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# Secant Pile Wall Model with Partially Saturated Soil

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ABSTRACT

The undertaking of deep excavations in areas characterized by high groundwater levels, industrial zones, and large-scale projects involving massive structures presents significant engineering challenges. Secant pile wall techniques offer highly effective solutions in such conditions. These walls are constructed using a combination of reinforced and plain concrete piles installed in an overlapping arrangement to form a continuous barrier that retains the surrounding soil and prevents collapse. The importance of secant pile walls lies in their high capacity to resist lateral earth pressures and control groundwater infiltration, making them a critical component in deep-excavation projects. Understanding the behavior of these walls, particularly under varying groundwater conditions, is essential to ensure their performance and stability. The dewatering process, which lowers the groundwater level, has a considerable impact on the deformation and stability of secant pile walls. Therefore, it is crucial to implement these systems in a manner that aligns with the excavation method and site-specific conditions to ensure structural safety and project efficiency. This study aims to investigate the behavior of a secant pile wall model when it supports sandy soil and is subjected to different water levels. This type of wall is commonly used in permeable sandy soils with high water content. As is well known, the excavation process is carried out gradually, accompanied by dewatering to prevent water from seeping into the excavation area. Therefore, we adopted an excavation and dewatering system that corresponds to the actual site conditions. The study looked into several different excavation depths on the passive side, including 0m, 0.2m, 0.4m, 0.6m, and 0.8. Moreover, water levels at different excavation depths (0.0, 0.2, and 0.4m) were measured Several parameters were evaluated, including the lateral total stress on both sides of the wall, horizontal and vertical displacements, and matric suction about the moisture content in the soil above the water level. According to the test results, the water level significantly influences the values of the lateral total stress. A decrease in the water level leads to a decrease in the amount of active total stress, while an increase in the magnitude of passive total stress occurs. Furthermore, lowering the water level causes a more substantial vertical displacement than a horizontal displacement at the top of the wall. The results indicate that lowering the groundwater level enhances the stability of the secant pile wall and increases the overall safety of excavation activities. However, this reduction in water level also leads to vertical settlement in nearby foundations. For example, when the water level is lowered from 0.2m to 0.0m, the vertical settlement increases to 0.25 mm at an excavation depth of 0.2m, while the horizontal displacement at the top of the wall remains unchanged at zero. This highlights a critical consideration for projects located near existing structures, as lowering the water level can induce settlement even when lateral movements are minimal.

***Keywords:*** Secant pile wall, Dewatering, Lateral stress, Lateral displacement, Vertical displacement, Soil water characteristic curve.

