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Effect of groundwater fluctuation on load carrying performance of shallow foundation

Donggyu Park[1a], Incheol Kim[2b], Garam Kim[2b] and Junhwan Lee[*2]

[1]*Dongah Construction Industrial, 85, Gwangnaru-ro 56-gil, Gwangjin-gu, Seoul 05116, Republic of Korea, School of Civil and Environmental Engineering, Yonsei University, Seoul, Republic of Korea*
[2]*School of Civil and Environmental Engineering, Yonsei University, 50, Yonsei-ro, Seodaemun-gu, Seoul 03722, Republic of Korea*

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Abstract. The groundwater level (GWL) is an important subsoil condition for the design of foundation. GWL tends to fluctuate often with seasonal variation, which may cause unexpected, additional settlements with some reductions in the safety margin of foundation. In this study, the effects of fluctuating GWL on the load carrying and settlement behavior of footing were investigated and quantified. A series of model load tests were conducted for various GWL and soil conditions using a hydraulically-controlled chamber system. Changes in load level and rising and falling GWL fluctuation cycle were considered in the tests. Settlements during GWL rise were greater than those during GWL fall. The depth of the GWL influence zone ($d_{w,inf}$) varied in the range of 0.3 to 1.5 times footing width and became shallower as GWL continued to fluctuate. Design equations for estimating GWL-induced settlements for footings were proposed. The GWL fluctuation cycle, load level and soil density were considered in the proposed method. Changes in settlement and factor of safety with GWL fluctuation were discussed.

Keywords: groundwater level; groundwater fluctuation; footings; settlement; factor of safety

1. Introduction

The groundwater level (GWL) is an important subsoil condition that is necessary for the design of foundations. GWL tends to fluctuate with seasonal variation due to periodically varying precipitation and river stage, which may cause unexpected settlements with some reductions in the safety margin of foundation (Ausilio and Conte 2005, Morgan *et al.* 2010, Mohamed *et al.* 2013, Shahriar *et al.* 2015). This would become more seriously issued in near-river urban area and coastal zone where GWL fluctuates with clearer periodicity (Yasuhara *et al.* 2007, Ducci and Sellerino 2015, Kim *et al.* 2016). As a design guideline, it was recommended that the effect of GWL on shallow foundation is assessed if there is any potential for the seasonal variation of water level (FHWA 2010).

The fluctuation of GWL directly affects the mechanical performance of shallow foundations in both bearing capacity and settlement. The effect of GWL on the bearing capacity was investigated mainly for static groundwater condition, based on the limit equilibrium analysis, limit analysis and the method of characteristics (Vesic 1973, Chen 1975, AASHTO 1998, Reddy and Manjunatha 1997, Ausilio and Conte 2005, Park *et al.* 2017). Park *et al.* (2017) showed that the influence of GWL on the bearing capacity of footings varies with soil density and, if submerged, the bearing capacity can be 15% lower than those theoretically obtained using the limit equilibrium or limit analysis. The influence of GWL on settlements of footings has also been investigated (Agarwal and Rana 1987, Morgan *et al.* 2010, Shahriar *et al.* 2012). Agarwal and Rana (1987) showed that footing settlement under submerged condition increased by 1.95 times that for dry condition while larger variation in the range of 5.5 to 12 times dry settlement were also reported (Morgan *et al.* 2010, Shahriar *et al.* 2015). Park *et al.* (2017) proposed the coupled effect of soil density and load level on footing settlement with GWL.

The majority of the previous investigations on the GWL-related footing behavior were conducted for a fixed, static GWL condition. The condition of fluctuating GWL, which would be more critical during the rainy season, has been addressed in fewer cases with limited condition (Morgan *et al.* 2010, Shahriar *et al.* 2015). Rising and falling phases in GWL fluctuation clearly differ in the mechanical consequence with changes in soil condition and stress state (Habibagahi and Mokhberi 1998, Khalili *et al.* 2004, Lloret-Cabot *et al.* 2018). During the rising phase of fluctuating GWL, the effective stress decreases raising the issue of stability. During the falling phase of fluctuating GWL, the effective stress increases and ground settles affecting the serviceability of structural system as often observed during excavation in urban area. The soil-water characteristics for unsaturated soil condition may also be involved during GWL fluctuation, affecting yielding and volume change behavior of foundation soil (Khalili *et al.* 2004, Lloret-Cabot *et al.* 2018).

The effect of fluctuating GWL represents the cumulative characteristic of GWL-induced settlement. Influence factors

∗Corresponding author, Professor
E-mail: junlee@yonsei.ac.kr
[a]Ph.D.
[b]Ph.D. Student

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to be considered then include the rising and falling phases of GWL fluctuation, number of GWL fluctuation, depth to GWL influence zone, and the magnitude of applied load, which have not been clarified and quantified yet in detail. All these need to be further investigated to fully characterize the influence of GWL fluctuation on the load carrying behavior and long-term performance of footing.

In this study, the effect of fluctuating GWL on the load response and settlement of footing was investigated experimentally. Focus was given on the compared effects of rising and falling GWL fluctuation phases on footing settlement. An experimental testing program was established and a series of model load tests were carried out for various GWL, load and soil conditions. Hydraulically-controlled chamber system was specifically manufactured to simulate rising and falling GWLs and adopted in the model load tests. Correlations for estimating footing settlement due to fluctuating GWL were proposed.

2. Effect of GWL on load response of footing level

2.1 Quantification of footing settlement with GWL

The effect of GWL on the load carrying behavior of footing has been investigated experimentally and analytically (Ausilio and Conte 2005, Park *et al.* 2017, Shahriar *et al.* 2012, Peck *et al.* 1974). Increases in footing settlement due to GWL can be expressed as a certain ratio for dry and GWL conditions given as follows (Shahriar *et al.* 2015)

$$S_w = \frac{s_w}{s_d} = \frac{\Delta s_w + s_d}{s_d} \tag{1}$$

where S_w = GWL factor on settlement; s_d and s_w = settlements for dry and GWL conditions; and Δs_w = settlement increase due to change in GWL. According to Peck *et al.* (1974), footing embedment affects the GWL effect and S_w increases nonlinearly with GWL given by

$$S_w = \frac{1}{0.5 + 0.5\left(\dfrac{d_w}{d_f + B}\right)} \tag{2}$$

where d_w = depth of GWL; d_f = depth of footing embedment; B = footing width. Shahriar *et al.* (2015) performed the finite difference analysis and suggested the following S_w equation

$$S_w = 1 + (S_{w,\max} - 1)\left(\frac{A_w}{A_t}\right)^n \tag{3}$$

where A_w and A_t = total and GWL areas of strain influence zone; $S_{w,max}$ = the maximum S_w; and n = density factor = 0.85 and 1.10 for loose and dense conditions, respectively.

