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Subsidence: Causes, Effects, and Mitigations in Geothermal Field

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Abstract

Subsidence is the motion of the ground surface as it moves down relatively. It can occur in a wide range of area. It is an impact of production of large mass and volume of saturation from the reservoir. It doesn't happen especially in geothermal fields only, but also in oil and gas industry. Large fluid volume production leads to the decrease of pore pressure inside reservoir. This decline disturbs the pressure stability and overburden pressure compress the pores. It results the drop in ground surface. The decrease in ground surface level induces a devastating effect in the construction of some facilities, such as building, pipeline, canal, and river. It may interrupt the balance in the ecosystems nearby. Good management and several survey methods (such as levelling and gravity) will reduce the risk of subsidence and the other effects related to it. This discussion output can be used as a guide for minimizing subsidence impact in the geothermal field in general.

1. Introduction

Energy demand increases rapidly over the past year and will be predicted to escalate for the following years. Therefore, people try to harness energy from nature, or renowned as a renewable energy, because fossil fuel is limited for only couple of years.

The geothermal energy has been known as a renewable energy in Indonesia and researcher has found a large number of field which has potential geothermal manifestation and resources. Indonesian government plans to develop many of those fields in the near future. However, we have to develop it in a good management because despite it is a sustainable energy, bad reservoir management will cause a problem in the future, such as land subsidence. Subsidence happens because of excessive withdrawal of fluid and rock compaction. We will discuss about the cause, the impact, and how the subsidence mitigated generally.

2. Definition

The land subsidence is the movement land on the reference datum that causes of differences variable [1]. The land subsidence is caused by loading on the surface, the lose of the fluid when it exploited excessively, the quake that wreck the land structure, the instability of the land related by a process, etc.



There are two kinds of subsidence. There are endogenic subsidence and exogenic subsidence. The endogenic subsidence related with the force from the earth such as tectonic movement, folding and fault. The exogenic subsidence cause by the human activities such as exploitation the hydrocarbon, taking groundwater and changing on land composition.

Theory that support on this paper refers to Terzaghis Principle, 1925 [2]. It will be explained with the following figure :

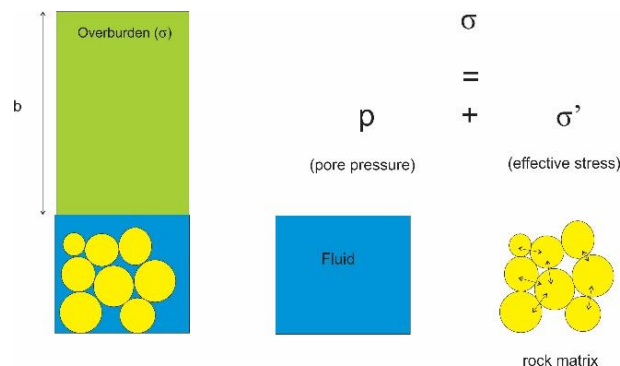


Figure 1. Overburden pressure concept [2].

Over burden is the total pressure of mass rock including pore pressure and effective stress. Pore pressure is pore related to cavity from the grain of the rock. Effective stress is related to grain rock contact. Compaction is related to decrease the pore pressure that causes the thickness of the rock reduce then affect the land subsidence. However, the failure compaction probably can be occurred. It is called disequilibrium compaction.

