NEW 2-D SUBSIDENCE MODELLING APPLIED TO WAIRAKEI-TAUHARA

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SUMMARY – Two-dimensional finite-element analysis has been applied to the question of subsidence in the Wairakei-Tauhara area, caused by abstraction of geothemal fluid. The software used has the facility to accommodate variable rock properties, including non-linear stress-strain behaviour, and the pre-consolidation history. It was found necessary to use strongly anisotropic permeabilities, which emphasises the importance of using a 2-D model. Results show a good match in time and space to historical subsidence. This has been achieved with a single set of rock properties for each geological unit, apart from locally enhanced vertical permeability under the Wairakei subsidence bowl. Compared to previous 1-D subsidence modelling, the current study shows a greater sensitivity to changes in reservoir pressure and strong control over the location of subsidence by the morphology of the lowest unit in the Huka Falls Formation. It is predicted that subsidence will continue for longer, and so eventually be larger, than previous modelling has predicted. However major subsidence is not anticipated to encroach on the Taupo urban area.

1. INTRODUCTION

Geothermal power development at Wairakei, mainly without reinjection, has caused large and laterally extensive pressure declines within the geothermal reservoir, and subsidence of the ground surface of varying magnitude across the surrounding area. Locally subsidence is much greater than has been observed at any other geothermal field worldwide, even where pressure declines are comparable. The adjacent Tauhara geothemal field (Figure 1) is hydrologically connected to Wairakei field. Cumulative subsidence of up to 2.3m has occurred at Tauhara since exploitation of Wairakei began in 1958.

