Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

Comparison of Coupled One-Dimensional Subsidence Models

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Keywords: Subsidence, Compaction, FEHM, TOUGH2, ABAQUS, Numerical Modelling

ABSTRACT

Subsidence as a result of the extraction of geothermal fluids for energy production is a significant problem at many sites around the world. At Wairakei geothermal field in New Zealand, subsidence has occurred since the onset of production in 1958. Subsidence is non-uniform and reaches as much as 15m in a small area known as the Wairakei subsidence bowl. The high level of subsidence is caused by a reduction of pore pressure in soft patches in the Huka Falls Formation (HFF), which is composed of pumice breccia and mudstone. In this study, one-dimensional models are used to investigate subsidence at the Wairakei Bowl. Two different approaches are used for handling compaction: the first couples a TOUGH2 simulation of heat and mass transfer with a simple manual calculation of compaction, while the second uses FEHM to calculate both the heat and mass transfer and the rock deformation. The results obtained using both methods are compared with field measurements from Wairakei and with previously published work (Allis & Zhan, 2000).

1. INTRODUCTION

Subsidence above oil, gas, water and geothermal reservoirs from which fluid is withdrawn is a phenomenon that is well known worldwide. As the fluid is withdrawn the reservoir pressure drops and the effective stress in the rock matrix increases thus inducing compaction. The effects of compaction appear at the surface as subsidence. A few examples of areas where subsidence has occurred are given in Table 1.

Table 1: Examples of major subsidence due to fluid withdrawal. Modified after (Gambolati *et al*., 2006).

Area	Depth of fluid extraction(m)		Maximum observed subsidence (m)	Size of area affected (km²)	Year of main occurrence
	Oil	Groundwater			
Ravenna, Italy	-	80 – 450	1	400	1955 – 1985
San Joaquin Valley, California	-	60-900	9	13500	1930 – 1975
Las Vegas, Nevada	-	200-300	2	250	1935 to present
Ping-Tung County, Taiwan	-	70-180	3.1	105	1972 to present
Ekofisk, North Sea	3000-3200		6.7	40	1970 to present
Wilmington, California	600-1200		9	70	1926 –1968
Lake Maracaibo, Venezuela	500-1000		4.5(1986)	500(1986)	1928 to present

In many instances, numerical methods have been used to investigate subsidence (e.g. Gambolati *et al.* 1991). The following options need to be considered in choosing a modelling technique:

a) Tight or Loose coupling. In the loosely coupled or uncoupled models fluid flow equations are solved to obtain pressures. These pressures are used to calculate pressure changes throughout a time interval which in turn are used to solve a quasi-static rock mechanics problem for the subsidence. In the geothermal context this will involve first using a reservoir simulator to calculate pressures and temperatures over many years (say 20-50). Then a rock mechanics code can be used to calculate subsidence, say every five years, solving a static solid mechanics problem each time. This approach was used by one of the authors to study subsidence at Wairakei (O'Sullivan and Yeh, 2007; Bromley *et al*., 2010).

   In a fully coupled approach both the heat and mass transfer problem and the rock mechanics problem are solved at every time step and the material properties such as porosity and permeability which control heat and mass transfer are allowed to vary with the stresses determined from the rock mechanics problem. The fully coupled thermo-hydro-mechanical (THM) approach has been used for studying problems such as permeability enhancement by cold water injection in geothermal reservoirs (e.g.

Pogacnik, *et al*., 2014) but has not been used for modelling subsidence and is probably more complicated than is necessary for this purpose.

Other levels of coupling are possible: for example the Finite Element Heat and Mass simulator (FEHM) (Zyvoloski *et al*., 1997; Zyvoloski, 2007) allows for updating of porosity and permeability to be lagged behind by one time step.

For our model we use an uncoupled model with the heat and mass transfer problem solved first followed by the solution of a sequence of quasi-static rock mechanics problems.

b) Constitutive relationship. Most past numerical models of subsidence in geothermal fields have assumed a linear elastic stress-strain relationship (e.g. Allis and Zhan, 2000; Lewis and Schrefler, 1987; Yeh and O'Sullivan, 2007). A few have used elasto-plastic models allowing for yielding (e.g. Bromley *et al*., 2013)

c) Dimensions. Past studies have used 1D models (Allis and Zhan, 2000; Bromley *et al*., 2013), 2D models (Terzaghi, 2004; White *et al*., 2005) and general 3D models (Yeh and O'Sullivan 2007, Bromley *et al*., 2010). In the current study a 1D model is used, although in the heat and mass transfer model some lateral recharge is allowed and so it could be considered as a 1.5D flow model.

d) Software. For modelling subsidence in geothermal fields the coupled heat and mass transfer processes must be considered requiring the use of a geothermal simulator such as TOUGH2 (Pruess *et al*., 1999) or FEHM (Zyvoloski et al., 1997; Zyvoloski, 2007). FEHM has a built-in rock mechanics solver whereas TOUGH2 does not. Various THM studies have used TOUGH2 coupled with commercial rock mechanics codes such as FLAC3D (Rutqvist *et al*. 2002, 2006) or ABAQUS (ABAQUS, 2003; Yeh and O'Sullivan, 2007). The originators of the TOUGH2/FLAC3D combination coined the name TOUGH-FLAC (Rutqvist, 2011) for the coupled codes. TOUGH-FLAC has been used for a few studies of subsidence in geothermal fields (e.g. Kiryukhin *et al*., 2014).

