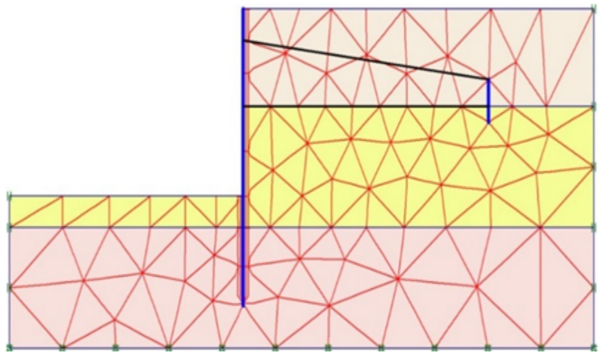
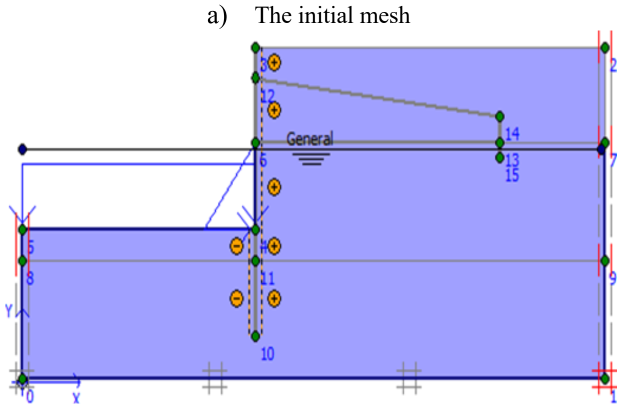


Figure 2 Anchored quay wall model



a) The initial mesh



b) Initial hydraulic conditions with water level at 30.60 m

Figure 3 a) The initial mesh; b) Initial hydraulic conditions of anchored quay wall model with water level at 30.60 m

2.2.1 Validation of the Numerical Model

The major objectives of numerical analysis are the predictions of displacements and forces. The results of this numerical analysis are represented in terms of horizontal displacements of the diaphragm wall. To validate such predictions a comparison between the actually observed results of the diaphragm wall and the numerically calculated displacements of the last phase are presented in Figure 4. The numerical experiments were carried out by Nguyen *et al.* (2005) using the two-dimensional, explicit finite elements program (CEZAR-LCPC). They stated that the anchored quay wall's horizontal displacement results correspond with Delattre's *et al.* (1999) experimental findings. Such results have been used to validate the numerical model developed for this investigation with PLAXIS 2D software. It is noted that the results of the displacements found by Nguyen *et al.* (2005) and carried out by the LCPC-CESAR software are underrated. According to Nguyen (2003), this difference is probably results from the approximation consisting of replacing the tie rods with an equivalent plate in the LCPC CESAR software, and it is therefore difficult to correct it in the context of two-dimensional modeling. It can also come from the absence of specific treatment of the interface between the backfill and the wall in the modeling presented while the results given by PLAXIS 2D are slightly overestimated by the calculation compared to the measured results. However, in the model developed by PLAXIS, the interface between the wall and the ground and also between the sheet pile and the soil and anchor rods were also used in the modeling. (Figure 4).

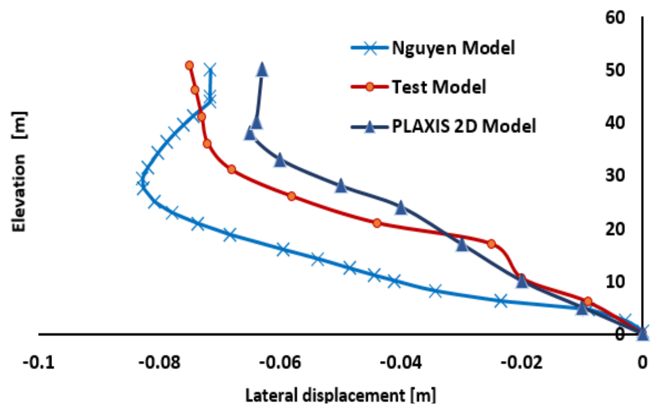
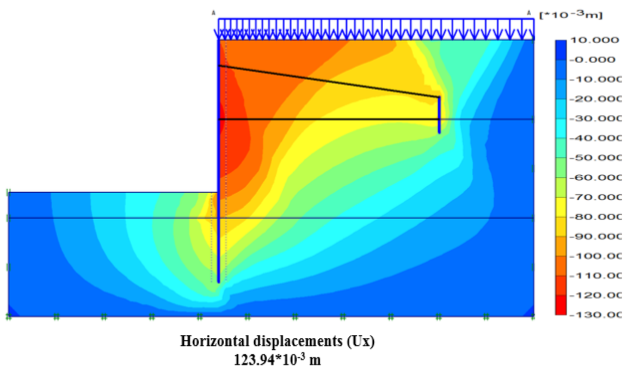
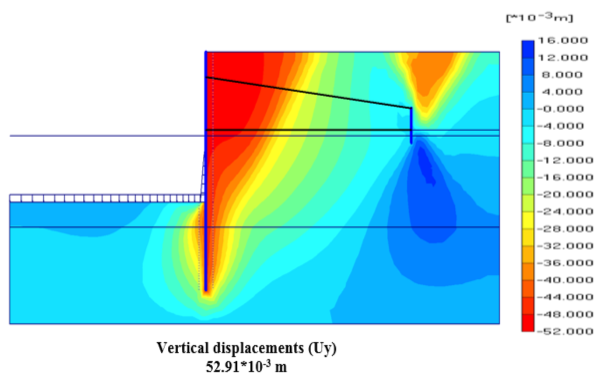


Figure 4 Comparison between horizontal displacements of models

Figure 5 shows the horizontal and vertical displacements of the anchored quay wall for original backfill at water level 30.60 m. They are around 123.94 mm for horizontal displacements and 52.91 mm for vertical displacements.



a)



b)

Figure 4 a) Horizontal displacements ; b) Vertical displacements of the anchored quay wall for the case (original backfill at water level 30.60 m)

2.3 Results and Discussions

Table 4 The results of displacements, stresses and bending moments in the anchored quay wall

WL [m]	U_{xx} x 10^{-3} [m]	U_{yy} x 10^{-3} [m]	σ_{xx} x 10^3 [kN/m²]	σ_{yy} x 10^3 [kN/m²]	M x 10^3 [kN·m]
30.6	123.94	52.91	0.693	0.944	2.40
40	115	100	0.681	0.946	2.47

Table 5 The results of displacements, stresses and bending moments in the anchor plate (sheet pile)

WL [m]	U_{xx} x 10^{-3} [m]	U_{yy} x 10^{-3} [m]	M x 10^3 [kN·m]
30.6	114.55	43.08	1.6
40	110.5	90.71	1.5

According to the results presented in Tables 4 and 5, we can deduce that:

• Horizontal displacements in the anchored quay wall decrease when the water level increases from 30.6 m to 40 m, but vertical displacements increase.

