Analysis of Flexible Anchored Hollow WPC Quay Walls of the New Berth in Tur, Egypt

Ayman Elsayed

1 Harbors Engineering and Marine Structures, Cairo, Egypt
dr_aymanz@yahoo.com

Abstract. A seawall, also known as a bulkhead or retaining wall, is a structure built to reduce the effects of strong waves and to defend coastal land from erosion. Traditionally, seawalls are made of steel, timber or concrete construction. Composite materials, however, have been recently introduced for their ease of installation/maintenance in dry processing, low cost, and environmentally friendly materials. A wood plastic composite (WPC) seawall system has been developed and patented for its unique hollow structure that can give greater stiffness and stability under various external stresses. This paper describes the development of design method used in the analysis of the WPC walls. The main challenge during the physical excavation works is to limit the deformations involved in order to minimize damage on adjacent structures. The deformations depend largely on the excavation and strutting procedures, but also on the properties of the structural elements like the soil, the sheet pile and strutting members. The detailed design procedure involves numerical analyses, national regulations and common practice considerations. The contribution of finite element method in this field was used herein to determine the lateral movements, the bending moments of the wall, the passive earth pressure of the soil and the tensile force exerted by the anchor rods. The overall objectives of this research can be divided into two categories, First calibration of the finite element model for the new Tur quay walls (the case study) and reviewing the results of the steel cross section that chosen and the suggested one. Second, analysis and comparing the results of WPC cross-sections with the designed Steel sheet pile wall (SPW).

1. Introduction

Anchored retaining walls are a class of geotechnical structures whose design is governed by the earth pressure imposed by the soil. These structures are widely used in many types of civil engineering construction, particularly in waterfront structures [1]. They are used to hold or prevent the backfill from sliding while may also provide protection against light-to-moderate wave action. They are also used for reclamation projects, where a fill is needed seaward of the existing shore and for marinas and other structures where deep water is needed directly at the shore.

The moment of inertia, is one of the most important properties for structural applications, of the novel WPC system shows up to 22,900 cm$^4$ which is higher than 19,900 cm$^4$ of a commercial polyvinyl chloride system or 16,200 cm$^4$ of a steel system categorized for light duty applications. The mean flexural stiffness EI of the WPC seawall is 8.07 x 104 kip-in$^2$/ft (Alvarez-Valencia 2009), where it can be categorized between very light duty and light duty defined by the US Army Corps of Engineers [2].

The TUR port, the old construction specs, land area equal 0.430 km$^2$, water area equal 1.20 km$^2$, open storage yards equal 0.30 km$^2$, storage yards covers 5600 m$^2$, the maximum design capacity 0.38
million tons of general cargo, number of quays equal 1 with 75 m long, with maximum draft 5.0 m, The new Tur quay (the case study) is the objective of this study, with total length of and with maximum draft 5.0 m.

![Figure 1. The new Tur master plan](image)

![Figure 2. The new Tur berth x-section](image)

1.1. The different methods for retaining wall analysis:

- Limit equilibrium analysis.
- Beam-spring approaches.
- Full numerical analysis, with the following different methods:
  - The Finite Difference Method (FDM) is widely used for problems with fairly well defined field functions and reasonable simple geometry of the boundaries. Pure elasticity and steady state ground water seepage are frequently modelled by FDM.
  - The Finite Element Method (FEM) is the method that has gained most popularity in structural (and geotechnical) engineering. Real problems with soil layers, soil-structure boundaries and different material behaviour in different zones may be modelled quite conveniently [3, 4].

1.2. Material behaviour

The material behaviour is described by the constitutive equations. Several reference platforms are introduced [5].
1.2.1. Elastic material models

Stress and strain increment directions coincide. Material parameters may vary with the stress or strain level and direction of loading (loading, unloading), bilinear and multi-linear models. Plasticity phenomena (where the orientation of the principle directions of the stress and strain increments do not necessarily coincide) cannot be simulated, no matter how complicated the material behavior is described.

