Modelling of Subsidence at the Wairakei Geothermal Field, New Zealand

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ABSTRACT

Significant localised ground subsidence related to geothermal production has been experienced within Wairakei geothermal field since the 1950s. Much of current knowledge of the cause of this subsidence anomaly has come from data gathered recently during an intensive subsidence investigation program. This anomaly is understood to be caused by both a reduction in pore pressure and hydrothermally altered weak formations. In order to quantitatively study the subsidence and predict its future behaviour, a subsidence modelling project is being carried out. A new radially symmetric subsidence model has been created combining geomechanics modelling using the finite element ABAQUS code and mass and heat flow modelling using TOUGH2. The coupled modelling approach calculates the local fluid pressure and temperature and then the related stress state using a nonlinear elasto-plastic constitutive model. The model parameters were determined using field data, laboratory measurements and calibration. The results show that the model is capable of accurately representing the subsidence that has occurred at Wairakei and that it will be a valuable tool for predicting rates of subsidence as a result of future production.

1. INTRODUCTION

1.1 Background

Subsidence related to geothermal fluid production has occurred at Wairakei geothermal field in New Zealand, as shown in Figure 1. Damage related to subsidence can result in significant economic loss. At Wairakei field, for instance, subsidence has caused casing damage, tension cracks, ponding of the Wairakei stream, all requiring remedial action. This phenomenon attracted attention as early as the 1970s, after its discovery through re-levelling surveys conducted since the 1950s.

Continuous monitoring of existing bench marks (BMs) has involved the use of variety of techniques that include First-Order levelling, a global positioning system (GPS) network (Energy Surveys, 2009) and, recently, Interferometric Synthetic Aperture Radar (InSAR) (Hole *et al*., 2007). This monitoring has produced important information regarding the magnitude and the rates of subsidence. The subsidence anomaly at Wairakei has evolved with time, as documented in publications by Hatton (1970), Allis (2000), Allis *et al*. (2009) and Bromley *et al*. (2015). Generally, subsidence results from compaction of low permeability, compressible layers when their effective stress is gradually increased as a result of pore pressure reduction. An increase in effective stress can be responsible for measurable deformation of reservoir material and this deformation is transmitted to the surface as subsidence.

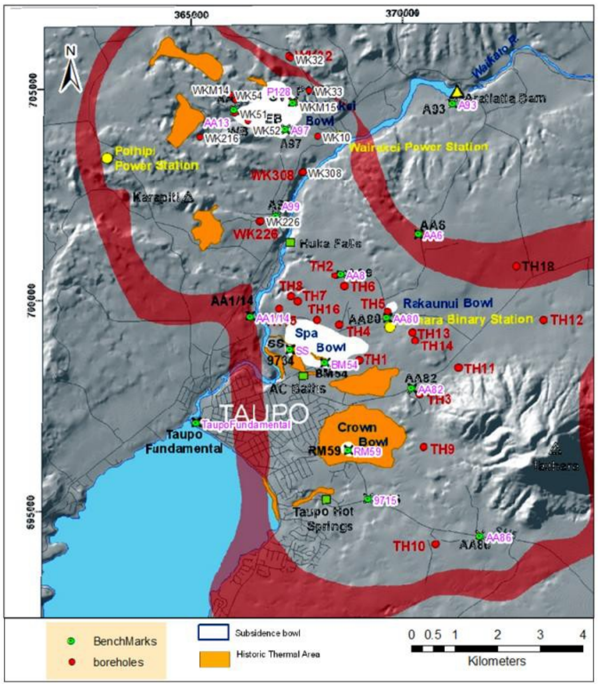


Figure 1: Subsidence bowls, monitoring wells (red) and bench marks (green) at Wairakei-Tauhara fields (modified after Bromley *et al.*, 2010).

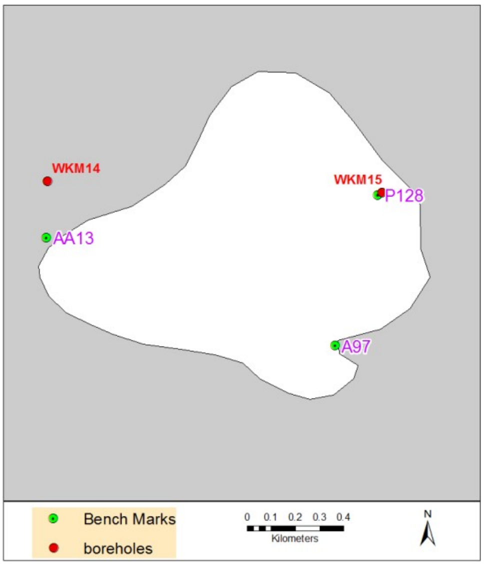


Figure 2: A map showing Wairakei subsidence bowl, key bench marks (BMs) and wells.

Subsidence at Wairakei has complex origins, arising from varying material properties and heterogeneous stratigraphy within the geothermal system. It is understood that ground subsidence at Wairakei is the response of local hydrothermally altered and compressible soft, porous materials to the changes in pressure within the geothermal system.

