COUPLED ONE-DIMENSIONAL SUBSIDENCE MODELLING USING ELASTIC-PLASTIC RHEOLOGY

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ABSTRACT

Subsidence as a result of extraction of geothermal fluids for energy production is a significant problem at many sites around the world. At the Wairakei geothermal field in New Zealand, subsidence has occurred since the onset of production in the 1950s. Subsidence is non-uniform and reaches as much as 15m in a small area known as the Wairakei subsidence bowl. The subsidence there is attributed to a reduction of pore pressure in the Huka Falls Formation (HFF), which is composed of pumice breccia and mudstone. The study described here uses a one-dimensional model to investigate subsidence at Wairakei. It is based on coupling the TOUGH2 heat and mass flow simulator with the ABAQUS solid mechanics modelling package through the use of Python scripting. We have used recent field data not available for past subsidence modelling exercises. The results from a linear elastic model are compared with the previously published work of Allis & Zhan (2000).

1. INTRODUCTION

The utilization of geothermal energy for electricity production can be challenging, hazardous and expensive (Allis, 2000; Brockman *et al*., 2011; Galloway and Riley, 1999; Gambolati *et al*., 2006). One potential environmental problem is subsidence resulting from an increase in effective stress due to the production-induced reduction of pore pressure in the reservoir (Allis and Zhan, 2000; Corapcioglu, 1984; Geertsma, 1973a; Hatton, 1970; Lewis *et al*., 1989; Lewis and Schrefler, 1998; O'Sullivan *et al*., 2010; Yeh, 2004). Predicting the magnitude of this subsidence is challenging (Allis, 2000; Brockman *et al*., 2011).

Subsidence is a complex thermo-hydro-mechanical (THM) problem. It is characterized by interaction between the heat and mass transfer processes and the important reservoir parameters (i.e., permeability and porosity) and the mechanical behavior of the host rock matrix (i.e., rock stress, strain and displacement). The decline of pore pressure due to production results in an increase in effective stress in the rock matrix and induces compaction. The cumulative effect of compaction appears at the surface as subsidence.

The stresses in porous reservoir rocks are coupled to pore pressures according to the effective stress principle (Terzaghi, 1936) and the theory of pressure dissipation (Biot, 1941; Biot, 1956). Typically, the effective stress principle is utilized in isothermal geotechnical applications, e.g. slope stability, geosynthetic reinforced soil structures, (Craig, 2005; Terzaghi *et al*., 1996) and in other poro-mechanical fields such as soil liquefaction (Coussy, 2005).

Some studies of geothermal subsidence have used software that couple isothermal single phase flow in a porous medium with a 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.

1.1 Subsidence at Wairakei

The Wairakei-Tauhara geothermal system is located to the North of Lake Taupo, at the centre of the North Island of 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 the much lower rates at present (Allis *et al*., 2009; Bromley *et al*., 2013; Currie, 2010). 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, 2010). The centre of the Wairakei bowl has dropped a total of approximately 15m since the 1950s. The area of the bowl where the subsidence rate is 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 Bromley *et al*., (2013). Sediments responsible for compaction in the Wairakei bowl consist of mudstone and pumice breccia in the HFF. Some of these sediments are very soft and both elastic and elasto-plastic constitutive laws have been used in modelling subsidence at Wairakei (Bromley *et al*., 2013; Wanninayake *et al*., 2010).

The pressure of the deep Wairakei reservoir has dropped by around 25 bar since the development of the field commenced 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.

1.2 Previous Work on Modelling Subsidence at Wairakei

Allis (Allis, 2004; Allis and Zhan, 2000) has studied subsidence at Wairakei-Tauhara for more than 15 years. He used Geertsma's techniques (Geertsma, 1973a) to identify the geological layer that contributes most to the subsidence bowl at Wairakei (Allis, 2004, Allis and Zhan, 2000). Allis and Zhan (2000) 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 and Zhan 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). Another limitation of the modelling technique is that it only allows for single-phase isothermal fluid flow and assumes a linear isotropic elastic model for rock deformation. Thus the flow in the two-phase zones of Wairakei-Tauhara and real material behavior 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, also they are two-dimensional rather than three-dimensional and assume linear elastic behavior of the rock material.