Park *et al.* (2017) conducted the model footing load tests and proposed an improved S_w correlation introducing the coupled effect of load level and soil density given as follows

$$S_w = 1 + S_{w,\max} e^{-2.2\left(\frac{d_w}{B}\right)} \tag{4}$$

$$S_{w,\max} = (2.98 - 2.7D_R)\frac{q}{q_{u,d}} + 0.6D_R \tag{5}$$

where $S_{w,max}$ = S_w value at d_w = 0 (submerged condition); d_w = depth of GWL; B = footing width; q = applied load; $q_{u,d}$ = bearing capacity for dry condition; and D_R = relative density.

2.2 Effect of fluctuating GWL condition

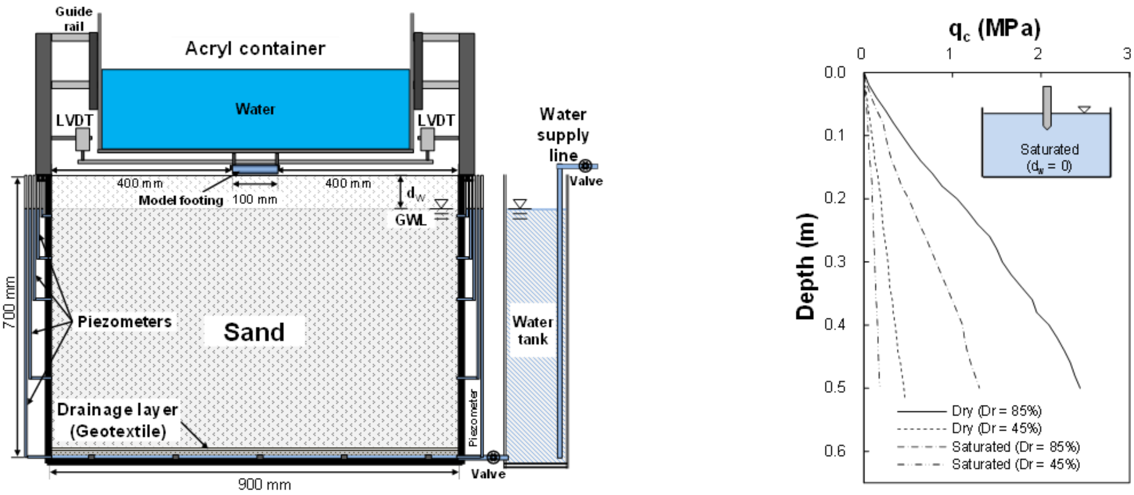
In terms of the stress state, the rising and falling phases of fluctuating GWL may be comparable to the processes of unloading and reloading, respectively, with sequential changes in the effective stress. Rising and falling GWLs are also comparable to wetting and drying processes in the soil-water characteristic relationship thereby changes in the negative pore pressure cause changes in yielding stress with additional ground settlement (Khalili *et al.* 2004). Shahriar *et al.* (2015) indicated that the effect of the negative pore pressure for footings in granular soils is small as design load is sufficiently larger than changes in the effective stress due to the negative pore pressure. The common design concept for foundation with GWL follows that rising GWL raises a stability problem because of reduced strength whereas settlement becomes issued when GWL falls due to increasing effective stress.

Morgan *et al.* (2010) and Shahriar *et al.* (2015) analyzed the effect of fluctuating GWL on footing focusing on rising phase and indicated that footing settlement with rising GWL can be 2.8 to 6.0 times larger than of fixed GWL condition. It was also reported that the influence zone for rising GWL is 5B to 6B, which were 2.5-3 times deeper than for fixed GWL condition. As GWL fluctuates often with seasonal periodicity, GWL fluctuation cycle should also be addressed. All these indicate that additional design consideration would arise when fluctuating GWL is concerned.

3. Experimental testing program

3.1 Test specimen and model foundation

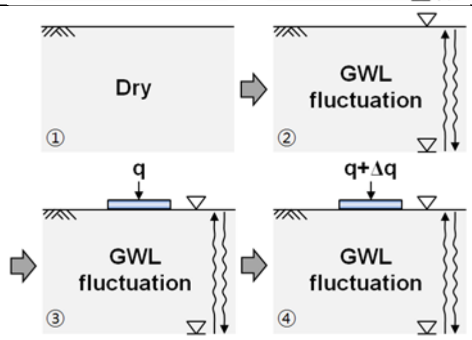
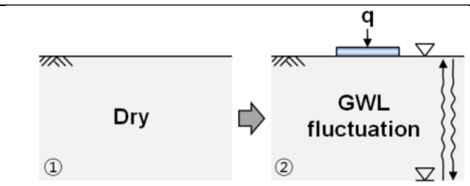
A series of model load tests were conducted to investigate the effect of fluctuating GWL on the load carrying behavior of footing for various GWL and soil conditions. A total of 11 tests were conducted using a 100×100-mm square model footing in sands within a hydraulically controlled chamber, specifically manufactured to simulate fluctuating GWL condition. Two relative densities of D_R = 45% and 85% were considered to prepare test soil specimens. The soil was Jumunjin sand, a clean silica sand with the minimum and maximum dry unit weights ($\gamma_{d,min}$, $\gamma_{d,max}$) of 13.31 and 16.28 kN/m^3, the mean particle size (D_{50}) of 0.55 mm and the specific gravity (G_s) of 2.63. The triaxial tests were conducted and the critical-state friction angle (ϕ'_c) was 31.5°. The peak friction angles



(a) (b)

Fig. 1 Description of model test using hydraulically controlled chamber system: (a) model footing load test with GWL fluctuation and (b) cone penetration test (CPT) results for dry and fully submerged (d_w = 0 mm) conditions

Table 1 Test conditions

Type	D_R	Load level (q, kPa)	Net load increase (Δq, kPa)	Test description
Type 1	45%	Self-weight (q = 0)	-	
	85%			
Type 2	45%	q_1 = 10	10	
		$q_2 = q_1 + \Delta q$ = 20	10	
	85%	q_1 = 15	15	
		$q_2 = q_1 + \Delta q$ = 40	25	
		$q_3 = q_2 + \Delta q$ = 70	30	
Type 3	45%	q_1 = 10	10	
	45%	q_1 = 20	20	
	85%	q_1 = 40	40	
	85%	q_1 = 70	70	

(ϕ'_p) were 33.5° and 38.7° for D_R = 45% and 85%, respectively.