Subsidence models are necessary to help understand the phenomenon. Previously one-dimensional models (Allis and Zhan, 2000; Allis, 2001; Koros *et al*. 2014, 2015) have been applied to model ground subsidence at Wairakei field. Generally, predictions made with one-dimensional models are limited. For example, they cannot predict the shape and extent of a subsidence bowl and hence the need for 2-D and 3-D multi-dimensional models. The present model is radially symmetric, utilizing r-z coordinates and thus is an approximation to the 3-D situation. Some horizontal detail can be represented in radial symmetry (r-z) and the vertical dimension is fully included.

The modelling approach used in this work is based on Biot's (1941) poroelastic theory and Terzaghi's 1923 concept of effective stress (Terzaghi, 1943). Biot's poro-elastic theory can be applied to purely elastic and reversible deformation only. However, some reservoir material at Wairakei field contains yielding components that produce nonlinear elasto-plastic behaviour. Therefore the concept of effective stress can be applied more broadly to elasto-plastic solid constitutive laws.

1.2 Purpose and scope

The goal of this study is to predict subsidence at Wairakei subsidence bowl with a radial symmetric model (r-z) (shown in Figure 2) using a realistic geological setting and accurate representation of both fluid flow and rock mechanics. We use a loose coupling approach to solve a separate mass and energy transport model from the rock mechanics model. The effects of the model resolution were also investigated by comparing results for the pressure evolution and subsidence from both fine and coarse grids.

The reservoir, mass and heat transfer, model was developed to reproduce the observed pressure response to production over the last 50 years. It covers a circle of radius 2970 m and extends from the surface down to a depth of 415 m. The model area includes a number of monitoring wells within and near the subsidence bowl.

The reservoir model is implemented using AUTOUGH2 (Yeh *et al*., 2012) the University of Auckland's version of TOUGH2 (Pruess, 1999). Calibration of the model was carried out by adjusting permeability (k_z and k_r), bottom mass flow and the model stratigraphy. This process was aimed at getting the model to match the observed pressure data.

The geomechanics model was created using ABAQUS (ABAQUS, 2002). One of the key aspects of the rock-mechanics model was the use of a nonlinear, elasto-plastic constitutive model for reservoir rock behaviour.The inclusion of plastic deformation has proven to be essential to accurately capture subsidence timing in Wairakei (Koros *et al*., 2014).The aim of calibration of the ABAQUS model was to match the subsidence data.

For the Wairakei subsidence bowl, sufficient data are available to calibrate the coupled THM (thermo-hydro-mechanical) radial model discussed here. With appropriate constitutive relationship, the calibrated model was able to capture the observed behavior and could be used to forecast potential future subsidence. The simulated results over a period of 50 years of production are presented and compared with the observed subsidence data.

1.3 Subsidence Mechanisms and History

Subsidence in the Wairakei bowl is attributed mainly to a pressure decline in the low pressure shallow steam zone and consequent compaction of intensely altered, highly porous and compressible sediments and tuff materials within the Huka Falls unit. This is discussed in greater detail in the report by Bromley *et al*. (2010). The investigators agreed that the subsurface decline of pore pressure as result of geothermal production and hydrothermal alteration of weak formations are the main causes of subsidence at Wairakei. These pressure declines associated with geothermal production resulted in an increase in effective stress.

Comparison of early levelling surveys of bench marks (BMs) conducted between the 1950s and 1970s at Wairakei field revealed the early development of subsidence. These surveys showed that the greatest subsidence had occurred at the eastern end of the Wairakei production field (Hatton, 1970; Allis, 1982). More re-levelling surveys of existing and newly established bench marks (survey networks), including the BMs shown in Figure 1, have shown continued ground subsidence, with a bowl shaped pattern, at BMs AA13, P128 and A97, as presented in Figure 3. All BMs start from a zero which in most cases was set in the 1950s. The surveys, which were limited in temporal and spatial details, indicated that subsidence continued slowly into the early 1960s. After which, the subsidence magnitude began increasing in the late 1960s and 1970s, as shown in Figure 3.

These rapid rates of subsidence were followed by gradually decreasing rates. The subsidence rate at Wairakei subsidence anomaly at BM P128, (near monitoring well WKM 15) had declined to 45mm/yr in the 2004-2009 re-levelling surveys and to 70 mm/yr (2001-2004), down from 240mm/yr in the 1991-1997 survey. At BM AA13 located at the edge of the bowl near monitoring well WKM 14, the subsidence rates have also declined to 34mm/yr (Energy Surveys, 2009).

The bench marks and GPS (global positioning systems) surveys and InSAR analysis have delineated three other localized subsidence bowls within the Tauhara sector of the Wairakei-Tauhara geothermal field (see Figure 1).

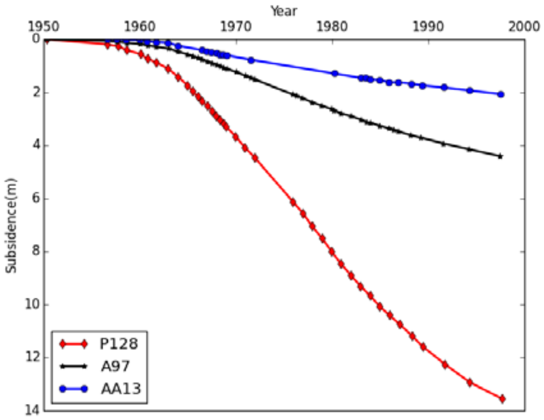


Figure 3: Subsidence trends at benchmarks (BMs) within and outside the Wairakei subsidence bowl from 1950-1997. BMs positions are shown in Figure 2.

