# A Study on the Influence of Ground Water Level on Foundation Settlement in Cohesionless Soil

## Étude de l'influence de la variation du niveau d'eau sur le tassement des fondations superficielles reposant sur sol granulaire

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ABSTRACT: Settlement calculation is an important part in the design of shallow foundations resting on granular soils. Rise of ground water level is believed to increase the settlement significantly and had been a topic of research for many years. Terzaghi (1943) suggested that the submergence of soil mass reduces the soil stiffness to half, which in turn doubles the settlement. Since then, various researchers proposed correction factors to account for the additional settlement due to water table fluctuation. However, a comprehensive settlement testing and its numerical modeling to account for the influence of ground water level has not been reported in the literature. The objective of this paper is to quantify the effect of water table rise on settlement through laboratory testing over wide range of footing shape, soil density, water table depth and stress level. The tests were carried out within a settlement tank. The footings under working load were subjected to water table rise, and the additional settlements were measured. The experimental setup was modelled in FLAC and the results were compared with the laboratory tests. The results obtained will be valuable in verifying Terzaghi's intuitive reasoning and explaining the observed additional settlement of footings found in the literature.

RÉSUMÉ : Le calcul du tassement est un élément important dans la conception des fondations superficielles reposant sur les sols granulaires. L'augmentation du niveau d'eau souterrain est supposée augmenter de façon significative le tassement et avait été un sujet de recherche pendant de nombreuses années. Terzaghi (1943) a suggéré que la submersion du dépôt de sol réduit la capacité du ce dernier de moitié, ce qui à son tour double le tassement. Depuis lors, plusieurs chercheurs ont proposés des facteurs de correction pour tenir compte du tassement additionnel en raison de la fluctuation du niveau d'eau dans le sol. Toutefois, on ne reporte pas d'étude expérimentale et/ou numérique dans la littérature pour tenir compte de l'influence du niveau de la nappe phréatique sur le tassement des fondations superficielles. L'objectif de cette étude est de quantifier l'effet de la variation du niveau d'eau sur le tassement par le biais d'essais au laboratoire sur une large gamme de forme de semelle, de densité du sol, de niveau de charge et de profondeur de la nappe phréatique. Les essais ont été réalisés dans un réservoir de tassement. Les semelles sous chargement ont été soumises à une variation du niveau d'eau et des tassements supplémentaires ont été enregistrés. Le montage expérimental a ensuite été modélisé à l'aide du logiciel FLAC et les résultats ont été comparés avec ceux obtenus au laboratoire. Les résultats obtenus seront utiles pour vérifier le résonnement intuitif de Terzaghi et pour expliquer le tassement supplémentaire des semelles rapporté dans la littérature.

KEYWORDS: correction factor, granular soil, settlement, shallow foundation, water table.

## 1 INTRODUCTION

Shallow foundations such as pad, strip or raft footings are often preferred by geotechnical engineers when the soil conditions are suitable. Bearing capacity and settlement are the major considerations in designing shallow foundations on granular soils. The designers try to ensure sufficient safety factor against bearing capacity failure and to limit the settlement within a tolerable value. More than 40 settlement prediction methods for footings on cohesionless soils are available in the literature (e.g. Terzaghi and Peck 1967, Schmertmann et al. 1978, Burland and Burbidge 1985, Mayne and Poulos 1999). These methods recognized that the major influencing factors for shallow foundation settlements are the applied pressure, soil stiffness and depth, width and shape of foundation.

Seasonal fluctuations such as floods or heavy rainfalls can raise the water table up to or beyond the footing level and produce additional settlements of shallow foundations. The soil loses its stiffness when submerged, and settles more. Substantial additional settlement may occur when the groundwater level changes, which can exceed the tolerable limit for settlement and threaten the integrity of structure. Very few works have been found in the literature investigating the influence of fluctuating water level on shallow foundation settlements. Some researchers suggested using a water table correction factor, which can be used as a multiplier on the settlements predicted for footings resting on dry sands, to get the settlements in submerged condition. Limited laboratory model tests have been conducted in the past, which did not cover the effect of foundation shape or varying stress level on additional settlement induced by water table rise.

In this paper, the authors have described a comprehensive laboratory test program carried out to quantify the additional settlement due to rise in water table with varying footing shape, soil density, water table depth and stress level. This was followed by modeling the experimental set up in geotechnical modeling software FLAC, and the results were compared with the experimental data.