## INTRODUCTION

Due to the limited space available in urban areas and the need to construct skyscrapers, deep excavation is essential. Secant pile walls are a viable substitute for traditional retaining walls, such as sheet piling, soldier piling and lagging, soil mix walls, and diaphragm walls. The walls are made of interlocking and overlapping bored concrete piles, including primary (unreinforced) and secondary (reinforced) piles. At first, primary piles are placed at pre-determined intervals along the perimeter. Afterward, more piles are driven or placed on the initial heaps. This construction method entails drilling piles to the specified diameter and depth. Figure (1) illustrates the many classifications of secant pile walls (DeepEX software program MANUAL Version 24.0.1.1). Research that has been conducted in the past, such as that conducted by Moormann (2004), which analyzed several case studies, it was shown that the average values of the normalized horizontal deflection (δh-max/H %) and the vertical displacement at the ground surface (δv-max/H%) for non-cohesive soil are roughly 0.25% and 0.33%, respectively. Compared to soft clay, where the maximum δh/H% is larger than 1%, and the maximum δv/H% is often equal to 1%, these results are insignificant. Mahesh (2019) presented a comprehensive examination of how the diameter of the secant pile wall affects deep excavation analysis. This research employed a time history approach to examine the capacity, lateral displacement, and bending moment of secant pile walls throughout the plastic and elastic phases. Hydrostatic pressure, seismic stresses, and lateral earth pressure were all factors in investigating vertical beams of varying diameters. It is worth noting that the bending moment and lateral displacement both increased as the distance between the secant pile walls grew, according to Mahesh's study. Changing the pile diameter from 0.6m to 0.8m decreased lateral displacement, but raised the secant pile wall's bending force amplitude. Successful application of the cap beam resulted in a decrease in horizontal displacement and flexural force, especially as the depth of the beam rose. The report said the secant pile wall distorted more due to stress and deformation as the excavation depth increased. The secant pile wall supporting system outperformed its rivals in tests conducted on sandy soil conditions. Ramadan (2020) presented a numerical study that examined the behavior of a cantilever secant pile wall supporting excavation in sandy soil, focusing primarily on ground movement issues and the potential harm to nearby buildings. In order to anticipate wall deflection and choose the right supporting system, the study investigated variables that affect lateral earth pressure and ground movement. This investigation culminated in a thorough parametric study. The study examined the efficacy of cantilever-secant pile walls in providing support for excavations in sandy soil by conducting a parametric analysis. The main discoveries consisted of the inverse correlation between sand density (Dr), excavation depth (H), and wall flexural stiffness (EpIp/Lp) with both horizontal (δh) and vertical (δv) deformations. Suggested guidelines involved excavating to a maximum depth of 2m prior to installing the initial support and using a design approach that estimates deformations using Dr, H, and EpIp for piles that are entirely bonded. The importance of the bonding between piles within the wall is emphasized, affecting deformations.

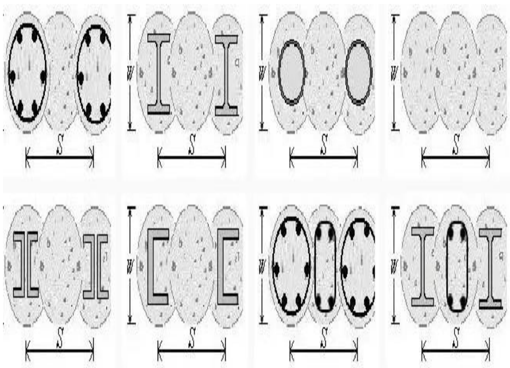


**Figure 1.** Different types of secant pile walls

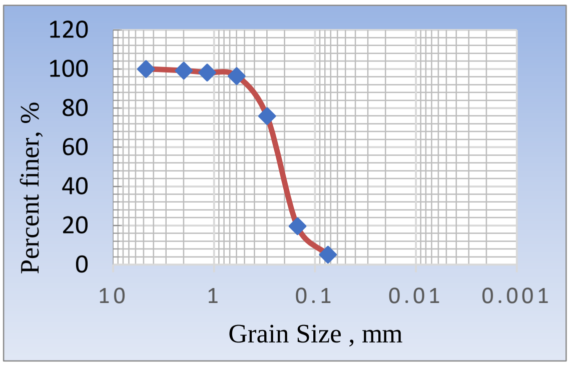



**Figure 2.** Grain size distribution of the soil used

This study aims to assess the impact of water level on the performance of a secant pile wall in sandy soils, specifically in terms of total lateral earth pressure, horizontal displacement at the top of the wall, and vertical settlement at the adjacent footing.

**Soil Properties**

The soil utilized for this study was collected from AL-MUTHANA AIRPORT (IRAQ GATE RESIDENTIAL COMPOUND PROJECT) area in Baghdad city. The sand was dug to a depth of about 10 meters below the natural ground level. Table 1 shows the physical properties of the used soil. As seen in Figure 2, the sand's grain size distribution is displayed. The soil is categorized as (SP) based on the unified soil classification system.

