# A Review of Subsidence in Geothermal Fields and Implications for Well Production

**John P. Hawuory**

**University of Nairobi**

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## ABSTRACT

Globally, in the last three decades, there has been a significant shift towards green energy and this trend is certain to continue into the foreseeable future. In this evolving energy matrix, geothermal energy is proving to be an important form of clean energy. However, given the massive resources involved in the exploration and development of geothermal resources, an imperative will be to increase the well production life especially in non-injected liquid-type reservoirs through reservoir management. With production exceeding natural recharge rates, the ground subsidence risk increases. It has been shown that subsidence results in significant pore pressure drop in both fractured and non-fractured reservoirs. A pore pressure drop of up to 2000 psi in non-fractured reservoirs has been shown to result in a subsidence of 0.18 inches while a similar pressure drop has been linked to a 2-inch subsidence in a fractured reservoir over a period of 35 – 40 years in both cases. The rates of subsidence vary depending on the amount of pressure the reservoir can support. Using a systematic empirical review of literature obtained from various databases; Elsevier, John Wiley & Sons, Science Direct and Springer, this paper argues that an increase in subsidence in liquid-type reservoirs under production conditions can significantly reduce well production life and power generation capacity over time if proper reinjection and reservoir management are not carried out. Hence, during the exploration phase, determining the potential subsidence characteristics of the rock is important, while in the production phase, regular good reservoir management practices are necessary.

## 1. Introduction

Like most wells and exploitable underground resources, such as, mining, oil and gas extraction and underground freshwater pumping, geothermal exploitation can be associated with ground subsidence. Ground subsidence is the downward movement of the ground on the reference datum

(Sektiawan, Prasetyo, Adli & Yuantoro, 2016). Subsidence is caused by loss of fluid from pore spaces when it is withdrawn or squeezed out leading to a corresponding loss of fluid pressure in the pores and compaction due to effective stress from the overburden (Osipov, 2015). The compaction can then result in reduction of porosity and thickness of rock layers. This can happen by means of natural forces or be human-induced, that is, endogenic and exogenic land subsidence respectively. The former can result from tectonic movement, seismic activities, faulting, folding and other higher magnitude ground movements. Exogenic subsidence on the other hand is caused largely by human exploitation of subsurface resources such as water, oil or minerals.

Shortall et al., (2015) explains that the extraction of geothermal fluids from underground reservoirs can induce subsidence of the surface due to drop in formation pressure. The presence of compressible rock formations or the presence of high-permeability paths contribute to subsidence during groundwater removal through pumping. For the most part, this type of reservoir deformation is common in liquid-dominated fields when the fluid loss is not equally compensated by natural groundwater recharge or artificial reinjection methods to maintain reservoir pressures (Gallup, 2009).

When underground operations are relatively shallow, that is less than 100 m deep, the deformations they cause on the surface are of a non-continuous type and include ledge structures, sinkholes, fissures, and trenches. On the other hand, continuous deformations known as subsidence basins develop either when the overburden is characterized by great plasticity or when subsurface operations are very deep underground. On the surface, these displacements manifest themselves by geomorphological effects, such as layer bending, subsidence or collapse of the ground. This will create a wet circular or elliptic subsidence basin and damage nearby human-made structures, such as buildings, roads, railways or geotechnical structures (Jankowskiet al.,2017; Abdikan et al., 2014). Geothermal related ground subsidence in the Wairakei geothermal field in New Zealand has been shown to have very high vertical displacement rates of up to 450 mm per year, totaling to a maximum displacement of 15 m while horizontal ground strains, associated with the subsidence, were about 110 at 250-m radius the centre of subsidence and about 15 at 750-m radius (Stilwell et al., 1975). Horizontal movement between 1967 and 2000 is up to 4.3 m.

