# SUBSIDENCE IN ALLUVIAL SOILS CAUSED BY INTENSIVE WATER WITHDRAWAL

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# 1. INTRODUCTION

Land subsidence is a gradual settling or sudden sinking of the earth's surface owing to subsurface movement of earth materials (IAHS, 1991; Zilkoski *et al.*, 2001; USGS, 2002; Quanlong, 2006). As reported by Gelt (1996), dropping of water table owing to a continuous overdraft of water from the alluvial fill is the most significant factor that cause subsidence in alluvial soils. Other activities such as heavy withdrawal of geothermal fluids, oil, gas from underground reservoirs, extraction of coal, sulpher, dissolution of limestone aquifers, oxidation of organic deposits, thawing permafrost, hydro-compaction, natural compaction and removal of rocks through underground mining operations are common causes of land subsidence (IAHS, 1991; Gelt, 1996; USGS, 2002; Leake, 2004).

Subsidence manifests upon the overlying strata in a variety of ways such as vertical displacement, horizontal displacement, slope (inclined displacement), horizontal strain, and vertical curvature (Blodgett and Kuipers, 2002). Other possible indicators of land subsidence include change in flood-inundation frequency and distribution, stagnation or reversals of streams, aqueducts, storm drainages, sewer lines; overtopping or reduction in freeboard along reaches of levees, reservoirs, canals, and flood-conveyance structures; cracks or changes in the gradient of structures such as pipelines and roadways (USGS, 2002). The formation of earth fissures in alluvial aquifer systems are indications of the occurrence of land subsidence (Gelt, 1996; USGS, 2002). As described by Gelt (1996), fissures occur due to differential settlement as a result of distinct geological formations of the area and rate of ground water withdrawal. Some areas may sink slightly deeper and at a different rate than other areas. Once fissuring begins in an area, the process tends to continue and increase in number with fissures forming adjacent and parallel to older fissures. Fissures spread at uneven speed and branching out in uncertain directions, sometimes forming complex patterns of multiple fissuring extending for kilometers. Fissures often cut across normal drainage patterns extending deep into the water table. Contaminants such as chemicals, animal waste may seep in to the water table, without percolating through the unsaturated zone for filtration. Pollution is also a concern as those fissures often used as convenient sites to dump trash and refuses.

Collapsing cavities with the sudden catastrophic land subsidence are commonly triggered by ground-water-level declines caused by pumping and enhanced percolation of water through susceptible rocks such as salt, gypsum, anhydride and carbonate minerals (USGS, 2002). Damages that can be resulted from subsidence and fissures often are costly and disruptive (Gelt, 1996).

To understand more about land subsidence, the mechanics and monitoring of land subsidence as well as measures that can be enforced in the future to minimize subsidence are discussed in detail in the following Chapters.

# 2. CAUSES OF LAND SUBSIDENCE

Land subsidence is a slow geological calamity whose emergency and development is difficult to detect. As it is a gradual phenomenon, its effects are cumulative and may lead to a sudden damage (Gelt, 1996; Quanlong, 2006). The rate of subsidence depends upon the underlying basin soil properties as fine-grained silt and clay compacts more than coarse-grained sediments (Gelt, 1996). When groundwater or hydrocarbons are extracted from sedimentary basins, the pores become empty and the solid particles tightly packed together and consolidate (Gupta and Onta, 1997; Jackson *et al.*, 2004). If the pumping continued without adequate recharge, the sediment continued to be compressed causing the land to settle or subside (Gelt, 1996).

With respect to aquifer depressurization, land subsidence may be considered as the manifestation at the land surface of cumulative non recoverable compression component of a series of fast draining permeable zones and more importantly slow draining interbed lenses and confining layers between the aquifer systems, which extend down to bedrock in the sedimentary sequence (Jackson *et al.*, 2004; Quanlong, 2006). As reported by Leake (2004) and USGS (2002), if an aquifer has beds of clay or silt within or next to it, the lowered water pressure in the sand and gravel causes slow drainage of water from the clay and silt beds. The reduced water pressure is a loss of support for the clay and silt beds as a result the clay or silt bed compress permanently. The confining clay layers and interbed lenses shown as in Figure 2.1.