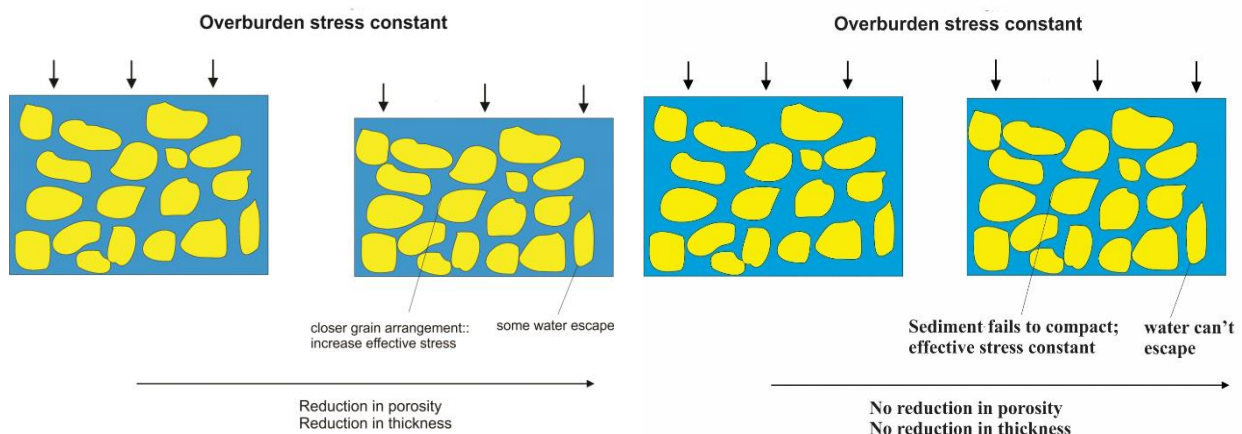


Figure 3. Compaction [2].

Figure 2. Disequilibrium Compaction [2].

3. Methods for identifying subsidence

In the paper that has been written, it uses two methods for identifying the subsidence in the geothermal field. The methods are levelling and gravity. The levelling has been used to know the size of the subsidence without knowing the inside of subsurface. The dimension of the subsidence is measured in length unit (m, feet). Then the gravity method is used to know the size of subsidence from the mass flow. This method knows where the brine (fluid) moving along with the mass flow. The size of the subsidence can be represented by the value of gravitation field that is measured in miliGal (mGal).

3.1. Levelling method

Levelling method is the one way to determine the elevation coverage the area. Several procedure must to be followed and would be explained in this section. The first is to set up the instrument within 100 meters (110 yards) of a point of known or assumed elevation. A rod or staff is held vertical on that point and the instrument is used manually or automatically to read the rod scale. This gives the height of the instrument above the starting (backsight) point and allows the height of the instrument (H.I.) above the datum to be computed.

The rod is then held on an unknown point and a reading is taken in the same manner, allowing the elevation of the new (foresight) point to be computed. The procedure is repeated until the destination point is reached. It is an usual practice to perform either a complete loop back to the starting point or close the traverse on a second point whose elevation is already known. The closure check guards against blunders in the operation, and allows residual error to be distributed in the most likely manner among the stations.

Some instruments provide three crosshairs which allow stadia measurement of the foresight and backsight distances. These also allow use of the average of the three readings (3-wire leveling) as a check against blunders and for averaging out the error of interpolation between marks on the rod scale.

The two main types of levelling are single-levelling as already described, and double-levelling (Double-rodging). In double-levelling, a surveyor takes two foresights and two backsights and makes sure the difference between the foresights and the difference between the backsights are equal, thereby reducing the amount of error. Double-levelling costs twice as much as single-levelling.

The curvature of the earth means that a line of sight that is horizontal at the instrument will be higher and higher above a spheroid at greater distances. The effect may be significant for some work at distances under 100 meters.

The line of sight is horizontal at the instrument, but is not a straight line because of refraction in the air. The change of air density with elevation causes the line of sight to bend toward the earth. The combined correction for refraction and curvature is approximately:

$$\Delta h_{meters} = 0.067 D_{km}^2 \quad (1)$$

$$\Delta h_{feet} = 0.021 \left(\frac{D_{ft}}{1000} \right)^2 \quad (2)$$

For precise work these effects need to be calculated and corrections applied. For most work it is sufficient to keep the foresight and backsight distances approximately equal so that the refraction and curvature effects cancel out. Refraction is generally the greatest source of error in leveling. For short level lines the effects of temperature and pressure are generally insignificant, but the effect of the temperature gradient dT/dh can lead to errors.

Assuming error-free measurements, if the Earth's gravity field were completely regular and gravity constant, leveling loops would always close precisely:

$$\sum_{i=0}^n \Delta h_i = 0 \quad (3)$$

around a loop. In the real gravity field of the Earth, this happens only approximately; on small loops typical of engineering projects, the loop closure is negligible, but on larger loops covering regions or continents it is not.