Some studies of geothermal subsidence have used software that couples isothermal single phase flow in a porous medium with stress-strain analysis. For example Allis and Zhan (2000) used a finite element code of this type to analyse subsidence at Wairakei and Ohaaki geothermal fields. The models of subsidence at Wairakei developed by Terzaghi and co-workers (Terzaghi 2004, White *et al*., 2005) used a finite-element package, PLAXIS, which simulates coupled compaction and isothermal fluid flow.

In the present study we use two approaches: the first couples TOUGH2 for modelling heat and mass transfer with a simple manual calculation of rock deformation and the second uses FEHM for the whole THM simulation.

2. SUBSIDENCE AT WAIRAKEI

The Wairakei-Tauhara geothermal system is located to the north of Lake Taupo, at the centre of the North Island, New Zealand. Subsidence was detected soon after the geothermal power plant started operation at Wairakei in 1958. The subsidence rates increased from the 1950s to a peak in the 1970s, followed by a decrease down to much lower rates at present (Currie, 2010, Allis *et al*., 2009, Bromley *et al*., 2013). In the most intense subsidence area, the Wairakei subsidence bowl near the Eastern Borefield, the peak rate was 498mm/year in 1978 but it has now slowed to a rate of 58mm/year (Currie, 2009). The centre of the Wairakei bowl has dropped a total of approximately 15m since the 1950s. The extent of the bowl where the subsidence rate is abnormally higher than surrounding areas is approximately 1km^2. Subsidence at a slower rate of between 5 and 100mm/year has occurred over most of the Wairakei-Tauhara area.

Recent surveys have shown the existence of three subsidence bowls in the Tauhara area at Crown Road, Rakaunui Road and the Spa Valley. These are shown by Allis *et al*. (2009) and by Bromley *et al.* (2013).

The pressure of the deep Wairakei reservoir has dropped by around 25bar since the development of the field in the 1950s (Allis, 2000; Bixley *et al*., 2009). Unlike the localised subsidence, the area of pressure drawdown is wide-spread and reasonably uniform within the resistivity boundary, which encloses more than 20km^2 in area. The deep reservoir pressure drawdown has also propagated to the Tauhara area.

3. PREVIOUS WORK ON MODELLING SUBSIDENCE AT WAIRAKEI

Allis (Allis and Zhan 2000, Allis 2004) has studied subsidence at Wairakei-Tauhara for more than 15 years. He used Geertsma's techniques (Geertsma, 1973) to try to identify the geological layer that contributes most to the subsidence bowl at Wairakei. Allis also used a one-dimensional finite-element model that couples compaction and fluid flow in porous materials to simulate the subsidence at Wairakei. The code was originally developed by Lewis and collaborators (Lewis and Schrefler 1987, Schrefler and Zhan 1993). Allis used it to set up one-dimensional models to match subsidence at the levelling bench marks at Wairakei. Some good fits were obtained, however, the models are limited because they are only one-dimensional and some three-dimensional effects may be important (Terzaghi, 2004, p. 15). Another limitation of Allis's modelling technique is that it only allows for single-phase flow. Thus the flow in the two-phase zones of Wairakei-Tauhara cannot be accurately represented.

Terzaghi and co-workers (Terzaghi 2004, White *et al*., 2005) also developed models of subsidence at Wairakei, using a finite-element package, PLAXIS that simulates coupled compaction and fluid flow. Several two-dimensional cross-sectional models were used to calculate subsidence at both the Wairakei bowl and the more recent Tauhara subsidence bowls. However the Terzaghi (2004) models are limited because they cannot represent two-phase flow, and also they are two-dimensional rather than three-dimensional.

All of these models give results that agree reasonably well with the past subsidence history at the selected points or along cross-sections. However, the authors of the different studies disagreed about the cause of the anomalous subsidence at the subsidence bowls and the available field data was insufficient to resolve the areas of disagreement.