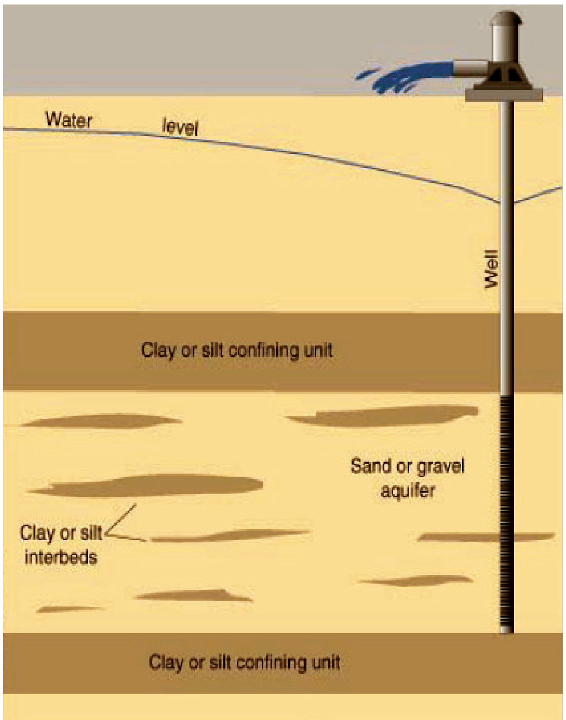


Figure 2.1 Clay and silt confining unit and interbeds (Leake, 2004)

Figure 2.2 shows the effect of thermal permafrost equilibrium disruption.

Figure 2.2 Damage caused by permafrost subsidence (USGS, 2002)

Water withdrawal also causes the formation of cavities same as cavities directly created by mining. Formation of cavity underneath results in subsidence as the hydro-geological properties of the associated strata changes (Blodgett and Kuipers, 2002). Figure 2.3 indicates cavity formed by dissolution of subsurface support.

Figure 2.3 Sinkhole subsidence (Gelt, 1996)

Increase in load due to high-rise buildings also cause subsidence. An increase in the effective stress of clay soil particles is attributed to pressure increase on the land (Quanlong, 2006). Terzaghi's principle of effective stress relates total stress, effective stress and pore-fluid pressure in the soil strata as shown in Equation 2.1 (Kasmarek and Strom, 2001; Quanlong, 2006).

$$\sigma_t = \sigma_e + P_P \qquad (2.1)$$

where

| | | |
|---|---|---|
| $\sigma_t$ | = | total vertical stress acting downward, |
| $\sigma_e$ | = | effective stress or resisting stress from the skeleton of soil grains, and |
| $P_P$ | = | pore pressure of the water (hydraulic head). |

The weight of the overburden of soil reservoir is supported by both fluid pressure and solid skeleton of the reservoir (Jacques, 1999; M, 2000; Quanlong, 2006). If a well is pumped, the extraction of water will suddenly decrease the pore pressure and the porosity with an attendant increase in the effective stress exerted by the matrix. As a result, the matrix will compress. If water is injected into the well, the reverse occurs (Jacques, 1999; M, 2000).

Land subsidence in urban areas may be caused by factors including groundwater extraction, load of constructions, natural consolidation of alluvium soil and geotectonic subsidence (Abidin, 2005). As reported by Quanlong (2006), an increase in the effective stress may be mainly caused in two distinct scenarios: when the total stress ($\sigma_t$) kept constant while the water stress ($P_P$) is decreasing due to continuous water withdrawal, the effective stress ($\sigma_e$) increases to bear the load imposed on the ground. This would increase pressure on the soil particles resulting consolidation of the ground surface. If water stress ($P_P$) kept constant while the total stress ($\sigma_t$) is increasing, to hold up the load, the effective stress ($\sigma_e$) increases. As a result the solid skeleton consolidates.

As reported by M (2000), hydro-compaction occurs when dry, low-density sediments collapse because of an increase in moisture content. These usually happen to collapsible soils such as mudflow deposits in alluvial fans and wind deposited silts (loess). Most collapsible soils have low densities because they remained moisture deficient through out their post-depositional history. When water percolates through the root zone into these soils, the structure collapses and localized subsidence may result. Drainage of organic soils, particularly peat and muck (spread manure) induces a series of process that reduces the volume of soil. These processes include biological oxidation, compaction and desiccation. In addition, the dissolution of rocks such as salt, gypsum and anhydride; carbonate minerals; an oxidation of organic maters cause land subsidence (USGS, 2002; Quanlong, 2006). In alluvial soils formation of fissures are results of land subsidence (Gelt, 1996). Figure 2.4 indicates fissure caused by subsidence.

