# GEOTECHNICAL INVESTIGATIONS OF SUBSIDENCE IN THE WAIRAKEI-TAUHARA GEOTHERMAL FIELD

Graham Ramsay[1], Trystan Glynn-Morris[2], Michael Pender[3] and Melvyn Griffiths[4]

[1] Beca Infrastructure Limited P O Box 3942 Wellington 6140, New Zealand graham.ramsay@beca.com

[2] Contact Energy limited Wairakei Private Bag 2001, Taupo 3352, New Zealand trystan.glynn-morris@contactenergy.co.nz mailto:

[3] University of Auckland, Engineering Department 20 Symonds St., Auckland 1142 New Zealand m.pender@auckland.ac.nz

[4]Griffiths Drilling (NZ) Ltd P O Box 40422 Upper Hutt, New Zealand mel@griffithsdrilling.co.nz

**Keywords:** *Geothermal Fluid, extraction, subsidence, geotechnical, investigations, testing.*

## ABSTRACT

The extraction of geothermal fluid from the Wairakei Field commenced in the 1950's and has resulted in the formation of a localised subsidence bowl one kilometre across with maximum subsidence of up to 15m. More recently a number of smaller subsidence features have developed above the adjoining and connected Tauhara Geothermal Field.

The operator of the field, Contact Energy Limited (Contact) required geotechnical investigations, sampling, and testing to be undertaken both to satisfy conditions attached to its consents for continued extraction from the Wairakei Field and also to support consent applications for a major increase in extraction from the Tauhara field. A particular aim was to seek to identify local anomalies that would explain the subsidence bowls.

The geotechnical investigations involved continuous coring and the undisturbed sampling of a variety of materials ranging from soft weak surface tephras to hard strong ignimbrites in geothermal conditions at depths of up to 800m.

This paper describes the techniques and procedures used to undertake the drilling, coring and recovery of the samples for testing to determine compressibility characteristics. The procedures needed to achieve the geotechnical objectives of maximum recovery of high quality core, while maintaining well security in geothermal conditions with high temperatures and pressures. An innovative technique was used to recover undisturbed samples for compressibility testing in special triaxial cells designed and built for the project.

The investigation programme involved nine geotechnical boreholes with a maximum depth of 774m and a total length of 4391m. A total of 3928m of core was recovered with 269 undisturbed samples from which 121 were selected for laboratory compressibility testing.

## 1. BACKGROUND

### 1.1 Historical Context

#### 1.1.1 Development History

The Wairakei geothermal field is near Taupo in the centre of the North Island of New Zealand. Extraction of geothermal fluid for power generation commenced in 1958 and has been ongoing, with extraction of approximately 150,000 tonnes per day of geothermal fluid as feed to the 171.5 MWe Wairakei Power Station. In 2007 Contact obtained Resource Consents for ongoing extraction and is in the process of developing new generation facilities to phase out the existing 55 year old Wairakei Power Station.

Contact has also identified and investigated the adjoining Tauhara Geothermal Field as a potential geothermal power generation opportunity. Until recently there has been some limited extraction of geothermal fluid from the field for direct use in forestry industry plants. In 2010, Contact's 23 MWe Te Huka binary plant started generating electricity. Resource consents have now been granted for a larger geothermal project (up to 240 MWe) on the Tauhara Geothermal Field.

Figure 1 shows the location of the Wairakei and Tauhara geothermal fields.

#### 1.1.2 Impacts of Extractions

The geothermal fluid has been extracted from the Waiora Formation shown in Figure 2. The formation extends under both the Wairakei and Tauhara areas.

In the 55 year period since extraction commenced at Wairakei the fluid pressure in the Waiora Formation has dropped by approximately 2000 kPa and that pressure drop has extended laterally under the Tauhara area. Limited readings also indicate a pressure drop in the Mid Huka Falls Formation, a permeable stratum typically 50- 100m above the Waiora Formation.