Fig. 1(a) shows the configuration of the test chamber and model load test. The model footing was made of square-shaped acryl with the width and thickness of 100 mm and 20 mm, respectively. Two LVDTs were installed on the model footing at opposite sides to measure settlement. Loads were applied using an acryl water container filled with water placed on the top of the model footing, and maintained during given GWL fluctuation sequence. The cone penetration tests (CPT) were conducted to characterize the test chamber specimens. The cone probe was of a miniature type with diameter of 16 mm and cross-sectional area of 2.0 cm^2. The width and depth of the chamber were then corresponding to 56 and 44 times the cone diameter, respectively. The miniature type of cone was used to minimize the chamber boundary effect. Four CPTs were conducted for the dry and fully submerged conditions with D_R = 45% and 85%. Fig. 1(b) shows the results from CPTs obtained for the dry and fully submerged specimens with D_R = 45% and 85%. The CPT cone resistance q_c is affected by various soil parameters including the relative density. The results in Fig. 1(b) show that the values of q_c for D_R = 85% are lower than for D_R = 45% in both dry and fully submerged specimen cases, which is consistent with the general effect of D_R on q_c. For the fully submerged, saturated condition, lower cone resistances were observed because of decreases in the effective stress.

3.2 Hydraulic chamber system

The model load tests were conducted within a steel chamber of 900 × 900 × 700 mm in width, length and height, respectively, equipped with the water supplying and piezometric system to simulate fluctuating GWL condition, as shown in Fig. 1(a). Soil specimens within the test chamber were formed by the raining method with the sand diffuser and hopper. The relative density of specimen was controlled by the fall height of sand particles from the sand hopper and hole size of the sand diffuser. Using the raining method, a 100-mm thickness sand layer was formed, repeated until the top specimen height of 700 mm was reached.

Fluctuating GWL condition was set within the chamber specimen by supplying water from the water supply tank through the drainage layer placed on the bottom of specimen box. When GWL rose up to the top of the chamber specimen (i.e., d_w = 0 mm), water was drained out through the bottom drainage layer until GWL falls down to the bottom (i.e., d_w = 700 mm). This procedure was repeated following the number of GWL fluctuation cycle. To prevent soil disturbance during water supplying, the rate of water supply was carefully controlled, maintaining constant, sufficiently slow increment of hydraulic pressure through piezometers. Five pairs of piezometers were installed along the lateral side of the chamber at the depths of 100, 200, 300, 500, and 700 mm to monitor GWL during water supplying and draining.

3.3 Test type and procedure

Table 1 shows the types of tests adopted in the testing program, designated as Types 1, 2 and 3. Type 1 indicates fluctuating GWL condition without footing load and thus results indicate ground subsidence (s_g). The number of GWL fluctuation cycle was two for Type-1 tests. Type 2 represents fluctuating GWL condition with footing load, conducted subsequently after Type-1 procedure using the same chamber specimen. Results from Type-2 tests therefore indicate footing settlements (s_f) induced by fluctuating GWL for given load level. GWL fluctuated in the same manner as for Type 1 and load applied on the model footing was maintained during GWL fluctuation.

To check the influence of load level on the effect of GWL fluctuation, different load levels were considered in Type-2 tests, increased sequentially after GWL fluctuation procedure for each load level. Higher load level was achieved by adding water (Δq) into the water container. Two and three load levels were adopted for D_R = 45% and 85%, respectively. Applied loads were q = 10 and 20 kPa for D_R = 45% and q = 15, 40 and 70 kPa for D_R = 85%. The load levels of q = 20 and 70 kPa for D_R = 45% and 85%, respectively, both correspond to the factor of safety (FS) equal to 3.

Type-3 tests were conducted using the same procedure as for Type-2 tests. Difference was the dry initial soil condition and single loading step without sequential increase in q. Results from Type-3 tests therefore include both ground subsidence (s_g) and footing settlement (s_f). Type-3 tests were introduced to analyze the influence of initial soil condition on the effect of GWL fluctuation as dry and wet soil conditions may occur seasonally. For Type-3 tests, the values of q were 10 and 20 kPa for D_R = 45% and 40 and 70 kPa for D_R = 85%.

It should be noted that the unsaturated soil condition takes place during GWL fluctuation within soil, affecting the load response and settlement of footing. Although metric suction and volumetric water content for the soil-water hysteresis curve were not specifically measured, it was supposed that the effect of the unsaturated soil condition was included in measurements from the tests.

4. Test results

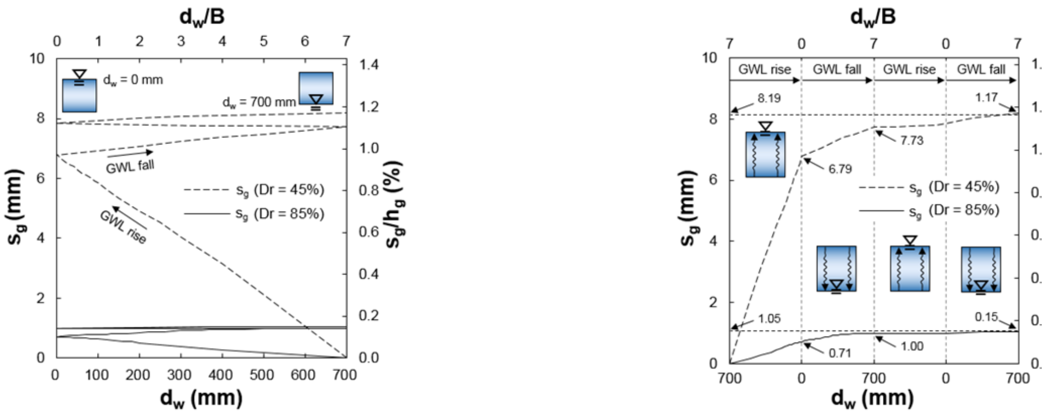
4.1 Ground subsidence with GWL fluctuation