After the extensive program of drilling, coring and scientific investigations undertaken by Contact Energy Ltd. during 2007-2009 much more became known about the rock properties in and around the subsidence bowls at Wairakei and Tauhara (see Bromley *et al*., 2013; Pender *et al.*, 2013). This new information was used in the 3D modelling study carried out by O'Sullivan and Yeh (included in the report by Bromley *et al*., 2010) based on the coupling of TOUGH2 and ABAQUS as discussed by Yeh and O'Sullivan (2007). The data were also used in recent studies by Bromley (Bromley *et al.*, 2010, Bromley et al., 2013) who used a simple 1D compaction calculation, including some yielding, to obtain a reasonable match to the subsidence at Wairakei and Tauhara. These calculations were based on measured and estimated pressures rather than pressures calculated from a reservoir simulator. Wanninayake (2010) used the same pressures as Bromley as input for a 1D numerical model implemented in FLAC3D (Itasca Consulting Group, 1997). He included a Cam-clay constitutive model calibrated using K_0 triaxial test data.

4. THEORY OF SUBSIDENCE

Mechanical compaction of clastic sediments by progressive increase in effective stress causes irreversible reduction in porosity as the sediments yields (Biot, 1941). Sediments responsible for compaction in Wairakei field consist of mudstone and pumice breccia in Huka Falls Formation (HFF). The HFF overlies the Waiora Formation that hosts the production reservoir (Rosenberg *et al*., 2009). The HFF undergoes normal compaction when mean effective stress acting on the sediments increases due to geothermal production. Goulty (2004) showed that compaction theory by Biot (1941) is simplistic for irreversible mechanical compaction process, though entirely valid for describing reversible poroelastic response to stress changes.

A useful concept in describing the behaviour of fluid saturated porous rock is that of effective stress. The effective stress tensor is defined as (Biot, 1941, 1956):

$$\sigma'_{ij} = \sigma_{ij} - \alpha P_p \delta_{ij} \tag{1}$$

Here σ'_{ij} is effective stress tensor, σ_{ij} is total stress tensor, P_p is pore pressure and δ_{ij} is Kronecker delta with $\delta_{ij} = 1$ if i=j and 0 otherwise. Biot's coefficient α describes the relative contribution of total stress and pore pressure to the deformation of the rock. There has been much discussion in the geotechnical literature about the factor α in (1). In some earlier work on modelling subsidence we followed the 1956 paper by Biot and used $\alpha=\phi$, where ϕ is the porosity (Yeh and O'Sullivan, 2007). However in the earlier work by Biot (1941) the following formula was used:

$$\alpha = 1 - \frac{K_g}{K_s} \tag{2}$$

where K_g is the bulk modulus of solid skeleton and K_s is the bulk modulus of solid material without pores (see Nur, 1971). A review article by Lade and de Boer (1997) concluded that (2) should be used in the calculation of effective stress. Pender (private communication) has evaluated α using properties typical of the Tauhara formations and obtained values for α close to 1.0. Biot's definition of effective stress with α=1 is the same as the formulation proposed earlier by Terzaghi (1936).

Production in a geothermal reservoir results in pressure drawdown causing an increase in effective stress. Consequently, sediments overlying the reservoir undergo mechanical compaction during production. The horizontally structured sediments become mechanically compacted under zero horizontal strain conditions with a reduction in thickness. Ratio of horizontal effective stress to vertical effective stress yields a coefficient of the lithostatic pressure at rest, K_0 given by:

$$K_0 = \frac{\sigma_{xx} - P_p}{\sigma_{zz} - P_p} \tag{3}$$

Here σ_{zz} represent lithostatic stress, σ_{lith}, at depth resulting from the weight of overburden and water above the point of interest. It can be expressed as:

$$\sigma_{lith} = p_{atm} + \rho_{rock} g h + \rho_{water} g h \tag{4}$$

In (3) and (4) P_p is pore pressure, σ_{xx} is minimum horizontal stress, ρ_{rock} is density of the overlying rock, ρ_{water} is density of water, h is depth, p_{atm} is atmospheric pressure and g is acceleration due to gravity. Under these conditions, horizontal stresses are isotropic, so that $\sigma_{yy} = \sigma_{xx}$.

Laboratory measurements by Jones (1994) show that K_0 is constant for a given lithology.

Reservoir compaction studies usually assume that the rock is linearly elastic and isotropic and thus Hookes' law applies. Thus the stress-strain law can be expressed in terms of Young's modulus E and Poisson's ratio ν as follows:

$$\varepsilon_{xx} = \frac{1}{E}\left[\sigma_{xx} - \nu(\sigma_{yy} + \sigma_{zz})\right] \tag{5a}$$

$$\varepsilon_{yy} = \frac{1}{E}\left[\sigma_{yy} - \nu(\sigma_{xx} + \sigma_{zz})\right] \tag{5b}$$

$$\varepsilon_{zz} = \frac{1}{E}\left[\sigma_{zz} - \nu(\sigma_{yy} + \sigma_{xx})\right] \tag{5c}$$

Here E is *Young's modulus*, which is a measure of the stiffness of a rock and ν is $Poisson's\ ratio$, which is a measure of lateral expansion relative to longitudinal contraction.