**Table 1.** Soil properties

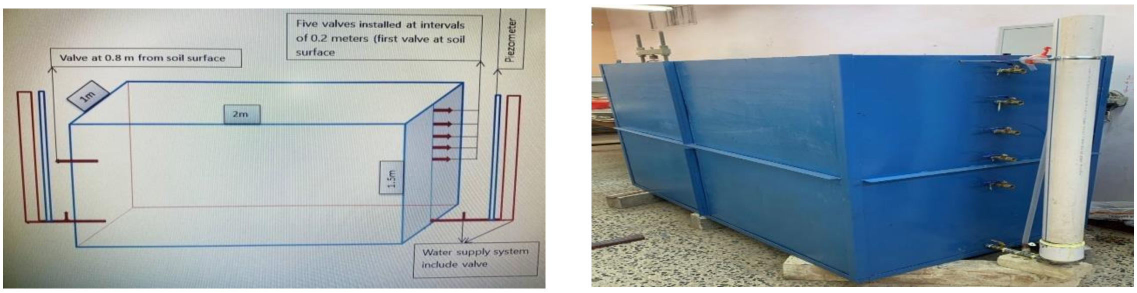
| Characteristic | | Magnitude | Reference |
|---|---|---|---|
| Specific gravity | GS | 2.65 | ASTM D-854 |
| Water content | WC, % | 15.5 | ASTM D-2216 |
| Particle size distribution by wet sieving, (%) | Sand% 0.075-4.75 mm | 100 | ASTM D-422 |
| D10, (mm) | D10 | 0.1 | |
| D30, (mm) | D30 | 0.173 | |
| D60, (mm) | D60 | 0.245 | |
| Coefficient of uniformity | Cu | 2.45 | |
| Coefficient of curvature | Cc | 1.221 | |
| Classification of soil | USCS | SP | ASTM D-2487 |
| Maximum dry unit weight (KN /m3) | γd(max) | 17.7 | ASTM D-4253 |
| Minimum dry unit weight ((KN /m3) | γd(min) | 14.0 | ASTM D-4254 |
| Dry unit weight at (RD = 60 %), kN/m3 | γd | 16.0 | |
| The angle of internal friction | ϕ | 35.5° | ASTM D-3080 |

**Preparation of Secant Pile Wall Model**

The secant pile wall, frequently employed in engineering applications, was chosen as the prototype for a model test to verify its practical suitability. The selected prototype dimensions for this investigation were designed with a diameter of 1 meter, a length of 20 meters, and an overlapping width of 0.15 meter. These measurements were intentionally chosen to represent common engineering methods accurately. In order to reduce the size of the prototype for the model test, a material property ratio of 1 and a geometric size ratio of 1/15 were established. The choice of a 1/15 scale was made based on available resources and practical considerations. The full-scale model was quite large, and testing it at a smaller scale was necessary to manage the testing process efficiently. A smaller scale reduces the model size and the effort required for tasks, like filling and saturation, which are essential for the accurate representation of soil-pile interactions in the model. As a result, the diameter of the model piles was adjusted to 0.067 m and their length to 1.333 m, with the overlapping width between the secant piles set to 0.01 m, ensuring that the model remained feasible while still replicating the behavior of the full-scale system.

**Model Preparation**

One meter in width, 1.5m in height, and 2 meters in length make up the tank domestically made. The structure comprises angle iron columns and beams and is strengthened at the corners and middle with 4-millimeter-thick steel plates. Reinforcement steel was added to further guarantee the tank's stability during inspections and while exposed to soil pressures and external stressors. The container had a water supply system on both sides, consisting of 4-inch plastic pipes connected to the tank *via* an iron pipe that was half an inch in diameter. In order to regulate the flow of water through the pipe as the earth is saturated, a valve is set up. Two piezometers were placed on either side of the tank to measure the water level in the container. Using five valves fixed along one side of the container installed at intervals of 0.2m from the surface of the soil and one valve at the other side at 0.8m from the surface, the container has been designed to simplify the process of saturation and unsaturation of the soil sample, as shown in Figure 3.