The extraction at Wairakei over 55 years has resulted in widespread general subsidence in the Wairakei area in the order of 1-2m and also the formation of a localized subsidence bowl one km across and with a maximum subsidence of the order of 15m. While the local subsidence bowl has caused significant disruption to roads and drainage structures, because all these are within the borefield area owned and controlled by Contact there has been no impact on private property.

More recently three smaller subsidence bowls have developed in the Tauhara area: at Spa Sights (2.9m settlement), Rakaunui Road (2.45m settlement), and Crown Road (0.88m settlement). General subsidence in the Tauhara area has varied from 0 – 1m.

The locations of the subsidence features are indicated in Figure 1 and details are provided in Bromley et al. (2010).

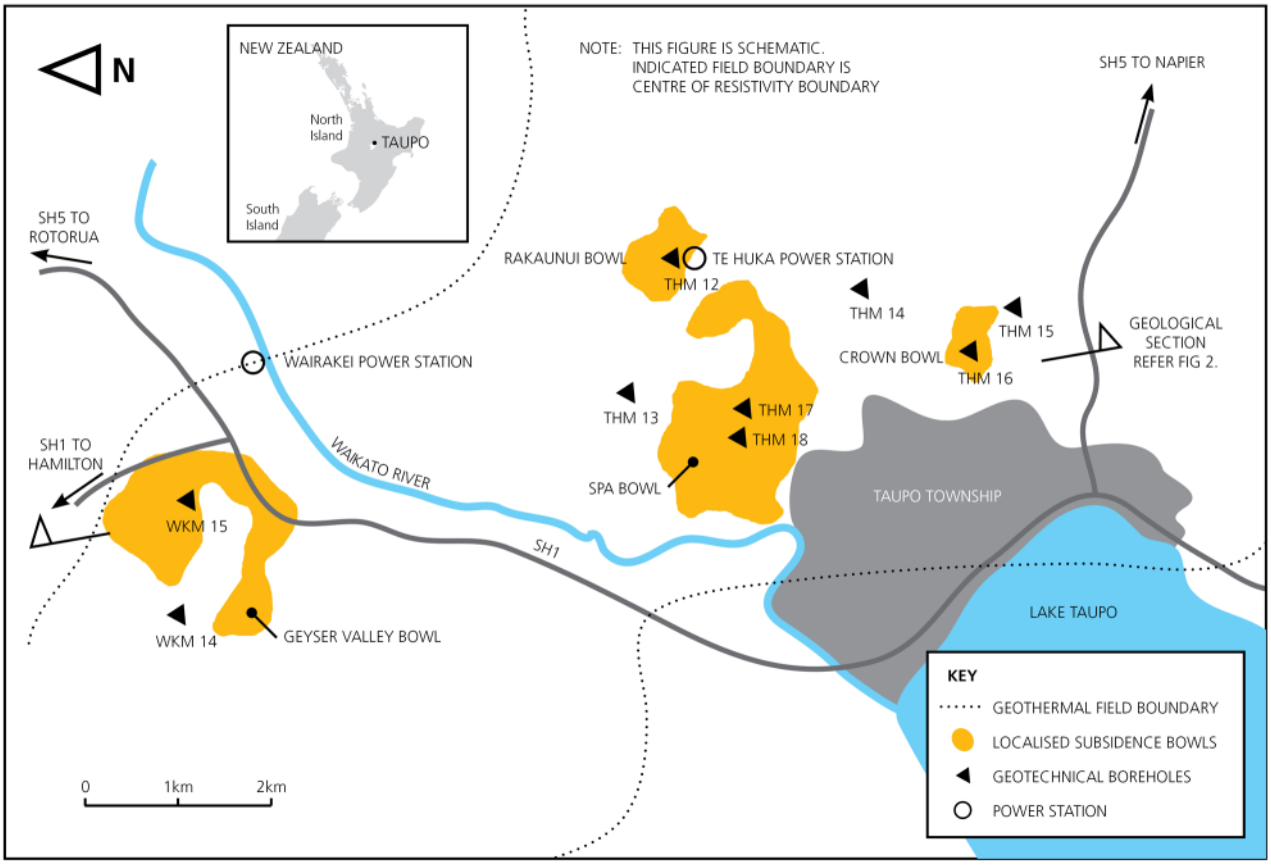



**Figure 1: Schematic Location of Wairakei and Tauhara Geothermal Fields**

### 1.2 Consenting for Geothermal Fluid Extraction

In New Zealand, resource consents for the extraction of geothermal fluid are required by the Resource Management Act. Such consents are typically issued for a period of 25-35 years and are normally subject to stringent environmental conditions.

