OPTIMISATION DESIGN OF PRECAST REINFORCED CONCRETE SHEET PILES FOR COASTAL RETAINING WALLS

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Abstract - This research introduces a novel method for optimising the design of precast reinforced concrete (SW) sheet piles that are used in coastal retaining walls. The study examined key parameters, including backfill embankment height, surcharge loads, and SW sheet pile geometry to evaluate the stability and performance of a retaining wall. Using the Python-Plaxis interface, a set of numerical models were developed automating the analysis and significantly reducing computational time. In total about 70 models were conducted; their results were used to establish a Gene Expression Programming (GEP) model between input and output parameters. The research results confirm that combining FEM and GEP is a valid approach for design optimisation of complex geotechnical structures. A parametric study indicated that the height of backfill embankment and the length of SW piles are critical variables. This integrated approach provides engineers an efficient tool in the design of soft soil in coastal regions.

Key words - Precast reinforced concrete sheet piles; Coastal retaining walls; Finite Element Method (FEM); Gene Expression Programming (GEP); Optimisation

1. Introduction

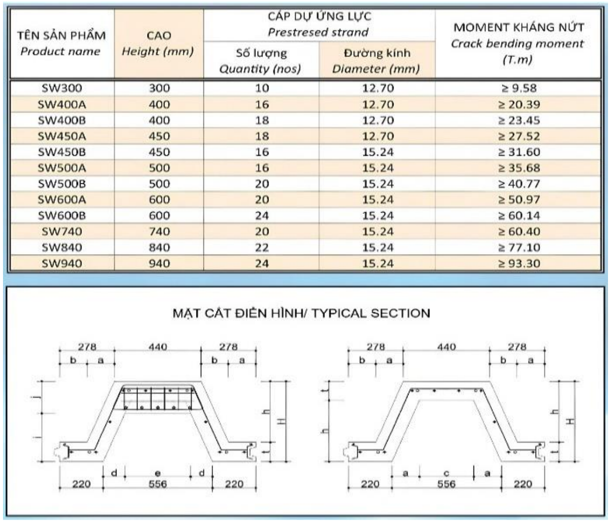
In recent decades, coastal erosion has emerged as a significant concern in many countries, especially in coastal areas where there are sediments with weak soil foundations and where climate change is high. According to the IPCC report in 2021 [1], global sea level has risen by approximately 0.20 meters between 1901 and now, and this is expected to increase in the next period. This has contributed to an increased risk of erosion, landslides, and saltwater intrusion, especially in a coastal region where large waves, high tides, and subsurface flows interact. At the same time, coastal urbanisation and economic development require a high demand for the construction of infrastructure works such as residential areas, protective embankments, sea ports, and coastal tourist areas to take place. Such investments would typically support an effective retaining wall solution for all offshore structures. Currently, Vietnam has developed many land reclamation projects to expand land resources and contribute to socioeconomic development, including 80 zones in 19 coastal provinces and cities [2].

For instance, the Free Trade Zone in Danang City is a huge reclamation project to create a new space for economic development with the free trade zone, a high-quality tourism area, an international financial centre, and a cultural hub. Additionally, the Can Gio coastal tourism urban area in Ho Chi Minh City is the largest land reclamation in Vietnam for some time. The total planned area is 2,870 hectares, with 1,357 hectares planned for reclamation (Figure 1). It shows that reclamation areas are growing very fast, and there is a strong demand for geotechnical and structural design solutions that will allow for the stability and durability of these sites.