Instead of height differences, *geopotential differences* do close around loops:

$$\sum_{i=0}^n \Delta h_i g_i \quad (4)$$

where g_i stands for gravity at the leveling interval i . For precise leveling networks on a national scale, the latter formula should always be used.

$$\Delta W_i = \Delta h_i g_i \quad (5)$$

Equation (5) should be used in all computations, producing geopotential values W_i for the benchmarks of the network.

3.2. Gravity method

This method is based on the gravitational force. Gravitational force has been generated from two particles or more that have a number of mass then the particles should be have a pull force to each other [3]. The force can be represented by the following equation:

$$F = G \frac{m_1 m_2}{r^2} \quad (6)$$

where F is gravity force (N), G is Newton gravity constant, m_1 is first mass (kg), m_2 is second mass (kg), r is distance between first and second mass (m).

3.2.1. *Correction.* There are several correction that must be done to have an anomaly gravitation value. Instrument reading correction, which adjusts device reading by converting into miligal unit.

$$\text{Read (mGal)} = ((\text{Read (scale)} - \text{Interval}) \times \text{Counter Reading}) + \text{Value in mGal}) \quad (7)$$

Tidal correction, which eliminates the gravitational influence of sun and moon that changes with latitude position and time

$$g_{st} = g_s + t \quad (8)$$

where g_{st} is tidal corrected gravity, g_s is gravity reading, and t = tidal corrected value.

Drift correction, which eliminates fatigue effect of the device that makes different gravity reading in the same measurement station at different time.

$$D_n = \frac{g_{st(n)} - g_{st(1)}}{T_n - T_1} (T_n - T_1) \quad (9)$$

where D_n is Drift in n-th station, $g_{st(n)}$ is tidal corrected gravity at station-n, $g_{st(1)}$ is tidal corrected gravity at station-1, T_n is last station measurement, T_1 is initial station time measurement, and T_1 = n-station time measurement.

Latitude correction, which corrects latitude position because of the shape of earth that makes different gravity measurement

$$g(\phi) = 978031.8(1 + 0.005304 \sin^2 \phi + 0.0000059 \sin^2 2\phi) \quad (10)$$

where $g(\phi)$ is latitude corrected gravity (ϕ = angle in radian).

Free air correction, which compensates point of measurement with datum (mean sea level).

$$g_{FA} = -0.3086 \times h \quad (11)$$

where g_{FA} is free air corrected gravity and h is elevation (m).

Bouguer correction, which compensates rock mass that is neglected when making free air correction

$$g_B = 0.04193 \times \rho \times h \quad (12)$$

where g_B is bouguer corrected gravity, ρ is density ($\frac{gr}{cc}$), and h is elevation (m).

Terrain correction, which is done to get gravity reading in the surface without topographic impact around

$$TC (mGal) = 0.04191 \frac{\rho}{n} [r_2 - r_1 + (r_1^2 + z^2)^{0.5} - (r_2^2 + z^2)^{0.5}] \quad (13)$$

where ρ is density ($\frac{gr}{cc}$), r_1 is compartment inner radius (m), r_2 is compartment outer radius (m), and n is length of zone.

After several corrections, gravity's data become a data that called by Complete Bouguer Anomaly. Complete Bouguer Anomaly is measured in Gal unit. Complete Bouguer Anomaly should be process to get anomaly density variation as spatial function with kriging method and creating depth anomaly

density section (then to be modelled the geolgy's strata and structure). Anomaly density variation (as figure 10 and 11) is the the one of final result after creating depth anomaly density section.