1.4 Stratigraphy and rock material properties

The stratigraphic sequence observed in WKM15 and WKM14 is a series of sedimentary and volcanic deposits. Geophysical and geological surveys have shown Wairakei field to consist of water-laid sediments and volcanics. They comprise inter-bedded mudstones, siltstones, sandstones and tephra lavas. The volcanic units dominate deeper part of the geothermal system while sediments are more common near the surface. Recently, new volcanic and sediment formations have been identified, key stratigraphic units established and their depths reviewed (Rosenberg *et al*., 2009; Bignall *et al*., 2010).

The recent exploratory drilling exercise provided knowledge and insights on geological controls on permeability in the reservoir. Wairakei Ignimbrite is covered by the Waiora formation. The Waiora Formation is made up of pyroclastic,volcaniclastic and lava deposits. Overlying the Waiora Formation is the Huka Falls Formation (HFF), which is made up of lacustrine sediments and water deposited tuffs (Grindley, 1965; Rosenberg *et al*., 2009). The HFF is subdivided into sub-units and is covered by superficial deposits up to the surface. The drilling in the subsidence bowl at WKM15 and outside the bowl at WKM14 revealed varying geology with different characteristics. Geotechnical investigations of compressibility of the cores from these wells provide the parameters which assisted the subsidence modelling discussed here.

The impracticality of obtaining compressibility information in the field required the use of laboratory tests on sample cores to provide rock properties. The selected cores were subjected to K_o tests whose results were reported in Pender, (2009) and Bromley *et al*. (2010).The cores from monitoring wells within and outside the subsidence bowl are of varying characteristics between and within different strata. In particular, cores from WKM15 in the upper Waiora Formation (depths: 240-360 m) were relatively weak. Huka Falls Formation units (depths:80-235 m) were weak, with a low stiffness as observed from Point Load Index results and stiffness values from K_0 tests, presented in Figure 10.9 in Bromley, *et al*. (2010). At the same depth ranges in WKM14, the formations are moderately strong and have a larger stiffness. The variation in strength and stiffness of these formations (from weak to strong and low to high stiffness) is sensitive to the mineralogical composition of each formation. For example, clay mineralogy (smectite) properties (e.g. compressibility) present in the Huka Falls units are affected by thermal and hydrological changes. Strength of materials within the formations is dependent on variables such as clay content and water content. For instance, a material with high smectite content, as evident in WKM15, is more compressible than the rock with a low smectite content observed at WKM14.

An increase in water content increases deformability. This is evidenced in Figure 10.9 in Bromley *et al*. (2010), which shows an increase in moisture content results in a reduction of uniaxial compressive strength and stiffness.

1.5 Approach to subsidence modeling

We solve the subsidence problem by coupling a mass and heat transfer problem and a rock mechanics problem. The loosely coupled approach, applied to study subsidence at Wairakei, consists of the following steps:

- An r-z reservoir model (TOUGH2) is run to determine pore pressure and temperature variation within the reservoir system in response to production.
- An r-z rock mechanics model (ABAQUS) uses the pore pressure decline and temperature provided by the reservoir model at a sequence of times to calculate stresses and strains in the rock matrix, and subsidence at the surface.

The reservoir model (TOUGH2) and geomechanics model (ABAQUS) were linked through a Python-based interface. A detailed explanation of this process is given in Pogacnik, *et al*. (2015).

The ABAQUS subsidence model implemented in this work is based on Biot's (1941) poro-elastic theory. Geothermal fluid production cause significant pore pressure decline within the reservoir system. As a consequence, the effective stress increases and changes the state of stress and deformation in the rock matrix, possibly leading to subsidence at the ground surface. According to both Biot (1941) and Terzaghi (1943), effective stress is responsible for deformation of reservoir rock matrix material and is expressed as:

(1)

Here , and are total stress tensor, pore fluid pressure and Kronecker delta respectively. The parameter is Biot's coefficient which controls the degree of pore pressure-stress coupling. It takes values between 0 and 1.

A realistic subsidence prediction model requires development of a model that takes into account compressibility variation with increase in effective stress. Here we use a nonlinear, elasto-plastic model to simulate subsidence due to geothermal fluid production. Appropriate material properties were obtained from a large dataset of K_o tests performed on core samples from a monitoring well within the Wairakei bowl (Pender, 2009).

2. COMPUTER MODEL DESCRIPTION

2.1 Geometry

An axisymmetric model was used, hence implying horizontal stratigraphy and radial symmetry of material properties. The model is centred at WKM15 and extends radially for 2970 m towards WKM14 located outside the bowl. The simulations performed use both coarse and fine grids. Our fine grid has 83 x 5 m blocks (415 m) and the coarse grid has 16 x 25 m blocks (400 m). The model grids are shown in Figure 4.