Fig. 2 shows the ground subsidence (s_g) curves from Type-1 tests where the GWL depth (d_w) from the top (0 mm) to bottom (700 mm) is given in single [Fig. 2(a)] and sequentially repeating [Fig. 2(b)] scales. Although indicated in difference scales, the values of s_g in both cases are the same. The normalized axes of d_w/B and s_g/h_g were also included in Fig. 2 where B and h_g were the footing width and specimen height, respectively. s_g gradually increased as GWL fluctuated, most significantly during the first fluctuation cycle. Increases in s_g were less pronounced as GWL further fluctuated, converging at s_g/h_g = 1.17% and 0.15% for D_R = 45% and 85%, respectively. For the first GWL fluctuation cycle, the values of s_g were 7.73 and 1.00 mm for D_R = 45% and 85%, corresponding to s_g/h_g of 1.17% and 0.15%, respectively. After the second GWL fluctuation cycle, the values of s_g were 8.19 and 1.05 mm for D_R = 45% and 85%, corresponding to net s_g increases (Δs_g) of 0.46 and 0.05 mm during the second GWL fluctuation cycle, respectively.

The results in Fig. 2 show that GWL rise and fall both induce ground subsidence while each process represents the opposite mechanical consequences of decreasing and increasing effective stresses, respectively. No strain reversal or heaving type of soil displacement took place during GWL rising. The soil-water characteristic relationship of soils indicates that less volume change occurs during the wetting process (i.e., rising GWL) than the drying process. Larger settlement during rising GWL in Fig. 2 should be then explained differently and can be attributed to the collapse mechanism of soils during the wetting process with the retraction of yield surface upon saturation with the loss of suction strength (Khalili *et al.* 2004). Settlements for rising and falling GWLs will further be compared and analyzed with footing load.

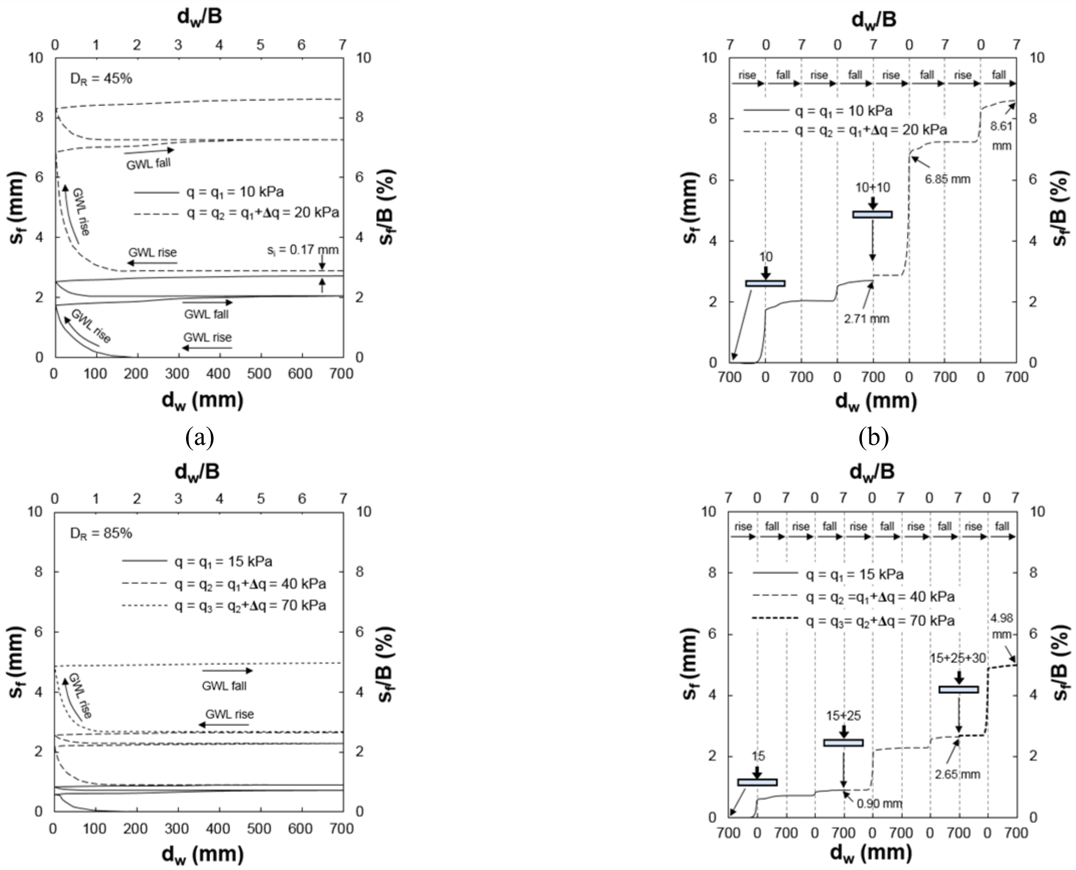
4.2 Footing settlements with GWL fluctuation

The values of footing settlement (s_f) with fluctuating GWL from Type-2 tests are shown in Fig. 3. The



(a) (b)

Fig. 2 Ground subsidence (s_g) curves from Type-1 tests with GWL depth (d_w) using (a) single and (b) sequentially repeating scales



(c) (d)

Fig. 3 Footing settlement (s_f) curves from Type-2 tests for D_R = 45% with d_w using (a) single and (b) sequentially repeating scales and for D_R = 85% with (c) single and (d) sequentially repeating scales

normalized GWL depth (d_w/B) and relative settlement (s_f/B) were included for comparison. For D_R = 45% in Figs. 3(a) and (b), two load levels of q = 10 and 20 kPa were adopted.

The load level of q = 20 kPa was achieved by adding 10 kPa to the previous load level of q = 10 kPa. For D_R = 85% in Figs. 3(c) and (d), three load levels of q = 15, 40 and 70 kPa were adopted. The load levels of q = 40 and 70 kPa were achieved by adding 25 and 30 kPa, respectively, for each load level. The values of s_f for q = 10 and 20 kPa with D_R = 45% were 2.71 and 8.61 mm, corresponding to s_f/B equal to 2.71% and 8.61%, respectively.