(a) (b)

**Figure 3.** (a) Sketch of the model details (b) Steel container picture

**Measuring Devices Used in the Test**

Table 2 lists the measuring devices used in the test to measure the soil's moisture content, displacement, matric suction, and total stresses to determine the impact of the wall's dropping water level. The model was prepared for testing as follows:

**Table 2.** Sensors and tools

| Sensors and tools | Purpose |
|---|---|
| RP-S40-ST Thin Film Pressure Sensor 40mm x 40mm | Measuring total stress |
| RK520-01 soil moisture and temperature | Measuring both the moisture content and the temperature of the soil |
| F252 Pancake Load cell | Measuring total stress |
| Tensiometer (IRROMETER) | Measuring matric suction |
| Dial Indicator with Magnetic Base 0-10mm | Measuring displacement |

1) **Filter Layer Addition**: A 100-millimeter-thick filter layer was added to the tank's base to let the soil become saturated with water from both directions.
2) **Layer Preparation**: The soil sample was prepared with six layers to ensure uniform density. Each layer was 0.2 m thick with a net surface area of approximately (1.0x0.965) m on both sides of the wall. In order to confirm density during compaction, soil samples were obtained using a circular iron mold.
3) **Total Stress Sensors' Installation**: Aluminum pieces, each 150 cm long, were installed on both sides of the wall, and the sensors were firmly mounted onto these pieces. This was carried out, because the semi-cylindrical shape of the wall made it difficult to install the sensors directly onto its surface. To protect the sensors and their connecting cables from water—which could negatively affect the accuracy of the readings—the aluminum pieces, the sensors, and the connection network were all carefully wrapped with a layer of light-weight nylon. This nylon covering acts as a waterproof barrier, ensuring that the sensors remain dry and providing reliable and consistent readings.
4) **Water Saturation**: Following soil compaction, a pipe system with fittings on both sides was used to saturate the models with water. It employed a 6-mm diameter steel tube that was connected to the box by a valve located at the bottom (50 mm from the base). A rigid plate foundation model with dimensions of (0.5 x 0.4 x 0.03) m and a load of 1.33 kN was placed on the soil surface. This load was calibrated to correspond to a stress of 100 kPa, which aligns with the typical bearing capacity values used for the soil under consideration.
5) The steps of model preparation are depicted in Figure 4. The final model layout is also depicted in Figure 5. The tested parameters were the depth of the excavation and the water level, as well as how much each parameter affects the behavior of the secant pile wall. Figure (6) depicts the experimental application of these conditions in the laboratory.