In 2001 Contact sought consents from the Waikato Regional Council (WRC) to continue the extraction from the Wairakei field. The Taupo District Council (TDC) made an appeal to the Environment Court (EC) against the WRC decision to grant the consents.

The TDC appeal was largely based on potential subsidence impacts and during the hearing of that appeal different hypotheses as to the cause and mechanism for the subsidence were put forward by expert witnesses representing Contact and TDC. In 2007 the Environment Court upheld the issuing of the consents, but it imposed a number of conditions including requiring Contact to install " monitoring wells in the vicinity of Crown Road" and to provide a " proposed programme and methodology for taking and properly conserving core samples and accurately measuring their geotechnical properties." Another condition required Contact to develop "a subsidence computer model of at least 2D capability".

A separate consent obtained from WRC in 2001 for extraction of 20,000 tonnes per day from the Tauhara field had a condition requiring Contact to install a number of monitoring wells at Tauhara to monitor pressure in the Mid Huka Falls Formation.

At the time of the EC decision in 2007, Contact was considering seeking consents to increase geothermal fluid extraction from the Tauhara field from 20,000 tonnes to 213,000 tonnes per day to support construction of geothermal power plant of 250MWe at Tauhara. An analysis of the EC decision by Contact suggested that any consent application for further fluid extraction might face difficulties if it not accompanied by a clear identification of the cause of the subsidence and of operating procedures (such as reinjection of the geothermal fluid) to control future subsidence.

### 1.3 Existing Geothermal Field Model

Extensive information on fluid pressures and temperatures in the Waiora Formation and some overlying strata has been gathered over the last 60 years and together with records of extraction (and more recently reinjection) has been used in the development and calibration of a comprehensive 3D reservoir model of the Wairakei and Tauhara fields. The model, which is now in TOUGH2 code, is described in O'Sullivan et al. (2009). It has been progressively developed and refined over 20 years and is extensively used for predicting the impact of extraction scenarios on pressure and temperature within the reservoir.

### 1.4 Subsidence Models

A number of models for analysing the observed subsidence were developed and presented at the Wairakei EC hearings by TDC and Contact expert witnesses. These models were all simplified and all contained a number of assumptions necessary in the absence of any measurements of the compressibility characteristics of geological materials.

Contact concluded that the appropriate approach to support the consent applications for increased extraction at Tauhara was to develop a 3D ABAQUS finite element model populated with measured soil compressibility parameters. The ABAQUS model would have a similar mesh arrangement to, and would be coupled with the TOUGH2 reservoir model. Thus the pore fluid pressure changes to be used in the ABAQUS model to represent past history and the various future extraction/reinjection scenarios would be obtained directly from the TOUGH2 model. A detailed description of the ABAQUS model is provided in O'Sullivan et al. (2010).

### 1.5 Geotechnical Investigation Programme Objectives

As a consequence of the conditions imposed by the Environment Court and its wish to seek consents for increased extraction at Tauhara, Contact initiated a geotechnical investigation programme, the objective of which was to drill boreholes which would have the combined functions of:

1. Providing the additional monitoring wells required under the consents for extraction of20,000 tonnes a day at Tauhara.
2. Satisfying the requirements under the Wairakei extraction consent conditions for geotechnical sample recovery and testing to be undertaken.
3. Providing geotechnical logs of the full depth of the geological profile seeking to identify any localized variations in geotechnical conditions that would explain the observed localised subsidence features.
4. Obtaining samples from the full depth of the geological profile suitable for laboratory testing to determine compressibility parameters for the ABAQUS finite element analysis.