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 (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 O'Sullivan *et al*., (2007). The data were also used in recent studies by Bromley (Bromley *et al*., 2013; Bromley *et al*., 2010) 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 *et al*., (2010) used the same pressures as Bromley as input for a 1D numerical model implemented in FLAC3D (Itasca Consulting Group, 1997). They included a Cam-Clay constitutive model calibrated using K_0 triaxial test data from Pender, (2009a).

2. THM MODELLING

2.1 Modelling approach

For our model, the heat and mass transfer problem is solved first using TOUGH2 followed by the solution with ABAQUS of a sequence of quasi-static rock mechanics problems that incorporate both linear elasticity and a more complete treatment of plastic deformation.

2.2 Coupling

Coupling methodologies developed around THM modelling are in two categories: loosely coupled and tightly coupled models (for a review of coupling strategies see Dean *et al*., 2006; Inoue and da Fontoura, 2009; Koros *et al*., 2015;(in press); Longuemare *et al*., 2002; Pogacnik *et al*., 2014a; Pogacnik *et al*., 2014b; Samier *et al*., 2006).

The subsidence modelling approach in this work involves loose coupling: the mass and energy transport model is solved separately from the rock mechanics model. The effects of deformation on the flow parameters (porosity and permeability) are not calculated and therefore are not fed back to the flow model. TOUGH2 is used to model the mass and energy transport while ABAQUS is used for calculating the rock deformation. As explained below both elastic and inelastic constitutive laws are used.

A Python-based interface was used for linking the TOUGH2 and ABAQUS simulators. It is explained in more detail in Pogacnik, *et al*., (2015) (in press). During a given timeframe, or sequence of time steps, first a TOUGH2 simulation was performed for heat and mass transport. The block-centered pressure and temperature values from TOUGH2 at the end of the time period were interpolated to the finite element nodal locations. The pressure and temperature at every node were fixed in the rock mechanics model and ABAQUS was then executed to determine the displacements/stresses in the domain. These were then subtracted from the values determined at the beginning of the time period being investigated and the difference in surface displacement gave the subsidence that had occurred.

2.3 Effective stress

The total stress in fractured rock saturated with water consists of the pore pressure in the fluid and the effective stress acting on the rock matrix (Terzaghi, 1936). The effective stress tensor is defined as (Biot, 1941, 1956):

$$\sigma'_{ij} = \sigma_{ij} - \alpha P_p \delta_{ij} \quad (1)$$

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.

2.4 Constitutive relationships

In this work, we test a linear elastic constitutive model and a more advanced poro-elastic/plastic constitutive model. In an elastic compaction model, the compaction of sediments can be recovered after the induced stress is removed. Typically, elastic models assume the sediments are linearly elastic and isotropic and thus a simple version of Hookes' law applies involving only two parameters: Young's modulus E and Poisson's ratio ν. In an inelastic compaction model, all of the deformation cannot be recovered after the stress is removed. Usually, a plasticity model is used by geotechnical engineers to simulate stress-strain behaviour of sediments and clays. A plasticity model introduces limits on deviatoric stresses and allows irrecoverable or permanent deformation (Roylance, 2000; Wood, 1990). This makes elasto-plastic models more realistic than elastic models for modelling the behaviour of soft materials (Bowers, 2007).

We tested the poroelasto-plastic model called the Modified Cam-Clay Model (MCC) (Brinkgreve, 2005; Roscoe and Burland, 1968; Schofield and Wroth, 1968). It captures 'softening' behavior of normally consolidated or slightly over-consolidated soils once they are pushed beyond their maximum past stress values. The MCC model is discussed in detail in Section 3 below.

3. THE MODIFIED CAM-CLAY MODEL (MCC)

Critical State Soil Mechanics (CSSM) is the basis of the MCC model. The main variables in CSSM theory are mean effective stress, p', deviatoric stress, q and void ratio, e. The stresses p' and q are defined by:

$$p' = \frac{1}{3}\ (\sigma_1' + \sigma_2' + \sigma_3') \qquad (2)$$

$$q = \sqrt{\left\{\frac{1}{2}\left[(\sigma_1' - \sigma_2')^2 + (\sigma_2' - \sigma_3')^2 + (\sigma_3' - \sigma_1')^2\right]\right\}} \qquad (3)$$

where $\sigma_1', \sigma_2', \sigma_3'$ are the principal effective stresses.

