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Land Subsidence: The Presence of Well and Clay Layer in Aquifer

¹Mochamad Arief Budihardjo, ²Amin Chegenizadeh and ³Hamid Nikraz

¹PhD candidate of the Department of Civil Engineering, Curtin University, Perth, Australia

²Researcher at the Department of Civil Engineering, Curtin University, Perth, Australia

³Professor at the Department of Civil Engineering, Curtin University, Perth, Australia

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ABSTRACT

Background: In general, the aquifer may contain a combination of different soil types. Response of the aquifer toward the changes of ground water level due to groundwater extraction depends on the characteristics of the soil constituent in the aquifer. Moreover, aquifer containing a combination of grain and fine soil, such as sand and clay which are completely different in the permeability coefficient, tends to react differently due to any change of the groundwater level. **Objective:** This paper aims to investigate land subsidence due to pumping. As part of this research, different clay zone thicknesses and types (i.e. continues and non-continues) were evaluated and examined. Wells were also inserted in different locations in the clay zone, a discharge rate applied at rate of 20m³/day and land subsidence measured. In this article, the difference of surface layer deformation response of some sand aquifers containing clay were investigated by using a finite element model. Several scenarios of aquifers alteration, such as the size of the clay layer, number of clay zone, variations in groundwater levels, location and number of wells and also changing of the groundwater levels were analysed using Plaxis 2D (a finite element software). In the simulation, groundwater discharge was determined at 20 m³/day and pumping time was prescribed for 5 years. **Results:** The results indicate that groundwater changes will trigger surface deformation in each simulated aquifer. However, the deformation of the ground surface in each aquifer is varies. It is obvious that the presence of clay layer in the aquifer influence the response of soil surface deformation after the groundwater was pumped for 5 years. The location and the number of wells also affect the degree of deformation of the ground surface. The thickness of clay layer and the number of clay zone also contribute on the change of the surface aquifer shape. **Conclusion:** It can be expected that the surface of the ground surface around the well sagging much more than the surrounding areas, the aquifer contains low- permeability layers underneath. Considering its effect on municipal areas, land subsidence resulting from excessive groundwater withdrawal must become an integral part of the urban planning process to achieve sustainable planning.

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INTRODUCTION

Land subsidence is an important issue in engineering, and as such has been a topic of interest to many researchers. Bergado *et al.*, (1987), Leake (1991), Nguyen and Helm (1995), Abidin *et al.* (2008; 2012), Budhu (2011), Xu *et al.* (2012) and Budhu and Adiyaman (2013) have investigated land subsidence resulting from a decreasing water table due to the pumping of water through a well system. . The results of the study describe the general cause of land subsidence include: declining of groundwater, aquifer compaction in clay, mining and sediment compaction, compression alluvial deposits naturally, heaps of soil and load building.

In the most recent work in this area, Budhu and Adiyaman (2013) investigated land subsidence by comparing a field study and simulation of the clay zone in one case. In reality, the clay zone may have different characteristics and as a consequence this study mainly concentrates on the different clay zone properties (i.e. size, patterns) and their effects on land subsidence. During this research, a number of wells were inserted at different locations to see whether or not they had a significant effect. The results will help the reader to evaluate the clay zone effect.

Terzaghi (1925) and Biot's (1941) equations can be used to calculate the effective stress changes (Terzaghi, 1925 and Biot, 1941). The equations can be applied to estimate land deformation in saturated and elastic conditions. In reality this can be challenged by the plastic behaviour of soil due to water removal, or in other

Corresponding Author: Mochamad Arief Budihardjo, PhD candidate of the Department of Civil Engineering, Curtin University, Perth, Australia.

words, due to pumping from a well nearby. As Budhu and Adiyaman (2010) reported, the expectation is that places close to the well will be affected more due to cone depression. Cone depression by itself will generate a large amount of land subsidence.