The deformation of rocks in a reservoir can be expressed in terms of changes in effective stress, using the initial state (prior to production) as the reference for strains, as follows:

$$E\varepsilon_{xx} = \Delta\sigma'_{xx} - \nu(\Delta\sigma'_{yy} + \Delta\sigma'_{zz}) \quad (6a)$$

$$E\varepsilon_{yy} = \Delta\sigma'_{yy} - \nu(\Delta\sigma'_{xx} + \Delta\sigma'_{zz}) \quad (6b)$$

$$E\varepsilon_{zz} = \Delta\sigma'_{zz} - \nu(\Delta\sigma'_{yy} + \Delta\sigma'_{xx}) \quad (6c)$$

This is the constitutive law used by Allis and Zhan (2000) (as discussed by Lewis and Schrefler 1987, p. 99).

From the vertical strain ε_{zz}, the change in thickness Δh of a layer of rock of thickness h can be calculated using

$$\Delta h = -\varepsilon_{zz} h \quad (7)$$

Then the surface subsidence can be calculated by summing Δh for all the layers in the reservoir.

For the one-dimensional subsidence considered here, we assume that the lateral strain is very small i.e.

$$\varepsilon_{xx} = \varepsilon_{yy} \cong 0 \quad (8)$$

By substituting (8) into (6a,b) we obtain

$$\Delta\sigma'_{xx} = \Delta\sigma'_{yy} = \frac{\nu}{1-\nu}\Delta\sigma'_{zz} \quad (9)$$

The total vertical stress acting on the reservoir remains constant during production as the total weight of the overburden remains constant and therefore $\Delta\sigma_{zz} = 0$, which gives:

$$\Delta\sigma'_{zz} = \Delta\sigma_{zz} - \alpha\Delta P_p = -\alpha\Delta P_p \quad (10)$$

By combining (9), (10), (6c) and (7) we arrive at the following expression for compaction in a layer:

$$\frac{\Delta h}{h} = \frac{1}{E}\left[\frac{(1+\nu)(1-2\nu)}{(1-\nu)}\right]\alpha\Delta P_p \quad (11)$$

Compaction resulting from pore pressure reduction can now be deduced from (11), provided the elastic properties (E and ν), poroelastic coefficient (α) and layer thickness (h) are known.

The compaction coefficient, C_m, is defined by

$$\frac{\Delta h}{h} = C_m\alpha\Delta P_p \quad (12)$$

The coefficient C_m can be related to other moduli of rock. It is equal to the inverse of the uniaxial compaction modulus and comparing (11) and (12) the following expression can be deduced:

$$C_m = \frac{1}{E}\left[\frac{(1+\nu)(1-2\nu)}{(1-\nu)}\right] \quad (13)$$

5. DESIGN OF THE MODEL AND RESULTS

The 1D model considered here was designed to be the same as that considered by Allis and Zhan (2000). They set up a 1D column model to simulate the subsidence at a bench mark called A97 close to the Wairakei subsidence bowl.

5.1 TOUGH2 Model

For our first model we used TOUGH2 for the heat and mass transfer calculation and used a manual calculation of the deformation. The geometry used for the model is shown in Figure 1 below. The model consists of a 150m column consisting of a lower layer of mudstone (100m) and an upper layer of pumice breccia (50m). We ran two versions of the model: first a natural state model to establish the pre-exploitation pressure and temperature profiles and then a production model covering a period of 50 years.

We experimented with various options for the top and bottom boundary conditions for the model. At first we tried specifying a mass withdrawal at the base of the model and allowing for an unsaturated zone at the top of the model with a falling water table. It proved to be difficult with this approach to exactly match the pressure vs. time plots shown by Allis and Zhan (2000) at the top and bottom of their model and we switched to specifying pressure vs. time at the top and bottom of our model. TOUGH2 does not allow for the implementation of time varying pressure boundary conditions but we were able to implement them by using pyTOUGH (Croucher, 2013; Wellmann *et al*., 2012) to adjust boundary pressures at each time step. The pressure at the top boundary shown by Allis and Zhan (2000) became negative after about 1990. To avoid this kind of unphysical behaviour, which cannot be reproduced by TOUGH2, we added 0.3MPa to all pressures. In the plots shown below the 0.3MPa has been subtracted again so that our results can be directly compared with those of Allis and Zhan (2000).

We included a temperature variation in our model with a temperature of 112°C at the bottom of the model and 15°C at the top, a profile typical of the shallow zone at Wairakei, outside areas of steaming ground where temperatures are higher The non-isothermal effects are very small and our results agree closely with those of Allis and Zhan who used a constant temperature throughout their model.