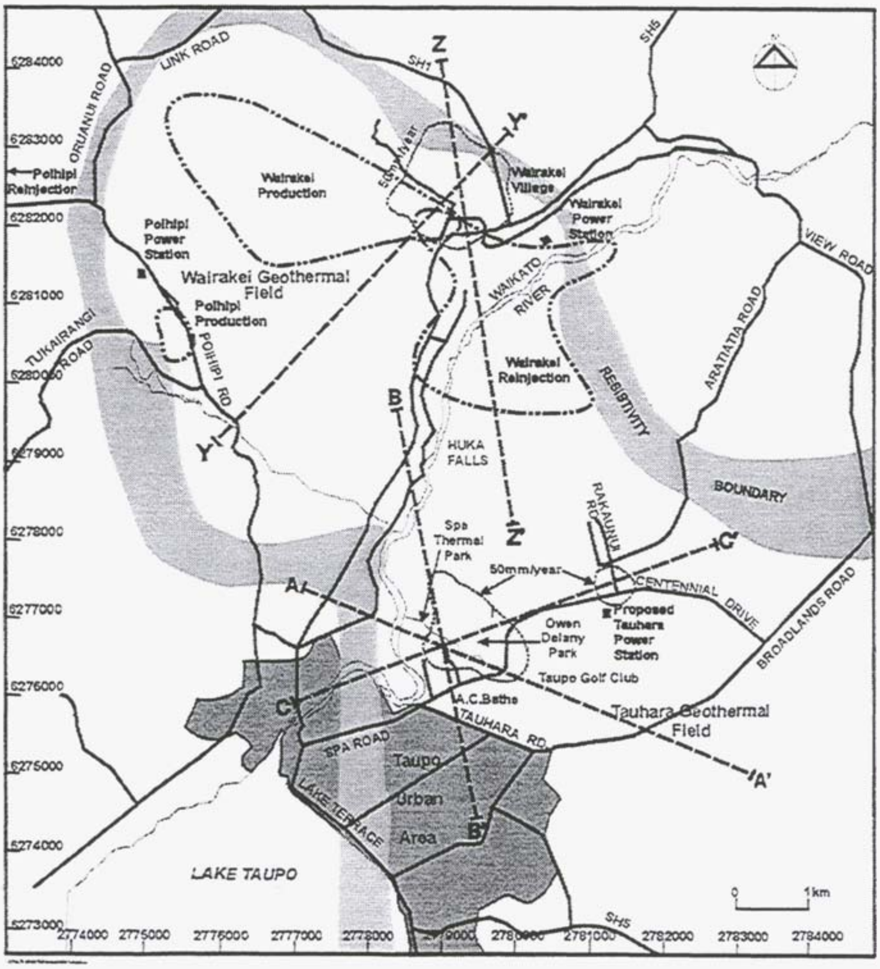

Figure 1 Location map: Wairakei and Tauhara

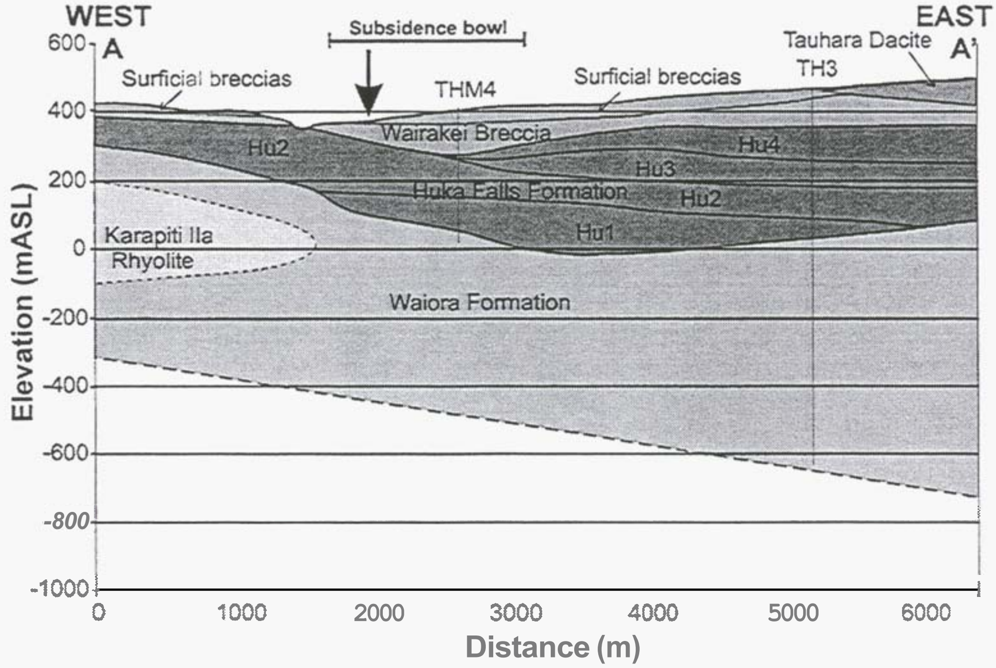

Figure 2: Geological cross section A-A' (2.5 times vertical exaggeration). The subsidence bowl shows the extent of the 50mm/year subsidence contour (1997-99 data), and subsidence is greatest beneath the arrow (benchmark 9734).

The Wairakei scheme now extracts about 140,000 tpd of fluid and hot water. Partial reinjection of separated waste water to wells on the eastern side of the Wairakei field began in 1996, and now comprises about 40,000 tonnes per day (tpd) (Contact 2001). The Poihipi power plant on the western side of the Wairakei geothermal resource produces from a shallow steam zone. The current take for the Poihipi power plant is 4,800 tpd, and all waste water is reinjected outside the geothermal field. There are numerous shallow geothermal wells at Tauhara, which tap a shallow aquifer for direct use, though the total take fkom these is small. Development of another 20,000 tpd of geothexmal fluid from the Tauhara field should occur by 2005. Further expansion of the Wairakei operation has been foreshadowed (Contact 2001).

Taupo District Council commissioned Sinclair Knight Merz Ltd (SKM) to carry out a quantitative study to investigate the mechanism of the subsidence process at Wairakei-Tauhara, and to provide input to the assessment of long term risks associated with further subsidence that may occur as a result of the existing and future extraction. The full report on that study, upon which this paper is based, has been made public by Taupo District Council.

Generally speaking, the extent of subsidence to date has been well described by others (e.g. *Allis* 1999), and that information is not repeated here. However, a recent survey of selected benchmarks in the Wairakei area (Energy Surveys 2000) documented positional surveys of benchmarks since the 1960s. The horizontal vectors of movement point to the centre of the subsidence bowl being about 200m south of benchmark P128, which has the greatest measured subsidence of any benchmark. The total subsidence (probably 15 to 20m) and the subsidence rates must be significantly higher at the centre of the subsidence bowl than at P128.