The importance of investigating the behaviour of soil due to pumping is clear. One area of interest to many researchers is the way that the patterns of clay zones and well location can affect land subsidence. The development of the finite element method (FEM) and computational tools make this effect easier to investigate. In the next section, the authors will consider the different patterns and properties of the clay zone.

MATERIALS AND METHODS

Software:

The study was conducted using a numerical simulation of geotechnical software PLAXIS 2D. The PLAXIS 2D software used to run the simulation was provided by Curtin University Australia. PLAXIS is a computer program that has ability to calculate consolidation phenomena based on Biot consolidation theory. This software can be used to analyse the deformation and the characteristic of various soil that can approach the actual behaviour (Plaxis, 1998). The program performs calculations based on the finite element method which is used specifically to analyse the deformation and stability for a variety of applications in the geotechnical field. The condition can actually be modelled in plane strain or in axisymetris. The hydrostatic pressure of the soil needs to be taken into account for the analysis involving the presence of ground water. This program implements the graphical interface method and can be classified as user-friendly software which is easy to use and allows the user to modelling the aquifer in various scenarios. It also can create the geometry model and the mesh element based on the cross-section of the state. The geometry allows the soil to be analyzed closely enough to be inputted. PLAXIS uses triangular elements with a choice of 6 nodes (points) or 15 points. The program consists of four sub-programs, namely input, calculation, output, and curves. The result of the analysis is quite accurate and reliable.

Soil Model:

The developed models simulate aquifer containing two different materials which are sand and clay. The sand represents non-recoverable soil while clay corresponds to recoverable soil. The properties of materials modelled are shown in Table 1. The entire model also links stress-strain behaviour and consolidation of the soil.

Table 1: The properties of sand and clay.

Soil type	Permeability k (cm/sec)	Effective angle of friction ϕ' (o)	γ_{sat} (kN/m ³)	Cohesion c_{ref} (kPa)	Poisson ratio ν	Initial void ratio e_0
Sand	5×10^{-2}	40	20	0	0.25	0.5
Clay	4.75×10^{-7}	30	18	30	0.3	1.1

Simulation:

In this paper, the effect of the size of clay zones as well as the number of clay zones present will be considered as other factors influencing changes in the formation of the ground surface. The scenarios proposed in this paper were developed based on previous work conducted by Budhu and Adiyaman (2013). Table 2 and Fig. 1 show the details of the scenarios simulated in this article. The first phase examined the effect of groundwater extraction in pure sand aquifers. The next simulation modelled a sand aquifer with a clay area underneath. Two different stages were performed in this simulation. The first stage set the water level at 10m below the surface while the second stage lowered the water level to 10m under the clay area. The next scenario examined the effect of clay zone size. Two different sizes of clay zone (thinner and thicker) were considered in the model. The effect of the number of clay zones was examined by introducing three clay zones into the sand aquifer, followed by groundwater extraction with one and two wells.

Table 2: Simulations of aquifers and proposed conditions.

Scenario	Phase	Well
Sand aquifer	Initial stage + transient from pumping	One, in the middle of aquifer
Sand aquifer, one clay zone	Initial stage + transient from pumping	One, in the middle of aquifer
	Initial stage + transient from pumping + GWL below the clay	One, in the middle of aquifer
	Initial stage + transient from pumping	Two, one in the middle of aquifer and another within 200m
Sand aquifer, one thinner clay zone	Initial stage + transient from pumping	One, in the middle of aquifer
Sand aquifer, one thicker clay zone	Initial stage + transient from pumping	One, in the middle of aquifer
Sand aquifer, three clay zones	Initial stage + transient from pumping	One, in the middle of aquifer
Sand aquifer, three clay zones	Initial stage + transient from pumping	Two, in the middle of clay zone 1 and 2