## 2 WATER TABLE RISE AND CORRECTION FACTOR

Terzaghi (1943) made an intuitive suggestion that when dry sand becomes saturated, the soil stiffness (Young's modulus) reduces by approximately 50%. He noted that, the effective vertical stress on soil under the water table reduces roughly to half; which reduces the effective confining stress by 50%. This leads to loss of stiffness of saturated soil to half of that in the dry condition. As a result, settlement in soil below the water table gets doubled.

When the water table rises to some depth below the footing, a correction factor for the new location of water table is used in the design of shallow foundations. The settlement under dry conditions is multiplied by this factor, to give the settlement expected due to the water table rise. The correction factor $C_w$ is greater than or equal to 1 and increases with rise in water table. It is defined as:

$$C_w = \frac{\text{settlement with water table below the footing level}}{\text{settlement in dry sand}} \qquad (1)$$

Various researchers (Terzaghi and Peck 1948, Teng 1962, Alpan 1964, Bazaraa 1967, Peck 1974, Bowles 1977) proposed correction factors to quantify the additional settlement due to the water table rise below the footing. The depth below the footing where the water table fluctuation will not have any effect is not unanimously agreed upon. The depth of embedment of the footing also affects the influence of water table on settlement, as the surcharge due to embedment increases the settlement in raised groundwater level. Throughout this paper, the correction factor for water table, foundation width, depth of water table below the foundation and the depth of embedment are denoted by $C_w$, $B$, $D_w$ and $D_f$, respectively, as illustrated in Figure 1.

Shahriar et al. (2012) made a critical review of the current state-of-the-art for predicting shallow foundation settlement due to rise in water table in granular soil. Theoretical studies by Vargas (1961), Brinch Hansen (1966) and Bazaraa (1967) suggested a maximum correction factor of 1.7, when the water table rises to the base of the foundation. Limited field investigations suggest that submergence of granular soil doubles the settlement when compared to dry condition, agreeing with Terzaghi's proposition. Numerical modeling conducted by Shahriar et al. (2012) shows that the settlement gets doubled in submerged sand if linear elastic model is used, but the use of hyperbolic non-linear elastic soil model gives higher additional settlements at high stress levels.

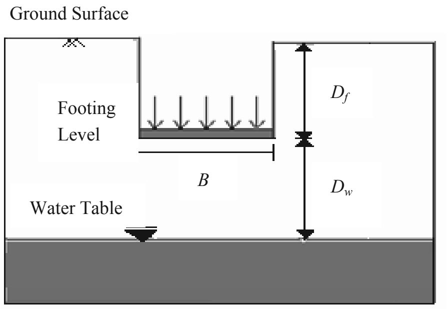


Figure 1. Schematic diagram of a shallow foundation.

Very little laboratory studies have been conducted so far and contradictory results have been found. Agarwal and Rana (1987) conducted tests on square footings of three different sizes. Their results support Terzaghi's proposition that the settlement gets doubled when the sand gets submerged. Murtaza et al. (1995) also used three different sized square footings and conducted the tests with loose, medium dense and dense sands. The results showed 8 to 12 times more settlement in submerged condition. Morgan et al. (2010) carried out settlement tests with a square footing in two different types of soils and found that the increase in settlement in submerged sand can be 5.3 times the dry sand. However, these experimental programs were small in scale and none of these considered the effect of varying footing shape and stress level.

## 3 LABORATORY MODEL STUDY

A Perspex rectangular tank 800 mm x 800 mm in plan and 600 mm high was built to carry out the settlement test. Various footing shapes were used. A circular footing of 100 mm diameter and square and rectangular footings with $B/L$ =1.0, 0.75, 0.50, 0.25 were used where the width, $B$ was fixed to 100 mm in each case. A locally available granular soil was used. In a model footing having smaller dimensions, the settlement might get affected by change in soil stiffness in a partially saturated area. From laboratory testing, it was observed that the capillary rise is higher in well graded soil. Hence, the finer particles were sieved out from the test soil to get a uniformly graded soil with soil grains large enough to significantly reduce the capillary height. The rate of capillary rise of the sieved soil was then tested using soil filled Perspex tubes protruding from water. At five minutes, the capillary height observed were 40 mm and 53 mm in loose and dense sands respectively. Five minutes was the maximum time to get the water level static during the settlement tests, so the capillary rise is expected to be limited within the range of 40-53 mm. In fact, the height of capillary rise was limited to 50 mm for most of the time during the tests. This height is reasonable when compared to the footing width (100 mm). In case of granular soil, the elastic modulus of the soil is a key parameter in predicting foundation settlement, and Vanapalli and Mohamed (2007) showed that the elastic modulus of unsaturated soil can be significantly influenced by matric suction. However, by limiting the capillary rise within a shorter range, the unsaturated zones in the model tests were kept quite small and hence, their effect on the overall settlement was negligible. The soil properties of sieved out sand are: effective size $D_{10}$=0.67 mm, co-efficient of uniformity, $C_u$=1.64, co-efficient of curvature $C_c$=0.89, specific gravity, $G_s$=2.61, maximum and minimum dry densities =1.53 t/m$^3$ and 1.382 t/m$^3$ respectively. Two different relative densities (37.6% and 77.4%) of the sand were used. Since the model tests represent the larger footings with higher densities in the field, maximum relative density was limited to 77.4%.