In our first version of the production model we did not include any lateral recharge but were unable to obtain results for pressure vs. depth that were close to those of Allis and Zhan (2000). When we added in lateral recharge (as shown in Figure 1) and adjusted the recharge coefficient we were then able to obtain a good match to the pressure profiles of Allis and Zhan (2000) (see Figures 2 and 4). The recharge formula used in TOUGH2 is:

$$q_m = A\,(P_{res} - P_0) \tag{14}$$

Here P_{res} is the pressure in the model, P_0 is the reference pressure (usually taken as the initial pressure in the reservoir block), q_m is the mass flow into or out of the model block and A is the recharge coefficient (usually taken proportional to the model permeability).

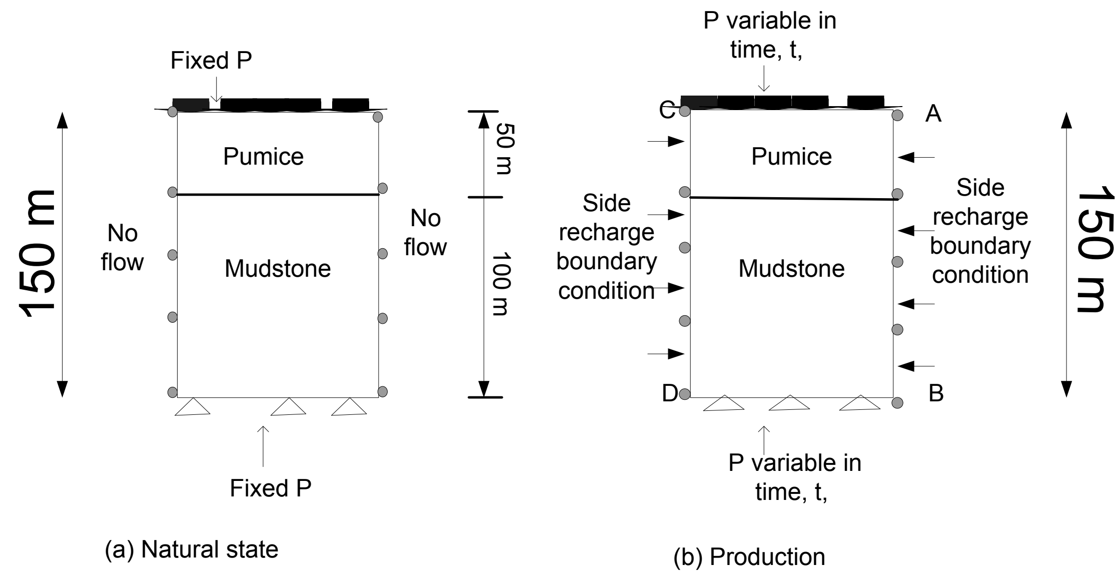


Figure 1: Geometry of the model showing the thickness of the mudstone and pumice layers and the boundary conditions.

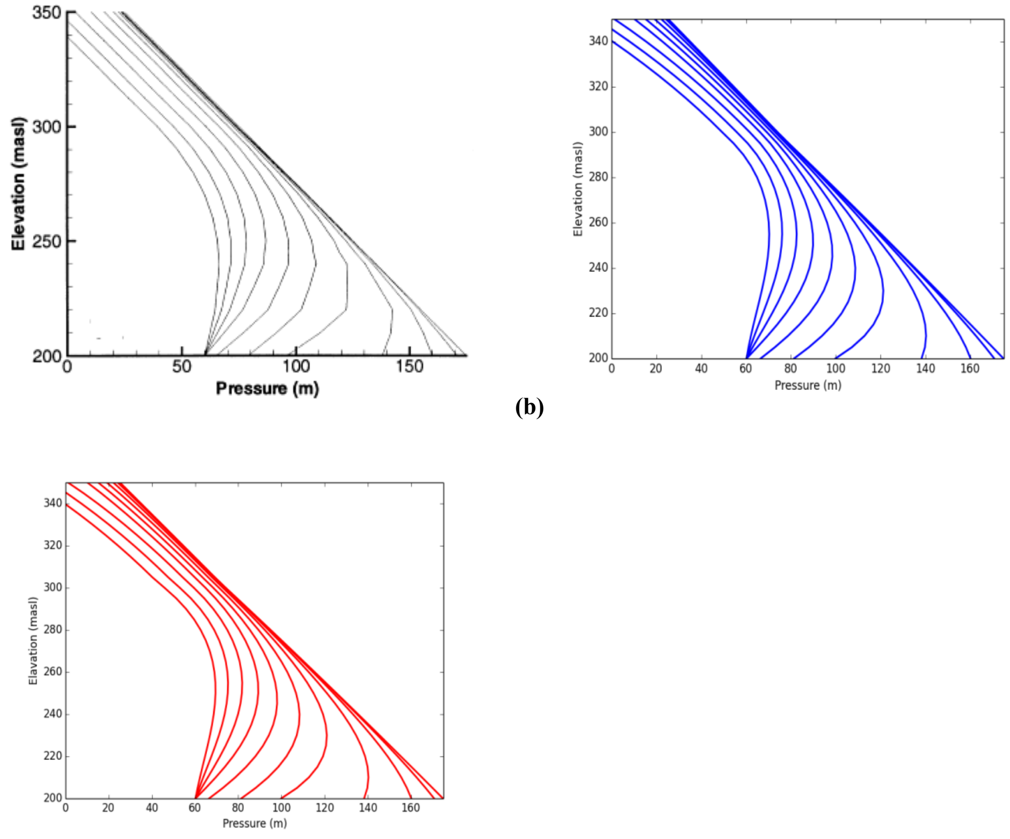
We then used (11), with the aid of a spreadsheet, to calculate the compaction in each layer in our model and then the total subsidence at the surface. We used the same values for rock properties as Allis and Zhan (2000) (see Table 2) and the initial conditions given in Table 3. Allis and Zhan (2000) did not give a value for the Biot coefficient but we found it necessary to use α=0.5 in order to obtain the good match to the subsidence results of Allis and Zhan (2000) shown in Figures 3 and 5. This value is in the range 0.4-0.6 reported by Suarez-Rivera (2013) and Fjær (2008) for mudstones.