Figure 2.4 Land fissures (USGS, 2002)

Protruding well casings are common in agricultural areas and some urban areas where ground water has been extracted from alluvial aquifer systems (USGS, 2002). The land surface and aquifer system are displaced downward relative to the well casing, which is generally anchored at a depth where there is less compaction. The stressed well casings are subject to failure through collapse and dislocation. Submersible pumps, pump columns, and the well itself may be damaged or require rehabilitation (USGS, 2002). Figure 2.5 indicates that protrude well above ground level due to subsidence.

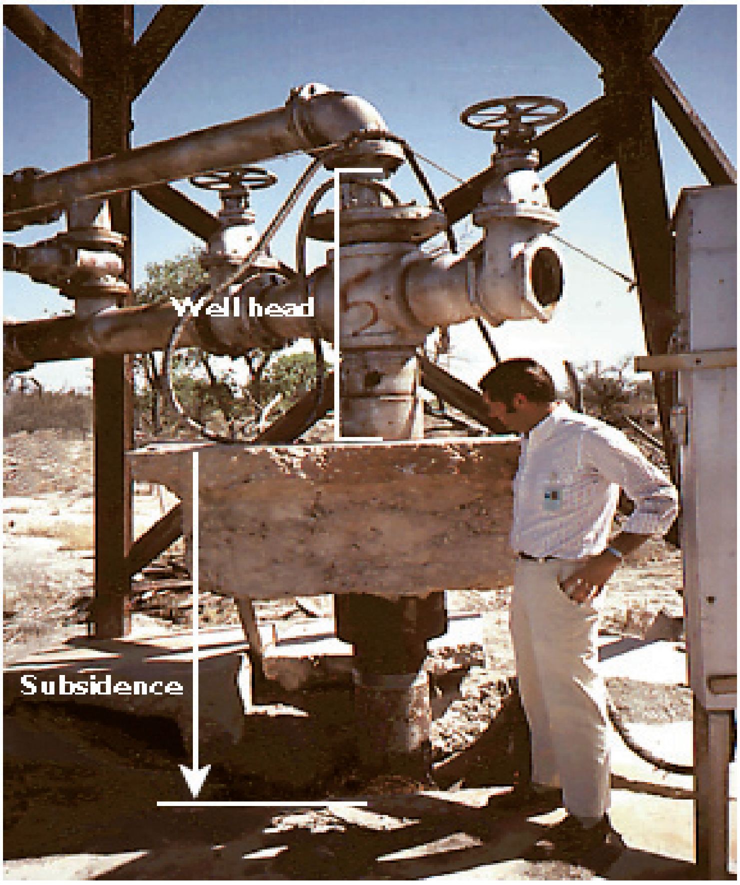

Figure 2.5 Well case protrudes above ground (USGS, 2002)

# 3. MONITORING LAND SUBSIDENCE

Since, subsidence caused by ground water mining and organic soil drainage is slow, in the absence of detecting clues such as protruding wells, failed well casings, broken pipelines and drainage reversals, a recurrent measurements of land-surface elevation are needed to monitor subsidence (USGS, 2002). Gelt (1996), USGS (2002), Leake (2004) and Abidin (2005) noted that subsidence prediction can be done using test wells and geographic surveys to establish soil profiles to measure the settlement of subsurface soils within an area. Well records of the areas can be examined to ascertain a history of pumpage. Benchmark placement reviews can be used to monitor subsidence. GPS and extensometers are also used to estimate the consequences and effects of land subsidence. Extensometers measure the tension in the soil to interpret the probability and development of fissures. In areas where there is an undergoing aquifer-system compaction, the extensometer is the most effective means of determining precise and continuous deformation at a point. If the subsurface bench mark is established below the base of the compacting aquifer system, the extensometer can be used as the stable reference or starting point for local geodetic surveys. Borehole extensometers generate a continuous record of change in vertical distance between the land surface and a reference point or subsurface bench mark at the bottom of a deep borehole (USGS, 2002). Borehole extensometers provide excellent subsidence data, but their cost prohibits their use in sufficient numbers to provide adequate information for the entire area (Zilkoski *et al.*, 2001). Designs that incorporate multiple-stage extensometers in a single instrument are being used to measure aquifer-system compaction simultaneously in different depth intervals (USGS, 2002).

According to Gelt (1996), aerial photography is reliable method to identify new fissures and monitor existing ones. Photographs can be taken periodically of certain areas and be compared with earlier images to determine fissure growth. Although useful, this method is limited, because complete photographic records of certain fissure areas are not available. Ordinary radar on a typical Earth-orbiting satellite has a very poor ground resolution of about 4.8 –6.4 kms because of the restricted size of the antenna on the satellite (USGS, 2002).