• The bending moments in the anchored quay wall and the anchor plate (sheet pile) recorded a slight increase when the water level changed from 30.6 m to 40 m.

• There is also an increase in the horizontal displacements of the anchor plate (sheet pile) on the other hand the vertical displacements recorded a decrease.

3. NUMERICAL MODELLING OF A QUAY WALL ANCHORED BY AN ANCHOR PLATE IN RECYCLED MATERIAL

Additives are one of the stabilizing techniques that may be applied in order to improve geotechnical characteristics of problematic soils. By adding the proper amounts of cement, lime, fly ash or a mixture of these materials to the sandy soil. The impact of adding recycled waste on the engineering characteristics of various soil types, including shear strength, compressibility, compaction, poison's ratio, and modulus of elasticity has been the subject of much research. (Likitlersuang *et al.,* 2018). An essential consideration in finite element analysis is the constitutive soil model and its parameters; in this work, the Mohr-Coulomb model parameters of a finite element analysis project were assessed. (Chheng *et al.,* 2018; Sukkarak et al. 2021) According to their analysis, the lightweight nature of recycled waste such as fly ash, tire chips improves the stiffness of the Material and makes it an excellent material for backfilling retaining walls and embankments. (Jamsawang *et al.,* 2021; Rouhanifar *et al.,* 2020).

3.1 Quay Wall with Sand + TC Tire Chips Backfill

Several researchers have invested significant time and energy in investigating the effects of adding waste tire shreds and tire chips on the engineering characteristics of various soil types, such permeability, shear strength, compaction properties, poison's ratio, and modulus of elasticity. According to them, tire chips' lightweight nature makes them an excellent material for backfilling embankments and retaining walls. (Edincliler *et al.,* 2010; Rahgozar and Saberian, 2016).

The use of recycled tire shreds in sand mixtures (STC) for retaining wall systems was the focus of a study. In this part, the backfill layer behind the anchored quay wall was replaced by a mixtures (sand + tire chips) (Kaneda, 2018).

Laboratory characterization tests were carried out by using scrap tire chips (TC) of (10 x 10) mm size and about 20 mm length in different STC mixtures (10%, 20%, 30%, 40%, and 50%). The properties of the mixture of sand and tire chips (STC) are presented in Table 6 (Reddy and Krishna, 2015).

Table 6 The Properties of the Sand + Tire Chips Mixture (Reddy and Krishxna, 2015)

% TC	γ (kN/m³)	φ (°)	C (kPa)	E (kPa)	υ
0%	18.15	41	0	47888	0.300
10%	16.30	37.2	1	32700	0.300
30%	16.11	38	13.98	45145	0.306
50%	14.89	35	31.21	42155	0.309

3.1.1 Results and Discussions

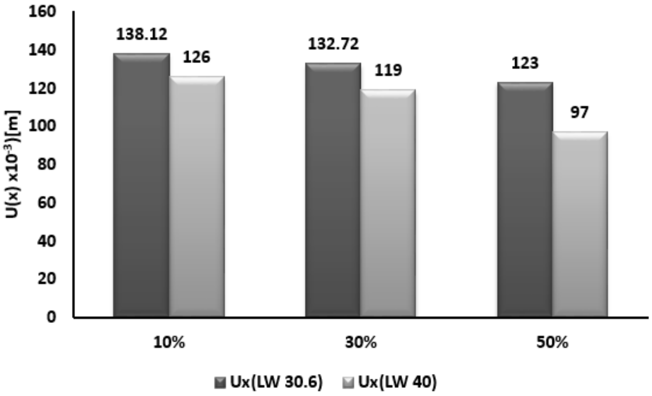


Figure 5 Comparison between horizontal displacements at water level 30.6 m and 40 m in the anchored quay wall for the case: backfill (sand + % TC and surcharge)

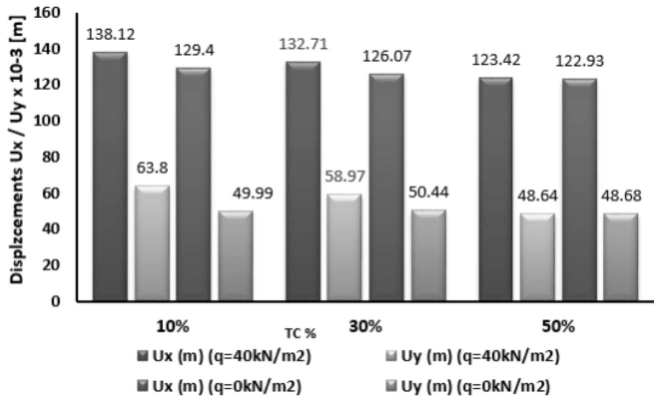


Figure 6 Comparison between the horizontal and vertical displacements in the anchored quay wall for the case backfill (sand + %Tc and surcharge) at water level 30.6 m

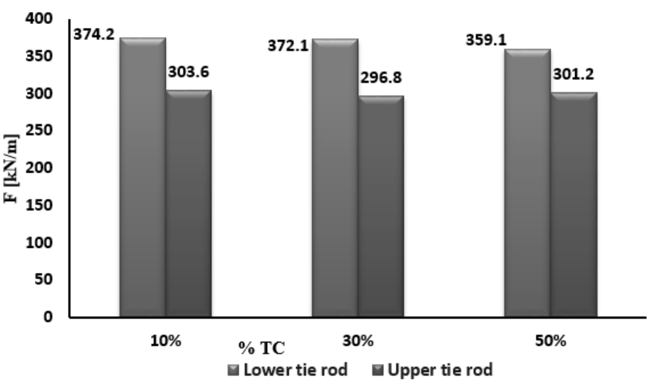


Figure 7 Efforts in tie rods case backfill: sand + (%Tc) and surcharge at water level 30.60 m