The left edge of the model coincides with the central axis of WKM15 (within the Wairakei bowl). The horizontal grid spacing is 25 m at the center of the subsidence bowl and increases logarithmically outward to 2970m.

The geology of the model domain (shown in Fig. 5) consists of several formations down to ~400 m depth according to the lithostratigraphy provided in Rosenberg *et al.* (2009).

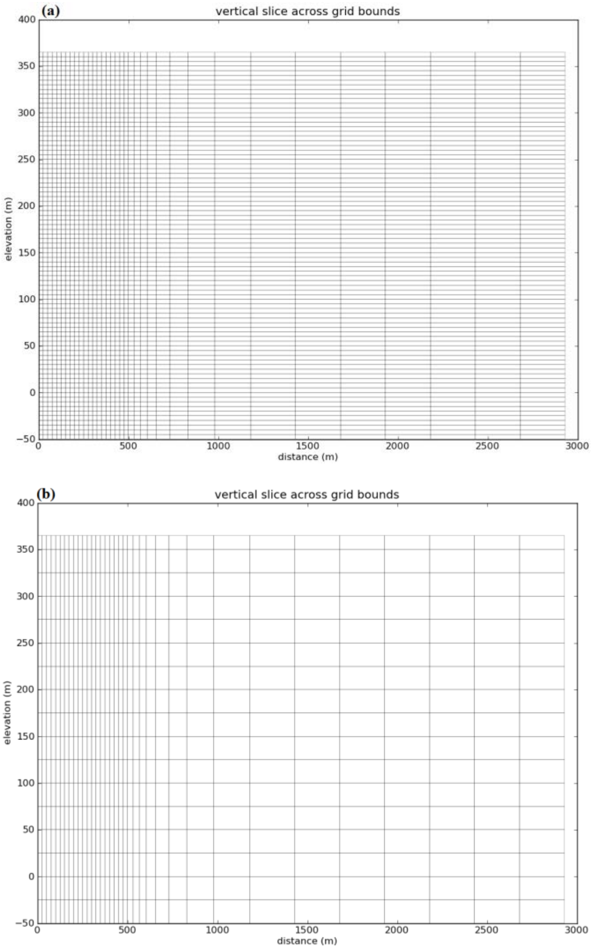


Figure 4: (a) Fine grid layout (b) Coarse grid layout.

2.2 TOUGH2 reservoir model

No-flow boundary conditions are imposed on the reservoir model at the left (centre of the subsidence bowl) and right (edge of the bowl) sides of the grid. The top (ground surface) boundary is maintained at a constant temperature of 15° C and pressure of 0.1 MPa to represent atmospheric conditions. The base of the reservoir system is at 415 m (400 m for coarse model) where a thick low-permeability Waiora unit begins. Initial temperature at the bottom of the model is 186° C consistent with typical bottom temperature at Eastern borefield wells (Bixley, 2009). At the base of the model mass is extracted to represent the effects of deep production. Part of the model calibration task is to adjust the production rate at the base of the model so that the deep pressure matches the field data. All simulations were done with TOUGH2, with a water-air fluid property module (EOS3).

2.3 ABAQUS rock mechanics model

Boundary conditions for the ABAQUS model are: no displacement on the right and bottom boundaries, vertical displacement only on the left boundary and traction-free conditions on the top boundary. Some of the reservoir material at Wairakei shows elasto-plastic behavior and a corresponding constitutive model was used, based on the elastic and non-elastic parameters obtained both from in situ measurements, laboratory tests and our previous 1-D subsidence modelling work.

2.4 Model Calibration

The *in situ* geological data along with pore fluid pressure measurements are available. These allowed for a realistic evaluation of geomechanical properties of the formations included in the model, which is essential for a reliable prediction of subsidence. The horizontal stratigraphy was manually adjusted to fit the correct lithostratigraphy, as shown in Figure 5. The fine model with populated geology produced better results compared to coarse model because of refined geology that represented entire geology within the bowl.

Permeability values and the mass flows at the base of the model were adjusted to match the pressure decline at three elevations. Manual calibration and the PEST software were used for parameter estimation.

PEST calibration software (Doherty, 2004) was integrated with TOUGH2 and ABAQUS simulators to carry out a joint inversion of both the reservoir and rock mechanics models together, after a reasonably good TOUGH2 model had been obtained. This automated calibration process involved searching for a set of model parameters that gives the lowest possible value of objective function. PEST was used to identify permeability and stiffness values of defined rock-types that give the closest match of the model results to the observed data. Stiffness values calibrated in this study fell within the range of values measured on core samples.

Good calibration of the reservoir model is required obtaining a good match to the pressure behavior in the reservoir and consequently obtaining a good match to the subsidence. Reservoir model calibration was achieved by matching the model output to the measured pressure profiles at a few representative points. The pressure observations started in late 1950s and have continued to the present time. The model was calibrated over 50 years (1950-2000). Mass drawn from the bottom of the model and permeabilities were adjusted to match historic pressure measurements (see Figure 6). These were achieved through application of pyTOUGH library (Croucher, 2011; Wellmann *et al.*, 2012).