One-dimensional analysis of the geothermal subsidence has previously been carried out, notably by *Allis* and Zhan (1997) and Grant (2000) and used as the basis for predictions of future subsidence under various scenarios. In the course of the analysis of existing subsidence data (SKM 2001), it became obvious that the 1-D methodology used could not account for the existing subsidence in a realistic manner.

2. GEOLOGY

The geology of the Wairakei-Tauhara area has been described by numerous authors from Grindley (1965) on. A cross-section corresponding to one of the subsidence model profiles is shown in Figure 2. The units which are most significant for this study are:

The **Waiora Formation** consists of various pumice breccia and ignimbrite layers, with interbedded sediments and interlayered extrusive rhyolite lava flows (**Haparangi** Rhyolites). The Waiora Formation forms the main productive reservoir at Wairakei, and probably also at Tauhara. It is the unit within which the major pressure drawdown has taken place in response to production. In most of the field it is overlain by:

The **Huka Falls Formation** consists of lacustrine sediments and pumiceous breccias, the latter comprising pyroclastic flow deposits and their re-worked equivalents, and hydrothermal eruption (Grindley 1965), or landslide collapse deposits (Wood & Browne 2000). Throughout the Wairakei-Tauhara area, the Huka Falls Formation is thin over the ignimbrite plateau and along the ridge of the Karapiti IIa Rhyolite, but thickens into the marginal basins. Grindley (1965) divided the unit into four members (Hu1-Hu4, with Hu1 being the oldest):

Hu1 mudstones have low permeability, although vertical flow paths for the geothermal fluids may exist in vertical fractures and faults. This study has demonstrated that most of the consolidation responsible for the subsidence is occurring within this unit.

Hu2 is an unconsolidated pumice breccia of generally moderate permeability that forms a shallow aquifer.

Hu3 is a well compacted, interbedded mudstone, siltstone and fine grained sandstone of very low permeability.

Hu4 is a poorly compacted, fine sandstone and mudstone member. It is of moderate to low permeability, and may be regarded as a partial aquiclude.

Above the Huka Falls Formation are a series of younger pyroclastics and minor lake sediments, which as a whole are sufficiently permeable that they constitute groundwater aquifers.

An important feature of Wairakei-Tauhara geology is that many units were deposited on significant pre-existing relief. The current study has demonstrated that the paleo-topography is critical in determining the location of the maximum subsidence.

3. SKM 2-D MODELS

A series of five 2-D models have been developed using the finite element analysis code Plaxis Version 7.2. Locations are shown in Figure 1. Main advantages of the SKM 2-D Plaxis models over previous 1-D models are:

- The two-dimensional model incorporates an approximation to the actual geological structure.
- Two-dimensional modelling of fluid flow and pressure changes in both horizontal and vertical directions is possible.
- Horizontal and vertical permeability can be independently defined for stratigraphic units. It was found necessary to use strongly anisotropic permeabilities. This is consistent with the geological nature of the materials (horizontally layered and diverse volcaniclastic and epiclastic sediments) and with other empirical observations from reservoir modelling at Wairakei.
- More advanced definitions of geotechnical properties of rocks and soils are possible. Examples include permeability changing with void ratio, non-linear stress-strain behaviour of units, and the model accounts for the pre-consolidation stress history.
- The model incorporates the coupled Biot Theory, modified to account for non-linearity, plasticity, and stress changes in the 2-D plane Strain.

15-node isoparametric triangular elements, employing a cubic interpolation function were used. The properties at high temperature have been estimated using published experimental data (*e.g.* Sydney 1966).

There are no adequate field or laboratory test data on the in-situ geotechnical properties of the rocks in the Wairakei-Tauhara geothermal system, such as cohesion, friction angle, permeability, stiffness, void ratio, and stress-strain behaviour. An initial set of geotechnical properties has been derived fiom previous studies involving similar materials including Allis (1999), Fairclough (2000), Grant (2000), Kelsey (1987), and Robertson (1984), whilst retaining the integrated geologic and hydrologic profiles as a consistent background. Past measurements of physical properties have been on selected individual samples, whereas for this study, representative bulk values were required. These properties have been optimised so that the calculated subsidence trend from 1952 matches the subsidence measurements.

Rock Properties

The units, Hu1, Hu2 and Hu3 were modelled with advanced soil models available in Plaxis Version 7.2 because these units appear to play a major role in the subsidence process. All the other rock units do not undergo any significant compaction (either because they are not subject to significant pressure changes in the case of the very-near-surface layers, or because they are too stiff) and therefore are modelled with a simple Mohr-Coulomb Model.

