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Evaluating pile foundation design due to groundwater level lowering

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ABSTRACT

In Viet Nam, ground subsidence has been occurring at an alarming rate, raising concerns for pile foundation design. This issue is primarily caused by excessive groundwater extraction for water supply, irrigation, aquaculture, and other uses. Thus, in this study, the evaluation of pile capacity due to groundwater level (GWL) lowering as a preliminary guideline for structures is proposed. This study analyzed different cases of GWL lowering from 0 m to 2 m, and pile size varied from 18 x 18 cm to 45 x 45 cm, to evaluate the allowable bearing capacities for single piles and pile groups. The results indicated that when lowering the GWL from 0 to 2 m, the allowed bearing capacity varied by 5.75–174.70 tons for single piles and 11.95–808.18 tons for pile groups. Besides, when the pile size increased, the bearing capacity increased in the range of 6.38–41.46 tons (size 18 x 18 cm) to 16.30–174.70 tons (size 45 x 45 cm) for a single pile and 11.95–191.81 tons (size 18 x 18 cm) to 33.49–808.18 tons (size 45 x 45 cm). The result of this study underscores the significance of predicting the bearing capacity of pile foundations due to the variation in groundwater level.

1. INTRODUCTION

Traditionally, the design has followed the 'piled foundation' concept, where all building loads are supported by piles. A proper evaluation of soil-structure interaction is crucial to ensure rational and effective design solutions for both the superstructure and the pile foundation. However, the land subsidence phenomenon is caused by a change in GWL, which mainly affects the piled foundation (Znamenski et al., 2021; Amornfa et al., 2023). For example, considering the preference for minimizing building settlement and potential gap formation underneath the pile cap in the long term, the design includes bearing resistance below the large-area pile cap and the occurrence of negative friction on the side surfaces of piles (Amornfa et al., 2012). Following that, there was an upward movement of the ground (Nikos et al., 2016; Wang et al., 2017), and a loss of foundation bearing capacity (Shahriar et al., 2013).

Several studies have been conducted to investigate pile-soil behavior and the capacity change of pile foundations with increasing GWL. For example, Armishaw and Cox (1980) proposed full-scale studies on ten driven piles in sand and gravel under controlled water pressure within well neighborhoods. Their findings revealed that ground movements corresponded to changes in water level, but pile movements with working loads of more than 50% of the ultimate load continuously settled with increasing pore pressures. Roh et al. (2019) using numerical methods for evaluating capacity in deep foundations with a change in groundwater level, derived the load–settlement curve and the axial load capacity of the piled–raft foundation, indicating that the static GWL affected the depth at which piled rafts were controlled. Although the capacity of a deep foundation was evaluated, the soil deformation and the groundwater levels did not consider changes in time, as in real-life situations. Recently, Saowiang and Giao (2021) used the finite element method was employed to assess soil deformation, pore-water pressure, and changes in effective stress resulting from long-term groundwater extraction and subsequent recovery in Bangkok aquifers; however, the pile structure was excluded from their numerical model. These analyses, however, indicated the changes in pore water pressure and effective stress over time, as well as the association between effective stress and undrained shear strength, which was utilized to estimate pile capacity reduction. In Viet Nam, industrialization and urbanization have driven a rapid increase in groundwater pumping, resulting in ground subsidence and affecting the infrastructure in general and the foundation of buildings in particular (Minh et al., 2015). Furthermore, the settlement of the foundation increased more when the GWL lowered over time, and the negative transfer of load from the pile to the soil (negative skin friction) occurred due to the subsidence (Amornfa et al., 2023).

This paper aims to evaluate the comprehensiveness of pile foundation design caused by GWL lowering. As a result, the evaluation of pile capacity due to GWL lowering preliminary guideline for structures is proposed.

2. MATERIALS AND METHOD

2.1. Analysis steps

Firstly, the soil parameters were collected from the laboratory (Figure 1). The samples were tested in the laboratory to ASTM and AASHTO standards.

The properties of the soil layers are shown in Table 1. The strength parameters of medium stiff clay and stiff clay were found to be are relatively low due to the soil's high plasticity to low plasticity. For medium stiff clay (Liquid Limit (LL) = 43.35–67.56%; Plasticity Index (PI) = 16.09–30.71%), and stiff clay (LL = 44.04–68.20%; PI = 26.63–38.92%).

After the soil parameters were calulcated, the calculation of the pile foundation was processed. Finally, the proposed optimal cases were carried out using the proposed foundation design concept.