(a) Filter covered with a perforated steel plate

(b) Secant pile wall installed it inside the model

(c) Soil compacted

(d) Rigid plate on the soil surface

**Figure 4.** The stages of model preparation

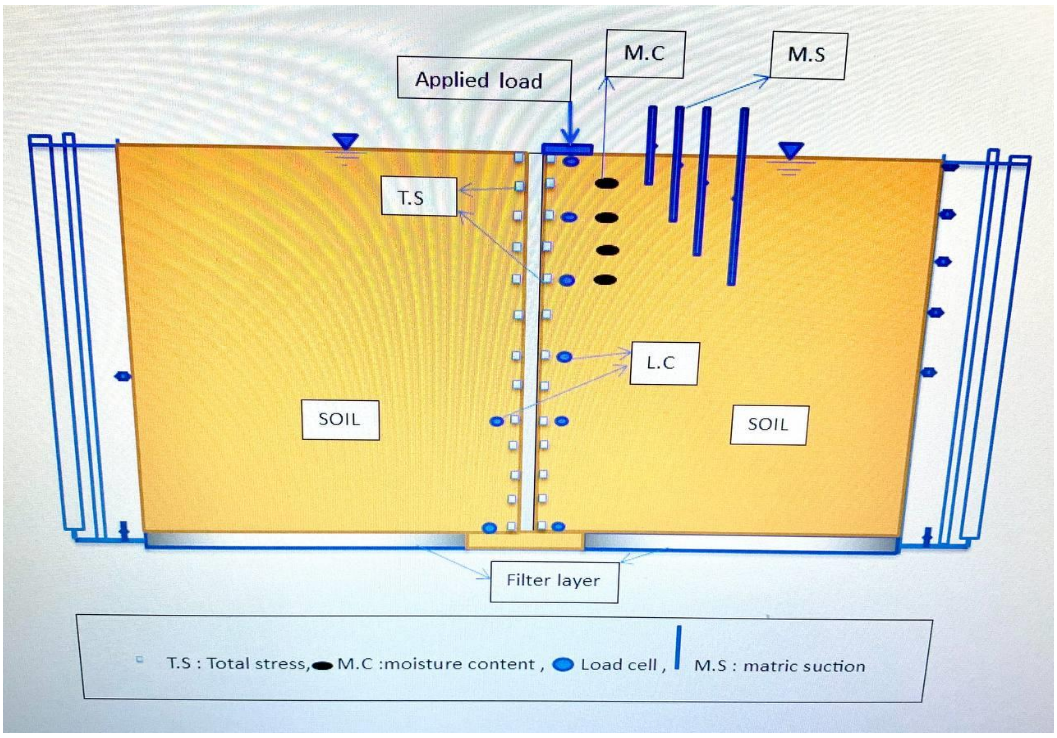



**Figure 5.** Schematic view of distribution of sensors in the models

a) Excavation depth equal zero

b) Excavation depth equal 0.4 m

c) Excavation depth equal 0.6 m

d) Excavation depth equal 0.8 m

**Figure 6.** Overview of model test results

## TESTS RESULTS

### - Total Stress Measurement

Figure 7 depicts the fluctuation in influencing pressures as water levels change. Figure 8 illustrates how the resistive pressures change as the water levels vary. The statistics and their visual representations indicate that when the water level decreases, the total pressures exerted on the active side that contribute to the situation decrease, while the total pressures that oppose the change increase. As the matric suction increases, the soil's cohesiveness and internal friction angle exhibit a non-linear increase. The references cited include Heni Pujiastuti's work from 2018 and Elsharief AM and Abdulaziz OA's work from 2015.