4. Subsidence in several geothermal field

4.1 Deformation analysis on macro and micro scale in oil field

Macro scale deformation are caused by pore pressure decrease and overburden pressure. Some studies describe the amount of subsidences [4]. They have correlated pressure drop to subsidence and time to subsidence on non-fractured reservoir. The datas are indicated below:

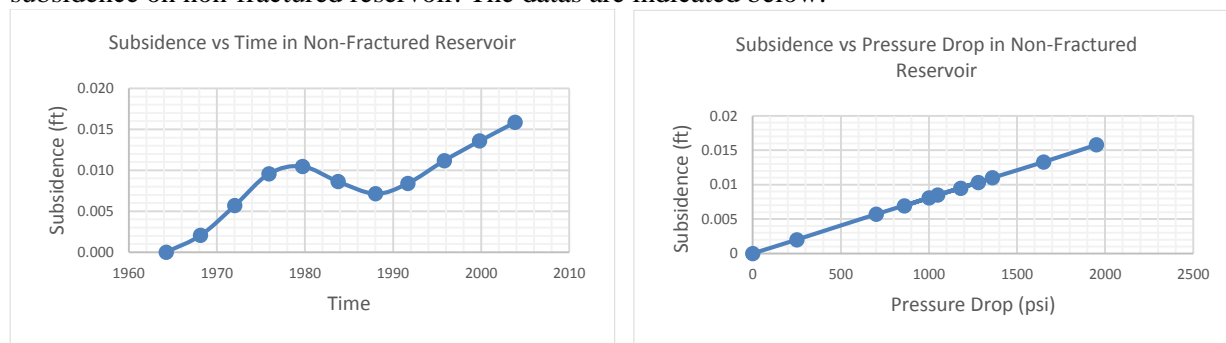


Figure 5. Subsidence variances during time on Doroud Field (Non-fractured reservoir) [4].

Figure 4. Subsidence variances vs. pressure drop on Doroud Field (Non-fractured reservoir) [4].

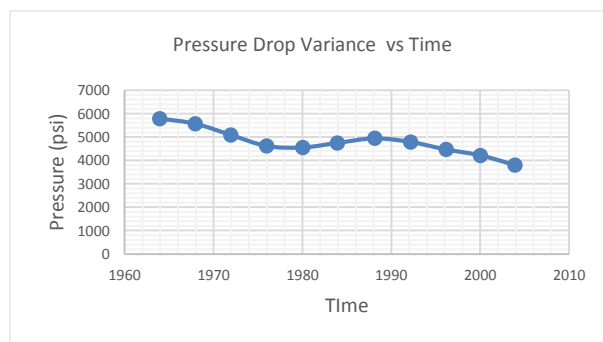


Figure 6. Pressure drop variances during time on Doroud Field [4].

Micro scale deformation is caused by fractured rock. The fractured rock properties are consist by aperture, orientation and fracture density. The same as before, they have generated the relationship between pressure drop, subsidence and time. The data are indicated below:

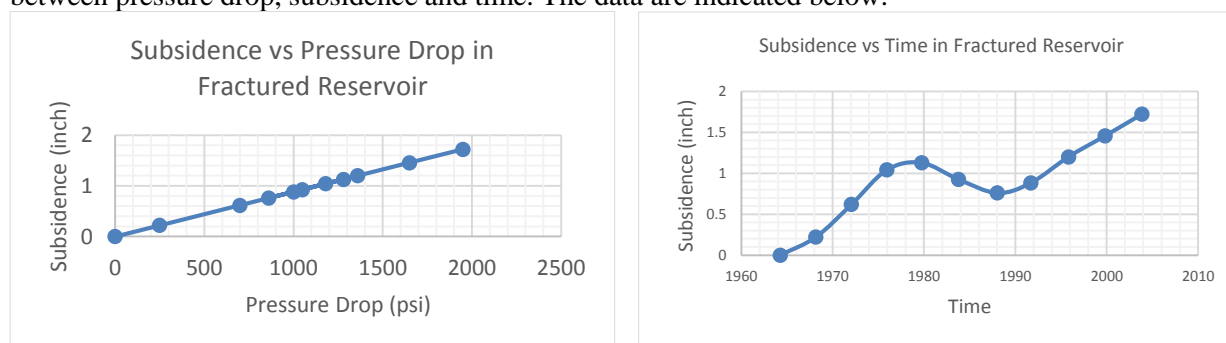


Figure 7. Subsidence vs pressure drop variances on Doroud Field (Fractured reservoir) [4].