Figure 1. Soil samples

2.2. Concepts of the design pile foundation

According to (Das, 2018), the ultimate load-carrying capacity Q_u of a pile is given by the equation (1):

$$Q_u = Q_p + Q_s \quad (1)$$

where

$Q_p =$ load carrying capacity of the pile point (Equation 2)

$Q_s =$ frictional resistance (skin friction) derived from the soil–pile interface (Equation 3)

$$Q_p = A_p q_p = A_p\left(cN_c + q'N_q\right) \quad (2)$$

where

$A_p =$ unit point resistance

$q_p =$ the ultimate resistance per unit area developed at the pile tip

$c =$ cohesion of the soil supporting the pile tip

$q' =$ effective vertical stress at the level of the pile tip

$N_c, N_q =$ the bearing capacity factors

$$Q_s = \Sigma(p\Delta Lf) \quad (3)$$

where

$p =$ perimeter of the pile section

$\Delta L =$ incremental pile length over which p and f are taken to be constant

$f =$ unit friction resistance at any depth (Equations 4 and 5)

$$f = (K \tan\delta)\sigma_v' \quad \text{for sandy soil} \quad (4)$$

$$f = \alpha c \quad \text{for clayey soil} \quad (5)$$

where

$K =$ earth pressure coefficient

$\delta =$ soil pile friction angle

$\sigma_v' =$ effective vertical stress at depth under consideration

α = empirical adhesion factor

The equations are theoretically sound, as they are described in all foundation engineering books. However, the calculation depends on the accuracy of soil parameter determination (e.g., N_q, α, and $K \tan \delta$), which are affected by many factors.

The pile foundation was designed with prestress concrete piles. The single pile has a varied depth of pile cap, about 1.0 m to 3.0 m. The pile group (2 piles to 6 piles) and the depth of the pile cap are equal to 1m. The GWL varies from the surface to 2 m below the surface. The design of the pile size is shown in Table 2.

2.3. Modification of bearing capacity equations for GWL

According to (Das, 2018), if the groundwater table (GWT) is close to the foundation, some modifications of the bearing capacity equations will be necessary (Figure 2).

Case I. If the GWT is at a depth equal or less than D_f $(0 \leq D_1 \leq D_f)$ the factor q in the bearing capacity equations takes the form

$$q = \gamma D_1 + D_2(\gamma_{sat} - \gamma_w) \qquad (6)$$

where

q = effective vertical stress at the level of the pile tip

γ_{sat} = saturated unit weight of soil

γ_w = unit weight of water

Also, the value of γ in the last term of the equations has to be replaced by $\gamma' = \gamma_{sat} - \gamma_w$

Case II. If the GWT is at the depth equal to or less than B $(0 \leq d \leq B)$

$$q = \gamma D_f \qquad (7)$$

D_f = depth of foundation measured from the ground surface

In this case, the factor γ in the last term of the bearing capacity equations must be replaced by the factor.

In this case, the factor γ in the last term of the bearing capacity equations must be replaced by the factor

$$\bar{\gamma} = \gamma' + \frac{d}{B}(\gamma - \gamma') \qquad (8)$$

The preceding modifications are based on the assumption that there is no seepage force in the soil.

Case III. If the GWT is at a depth equal to or less than d $(d \geq B)$, the water will have no effect on the ultimate bearing capacity.

Table 1. Properties of subsoils

Soil description	SPT N-value (Blow/ft)	Thickness (m)	Unit weight (t/m^2)	Strength parameter		
				S_u (kg/cm^2)	c(kPa)	ϕ (degree)
Fill soil	-	3.0	3.10	0.82	-	-
Medium stiff clay	9	3.5	5.03	-	36	-
Stiff clay	11	3.5	7.22	-	44	-
Medium sand	26	2.5	9.31	-	-	31.65
Dense sand	35	4.5	12.10	-	-	32.57
Very dense sand	99	3.0	15.10	-	-	40.20

S_u = undrained shear strength, ϕ = Friction angle, c = cohesion of soil

Table 2. Design of pile foundation

Size of solid square pile, B (cm)	Area (cm^2)	Perimeter (cm)	Unit weight (kg/m)	Maximum length (m)
18 x 18	324	72	78	14
22 x 22	484	88	116	21
26 x 26	676	104	162	21
30x30	900	120	216	23
35x35	1,225	140	294	24
40x40	1,600	160	384	25
45x45	2,025	180	486	28

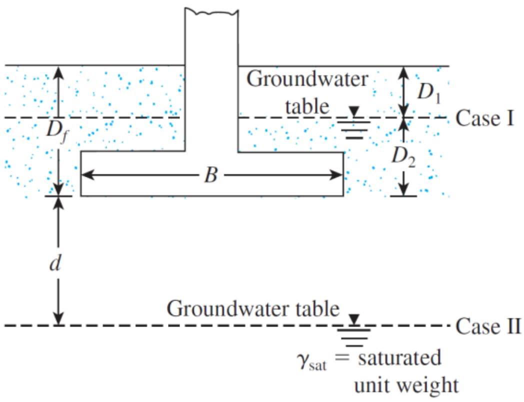


Figure 2. Modification of bearing capacity equations for groundwater table (Das, 2018).