The tank was filled with sand in multiple lifts. The height of each lift was equal to the foundation width. The mass of soil for each layer was determined from the required density. Soil was poured through a funnel moving around the tank and to achieve a uniform density, a specific height of fall was maintained. A wooden float was used to compact and level the soil top after every lift. The density achieved by compaction was checked by putting square cans at various levels and reasonable accuracy was observed. Water was supplied through rubber tubing attached to a nozzle located at the bottom of the tank. Water table was raised at a lift height of 100 mm (foundation width, *B*) from the bottom of the tanks up to a depth of *B* below the footing level. Then the rise was reduced to *B*/5 until the water table reached footing level. The height of water table rise was monitored by a glass tube attached to the soil tank. The load was applied with a hydraulic jack. Settlement for each water table lift was obtained by averaging the two dial gauge readings placed on top of the footings. Figure 2 shows a close view of the experimental setup used in the tests.

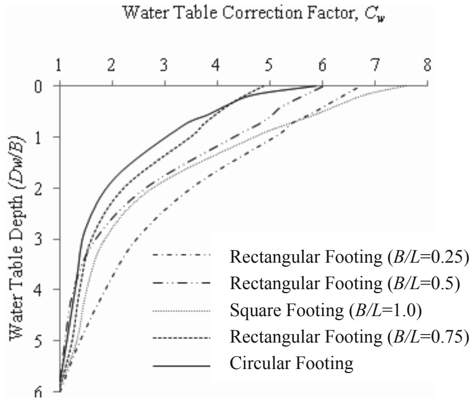
Figure 2. Experimental Setup with model footing, dial gauges and loading arrangement.

Initially, pressure-settlement curves were obtained for each case by applying vertical pressure in increments and measuring corresponding settlements in dry condition. Then double tangent method was used to determine bearing capacity of the footings. This means the ultimate bearing capacity was taken as the intersection of the two tangents drawn from the two linear segments of the load-settlement plot. The working load was taken as one-third of the bearing capacity, keeping the factor of safety at 3. In the next step, the footings were subjected to working loads and the water level was raised gradually from bottom of the tank up to the footing level.

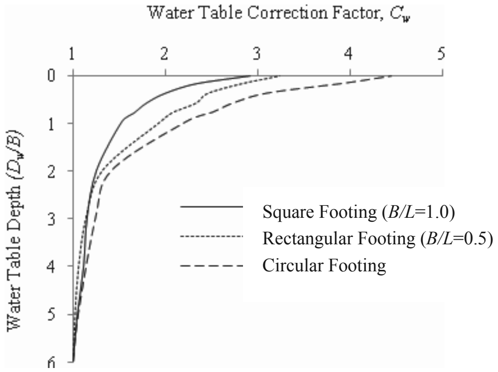
## 4 INTERPRETATION OF EXPERIMENTAL RESULTS

From the additional settlements measured at various water table depths, the water table correction factor diagrams were obtained. Figure 3 shows the correction factor diagrams for various footing shapes in loose and dense condition. The figure shows that the additional settlement due to water table rise is higher in loose sands, with $C_w$ ranging from 4.9 to 7.6 times the settlement in dry condition. Footings on dense sand experienced less additional settlements than in loose sands, with $C_w$ ranging from 2.9 to 4.4. The results indicate significantly higher additional settlement due to rise in water table than what was suggested by Terzaghi (1943).

It is evident from the curves in Figure 3 that the increment in correction factor is not linear with water table rise, instead, settlement increases at a faster rate when the water table gets closer to the footing. The stress level immediately below the footing is very high, which causes significant additional settlements.



(a)



(b)

Figure 3. Water table correction factor diagrams for model footings on a) loose sand, b) dense sand.

Figure 4 shows the load-settlement curves for square footing resting on dense sand in dry (solid line) and submerged condition (dotted line). It shows that the additional settlement in submerged sand rises from 2.92 to 3.25 times as the applied pressure rises from 40 kPa to 75 kPa. This reflects the effect of stress level on additional settlement due to submergence. The bearing capacity of soil gets reduced while submerged, which induces high additional settlements at higher stresses.