Ground subsidence poses a significant risk in geothermal production areas. It leads to destruction of infrastructure, such as, housing, roads, powerlines, underground cables and piping among other things (Mayoral et al., 2019). In low lying areas, subsidence can cause inundation (Marfai & King, 2008; Wang, Gao, Xu & Yu, 2012). In fluid production areas such as oil and gas fields as well as geothermal wells, subsidence can also have a surface effect on the extraction infrastructure that must be mitigated. Subsidence has been attributed to the damage caused to oil, water and geothermal wells. Water wells have been pushed out of the ground as the ground subsides. At Mexico City, some wells protrude from the ground by over 5 metres.

In New Zealand, subsidence has caused some problems with the steam-field operations in Wairakei and Ohaaki geothermal field, particularly the period of greatest subsidence rates (Bloomer & Currie, 2001). The effects are most noticeable on long structures, such as pipelines, drains and power lines. Stretching and compression of pipelines in both fields has made it necessary to remove sections of pipe - in areas of compression - to realign the pipeline with its supports or to prevent over rotation of bellows-type expansion joints. In other areas, sections of pipe have been added. Bixley and Hattersley (1983) observed that wells at Wairakei and Ohaaki had been damaged in greatest subsidence areas, as the compression of the draining aquiclude had been transferred into the well casings: in some cases, this had resulted in well abandonment.

The effects of ground subsidence on geothermal reservoir potential and its future production prospects are, however, still not well understood and few studies have attempted to explain how the deformed reservoir can affect fluid production and future energy yields. In contrast, there is increasing research evidence suggesting that excessive extraction of groundwater from shallower wells result in diminishing groundwater levels and, hence, requiring deeper boreholes and pumping which come at a significant cost (Yagbasan, 2016).

Groundwater reservoirs are frequently associated with compressible layers of silt or clay. As the groundwater is pumped out, the effective stress changes, precipitating consolidation, which can be non-reversible if the recharge is not commensurate with the loss (Castellazzi et al., 2016). Thus, the total volume of the silts and clays is reduced, resulting in the lowering of the surface. The damage at the surface is much greater if there is differential settlement, or large-scale features, such as sinkholes and fissures. Reservoir compaction is a significant concern along with pumping-induced land subsidence. A large portion of the groundwater storage potential of many reservoirs can be significantly reduced when long-term groundwater extraction, and the resulting groundwater level decline, causing permanent compaction of fine sediment layers (silts and clays) (Guzy & Malinowska, 2020). In Kerman Province Iran, overdraft of groundwater found to be increasing at an approximate rate of 6 times over a 30-year period from 1969 to 1999, was attributed to a decline in groundwater levels of up to 28 m. The recent rates of subsidence were estimated at about 5-15 cm for the decline of about one meter in groundwater level (Solaimani & Mortazavi, 2008).

Evidently, ground subsidence risk increases when fluid extraction exceeds natural recharge rates. While this is not guaranteed in all geothermal production fields, in some areas it is more pronounced owing to the geology of the area. Even with reinjection, compensating fully for the loss in fluid pressure in the reservoir may not be guaranteed. Further, reinjection can lead to other drawbacks such as thermal breakthrough in some cases and lower the amortization time of the wells (Axelsson et al., 2005). Failure to mitigate ground subsidence can damage the production infrastructure as well leading to losses in investment. An imperative, therefore, is to exploit geothermal resources while minimizing the deleterious effects of land subsidence to acceptable limits. However, existing studies on ground subsidence in geothermal fields have focused only on the damages to infrastructure with little attention being given to the effects of mitigating subsidence on the future production potential of the reservoirs. This paper, therefore, reviews subsidence in geothermal fields and implications for well production.

## 2. Materials and Methods

This study used a systematic literature review approach where apart from the conceptual and theoretical literature, the study relied on empirical studies for data and for conclusions of the study. Several search terms were used in the survey of the literature as shown in Table 1.

**Table 1: Tabulation of Search Terms**

| Key Terms | Related words/phrases |
|---|---|
| Subsidence | Land subsidence, ground subsidence, ground compaction, geo-pressured |
| Geothermal | Geothermal fields, geothermal wells |
| Power | Power output, power generation, electricity generation |
| Production | Power production, power yields, production losses |
| Reservoir | Geothermal reservoir, underground reservoir, aquifer |
| Reinjection | Recharge, ground recharge, artificial recharge, natural recharge |

These terms were searched online using search engines such as, Science Direct, Wiley Online Library and Taylor & Francis. The documents were assessed on the basis of the inclusion and exclusion criteria and those that met the initial inclusion criteria were further reviewed and excluded if they failed to meet in-depth review requirements. Table 2 shows the summary of the search results.