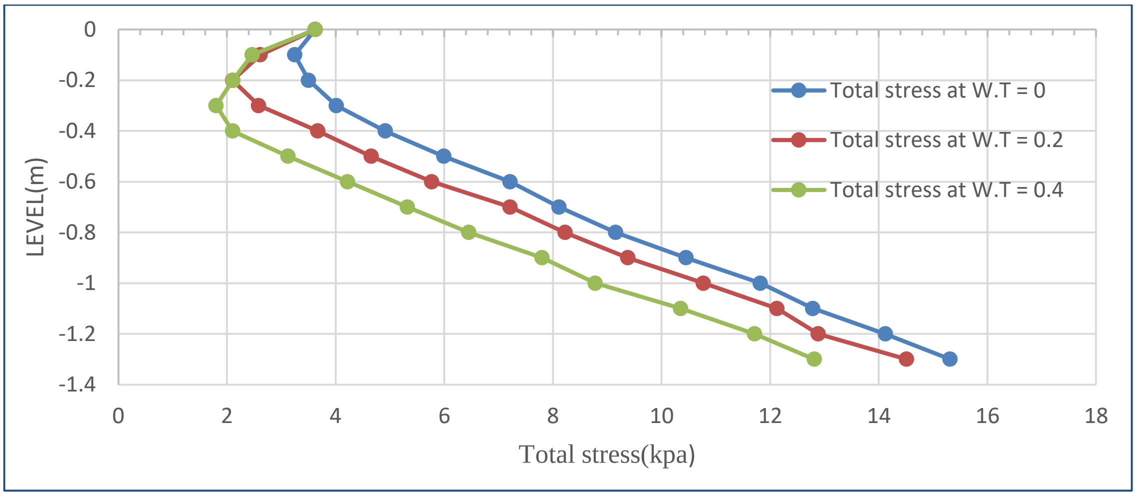



**Figure 7.** Total active stress and water table level relationship at an excavation depth = 0.2m

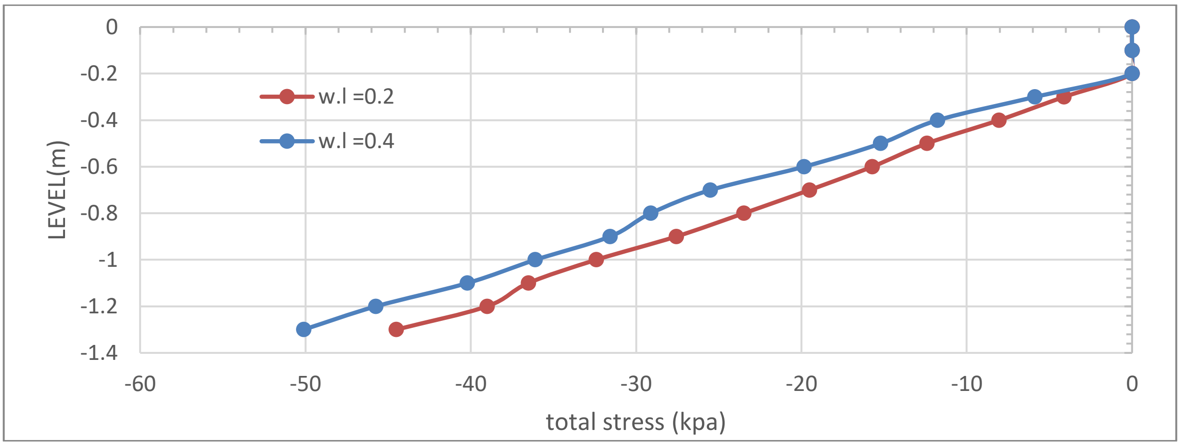



**Figure 8.** Total passive stress and water table level relationship at an excavation depth = 0.2m

**- Horizontal Deflection and Vertical Displacement**

In order to keep the wall stable during excavation, it is essential to determine the horizontal displacement at the top of the wall. In addition, seepage from neighboring building foundations can occur, especially in sandy soil conditions due to the dewatering process. In this investigation, we measured the settlement at the nearby foundation and monitored the horizontal displacement at the top of the wall using the dial indicator. Results for horizontal displacement are shown in Figure 9. Figure 10 shows the results of settlement at the nearby foundation. The data shows that by lowering the water level, there is little horizontal displacement at the wall top, but it grows as the excavation depth increases. This is because when the water level decreases, the lateral pressures also decrease. This is because water exerts a great deal of pressure on the wall, which is reduced as the water recedes.