3. RESULTS AND DISCUSSION

3.1. Single pile capacity

As shown in Figures 3 to 5, when GWL was lowered from 0 to 2 m, the allowable bearing capacity increased in the range of 5.75–174.70 tons (GWL = 0 m: 5.75–172.19 tons, GWL = -1 m: 5.75–173.35 tons, GWL = -2 m: 5.75–174.70 tons). The bearing capacity of the foundation decreases as the GWL cycles increase. The increased of the GWL reduces the foundation's bearing capacity. Thus, the GWL has an impact on bearing capacity, however it is not considerable.

The bearing capacity increased when pile size increased (size 18 x 18 cm: 6.38–41.46 tons, size 22 x 22 cm: 7.17–55.82 tons, size 26x26 cm: 8.64–72.05 tons, size 30 x 30 cm: 10.16–90.16 tons, size 35 x 35 cm: 12.13–115.43 tons, size 40 x 40 cm: 14.17–143.60 tons, and size 45 x 45 cm: 16.30–174.70 tons). In addition, the depth of the foundation (D_f) was measured from the ground surface (D_f = -1 m, size 18 x 18 cm to 45 x 45 cm: 6.38–174.70 tons; D_f = -2 m, size 18 x 18 cm to 45 x 45 cm: 6.06–171.52 tons; D_f= -3 m, size 18 x 18 cm to 45 x 45 cm: 5.75–168.33 tons), the bearing capacity decreased.

It is clear that the bearing capacity values depend on the lowering of the GWL, the pile size, and the depth of the foundation. The bearing capacity increased when the GWL was lowered. When the pile size increased, the bearing capacity increased. And when the depth of the foundation increased, the bearing capacity decreased.

3.2. Pile group capacity

As illustrated in Figures 6–8, lowering the GWL from 0 to 2 m increases the allowable bearing capacity by 11.95–808.18 tons (GWL = 0 m: 11.95–796.57 tons, GWL = -1 m: 11.95–801.90 tons, and GWL = -2 m: 11.95–808.18 tons).

The result shows that the bearing capacity of the foundation decreases with the rise of the GLW, which can result in additional settlement of the foundation. The bearing capacity is affected by GWL; however, the effect is minor.