Non-linear change in stress-strain behaviour has been observed in similar pumiceous material. There are two separate aspects to the non-linearity, one being related to a notional unload reload (or crushing), the other to a change in stiffness due to increase in confining pressure. Both of these changes have been observed to varying degrees in the materials tested to date. The subsidence rates at Tauhara suddenly increased at many benchmark locations in the 1980's when the pressure was starting to stabilise, suggesting a distinct change in the stiffness of the compacting material.

The stiffnesses of the materials used are low compared to other comparable materials. This is a consequence of the elevated temperatures and nature of the materials themselves (Lewis & Schrefler 1998, Sydney 1966).

A single consistent set of soil properties was used for the three Tauhara models, and achieved a good match to historical subsidence in time and space. However, the same properties did not give a good match to historical subsidence at Wairakei. This led to the introduction of a zone of enhanced permeability under the subsidence in the Wairakei models to account for the effects of faults or other near-vertical permeable zones on the subsidence process. This is consistent with observations that hot springs occurred at the subsidence bowl location prior to the commencement of geothermal production, suggesting a vertical flow path. This vertical upflow is thought to occur on faults, although hydrothermal eruption vents could also play a role. In this zone, the vertical permeability of the Huka Falls Formation and Waiora Formation was increased in the model so that the horizontal permeability is one order of magnitude greater than the vertical permeability in these layers. This means that the zones of enhanced vertical permeability will have greater effects on highly anisotropic units such as Hul.

Fluid Properties

Sufficient reservoir pressure and temperature data exist at Wairakei to input directly into the subsidence model. Most of the model data were obtained from those reported by Clotworthy (2001), including his liquid pressure map to account for the spatial variation of the pressure drawdown. More limited data are available on the history of pressure drawdown in Tauhara field. Therefore, the model input pressure for Tauhara were interpolated from a reservoir model with TOUGH2.

For the future prediction of subsidence trends under the status quo production, the pressure state of 1997 was assumed to remain unchanged over the next 100 years. For predicting the effects of the proposed 20,000 tpd production at Tauhara, O'Sullivan's (1999) reservoir modelling results were used. These predict an incremental pressure decline of approximately 2 bar at Tauhara, assuming development would commence in 2005.

4. RESULTS

Matches in Space

The results of matching of the models in space to historical subsidence along two 2-D profiles at Wairakei and Tauhara are shown in Figures 3 and 4. These demonstrate a good match. Comparably good results were obtained along the other model profiles expect for line BB' where 3-D effects were apparent, causing the model to under-estimate the subsidence. The magnitude of subsidence depends on the thickness of the compacting layer, while the rate of subsidence is dictated by the morphology of the lower boundary. Section B-B' is almost parallel to the structural contours of the basal contact of the compacting layer. Therefore the compacting layer slopes in the out-of-plane direction along section B-B', and significant out-of-plane drainage of fluid occurs as a result.

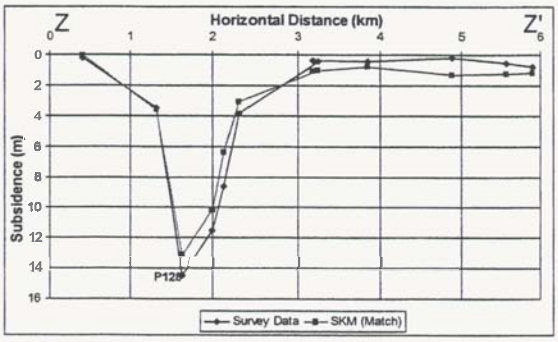

Figure 3: Past subsidence from the 2-D model and from survey data: Section Z-Z', Wairakei

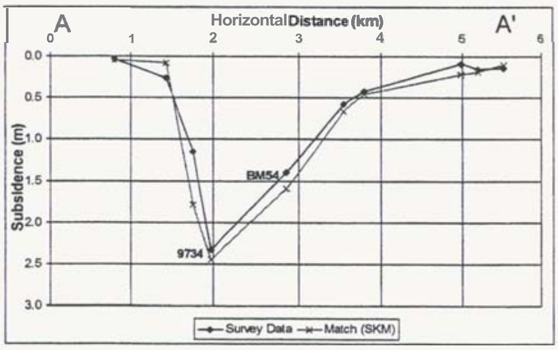

Figure 4: Past subsidence fkom the 2-D model and from survey data: Section A-A', Tauhara

Matches in Time

Matches of the models in time at selected benchmarks are shown in Figures 5 and 6 for Wairakei and Tauhara respectively. These figures also show the predicted subsidence for the next 100 years.