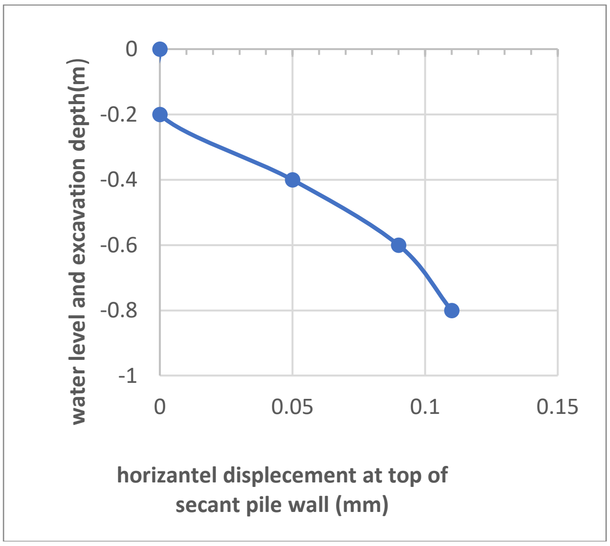



**Figure 9**. Horizontal displacement with depth of excavation and water level relationship

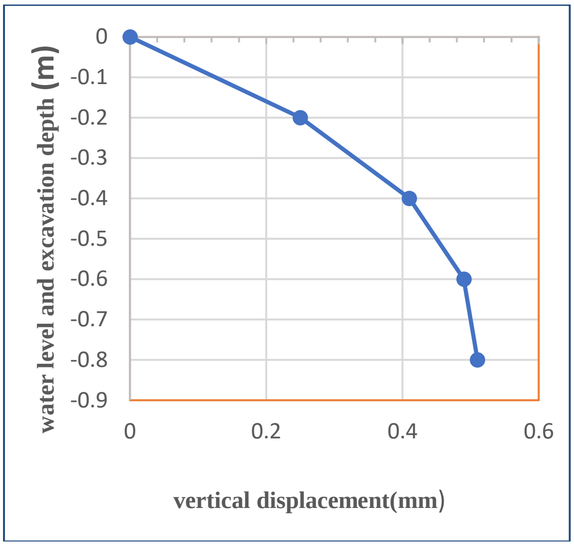



**Figure 10.** Vertical displacement at the adjacent foundation

Moreover, the findings indicate that the vertical displacement (also known as the settlement) derived from the neighboring foundation is greater than the horizontal displacement. This settlement is associated with decreasing water content in the sandy soil. Leakage in saturated sands will almost certainly result in the inflow of a sand-water combination that will cause sinkholes behind the wall and scour (M. Korff, 2006).

**- Soil Water Characteristic Curve (SWCC)**

The Soil-Water Characteristic Curve (SWCC) is a crucial concept in unsaturated soil mechanics, as it illustrates the relationship between soil water content and matric suction. This curve is essential for understanding how water behaves in soils under unsaturated conditions, which is significant for a wide range of geotechnical and environmental applications. In our study, we lowered the water level to depths of 0.2, 0.4, 0.6, and 0.8m, and measured matric suction at the midpoint of each depth, along with the corresponding water content. This data allows for the characterization of unsaturated soil behavior and provides the foundation for developing accurate models of soil-water interactions. In SWCC, several models have been introduced in the last few decades. A number of soil types' Soil-Water Characteristic Curves (SWCCs) can be described using the van Genuchten model (1980). The estimation of fitting parameters of (vG**)** model was carried out using the particle size distribution data and using the capabilities of Genetic Programming (GP). Tree structures consist of a set of functions (such as the mathematical functions used in equations) and a set of terminals (that is, variables of a problem and constants) (A. Taban, 2017).

Figure 11 illustrates the variations in suction with respect to the degree of saturation, comparing the results predicted by the GP model, as well as those obtained by van Genuchten model and Benson's PTFs (pedo transfer functions, 2014) for sand soil. This comparison highlights the importance of accurate modeling for predicting unsaturated soil behavior. The SWCC and these predictive models are critical for understanding soil’s water retention and drainage properties, which are vital for engineering applications such as foundation design, slope stability analysis, and water management systems.