Subscripts 1 and 3 in (2) and (3) refer to major and minor principal stresses respectively. The incremental volumetric strain is defined as:

$$\Delta v = -\frac{\Delta e}{1+e} \qquad (4)$$

where Δe is change in the void ratio.

The parameters that are required by the MCC model can be obtained from standard experimental measurements. They are: λ the slope of normal consolidation line in a $e - \ln(p')$ space, κ the slope of the swelling and recompression lines in a $e - \ln(p')$ space, and M a constant defining the slope of a critical state line.

Jaeger *et al*., (2007) explain that M is the coefficient in the linear relationship between q (the part of stress tensor that causes distortion) and p':

$$q = Mp' \qquad (5)$$

The stress ratio critical state parameter M is related to the effective friction angle, ϕ', (see (Wood, 1990) for details) through the expression:

$$M = (6sin\phi')/(3 - sin\phi'\ ) \qquad (6)$$

The yield surface for the MCC model in $p' - q$ space (Figure 1) according to Roscoe and Burland (1968) is defined as:

$$\frac{q^2}{p'^2} + M^2\left(1 - \frac{p_o'}{p'}\right) = 0 \qquad (7)$$

where p_o' is the pre-consolidation pressure (the past maximum mean stress) which controls the size of the yield surface and acts as a hardening parameter. The stress state of a soil specimen (p', q) within the yield surface (see Figure 1) is considered to be elastic and reversible, but when the stress state of the specimen is outside the yield surface, the specimen behaves in a plastic manner.

We used the MCC model implemented in ABAQUS for geomaterials, called the 'Clay plasticity' model (see (ABAQUS, 2002) for details). This model is more general than the model originally proposed by Cambridge Soil Mechanics Group (MCC-CSSM) (Roscoe and Burland, 1968) described above; which is a special case of the model in ABAQUS. The ABAQUS model is based on the following yield surface:

$$\frac{1}{\beta^2}\left(\frac{p'}{a} - 1\right)^2 + \left(\frac{q}{Ma}\right)^2 - 1 = 0 \qquad (8)$$

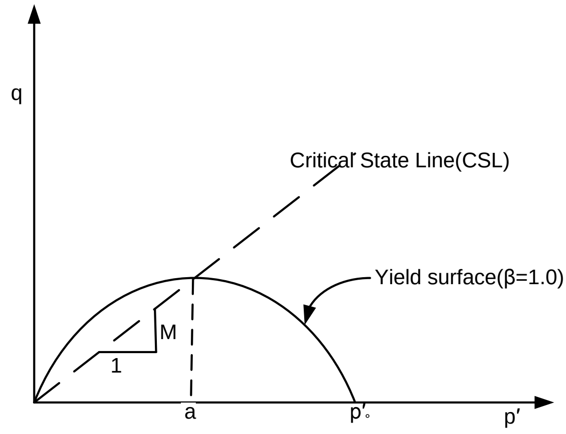


Figure 1: Modified Cam-Clay yield surface (in $p' - q$) space

where p' the mean effective pressure stress, q is the deviatoric stress, β is a constant used to modify the shape of the yield surface and a is a hardening parameter ($a = \frac{p_0'}{(1+\beta)}$) (defined as a point on the p'-axis at which the yield surface intersects the critical state line in Figure 1). Equation (8) reduces to (7) in the case β=1.

4. DESIGN OF THE MODEL AND RESULTS

The 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. Their model allows for single phase isothermal fluid flow and assumes linear isotropic elastic behaviour for the rock deformation.

5.1 TOUGH-2 Model

In the first stage of our subsidence calculation, we used TOUGH2 for a mass and energy transport calculation. The geometry used for the model is shown in Figure 2. The model consisted of a 150m column with a lower layer of mudstone (100m) and an upper layer of pumice breccia (50m). The model was designed to represent the shallow zone between elevations of 200 mRL and 350 mRL (surface elevation), which is the region where most of the subsidence is believed to have occurred. We ran two versions of the TOUGH2 model: first a natural state model to establish the pre-exploitation pressure and temperature profiles and then a production model for a period of 50 years. The parameters used by Allis and Zhan (2000) are given in Table 1.

We experimented with various options for the top and bottom boundary conditions for the model. We first tried specifying a mass withdrawal at the base of the model and allowed 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 therefore we switched to specifying the same pressure vs. time as Allis and Zhan (2000) at both the top and bottom of our model.