Fig. 1 shows the illustration of each scenario modelled in this simulation. The main aquifer proposed in this simulation was sand aquifer with 150m of depth and 800m of length. The groundwater extraction was executed by installing the pumping well in 140m of depth. The pumping capacity of the well was 20m³/day. Once another extra well where placed in the model, the total capacity of ground water extraction was become 40 m³/day. To simulate the change of the ground water level, the ground water flow was set up to transient groundwater flow. Meanwhile, the initial groundwater level was set up at 10m below the ground surface. To examine the effect of the presence of low permeability soil in the sand aquifer to the ground surface deformation, a clay zone was placed in 40 m below the ground surface. The effect of ground water level to the land settlement was also examined by lowering the groundwater level to 10m below clay zone. The effect of well location and pumping rate toward surface deformation was also examined by introducing an extra well in another location. In this paper, the effect of the size of clay zones as well as the presence number of clay zones was also considered as other factors influencing changes in the formation of the ground surface.

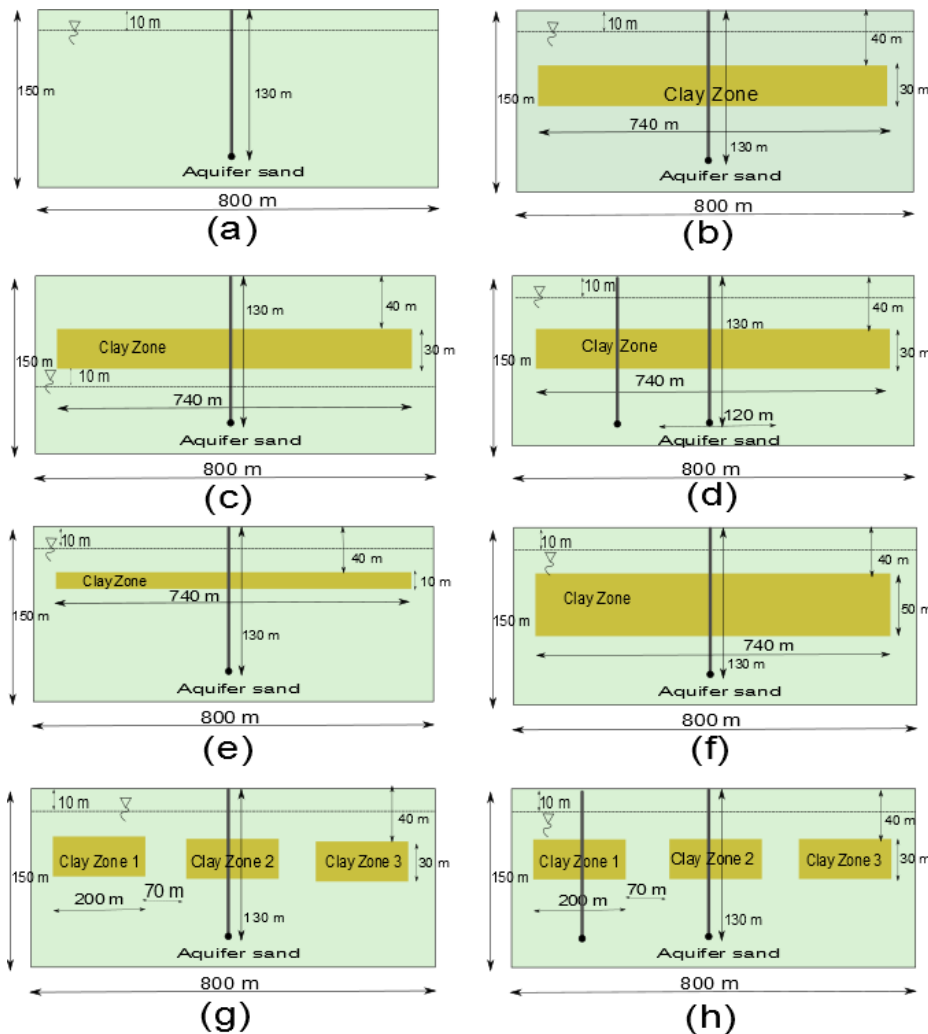


Fig. 1: Aquifer scenarios: (a) sand without clay, (b) sand with one continuous clay zone, (c) sand with clay and low groundwater level, (d) sand with clay and two wells, (e) sand with thinner clay zone, (f) sand with thicker clay, (g) sand with three thicker clay zones, (h) sand with three clay zones and two wells.