1.2.2. Elastoplastic material models

A yield surface is described in the stress space. Stress states within the yield surface are described by linear to multi-linear elastic material behaviour. When the stress states reaches the yield surface, the material behaviour is described by the theory of plasticity where the plastic strains are described by a flow rule.

1.3. The research by finite element program

WALLAP offers two separate types of analysis within the program:
- Limit Equilibrium Analysis: Calculation of Factors of Safety according to one of the following methods: CP2, BSC Piling Handbook, Burland-Potts, and Strength factor method.
- Bending moment and Displacement Analysis: Modelling of the stage-by-stage development of forces and wall movements as construction proceeds.

The wall and soil are modelled as a beam and springs. Two spring models are available: Subgrade reaction analysis (for routine design), 2-D Finite element analysis (for a more rigorous approach), [6].

2. Guided design tables

Three sizes of PVC ribbed sections currently available (egg. Table 1.) on the market were selected, and nine alternative WPC hollow sections were designed. The three all-vinyl sections correspond to the C-LOC 550, C-LOC 650, and C-LOC 950 manufactured by Crane Materials International (Crane Materials International, 2004). These sections have depths ranging from 8” (203.2 mm) to an 11.75” (298.5 mm) [8].

The following tables incorporates both long term and short term deflections. Short term deflection has allowable deflection limits of L/40 and L/60; and long term deflection has the same limits with an
additional safety factor of 3. Table 2 is an example of a design table for a 200 psf (9576 Pa) surcharge; the design tables show the range of allowable wall heights achievable with the proposed WPC sections. The wall height is the length of the wall from the top of the pile to the embedment location [9].

Table 1. Preliminary Dimensions of Existing Ribbed and Proposed Hollow Sections - Web Hollows, [10]

| Deflection | L/40 | L/60 |
|------------|------|------|
| Walers     | 1    | 2    |
| 8 Inch Section* (Web and Flange Hollows) | | |
| Loose Fine Sand | 11.5 [3.5] | 17 [5.2] | 11.5 [3.5] | 17 [5.2] |
| Dense Fine Sand | 13.2 [4.0] | 18 [5.5] | 13.2 [4.0] | 18 [5.5] |
| Loose Gravel | 11.5 [3.5] | 16.7 [5.1] | 11.5 [3.5] | 16.7 [5.1] |
| 10 Inch Section* (Web and Flange Hollows) | | |
| Loose Fine Sand | 13.5 [4.1] | 19.3 [5.9] | 10.5 [3.2] | 17.5 [5.3] |
| Dense Fine Sand | 14.2 [4.3] | 22.5 [6.9] | 13.5 [4.1] | 22.5 [6.9] |
| Loose Gravel | 15.6 [4.8] | 22.5 [6.9] | 13.7 [4.2] | 22.3 [6.8] |
| 11.75 Inch Section* | | | |

Table 2. Design table for a 200 psf (9576 Pa) surcharge: Allowable Wall Height (ft. [m])
3. Steel SPW full numerical analysis by the FEM

The FEM model extends 20m horizontally from the centreline of the excavation. The bottom boundary is set at elevation -10m whereas the original terrain lies at elevation 0. Two soil layers are defined, dry sand above elevation -6.0 and saturated sand (or wet sand) below elevation -6.0. The sheet pile wall is defined through a vertical beam, 10m long. The strut is defined as a fixed end anchor at elevation -1.0m. Two surface loads are defined, A-A extending 3m and B-B extending the remaining 14m over the surface. Due to the passive earth pressure resistance above the strut level the load A-A is set to zero.

The sheet pile is "surrounded" by interface elements describing an ultimate roughness ratio |rult|=0.5 at the soil-sheet pile interface. In order to partly dampen the singularity problems at skirt tip the interface elements are extended down to elevation -12.2 m below the skirt tip. The pore pressures are defined to vary hydrostatic from elevation -6.0. The modelling is shown in Figure 5.

3.1 Elastoplastic soil model

The elastoplastic model (EP) was run with coarse mesh, 15 nodes triangular elements leading to 97 elements, 883 nodes and 1164 stress points. The Φ-c reduction phase indicates a material factor of γ=1.5 or an average degree of shear mobilization f=0.67.