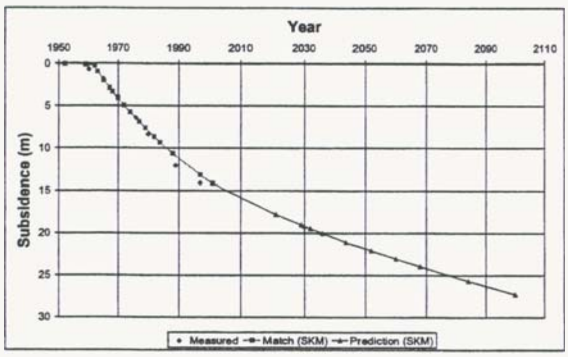

Figure 5: SKM future subsidence prediction for P128, Wairakei

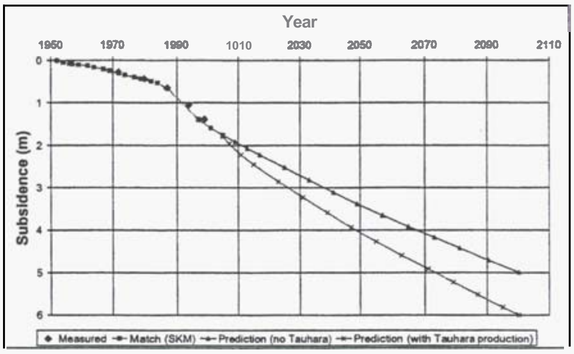

Figure 6: SKM future subsidence prediction for BM54, Tauhara

Note the model subsidence at P128 near the centre of the Wairakei subsidence bowl correctly simulates the acceleration of subsidence in the early 1960's and subsequent decrease in the subsidence rate towards the late 1980's and early 1990's. The model appears to understate actual subsidence after the late 1980's by about 7%.

Benchmark BM54 is located near the edge of the Tauhara subsidence bowl, and has a long history of monitoring, though not the greatest subsidence rate. Monitoring of this benchmark commenced in 1971, and survey measurements taken at a reasonable frequency over a relatively long period of time are available. Subsidence at this benchmark prior to the commencement of the monitoring in 1971 has been estimated by comparing with an adjacent benchmark AA8.

The matches obtained by the SKM model and Allis (1999) appear to be of similar quality. However, unlike Allis' model, the SKM model did not require any modification of the input pressure data to achieve the match, and apart from the enhanced permeability at Wairakei, used a single consistent set of rock properties.

Future Forecasts

Pressure measurements taken at various wells at Wairakei and Tauhara indicate that the reservoir pressure started stabilising in the 1980's. It was therefore assumed that there would be no change in the reservoir pressure profile after the year 1997 under the status quo production fiom Wairakei. Based on this assumption, the future subsidence at Wairakei and Tauhara up to the year 2100 has been predicted with the same input pressures that were used in the history matching. Selected results are presented in Figures 5 and 6.

At Wairakei, the rate of subsidence is anticipated to continue slowly decreasing, but subsidence will continue to 2100 and beyond. Total subsidence (including that which has already occurred) to 2100 at P128 is expected to exceed 27 m.

At Tauhara, the recent acceleration of subsidence rates is not expected to continue. Rates of subsidence will stabilise and then diminish slightly, but not as much as at Wairakei, reflecting the lesser vertical permeability. Subsidence will continue at almost as great a rate as today through to 2100. Total subsidence to 2100 is anticipated to exceed 7 m at 9734, and reach 5 m at BM54.

By considering subsidence predictions along the model profiles in combination, prediction of the lateral extent of subsidence can be made. The extent of the areas of large subsidence (the "subsidence bowls") will broaden somewhat, but not to a great extent.

In Figure 6, the predicted effects of the proposed 20,000 tpd Tauhara development are also shown. The effects increase the rate of subsidence by 30-50% immediately, and total subsidence by 1-2 m by 2100. In contrast, Allis (1999) predicted that the 20,000 tpd development of Tauhara field would have no significant effects on the future Subsidence.