Note that s_f/B = 8.61% is close to 0.1B that is often adopted to define the ultimate limit state or bearing capacity of footing. For D_R = 85%, the values of s_f were 0.9, 2.65 and 4.98 mm for q = 15, 40 and 70 kPa, s_f/B equal to 0.9%, 2.65% and 4.98%, respectively. Immediate settlements (s_i) upon loading, as indicated in Fig. 3(a), were not significant for all cases, compared to settlements induced by GWL

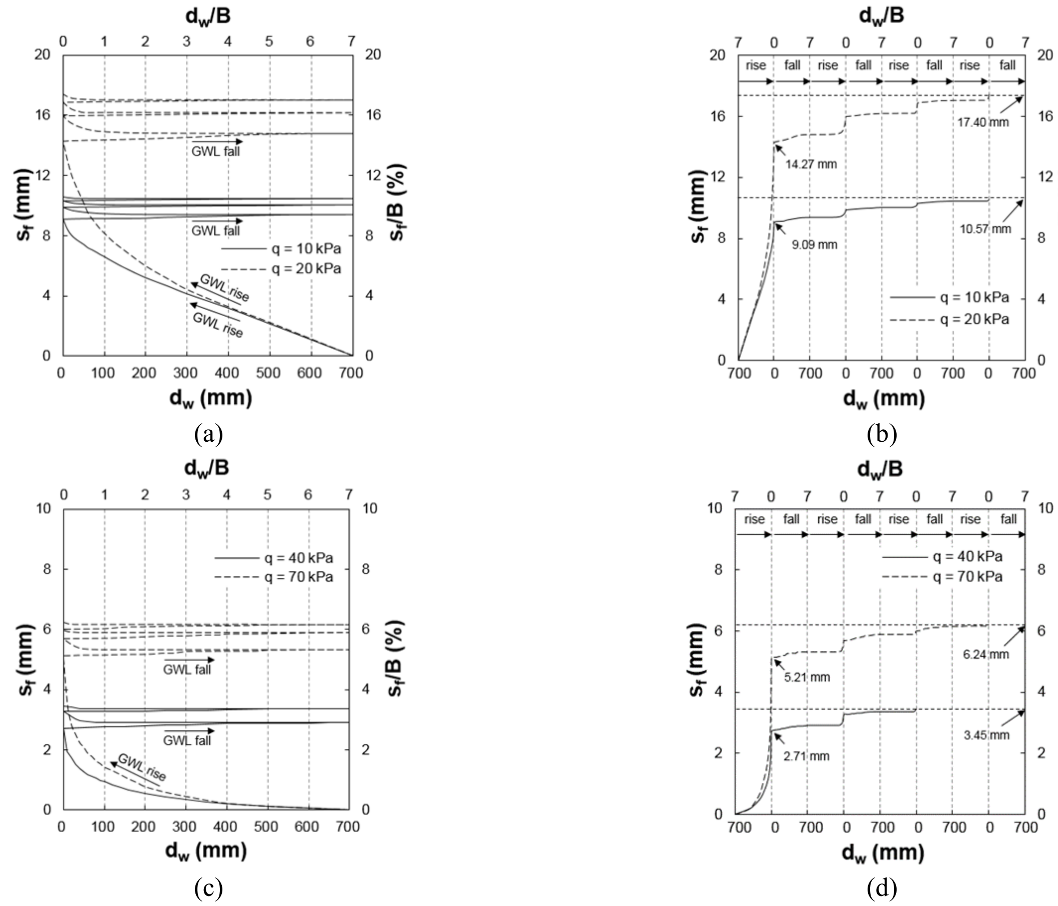


Fig. 4 Footing settlement (s_f) curves from Type-3 tests for D_R = 45% with d_w using (a) single and (b) sequentially repeating scales and for D_R = 85% with (c) single and (d) sequentially repeating scales

fluctuation. Other important influencing components found from Fig. 3 were the rising and falling GWL fluctuation phases, GWL fluctuation cycle and load level, which will be further analyzed later in detail.

The s_f curves with GWL fluctuation from Type-3 tests are shown in Fig. 4. Type-3 tests were conducted using initially dry specimens with two load levels of q = 10 and 20 kPa for D_R = 45% and 40 and 70 kPa for D_R = 85%, all imposed as single loading step. Note that the footing load tests of Type-3 were conducted for initially dry soil conditions. The values of s_f for Type-3 tests were therefore larger than those for Type-2 tests as the ground subsidence (s_g) was included in s_f. The values of s_f during the first GWL rise were 9.09 and 14.27 mm for q = 10 and 20 kPa with D_R = 45%, and 2.71 and 5.21 mm for q = 40 and 70 kPa with D_R = 85%, respectively. The value of s_f = 2.71 mm in Fig. 4(d) was close to s_f = 2.84 mm of Shahriar *et al.* (2015) obtained for the similar test condition. During the second GWL rise, net increases in s_f (Δs_f) of Type-3 tests were similar to those of Type-2 tests, implying that most significant ground subsidence (s_g) took place during the first GWL fluctuation.

The values of s_f at the end of Type-3 tests were 10.57 and 17.40 mm for q = 10 and 20 kPa with D_R = 45% and 3.45 and 6.24 mm for q = 40 and 70 kPa with D_R = 85%, respectively. s_f = 17.40 mm corresponds to s_f/B = 17.4%, far exceeds the 0.1B criterion and would not be acceptable in design. This indicates that footing settlement with GWL fluctuation is affected by initial soil condition and past GWL fluctuation history, which all should be considered for short- and long-term performances.