Figure 1. *Can Gio coastal urban area [3]*

Initially, prestressed reinforced concrete sheet piles (SW), produced per the Japanese Industrial Standards (JIS), have been used increasingly in several projects in Vietnam. SW sheet piles have a specific role in coastal earth-retaining structures with high durability, resistance, and load-bearing capacity. The SW sheet piles include W120 to W1200 type with lengths up to 34 meters [4]. Figure 2 illustrates the cross-section of SW piles. The width of the SW pile is 996 mm, and the prestressing system uses high-tension steel strands of type SWPR-7B with either 12.7 mm or 15.2 mm diameter to generate the prestressing forces for structural performance. The combination of vibratory driving and water jetting is the most commonly used method for installation processes. This method led to minimal dynamic stress on the installed pile. Water is injected at the pile tip through internally pre-installed conduits, typically with drivelines of either D15 or D17 and high capacity. The injected water softens and loosens the soil profile to the bottom of the pile and allows the pile to be merged or pushed deeper into soils with reduced resistance and disturbance to the surrounding earth.

According to Han and Liu [5], numerical simulations are a reliable method to examine the efficiency and stability of geotechnical problems. Plaxis is a common finite element analysis software developed by Bentley Systems and offers a functional option for modelling soil–structure interaction under different load and boundary conditions. The Plaxis API is mostly written in Python, which allows users to improve workflows by automating simulations, systematically varying design parameters, extracting output data, and generating batch simulations without manually inputting data via the graphical user interface. The API can be used to improve designs through a relatively quick exploration of several design alternatives, conduct a sensitivity analysis on key parameters, and assess reliability under complex geotechnical conditions.



TÊN SẢN PHẨM *Product name*	CAO *Height (mm)*	CÁP DỰ ỨNG LỰC *Prestresed strand*		MOMENT KHÁNG NỨT *Crack bending moment (T.m)*
		Số lượng *Quantity (nos)*	Đường kính *Diameter (mm)*	
SW300	300	10	12.70	≥ 9.58
SW400A	400	16	12.70	≥ 20.39
SW400B	400	18	12.70	≥ 23.45
SW450A	450	18	12.70	≥ 27.52
SW450B	450	16	15.24	≥ 31.60
SW500A	500	16	15.24	≥ 35.68
SW500B	500	20	15.24	≥ 40.77
SW600A	600	20	15.24	≥ 50.97
SW600B	600	24	15.24	≥ 60.14
SW740	740	20	15.24	≥ 60.40
SW840	840	22	15.24	≥ 77.10
SW940	940	24	15.24	≥ 93.30

Figure 2. *Typical cross-section of SW piles*

Notably, in conjunction with machine learning algorithms or optimisation methods, the Plaxis API fosters a new, intelligent approach to geotechnical design that increases safety and performance at a significant reduction in time and cost. Gene Expression Programming (GEP), a machine learning algorithm, is in the class of evolutionary algorithms and was developed by Ferreira [6]. GEP uses the benefits of Genetic Programming (GP) and Genetic Algorithms (GA), and generates and develops mathematical models in the expression format. Unlike a time-less machine learning kind of approach, GEP provides a computing approach that not only reaches a significant level of accuracy, but also bolsters interpretable computing models for engineering analysis and application.

In the fields of geotechnical engineering and structural design, the GEP algorithm is becoming more prevalent to model complex nonlinear relationships between design parameters and a performance metric (e.g., settlement, earth pressures, stress and strain behaviour, lateral displacement, or bearing capacity). A primary advantage of GEP is its ability to automatically discover hidden relationships in numerical or experimental data without specified pre-assumptions as to the model structure. This provides a possible, reliable estimate of a predictive formula with a rationale physical interpretation. GEP demonstrates its outperformance in prediction accuracy and low complexity in comparison with other Machine Learning techniques [7, 8].

In correlation with numerical simulation results (e.g., Plaxis), GEP can also produce models or objective functions for design optimisation to reduce the required number of simulations and therefore save time and computational cost. In the context of the application of retaining wall design, deep foundations, and/or ground improvement for soft soils, GEP allows for the rapid identification of the optimal combination of parameters that lead to the optimum solutions (with respect to safety and cost-effectiveness for geotechnical solutions) [9].

Thus, this study is going to apply Plaxis API to analyse several scenarios of retaining walls and develop a GEP-based model to estimate the lateral displacement of SW sheet piles. The parametric study could help engineers choose a reasonable pile length to meet the stability requirements of the retaining structures.