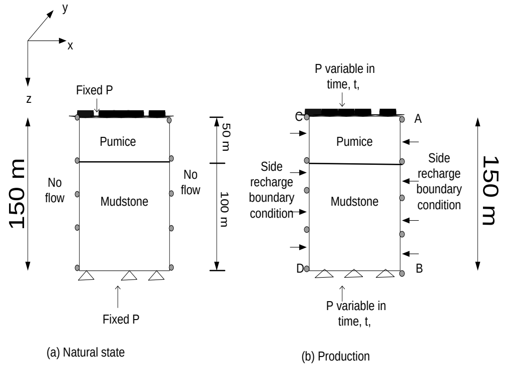


Figure 2: Geometry of the model showing the thickness of the mudstone and pumice layers and the boundary conditions.

TOUGH2 does not allow for the implementation of time varying pressure boundary conditions but we were able to implement them by using pyTOUGH (Croucher, 2011; Wellmann *et al*., 2012) to adjust pressures in the boundary block at each time step.

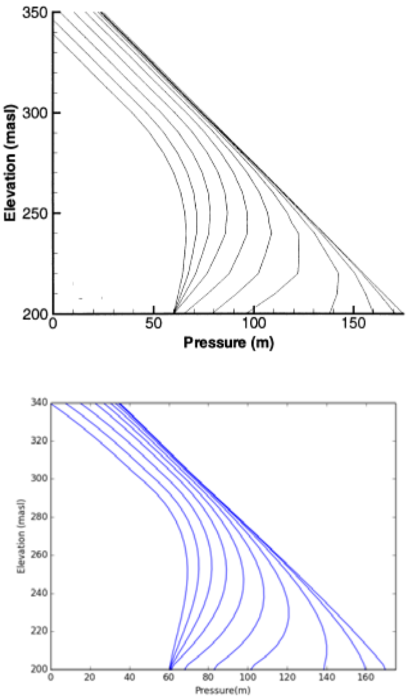
The pressure at the top boundary shown by Allis and Zhan (2000) became negative after about 1990. To avoid this kind of unphysical behaviour, which cannot be reproduced by TOUGH2, we added 0.3MPa to the pressure in every block. In the plots shown (in Figures 3 and Figures 4) and the 0.3MPa has been subtracted 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^{o}C at the bottom of the model and 15^{o}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 the first version of the production model, we did not include any lateral recharge. This made it impossible to obtain the results for pressure vs. depth that were similar to those given by Allis and Zhan (2000). We then added some lateral recharge (as shown in Figure 2 (b)) and by adjusting the recharge coefficient we were able to obtain a good match to the pressure profiles of Allis and Zhan (2000) (see Figures 3 and 4). The recharge formula used in AUTOUGH2 is:

$$q_m = A\,(P_{res} - P_0) \qquad (9)$$

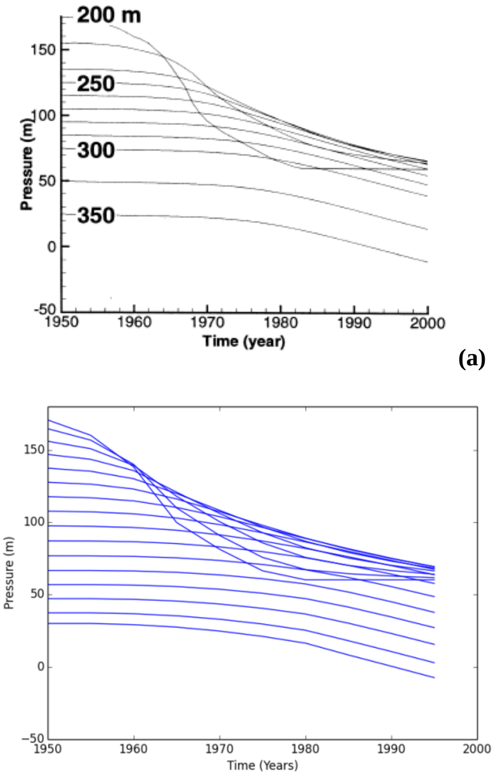
Here P_{res} is the pressure in the model, P_0 is the reference pressure (usually taken as the initial pressure in the reservoir block), q_m is the mass flow into or out of the model block and A is the recharge coefficient (usually taken proportional to the model permeability).This option is available in AUTOUGH2 but not in the standard version of TOUGH2. The TOUGH2 model parameters used in this study are given in Table 1 and the initial boundary conditions for the top and bottom blocks of the model are presented in Table 2.



