Reliable prediction of structure settlement in Al-Najaf city using laboratory testing

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Abstract. This paper studies the effect of the specimen sizes and shapes on the settlement behaviour of sand soil with gypsum from Al-Najaf city in Iraq. The investigation aimed to verify the impact of the studied parameters of the prediction of the settlement using reliability-based analysis. Three sets of soil samples with different shapes and sizes, 60 mm diameter Oedometer cell, 60 x 60 mm box container and 100 x 100 mm box container were remoulded with three different densities related to the maximum dry density, 100%, 95% and 92%. The results reveal that different settlement behaviours were determined at several normal stress levels during the soaking process. The samples exhibited reductions in volume due to the applied stresses, while under the same level of normal stress, the final settlement values due to soaking were higher for the samples with a lower value of initial relative compaction. Further, the test results showed that at any initial relative compaction and applied vertical stress, the higher settlement value is achieved by the larger square specimen (100x100)mm.

1. Introduction
Prediction of the settlements of shallow foundations has been more attention by geotechnical specialists. There are abundant methods for settlement estimation based on the elasticity theory, in-situ tests, semi-empirical and numerical modelling [1]. Elastic settlement occurs in sandy, silty, and clayey soils. Consolidation settlement occurs in cohesive soils due to the expulsion of the water from the voids. Because of the soil permeability, the rate of settlement may vary from soil to another. Also, the variation in the rate of consolidation settlement depends on the boundary conditions [2]. Sand deposit compresses immediately on load application, loose and dense sand deposits tend towards the same void ratio [3].

There is a growing body of literature that recognizes the importance of soaking process on the gypseous sand in Al-Najaf. Recently, there has been renewed interest in estimation of the settlement and collapse potential of sand soil with gypsum content from Al-Najaf city. The estimation depended on the laboratory tests on undisturbed soil samples using computerized Oedometer cell. Mahmood et al. (2018) investigated
the effect of soaking for different periods on the deformation of gypseous sand in Al-Najaf city using Oedometer testing, and they stated that there was increasing in the settlement due to soaking process, but no collapse according to Jennings and Knight (1975) criteria [4]. Mahmood (2018) tested the discrepancy in settlement of two neighbour points of different initial characteristics using laboratory work (Oedometer). He identified that the settlement discrepancy was eliminated with increasing the normal stress [5]. Mahmood et al. (2019) investigate the collapse potential of medium-high gypsum sand soil in Al-Najaf city under different soaking periods, and they concluded that with increasing of soaking periods and stress levels, there are increasing in collapse potential of such soils (from <1% to 8%) according to Jennings and Knight (1975) [6]. Mustafa et al. (2019) compared the settlement behaviour from soaked Oedometer samples with unsaturated triaxial test and they believe that there is a steep trend in strains in the unsaturated test with increasing in the saturation compared with the two-week soaking Oedometer test (-32.5% to +11% under stress from 2.5 to 5 kg/cm²) [7]. The soaking process is the main reason for the alteration of gypseous sand soil in Al-Najaf city. All researchers suggested that take cautions in selection and analysis of soil properties of such soils in the design of structures. The main disadvantage of the Oedometer cell is that there is an effect of side friction and shear stresses in the Oedometer test and can minimize this effect by keeping the ratio of thickness-diameter (H/D) of the specimen as small as workable (1/3) [8].

Voids were changed increasingly for higher gypseous soils upon leaching process [9]. In unsaturated soils, collapse potential of the soils increases upon soaking as a result of a reduction in matric suction [10,11].

There are many research made to predict the settlement of the foundation using physical and numerical modelling to minimize the cost and time. A very good fit in the load-settlement between applied pressures and in-situ penetration for different sizes of square footings at Texas A&M University [1]. A comparison was made between the settlement from the long-term measurement, and the neural network model of high-rise buildings and the relative difference of the prediction was ranged from about 0.91% - 2.11% [12]. A performed parametric statistics and finite element method study show that there is a direct relation from variability increasing of elastic modulus on the settlement and differential settlement while the variability of Poisson ratio can be neglected [13]. Novel grey forecasting model (NGM) to predict the settlement shows an excellent prediction accuracy [14]. Based on finite element package, there is a gave good estimations of foundation settlement using methods proposed by Canadian Foundation Engineering Manual, Burland and Burbidge, Schmertmann et al. and Mayne and Poulos among the 15 models [15].