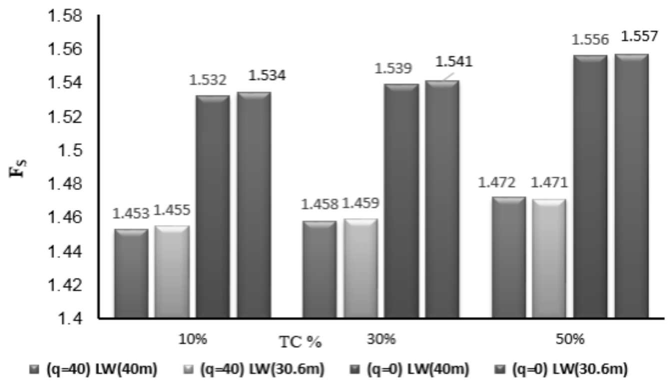


Figure 8 Comparison between safety factors at water level 30.60 m and 40 m case: backfill (sand +% Tc + surcharge)

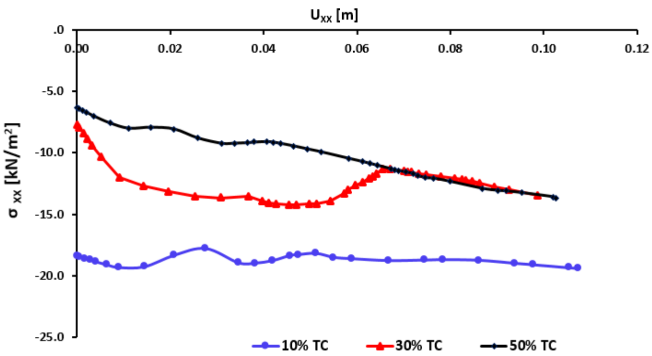


Figure 9 Variation of horizontal stresses in the anchored wall according to the percentages of TC

From the results obtained:

As shown in Figure 5, the horizontal and vertical displacements decrease with the increase in the percentage of TC in the assembly (Soil - wall - anchor). The percentage 50% recorded the minimum value for both water levels 30.6 m and 40 m. As seen in Figure 6, the displacements are increased when the overload is applied behind the wall. Figure 7 shows that when the percentage of tire chips increases, the forces in the anchor rods significantly decrease. The maximum forces are recorded at the lower tie rod. According to Figure 8, Safety coefficients are maximum for the percentage (50% TC), they are around 1.55. The increase in the water level leads to the saturation of the embankment, which reduces the friction between the elements of the soil. When TC is increased to 50%, the angle of friction is reduced. Additionally, water will fill in the voids between the elements when the water level reaches 40 m, lowering the soil's density and safety coefficient of the quay wall.

The lowest horizontal stresses were observed at 50% of TC, as shown in Figure 9. Low horizontal pressure is produced on the rear of the anchored quay walls using TC geomaterials since they are lightweight and have a high shear strength. Furthermore, these materials drain freely.

3.2 Quay Wall with Sand + Glass Fiber + Polymer Backfill

The use of additives is one stabilizing technique that may be performed in order to improve the geotechnical characteristics of problematic soils. Fiberglass is one of the artificial synthetic fibers that is most frequently utilized in engineering (Prabakar, 2002). There are two types of fibers that are added to the sand: artificial synthetic fibers and natural fibers like cotton, wool, and straw fiber. Natural fibers are frequently hydrolyzed in the natural environment, which degrades them and interferes with their reinforcing action. Fiber glass is one of the artificial synthetic fibers that is most frequently used in engineering applications. (Consoli *et al.,* 2012).

Fiber glass and an organic polymer with a water basis were utilized as the materials for the sand reinforcement. The sand reinforcement material was a form of fiber glass and a water-based organic polymer. In order to make the specimens with the desired shape, specific quantities of sand, fiber glass, water, and water-based organic polymer were mixed. To determine the reinforcing effects, three strength tests such the tensile test, the unconfined compression test, and the direct shear test as well as scanning electron microscopy were used.

The final layer behind the anchored quay wall was replaced with a mixture of sand, fiberglass, and polymer. The characteristics of the mixtures are presented in Table 7. The fiberglass used in this study is 18 mm long and 0.08 mm in diameter. (Liu *et al.,* 2018).

Table 7 Properties of the sand + fiberglass + polymer mixture (Liu *et al.,* 2018)

% fiber glass + 2% polymer	γ (kN/m³)	φ(°)	C (kPa)	E (kPa)	υ
0.2%	15	27.72	11.26	20900	0.300
0.4%	15	27.35	15.19	21300	0.300
0.6%	15	26.85	20.48	21900	0.300

3.2.1 Results and Discussions

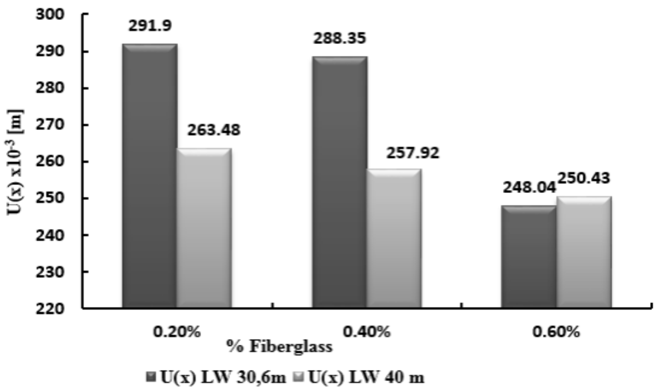


Figure 10 Horizontal displacements of the anchored quay wall for the case backfill: sand + % fiber glass and 2% polymer at water level 30.6 m and 40 m