2. Retaining wall design

2.1. Geotechnical solutions for retaining walls

The standard geological situation at Da Nang Port is represented by a weak clayey silt layer (S_u = 15–25 kPa), typically between 8 to 15 m thick, a shallow groundwater table, and a large void ratio [10]. The design and construction of prestressed reinforced concrete sheet pile walls to support embankments of 2 to 5 meters in height in these conditions results in excessive lateral displacement, bending moments, and low safe factors. Therefore, additional integrated engineering solutions need to be designed and incorporated into the system to increase overall stability performance. The following sections will evaluate each key solution in more detail.

2.1.1. Geogrid reinforcement

Geogrids are geosynthetics made from materials such as polypropylene (PP), polyethene (PE), or polyester (PET) and have an open grid configuration. Primary applications for geogrids are reinforcement by means of interlocking within soil particles, which provides mechanical enhancement of the soil mass. Geogrids provide good tensile strength, are chemically resistant, and provide long-term durability in soil environments [11]. Geogrids are typically placed horizontally within the retained soil mass behind a retaining wall, with each layer placed vertically spaced at 0.4 m to 1.0 m, depending on wall height and load conditions.

2.1.2. Geocells reinforcement

Geocells are 3-D structures fabricated from strips of high-density polyethene (HDPE) or Novel Polymeric Alloy (NPA) that have been ultrasonically welded together to appear like honeycombs. Geocells are placed in the backfill behind a retaining wall in layers that are arranged parallel to the ground surface. Geocells improve the shear resistance and stiffness of the infill material. The confinement and membrane effects could reduce lateral earth pressures on the retaining wall and minimise shearing deformations of the backfill material [12]. Geocells may help redistribute loads and reduce localised failures in soft or loose soils.

2.1.3. Deep cement mixing reinforcement

Deep Cement Mixing (DCM) piles are a type of ground improvement technique which are created with an auger (or other tools) by mechanically mixing the existing soft soil with a cement-based binder in situ. This results in a column of soil-cement with increased strength and stiffness. DCM piles can be used extensively to improve the bearing capacity of soft soils, control settlement, and stabilise backfill in earth-retaining applications. The DCM piles have a vertical orientation, placed beneath or around the backfill zone behind or in front of retaining walls, placed in a regular grid or strip pattern as determined by design [13]. DCM piles function as semi-rigid inclusions that resist deformation in weak, compressible subgrades and provide improved resistance to lateral displacement and shear.

2.2. Numerical simulation

This study was conducted based on the geotechnical conditions in the coastal area of Da Nang City. The geological profile is presented in Table 1 [10]. The quay retaining wall is supported by SW840 sheet piles. The backfill behind the wall is installed in several stages, each stage of which will be combined in sequence, embankment and foundation stabilisation for a total of about 20 to 30 days. The embankment comprises well-compacted sand, with a relative compaction of K95. A series of simulations was conducted to investigate the efficiency of ground improvement techniques and the stability of retaining structures, including: (i) no ground improvement, (ii) reinforcement of the embankment base using geogrids, (iii) reinforcement using geocells, and (iv) ground improvement by installing DCM columns.

Table 1. *Typical Geological Profile at Danang city [10]*

Soil Layer	Soil Type and Characteristics	Thickness
Layer 1	High-plasticity clay, from soft to very soft consistency	3.6–19.6 m
Layer 2	Clayey sand, medium dense state	1.3–8.5 m
Layer 3	Low-plasticity clay, stiff consistency	2.0–10.0 m
Layer 4	Low-plasticity clay, hard consistency	5.0–30.0 m