RESULT AND DISCUSSION

Ground surface deformation:

The initial shape of the homogenous sand aquifer is shown in Fig. 2(a). The surface of the sand aquifer was assumed to be flat along its area. A well was placed in the middle of the aquifer with a depth of 140m. The initial groundwater level was set up at 10m below the surface. The groundwater extraction was set up for five years at a rate of 20m³/day. Once the pumping commenced, the groundwater level started to drop and trigger the sand aquifer to shrink in the direction of the well location, causing the ground surface to deform. A noticeable change of ground surface level after five years of pumping is shown in Fig. 2(b). The maximum ground surface

deformation of 1.135m in the sand aquifer occurred in the area close to the well face. Meanwhile, there was less settlement in the area further away from the well.

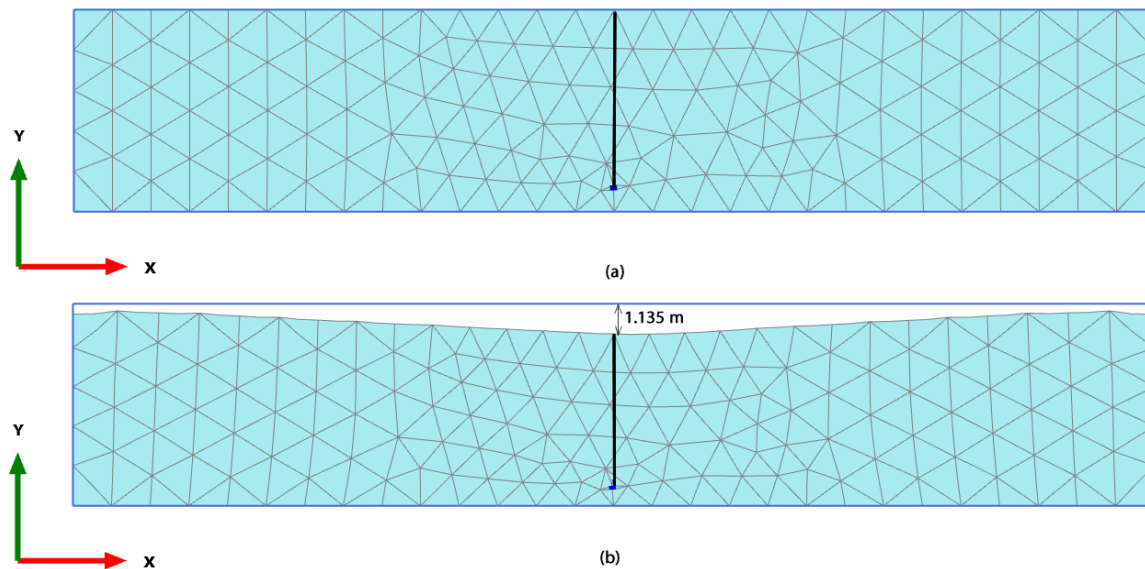


Fig. 2: The changes in the ground surface of a sand aquifer (a) before pumping and (b) after pumping.

The effect of the presence of a clay zone on land subsidence is depicted in Fig. 3, which shows that developments in the sand beneath the clay layer appear to draw the clay zone downward. The downward vertical movement of the surface area, following the clay zone, is also shown. In the sand aquifer with one large clay zone, the land surface deformation seemed to happen along the surface area with an estimated maximum displacement of about 1.510m. The maximum subsidence also occurred close to the well face. By contrast with the pure sand aquifer, the presence of a clay zone appears to trigger greater settlement in the ground surface area.

