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Footing Under Static Loading: Land Subsidence

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Abstract: Land and footing subsidence caused by groundwater extraction is a source of many problems for buildings and infrastructures. This study aims at extending the knowledge of footing subsidence causing by ground water pumping by considering various well and load conditions. The approach is to use PLAXIS simulation to investigate the influence of well conditions on the subsidence of surface footing subjected to combined distributed load. A number of soil models with plain strain, homogeneous and transient flow behavior were built. While the groundwater extraction rate was set up at 20 m^3/day for each well, the obvious influence of important parameters including well numbers, well location and load magnitude on footing subsidence and surface profile were investigated. It was found that increasing the number of wells will trigger greater footing subsidence, while the location of the wells will slightly affect the surface profile of both the aquifer and footing. In this study, the effect of distributed load above the footing to the footing itself was also investigated by doubling the distributed load applied. The simulation results showed that distributed load significantly contribute to the subsidence of footing.

Keywords: Subsidence, Footing, Load, Wells

Introduction

The phenomena of ground surface sinking as a result of overburden stress on the ground surface and over extraction of ground water has gained more attention worldwide (Chaussard *et al*., 2014). The excessive subsidence of footing has incurred widespread concern due to its influence on the stability and serviceability of foundations and the buildings above them. Factors such as the lowering of water levels, transported deposits, imposition of extra loading etc. will all cause subsidence of land and the footings established upon it. Among all of the subsidence triggers, the lowering of the water level is of particular concern due to the prevalence of water exploitation activities around the world arising from increasing water demand. Removal of water from soil layers, especially from compressible and highly permeable layers, will cause large and rapid land subsidence. Water pumping along wells is a typical means of groundwater exploitation.

A number of case studies have examined this issue. For instance, in Hanoi, various kinds of structures including roads and buildings have been damaged by settlement (Dang *et al*., 2014). Similarly, in Mexico heavy water pumping in the middle of city has caused extensive land subsidence in previous decades, resulting in severe harm to building foundations, transportation and sewage systems (Pacheco-Martínez *et al*., 2013). There have also been a number of other studies into municipal subsidence caused by lowering of groundwater levels (Shi *et al*., 2007; Zhang *et al*., 2014).

Increases in the effective stress and both permanent and irrecoverable settlements of underlying soil are believed to be fundamental mechanisms of land subsidence along with water pumping and the magnitude of subsidence depends on the increase in the effective stress and the decrease in the water head (Galloway and Burbey, 2011).

Budhu and Adiyaman (2010) established a governing formulation for stress changes in the case of groundwater pumping by dividing land subsidence into consolidation (vertical compression), shear displacement and macro rotation. Using this mechanism, Budhu (2011) studied earth fissure formation on a unconfined aquifer alluvium. Budhu and Adiyaman (2013) also find that number of clay areas and wells and their locations were considered to affect ground surface subsidence and profile (Budihardjo *et al*., 2014).

In considering the damage to footings that subsidence may cause, Shahriar *et al*. (2013) used laboratory testing and numerical verification to carry out a quantitative investigation of the influence of water table fluctuation on the settlement of various types of foundations. They also considered other parameters like soil density, stress level and foundation shape. It is important to numerically evaluate the characteristics and magnitude of influence caused by subsidence and its relevant parameters. Moreover, footings subject to different modes of load, such as bending and vertical pressure, may show different responses and have a different impact on the underlying soil when subsidence happens. These are the aspects that are investigated in this study. In Curtin University, Budihardjo *et al*. (2014) investigated a parametric study on clay zones effect on land subsidence. This study is part of a big project on subsidence in Curtin University. This study also extents the knowledge of footing subsidence by considering various well location and different load on footing.