Table 2. *Parameters and Models of Soil Layers*

Para-meters	Unit	Back-Fill material	Soft soil	Sandy Clay	DCM	Geo-cell
Model		HS	SS	HS	LE	MC
γ_{unsat}	kN/m³	17	16.7	19.2	19	19
γ_{sat}	kN/m³	17	16.7	19.5	19	19
E_{50}^{ref}	kN/m²	2.0E4	-	1.4E4	3.0E5	2.4E5
φ	deg	25	12	33.8	-	40
c^{ref}	kN/m²	1	10	1	-	50
ν_{ur}		0.2	0.2	0.2	0.2	0.2
λ*		-	0.12	-	-	-
κ*		-	0.02	-	-	-
k_x; k_y	m/day	0.1	1.0E-5	0.1	-	-
EA	kN/m	-	-	-	-	-
R_{inter}		0.67	0.67	0.67	0.85	0.9

Note: HS = Hardening Soil, SS = Soft Soil; MC = Mohr-Coulomb; LN = Linear Elastic.

The finite element method with the Plaxis 2D software was used to simulate the staged construction of the embankment. For the material models, the Soft Soil model was used for the soft clay layer, and the Hardening Soil model was used for the other soil layers. The DCM columns and geogrid materials were modelled using the Linear Elastic and Elastic models, accordingly to Voottipruex, et al. [13]. The geocell was modelled as an equivalent material layer with the Mohr-Coulomb model. Table 2 summarises the material models and their respective parameters for the soil layers and reinforcement materials in the study.

Calculation phases:

Phase 1: Installation of the SW840 reinforced concrete sheet pile wall system.

Phase 2: Installation of the geosynthetics (i.e., geotextile, geocell, and DCM columns) and filling in embankment incrementally.

Phase 3: Application of external loading acting on the quay structure.

Phase 4: Monitoring the wall's behaviour, including measuring lateral displacement at the top of the sheet pile and calculating a factor of safety for overall stability of the retaining system.

Table 3. *Parameters and Models of SW pile and Geogrid*

Parameters	Unit	SW840	Geogrid
Material type		Elastic	Elastic
EA	kN/m	11.2E6	50
EI	kN m²/m	7.65E5	-
d	m	0.84	-
w	kN/m/m	24	-

2.3. Simulation results

The validation model was established based on the study of Tan, et al. [14]. The proposed model in this study provided the highest lateral displacement of the pile sheet of 40.5 mm, which is close to the measured value of 41.1 mm [14]. The error is acceptable, so the simulation model could be confidently applied for further study.

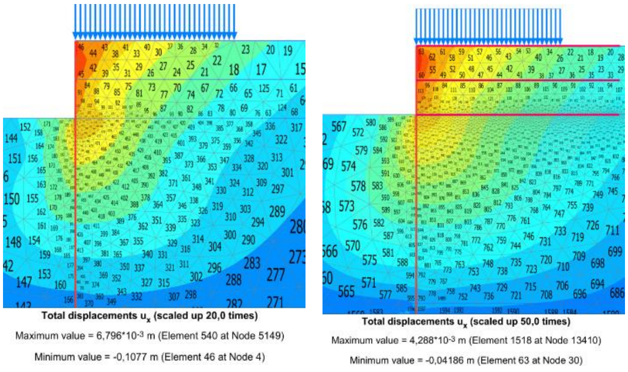
Table 4. *Retaining wall with and without reinforcements*

Reinforcement techniques	U_x (mm)	F_s
Without a reinforcement solution	107.7	1.35
Geogrid reinforcement	41.9	1.75
Geocell reinforcement	32.9	1.94
DCM reinforcement	18.8	2.9