The pore-water pressure and temperature results from the reservoir model at five-yearly intervals were used as input for stress-deformation analysis carried out with ABAQUS, and hence the calculation of subsidence. A loosely coupled model was used, i.e., the effect of stress changes on permeability, porosity and hence fluid flow was not considered. The rock-type structures of the two models are shown in Figure 5. As expected some of the detail of the fine model is lost in the coarse model.

Decisions were made about the values of material parameters applicable to Wairakei geothermal field. For example, the magnitude of Biot's coefficient depends on the ratio of grain and bulk compressibility and this coefficient has not been determined for Wairakei rocks. However, laboratory measurements have been conducted on other sedimentary core samples to determine its value (Fabre and Gostkiewicz, 1997; Hou *et al.*, 2005; Braun, 2009). Their observations revealed the magnitude of for clay-like material and high porosity sedimentary rocks ranges between 0.45-0.645. Therefore, Biot-Willis coefficient was set to 0.5, hopefully typical of soft material at Wairakei.

Elasto-plastic behaviour for the rock matrix was applied, assuming von Mises' yield condition applies and isotropic hardening was applied in predicting where yielding occurs.

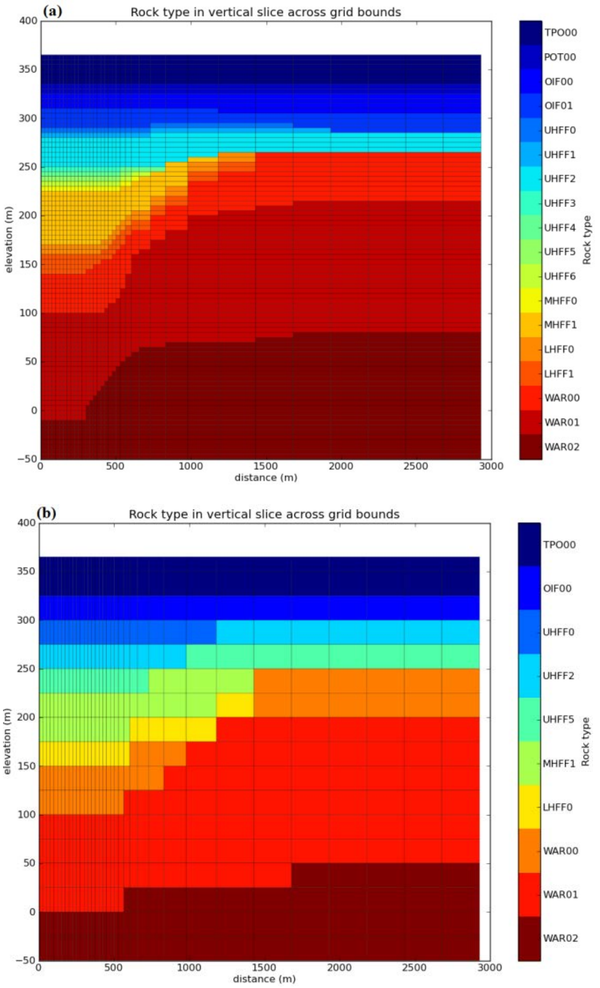


Figure 5: Grid layout with calibrated geology for (a) Fine model and (b) Coarse model.

A more detailed discussion of this constitutive relation is given in Chaboche (2008) and Khan & Huang (1995). In addition, for yielding materials, a critical state parameter, initial and yield stresses and the corresponding plastic strains were defined. For detailed discussion on these parameters see Pogacnik, *et al.* (2015).

3. DISCUSSION OF RESULTS

3.1 General discussion

The modelling results presented in this study are derived from a loose coupling of TOUGH2 and ABAQUS models and involved use of both fine and coarse grids. Good simulation results were obtained, both at the centre of the bowl and some distance away from the centre.

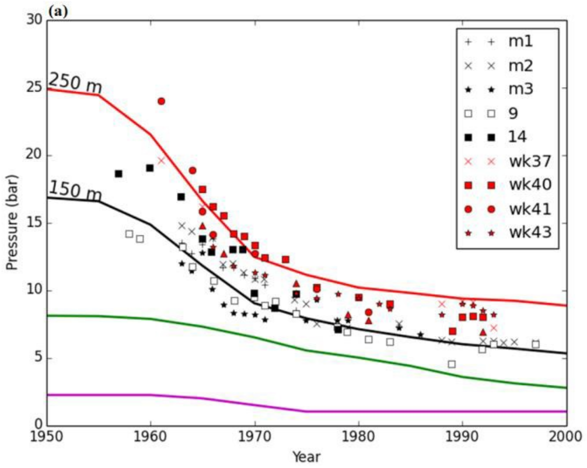
3.2 TOUGH2 Reservoir Model

At Wairakei bowl, most of the subsidence occurs within Upper Huka Falls and Upper Waiora Formations. These formations are at elevations 292.5-202.5, 139-117.5 m.a.s.l respectively. The reservoir materials are subdivided into sedimentary units that can be accurately matched to the geological model in the fine grid model. In the coarse grid, the subdivided Huka Falls, Taupo and Oruanui Formations sedimentary units used in the fine model had to be amalgamated in some cases. It was expected that the use of the fine rather than the coarse grid might have a significant impact on the mass and heat flow and hence subsidence. However the differences between the fine and coarse grids results are surprisingly small.