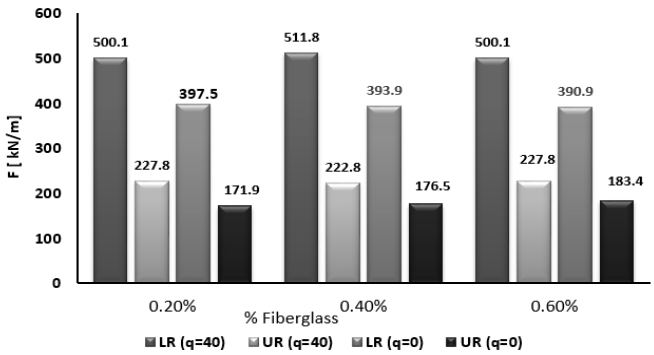
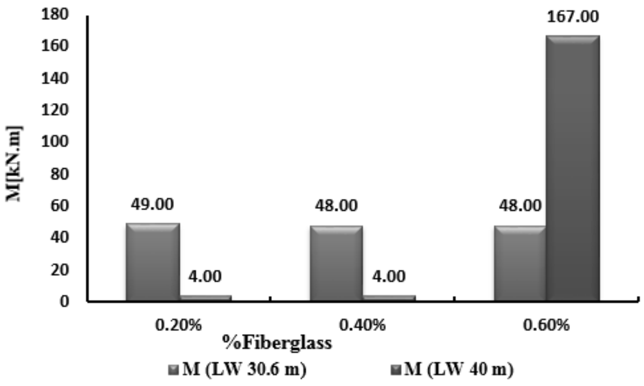
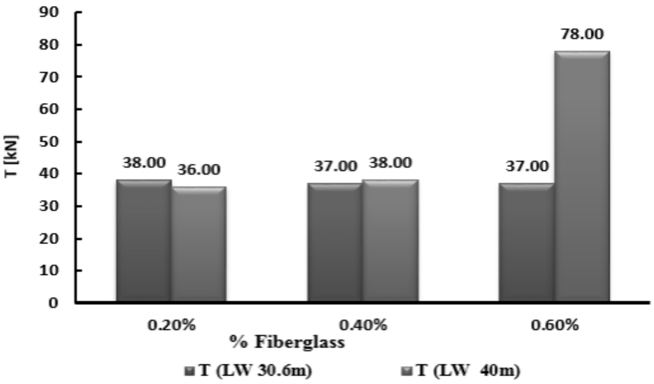


Figure 11 Forces in tie rods for the case backfill: sand + % fiberglass and 2% polymer and surcharge at water level 40 m



a)



b)

Figure 12 a) Bending moments; b) Shear forces in tie anchor (sheet pile) case: sand + % fiberglass and 2% polymer at water level 30.60 m and 40 m

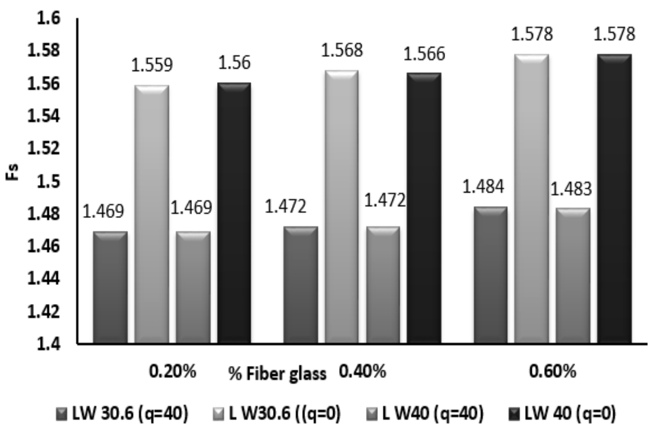
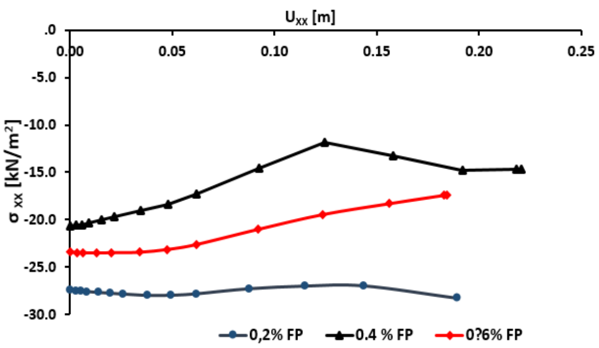
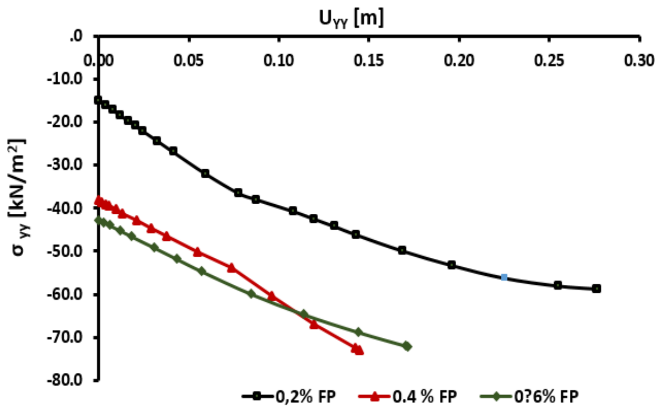


Figure 13 Comparison between safety factors at water level 30.60 m and 40m for the case backfill: sand + % fiber glass and 2% polymer + surcharge)



a)



b)

Figure 14 a) Horizontal stresses b) Vertical stresses behind anchor plate (sheet pile) at water level 40 m for the case backfill: sand + % fiber glass and 2% polymer + surcharge)

As shown in Figure 10, the 0.6% fiber glass and 2% polymer recorded the minimum horizontal displacements for both water levels (30.6 m and 40 m). The 30.6 m water level recorded maximum horizontal displacements compared to the 40 m water level.

As shown in Figure 11, the percentage 0.4% of fiberglass and 2% polymer recorded the maximum efforts in the lower and upper tie whatever the overload and the lower tie rod recorded the maximum forces.

As shown in Figure 12, the percentage 0.6% of fiberglass and 2% of polymer recorded the maximum bending moments and Shear forces in tie anchor (sheet pile) whatever the overload.

According to Figure 13, the safety coefficients are maximum for the percentage 0.6% fiber glass and 2% of polymer at water level 40 m and surcharge q=40 kN/m^2

As shown in Figure 14a, the horizontal stresses are maximum for the percentage 0.4% of fiberglass + 2% of polymer, Additionally, the horizontal strains increase as the horizontal displacements rise. As shown in Figure 14b, the vertical stresses are maximum for the percentage 0.2% of fiberglass + 2% of polymer; we note that as vertical displacements increase, the vertical stresses decrease.