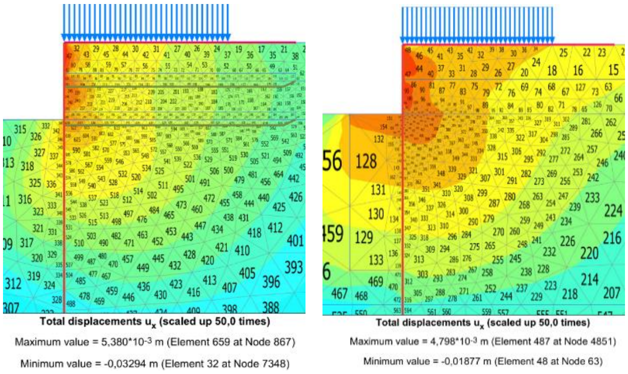
Table 4 presents the simulation results for a 4-meter-high embankment positioned behind a 20-meter-long SW sheet pile wall, subjected to a uniform surcharge load of 5 kPa. Figure 3a indicates that the maximum lateral displacement in the retaining wall is 107.7 mm, and the global factor of safety (F_s) is 1.35. For design purposes, the allowable lateral displacement of a cantilever sheet pile wall is typically 0.5%–1.5 % of wall height, which equals 20–60 mm, and the minimum factor of safety is $F_s \geq 1.5$. Thus, the wall does not meet the criteria for displacement control and global stability in this scenario. Figure 3b shows that lateral displacement at the top of the wall is reduced to 41.9 mm and the global factor of safety improved to $F_s = 1.75$ when the backfill is reinforced with geotextile layers spaced at intervals of 2 meters. This result shows the effectiveness of geotextile reinforcement to reduce the active earth pressure on the retaining structure and improve the stability of the embankment.

The performance of the geocell-reinforced embankment is illustrated in Figure 3c. The geocell layer provides a considerable reinforcement effect, increasing internal friction and cohesion while reducing both vertical and horizontal stresses. Thus, the active earth pressure acting on the retaining wall is reduced, and overall embankment stability is increased.

In the example where DCM columns are utilised to reinforce the structure on the front of the sheet pile wall, the wall displacement is reduced significantly to 18.8 mm, and the global factor of safety is increased to 2.9. It indicates that the passive earth pressure acting on the wall is improved and resulting in an increase in the stability of the wall. This is a suitable solution for soft foundation soils or high embankments (5-10 m) behind the retaining structure, as it will provide sufficient resistance to enhance the stability of the wall. However, it may result in a higher cost of construction and the duration of implementation in comparison to the previous methods of reinforcement.



(a) Without reinforcement *(b) Geogrid reinforcement*

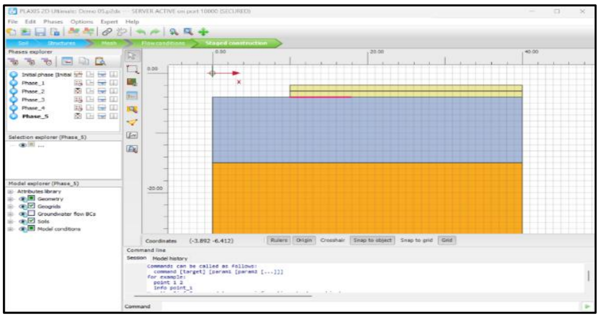


(c) Geocell reinforcement *(d) DCM reinforcement*

Figure 3. *Simulation results on the retaining wall reinforcements*

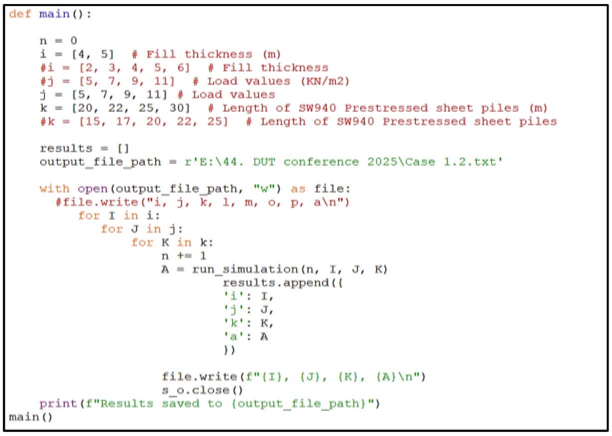
3. Optimisation design using Plaxis API và GEP