Research on the subject has been restricted to limited comparisons of results. A much-debated question is whether the results of the settlement will be different in the other soil types, nature and sizes and shapes of soil specimens? The generalizability of much-published research on this issue is problematic. However, much of the research until now has been descriptive in nature of reliability analysis. A small physical model still cheaper and faster method in the prediction of the settlement behaviour. Uncertainty is unavoidable in geotechnical engineering, and this uncertainty may be caused by variability, measurement errors, and transformation uncertainty [16]. Reliability has been a slow but worldwide over the last two decades, there [17] and the reliability is the probability of success [18]. Reliability analysis shows that there is a higher probability of larger settlement values with the increasing variability of geotechnical properties at a site [19,20,21].

Different dimensions and shapes of small physical models are used in this paper to predict the settlement of the soil specimens from Al-Najaf city. This investigation aimed to verify the effect of the studied parameters of the prediction of the settlement using reliability-based analysis.

2. Work methodology

2.1. Soil sampling

Soil samples were taken from a nearby site of the Civil Engineering Department at the University of Kufa and from the site near the Faculty of Engineering Club, as in figure 1. All the tests were carried out in the
Soil Laboratory in the Civil Department / Faculty of Engineering at the University of Kufa. One disturbing sample was taken from the University of Kufa. Samples were at a depth of 0.25m from the soil surface after scraping the surface soil that may contain debris or materials that are not part of the soil composition to obtain a real more representative soil sample. The weight of the sample taken is about 20 kg.

**Figure 1.** Shows the sample’s site (Google Earth).

### 2.2. Identification of the soil

Figure 2 shows the gradient curve of natural soil grains. According to the USCS, the soil is SW type. The percentages of fines are 2.17%, the gravel percentages are 0.44%, and the sand ratio is 97.39%. Figure 3 shows the results of the standard Procter test for a soil sample, and the maximum dry density is 1.9 gm/cm³. The optimum moisture content is 11%. It can be observed that the maximum value falls within the range of 5-10% air content, although the density curve has not touched the air content curve by 0% and is identical to the results of the standard tests. The basic properties of the soil are shown in table 1. The result of the soil sulphate and gypsum test for the soil sample showed that the gypsum content is 5.3%. The gypsum content is equal to 2.15 * sulphate. The soil can be classified according to gypsum content as slight gypsiferous soils according to Barazanchi [22].

**Figure 2.** Analysis of the soil particles.
Figure 3. Results of the standard proctor test.

Table 1. Summary of the soil properties.

| Soil Characteristics               | Value       |
|------------------------------------|-------------|
| Gravel, %                          | 0.44        |
| Sand, %                            | 97.39       |
| Fine, %                            | 2.17        |
| D_{10}, mm                         | 0.15        |
| D_{30}, mm                         | 0.3         |
| D_{60}, mm                         | 0.6         |
| coefficient of uniformity (Cu)     | 4           |
| coefficient of curvature (Cc)      | 1           |
| Soil Classification (USCS)         | SW          |
| Field water content, %             | 3           |
| Max. dry density, gm/cm^3          | 1.9         |
| Optimum moisture content (OMC), %  | 11          |
| Gypsum content, %                  | 5.3         |

2.3. Methods

Oedometer one of the most well-known tools for assessing the value and rate of deformation for the soils. A case study approach is used to allow verification of sand soil deformation from different shapes and sizes of the specimens to ensure that there is (or not) an effect on the test results. Three sets of experimental tests were made on the soil sample in three different shapes and sizes of the specimens, 60 mm diameter Oedometer cell, 60x60 mm box container and 100x100 mm box container. The soil samples were remoulded in the selected specimens with three different density related to the maximum dry density, 100%, 95% and 92%. Figure 4 presents the tests program.
3. Results

Changes in settlement and time were compared for different relative compaction \( \text{RC} = \frac{\rho_{\text{dry}}}{\rho_{\text{dry, max}}} \) under different normal stress using the cylindrical and rectangular specimens. The first set of analyses examined the impact of relative compaction (RC). Figure 5 compares the experimental data on settlement versus time for the circular specimen (Oedometer cell or D6). The results indicate that the settlement is quick and little, where more than 75% of the final settlement occurred within a few seconds (less than 10 seconds). With decreasing the relative compaction of the sample, the settlement increases under the different normal stress, as expected.