5. Characterization of fluctuating GWL effects

5.1 Effects of rising and falling GWL phases

Key findings from the results in Figs. 3 and 4 are the marked effect of GWL rise with larger s_f than for GWL fall, contrary to the common design consideration in practice. This is shown more clearly in Fig. 5 where net s_f increases (Δs_f) during the rising and falling GWL phases are directly compared. The marked effect of GWL rise on s_f can be attributed to the collapse mechanism of soils during the wetting process (Khalili *et al.* 2004), described previously, and the consequence of decreasing confining stress and soil stiffness. Fig. 6(a) shows the stress path during GWL rise where the effective confining stress (p′) decreases while the shear stress (q) is kept constant due to the condition of sustained load. Through the process of GWL rise, the transition of stress state into lower effective stress and stiffness takes place producing additional strains ($\Delta\gamma$) as described in Fig. 6(b). The process of GWL fall with increasing effective stress, on the other hand, induces

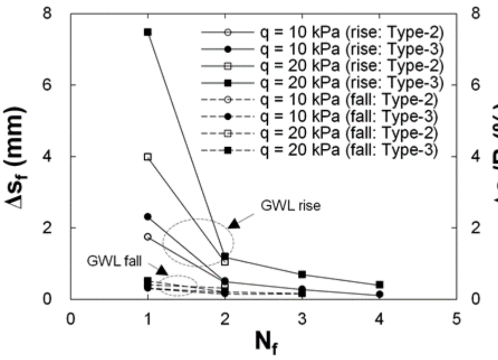
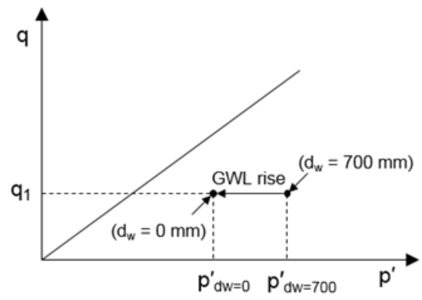
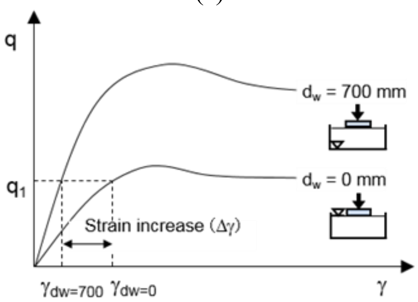


Fig. 5 Compared footing settlement increases (Δs_f) during GWL rising and falling phases



(a)



(b)

Fig. 6 Stress states during GWL fluctuation: (a) stress path and (b) stress-strain relationship

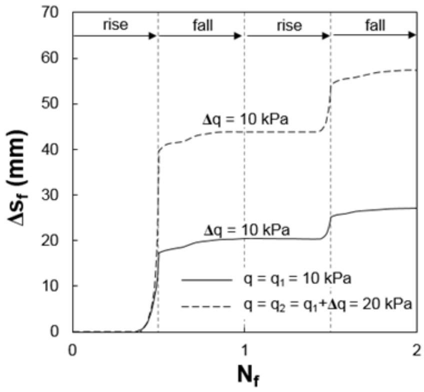
compressive volumetric strains, which would be smaller than those during GWL rise. Note that the unsaturated condition during GWL fluctuation would affect the magnitude and rate of changes in the stress state in Fig. 6. However, the general trend of decreasing effective stress with rising GWL is still valid where reduced stiffness with more strains would take place as described in Fig. 6(b).

From Figs. 3 and 4, it is also seen that Δs_f gradually decreases and tends to converge as GWL continued to fluctuate. For Type-2 tests in Figs. 3 and 5, Δs_f decreased by 74% from the first to second fluctuation cycles beyond which Δs_f decreased much less. Noted that rising and falling

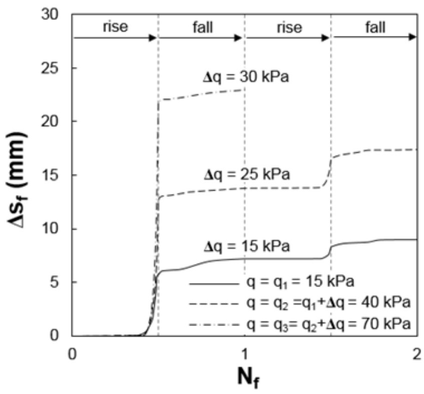
GWLs are comparable to the process of unloading and reloading with repeating over-consolidated stress state, which would be therefore responsible, in part, for a decrease in Δs_f with continuous GWL fluctuation.

5.2 Effect of load level

The results in Fig. 3 indicate that load level is another influencing factor on GWL-related footing settlement.



(a)



(b)

Fig. 7 Values of Δs_f with GWL fluctuation for (a) D_R = 45% and (b) D_R = 85%

Increases in load level initiated a new, additional sequence of Δs_f mobilization with GWL fluctuation while settlements at the previous loading stage with fluctuating GWL already converged. From Figs. 3(b) and (c), the values of Δs_f through rising and falling GWL for each load level were separated and plotted in Fig. 7 where N_f represents the

number of GWL fluctuation. As shown in Fig. 7(a) for D_R = 45%, while the values of net load increase (Δq) were the same as equal to 10 kPa, the load level of q = 20 kPa produced settlements 2 times larger than those for q = 10 kPa. The similar effect was observed for D_R = 85% in Fig. 7(b).

These results raise an important design implication for structures that will be newly extended or modified. In the routine design procedure, settlements for such cases are checked only based on net load increase due to the structural extension or modification. The results in this study, however, indicate that the magnitude of s_f through the process of GWL fluctuation is considerably large and may control the design when structural modification and extension are involved.

5.3 Compared effects of fixed and fluctuating GWLs

The effects of fixed and fluctuating GWLs on footing settlement are different because of different mechanical consequences in the stress state. The condition of fixed

GWL is an in-situ condition with the stress state and soil condition set as state variables. Fluctuating, moving GWL represents a varying stress state with changes in the effective stress, which may be comparable to loading and unloading processes as described previously. For q = 20 kPa with D_R = 45%, s_f for fixed GWL with d_w = 0 m was 2.39 mm, as reported in Park *et al.* (2017). For the same test condition, the values of s_f for fluctuating GWL in this study were 8.61 and 10.57 mm for Type-2 and -3 cases, respectively [Figs. 3(b) and 4(b)]. These are 4.4 times larger than for the fixed GWL condition. This confirms that footing settlement with fluctuating GWL is much larger than for fixed GWL and may reach a level intolerable or unacceptable even without imposing additional load.

6. Design application

6.1 Normalized settlement relationship

The s_f curves in Figs. 3 and 4 were normalized, using the settlement for the first GWL rise, as defined as $s_{f,1(r)}$, and plotted in Fig. 8. For Type 3 in Fig. 4, net footing settlements were only adopted, excluding ground subsidence (s_g). It was found that the normalized $s_f/s_{f,1(r)}$ curves in Fig. 8 were approximately unique, dependent only on density condition. $s_f/s_{f,1(r)}$ was higher for lower density and converged at 1.85 and 1.50 for D_R = 45% and 85%, respectively. The unique $s_f/s_{f,1(r)}$ curves in Fig. 8 imply that settlement increase due to GWL fluctuation is predictable and can be considered in the design stage.