Simulated results of pressure decline at three elevations are shown in Figure 6. These good results were obtained after calibrating the mass withdrawn from the base and the permeabilities. Pressure trends show a rapid decline after 1960 but a slow decline by the 1980s. A lag in the onset of significant pressure decline causes a delay at the start of subsidence. Changes in pressure trends cause the most significant changes in the subsidence values. These pressure-trends have been applied in modelling subsidence at BMs AA13, A97 (outside the bowl) and BM P128 (center of the bowl). The results of mass and heat transfer model are presented in the form of pressure profiles. The pressure profiles generated due to lowering of water-table and decreases in pore-pressure over 50 years of production are shown in Figure 6. These results were imported into ABAQUS for stress-deformation analysis and to predict subsidence.

The plots show that the fine model results are better than the coarse model results, i.e. they fit the data better, but they are both quite similar.

A limited amount of time was spent on calibrating the coarse model and it probably could be further improved.



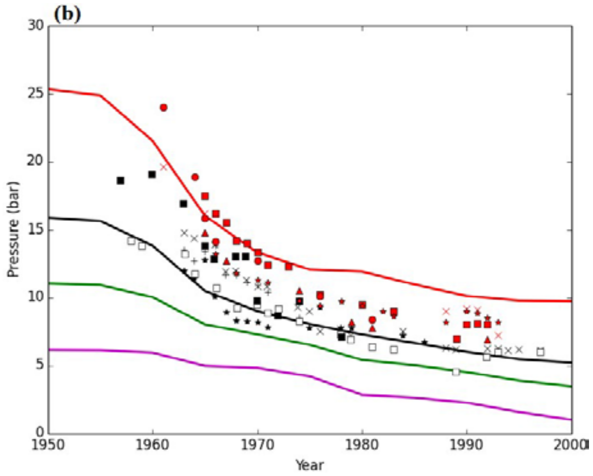


Figure 6: Pressure trends from (a) fine model and (b) Coarse model at depths 150 m and 250 m (elevations:117 masl and 202 masl respectively) at the Wairakei bowl. Symbols are well data and lines (red, black, green, magenta) are simulated profiles from depth 250 m towards the surface (elevations: 290 masl and 350 masl respectively).

Plots of pressure vs. depth, at five-yearly intervals are shown in Fig. 7. The pressures near the key zones for subsidence (292.5-202.5, 139-117.5 m.a.s.l) are similar.

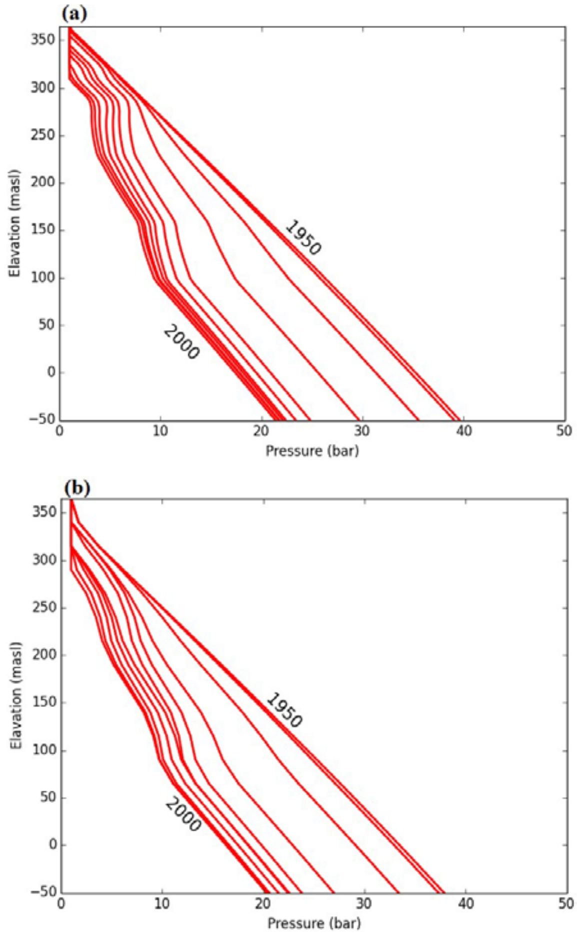


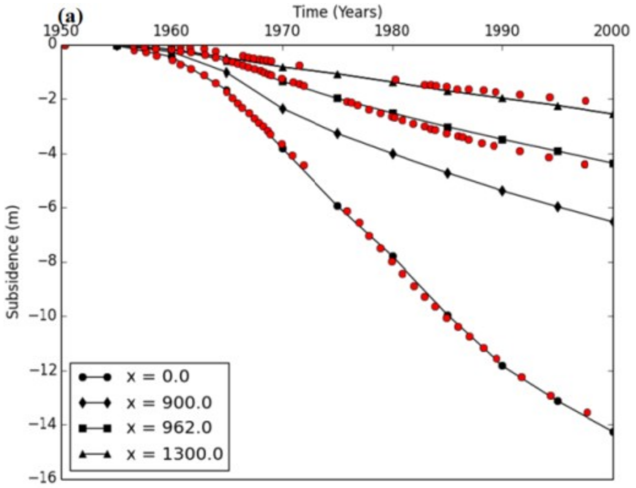
Figure 7: Simulated pressure-elevation trends for (a) Fine model and (b) Coarse model, at 5-yearly time increments between 1950 and 2000.