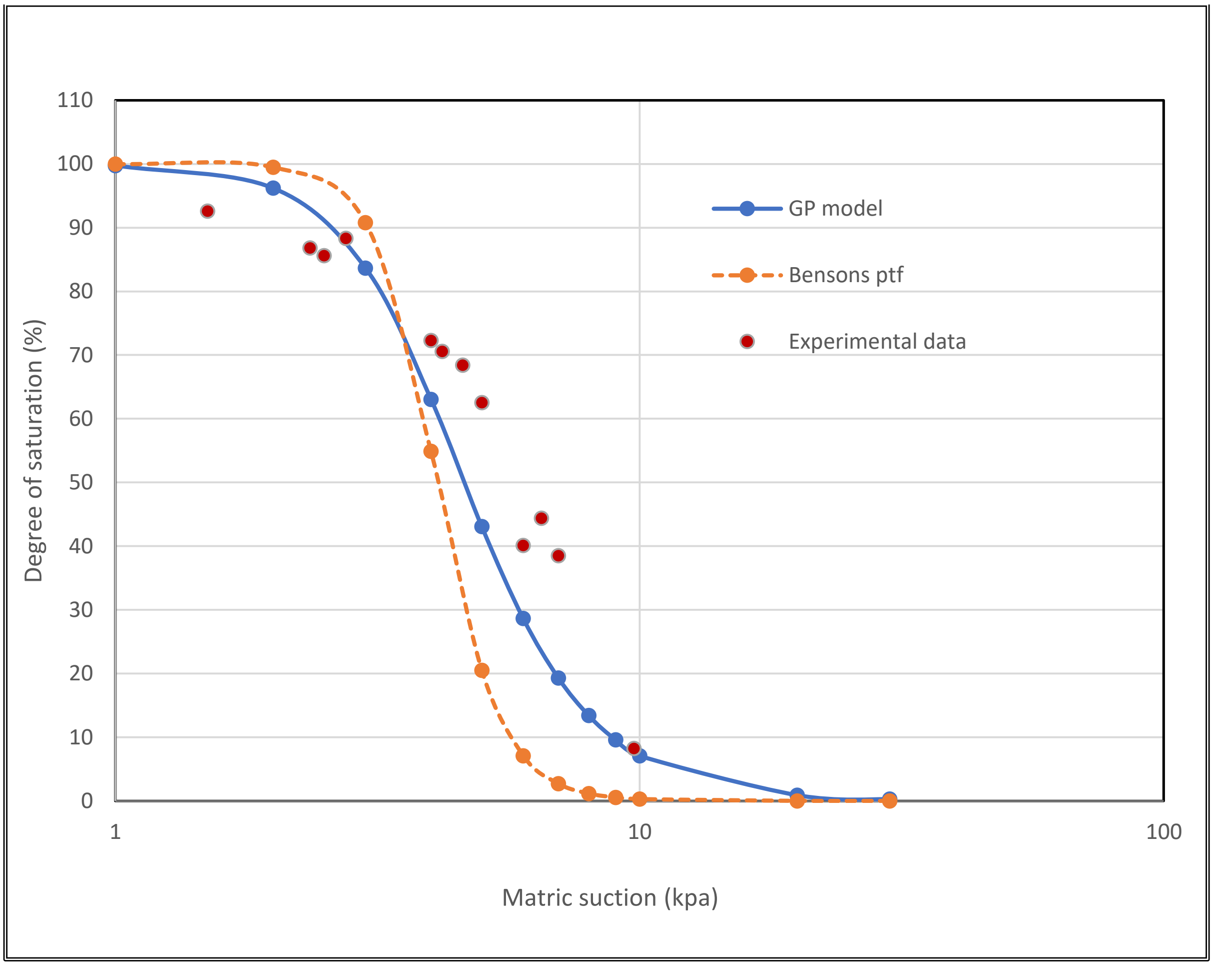



**Figure 11.** SWCC predicted by the GP model equations and Benson's PTF prediction compared with the experimental data for a sand sample

## CONCLUSIONS

The present research studies the behavior of secant pile walls in supporting excavation in sandy soil with lowering water level. The following conclusions have been drawn from the deep excavation analysis using a secant pile wall with lowering water level:

1) Total lateral earth pressure in the active side with lowering water level decreases and total lateral earth pressure in the passive side with lowering water level increases.
2) Decreasing the water level results in increased vertical displacement in the adjacent foundation.
3) The findings suggest that reducing the water level makes the secant wall and excavation work safer. However, this reduction has an adverse effect on the nearby buildings because of the increased foundation settlement.

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