The decision was also made that the compressibility testing would be undertaken at The University of Auckland using techniques previously used in 2004 on testing of samples from the Tauhara area as part of the preparation for the Wairakei EC hearings. Details of these techniques are contained in Pender (2010).

Contact recognized that specialist geotechnical expertise was required to complement its own extensive geothermal drilling experience and engaged a geotechnical engineering consultancy to scope and manage the geotechnical investigation programme.

Contact also engaged a specialist geotechnical drilling contractor to address the significant differences between the requirements and techniques for geotechnical investigation drilling and those for the geothermal resource proving and monitoring drilling traditionally undertaken by Contact.

A comprehensive report on all aspects of the subsidence observations and the geotechnical investigations and analysis of the subsidence is provided in Bromley et al. (2010).

## 2. GEOLOGICAL CONTEXT

Details of the geology are provided in Rosenberg et al. (2009) and geological cross-sections through individual subsidence bowls are provided in Bromley et al. (2010). Figure 2 is a composite schematic cross-section (at a highly distorted (1V:5H) scale) of individual cross-sections from Bromley et.al

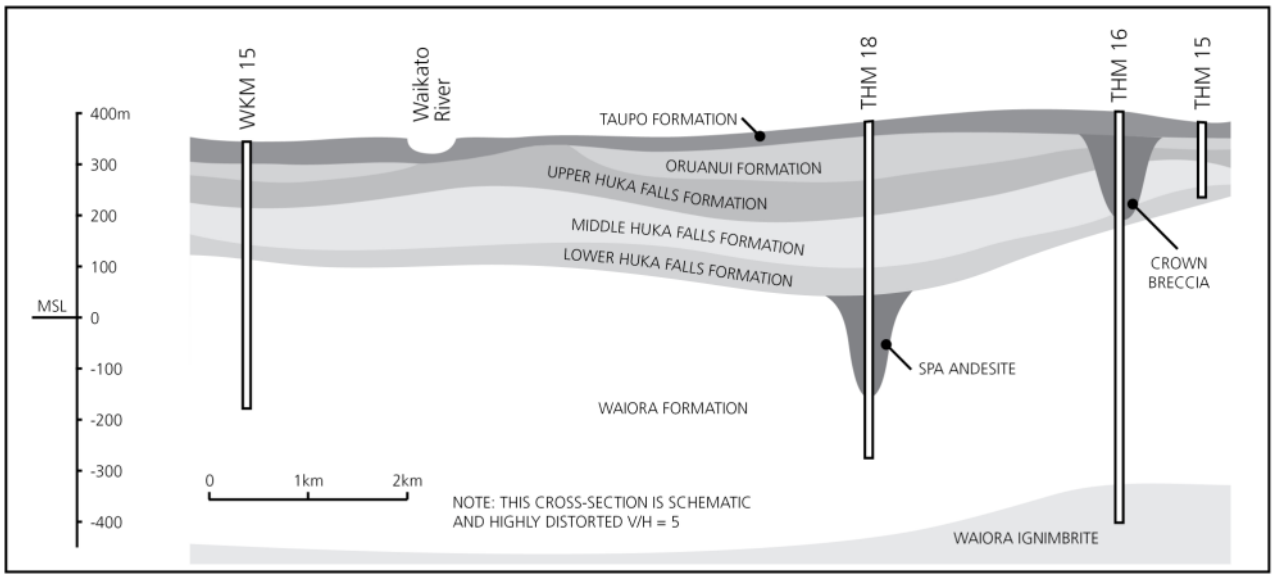



**Figure 2: Schematic Geological Section across Wairakei and Tauhara Geothermal Fields**

In simplified terms the geological profile can be subdivided from the top into three formations:

1. Surface deposits of the Taupo and Oruanui Formations which are a typically 100 - 125m thick and are a complex sequence of recent pumice breccias, ash and other predominantly air fall materials with consistencies ranging from soft soil to weak rocks.
2. The Oruanui Formation is underlain by the Huka Falls Formation which is a lacustrine deposit subdivided into three sub-formations, the Upper and Lower being predominantly low permeability siltstones and sandstones while the Middle is high permeability pumice breccia. The total Huka Falls formation is typically 200-300m thick. The Huka Falls Formation acts as the low permeability cap to the reservoir,

restricting the upward migration of the hot and more buoyant geothermal fluid.