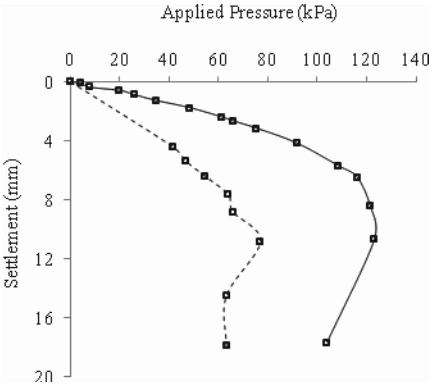


Figure 4. Applied pressure-settlement curves for 100 mm square footing in dry and submerged condition.

## 5 NUMERICAL MODELING OF EXPERIMENTAL SETUP

The authors modeled the experimental setup in FLAC 6.0 (Itasca, 2008), a finite difference code used in geotechnical modeling. A hyperbolic non-linear elastic model was used in the simulation. The model relies on the nonlinear stress-strain relationship suggested by Kondner and Zelaska (1963):

$$(\sigma_1-\sigma_3)=\frac{\varepsilon}{\frac{1}{E_i}+\frac{\varepsilon}{(\sigma_1-\sigma_3)_{\max}}} \qquad (2)$$

where: $(\sigma_1\text{-}\sigma_3)_{\max} =$ asymptotic value of stress difference
$\varepsilon =$ axial strain
$E_i =$ initial tangent modulus i.e., the slope of $\sigma - \varepsilon$ curve

While modeling, the initial Young's modulus was assumed to be 5 MPa for dry sand considering the lower soil stiffness in small scale footings. Following Terzaghi's (1943) suggestion that the Young's modulus reduces by 50% in submerged sand, the initial Young's modulus in this sand was taken as half of that of the dry sand. The asymptotic stress difference relates closely to the ultimate strength of the soil mass and was taken as the bearing capacities of footings on dry and submerged sands obtained from pressure-settlement curves derived from the model tests. The test on circular footing placed on dense sand was modeled in this paper. The rise of water table depth was simulated using appropriate parameters and correction factors at various water table depths were observed.

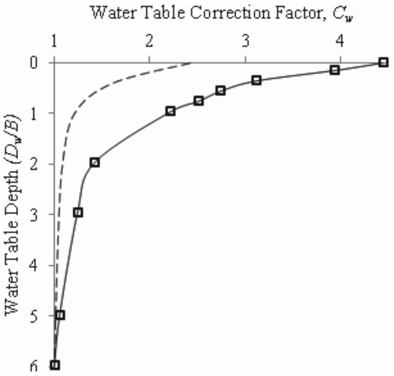


Figure 5. Water table correction factor diagram for 100 mm diameter circular footing obtained from experimental results and numerical modeling.

Figure 5 shows the comparison of water table correction factor diagrams obtained from numerical modeling (dotted line) and experimental results (solid line). The diagrams were similar in shape, both being curved rather than linear as previously proposed by some researchers. Also, both the curves indicate that the effect of water table depth is negligible at a greater depth, whereas settlement increases rapidly as the water table gets closer to the footing base. The assumed soil parameters may contribute to the differences in correction factors obtained from numerical modeling and laboratory testing.

## 6 SUMMARY AND CONCLUSIONS

Laboratory model tests were carried out to investigate the effect of various factors on increase in shallow foundation settlement when subjected to fluctuation in ground water level. Additional settlements at various water table depths were observed and water table correction factor diagram for each case was obtained.

The results show significant increase in settlement as the soil immediately below the footing level gets saturated. The results clearly indicated that the increment is higher in soils having lower density; however, the increment is significant even in dense soils. The effect of footing shapes on additional settlement in saturated sand was not evident from the results. Comparison of applied pressure-settlement curves in dry and submerged sands suggest that the additional settlement due to submergence increases with the stress level. Modeling a circular footing in FLAC and its comparison with test data confirms that the correction factor diagram is not linear, and the correction factor increases at a faster rate in the vicinity of the footing. The results obtained will help to understand how the fluctuating water level affects the shallow foundation settlements on granular soils and will allow designers to apply appropriate correction factors for water level rise. There is a scope for further investigations to identify the effect of other important factors (e.g. depth of embedment, footing width, and soil gradation) in settlement behaviour of shallow footings with changing groundwater level. More laboratory testing with different initial densities might be useful to develop water table correction factor charts for varying relative densities and shear strength parameters. Also, advanced soil models can be used to study the effect of rising water table on shallow foundation settlement on cohesionless soils.

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