Figure 8. Subsidence variances during time on Doroud Field (Fractured reservoir) [4].

4.2 Levelling and gravity measurement in geothermal field

For example, we look closer to Reykjanes Peninsula, which is located in Iceland [5]. There are 3 high temperature geothermal fields, Svartsengi, Eldvorp, and Reykjanes and only Svartsengi which has been put into operation since 1975. The elevation and gravity has been monitored since 1976. Svartsengi geothermal field started operation in 1976 and is now producing 45 MWe electricity. The productive area as outlined by 7 productive wells is in 1 km². The average production in 1998 was 226 kg/s and 28 kg/s mass is reinjected into reservoir.

Some 220 benchmarks have been used in the outer part of Reykjanes peninsula for monitoring subsidence after production in Svartsengi commenced in 1976. Every benchmarks was not used in every measurement since the initial strategy was to determine some part of the network or so. This led to the difficulty in comparing the result from one survey to another survey, therefore since 1992 all benchmarks was measured and the survey only repeated in longer period of time than before. The reference point is the northernmost point on SE-NW profile. Figure below shows us the outcome of survey at benchmark SN-H2, which indicated that it is the maximum subsidence measured during 1976-1999.

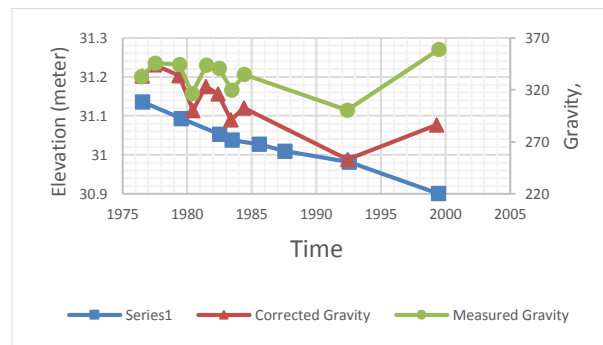


Figure 9. Elevation and gravity variation with time at benchmark SN-H2, Svartsengi geothermal field [5].

The following figure shows about the value of variation gravity. The minimal value is shown on red color to white. The red color to white color could explain why the geothermal field run into subsidence. The subsidence is closely related to the injection water and taking production on reservoir fluids. The little time-lapse gravity variation will be shown by the following figure :

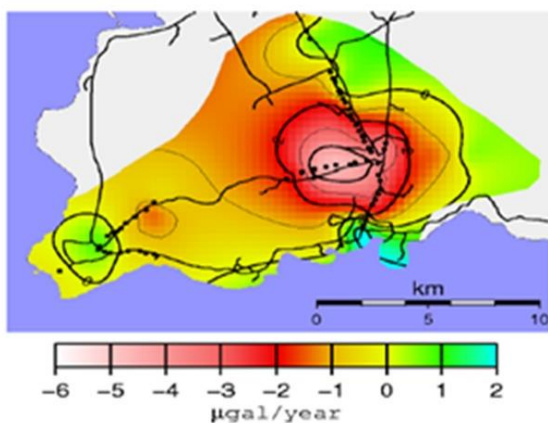


Figure 11. Mean gravity variation 1975-1999 [5].

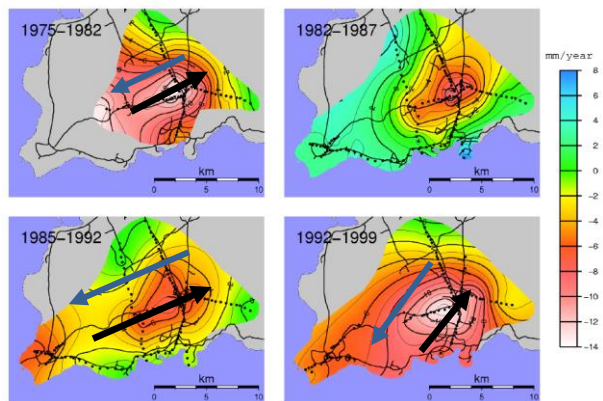


Figure 10. Subsidence rate at the outer part of Reykjanes peninsula for four times interval [5].