## 3. Results

This review found that majority of the studies on subsidence have been done in New Zealand with the Wairakei geothermal field being the most prominent case study. Other studies on subsidence were also undertaken on the Ohaaki geothermal field. Cases of geothermal production induced subsidence have also been extensively studied in the USA (Ali et al., 2016; Dianala et al., 2020) Mexico (Glowacka et al., 2005) and China (Fu-chun et al., 2002). Surveys of land subsidence related to geothermal production have also been carried out in Kenya (Koros, 2017). The studies showed that geothermal fluid withdrawal was mostly responsible for ground subsidence. In majority of the studies, the environmental effect of subsidence was the most visible and prominent with observable vertical shifts in ground levels of up to 15m in Wairakei and also subsidence bowls (Bloomer & Currie, 2001). However, subsidence was not linear and neither was it limited to the vertical effect alone. There was also evidence of horizontal movement in the production area. Studies showed that earlier production was accompanied by increased subsidence owing to the poor or non-existent recharge of the reservoirs, however, the subsidence rates began to stabilize with artificial reinjection. However, reinjection has been linked to seismicity which can have both adverse effects (Diaz et al., 2016) but can also be used to trace the movement of the reinjected water (Gurbuz et al., 2011).

There have, however, been relatively few studies that link the subsidence to geothermal reservoir production capacity Garg (1975). The majority of the studies, however, show no direct correlation between subsidence and eventual power production. However, it is evident that the parameters of production such as pore pressure, deep liquid pressure and reservoir temperature have been shown to be affected by subsidence. For example, Clotworth et al., (1995) and Lee and Bacon (2000) showed that deep liquid pressure had been significantly declining in the Ohaaki geothermal field in New Zealand since production began in 1988 by up to 15-20 bar in the production areas. A simulation study of Wairakei by Pritchett et al., (1976), however, found non-linear rock behavior during production at Wairakei with a slope of the (pseudo) stress-strain curve having a variance factor of 15 between 1963 and 1975. After fitting actual data from the field, the study attributed the non-linear behaviour of the rock to possible structural failure at late times and/or decrease in bulk modulus.

A study by Atashbari and Ahmadi (2007, cited in Sektiawan et al., 2016), however, found a linear relationship between pore pressure drop and subsidence increase in the Doroud Oil field in Iran (Fig. 1).

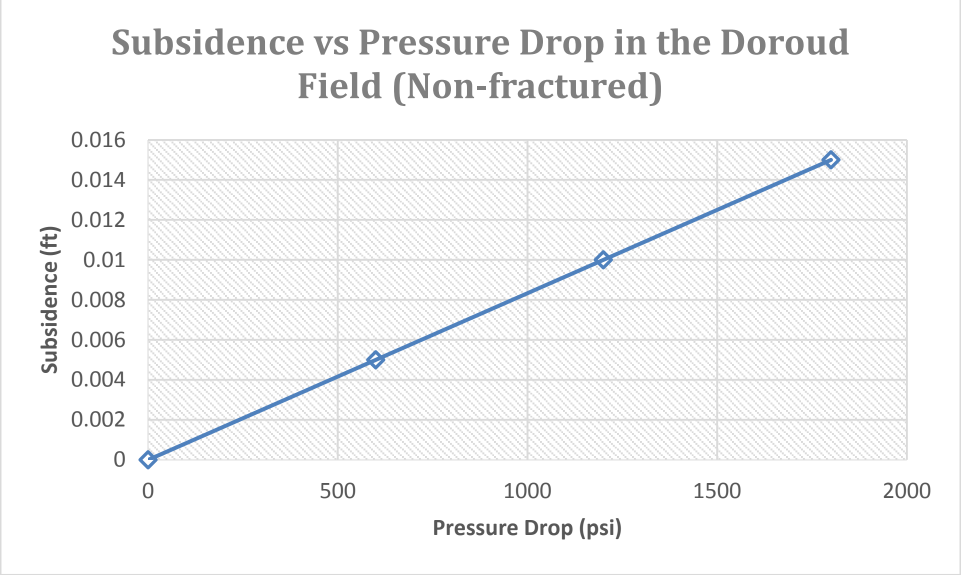

**Figure 1: Subsidence vs Pressure Drop in non-fractured reservoir in the Doroud Field (Source: Sektiawan et al., 2016)**