To choose a suitable SW sheet pile length related to different heights of embankment, Plaxis 2D simulations and a Gene Expression Programming (GEP) algorithm were used. In this study, the embankment height varies between 2 to 5 meters, and the uniformly distributed load behind the retaining wall varies from 5 to 11 kPa. The prestressed concrete sheet piles (SW840 type) were assumed to have design lengths between 15 to 30 m. The conceptual model of the retaining wall system used in the analysis is illustrated in Figure 4. A Python script was created to facilitate interaction with Plaxis. A flowchart showing the integration between PLAXIS 2D and the Python API for automated modeling and output extraction could be fully explained in the study of Pham [9]. The input parameters were varied randomly and combined at each model run, including the height of embankment, surcharge load, and pile length. The model analysed was simulated automatically, and the maximum displacement of the wall was directly extracted and recorded. A partial example of the Python code may be found in Figure 5. In approximately two hours, 70 cases of simulation were completed, corresponding to 70 different models. The results demonstrate the efficiency and robustness of the automated analysis method. It also significantly decreased the amount of time and effort needed to create numerical models for a wide range of design scenarios.



```
Commands can be called as follows:
  command [target] [param1 [param2 [...]]]
For example:
  point 1 2
  info point_1
```

Figure 4. *Plaxis 2D model for automated analysis*



```
def main():

    n = 0
    i = [4, 5]  # Fill thickness (m)
    #i = [2, 3, 4, 5, 6]  # Fill thickness
    #j = [5, 7, 9, 11]  # Load values (KN/m2)
    j = [5, 7, 9, 11] # Load values
    k = [20, 22, 25, 30]  # Length of SW940 Prestressed sheet piles (m)
    #k = [15, 17, 20, 22, 25]  # Length of SW940 Prestressed sheet piles

    results = []
    output_file_path = r'E:\44. DUT conference 2025\Case 1.2.txt'

    with open(output_file_path, "w") as file:
      #file.write("i, j, k, l, m, o, p, a\n")
         for I in i:
            for J in j:
                for K in k:
                    n += 1
                    A = run_simulation(n, I, J, K)
                            results.append({
                            'i': I,
                            'j': J,
                            'k': K,
                            'a': A
                            })

                    file.write(f"{I}, {J}, {K}, {A}\n")
                    s_o.close()
    print(f"Results saved to {output_file_path}")
main()
```

Figure 5. *Python code for Plaxis API*

3.1. Data preparation

The data obtained from the FEM analysis were used to develop correlation models between the input variables and the output. The statistical properties of the independent variables and the output variable are shown in Table 5. The data were split into two subsets with a 70%–30% ratio employing K-Fold cross-validation. The model was trained with around 49 samples, while there were 21 samples for the validation of the model.

3.2. GEP model

GeneXpro Tools 5.0 was utilised to create the Gene Expression Programming (GEP) model, which is an effective and powerful tool for symbolic regression modelling. Figure 6 shows the selected parameter settings used for model development, and thirteen mathematical functions were used. The optimum model was selected with a high predictive accuracy and low error values during the training and validation phases.

Table 5. *Statistical properties of the variables*

Parameters	Backfill height	Surcharge load	SW length	Displace-ment
maximum	5	11	30	141.4
minimum	2	5	15	6.6
range	3	6	15	134.8
mean	3.40	7.94	21.97	30.7
SD	1.13	2.25	4.19	26.4
CoV	1.29	5.07	17.59	696.8

The four sub-expressions (Sub-ETs) from the selected model, including the relevant Python code, are shown in Figure 7. The final mathematical expression appears as Equation (1).

$$Y = 2.41 \cdot d_0^2 - d_1 - d_2 + \frac{1}{7.14 - 2d_0} + 18.53 + d_1^{\,1-\frac{1}{4.94d_0 - d_2 + 5.81}} \quad (1)$$

Where: Y is the predicted displacement of the top of the retaining wall, d_i are the independent variables.