Table 2: Model parameters

Property	Mudstone	Pumice breccia
Young's modulus E(MPa)	6.6228	94.706
Poisson's ratio ν	0.15	0.15
Vertical permeability k_z (m^2)	6.3E-17	1.0E-13
Porosity ϕ	0.1	0.1
Thermal conductivity K (W/m K)	2.5	2.5
Density of rock ρ_{rock} (kg/m^3)	2500	2500
Specific heat of rock C (J/kg K)	1000	1000
Recharge coefficient A	3E-8	9E-6
Biot coefficient α	0.5	0.5
Layer thickness (m)	100	50

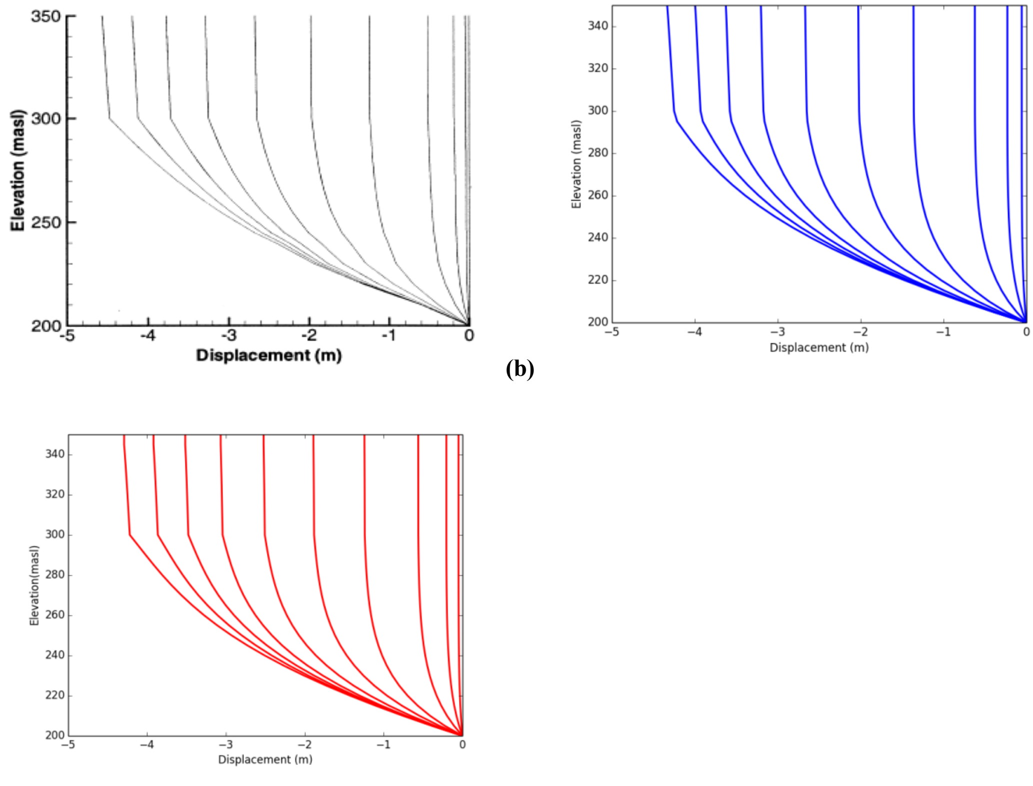
Table 3: Other parameters used

Initial pressure (MPa)	Bottom	2.09812
	Top	0.60135
Initial temperature (°C)	Bottom	112.0
	Top	15.0