Figure 11. shows 4 periods of monitoring in 1975 to 1999. The first monitoring is in 1975-1982, the figure shows that the subsidence is high from the sign of red-white color. The trend of the over subsidence is indicated by the sign of black arrow. The cause of highly subsidence is strongly related by the water withdrawal on geothermal well. The second monitoring in 1982 to 1987, the figure shows that the subsidence happened around the well production. The enclosed contour represented the subsidence over the area has diminished to become more stable than. This condition related by reducing of the production reservoir fluid and injecting more water. The third monitoring is in 1985-1992, the figure shows that the subsidence spreads to a larger area, which is shown by the green color contour from the second monitoring changes to the yellow-red contour that has more negative value. The forth monitoring in 1992-1999 shows that the subsidence is high from the sign of red-white color. The trend of the over subsidence is similar to the direction of the first monitoring.

Another field example case is the Wairakei field, NZ [6]. The area produce heat with maximum fluid withdrawal of 2300 kg/s which started the production in 1950. The subsidence is started in 1960 after 10 years production (Figure 12). Benchmark A97 in the eastern borefield, and at P128 in the centre of the subsidence bowl. The rate of the subsidence has increase until in maximum point in 1970s (Figure 13). But after that the subsidence rate has decrease because the situation in the aquifer already stable.

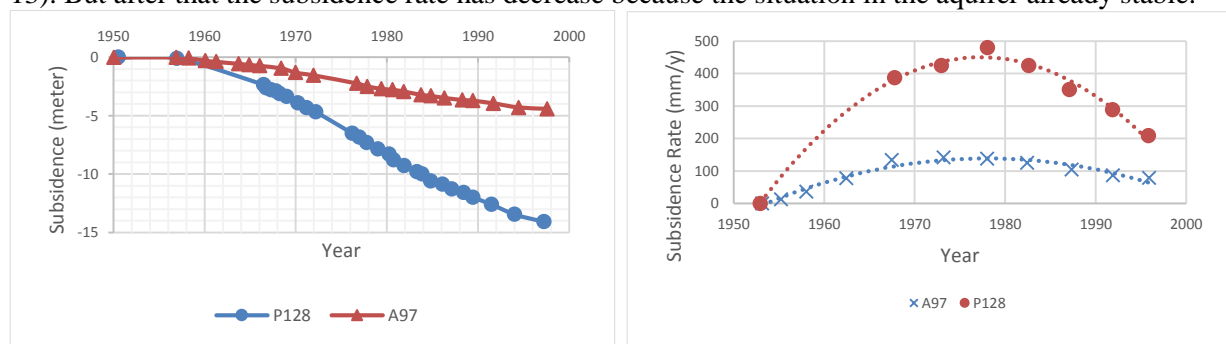


Figure 13. Subsidence and time diagram in Wairakei [6].

Mass and heat flow rate went up to the peak in 1960s. When the subsidence began to take place, mass and heat flow rate decreased gradually to be more stable than before. As can be seen from figure 12 and 13 above, rate of subsidence is significant because the pore pressure decreases overtime and there was no fluid injection to the reservoir. Injection process was undertaken in 1993 and Figure 14 below tells that after injection, the reservoir pressure remains constant.

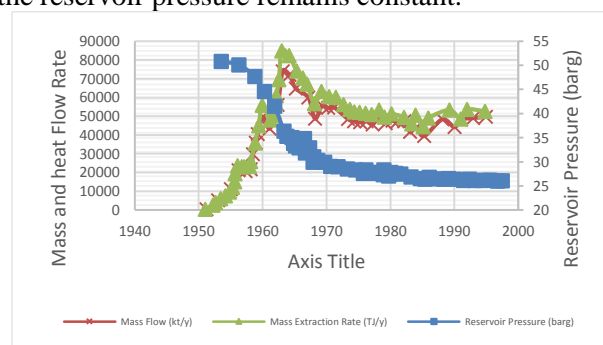


Figure 14. Mass and Heat flow rate and reservoir pressure vs time in Wairakei [6].