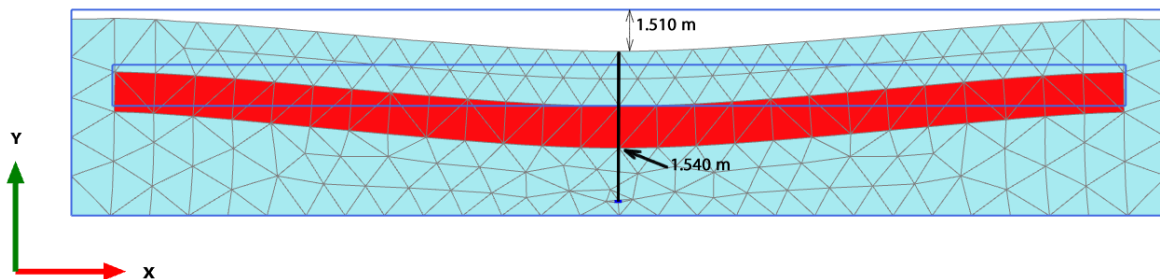


Fig. 3: Land subsidence in a sand aquifer containing one large clay zone.

Effect of groundwater level alteration and additional pumping well:

The effect of groundwater level was examined by lowering the groundwater level to below the clay layer. It was expected that the change in groundwater level would affect the ground deformation pattern. The saturation level of the sand was expected to be lower than for the previous simulation. The groundwater extraction rate was maintained at $20\text{m}^3/\text{day}$. After five years of groundwater pumping, the deformation of the sand-clay aquifer with an initial groundwater level below the clay layer showed a significantly different pattern (Fig. 4), with the ground tending to settle evenly along its surface area. The ground surface displacement was between 2.807 and 2.944m. Surprisingly, the maximum deformation occurred in the area most distant from the well location. The clay layer displayed the same displacement pattern as the ground surface. By examining the deformation of the mesh, it can be seen that pore stresses also arise in the area below the clay layer.

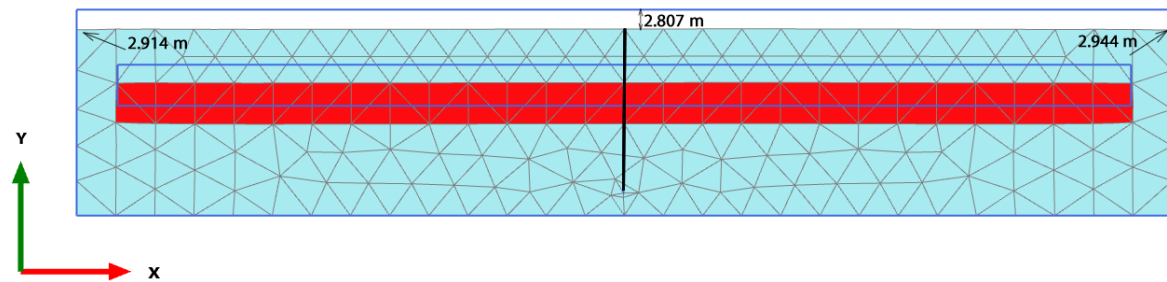


Fig. 4: Effect of lowering the groundwater level upon the deformation of the ground surface.

Fig. 5 shows the results of the simulation of a sand aquifer containing clay, where an additional well was placed about 200 metres from the existing well in the middle of the aquifer. The purpose of this simulation was to investigate the effect of well location and excessive groundwater extraction upon ground surface deformation. The groundwater level was maintained at 10m below the surface in order to achieve a fully saturated clay zone. Both pumping wells extracted water at a rate of $20\text{m}^3/\text{day}$ for five years. The result shows that the maximum ground surface settlement of 3.453m occurred in the area between well face 1 and 2. The shape of the surface seems to be wavy with less deformation occurring near the edge of the area. The deformation in both edges of the area seems about the same, but the left edge area has settled more than the right edge area. This could be because well number 1 was installed on the left side of the aquifer. It is also possible to see that a similar pattern of deformation occurred in the clay layer, with the clay zone becoming significantly deformed after excessive groundwater extraction.