The excavation stages are intended to be as follows in the modelling process:

- Excavation to 2m depth
- Placing of the struts at level -1.5, pre-stressing to 100 kN/strut (cc 2m)
- Excavation to elevation -6
- Loading the terrain with 16 kPa.

![Figure 4. FEA model for AZ12 steel SPW](image-url)
3.2. Deflection, shearing force and bending moments

![Graph showing bending moment, shear force, and displacement envelopes.]

**Figure 5.** Total deflection, shearing force and bending moments for AZ12 steel SPW

4. WPC wall model

The material properties of polypropylene wood plastic composites (WPC) vary with the specific formulation used. In this FEA model, the WPC is modelled as a material with a modulus of elasticity (E) of (3000 MPa) and a Poisson’s ratio (ν) of 0.33. These values were obtained from laboratory testing performed at the University of Maine (Dura 2005). The average ultimate tensile and compressive strength are assumed to be 17.2 MPa and 43.5 MPa respectively.

4.1 WPC wall evaluation

- A factor of safety of four was used for calculating the allowable bending strength from the mean ultimate bending strength. This is to account for creep and additional serviceability issues. This number was based on current data available on the creep behaviour of WPC members.
- The deflection limits used are unsupported height/40 and unsupported height/60. These limits are based on the standard design utilized currently for PVC ribbed sheet piles. The length used for these calculations is the maximum unsupported height of the wall. For two walers the height is the distance between the walers. For one waler the height is between the embedment location and the waler.

![FEA model for WPC 10" sheet walls.]

**Figure 6.** FEA model for WPC 10" sheet walls
4.2 Deflection, shearing force and Bending Moments

![Bending moment, shear force, displacement envelopes](image)

**Figure 7.** Total deflection, shearing force and bending moments for WPC 10" SPW

5. Analysis

5.1. Lateral movements

Figure 8, shows the results of lateral movements’ ratio, $\Delta/H_f$ of the anchored sheet pile walls (case one Waler model) of different stiffness, $Ei$. Two values for WPC sections and one for steel section proposed AZ12, which ranged from low to high wall stiffness, were examined. The results show that when the stiffness of the wall increases, the lateral movement ratio, $\Delta/H_f$ of the sheet pile wall significantly decreases. The results of very low wall stiffness show unacceptable wall movements for WPC 8.10 and 11.75 sections, with $Ei = 1.1*10^2, 3*10^2$ and $6.2*10^2$ kN.m$^2$ while the steel AZ12 shows an acceptable movement.

![\(\Delta/H_f\) versus wall stiffness](image)

**Figure 8.** $\Delta/H_f$ versus wall stiffness (One Waler model)

Figure 9. shows the results of lateral movements’ ratio, $\Delta/H_f$ of the anchored sheet pile walls (case two Waler model) of different stiffness $Ei$. But only using WPC sections 8.10 and 11.75, and for this model the deformations results is accepted for the two sections 10 and 11.75 only.

![\(\Delta/H_f\) versus wall stiffness for WPC](image)

**Figure 9.** $\Delta/H_f$ versus wall stiffness for WPC (Two Waler model)
The results also show that the maximum lateral movements happened approximately, at the same point for different wall stiffness, approximately at 0.65 of the free height of the wall, $H_f$. As well as, the displacements at the anchored level and the dredge line significantly reduced as the wall stiffness increase.

5.2. Bending moments
Figure 10, presents the distribution of bending moments along the height of the anchored sheet pile wall (case of one waler model) under different values of $EI$. Excluding the results from walls of low stiffness, the plots show an increase in the maximum bending moments happened in the free height of the wall when the wall stiffness, $EI$ increases. In addition, from this figure, we can see that the position of the maximum bending moment about 63 KN.m/m occurs, approximately, at the same distance from the dredge level. It happened at a point very close to the point at which the maximum lateral movement occurred, approximately at 0.60 $H_f$.