3.3 Quay Wall with Sand + Plastic Strips Backfill

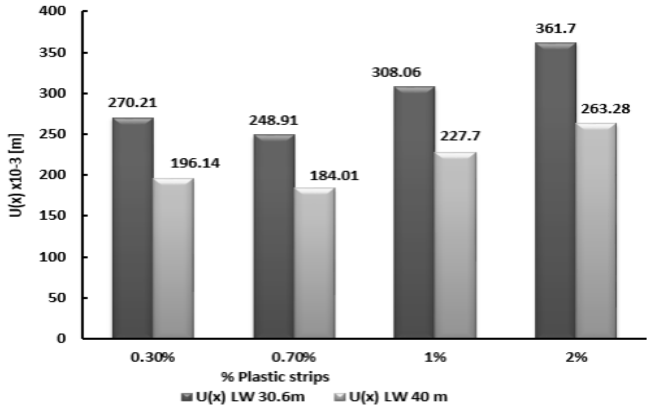
In this part of study, an attempt has been made to use waste plastic bottle strips as a reinforcing element to improve the engineering properties of the soil, especially with respect to shear strength and load carrying capacity (Vismaya *et al.,* 2022). In order to improve the shear strength parameters, the shredded plastic strips were randomly distributed with the soil. A static loading test was carried out in a mild steel tank that was constructed, using a model circular footing, to determine the improvement in shear resistance and the settled behavior of the treated sand. The PET plastic filler particles can reduce the weight of the backfill material overall while providing appropriate strength and stability. In regions where weight limits or settlement issues are a problem, this can be highly beneficial. (Dutta and Mandal, 2013).

Using plastic PET (Polyethylene terephthalate) with sand in backfill can offer certain advantages in certain situations. Plastic PET, when properly recycled and processed, can be used as a lightweight and environmentally friendly alternative to traditional materials in backfill applications The properties of the mixtures are presented in Table 8 (Gangadhara1 *et al.,* 2016)

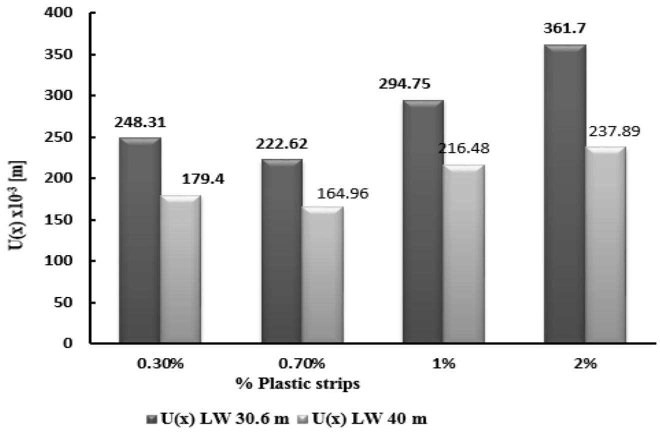
Table 8 The properties of the sand + plastic mixture (Gangadhara *et al.*, 2016)

% plastic	γ (kN/m³)	φ (°)	C (kPa)	E (kPa)	υ
0%	15.82	45	0	4000	0.300
0.3 %	15.82	43	19	5500	0.300
0.7	15.82	35	39	6923	0.300
1 %	15.82	45	12	3500	0.300
2%	15.82	23	22	4500	0.300

3.3.1 Results and Discussions



a)



b)

Figure 15 a) Horizontal displacements in the anchored quay wall; b) Horizontal displacements in the anchor plate (sheet pile) for the case: backfill (sand + % plastic strips + surcharge) at water level 30.6 m and 40 m

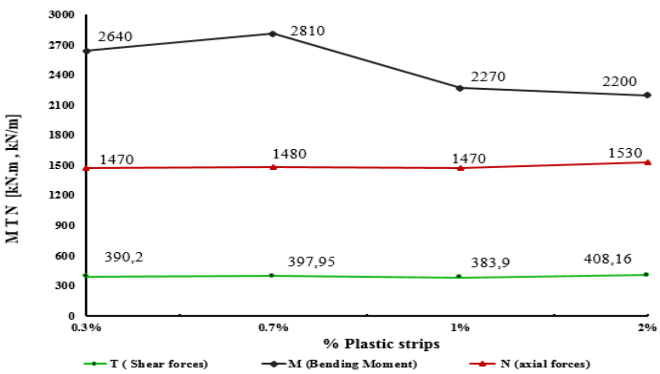


Figure 16 Axial forces, shear forces and bending moment in anchored quay wall for the case backfill: sand + % plastic strips for the water level 30.6 m

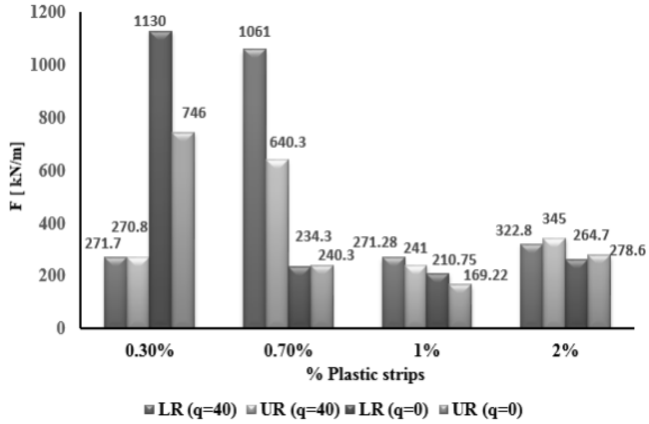


Figure 17 Forces in tie rods for the case backfill: sand + plastic strips and surcharge at water level 40 m

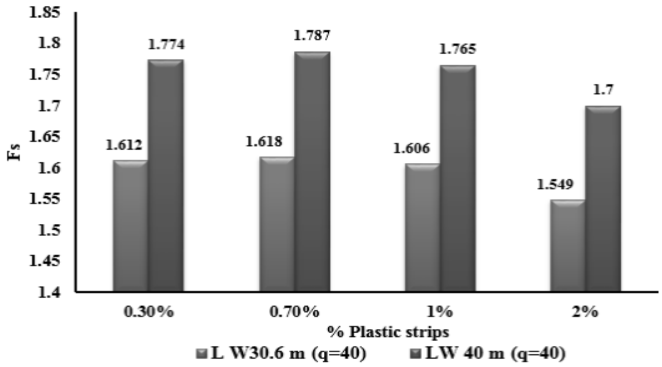
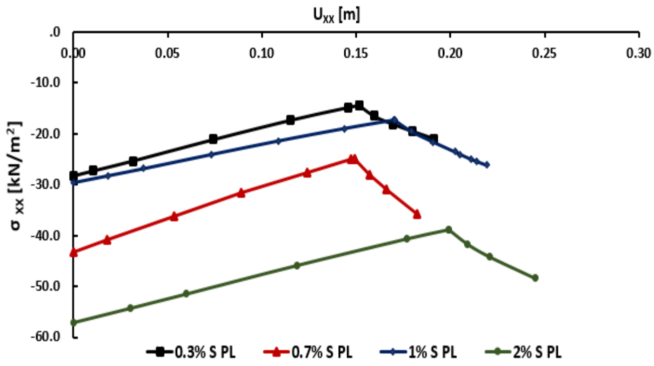
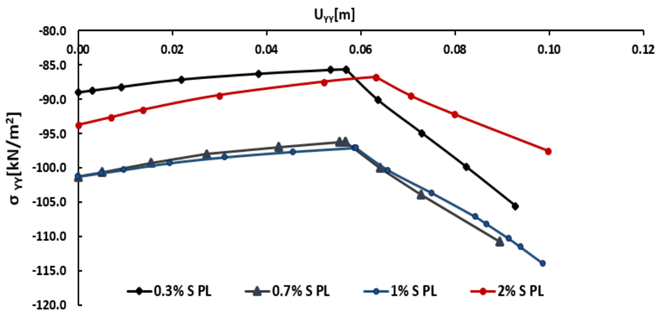