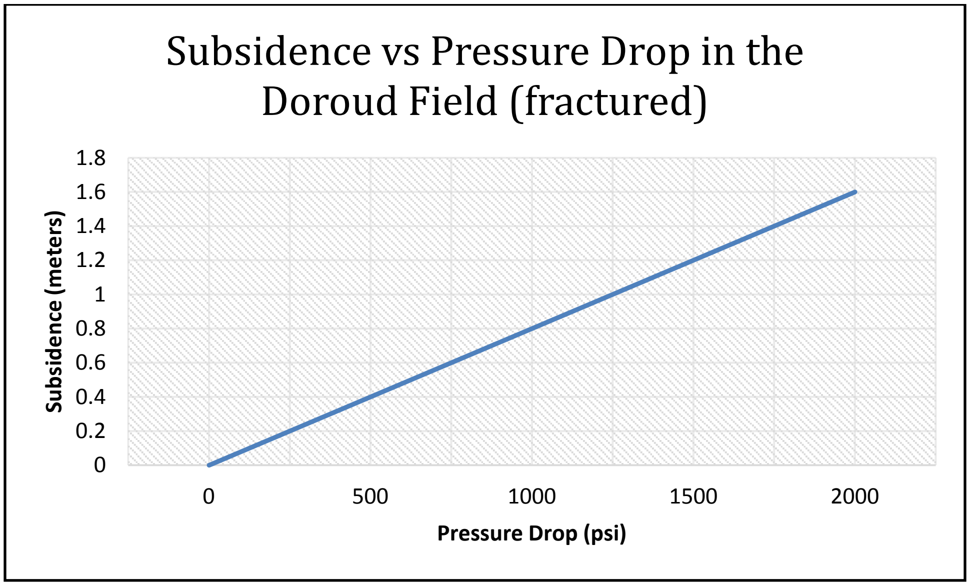

**Figure 2: Subsidence vs Pressure Drop in fractured reservoir in the Doroud Field (Source: Sektiawan et al., 2016)**

From Figures 1 and 2, it is evident that subsidence resulting from pressure drop was much higher in fractured reservoirs than in non-fractured reservoirs.

In geothermal reservoirs in Wairakei, Allis (2000) showed that subsidence tended to be much higher at the centre of the subsidence bowl (P128) than on the eastern edge (A97).