Figure 6 presents the results of time-settlement of rectangular soil specimen, W6 (6x6 cm box) for different levels of normal stress and relative compaction, \( \text{RC} = \frac{\rho_{\text{dry}}}{\rho_{\text{dry, max}}} \). In a similar trend, the results indicate that the settlement is quick and little, where more than 75% of the final settlement occurred within a few seconds (less than 10 seconds). Also, as indicated in D6, with decreasing the relative compaction of the sample, there is little increase in settlement and this increasing be significant at higher stress. However, under the same level of normal stress, the resulted settlement values are lower than from Oedometer cell.

Figure 7 shows the results of time-settlement of the soil sample in W10 (10x10 cm box) for different levels of normal stress and relative compaction, \( \text{RC} = \frac{\rho_{\text{dry}}}{\rho_{\text{dry, max}}} \). Similarly, the results indicate that the settlement is quick and little, where more than 75% of the final settlement occurred within a few seconds (less than 10 seconds). As in previous experiments rectangular specimen, W6, with decreasing the relative compaction of the sample, the settlement increases, but with small differences, as unexpected. There are similar and approximately matched trends of settlement behaviour. The resulted settlement values are larger than from Oedometer cell under the same level of normal stress.
Figure 5. Settlement versus time from oedometer cell (D6) under different stresses and relative compaction (RC).

Figure 6. Settlement versus time from 6x6cm box specimen (W6) under different stress and relative compaction (RC).
Figure 7. Settlement versus time from 10x10cm box specimen (W10) under different stress and relative compaction (RC).

Table 2 presents the resulted final settlement versus stresses for each specimen D6, W6 and W10 and different relative compactions (RC). What stands out in the table is the obtained Δε from the preliminary analysis of deformation illustrated that there is a clear trend (increasing in Δε with increasing in the stress) from Oedometer cell (D6) under different stresses and relative compaction (RC), while the results from different boxes (W6 and W10) are misleading. This situation may be caused by the effect of side friction, weak corners and density homogeny issues of the box specimens.

4. Discussion

Depending on the results in table 2, figure 8 presents the relationships of void ratio (ε) versus stress from the different specimens (D6, W6 and W10) in relative compaction of 100% together for comparison purpose. The results illustrate that the larger square specimen (W10) achieve larger settlement values under a certain level of the normal stress, but, in the same trend of the Oedometer cell results. With decreasing of the relative compaction (95%), the 10x10cm specimen still gives the larger values of the settlement under certain normal stress level, as in figure 9, with an undefined trend.
### Table 2. Summary of total settlement and change in void ratio for the different soil specimens.

| Specimen Symbol | Stress Level, kPa | Relative compaction (RC), % | Total Settlement, mm | Total Settlement, mm | Total Settlement, mm | Total Settlement, mm |
|-----------------|------------------|----------------------------|----------------------|----------------------|----------------------|----------------------|
|                 |                  | 100 | 95 | 92 |                  | (S<sub>total</sub>/H) | (S<sub>total</sub>/H) | (S<sub>total</sub>/H) | (S<sub>total</sub>/H) |
| D6              | 32               | -0.090 | 0.0045 | -0.220 | 0.0110 | -0.480 | 0.0240 |
|                 | 64               | -0.220 | 0.0110 | -0.370 | 0.0185 | -0.580 | 0.0290 |
|                 | 128              | -0.440 | 0.0220 | -0.620 | 0.0310 | -0.800 | 0.0400 |
|                 | 257              | -0.850 | 0.0425 | -0.950 | 0.0475 | -1.240 | 0.0620 |
| W6              | 28               | -0.002 | 0.0001 | -0.089 | 0.0045 | -0.226 | 0.0113 |
|                 | 56               | -0.117 | 0.0059 | -0.197 | 0.0099 | -0.305 | 0.0153 |
|                 | 111              | -0.220 | 0.0110 | -0.343 | 0.0172 | -0.437 | 0.0219 |
|                 | 222              | -0.392 | 0.0196 | -0.495 | 0.0248 | -0.652 | 0.0326 |
| W10             | 20               | -0.202 | 0.0101 | -0.270 | 0.0135 | -0.369 | 0.0185 |
|                 | 40               | -0.360 | 0.0180 | -0.379 | 0.0190 | -0.472 | 0.0236 |
|                 | 80               | -0.565 | 0.0283 | -0.680 | 0.0340 | -0.605 | 0.0303 |
|                 | 160              | -0.766 | 0.0383 | -0.882 | 0.0441 | -0.757 | 0.0379 |

*Figure 8.* Void ratio versus stress for different specimens for relative compaction of 100%.
Then, with lower relative compaction (92%), the settlement values of specimens from the larger square (W10) and Oedometer cell are approximately coincided, as shown in figure 10. Even the larger square is contributed larger settlement values (as in high-relative compaction), but, practically the preparation of the specimens using Oedometer cell, without corners, is more easily and can be achieved more homogenous soil.