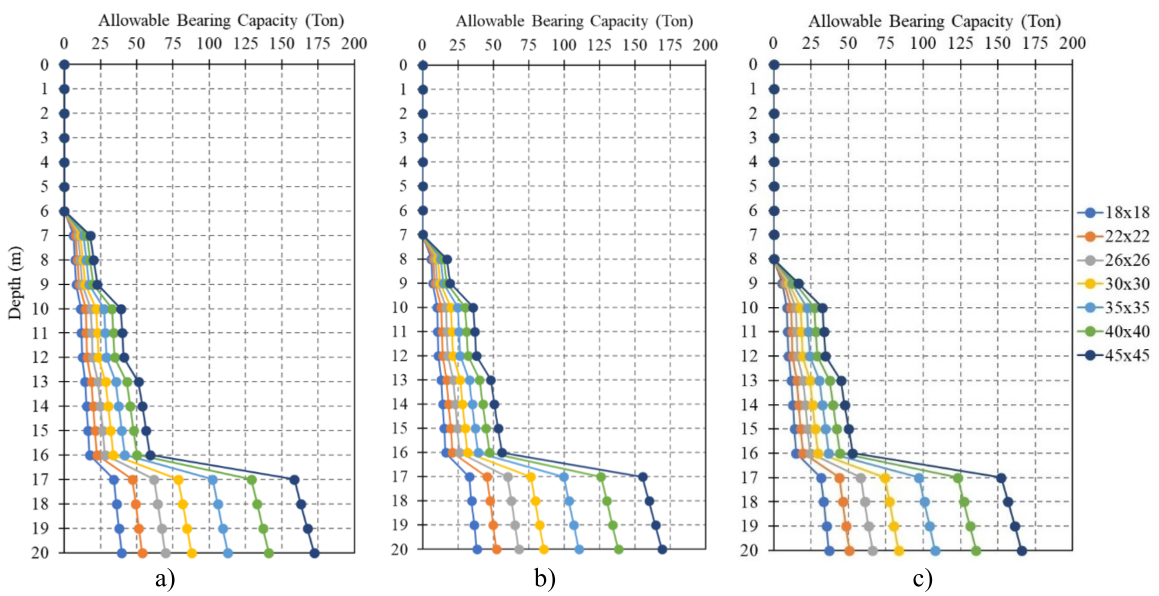
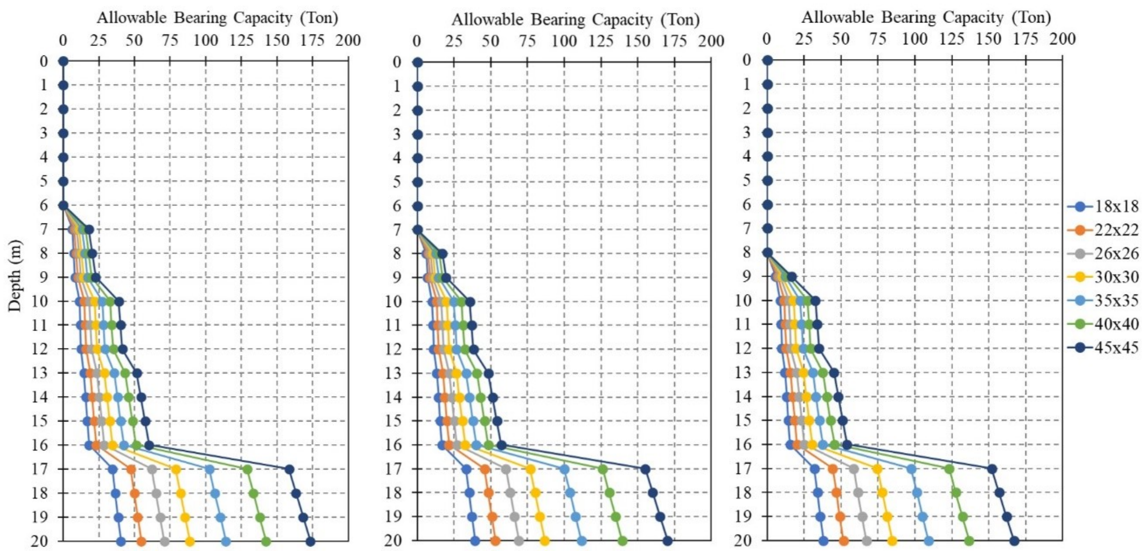
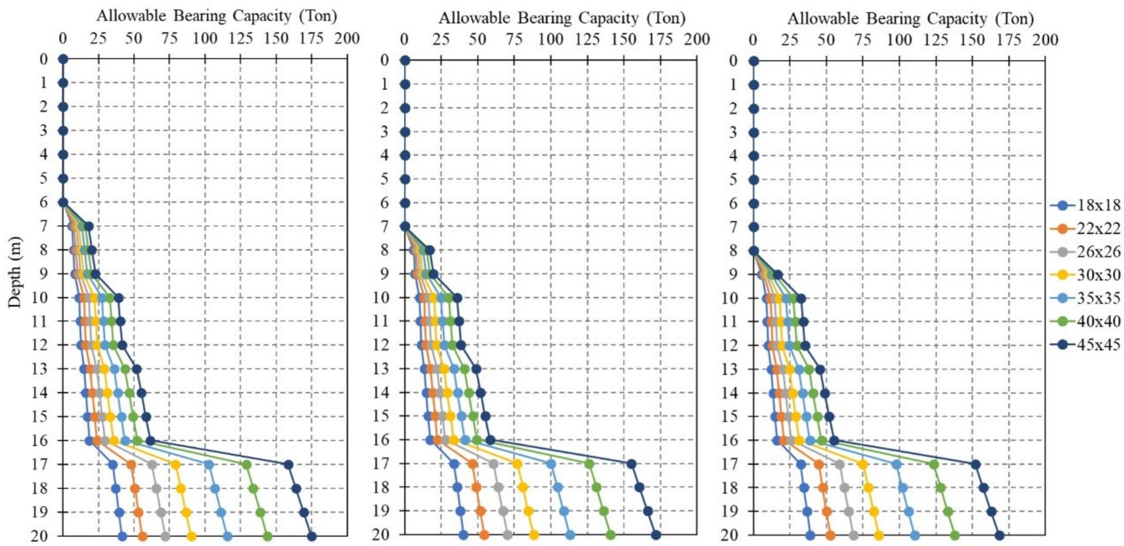