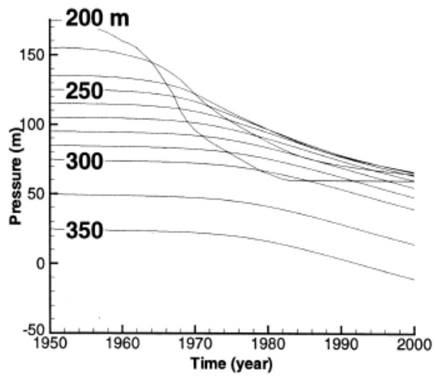
(a) (b) (c)

Figure 2: Pressure profiles from 1950-2000. (a) Allis and Zhan, (2000), (b) FEHM, (c) TOUGH2

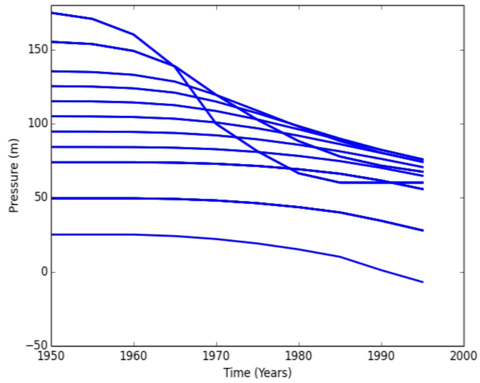


(a) (b) (c)

Figure 3: Displacement versus elevation at 5 year increments. (a) Allis and Zhan, (2000), (b) FEHM, (c) TOUGH2



(a)



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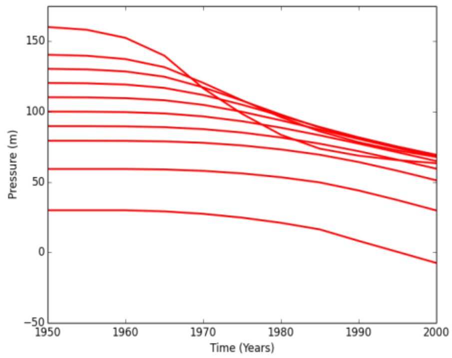
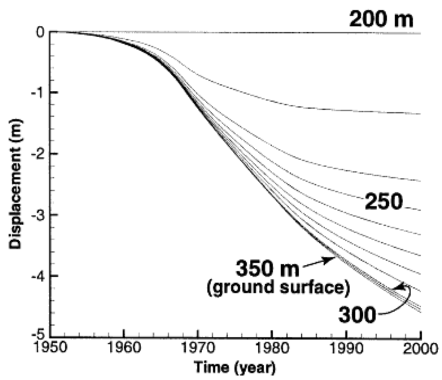
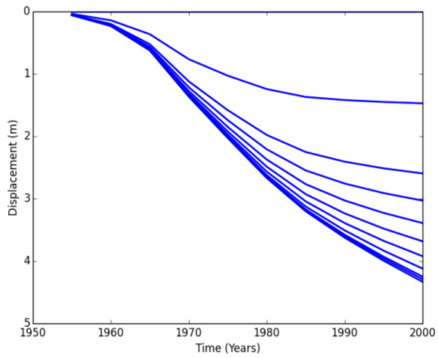


(c)

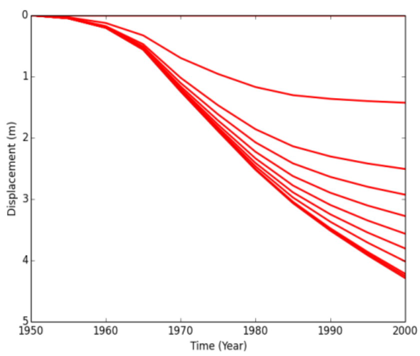
Figure 4: Pressure vs time at different elevations. (a) Allis and Zhan, (2000), (b) FEHM, (c) TOUGH2



(a)



(b)



(c)

Figure 5: Displacement versus time at different elevations. (a) Allis and Zhan, (2000), (b) FEHM, (c) TOUGH2

5.2 FEHM model

The second model we set up was essentially the same as our first model but instead of using TOUGH2 and a manual deformation calculation we used FEHM for the whole THM simulation. FEHM has the same functionality as TOUGH2 for heat and mass transfer calculations but has a slightly different system for defining the block structure and the boundary conditions. With FEHM we were able to directly specify the time varying top and bottom boundary pressures. For our TOUGH2 model we used 30 blocks, each 5m thick, in our model whereas in FEHM we used a "half" block, 2.5m thick, next to the top and bottom boundaries.