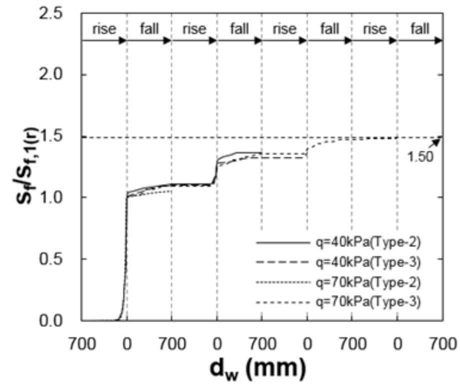
As the effect of GWL rise was predominant, the s_f curves for GWL rise were obtained from Figs. 3 and 4 and plotted in Fig. 9 with $s_f/s_{f,(r)}$ and d_w/B where $s_{f,(r)}$ and B represent the value of s_f for each GWL rise and footing width, respectively. The $s_f/s_{f,(r)}$–d_w/B curves in Fig. 9 indicate that the depth to GWL influence zone varies depending on GWL fluctuation cycle and D_R. From Fig. 9, the depth to GWL influence zone ($d_{w,inf}$), defined as a depth (d_w) where $s_f/s_{f,(r)}$ in Fig. 9 becomes smaller than 0.05, was obtained for each case and plotted in Fig. 10 with the number of GWL fluctuation cycle (N_f). For all cases, $d_{w,inf}$ decreased with increasing N_f. All $d_{w,inf}/B$ values in Fig. 10 were smaller than 2, which were smaller than 5 to 6 proposed previously (Morgan *et al.* 2010; Shahriar *et al.* 2015). Note that the deeper GWL influence zone of $d_{w,inf}$ = 5B to 6B included ground subsidence, similarly to Type-3 test in Fig. 4, and thus overestimates the GWL effect when adopted in practice.

Using $d_{w,inf}$ in Fig. 10, the values of $s_f/s_{f,(r)}$ were plotted with the normalized GWL depth of $d_w/d_{w,inf}$ in Fig. 11.

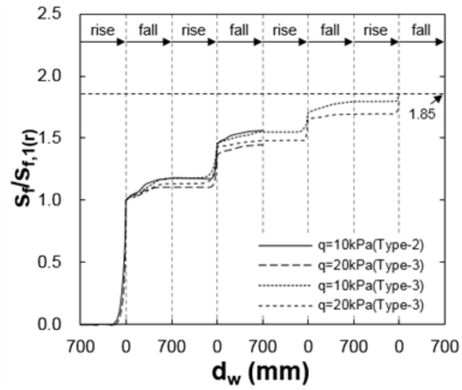
The $s_f/s_{f,(r)}$–$d_w/d_{w,inf}$ relationship shown in Fig. 11 was fairly unique and approximated using the following correlation

$$\frac{s_f}{s_{f,(r)}} = \exp\left(-3.0 \cdot \frac{d_w}{d_{w,\text{inf}}}\right) \quad (6)$$

where s_f = settlement at certain GWL depth of d_w for given GWL rise phase; $s_{f,(r)}$ = settlement observed during GWL

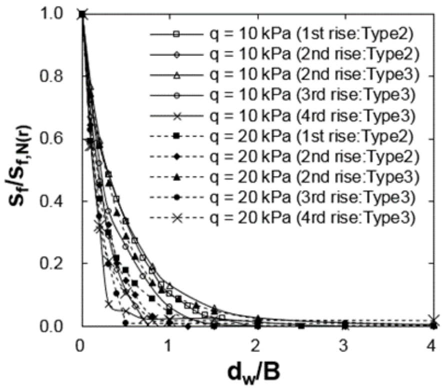


(a)

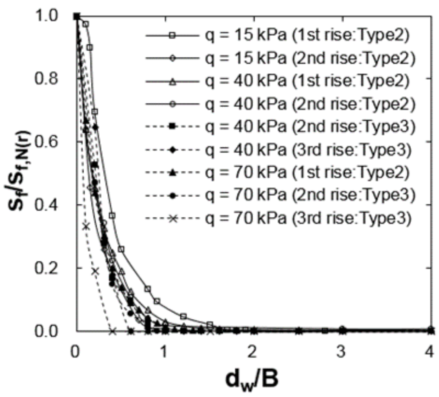


(b)

Fig. 8 Normalized $s_f/s_{f,1(r)}$ curves with GWL fluctuation for (a) D_R = 45% and (b) D_R = 85%



(a)



(b)

Fig. 9 Normalized $s_f/s_{f,(r)}$-d_w/B curves for (a) D_R = 45% and (b) D_R = 85%

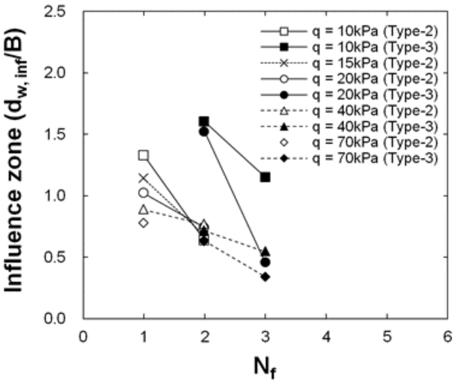


Fig. 10 Depth of GWL influence zone with GWL fluctuation

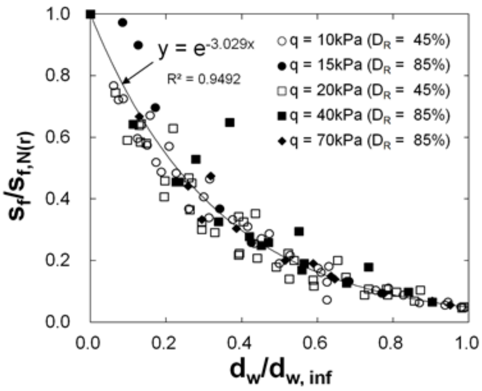
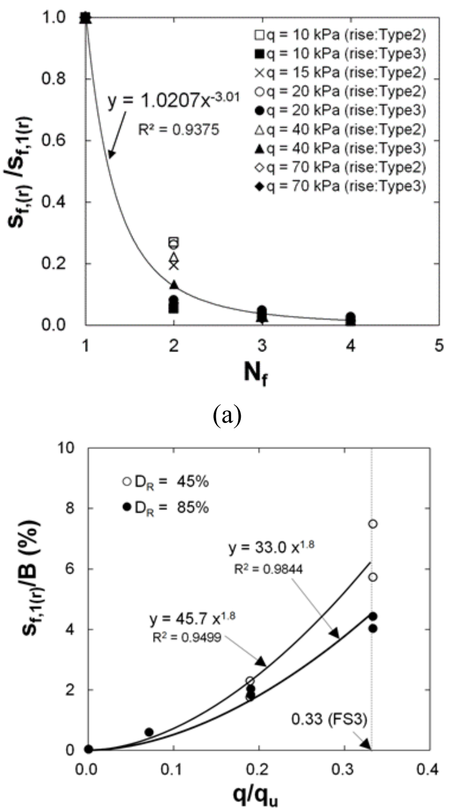