Figure 18 Comparison between safety factors at water level 30.60 m and 40 m for the case backfill: sand + % plastic strips



a)



b)

Figure 19 a) Horizontal Stress; b) Vertical Stress behind anchored quay wall at water level 40 m for the case backfill: backfill (sand + % plastic strips + surcharge)

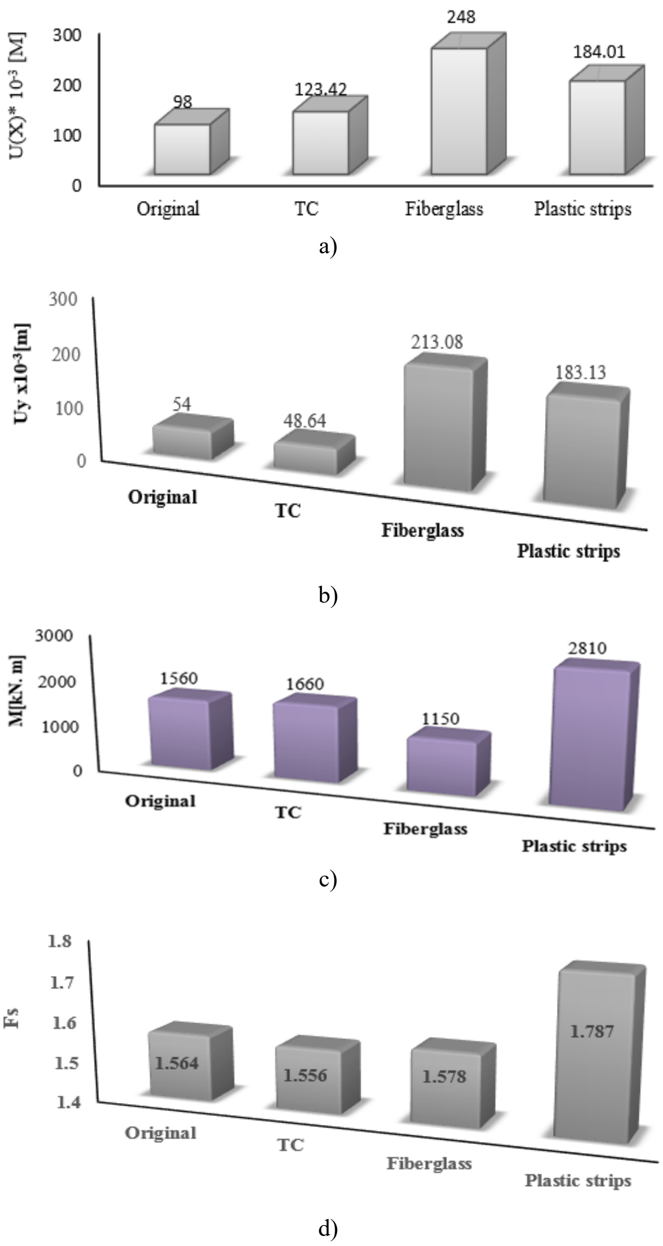


Figure 20 Comparison of improved backfill according to the types of waste used at level water 40 m a) horizontal displacements b) vertical displacements c) Bending moment in the quay wall d) safety factor

As shown in Figure 15, the 0.7% of plastic strips recorded the minimum horizontal displacements for both anchored quay wall and anchor plate (sheet pile) at water levels (30.6 m and 40 m). The 30.6 m water level recorded maximum horizontal displacements compared to the 40 m water level.

As shown in Figure 16, the maximum axial forces, bending moments, and shear forces in the tie anchor plate (sheet pile), irrespective of overload, were recorded by the 0.7% of plastic strips. However, the minimum values were recorded in the percentage of 1% of plastic strips.

As shown in Figure 17, the percentage 1% of plastic strips recorded the minimum efforts in the lower and upper tie rods at water level 40 m whatever the overload, the lower tie rod recorded the maximum forces. Figure 18 shows for the surcharge q=40 kN/m^2 and a water level of 40 m, the safety coefficients are at their most significant for the percentage 0.7% plastic strips.

The horizontal and vertical stresses are greatest for plastic strips that are 0.3%, as shown in Figure 19a, they also reach as the horizontal and vertical displacements increases. At 2% of a percentage, the lowest stresses were observed.

Figure 19b shows that vertical displacements are recorded with a plastic strips percentage of 0.7%.

Based on the results, it can be concluded that recycled waste tire chips, fiberglass, and plastic strips have a positive impact with respect to the reduction of horizontal and vertical displacements as well as vertical stresses, with percentages of 30%, 0.6%, and 0.7%, respectively. Additionally, we saw an increase in the safety coefficients. To enhance the performance of the different wastes used, we compared the mechanical characteristics of the improved soils for each type of waste which are presented in Figure 20.

The addition of tire chips has minimal displacements compared to other waste; this is the same observation for vertical displacements. Furthermore, plastic waste records the highest safety factor compared to different waste and original backfill with acceptable horizontal and vertical displacements and lower forces in the tie rod.

4. CONCLUSIONS

A numerical study using finite element software, PLAXIS 8.6 has been carried out on a quay wall anchored by passive anchor tie rod to expand the field of use of recycled waste materials.

In order to generalize the use of recycled materials in the geotechnical field, three backfills based on sand / tire chips / glass fiber and polymer and strips plastic were chosen to replace the original backfill of a quay wall anchored by plate anchor.