Figure 3. Relationship between the allowable bearing capacity of a single pile and the depth of the pile tip at GWL = 0 m: a) Pile cap = -1 m, b) Pile cap = -2 m, c) Pile cap = -3 m



a) b) c)

Figure 4. Relationship between the allowable bearing capacity of a single pile and the depth of the pile tip at GWL = -1 m: a) Pile cap = -1 m, b) Pile cap = -2 m, c) Pile cap = -3 m



a) b) c)

Figure 5. Relationship between the allowable bearing capacity of a single pile and the depth of the pile tip at GWL = -2 m: a) Pile cap = -1 m, b) Pile cap = -2 m, c) Pile cap = -3 m

Besides, with the increase in pile number (2 piles to 6 piles), the allowable bearing capacity increased (2 piles: 11.95–327.57 tons, 3 piles: 16.74–458.60 tons, 4 piles: 20.73–568.13 tons, 5 piles: 25.50–698.81 tons, 6 piles: 29.49–808.18 tons). Moreover, the pile's allowable bearing capacity increased when the pile size increased from 18x18 cm to 45 x 45 cm (size 18 x 18 cm: 11.95–191.81 tons, size 22 x 22 cm: 14.87–258.24 tons, size 26 x 26 cm: 17.89–333.34 tons, size 30 x 30 cm: 20.99–417.07 tons, size 35 x 35 cm: 25.01–533.91 tons, size 40 x 40 cm: 29.18–664.28 tons, and size 45 x 45 cm: 33.49–808.18 tons).

The behavior of a single pile varies from that of an individual pile in a group. A pile group can be a cluster of piles where the group effect governs all directions of load and movement. To avoid the difference in settlement between pile cap contact ground and pile cap above ground, the pile groups should be calculated independently to choose a reasonable embedment length of the pile.

3.3. Discussion

In this study, the unit friction resistance was calculated using Equation (5); however, its accuracy in clayey soils remains limited due to the empirical adhesion factor, which is difficult to determine. The adhesion factor, which reflects the ratio between the cohesive and adhesive strengths of clay under different water contents, varies heavily, depending on the local water content. Moreover, in soft soil layers, piles are frequently loaded laterally by horizontal soil movements.