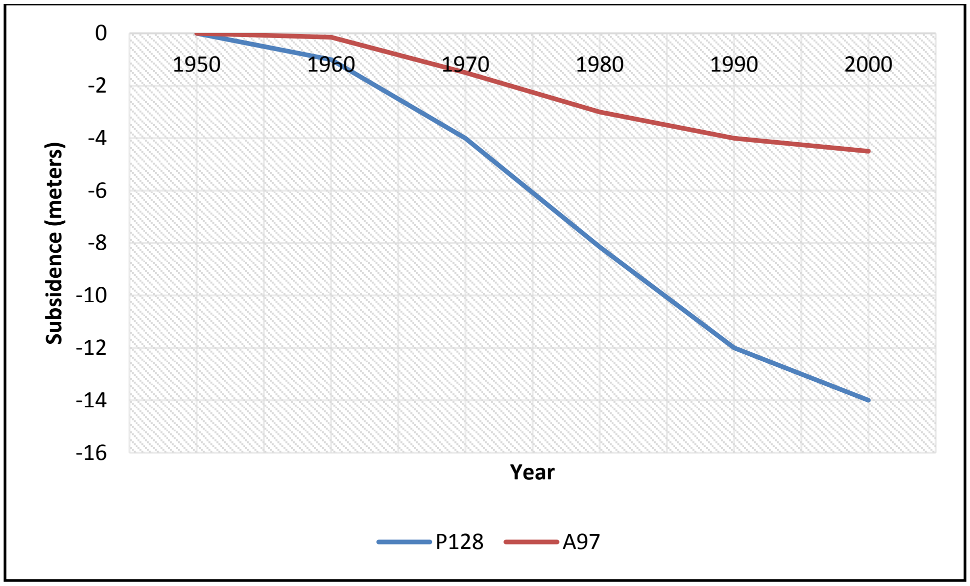

**Figure 3: Subsidence vs Time diagram in Wairakei (Allis, 2000)**

Yao et al., (2022) study in China found that different geothermal reservoirs characteristics presented different ground subsidence results. For instance, the study observed that the maximum ground subsidence form from 1983 to 2019 in carbonate reservoirs (0,29 mm/a) was 30 times less than that of a sandstone reservoir (8.9 mm/a) in the same area over a 36 year period from 1983 to 2019.

## 4. Discussion

The reduction of reservoir volume due to fluid withdrawal and the subsequent subsidence remains a significant challenge to geothermal production. Garg (1975) argued that subsidence, which is an indication of reducing pore pressure in the reservoir, is potentially a more serious threat in geothermal production due to the much larger volume of fluid required to produce a given amount of energy. Therefore, evidence of increasing subsidence in geothermal reservoirs is a matter of concern. As evident in the studies reviewed, subsidence in geothermal fields can lead to infrastructural damage in the areas affected leading to significant reparation costs. Subsidence too can lead to damage of geothermal infrastructure and, therefore, lead to significant maintenance or repair costs. However, the potential for subsidence to disrupt actual production flows apart from environmental damage have not been given much consideration especially after reinjection of wells proved to be instrumental in arresting subsidence. White et al., (2005) observed that geothermal power generation at Wairakei with little reinjection had caused substantial pressure decline within the reservoir (-25 bars), and subsidence of the ground surface.

Narasimhan and Goyal (1984) also argue that the deformations of the geothermal reservoir owing to depletion of fluid storage could also result from thermal contraction which can be explained by the pressure drop. Majer et al., (1980) also observed that increased fluid withdrawal may cause reduction in pore pressure and temperature gradients. Inadequate fluid recharges lead to large pressure drops in the reservoir. As pressure decreases the temperature also decreases (Lee & Bacon, 2000).

High-temperature geothermal fluid is required to produce electricity from geothermal energy (Özcan & Akkurt, 2011) and, therefore, there is need to optimize the reservoir temperature. Gaining the highest thermal output is an objective in geothermal energy production (Kamila et al., 2021). Özcan and Akkurt (2011) further observed that while low-to-medium temperature geothermal reservoirs with temperatures between about 85 and 150°Care not hot enough to flash enough steam, they can still be used to produce electricity in binary power plants (also referred to as Organic Rankine Cycle (ORC) power plants). Lee and Bacon (2000) also observed that the presence of cooler waters in the recharge areas was responsible for declining discharge enthalpies, the occurrence of calcite scaling and in some cases increases in gas content in separated steam with the gas becoming increasingly concentrated in the diminishing steam fraction. Such developments led to low production energy yields over time and can lead to the abandonment of the well or drilling of new deeper wells in the area. In the case of the West Bank in Ohaaki cited by Lee and Bacon (2000), the development was attributed to intrusion of cooler waters probably from the presence of cooler aquifers in the area or seepage from surface water bodies. However, the presence of cooler waters from reinjection was not accounted for in this development. Nevertheless, there have been evidences of significant fluid pressure losses in production areas in Ohaaki.