Materials and Methods

Software

Curtin University's geotechnical software PLAXIS 2D was used for the numerical simulation in this study (PLAXIS 2D Software, 2012). PLAXIS is a computer program with the ability to calculate consolidation phenomena based on Biot's consolidation theory. This software can be used to analyze the deformation and characteristics of various soils in a way that approaches the actual behavior (Brinkgreve *et al*., 2010). The program has a user-friendly graphical interface, which enables the user to simulate various aquifer scenarios. The finite element method is used for the calculation of deformation analysis and various stability analyses for a variety of geotechnical applications. Also, based on a cross-section of the state, a mesh element and geometry model can be created, which allows the soil to be analysed sufficiently close to the input data. In this case, plane strain or axisymmetry can be used for modelling. The hydrostatic pressure of the soil is taken into account when groundwater is present. Triangular elements with a choice of six nodes (points) or 15 points are available in PLAXIS, which consists of four sub-programs, namely input, calculation, output and curves. It is widely accepted that results from PLAXIS are reliable. PLAXIS also has been used to analyse the association of soil and structural foundation (Huat and Mohammed, 2006).

Soil Model

Sand was selected to constiue the models. The sand has permeability 5×10^{-2} cm/sec, with effective fiction angle 35°C. Both the stress-strain behavior and the consolidation of the soil are taken into account in the model.

Simulation

This study investigated the influence of well number and well location on footing subsidence. A point load of 100 kN/m was applied on the left side of the footing and a bending moment of 100 kNm/m, plus two different distributed loads of 150 and 300 kN/m. The model area was 50×200 m. The well discharge rate was 20 m^3/day for each well. The well depth was 40 m below the surface in two cases. The initial groundwater level was set at 10 m below the surface at the beginning of all stages and a transient flow model was used throughout all models. In general, the control variables in the simulation were the pump rate, soil and footing parameters. Soe o f the important parameters which were monitored in the simulation were ground surface and ground water level changes.

Results

Single Well Model

The single well model was developed by placing one well on the right hand side of the soil area. The well face was located 30 m from the right end of the footing and about 70 m from the point where load was applied. The groundwater extraction was set at 20 m^3/day. The vertical displacement of the ground surface area at some points (3 nodes) was recorded. The detail result are presented in Table 1.

Two Wells Model

The two well model was created by placing a new well on the left hand side of the soil area. The second well was located 30 m from the left corner of the footing. The depth of the well was fixed at 40 m under ground and the extraction capacity of the well was 20 m^3/day. In total, 40 m^3 of groundwater was pumped out of the ground each day.

Model with Doubled Distributed Load

The effect of the magnitude of distributed load on footing subsidence for footings on sand aquifers with pumping wells was investigated. The distributed load on the footings was doubled to 300 kN/m for all single well, dual well and three well systems. The results are shown in Fig. 3 and 4 with the magnitude of deformation for significant points listed in Table 3 and 4.

Discussion

Effect of Well Numbers/Locations

According to Fig. 1, the maximum deformation hap.pens at node 475, located in the middle of the footing, with a deformation of 152.262×10^{-3} m. The left hand edge of the footing (node 691) deforms more than the right hand verge as a result of a point load and bending moment applied in left hand verge of the footing. Interestingly, there was more displacement occur in the right hand side area of the soil model which is slightly more than displacement on the left hand side of soil model. This is assumed to have been caused by an imbalance of the water head. The water level in the right side of soil model is lower than left area due to the location of pumping well. The footing was subjected to relatively lower displacement compared to the neighboring soil profile.

When two wells are installed symmetrically with respect to the centre of the footing, the maximum vertical displacement also occurs at node 404 (Fig. 2), which is also the centre of the footing. From the PLAXIS results, the maximum displacement was 163.78×10^{-3} m (Table 2), slightly higher than that of the one well system discussed above. Also, the water table was a bit lower and level after pumping compared to the single well system, which corresponds well to the greater subsidence compared to Fig. 1 and Table 1. In theory, this could have been due to a higher effective stress and grain repositioning. However, the location corresponding to the lowest point of the water table is not where the maximum displacement occurs. According to the surface profile, the displacement increases when the point approaches the centre of the footing. The surface profile is generally sagging in the area where the footing is placed. On the other hand, land subsidence simulation without any footing or load created the lowest sagging area close to the wellhead location (Budihardjo *et al*., 2014).