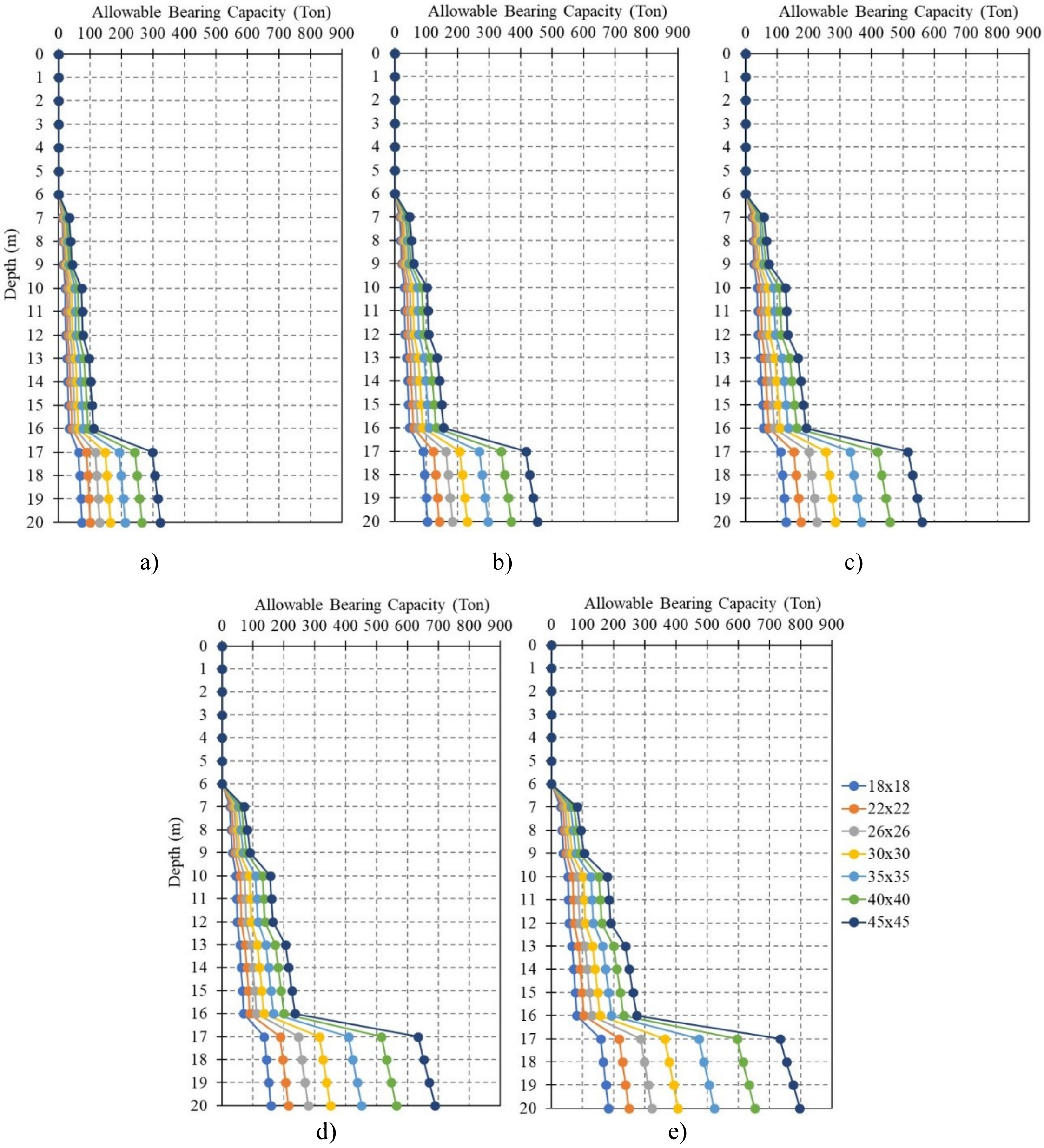


Figure 6. Relationship between allowable bearing capacity of piles with depth of pile tip (pile cap = -1 m, GWL= 0 m): a) Pile number = 2, b) Pile number = 3, c) Pile number = 4, d) Pile number = 5, e) Pile number = 6