Further, statistical tests were made to correlate the change in the void ratio ($\Delta e$) for the different soil specimens (D6, W6 and W10) under corresponding stress and the results are presented as an $\Delta e$ ratio ($\Delta e_{D6}/\Delta e_{W6}$ and $\Delta e_{D6}/\Delta e_{W10}$). Table 3 illustrates the statistical analysis of the $\Delta e$ ratios. The analysis revealed that, as previously mentioned, there is a scattering in the $\Delta e$ from the W10 (10x10 cm box) in the condition of relative compaction of 100% ($R^2 = 0.374$), then, this scattering decreases with decreasing of relative compaction ($R^2<0.99$).
Table 3. Statistical analysis of the $\Delta e$ ratios.

| Relative compaction (RC), % | $\Delta e_{D6}/\Delta e_{W6}$ Mean | Standard Deviation | $\Delta e_{D6}/\Delta e_{W10}$ Mean | Standard Deviation | Correlation of values in (1) and (2), $R^2$ |
|-----------------------------|-----------------------------------|--------------------|-----------------------------------|--------------------|------------------------------------------|
| 100                         | 1.786                             | 0.16               | 0.457                             | 0.18               | 0.374                                    |
| 95                          | 2.008                             | 0.22               | 0.748                             | 0.08               | 0.992                                    |
| 92                          | 1.817                             | 0.09               | 1.145                             | 0.12               | 0.996                                    |

A probability density function (pdf) curves are produced depending on the mean and standard values in Table 3. These analyses (pdf) are made using the continuous random variable method with the aid of computer software named "Risk Tools (RT)" after Mahsuli, 2014 [23]. Figure 11. illustrates the pdf for the $\Delta e_{D6}/\Delta e_{W6}$ ratios for the different relative compactions (RC). All values are far from 1, and the maximum ratios occurred within RC equal to 95%, and there is no significant trend in the behaviour. With RC = 92%, the values of $\Delta e_{D6}/\Delta e_{W6}$ are near the mean value which indicates an approximately unique value of the ratio, while the values from RC = 100% and RC = 95% are not. For the ratios of $\Delta e_{D6}/\Delta e_{W10}$, there is a significant difference trend, and the values are under 1, but, with decreasing the RC up to 92%, the values of $\Delta e_{D6}/\Delta e_{W10}$ ratios increasing over 1 and the values near the mean value of the ratio, as shown in figure 12.

Overall, these results indicate that the change in the void ratio can be unexpected from the box specimens, while the void ratio is overestimated from the 10x10 cm specimen and underestimated from the 6x6 cm box. These results may be contributed by the different reasons, such as increases of side friction, non-homogeneity in the box specimens.

![Figure 11. Probability density function (pdf) for $\Delta e_{D6}/\Delta e_{W6}$ ratios and different relative compactions.](image-url)
5. Conclusions

Multiple sets of experimental tests were performed to study the effect of the specimen sizes and shapes (60 mm diameter Oedometer cell, 60x60 mm box container and 100x100 mm box container) on the settlement value and rate. Samples of sand soil with gypsum content were remoulded with three different density related to the maximum dry density, 100%, 95% and 92%, then subjected to four stress levels. Further, statistical tests were made to correlate the change in the void ratio ($e$) for the different soil specimens (D6, W6 and W10) under corresponding stress.

The results show that:

1. The larger square specimen (W10) achieve larger settlement values under a certain level of the normal stress.
2. There is a scattering in the $e$ from the W10 (10x10 cm box) in the condition of relative compaction of 100%, then, this scattering decreases with decreasing of relative compaction.
3. Moreover, because of unincreased of side friction and non-homogeny in the box specimens, results of a probability density function (pdf) curves indicate that the change in the void ratio is overestimated from the 10x10 cm specimen and underestimated from the 6x6 cm box.

6. References

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