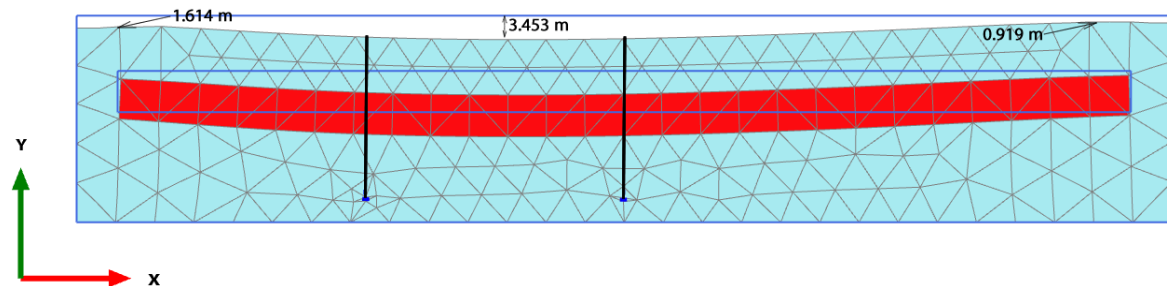


Fig. 5: Effect of additional well upon ground surface deformation.

Effect of clay zone dimensions upon surface deformation:

The effect of clay zone dimensions upon ground surface deformation was examined by modifying the thickness of the clay zone. In the first simulation, the thickness of the clay zone was reduced from 30m to 10m (Fig. 6) and then followed by an increase in thickness to 50m (Fig. 7) for the following scenario. The groundwater level was set up at 10m below the ground surface, and the groundwater was extracted by one pumping well at a rate of $20\text{m}^3/\text{day}$ over 5 years. For the thinner clay zone simulation, the maximum displacement was approximately 2.630m and occurred in the middle of clay zone around the well face. The clay zone became deformed in a similar manner when groundwater extraction was simulated. The changes in the ground surface on the top of the clay layer area can be seen in Fig. 6. The change of clay thickness from 30m to 10m affected the deformation. Compared to the previous simulation, which employed a pure sand aquifer and a sand clay aquifer with 30m of thickness, the thinner clay layer seems to trigger more surface deformation.

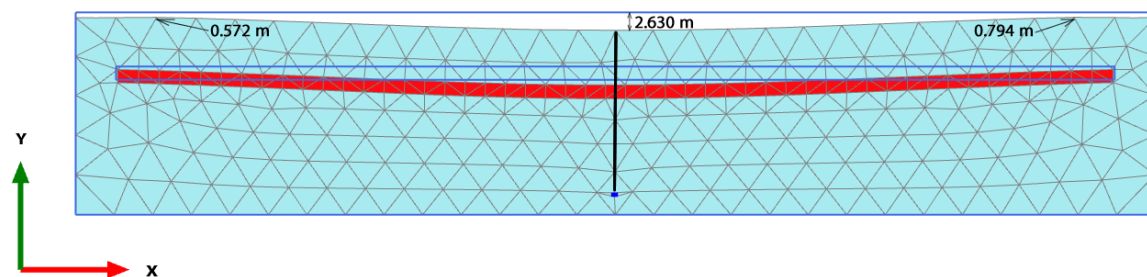


Fig. 6: The ground surface deformation in an aquifer with a thinner clay zone.

The following simulation (Fig. 7) was also performed to examine the effect of a thicker clay zone upon land settlement, compared with that of thinner clay zones (10 and 30m). To simulate the proposed scenario, the clay zone thickness was increased to 50m. The groundwater level also was also set up at 10m below the surface and

pumped out at $20\text{m}^3/\text{day}$ for five years. The pump was located in the middle of the aquifer. This scenario results in a similar surface deformation pattern to that of the previous model (clay zone of 30m and 10m in thickness). However, the ground surface showed greater deformation than in the previous simulation, with a maximum deformation in this simulation of about 2.840m.

The next scenario modelled three clay zones in a sand aquifer (Fig. 8). The initial groundwater level was 10m below the surface. The well was located beneath clay zone 2 and was pumped at a rate of $20\text{m}^3/\text{day}$. Surprisingly, the pattern of ground surface deformation in this scenario was similar to the previous simulation (Fig. 7), and the maximum surface deformation was exactly the same, at 2.840m.