The output fkom the SKM 2-D model indicates that the excess pore pressure in Hul unit (relative to the underlying formations) will still exceed 1,000 kPa (10 bar) in the year 2100. This means that there is potential for substantial subsidence to occur even after 2100 as this excess pore pressure dissipates slowly over time. It is expected that the rate of dissipation of the excess pressure will be very slow, and it will take hundreds of years for the excess pore pressure to dissipate completely. In the longer term, as the subsidence of the ground continues, the position of the subsidence bowl will shift to where the compressible Hul layer is thickest. At Taupo, this will result in elongation of the subsidence bowl towards the southeast and possibly towards Rakaunui Road based on a general consideration of the geology. However, it is likely that the rates will be lower. The greatest subsidence in Taupo will eventually occur where Hul, the compacting layer, is thickest, that is believed to be between the Golf Course and Rakaunui Road.

5. DISCUSSION

The model indicates that a concentrated high volumetric strain occurs at the edge of the compressible Hul unit where water drains laterally relatively freely as the pressure declines in the underlying Waiora Formation. The assumed anisotropy for the mudstone unit controls the position of the subsidence bowl. That is, the fluid is flowing laterally rather than vertically, while the subsidence is vertical. The subsidence happens most rapidly where the fluid can exit, that is to say where there are inclined side walls on the edge of the consolidating unit. This phenomenon explains why the subsidence is occurring at specific locations. The subsidence bowl will shift and enlarge as the pressure change propagates further into the Hul unit.

The results of the two-dimensional analysis clearly demonstrate that the subsidence mechanism assumed by Allis **(1999)** is improbable. He assumed a **uniform** thickness of **100** m for the **Hu3** layer, and most of the subsidence was assumed to occur within this Hu3 layer. Allis concluded that the varying rates of subsidence at Tauhara field are due to the lateral variations in the properties of the compacting mudstone layer. There is no geological or geophysical evidence to support this conclusion. The two dimensional modelling demonstrates that **Hul** is the major compacting layer, and **Hu3** is undergoing only small volumetric strain. Hu3 has not yet experienced any major pressure changes due to drainage fkom below, and the pressure gradient is controlled **fkom** above by shallow groundwater. In fact, the major subsidence at Tauhara is occurring at a position without Hu3 present.

The nature of the materials present will tend to exacerbate the differential settlement, that is, concentrate the settlement contours. This is consistent with the interpretation that the consolidation is taking place in a deeper stratum than previously suggested.

6. CONCLUSIONS

The geothermal subsidence process at Wairakei and Tauhara fields has been analysed using two-dimensional finite element models with Plaxis software. The models demonstrate that the subsidence at Wairakei and Taupo is largely occurring by compaction of the Hul compressible layer as it responds to an exploitation-induced pressure decline in the Waiora Formation below.

An excellent model fit in time and space was generally achieved for all of the five study sections, although one section was strongly affected by 3D effects.

Subsidence to the year **2100** has been predicted for two future production scenarios. The first scenario assumes that no development will take place at Tauhara, and the production rate at Wairakei remains unchanged. In the second scenario, the incremental effects of the currently proposed **20,000** tpd development of Tauhara field are considered. The **20,000** tpd development of Tauhara field will increase the rate of future subsidence at Taupo by **30-50%.** By the year **2100,** the **maximum** subsidence will be approximately **27m** at Wairakei. At Taupo, the **maximum** subsidence will be over 7m with the current Wairakei development only, or 8 to 9m with the future Tauhara development.

It is predicted that the subsidence will continue, gradually diminishing, for hundreds of years if the current state of pressure within the geothermal field remains unchanged. The area significantly affected will not be much larger than previously predicted, but within that area the effects will continue for longer and be more severe. The Tauhara subsidence bowl will widen and shift away fiom the Waikato River. It is not, however, anticipated that the area of severe subsidence will impinge on any major part of the current urban area.

Because the rate of subsidence is sensitive to small pressure changes in the underlying formations, and because the location of the subsidence is controlled by the geology, it may be possible to slow down or reduce the long term future subsidence if the reservoir pressures can be raised by reinjecting the geothermal fluids in appropriate locations.

7. ACKNOWLEDGMENTS

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