(a)

(b)

Figure 3: Pressure profiles from 1950-2000. (a) Allis and Zhan (2000), (b) TOUGH2



(a)

(b)

Figure 4: Pressure variation with depth. (a)Allis and Zhan (2000), (b) TOUGH2

Table 1: TOUGH 2 Model parameters

Property	Mudstone	Pumice breccia
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

Table 2: TOUGH2 Model Initial Boundary Conditions

Initial pressure (MPa)	Bottom	2.09812
	Top	0.60135
Initial temperature (^{o}C)	Bottom	112.0
	Top	15.0

5.2 ABAQUS Model

In our model we used the same values for rock properties as Allis and Zhan (2000) (see 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 their work shown in Figures 4(a) and 5(a). This value is in the range 0.4-0.6 reported by Suarez-Rivera and Fjær (2013) for mudstones.

A 1D mesh was used with a total of 30 elements covering both the Mudstone and Pumice breccia, as shown in Figure 2. The boundary conditions applied for this model are:

- Bottom surface fixed with no vertical displacement ($u_z = 0$)
- Horizontal displacement and shear stress fixed at zero on sides: ($u_x = u_y = 0, \sigma_{xz} = \sigma_{yz} = 0$)
- Top surface: zero traction boundary condition.

The model was run in ten steps (extracting TOUGH2 results at five yearly intervals) for two cases: linear elastic and the Modified Cam Clay model.

5.3 Results for Case I: Linear elastic model

For Case I, we assigned a linear isotropic elastic material (ABAQUS, 2002) uniformly to the entire model with the same properties as those used by Allis and Zhan (2000) (see Table 3). Plots of displacement versus elevation at various times for this model are given in Figure 5 and plots of displacement versus time at different elevations are given in Figure 6. In both figures the results from Allis and Zhan (2000) are also shown. A reasonably good match of subsidence results to Allis and Zhan (2000) for simulated pressure trends can be seen in the plots.

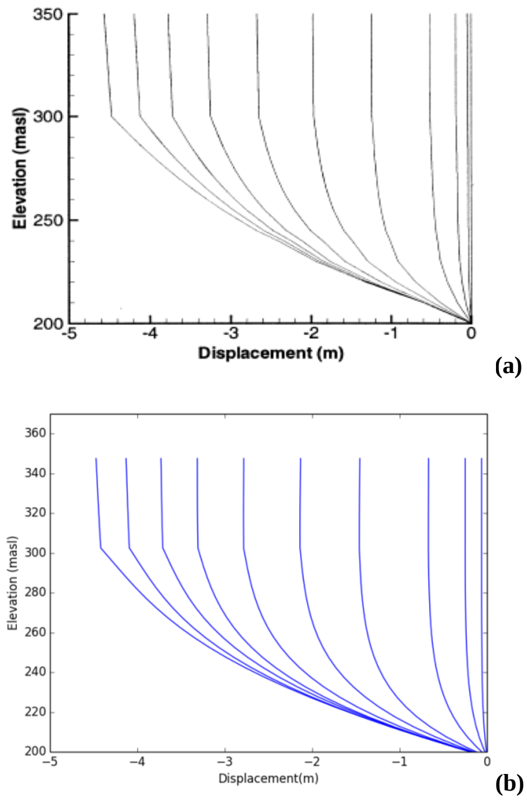


Figure 5: Displacement versus Elevation at 5-year increments. (a) (Allis and Zhan, 2000) (b) ABAQUS