In the final scenario, an extra well was placed in a sand aquifer containing three clay zones. Fig. 9 shows the subsidence of the three clay zones, all of which affect the ground surface level. In the sand aquifer with three clay zones, the maximum displacement was about 1.627m and was located in between the first and second clay zone. Other marked surface movement did occur on the ground surface above the left side of clay zone number 1.

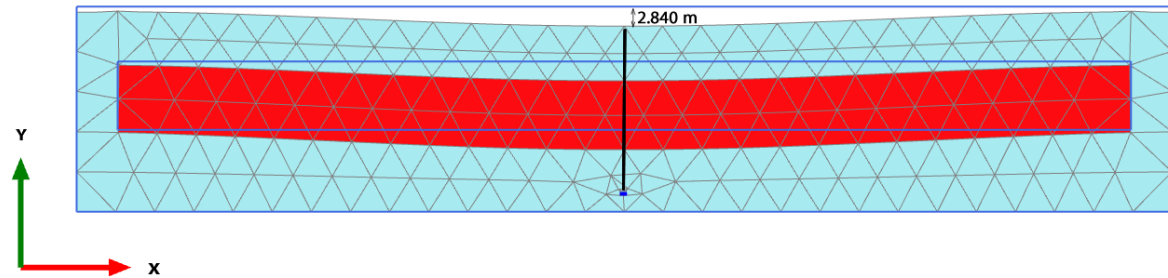


Fig. 7: The ground surface deformation in an aquifer with a thicker clay zone.

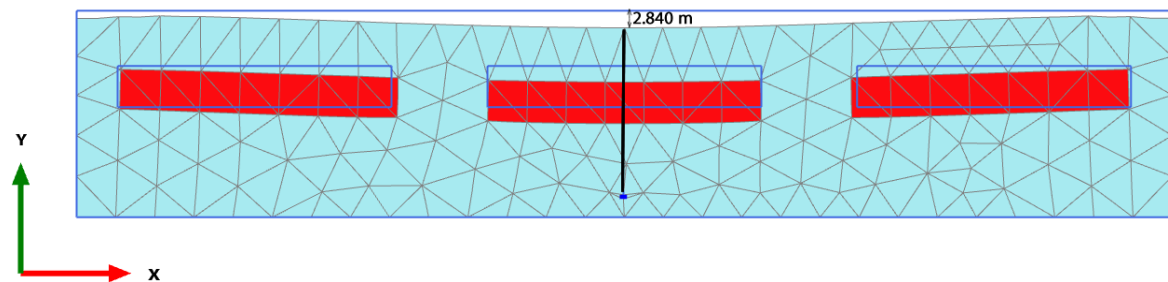


Fig. 8: Land subsidence in an aquifer containing three clay zones and one well.

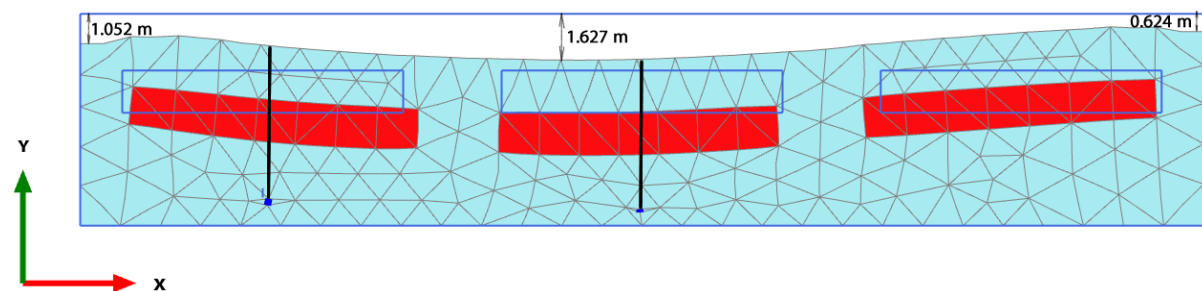


Fig. 9: Land subsidence in an aquifer containing three clay zones and two wells.