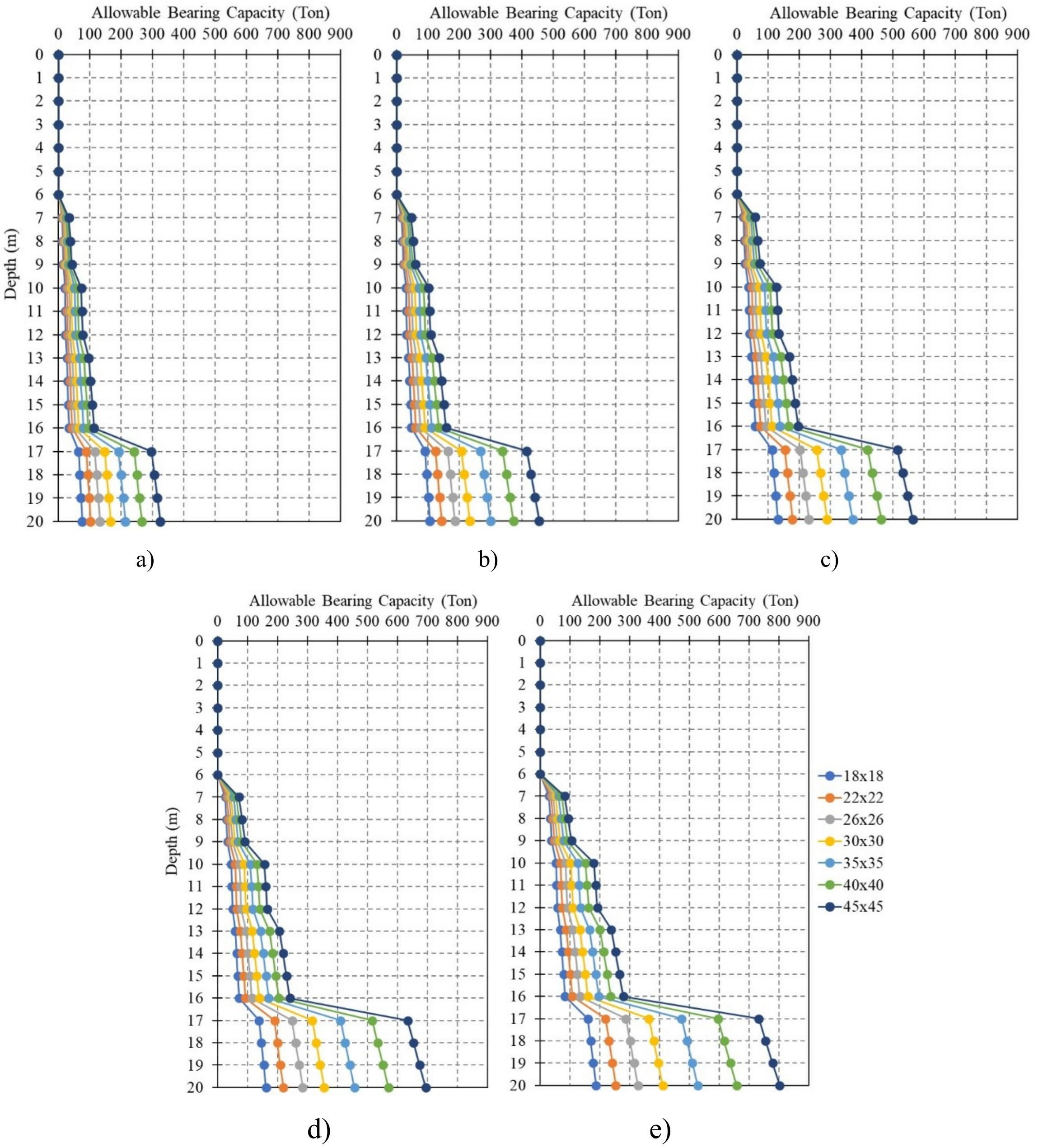


Figure 7. Relationship between allowable bearing capacity of piles with depth of pile tip (pile cap = -1 m, GWL= -1 m): a) Pile number = 2, b) Pile number = 3, c) Pile number = 4, d) Pile number = 5, e) Pile number = 6

As a result, in many cases, the lateral pressure acting on piles caused by horizontal soil movements can be measured empirically or analytically using model tests and numerical simulation-based methods, respectively.