In summary, the numerical results align with the findings of the experimental investigation. It can be concluded that the mixtures of sand with tire chips (TC), glass fiber and polymer and plastic strips contribute effectively to the stabilization of the quay wall by increasing the safety factor of the structure.

A slight decrease in horizontal displacements is observed behind the quay wall backfilled by three mixtures of materials used behind the retaining wall.

Horizontal and vertical displacements are minimal at the level of percentage 10% TC, 0.6% fiber glass and 0.7% of plastic strips.

A numerical analysis conducted on anchored quay walls backfilled with a mixture of recycled waste material (TC, fiber glass, plastic strips) and sand revealed a considerable reduction in the bending moments, shear forces, and displacements in tie anchor (sheet pile) and the anchored quay wall.

The lower tie rod recorded the maximum forces compared to the upper tie rod and the anchor plates must be of high quality and comply with construction standards.

This study implies that laboratory testing is often used to assess the utilization of recycled waste combined with sand at precise percentages.

5. REFERENCES

Adnan, A. and Basma. (1991). “Safety and Reliabilty of Anchored Bulkhead Walls.” *Structural Safety,* 10, Issue 4, 283-295 https://doi.org/10.1016/0167-4730(91)90035-8.

Amrutha, T. P., Krishnan, A. (2015). “An Overview on Plastic Waste as Soil Stabilizing Agent.” *Int. J. Adv. Res. Trends. Eng.,* Technol 2, Issue 10, 36–39.

Bilgin, Ö. (2010). “Numerical Studies of Anchored Sheet Pile Wall Behavior Constructed in Cut and Fill Conditions.” *Computers and Geotechnics,* 37, Issue 3, 399-407. https://doi.org/10.1016/j.com pgeo.2010.01.002.

Brinkgreve, R. B. J. (2003). "Manel de Référence de PLAXIS Version 8.6: Delft University of Technology." *Delft, Netherlands, and PLAXIS BV, Pays-Bas, Netherlands.*

Chheng, C., Likitlersuang, S. (2018). "Underground Excavation Behaviour in Bangkok using Three-Dimensional Finite Element Method." *Computers and Geotechnics,* 95, 68-81, https://doi.org/10.1016/j.compgeo.2017.09.016.

Cheng, Y., Xu, Y., Wang, L., Wang, L. (2022). "Stability of Expansive Soil Slopes Reinforced with Anchor Cables Based on Rotational-Translational Mechanisms." *Computers and Geotechnics,* 146. https://doi.org/10.1016/j.compgeo.104747.

Chen, S., Guan, Y., Dai, J. (2023). "Behaviour of Anchored Sheet Pile Quay Stabilized with Deep Cement Mixing Columns in Soft Soil: Centrifuge and Numerical Modelling." Computers and Geotechnics, 160, https://doi.org/10.1016/j.compgeo.2023.105504.

Chompoorat, T., Maikhun, T., Likitlersuang, S. (2019). "Cement Improved Lake Bed Sedimentary Soil for Road Construction." *Proceedings of the Institution of Civil Engineers – Ground Improvement,* 172, Issue 3, 192–201. http://doi.org/10.1680/jgrim.18.00076.

Chompoorat, T., Likitlersuang, S., Sitthiawiruth, S., Komolvilas, V., Jamsawang, P., Jongpradist, P. (2021). "Mechanical Properties and Microstructures of Stabilised Dredged Expansive Soil from Coal Mine." *Geomechanics and Engineering,* 25, Issue 2, 143-157. https://doi.org/10.1 2989/gae.2021.25.2.143.

Chompoorat, T., Thepumong, T., Taesinlapachai, S., Likitlersuang, S. (2021). "Repurposing of Stabilised Dredged Lakebed Sediment in Road Base Construction." *J Soils and Sediments,* 21, 2719–2730. https://doi.org/10.1007/s11368-021-02974-3.

Chompoorat, T, Thepumong, T., Khamplod, A., Likitlersuang, S. (2022). "Improving Mechanical Properties and Shrinkage Cracking Characteristics of Soft Clay in Deep Soil Mixing." *Construction and Building Materials,* 316, doi:10.1016/j.conbuildmat.2021.125858.

Consoli, N. C., Bellaver Corte, M., Festugato, L. (2012). "Key Parameter for Tensile and Compressive Strength of Fibre-Reinforced Soil-Lime Mixtures." *Geosynth. Int.,* 19, 409–414. https://doi.org/10.1680/gein.12.00026.

Das, B. M. (1995). "Principles of Foundation Engineering." *4th Ed., PWS Publishing Co., Boston, U.S.A.*

Delattre, L. (1999). "Comportement des Ecrans de Soutènement. Expérimentations et Calculs." *Thèse de doctorat, ENPC,* 498. https://www.theses.fr/1999ENPC9932.

Delattre, L., and Mespoulhe, L. (1999). "Étude Expérimentale du Comportement du Quai en eau Profonde du Port de Calais." *Collection Études et Recherches des Laboratoire des Ponts et Chaussées,* GT 65, 191.

Djadouni, H., Trouzine, H., Gomes, A., Correia, da Silva Miranda, T. F. (2019). "2D Numerical Analysis of a Cantilever Retaining Wall Backfilled with Sand–Tire Chips Mixtures." European Journal of Environmental and Civil Engineering, 25, Issue 6, 1119-1135. https://doi.org./:10.1080/19648189.2019.1570870.

Dutta, S., and Mandal, J. N. (2013) "Feasibility Study on Waste Plastic Water Bottles as Encasements of Stone Columns for Ground Improvement." *Int. Symp. on Design and Practice of Geosynthetic-Reinforced Soil Structures,* 14-16 October University of Bologna, Italy, 379-388.

Edincliler, A., Cabalar, A. F., Cagatay, A. and Cevik, A. (2012). "Triaxial Compression Behavior of Sand and Tire Wastes using Neural Networks." Neural Computing and Applications, 21, 441-452. https://doi.org/10.1007/s0052 1-010-0430-4.

Gangadhara, S., Vivek, S., Ranganath (2016). "Effect of Addition of Plastic Waste on Engineering Properties of Soil." *International Research Journal of Engineering and Technology (IRJET),* 3, Issue 11.

Hsisung, C. B. B, Likitlersuang, S., Phan, K. H., Pisitsopon, P. (2020). "Impacts of the Plane Strain Ratio on Excavations in Soft Alluvium Deposits." *Acta Geotech,* 16, Issue 2. https://doi.org/10.1007/s11440-020-01115-3.