Abidin (2005) suggests the combination of levelling, GPS surveys, and InSAR is a better approach as the results obtained from the combination of these instruments are useful for studying and monitoring land subsidence. Besides complementing each other both spatially and temporally, they can also be checked against one another for quality assurance purposes. However, in order to be more meaningful and to obtain more insights into land-subsidence mechanisms, the results of these geodetic techniques should be correlated with the hydro geological and geotechnical characteristics of the subsiding areas. A brief over view of InSAR is discussed as follows:

## 3.1 Interferometric Synthetic Aperture Radar (InSAR)

As reported by USGS (2002), Interferometric Synthetic Aperture Radar (InSAR) is a powerful new tool that uses radar signals to measure deformation of the earth's crust at an unprecedented level of spatial detail and high degree of measurement resolution. Geophysical applications of radar interferometry take advantage of the phase component of reflected radar signals to measure apparent changes in the range distance of the land surface. Under best conditions, land-surface elevation changes can be measured on the order of 2.5 cm or less with InSAR (Leake, 2004).

According to USGS (2002), Synthetic Aperture Radar (SAR) takes advantage of the motion of the spacecraft along its orbital track to mathematically reconstruct (synthesize) an operationally larger antenna and yield high-spatial-resolution. For landscapes with more or less stable radar reflectors such as buildings or undisturbed rocks and ground surfaces over a specified period, it is possible to make high precision measurements by subtracting or "interfering" two radar scans made of the same area at different times.

# 4. MINIMISING FUTURE SUBSIDENCE

As noted by IAHS (1991), Gupta and Onta (1997) and Leake (2004), in areas where climate change results in less precipitation and reduced surface-water supplies, communities will pump more ground water. Groundwater has always been considered to be a readily available source of water for domestic, agricultural and industrial use. In the past, major subsidence areas have been in agricultural settings where ground water has been pumped for irrigation. In the future, however, increasing population may result in subsidence problems in metropolitan areas where damage from subsidence will be great. Consequently, the environmental impacts may worsen over time as the ground continues to settle and aquifers are de-watered or degraded (Blodgett and Kuipers, 2002). Catastrophic subsidence is most commonly induced by water table lowering and rapid water table fluctuation, diversion of surface water, construction of use of explosives or impoundment of water (M, 2000).

In some areas where ground water pumping has caused subsidence, the subsidence has been stopped by switching from ground water to surface-water supplies. If surface water is not available, then other means must be taken to reduce subsidence. Possible measures include reducing water use and determining locations for pumping and artificial recharge that will minimise subsidence. Optimization models coupled with ground-water flow models can be used to develop such strategies (Leake, 2004).

Monitoring land subsidence in suspected cities is required for groundwater extraction regulation, effective flood control and sea water intrusion, conservation of environment, construction of infrastructure and spatial development planning in general (Abidin, 2005). If both ground-water level and compaction of sediment are measured, then the data can be analyzed to determine properties that can be used to predict future subsidence (Leake, 2004).

Subsidence and hydrologic impacts cannot be avoided as a consequence of ground water mining; such activities should be considered inappropriate in national parks, wilderness areas, and adjoining localities that might be affected by subsidence (Blodgett and Kuipers, 2002).

# 5. SUMMARY

Land subsidence is a gradual settling or sudden sinking of the earth's surface owing to subsurface movement of earth materials. It is a slow geological calamity whose emergency and development is not detected easily. Collapsing cavities with the sudden catastrophic land subsidence are commonly triggered by ground-water-level decline caused by pumping and by enhanced percolation of water through susceptible rocks such as salt, gypsum, anhydride and carbonate minerals. Damages that can be resulted from subsidence and fissures often are costly and disruptive as it is a gradual phenomenon; its effects are cumulative and may lead to a sudden damage. Areas that had never seen inundation before may be flooded due to lowering or settlement of land. This could happen in cities or villages that are located along rivers and sea. Formation of land fissures, inundation and damage of structures are consequences of land subsidence as well.

Since the process of land subsidence is slow and difficult to detect in the absence of clues such as protruding wells, failed well casings, broken pipelines and drainage reversals, a recurrent measurements of land-surface elevation are needed to monitor subsidence. Monitoring can be done using conventional surveying instruments such as levels, GPS, extensometers and satellite radars. Although the Interferometric Synthetic Aperture Radar (InSAR) measurement system is under development and testing stage, it has shown promising results in the earlier studies.

Since the main causes of subsidence in alluvial soil are an overdraft of ground water, equilibrium should be maintained between recharge and withdrawal in order to minimize the damage that can be imposed by extensive use or an overdraft of ground water.

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