Fig. 11 Normalized $s_f/s_{f,(r)}$–$d_w/d_{w,inf}$ curves



(a)

(b)

Fig. 12 Values of (a) $s_{f,(r)}/s_{f,1(r)}$ with GWL fluctuation cycle N_f and (b) $s_{f,1(r)}$/B with normalized load level q/q_u

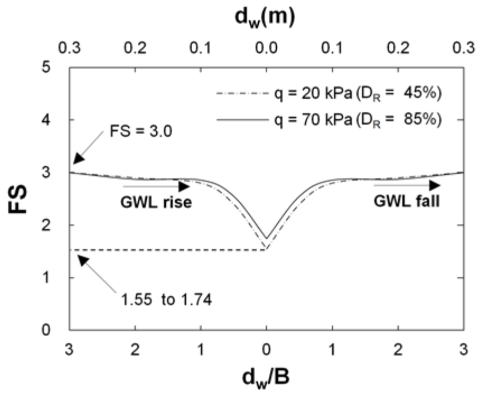


Fig. 13 Changes in factor of safety with GWL fluctuation

rise; and $d_{w,inf}$ = GWL influence depth.

$s_{f,(r)}$ in Eq. (6) decreases with N_f as it is largest for the first cycle as given by $s_{f,1(r)}$. To quantify the variation of $s_{f,(r)}$, the values of $s_{f,(r)}$ were normalized with $s_{f,1(r)}$ for each GWL fluctuation and plotted in Fig. 12(a) with N_f. The $s_{f,(r)}/s_{f,1(r)}$-N_f correlation in Fig. 12(a) was

$$\frac{s_{f,(r)}}{s_{f,1(r)}} = \left(\frac{1}{N_f}\right)^{3.0} \tag{7}$$

where $s_{f,(r)}$ = the amount of s_f during N_f^{th} GWL rise; $s_{f,1(r)}$ = the amount of s_f during the first GWL rise; and N_f = number of GWL fluctuation cycle. As discussed from Figs. 3 and 4, $s_{f,1(r)}$ in Eq. (7) increases with load level (q). This was plotted in Fig. 12(b) with $s_{f,1(r)}$/B and q/q_u where B and q_u represent footing width and the dry bearing capacity. The correlation given in Fig. 12(b) was obtained as

$$\frac{s_{f,1(r)}}{B} = \xi \cdot \left(\frac{q}{q_u}\right)^{1.8} \tag{8}$$

where q = load; q_u = bearing capacity for dry condition; ξ = correlation parameter = 45.7 and 33.0 for D_R = 45% and 85%, respectively. Using Eqs. (6)-(8), GWL-induced settlement (s_f) can be obtained and considered into the assessment of long-term performance of footings for given hydrological and climate scenario associated with GWL fluctuation.

6.2 Implication to design

Changes in the factor of safety (FS) through GWL rise and fall were evaluated for loads imposed on the model footing as plotted in Fig. 13. The bearing capacities of the model footing to calculate FS in Fig. 13 were given in Park *et al.* (2017). The load levels of q = 20 and 70 kPa for D_R = 45% and 85% both corresponded to FS = 3. FS decreased with rising GWL and became lowest equal to 1.55 and 1.74 for q = 20 and 70 kPa, respectively, at d_w = 0 mm. These FSs during GWL rise are lower than the initial FS = 3, which would not be detected unless any visible changes actually occurred.

Settlements during GWL fluctuation accumulate and thus should be properly monitored. The results obtained in this study indicated that settlements by fluctuating GWL would control the design rather than immediate settlements or those with fixed GWL. FS would decrease with GWL rise and recover with GWL fall. In terms of both stability and settlement, therefore, it is supposed that the mechanical consequence during GWL rise is more critical and should be checked during the design.

7. Conclusions

In this study, the effect of fluctuating GWL on the load response and settlement (s_f) of footing was investigated based on the results from the model load tests conducted using the hydraulically-controlled chamber system. The ground subsidence (s_g) increased as GWL fluctuated, most significantly during the first fluctuation cycle. s_f was greater for GWL rise than for GWL fall as GWL rise caused decreases in the effective stress and soil stiffness, which would further induce shear-strain mobilization at the lower effective level. Increases in load level initiated a new, additional sequence of settlement mobilization with GWL fluctuation. Settlements with fluctuating GWL condition were much larger than for fixed GWL condition.

The normalized settlement relationship of $s_f/s_{f,1(r)}$-d_w with GWL fluctuation was unique, dependent only on density condition showing larger $s_f/s_{f,1(r)}$ for lower relative density. The depth of GWL influence zone ($d_{w,inf}$) was evaluated, which became shallower with increasing GWL fluctuation cycle. A design method for estimating s_f with GWL fluctuation was proposed based on the normalized settlement relationship of footing with GWL fluctuation. The correlations of $s_{f,(r)}$-$s_{f,1(r)}$ and $s_{f,1(r)}/B$-q/q_u were established, adopted into the proposed s_f estimation method. The values of $s_{f,1(r)}$ increased with increasing load level (q).

The factor of safety (FS) considered in the design of footing was evaluated through GWL rising and falling phases. The values of FS during GWL rise were lower than the initial FS, which may violate the originally specified design requirement. As s_f increases and becomes accumulated with GWL fluctuation, it should be more carefully monitored, in particular, when there is chances of load increase. In any cases, it was obvious that settlements caused by GWL fluctuation affect the design and engineering performance of footings.

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