Settings

General

Chromosomes: 150

Genes: 4

Head Size: 7

Tail Size: 15

Dc Size: 15

Gene Size: 37

Linking Function: Addition

Fitness Function

Function: RMSE

Figure 6. *Setting parameters for GEP modelling*

To assess the model's predictive performance, several statistical indicators were used: correlation coefficient (R), root mean square error (RMSE), and mean absolute error (MAE) [9]. Table 6 summarises the results of the selected model, indicating high accuracy in predicting with R ≈ 0.99, RMSE < 4.2 mm, and MAE < 3.2 mm. It illustrates the reliability and applicability of the model for parametric analysis.

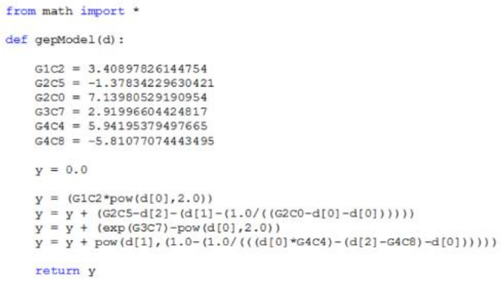
Table 6. *Model performance*

Phase	Training	Validation	All data
R^2	0.977	0.982	0.978
RMSE	4.2	3.2	3.9
MAE	3.2	2.6	3.0
R	0.988	0.991	0.989

3.3. Parametric study

Figure 8 presents the variable contribution where the height of the backfill embankment and the length of SW sheet piles show a significant impact on the lateral displacement of the retaining wall. In addition, a parametric study was conducted to analyse the influence of these parameters on the displacement at the top of the retaining wall.

A significant factor with regard to the pressure on the retaining wall is the backfill height. Figure 9a indicates that the heavier the weight of the soil behind the retaining wall, the higher the lateral load acting on the wall, which leads to increased displacement at the top of the wall. The analysis of the backfill height from 2 m to 5 m in the study displayed a linear increase in lateral displacement at the top of the wall. This indicates the importance of considering backfill height in retaining wall designs, particularly when attempting to minimise displacement and maintain stability.



```
from math import *

def gepModel(d):

    G1C2 = 3.40897826144754
    G2C5 = -1.37834229630421
    G2C0 = 7.13980529190954
    G3C7 = 2.91996604424817
    G4C4 = 5.94195379497665
    G4C8 = -5.81077074443495

    y = 0.0

    y = (G1C2*pow(d[0],2.0))
    y = y + (G2C5-d[2]-(d[1]-(1.0/((G2C0-d[0]-d[0])))))
    y = y + (exp(G3C7)-pow(d[0],2.0))
    y = y + pow(d[1],(1.0-(1.0/(((d[0]*G4C4)-(d[2]-G4C8)-d[0])))))

    return y
```

Figure 7. *Python code expression of the proposed GEP model*

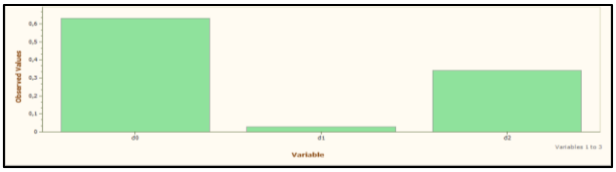


Figure 8. *Variable importance exported from GeneXpro Tools*

The surcharge load behind the wall has a notable effect on how the wall behaves. In this research, loads of 5 kPa to 11 kPa were introduced, simulating various soil pressures behind the wall. Figure 9b illustrates that a higher lateral load results in slightly larger displacements at the top of the wall. This shows the importance of accurately simulating load distribution should be practised to improve safety and functionality for coastal retaining walls from soil pressures.

