Geothermal Resources Council Transactions, Vol. 27, October 12-15, 2003

Two Dimensional Subsidence Modelling at Wairakei-Tauhara, New Zealand

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Keywords

Wairakei, Tauhara, subsidence modelling

ABSTRACT

Subsidence at Wairakei-Tauhara due to almost 50 years of geothermal fluid extraction was modelled by two dimensional finite-element analysis. The modelling accommodates variable rock properties, including non-linear stress-strain behaviour, and pre-consolidation history. A good match to historical subsidence in time and space was achieved with a single set of rock properties for each geological unit, apart from two local zones with different permeability. Compared to previous 1-D subsidence modelling, this 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 may lead to subsurface shear failure, which will enhance vertical permeability, and therefore cause an acceleration of subsidence rates.

Introduction

Almost 50 years of geothermal power generation at Wairakei, mainly without reinjection, has caused extensive pressure decline within the reservoir, and subsidence of the ground surface. This locally exceeds 15 m, which is greater than at any other geothermal field, even where there have been comparable pressure declines. The Tauhara geothermal field (Figure 1) is hydrologically connected to Wairakei, and following declining pressures in the 1960s, there has been up to 2.5 and 1.6 m of subsidence in two separate subsidence bowls (Figure 1). In recent years, the pressure decline appears to be extending to southern Tauhara, and a new area of subsidence has formed there, near the Taupo urban area.

Wairakei power plant (commissioned in 1958) extracts about 140,000 tonnes per day (tpd) of fluid. Partial reinjection (begun in 1996), now comprises about 40,000 tpd. Poihipi power plant on the western side of Wairakei field (commissioned in 1997) produces 4,800 tpd from a shallow steam zone, with all condensate reinjected outside the field. A development at Tauhara that will extract another 20,000 tpd (with full reinjection) should occur by 2005, and further expansion is planned for Wairakei (Contact 2001, Geotherm 2001). Past 1-D by Allis and Zhan (1997) and others has been used to predict future subsidence. However, there are significant shortcomings with the 1-D method; hence the need for detailed 2-D modelling.

Geology

The geology of Wairakei-Tauhara has been described by numerous authors, dating back to Grindley (1965). A cross-section

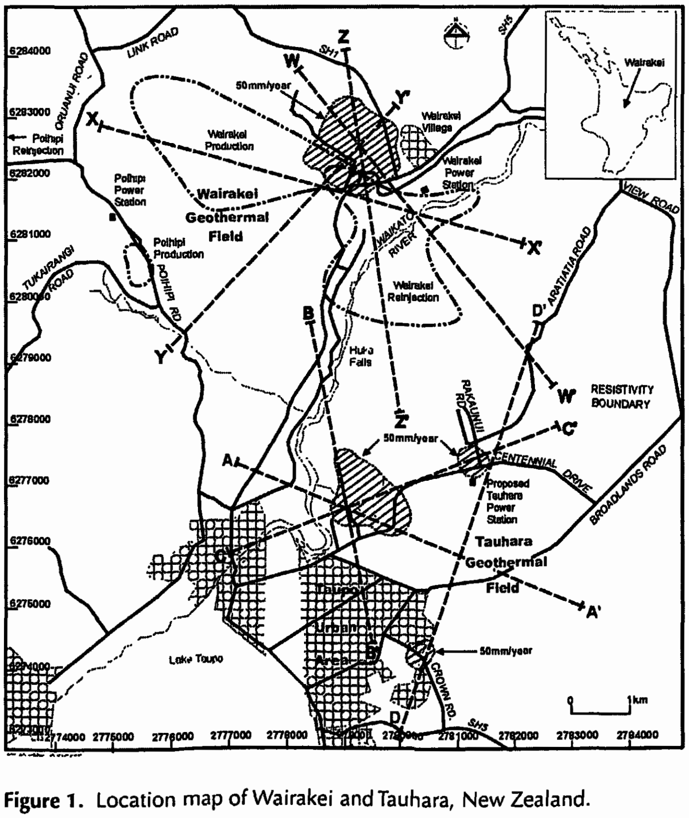

Figure 1. Location map of Wairakei and Tauhara, New Zealand.