Table 1. Data of the points on the surface profile of Fig. 1

Node	y deformation (10^{-3} m)
691	127.641
475	152.262
311	115.498

Table 2. Data of the points on the surface profile of Fig. 2

Node	y deformation (10^{-3} m)
729	149.066
404	163.788
307	127.770

Table 3. Data of the points on the surface profile of Fig. 3

Node	y deformation (10^{-3} m)
691	193.184
475	252.245
311	180.621

Table 4. Data of the points on the surface profile of Fig. 4

Node	y deformation (10^{-3} m)
729	149.066
404	163.788
307	127.770

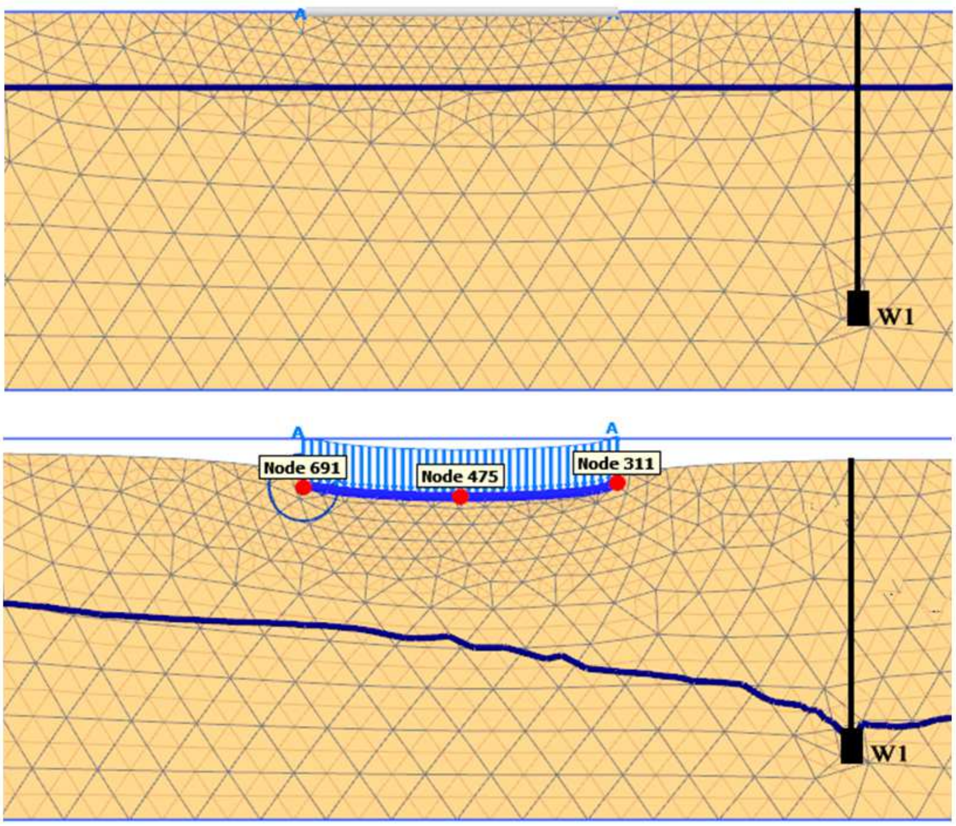

Fig. 1. Initial mesh (upper image) and final deformed mesh (lower image) of single well model with distributed load of 150 kN/m