The advent of reinjection was a significant milestone in the development of geothermal resources, specifically in the mitigation of subsidence and its associated environmental damages. Reinjection also meant that the reservoir could be recharged as rates higher than the natural recharge rates and, hence, keep the cycle in motion. The reinjection is expected to maintain reservoir pressure and avoid subsidence (Markó et al., 2021). According to Yuan et al., (2021), production without reinjection induces the highest production temperature and water level drawdown. However, reinjection itself has significant challenges among them the fact that contingent on the geology of the reservoir, it may not replenish the withdrawn waters on equivalent terms and also that a requirement is that it abstracts heat from the rock in the reservoir before it is withdrawn for energy producing purposes. However, Yuan et al., (2021) observes that the extracted thermal energy is highly affected by the reduction in the reinjection temperature, a phenomenon known as thermal breakthrough. Thermal breakthrough will cause the temperature to decline because the injected water may be under-heated when flowing through the reservoir (Pandey & Vishal, 2017). An increase in the production rate affects the thermal breakthrough highly and shortens the lifetime of the geothermal system.

Consequently, there are currently different reinjection methodologies in offsetting the problems of subsidence and reservoir management. Further, according to Kocabas and Horne (1990) success of a reinjection process depends on the method used for estimating the thermal breakthrough time. Therefore, infield reinjection, outfield reinjection and deep reinjection have emerged as suitable methods for reinjection (Kaya et al., 2011). Infield reinjection provides pressure support and thus reduces drawdown and the potential for subsidence. Differently outfield reinjection reduces the risk of cold water returning to the production area while deep reinjection reduces the risk of groundwater contamination and ground surface inflation (Kaya et al., 2011). The risk of cold water reinjection has been examined by through a simulation study by Xu et al., (2022) who found that while the temperature remained stable in the first 6 years it started to decrease afterwards and the outflow temperature decreased significantly in the 32nd year, making it less viable for subsequent sustainable exploitation. Moreover, reinjection itself can induce seismicity and while it could be advantageous in providing seismic information that can be instrumental in exploration of subsurface features including the movement of the water in the reservoir, it can induce subsidence and also cause earthquakes in the region (Bromley, 2014).

It can be seen from the above that reduction of pore pressure can significantly affect geothermal reservoir performance and energy production if not mitigated by reinjection. It would mean the wells could have a shorter life with maximum production being experienced only for a short period of time after initial production. This may affect the economic viability of the projects as shorter production lives may mean low returns on investment and the need to drill new and deeper wells in the area. Subsidence resulting from declining pore pressure can also have significant impact on the production infrastructure, therefore, leading to disruption of production and losses if not well addressed. While reinjection is proving to be a very promising and sustainable approach in mitigating subsidence and related effects, the risk of thermal breakthrough could attenuate its effects leading to the wells having shorter production lives. Therefore, it is evident that failure to mitigate or properly mitigate subsidence can result in poor reservoir performance and a shortening of production life leading to poor returns.

## 5. Conclusions

The foregoing discussions have traced ground subsidence in geothermal fields and have also shown the effects of subsidence on the infrastructure and geothermal production. However, the findings show that while the environmental effects are explicit, the production effects are largely by implication and, as such, there have been limited studies towards this end. However, going by the reservoir parameters of temperature and pressure and production histories of some well-known fields, it is possible that reduction in pore pressure has been responsible for the production declines and also ground subsidence. However, while reinjection to stabilize the reservoir pressures and mitigate subsidence has led to gains in reduction of subsidence and recovery of pressure necessary for sustained production, reinjection carries with it the risk of thermal breakthrough. This is because the reinjection efforts are constrained by other factors like the geology of the areas and the temperature breakthrough which if not well taken into consideration may end addressing the subsidence problem while failing to address the production problem.

In the light of the study findings and conclusions, it is recommended that the best reinjection measures be undertaken not just with the aim of addressing environmental effects of subsidence, but also ensuring that power production is optimized at all times while lengthening the wells' production life. Also, the focus of most research has been on the surface effects of subsidence with little attention being paid to the effects of reservoir deformation through subsidence on the production capabilities of the geothermal wells. Therefore, the study recommends that more studies and data should be availed towards this end so as to increase our understanding of the consequences of subsidence on geothermal power production. Finally, during the exploration, the petrophysical characteristics of the reservoir and the area in general need to be taken into account.

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