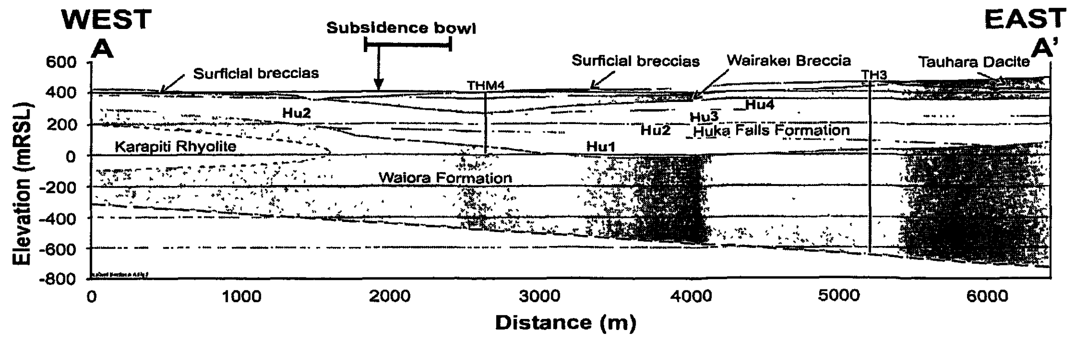

Figure 2. Geological cross section A-A' (no vertical exaggeration). The subsidence bowl shows the extent of the 50mm/year subsidence contour (1997-99 data), and subsidence is greatest beneath the arrow (benchmark 9734).

corresponding to one of the subsidence model profiles is shown in Figure 2. The units that are most significant for this study are:

Waiora Formation: pumice breccia and ignimbrite layers, with interbedded sediments and interlayered extrusive rhyolite lava flows (including Karapiti Rhyolite). This formation is the main productive reservoir at Wairakei, and the major pressure decline due to production has occurred within this formation. In most of the field it is overlain by:

Huka Falls Formation: lacustrine sediments and pumiceous breccias, the latter comprising pyroclastic flow deposits and their re-worked equivalents. Grindley (1965) distinguished four members (Hu1-Hu4, with Hu1 being the oldest): Hu1 and Hu3, predominantly low permeability mudstones, Hu2, unconsolidated pumice breccia of moderate permeability that forms a shallow aquifer, and Hu4, fine sandstone and mudstone, forming a partial aquiclude.

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

Two Dimensional Subsidence Modelling

Eight 2-D models were developed using the finite element analysis code Plaxis Version 7.2 at the locations shown in Figure 1. The main advantages of 2-D over past 1-D modelling are that 2-D modelling:

- is based on the known geological structure.
- allows more advanced definition of geotechnical properties (*e.g.* permeability varying with void ratio, non-linear stress-strain behaviour, and pre-consolidation stress history).
- incorporates the coupled Biot Theory, modified to account for non-linearity, plasticity, and stress changes in the 2-D plane strain.
- allows fluid flow and pressure changes to be modelled both horizontally and vertically.
- allows horizontal and vertical permeability to be set independently. Strongly anisotropic permeabilities are consistent with the nature of these units (particularly the Huka Falls Formation lacustrine mudstones) and with reservoir model data.

Input Data

There is limited laboratory test data on the geotechnical properties of units in the Wairakei-Tauhara geothermal system (*e.g.* cohesion, friction angle, permeability, stiffness, void ratio, and stress-strain behaviour). An initial set of geotechnical properties was derived from previous studies involving similar materials (including Robertson 1984, Kelsey 1987, Allis 1999, Fairclough 2000, and Grant 2000). These properties were optimised to match the model subsidence trend from 1950 with subsidence measurements. A single consistent set of reference parameters (which are adjusted by the model to account for stress state, void ratio, and pre-consolidation pressure) was used throughout, with two exceptions. Beneath the Wairakei subsidence bowl, enhanced permeability was introduced to model near-vertical permeable zones (faults or hydrothermal eruption vents), which fed hot springs there. A zone of low permeability was introduced to explain the delay in the pressure decline reaching southern Tauhara.

