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Modeling compaction of multi-layer-aquifer system due to groundwater withdrawal

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ABSTRACT

Excessive groundwater extraction in a sedimentary environment can result in subsidence, which not only deteriorates land and agricultural resources but also endangers public infrastructure. Subsidence can be contributed by compaction in different layers. Clarifying the causes and estimating the amount of compaction remain a challenge for a multi-layer aquifer system with spatially and temporally varying pumping activities. A distributed model that comprises an analytical quasi-three-dimensional groundwater model and a one-dimensional deformation model is proposed to model the groundwater flow and deformation for a multi-layer aquifer system. Using the analytical solution, the groundwater level variation around a pumping well can be adequately modeled and then the compaction of soil layers can be calculated. Superposition allows the results to be extended to a system with multi-well and/or multi-layer pumping. The integrated model was applied to Yuanchang, in the center of the Yunlin subsidence area, Taiwan. Data of groundwater level and compaction at aquifers 2 and 3 in dry-season periods were used to explore the pumping effects on compaction. The results show that single-layer groundwater users are responsible for the large-area compaction and that significant local compaction can be attributed to multi-layer users. Constraining multi-layer pumping activities and reducing the amount of groundwater exploitation are required to mitigate the subsidence in Yunlin.

1. Introduction

Land subsidence is the gradual settling or sudden sinking of the Earth's surface. It has occurred in many areas of the world (Galloway and Burbey, 2011), such as the United States (Galloway and Hoffmann, 2007), Mexico (Lopez-Quiroz et al., 2009), Japan (Munekane et al., 2008), Italy (Teatini et al., 2005), China (Hu et al., 2009), and Taiwan (Hu et al., 2006). Subsidence deteriorates scarce resources, endangers public infrastructure, and leads to significant economic loss (Galloway et al., 2013). Moreover, land subsidence is essentially an irreversible process.

Land subsidence can be natural or anthropogenic, local or extensive, sudden or gradual, and minor or significant. Most subsidence is caused by groundwater withdrawal. For example, more than 80% of the identified existing subsidence in the United States is due to the exploitation of groundwater (Galloway et al., 1999). The subsidence area in Taiwan is one tenth of the total plain area (about 2400 km^2), with the largest subsidence being 3.4 m, which occurred after massive groundwater use in 1970 (Hung et al., 2012). Increasing worldwide demand for land and water resources exacerbates existing land subsidence problems and initiates new ones (Galloway et al., 1999).

Subsidence due to groundwater withdrawal in sedimentary environments can be attributed to the compaction of soil layers. The magnitude and location of compaction are sensitive not only to the formation properties but also to the amount of extracted groundwater and the layers where groundwater was taken. Quantitatively identifying the cause of compaction of a soil layer is key to mitigating or preventing further subsidence. This remains a challenge for areas with complicated sedimentary structures and multiple groundwater users.

Compaction exhibits complex behavior that is related to primary consolidation or secondary compression. Primary consolidation results from the gradual dissipation of excess pore water pressure. Secondary compression is a continuing settlement even after all excess pore pressure has been dissipated. Secondary compression can be caused by creep (Augustesen et al., 2004; Zhang et al., 2010), viscous behavior of the clay–water system (Takeda et al., 2012), compression of organic-rich soil (Al-Shamrani, 2005; Puppala et al., 2007; Venda Oliveira et al., 2012), microstructural change in soil (Delage and Lefebvre, 1984), and other processes. For coarse material such as sand, settlement caused by secondary compression is small, but it is significant for peat and thick aquifers.

The mechanism of soil compaction can be explained by the principle of effective stress (Terzaghi, 1925). Effective stress is the average stress carried by the soil skeleton. Associated with the pore water pressure, the effective stress supports the total loading that is attributed from

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solid material and fluid. When the total stress is given, groundwater extraction causes a decrease in pore water pressure and results in an increase in the strain and effective stress, which compress the soil skeleton and thus compact the stratum.

The relation of strain and stress controls the soil deformation behavior. Various strain–stress models have been proposed, including the elastic model, plastic model, viscous model, and their combinations (Zhang et al., 2012). The elastic model shows reversible stress–strain behavior. The plastic model shows irreversible behavior. A permanent deformation is created when the applied stress is above the yielding point. The viscous model considers the time-dependent strain–stress behavior. Unlike the elastic and plastic models, which show an instantaneous strain–stress reaction, the viscous model may take several years to show the effect of compaction. Terzaghi's consolidation theory (1925) is a simple elastic model and is commonly used to model deformation. The pore water pressure is calculated by solving diffusion equations and then the instantaneous response of deformation is estimated based on the change of pore water pressure. Since the mechanism is easy to follow and the governing equations remain linear, this approach has been widely applied to compaction analysis (Galloway and Burbey, 2011).

In the last few decades, in situ data has been collected and studied to understand land subsidence in various hydrogeological environments. For a summary of subsidence studies from around the world, refer to Galloway and Burbey (2011). Compaction in a sedimentary environment due to heavy anthropogenic activities has been extensively studied (Riley, 1969; Poland et al., 1975; Burbey, 2001; Zhang et al., 2007). Sedimentary basins often consist of a number of relatively high-permeability aquifers alternating with relatively low-permeability aquitards. Production wells for groundwater supply may be screened in multiple aquifers. Simultaneous pumping at several depths and locations complicates the compaction of multi-layer aquifer systems. Although the major concern of compaction is for aquitards, recent evidence shows that aquifers can serve as the major compaction unit because of the high interbedding of high- and low-permeable layers (Zhang et al., 2007).