A brief comparison of each developed model is presented in Table 3. The greatest surface deformation occurred in the sand aquifer containing a clay layer of 30m thickness and two wells. The total groundwater extraction in this model was $40\text{m}^3/\text{day}$. Surprisingly, the aquifer model with three clay zones, each 30m thick, and two wells with a cumulative pumping rate of $40\text{m}^3/\text{day}$, showed a maximum surface deformation of only 1.627m. This suggests that an elongated and continuous clay zone may cause more deformation to the aquifer surface than no-continuous clay zones when the groundwater is pumped at the same rate. The results also suggest that a sand aquifer without any clay layer underneath is more stable and generates less surface deformation compared to a sand aquifer containing clay.

Previous research (Nguyen and Helm, 1995; Abidin *et al.*, 2008, 2012) has reported excessive groundwater withdrawal as being one of the factors in the triggering of ground surface deformation in municipalities. The consequences of ground surface deformation in urban areas can be varied, and may include damage to buildings and infrastructures, expansion of flooding areas and failures in drainage systems. Furthermore, land subsidence can also degrade the quality of community health and sanitation along with creating increased costs for infrastructure maintenance (Primanita, 2010). The effects of land subsidence can be not only direct or indirect,

they are also costly and far-reaching. It is therefore essential that they be taken into consideration in the urban planning process.

The application of the modelling of land subsidence prediction plays a significant role in urban planning. Land subsidence models can be used to directly discover the characteristics of land subsidence and to ascertain the magnitude and rate of land subsidence in urban areas. These models indirectly assist the urban planner to anticipate the causes and impact of land subsidence and they assist in the estimation of economic losses from land subsidence. They also support the urban planner in regulating groundwater extraction, developing flood mitigation plans, controlling sea water intrusion, organising sub-surface utilities, considering spatial planning, proposing environmental conservation, designing infrastructure and construction and plotting sewerage and drainage systems (Abidin *et al.*, 2012). In order to establish sustainable urban planning, land subsidence scenarios should be performed predominantly in those urban areas where there is a combination of high and low permeability aquifers underneath the ground surface.

Table 3: Comparison between scenarios.

Aquifer	Clay Thickness (m)	GWL	Number of Clay Zones	Number of Wells	Max. Surface Deformation (m)	Surface shape
Sand	N/A	Above clay zone	1	1	1.135	Lowest sagging area is close to the well
Sand-Clay	30	Above clay zone	1	1	1.51	Lowest sagging area is close to the well
Sand-Clay	30	Below clay zone	1	1	2.807	Nearly flat
Sand-Clay	30	Above clay zone	1	2	3.453	Lowest sagging area is close to the well
Sand-Clay	10	Above clay zone	1	1	2.63	Lowest sagging area is close to the well
Sand-Clay	50	Above clay zone	1	1	2.84	Lowest sagging area is close to the well
Sand-Clay	30	Above clay zone	3	1	2.84	Wavy, lowest area is close to the well
Sand-Clay	30	Above clay zone	3	2	1.627	Wavy, sagging in between wells

Conclusion:

The fine-grain material composition of aquifers, groundwater level, rate of groundwater extraction, well location and the dimensions of the fine layer all affect the amount and the rate of land subsidence. There was considerable consistency in ground surface appearance after groundwater pumping under all conditions except for the low initial groundwater level. A wavy ground surface as a result of surface deformation appears in aquifer where the groundwater extraction took place. Increasing the groundwater extraction rate will speed up the surface deformation process. Ground surface subsidence will continue to take place even the low permeability materials are far away from the well location. Saggy ground surface could be one indication of the present of low permeability material in the aquifer. Considering the drastic effect on municipalities, land subsidence resulting from excessive groundwater withdrawal must become an integral part of the urban planning process in order to create and/or maintain sustainable planning.

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