Historical reservoir pressure and temperature data from the Contact reservoir model was used for Wairakei, with some modifications to fit field measurements reported by Clotworthy (2001) and geological controls. With limited historical data for Tauhara, input pressures were interpolated from reservoir models. For assessing future subsidence under the status quo scenario, future pressures were assumed to remain unchanged over the next 50 years. Reservoir model predictions were used for other scenarios, including O'Sullivan's (1999) prediction of a 2 bar incremental pressure decline at Tauhara for the 20,000 tpd development.

Stress due to reservoir temperature change was not included in this modelling as this was estimated to be a second or third order effect compared to observed levels of subsidence.

Results and Discussion

Matches in Space

The model match to historical subsidence along one of the 2-D profiles is shown in Figure 3. Although the magnitude of subsidence will depend on the thickness of the compacting layer, the rate of subsidence is controlled by the slope of the lower boundary, because fluid flows laterally out of the mudstones. Subsidence is most rapid where the fluid can exit, that is to say where there are inclined side walls on the edge of the consolidating unit. This explains why the subsidence is greatest at specific locations. The subsidence bowl will shift and enlarge as the pressure change propagates further into the Hu1 unit.

A similar match was obtained on most other model profiles, expect for those which parallel the structural contours on the base of the compacting layer. The third dimension (out-of-plane) drainage that will result causes the model to under-estimate subsidence on these sections.

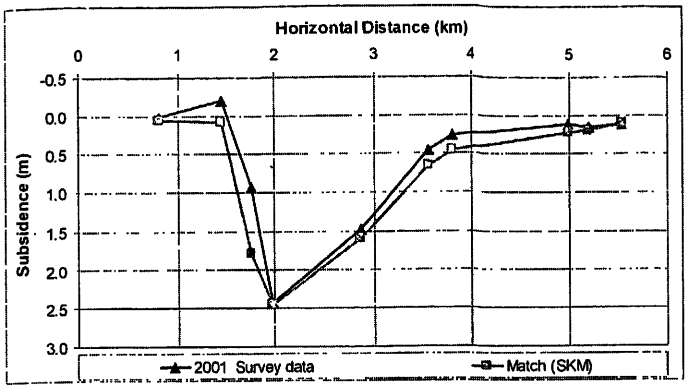

Figure 3. Comparison of actual and calculated subsidence to date, section A-A′.

Matches in Time

The model match with time for two benchmarks is shown in Figures 4 and 5, including predicted subsidence for the next 50 years. 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, though the model generally overstates subsidence by 10-15%. Benchmark 9734 (near the centre of the Tauhara subsidence bowl) was first monitored in 1997, so prior subsidence was calculated by comparing with adjacent benchmarks. A good match was achieved to past subsidence.

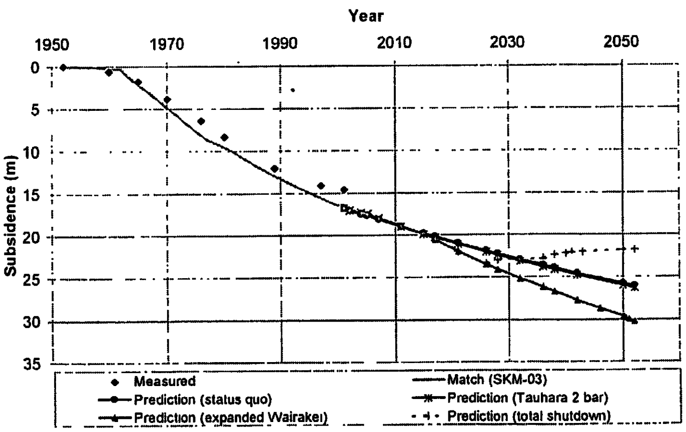

Figure 4. History matching for benchmark P128, Wairakei subsidence bowl.