Numerical models are flexible and useful for taking complicated aquifer properties, boundary geometry, and pumping activity into account in compaction simulations. Gambolati (1975) developed a quasi-three-dimensional (3D) consolidation numerical model and applied it to land subsidence on gas-oil reservoirs. Neuman et al. (1982) presented a quasi-3D finite-element numerical model composed of a two-dimensional horizontal flow associated with a one-dimensional (1D) vertical deformation model. More recently, studies on compaction have considered the coupled interaction of soil and water (Shi et al., 2012). Poroelasticity and poroviscosity have been applied to subsidence analysis (Hsieh, 1996; Castelletto et al., 2008). Kihm et al. (2007) used a 3D hydro-mechanical numerical model for subsidence simulation in an unsaturated fluvial aquifer system. Numerical models have been applied to various places, such as the Los Banos–Kettleman City area in California (Larson et al., 2001), the Emilia-Romagna coastland of Italy (Teatini et al., 2006), and the Shanghai area of China (Zhang et al., 2007).

Although many advantages of numerical approaches have been recognized, there are also inherent limitations. Proper domain discretization is required for reasonable modeling results. Very fine discretization is needed near pumping locations, where the groundwater level may change dramatically. Fine-grid modeling has a high computational demand when multiple wells are operated at the same time. For modeling radial flow to mimic the pumping/injection situation, the model input data in Cartesian coordinates must be transformed into 1D axis-symmetric flow numerically (Wallis et al., 2013). As an alternative to numerical simulation models, analytical solutions can be employed. They are very efficient with regard to calculation time and do not require spatial discretization and transformation. The solution provides insight into the physical system. Analytical solutions can be useful for preliminary investigation, sensitivity and uncertainty quantification, and verification of numerical models. As long as a linear mathematical frame is maintained, such as the compaction model for the saturated groundwater flow associated with Terzaghi's (1925) consolidation theory, superposition is valid for multi-well and multi-depth pumping. Such a liner model is not unreasonable for studying short-time compaction behavior because different models perform equally well with only slight differences (see Fig. 14 of Zhang et al., 2012). Analytical solutions are thus particularly suitable for dealing with a large number of operation wells at various depths, which, for numerical simulations, would require local mesh refinement around each well to assure accurate results.

Yunlin is located in the Choushui River alluvial fan. It has a multi-layer aquifer system and is one of the most important agricultural areas in Taiwan. Massive amounts of ground water are pumped in this area from multiple layers and from multiple wells, causing the compaction of different layers. This area has had the fastest subsidence rate and is the largest continuous subsiding area in Taiwan in recent years. The maximum cumulative subsidence has exceeded more than 2 m in the last four decades, with a subsidence of 7.4 cm in 2012. There is also public concern regarding the safety of the Taiwan high-speed railway, which passes through this area. However, the cause of land deformation is still unclear due to insufficient water use and compaction data and detailed hydrogeological conditions. To prevent or mitigate further land deformation, quantitatively evaluating compaction at different layers is imperative.

The contribution of this study is the exploration of the pumping effects on the compaction of a multi-layer aquifer system in Yunlin, Taiwan. Groundwater extraction at various depths by various users is taken into account. Since several factors may cause the groundwater level to fluctuate simultaneously, data of groundwater level and compaction need to be preprocessed to differentiate the pumping effect from other effects, such as seasonal recharge/discharge variations. The approach used here is novel, as it combines an analytical model for flow in a layered system due to pumping (Neuman and Witherspoon, 1969) and a 1D subsidence model based on consolidation theory (Terzaghi, 1943) to evaluate the compaction. Different from numerical models such as IBS2 (Leake, 1990), IBS1 (Leake, 1991), SUB (Hoffmann et al., 2003), and COMPAC (Helm, 1986), pore water change and compaction near the well field can be calculated without the limitations of spatial discretization. Furthermore, the effects of multi-layer and multi-user pumping on drawdown and subsidence near wells can be determined through the principal of superposition.

2. Groundwater flow model

The analytical solutions for problems involving pumping in a multi-layer aquifer system have been developed for various scenarios. Hantush (1960) considered the flow in a two-aquifer/one-aquitard system. The top aquifer is infinite and the aquitard storage is considered. Neuman and Witherspoon (1969) considered the same layered system but without the assumption of an infinite top aquifer. Moench (1985) improved the solution to allow for pumping wells of a large diameter with well skin effects. Zhou et al. (2009) considered a laterally bounded aquifer–aquitard system. The solution was then extended to any number of aquifers (Hemker and Maas, 1987).

Considering the applicability of the model to the study site and the availability of data, the solution developed by Neuman and Witherspoon (1969) for a two-aquifer/one-aquitard system was adopted. The approach is general and other analytical solutions can be used if model conditions are appropriately satisfied. Fig. 1 shows a schematic diagram of the flow system. Aquifer i has hydraulic conductivity K_i, specific storage S_{Si}, and thickness b_i. The aquitard between aquifers has hydraulic conductivity K_i', specific storage S_{Si}', and thickness b_i'. In our model, a well with an infinitesimal radius completely penetrates the pumped aquifer and discharges at a constant rate Q_1. All layers are assumed to be homogeneous and isotropic and to infinitely extend from the well radius. The system is fully saturated at any time, and