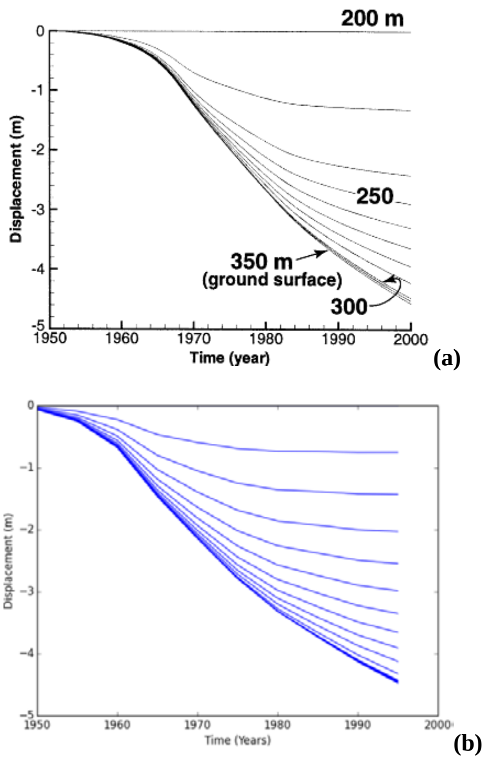


Figure 6: Displacement versus time at different elevations. (a) Allis and Zhan, (2000), (b) ABAQUS

Table 3: ABAQUS rock mechanics parameters

Property	Mudstone	Pumice breccia
Young's modulus E(MPa)	6.6228	94.706
Poisson's ratio ν	0.15	0.15
Biot coefficient α	0.5	0.5
Layer thickness	100	50

5.4 Updated rock parameters

A recent major study of subsidence at Wairakei-Tauhara was commissioned by the field operator Contact Energy Limited and resulted in measurement of rock properties (Bromley *et al.*, 2010; Pender *et al.*, 2013, Pender, 2009a, Pender, 2009b). We sought to populate our model with the measured values for material properties given in these reports for the depths used by Allis and Zhan (2000). The values of Young's modulus E for samples taken from the Wairakei subsidence bowl are listed in Table 4. Also note that the layer thicknesses of the Mudstone and Pumice breccia have been switched to match the *in situ* conditions reported in Bromley, *et al.* (2010).

Table 4: Compressibility properties of rocks 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	50	100

The AUTOUGH2/ABAQUS coupled model was re-run using the measured rock properties shown in Table 4 with the new thicknesses of each rock layer. All of the other model parameters were left unchanged. The results obtained for total subsidence at the surface are shown in Figure 7.

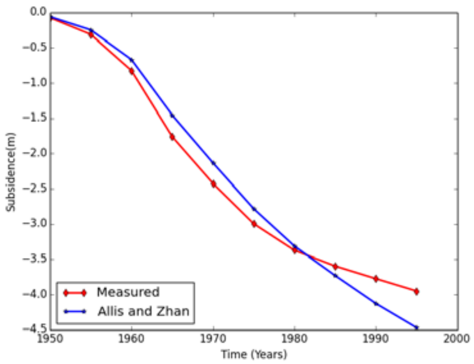


Figure 7: Total subsidence at the surface using rock properties from Allis and Zhan (2000) (blue) and measured data (red).

The results from the Allis and Zhan (2000) model in Figure 7, which was calibrated to match field data reasonably well, do not match with results using the measured rock properties. The fact that the model diverges from actual subsidence values indicates that some of the physics of the system are poorly represented in this 1-D column approach. An interesting feature of Figure 7 is that the model with measured material properties shows less subsidence, though the equivalent Young's modulus is actually lower. This is due to the higher value of Poisson's ratio as well as the increase in the thickness of the Pumice layer where horizontal recharge rates were higher. The higher recharge rate results in less pore fluid pressure decline and, thus, less subsidence.

5.5 Results for Case II: Cam Clay model.

For the second case, the mudstone sediment was modelled as a porous, elasto-plastic material of the Cam-Clay type. The input parameters used were representative of normally consolidated mudstones within the HFF (Pender, 2009a; Pender, 2009b; Wood, 1990). The Cam-Clay model parameters and those determined from field data for the mudstone stratum are summarized in Table 4 and Table 5. The values used for the wet yield surface size, β and flow stress rate, K in Table 5 were the ABAQUS default values while the stress ratio M was fine-tuned to match the model results to the measured subsidence values. The best-fit stress ratio, M=0.9855, which was close to that calculated from data, was used to describe the ultimate critical state condition of mudstone. The corresponding simulation results are shown in Figure 9.