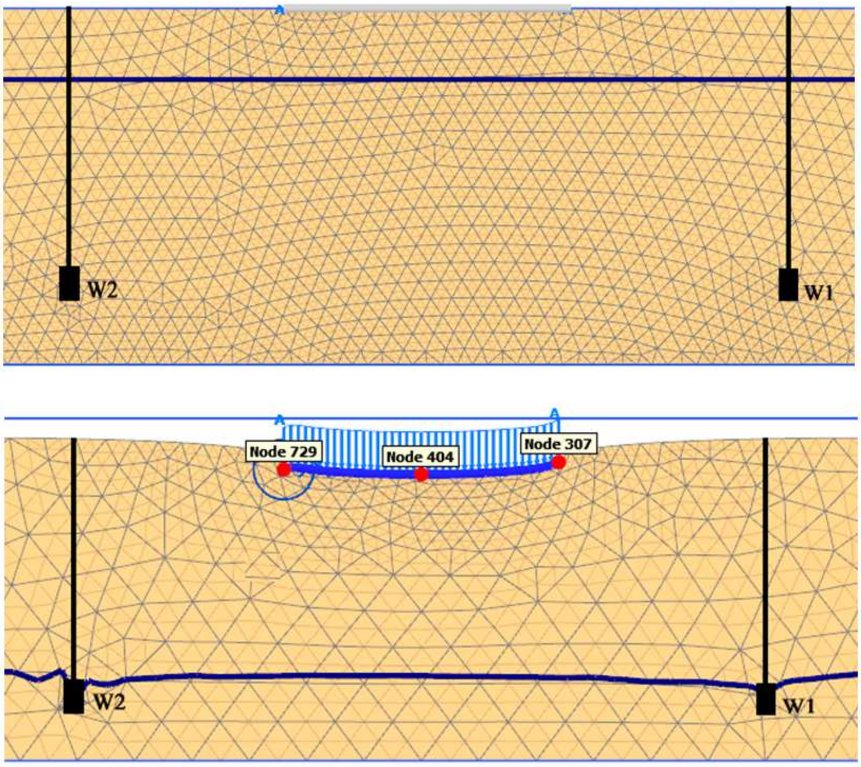

Fig. 2. Initial mesh (upper image) and final deformed mesh (lower image) of two well model with distributed load of 150 kN/m

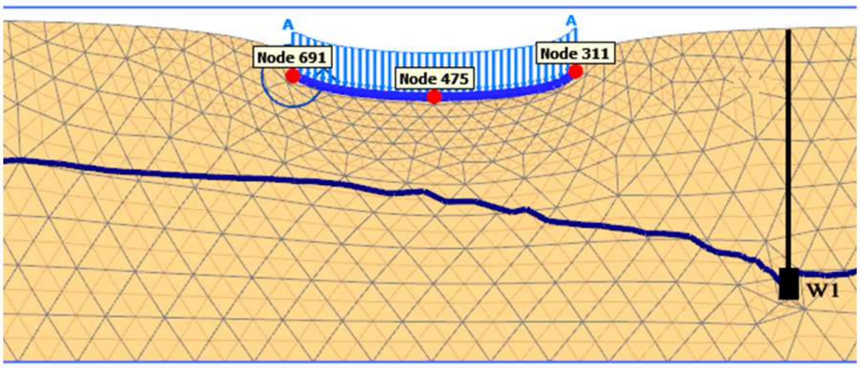

Fig. 3. Deformed mesh of one well model with distributed load of 300 KN/m

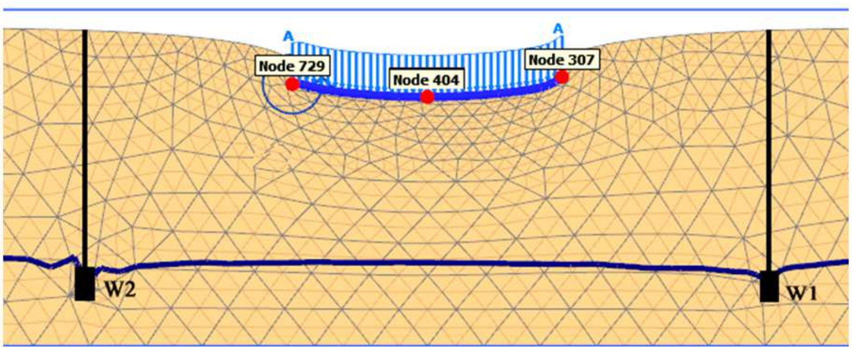

Fig. 4. Deformed mesh of two well model with distributed load of 300 KN/m

Effects of Load Magnitude

Compared to the figures and tables illustrating the results for the models with a distributed load of 150 kN/m, the profiles for both the surface and footing for one and two systems remained the same. There was no change in symmetry or location of maximum subsidence for the models with the same well conditions but a different distributed load. For instance, both Fig. 1 and 3 (one well system) showed a sagging surface profiles in the footing area and the centre of footing as the location of maximum footing subsidence. Similar comparisons can be found between Fig. 2 and 4.