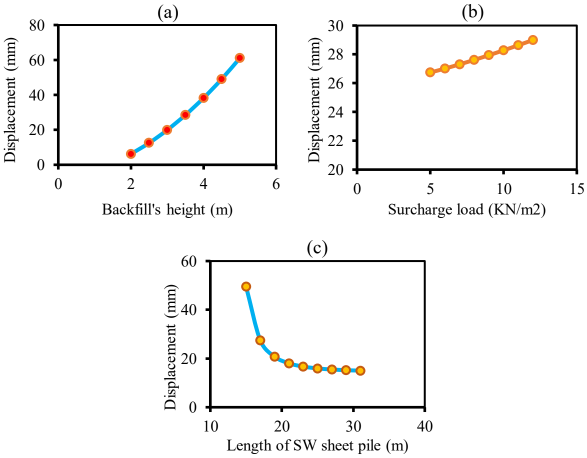


Figure 9. *Effects of key variables on the lateral displacement of the retaining wall*

Figure 9c shows that the length of the SW sheet pile wall has an important impact on the displacement behaviour. Variations in wall length between 15 m and 30 m demonstrated that shorter walls had greater displacements than longer walls under the same backfill height and lateral load conditions. This occurs as longer walls have greater depth of embedding, which allows the wall to better resist lateral forces, therefore reducing the top displacement. In detail, for an average embankment height and a uniform surcharge of 20 kPa applied above the wall, the maximum horizontal displacement at the top of the wall reduced from around 50 mm (L = 15 m) to 19.5 mm (L = 20 m), or about 61% improvement in performance. However, increasing the pile length further from 25 to 30 m only marginally improved the reduced displacement to 15 - 16 mm.

For an optimised pile length, it is important to ensure a balance between performance and construction costs. Depending on the height of the backfill embankment, the allowable displacement is approximately 0.5%H. For low backfill (H < 2 m), the short SW pile could be used as the maximum lateral displacement is insignificant. However, Figure 10 indicates that the longer SW pile (20 m and 24 m in length) should be considered for the case of 3.5 m and 5 m backfill height, respectively. This suggests a diminishing return in performance after a certain critical length. Thus, it notes that optimising the sheet pile length can greatly improve the behaviour of retaining walls, particularly under high lateral loading conditions.

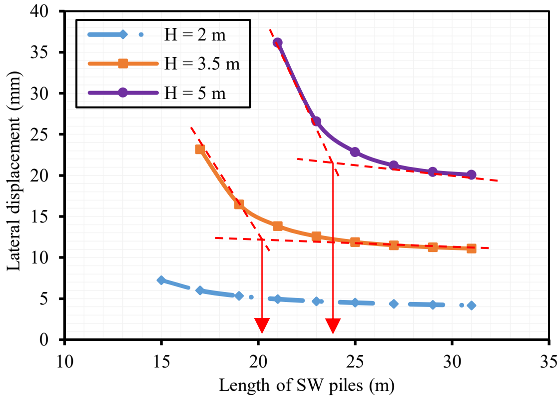


Figure 10. *Effects of key variables on the lateral displacement of the retaining wall*

4. Conclusions

This research presents a methodology to select the precast prestressed concrete sheet pile walls (SW) that are part of coastal retaining structures that utilises finite element modelling (Plaxis 2D) in conjunction with Gene Expression Programming (GEP). A thorough parametric analysis was performed to assess the effects of the main design parameters (backfill height, surcharge load, and sheet pile wall length) on the lateral displacement of the top of the wall. In this study, an automated Python program was created in order to develop and assess the generated numerical models. The automation greatly reduced the time and the effort involved in performing the computations. The results from the finite element simulations were used to train and verify the GEP model. The selected GEP model showed promising results with a high correlation coefficient (R ≈ 0.99), a low RMSE (< 4.2 mm), and a low MAE (< 3.2 mm).

The parametric study indicates that the wall displacement is increased significantly for higher backfill heights and surcharge loads, but is reduced when the embedded length of the sheet-pile is increased. This study provides important information on the performance of coastal retaining wall structures and provides a scientific basis for their design in an efficient and rational manner. Overall, the study shows promise in using numerical simulation and machine learning techniques in geotechnical engineering design, as numerical simulation will improve the accuracy of the design, and machine learning techniques will support faster decision-making in practice, where complex coastal conditions exist. As such, the GEP model developed in this study can be seen as an effective, preliminary design tool for examining the sensitivity or variations within rejected engineering designs in any future construction project.

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