Figure 11 presents the distribution of bending moments along the height of the anchored sheet pile wall (case of two waler model) under different values of $EI$. In this case the maximum bending moments decreased to 19 KN.m/m, about 70 % less than the last case of one waler, and the WPC 10 &11.75 is safe in bending stresses and occurs, approximately, at the same distance from the dredge level. It happened at a point very close to the point at which the maximum lateral movement occurred, approximately at 0.70 $H_f$.

5.3. Shearing force
Figure 12, presents the distribution of shearing forces along the height of the anchored sheet pile wall (case of one waler model) under different values of $EI$. Excluding the results from walls of low stiffness, the plots show an increase in the maximum shearing forces happened in the free height of the wall when the wall stiffness, $EI$ increases. In addition, from this figure, we can see that the position of the maximum shearing force about 40 KN/m occurs approximately, at 0.30 $H_f$ from the dredge line.

Figure 13 presents the distribution of shearing forces along the height of the anchored sheet pile wall (case of two waler model) under different values of $EI$. In this case the maximum shearing force decreased to 10 KN/m, about 70 % from the last case of one waler , and the WPC 10 &11.75 is safe in shearing stresses and occurs, approximately at 0.70 $H_f$ from the dredge line.
6. Conclusions

The finite element model verifies the initial design assumptions stated in previous section. This is through the agreement of the maximum deflections between the two models. The design method used for preliminary design limits the stress in the material to much less than the allowable stress; therefore the assumption that WPC is a linear material is valid for this specific situation. The case of two waler model is consisted with the Tur SPW model with accepted and safe deformations and stresses, so we can use this new material WPC in all Egypt harbours under water depth of 6.0 m, for economic reasons and easy installations.

The next step is to use the FEA modelling for design to predict the behaviour of this geometry and material under various service conditions, which was successfully completed. Therefore, the FEA analysis can be used as a tool for the WPC sheet pile design.

References

[1] Brandt, C. W. (2001). Load-Duration Behavior of Extruded Wood-Plastic Composites. Department of Civil and Environmental Engineering. Pullman, WA, Washington State University. M.S.

[2] Clemons, C. (June 2002). "Wood-Plastic Composites in the United States" Forest Products Journal 52(No. 6). CMI. (2005). "Crane Materials International" 2005.

[3] Dagher, H. J., Lopez-Anido, R.A., Gardner, D.J., Dura, M.J., and Stephens, K.L. (2004). Sheet Piling Panels with Elongated Hollows. U. S. P. Application. 11,013,301.

[4] Dura, M., Lopez-Anido, R., Dagher, H., Gardner, D., O'Neil, S. and Stephens, K. (2005). Experimental Behavior of Hybrid Wood-Plastic Composite-FRP Structural Members for Use in Sustained Loading Applications.8th International Conference on Wood fiber-Plastic Composites. Madison, WI. pp 189

[5] Dutta, P. K. and U. Vaidya (2003). A Study of the Long-Term Applications of Vinyl Sheet Piles. U. A. C. o. Engineers.

[6] Giroux, C. (2000). Analysis of the Flexural Behaviour of a Fibreglass Composite Seawall Department of Civil Engineering and Applied Mechanics. Montreal, McGill University. Master of Engineering: 119.

[7] Kahl, M., Dagher, H., Lopez-Anido, R., Gardner, D., and Dura, M. (2005). Design of Innovative Hollow Extruded WPC Sheet Piling.8th International Conference on Wood fiber-Plastic Composites. Madison, WI. Limited. O. (1992). Polypropylene.

[8] K. Terzaghi, Special Footings and Beams on Elastic Foundations, Foundation Analysis and
Design, McGraw-Hill Book Co., NY, pp. 380-432 (1988).

[9] Lampo, R., T. Nosker, et al. (1998). Development and Demonstration of FRP Composite Fender, Loadbearing, and Sheet Piling Systems. Construction Productivity Advancement Research (CPAR) Program. U. A. C. o. Engineers.

[10] Prasad, P., J. Mark, et al. (1998). Science and Technology of Polymers and Advanced Materials Emerging Technologies and Business Opportunities. Fourth International Conference on Frontiers of Polymers and Advanced Materials, Cairo, Egypt.