3.2 ABAQUS Rock Mechanics Model

The geometry for stress-deformation model analysis in ABAQUS was imported from the both fine and coarse reservoir models shown in Figure 4. Material properties used in stress-deformation analysis were determined from a combination of laboratory tests results and *in situ* values published in geotechnical reports (Bromley *et al*, 2010; Pender, 2009). The simulation of the loosely-coupled TOUGH2-ABAQUS model was conducted for the period 1950-2000. The results of the calculated subsidence, together with observed values at BM AA13 (outside the bowl near WKM 14), A97 (outside the bowl near WK 10) and BM P128 (at the centre of the bowl near WKM 15) for the period 1950s to 1997 are presented in Figure 8. The total observed subsidence from 1950 to 1997 is about 2.07 m and 13.54 m at BM AA13 and P128 respectively.

The vertical deformation in the models matches the data well. The largest subsidence of about 14.25 m occurred at the centre of the bowl, with decreasing subsidence modelled with increasing radial distance from the centre. Simulated subsidence at 962 m and 1300 m was about 4.5 m and 2.1 m respectively in both coarse and fine models. A comparison between the observed subsidence and the results from the simulations in both model grids shows a good match. The match is somewhat better for the fine model but further calibration could improve the coarse model results.

Detailed geology was only available at WKM 15 at the inner boundary of the model and WKM 14 near the outer boundary of the model. The geology in between was assigned by interpolation with some adjustments made during the calibration process.



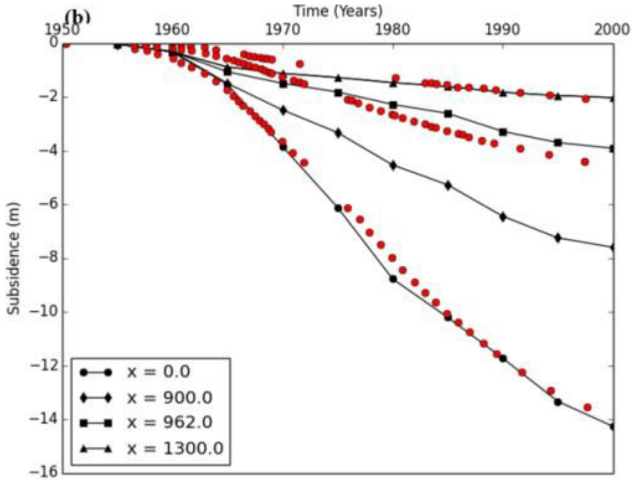


Figure 8: Subsidence profiles for (a) Fine model and (b) Coarse model for 50 years (1950-2000) of production. Horizontal distance is given as x: at x= 0.0 m (BM P128, near WKM15; at x=962.0 m (BM A97, near WK10, outside the bowl) and at x=1300.0 m (BM AA13, near WKM14, outside the bowl).

4. CONCLUSION

Numerical simulations were conducted, with a radially symmetric model, with loosely coupled mass and heat transfer and rock mechanics to model subsidence at Wairakei geothermal field. Both coarse and fine models were applied. Simulations with the calibrated models gave acceptable results for the 50 years of production. Simulation results revealed the following:

- Calibration of key parameters, particularly permeability, the mass withdrawal, stiffness and yield parameters led to achieving a good match to the surface displacement.
- The subsidence model was progressively developed by first calibrating the TOUGH2 reservoir model to match the observed pressure decline and then calibrating the ABAQUS rock mechanics model to match subsidence. The magnitude of subsidence is very high at the centre of the bowl compared that further out.
- Attention was also focused on constitutive behaviour of the rocks. An elasto-plastic constitutive model was required to effectively represent the behaviour of some of the soft rocks.

The application of an axisymmetric model, with fine and coarse grids, to modelling subsidence at Wairakei has shown that it is possible to make good models of subsidence if sufficient data are available.

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REFERENCES

ABAQUS User’s Manual: ABAQUS/Standard User’s Manual, Volume II, Version 6.3. Hibbit & Sorenson, Inc., Pawtucket, Rhode Island. (2002).

Allis, R., Bromley, C. Currie, S.: Update on subsidence at the Wairakei-Tauhara geothermal system, New Zealand. *Geothermics*, **38**, 169-180 (2009).

Allis, R.G.: Review of subsidence at Wairakei field, New Zealand. *Geothermics*, **29**, 455-478 (2000).

Allis, R. G.: Comparison of Subsidence at Wairakei, Broadlands and Kawerau Fields, New Zealand. *Proc. 8th Workshop Geothermal Reservoir Engineering*, Stanford University, California. 183-188 (1982).

Biot, M.A.: General theory of three-dimensional consolidation. *Journal of Applied Phys*ics,**12**(2), 155-164 (1941).