Jamsawang, P., Charoensil, S., Namjan, T., Jongpradist, P., Likitlersuang, S. (2021). "Mechanical and Microstructural Properties of Dredged Sediments Treated with Cement and Fly Ash for Use as Road Materials. Road Mater. Pavement." 22, Issue 11, 2498–2522. https://doi.org/10.1080/14680629.2020.1772349.

Kaneda, K., Hazarika, H., Yamazaki, H., (2018). "Examination of Earth Pressure Reduction Mechanism using Tire-Chip Inclusion in Sandy Backfill via Numerical Simulation." Soils and Foundations, 58, Issue 5, 1272-1281. https://doi.org/10.1016/j.sandf.2018.06.002.

Likitlersuang, S., Surarak, C., Suwansawat, S., Wanatowski, D., Oh, E., Balasubramaniam, A. (2014). "Simplified Finite-Element Modelling for Tunnelling-Induced Settlements." *Geotechnical Research,* 1, Issue 4, 133 – 152. https://doi.org/10/1680/gr.14.00016.

Likitlersuang, S., Chheng, C., Keawsawasvong, S. (2019). "Structural Modelling in Finite Element Analysis of Deep Excavation." *Journal of GeoEngineering,* 14, Issue 3, 121-128, doi:10. 6310/jog.201909_14(3).1.

Likitlersuang, S., Pholkainuwatra, P., Chompoorat, T., Keawsawasvong, S. (2018). "Numerical Modelling of Railway Embankments for High-Speed Train Constructed on Soft Soil." *Journal of GeoEngineering*, 13, Issue 3, 149-159. doi:10.6310/jog.201809_13(3).6.

Likitlersuang, S., Chheng, C., Chanaton, S., Balasubramaniam, A., (2018). "Strength and Stiffness Parameters of Bangkok Clays for Finite Element Analysis." *Geotechnical Engineering Journal of the SEAGS & AGSSEA,* 49, Issue 2, 150 – 156

Liu, J., Song, Z., Lu, Y., Wang, Q., Kong, Bu, F., Kanungo, D.P., Sun, S. (2018). "Improvement Effect of Water-Based Organic Polymer on the Strength Properties of Fiber Glass Reinforced Sand, Polymers." 10, Issue 8, 836. https://doi.org/10.3390/polym10080836.

Nguyen P. D., Bourgeois, E., Delattre, L., Magnan, J. P. (2005). "Deux Modélisations par Elements Finis D'écrans de Soutènement Instrumentés." *Bulletin des Laboratoires des Ponts et Chaussées,* 254, RÉF. 4548, 41-59.

Nguyen, T. S., and Likitlersuang, S. (2020). "Influence of the Spatial Variability of Shear Strength Parameters on Deep Excavation Analysis: A Case Study of a Bangkok Underground MRT Station." *International Journal of Geomechanics,* 21, Issue 2; https://doi.org/10.1061/(ASCE)GM.1943-5622.0001914.

Nguyen, T. S, Phan, T. N., Likitlersuang, S., Bergado, D. T. (2022). "Characterization of Stationary and Non-Stationary Random Fields with Different Copulas on Undrained Shear Strength of Soils: A Probabilistic Analysis of Embankment Stability on Soft Ground." *International Journal of Geomechanics,* 22, Issue 7, doi:https://doi.org/10.1061/(ASCE)GM.1943-5622.0002444.

Peddaiah, S., Burman, A., and Sreedeep, S. (2018). "Experimental Study on Effect of Waste Plastic Bottle Strips in Soil Improvement." *Geotech Geol Eng,* 36, Issue 10, 2907–2920. https://doi.org/10.1007/s10706-018-0512-0.

Por, S., Likitlersuang, S., Nishimura, S. (2015). "Investigation of Shrinkage and Swelling Behaviour of Expansive/Non-Expansive Clay Mixtures." *Geotech. Eng. J.*, 46, Issue 1. 117–127.

Prabakar, J., Sridhar, R. S., (2002). "Effect of Random Inclusion of Sisal Fibre on Strength Behaviour of Soil." *Construction and Building Materials,* 16, Issue 2, 123-131. https://doi.org/10.1016/S0950-0618(02)0008-9.

Punnoi, B., Arpajirakul, S., Pungrasmi, W., Chompoorat, T., Likitlersuang, S., (2021). "Use of Microbially Induced Calcite Precipitation for Soil Improvement in Compacted Clays." *Int. J. of Geosynth. and Ground Eng.,* 7, Issue 4. https://doi.org/10.1007/s40891-021-00327-1.

Rahgozar, M. A., and Saberian, M. (2016). "Geotechnical Properties of Peat Soil Stabilised with Shredded Waste Tyre Chips." *Mires & Peat,* 18, 1–12. https://doi:10.19189/MaP.2015.OMB.205.

Reddy, S. B., and Krishna, A. M., (2015). "Recycled Tire Chips Mixed with Sand as Lightweight Backfill Material in Retaining Wall Applications: An Experimental Investigation." *International*

Journal of Geosynthetics and Ground Engineering, 1, Issue 4. https://doi.org/10.1007/s40891-015-0036-0.

Rouhanifar, S., Afrazi, M., Fakhimi, A., and Yazdani, M. (2021). "Strength and Deformation Behaviour of Sand-Rubber Mixture." *International Journal of Geotechnical Engineering,* 15, 1078-1092. https://doi.org/10.1080/19386362.2020.1812193.

Sukkarak, R., Likitlersuang, S., Jongpradist, P., Jamsawang, P. (2021). "Strength and Stiffness Parameters for Hardening Soil Model of Rockfill Materials." *Soils and Foundations,* 61, Issue 6, 1597-1614, https://doi.org/10.1016/j.sandf.2021.09.007.

Vidal, H., (1966) "La terre Armée." *Ann. I.T.B.T.P.*

Vieira, C. S., Pereira, P. M. (2018). "Use of Mixed Construction and Demolition Recycled Materials in Geosynthetic Reinforced Embankments." *Indian Geotech J,* 48, 279–292. https://doi.org/10.1007/s40098-017-0254-6.

Vismaya, A., Simon, M., Jayasree, P. K. (2022). "Effect of Submergence on Settlement and Bearing Capacity of Sand Reinforced with Pet Bottle Geocell." *Published in book: Ground Improvement and Reinforced Soil Structures,* 601-608. https://doi.org/10.1007/978-981-16-1831-4_53.