The magnitude of subsidence increased with the increase in load. For example, the centre of the footing (node 475) in Fig. 3 and Table 3 showed a vertical deformation of 252.245×10^{-3} m, which is much greater to that seen in Fig. 1 and Table 1 (node 475) with the subsidence difference between those two points is about 99.983×10^{-3} m.

The same results can also be found between corresponding points between points in Table 2 and 4. There are some values which vary slightly with each other, moreover, in the left and right edge areas of soil model, but these are negligible for the purposes of drawing a conclusion, since it is obvious they are due to inevitable computational variations.

As a result, the subsidence of footing is mainly affected by the load applied into the footing. Interestingly, even the applied load was distributed along the footing, however, more subsidence occurs in the middle of the footing compared to any other area. In the mean time, pumping wells and how much water is extracted has been lowering the water table and causing an increase in effective stress and vertical deformation along the ground surface area.

Land Subsidence Prevention

It is very useful to perform a regular measurement of ground water level to monitor pumping effect on ground water level. The data then can be analysed to develop local groundwater mapping which consists of discharge and recharge areas (Anomohanran, 2013). As an instance, in one of the research which was conducted by Sundara Rajulu and Rajani (2012) a geo-information system of ground water identification was developed using neural network and component analysis, which can also be used to monitor the ground water availability.

Furtheremore, instead of using advance technology, the ground water level monitoring can also be performed by a simple method which involving a number of control wells which function like piezometers. This method has also been widely applied by the landfill operator to control the concentration of pollution as well as measuring the ground water level (Benmenni and Benrachedi, 2010).

In order to reduce the potential of land subsidence which mostly occur in rapid development cities, urban management planning should consider ground water extraction policy and engage soil modelling approach to simulate any potential issues toward development of a city involving structural construction. A heavy structural construction which contribute to overburden stress on the ground surface should be precisely calculated and anticipated using computational simulation. Groundwater extractions should be taken into account as part of urban planning (Russo and Taddia, 2009). Soil simulation will be very useful tool to help avoiding potential problems related to land subsidence and structural failure in respect to ground water extraction.

Conclusion

PLAXIS software was used to investigate the influence of pumping well conditions on the subsidence of footing subjected to combined load conditions. Two PLAXIS models including one and two wells were made and the results of surface and footing deformation were presented in figures and tables. The following is a list of findings from this research:

- All well system has a generally even and symmetric surface profile with maximum subsidence at the centre of the footing
- Footing subsidence increases with the number of wells, with a two well system incurring much greater subsidence than a single well system
- On the scale investigated, changing the distributed load on the footing has great effect on the footing subsidence and the maximum footing subsidence occurs at the centre of the footing
- The well conditions described previously are the dominant factors affecting the behavior of the entire sand aquifers deformation with pumping wells

Future research should investigate other influences on footing subsidence, including the dynamics or earthquake load, the magnitude of water table influence, different footing shapes/rigidity, different soil types etc.

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Author's Contributions

Mochamad Arief Budihardjo: Participated in modelling development, helped in the result analysis and contributed to the writing of the manuscript.

Su Yang: Participated in modelling development, helped in the result analysis and contributed to the writing of the manuscript.

Amin Chegenizadeh: Provided the research idea/plan, coordinated the research, helped in the result analysis, coordinated and contributed to the writing of the manuscript and provided critical review of the manuscripts.

Hamid Nikraz: Provided the research idea/plan, helped in the result analysis, coordinated the research, contributed to the writing of the manuscript and provided critical review of the manuscripts.

Ethics

This article is original and has not been published anywhere else. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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