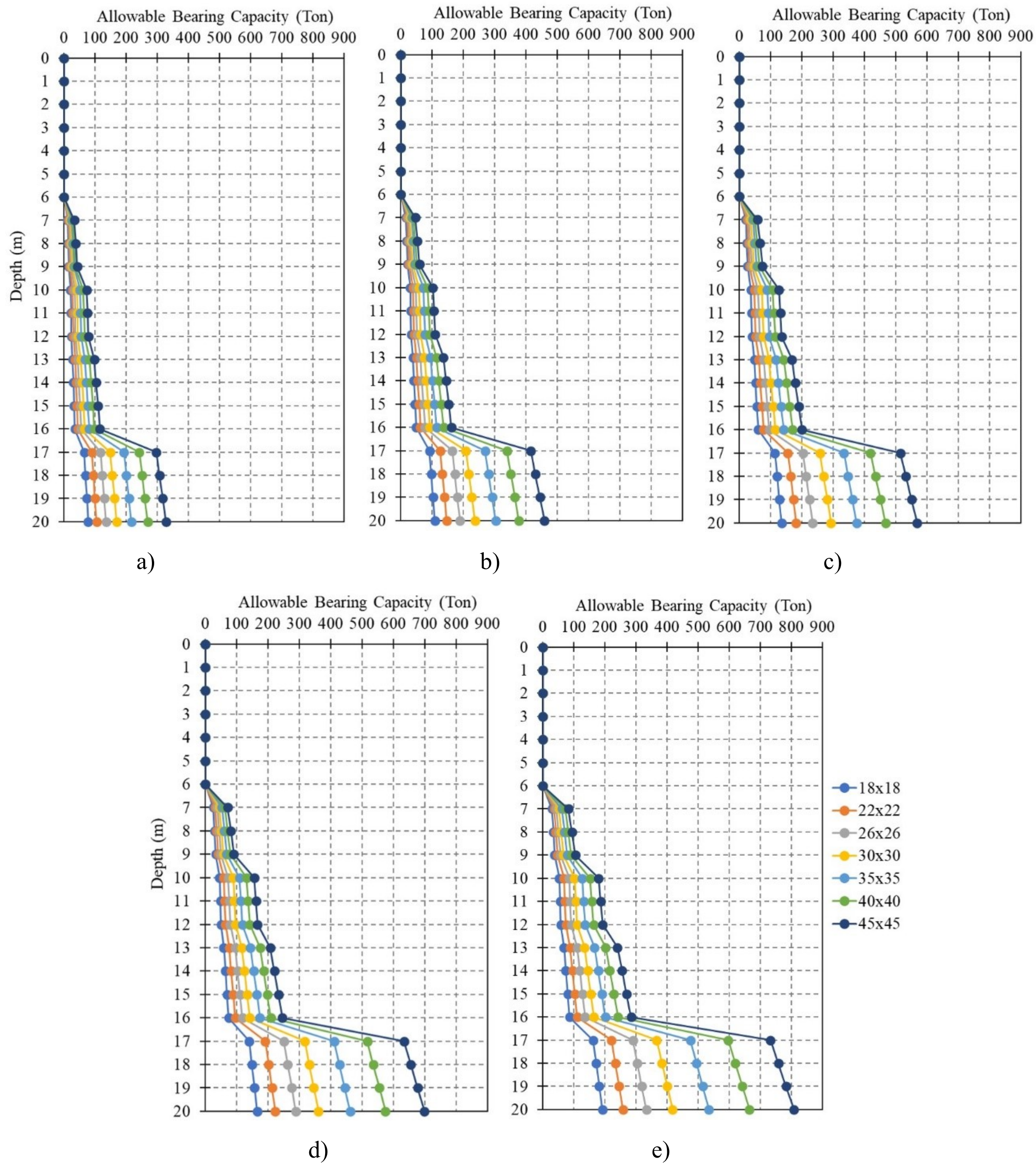


Figure 8. Relationship between allowable bearing capacity of piles with depth of pile tip (pile cap = -2 m, GWL= -1 m): a) Pile number = 2, b) Pile number = 3, c) Pile number = 4, d) Pile number = 5, e) Pile number = 6

The allowed bearing capacity depends on the load-carrying capacity of the pile point and the frictional resistance derived from the soil-pile interface. To increase the allowed bearing capacity, the pile tip should be located in strong soil layers. As a result, depending on the depth and properties of the soil, the frictional resistance derived from the soil-pile interface will change. Therefore, this study proposes using regression analysis to measure the level of correlation between the depth of pile tips and the allowed bearing capacity in different cases.

The bearing capacity of the soil layer was shown to be dependent on the GWL, which should be considered in foundation design since reducing the GWL could affect pore-water pressure in the aquifer, reduce effective stresses in the soil layers, and affect soil strength. For example, a change in GWL will change the effective stress in the foundation soil, causing settlement of the soil foundation; the seepage flow created by GWL will cause seepage force and increase the pore-water pressure of soil, which will directly affect the stability and safety of buildings and their foundations; and the change in GWL will result in a change in soil moisture content, which will affect the mechanical properties of the soil and cause a change in the bearing capacity of the foundation soil. Pumping will lead to a reduction in GWL, resulting in foundation soil consolidation and uneven building settlement, etc. Currently, ground subsidence has happened because of the GWL alteration, which has impacted the foundation in particular and the infrastructure in general. For example, lowering the GWL leads to the development of negative friction and axial forces in the pile, which should be considered while designing pile foundations in soft soils in areas with the problem of GWL lowering. Furthermore, if GWL pumping cannot be managed in the future due to fast urbanization, industrialization, and population growth, the building industry will face a slew of problems. Charging and other rules for groundwater exploitation are required to support sustainable management.

Our study's findings on the bearing capacity of pile foundations when lowering GWL are the primary step when compared with broader research on the behavior of piles across the world (Znamenski et al., 2021; Amornfa et al., 2023). The most important problem is due to the lowering GWL, the bearing capacity of the existing piles could be reduced significantly due to development of the negative skin friction (Znamenski et al., 2021). Therefore, the significant effect of lowering the GWL on the development of negative friction and axial forces in the pile should be carefully considered during the design process.

4. CONCLUSIONS

In pile foundation design, the bearing capacity of the foundation decreases as groundwater level fluctuations increase. However, by increasing the size of the pile, the allowable bearing capacity can be enhanced. From the case of size 40 x 40 to 45 x 45 cm, the allowable bearing capacity is the most significant increase. In the same way, when the pile tip was put in more and more depth, the allowable bearing capacity increased. The GWL affects the bearing capacity, but it is not significant. The settlement of pile foundations in this research was ignored. Because the hard soil layer is not too deep, around 13 m in depth. Therefore, we proposed that the pile tip should be in this layer. The GWL may influence foundation design. A high GWL could strain the foundation, causing it to fracture or collapse. If the GWL is too low, the foundation may be inadequately supported, resulting in fracture or collapse. If the soil drains efficiently and there is a relatively low GWL, it may not be problematic. However, if the soil is dense and absorbent and the GWL is high, the ground around a home may swell and become saturated. In general, this research can be used to estimate and design the bearing capacity of soil with changing GWL. However, in the future, the next research should use numerical modeling to achieve more accurate results by setting up boundary conditions such as pore water pressure, permeability, saturated and unsaturated soil. Consequently, in order to manage the groundwater level extraction for the safety of the project and construction, people need to give it due attention and take the appropriate action.

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