For the deformation problem FEHM uses a finite element grid whose nodes form the corners of the finite volume blocks used in the heat and mass transfer calculation. For the deformation problem we used the following boundary conditions:

- Bottom nodes: zero displacement in all directions
- Side nodes: zero perpendicular displacement, zero shear stress
- Top nodes: zero perpendicular displacement, zero shear stress, zero vertical stress

The results generated with FEHM are shown in Figures 2-5. Reassuringly they agree well with the TOUGH2 results and those of Allis and Zhan (2000).

5.3 Updated rock parameters

Recently a major study of subsidence at Wairakei-Tauhara was commissioned by the field operator Contact Energy Limited and rock properties were measured (Bromley *et al*., 2010; Pender *et al*., 2013). The values of Young's modulus for samples taken from the Wairakei subsidence bowl are listed in Table 4, together with layer thicknesses of Mudstone and Pumice breccia which have been switched to match *in situ* conditions reported in Bromley, *et al*., (2010).

Table 4: Compressibility properties of rock at the Wairakei subsidence bowl.

Property	Mudstone	Pumice breccia
Young's modulus E(MPa)	4.0	42.0
Poisson's ratio ν	0.25	0.25
Biot coefficient α	0.5	0.5
Layer thickness(m)	50	100

We then re-ran the FEHM model using the measured rock properties shown in Table 4. All of the other model parameters were left unchanged. The results obtained for total subsidence at the surface are shown in Figure 6.

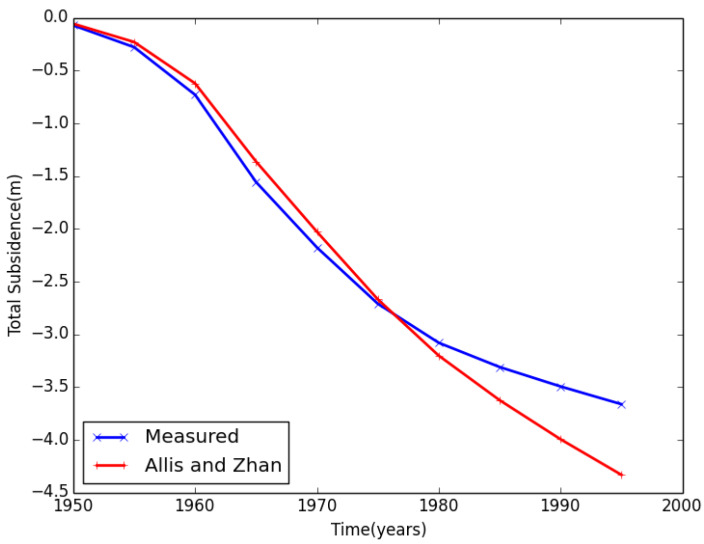


Figure 6: Total subsidence at the surface using rock properties from Allis and Zhan (2000) (red) and measured data (blue).

The results from the model using measured rock properties do not match the results from the Allis and Zhan (2000) model which was calibrated to match the field data reasonably well. However the model used unchanged permeabilities and recharge coefficients and some re-calibration of these parameters is warranted. In general a low Young's modulus will be associated with a low permeability and probably a variable permeability should be used in the model, matching the variation in Young's modulus. The model with measured material properties in Figure 6 depicts less subsidence, though equivalent Young's modulus is actually lower. This is due to a higher value of Poisson's ratio besides an increase in thickness of Pumice layer where horizontal recharge rates were higher. A higher recharge rate results in less pore fluid pressure decline thus less subsidence.

6. CONCLUSIONS

We have been able to reproduce the results of Allis and Zhan (2000) in modelling subsidence at the A97 bench mark near the Wairakei subsidence bowl. In order to achieve this good match to their results some unsatisfactory features had to be used in our model. For example we imposed a time dependent pressure at the top boundary of our model corresponding to the boundary condition used by Allis and Zhan (2000). It would be more physically realistic to extend the model up to ground surface and include an unsaturated zone at the top of the model. Then, if the model is working well, the water table should fall in a manner which matches the change of pressure with time at the top of the model discussed above.

When we modified our model to include values of Young's modulus measured from core samples taken near the Wairakei subsidence bowl the match of our model results to the field data is degraded. However further re-calibration of the model adjusting permeabilities and recharge coefficients may recover the quality of the match. This work will be carried out in the future.

Also in future work we wish to investigate the use of more complex constitutive laws for the deformation of rock, possibly including elasto-plastic yielding behaviour by utilising a more advanced solid mechanics simulator –such as ABAQUS (ABAQUS 2003).

The importance of the lateral recharge coefficient in determining the behaviour of our 1D column model is an indication that the 1D approach is not adequate and in the future we will investigate radially symmetric (r-z) models and fully 3D models.

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