Bignall, G.,Milicich, S.D., Ramirez, L.E., Rosenberg, M.D., Kilgour, G.N.,Rae, A.J.: Geology of the Wairakei-Tauhara Geothermal System, New Zealand. *Proc. Worlds Geothermal Congress 2010*, Bali, Indonesia. 8 pp. (2010).

Braun E.: Determination with RACOS® of the 3D in situ loadings, the pore pressure effectivenesses and the deformation parameters for several strata in the Salzwedel reservoir area. Report submitted to TU Clausthal, 64 pp. (2009).

Bromley, C.J., Currie, S., Jolly, S., Mannington, W.: Subsidence: an Update on New Zealand Geothermal Deformation Observations and Mechanisms. *Proc. World Geothermal Congress 2015*, Melbourne, Australia. 9 pp. (2015).

Bromley, C.J., Currie, S., Ramsay, G., Rosenberg, M., Pender, M., O’Sullivan, M., Lynne, B., Lee, S.G., Brockbank, K., Glynn-Morris, T., Mannington, W., Garvey, J.: *Tauhara Stage II Geothermal Project: Subsidence Report*, GNS Science. (2010).

Chaboche, J.L.: A review of some plasticity and viscoplasticity constitutive theories. *International Journal of Plasticity*, 24, 1642-1693 (2008).

Croucher, A.E.: PyTOUGH: a Python scripting library for automating TOUGH2 simulations, *Proc. 33rd New Zealand Geothermal Workshop*, University of Auckland, Auckland, NZ. (2011).

Doherty, J.: *PEST, Model-Independent Parameter Estimation, User Manual: 5th Edition*, Watermark Numerical Computing, Brisbane, Australia. (2004)

Energy surveys,: *Regional Precise levelling surveys for Wairakei &Tauhara*. Report submitted to Contact Energy. (2009).

Fabre, D., Gustkiewicz, J.: Poroelastic properties of limestones and sandstones under hydrostatic conditions. *Int. J. Rock Mech. Min. Sci*. **34** (1), 127-134. (1997).

Grindley, G.W.: The geology, structure and exploitation of the Wairakei field, Taupo, New Zealand. *NZ Geological Survey Bulletin*, 75, 131 pp. (1965).

Hatton, J. W.: Ground Subsidence of a Geothermal Field during exploitation. *Geothermics*, **2**, 1294-1296 (1970).

Hole, J. K., Bromley, C. J., Stevens, N. F., Wadge, G.: Subsidence in the geothermal fields of the Taupo Volcanic Zone, New Zealand from 1996 to 2005 measured by InSAR. *Journal of Volcanology and Geothermal Research*, **166**, 125–146 (2007).

Hou, Z., Somerville, J., Hutcheon, R.: Experimental investigation of the hydro-mechanical behavior of tight gas formation sandstone and its impacts on the wellbore stability. *ISRM-Eurock*, Brno, Czech Republic. 205-210 (2005).

Khan, A.S., Huang, S.: *Continuum Theory of Plasticity*. John Wiley & Sons Inc., New York. (2005).

Koros, W., O'Sullivan, M., Pogacnik, J., O'Sullivan, J.: Coupled One-Dimensional Subsidence Modelling Using Elastic-Plastic Rheology. *Proc. 36th New Zealand Geothermal Workshop*, Auckland, New Zealand. 9 pp. (2014).

Koros, W., O'Sullivan, M., Pogacnik, J., O'Sullivan, J.: Comparison of Coupled One-Dimensional Subsidence Models. *Proc. World Geothermal Congress 2015*, Melbourne, Australia. 10 pp. (2015).

Pender, M.: Appendix 9: *Triaxial testing on core from the Wairakei-Tauhara geothermal field*. Interpretive Procedures Report,University of Auckland, Auckland. (2009).

Pogacnik, J., Koros, W., O'Sullivan, J., O'Sullivan, M.: Using ABAQUS to Simulate the Triaxial Stress Strain Behavior of Core Samples from the Wairakei/Tauhara Geothermal Field. *Proc. 37th New Zealand Geothermal Workshop*, Taupo, New Zealand. 11 pp. (2015).

Pruess, K., Oldenburg, C., Moridis, G.: *TOUGH2 User's Guide Version 2.0*, University of California, Berkeley, California, USA. (1999).

Rosenberg, M.D., Bignall, G., Rae, A.J.: The geological framework of the Wairakei-Tauhara Geothermal System, New Zealand. *Geothermics*, **38**, 72-84 (2009).

Terzaghi, K.: *Theoretical Soil Mechanics*, Wiley, New York, N. Y., 510 pp. (1943).

Wellmann, J.F., Croucher, A.E., and Regenauer-Lieb, K.: Python scripting libraries for subsurface fluid and heat flow simulations with TOUGH2 and SHEMAT. *Computers & Geosciences*, **43**, 197-206 (2012).

Yeh, A., Croucher, A. E., and O'Sullivan, M. J.: Recent developments in the AUTOUGH2 simulator. *Proceedings of the TOUGH Symposium* 2012. Lawrence Berkeley National Laboratory, Berkeley, California. 8pp (2012).