5. Impact of subsidence in the surface

5.1 Flooding

Subsidence probably doesn't cause any damage and can only be observed by using precise survey. However, slight subsidence which occurs in flat area or near a water body can cause specific environment effect nearby. The effect impacts dramatically when it happens close to sea or lake. The water from them can flow to the region which is lower and overwhelms the area. The remedy action should be prepared to restore the area, such as pumping water out of the swamp, constructing sewers, repairing the well, and building embankment which cost lots of money [7].

5.2 Structural effect

Building. Building structure usually provide maximum limits in deformation, which is based on total load applies in the beam or floors movement. Building component such as doors or windows, will alter because of excessive sags and the function will reduce. The effect of subsidence in building can be felt if the subsiding rates is different in respect to the building. The floors doesn't remain in a plane that leads to cracking of components or leakage in drainage. But, uniform subsiding rate will not be noticed because of no or slight damage [7].

Surface facilities. The effects of subsidence is most noticeable on long structure like pipelines, drainages, roads and powerlines. Pipelines are impacted by compression and tension forces due to land depression, therefore such a treatment needs to be undertaken. It is necessary to realign the pipelines by removing some sections of the pipe or replacing the stretched part of the pipe.

An example of the effect in drainage is the concrete at Wairakei [7], separated water drainage channel that has been damaged by compression in the edge of subsidence bowl. Repairing action has been undertaken and it is mitigated by placing sliding joints where the drainage descends to the Wairakei stream.

There are two high-voltage transmission lines which cross over maximum subsiding area in Wairakei. The tilting of some of the stake is extreme that is necessary to undertake a remediation as the lines are over-tension. It causes the insulators to rotate more than operational limits. Movement of the pylon at the top is about 1 meter for 24 meters high pylon [7].

Roads experience a moderate damage caused by subsidence. Near steam main overbridge, there has been a cracking in the pavement of State Highway 1 near Wairakei [7]. The lateral movement is up to 40mm/year, with subsidence of 100 mm/year in steam main bridge. Pavement cracking is still taking place proximate to the steam main bridge. A narrow depression across the highway, parallel to the bridge abutments is found a damage. Subsurface cracking may cause the failure. The direction of cracking is toward the center of subsidence and about perpendicular to the highway.

6. Mitigation

As shown in the field example of Wairakei that maintain a constant after injection since 1993, injection strategy has proved to be the best practice to overcome and reduce subsidence rate. An injection management should be adapted and configured based on the field condition [8]. The goal is to control and restrict excessive induced stress and strain changes without losing the long-term benefits of reservoir development for sustainable energy extraction.

7. Conclusion

Subsidence happens because of pore pressure decreases, so the effective stress goes up. The physical effect related to it is pore volume drops and compression takes place in the rocks.

Monitoring activity for alleviating subsidence is undertaken by leveling and gravity measurement. Both measurement should be performed regularly in a period of time. The result then is analyzed to predict the subsidence pattern over the measured area. It is known that fluid withdrawal is strongly related to subsidence. Blue arrow as shown in figure 11 indicates fluid movement and black arrow shows

subsidence magnitude from the smallest to the biggest number. A benchmark point (SN-H2) which is located in the northern part of Svartsengi Field has the biggest subsidence level as indicated in figure 9.

The impact of subsidence which had been observed in some geothermal field in New Zealand are flooding in an area near water body and structural deformation in building which is located in the subsidence-influenced area as well as pipeline and transmission grid failure.

Monitoring activity for alleviating subsidence is undertaken by leveling and gravity measurement. Both measurement should be performed regularly in a period of time. The result then is analyzed to predict the subsidence pattern over the measured area. It is known that fluid withdrawal is strongly related to subsidence. Blue arrow as shown in figure 11 indicates fluid movement and black arrow shows subsidence magnitude from the smallest to the biggest number. A benchmark point (SN-H2) which is located in the northern part of Svartsengi Field has the biggest subsidence level as indicated in figure 9.

Injection management also should be undertaken that is based on specific needs of the field, because it has been proved that it could maintain reservoir pressure, as shown in Wairakei field in figure 14.

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