Future Predictions

Future subsidence at Wairakei and Tauhara was predicted to 2052, based on various development options, including the status quo, the 20,000 tpd Tauhara development going ahead, the proposed Wairakei expansion going ahead, and total shutdown in 2026. Predictions for two benchmarks are presented in Figures 4 and 5.

Under the status quo scenario, the rate of subsidence will continue slowly decreasing, but subsidence will continue to 2052 and

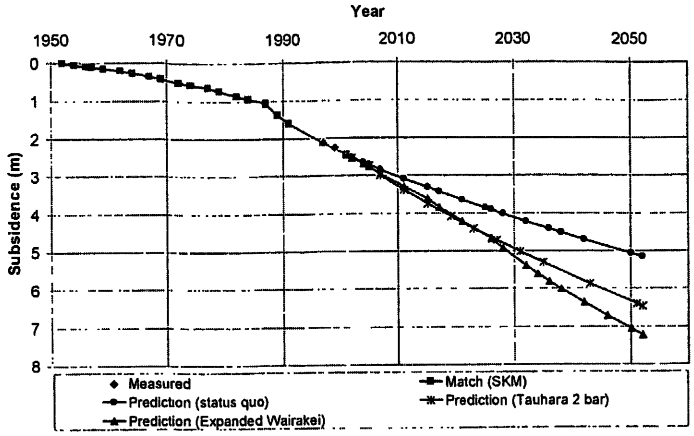

Figure 5. History matching for benchmark 9734, Tauhara subsidence bowl.

beyond. Total (including past) subsidence to 2052 is predicted to exceed 26 m at P128 (Wairakei), and 5 m at 9734 (Tauhara). Any additional fluid extraction will increase subsidence rates and total subsidence significantly. In contrast, based on 1-D modelling, Allis (1999) predicted that the 20,000 tpd Tauhara development would have no significant effect on future subsidence rates. A total shutdown would result in a small, gradual rebound, though most subsidence is not reversible.

Other Effects

Detailed modelling indicates that shear failure may occur in the Huka 1 unit at differential settlements of about 0.8° (approximately 1:70 tilt) at the ground surface. The precise value will vary because the thicknesses and depths of units vary, but this provides a sensible guideline for future monitoring of ground deformation. Differential subsidence of this magnitude has already occurred at some locations within Wairakei-Tauhara, including around the Wairakei and northern Tauhara subsidence bowls. Subsurface shear failure is likely to cause enhanced vertical permeability, and therefore an acceleration of subsidence rates, and possibly thermal activity due to increased steam upflow and/or groundwater drainage.

At all of the subsidence bowls, differential settlement could potentially cause damage to structures and infrastructure. However, because subsidence rates are sensitive to small pressure changes in underlying formations, and because the subsidence location is controlled by the geology, targeted reinjection could potentially be used to reduce future subsidence.

Conclusions

Geothermal subsidence at Wairakei and Tauhara has been analysed using two-dimensional finite element modelling. The models indicate that subsidence at Wairakei and Tauhara is largely occurring by compaction of the Hu1 mudstone layer as it responds to an exploitation-induced pressure decline in the Waiora Formation below.

By 2052, total subsidence will be 26-30 m at Wairakei, and 5-7 m at Tauhara, depending on future extraction rates. Subsidence is predicted to cause damage to structures and infrastructure, but future subsidence could potentially be reduced with targeted reinjection.

Acknowledgements

The subsidence model was developed under a Sinclair Knight Merz Technology Development grant. Data on historical subsidence and geology were provided by Contact Energy, through Environment Waikato. The model methodology and results were reviewed at various stages by Rob Davis, Malcolm Grant, Karsten Pruess and Graham Wheeler. Permission from Taupo District Council to publish the results is gratefully acknowledged.

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