Table 5: Cam-Clay Model Plasticity Parameters and measured parameters determined from isotropic K_o triaxial test

Plasticity Parameter	Model	Measured Effective friction angle, ϕ'=23.44°
Stress ratio,M	0.9855	0.920503
Wet yield surface size,β	1.0	1.0
Flow stress rate,K	1.0	1.0

Figure 8 shows the stress-strain relationship for the mudstone using the Cam-Clay plasticity model. There was noticeable softening and yield after the material was stressed beyond its elastic limit due to the pore pressure decrease.

Figure 9 shows subsidence at the surface over 50 years and compares our model results for Case I (elastic only) and Case II (elastic-plastic). The Case II model does not match the field data very well. However, we have calibrated the soft mudstone to yield at a stress value of 3685 kPa consistent with data reported in Table 9.1 in Bromley, *et al.* (2010). According to Figure 9, yield is expected in this system for realistic material properties. This further highlights the fact that a higher dimension, more advanced model is necessary to well represent the subsidence at Wairakei. Further, the model also used unchanged permeability and recharge coefficients. Re-calibration of these parameters for the compacting unit may improve the fit.

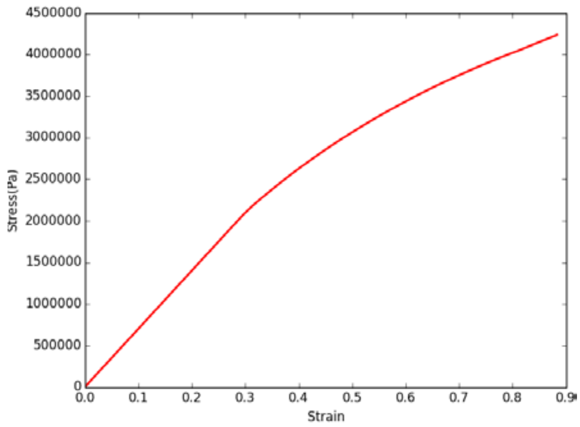


Figure 8: Mudstone compressive response using the Modified Cam-Clay model.

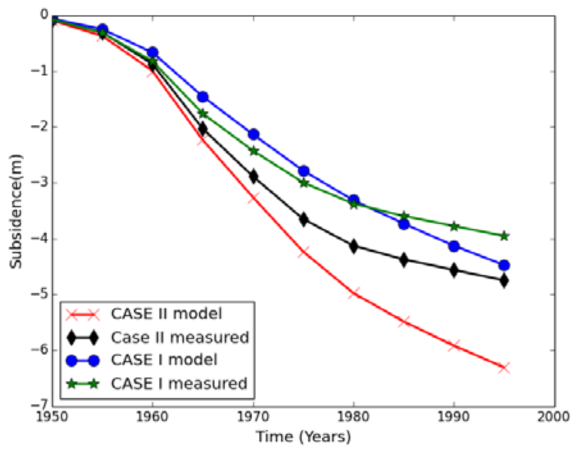


Figure 9: Total subsidence at the surface. Case I: using rock properties from Allis and Zhan (2000) and measured data from Bromley *et al.* (2010). Case II: application of an elasto-plastic Cam-Clay Model.

6. CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

We have been able to reproduce the results of Allis and Zhan (2000) in modelling the subsidence at the A97 bench mark near Wairakei bowl using a linear elastic model. We were also able to use a Cam-Clay model to model the same subsidence. With the Cam-Clay model, the stress-strain behavior of mudstone at A97 can be divided into two stages: an elastic stage and a plastic yielding stage. The plastic portion of the subsidence is irreversible, but the elastic portion is reversible if the reservoir were to be re-pressurised.

6.2 Future work

In the future, we would like to implement a more realistic top boundary condition. Allis and Zhan (2000) show a surface water level at the top of the model that drops in time. We have modelled that behavior by imposing a time-dependent pressure at the top boundary of the model. A more physically realistic simulation would be to extend the model to the ground surface and include an unsaturated zone at the top of the model. During production, the water table should fall in a manner that matches the change in pressure with time as in the Allis and Zhan work.

We note that our model is not set up to capture unloading behavior. More work is needed in order to accurately simulate a production/re-injection scenario to determine what degree of the subsidence is recoverable. We also did not investigate the effect that compaction has on porosity and permeability. Allowing those properties to change with production related compaction could further change the predicted subsidence result.

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 an adequate representation of the physical system. In the future, we will investigate radially symmetric (r-z) models and fully 3D models, including the use of complex constitutive laws such as the MCC model.

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