3. The Huka Falls Formation is underlain by the Waiora Formation which is a thick interlayered sequence of volcanic (lavas tuffs and ignimbrites) and sedimentary deposits. The thickness of Waiora formation above the underlying greywacke bedrock has not been established by drilling but has been estimated as greater than 2000m. The Waiora is the main host to the liquid dominated geothermal reservoir.

## 3. DRILLING TECHNIQUES

### 3.1 Established Geothermal Drilling Procedures

As described in Glynn-Morris et al. (2009), Contact has well established procedures for and contractors experienced in geothermal drilling. The essential requirements for this work are the need:

- to provide a means of inserting and extracting the boring or coring equipment from the well without releasing highly pressurised hot geothermal fluid;
- to seal the casings of the completed well against the ground to prevent tracking of the geothermal fluid under pressure to the surface; and
- to provide a back-up "Blow out Preventer" (BOP) to close down the well in the event of a blow out during the drilling operation.

In general well drilling, Contact uses rotary drilling techniques which achieve fast hole advancement. Drilling bits used are either Tri-Cone Roller bits or Polycrystaline Diamond Drag (PDC) bits. Cuttings typically 5mm in size are recovered for geological control, but intact core is seldom sought unless a new geological unit of interest is encountered. Because of well control requirements, drilling is normally carried out continuously 24 hours a day with breaks while permanent casing is installed and cement is grouted in place to seal it to the surrounding rock.

Thus, while upward of 200 wells have been drilled in the last 55 years at Wairakei totaling some 150 km, very little information of geotechnical significance is available from that drilling.

### 3.2 Geotechnical drilling requirements

Geotechnical drilling seeks the recovery of core or samples that enable the total material fabric to be examined and for this project the objective was to recover continuous core in all of the materials present ranging from soft soil materials to hard rock.

The drilling rig characteristics required to achieve optimal production and high levels of recovery in coring operations (relatively high speed of rotation, low applied torque, and low pressure and volume of water for bit flushing) are very different to those for high production rotary drilling. With core recovery, additional working space is required for extracting and processing the core.

With the wireline coring technique commonly used in geotechnical drilling, the casing acts as rods with the drilling or coring bit "latching" into the bottom of the casing. The casing is fitted at its bottom with a casing bit which cuts out the annulus to accommodate the casing as it is advanced. The drilling or coring bit is sent down and recovered on a wireline without the need to withdraw rods.

### 3.3 Geotechnical drilling arrangements adopted

Contact hired a drilling rig specifically for the geotechnical investigation programme which was different from that traditionally used at Wairakei, having both conventional rotary tri-cone drilling capability and a top-drive to provide wireline coring capabilities.

The drilling contractor designed and constructed a substantial elevated steel drilling platform to accommodate the rig and provide space for core handling and casing grouting, as well as space beneath to accommodate the BOP equipment.

Contact's geothermal drilling specialists undertook the design of the casing and grouting arrangements required to contain the geothermal fluid pressures.

## 4. CORING AND SAMPLING TECHNIQUES

### 4.1 General Requirements and Approach

The objective of the investigations was to determine whether there were significant differences in the geotechnical profiles within and outside observed subsidence bowls that would explain the existence of the differential subsidence.

To achieve this, the aim was to obtain continuous core interspersed with the taking of a large number of "undisturbed" samples suitable for laboratory testing to determine compressibility characteristics. The samples were taken at predetermined (typically 12 – 24m) intervals.

Decisions on which samples to test for compressibility were based on an examination of descriptions of the core and on "classification" tests undertaken on samples taken from the core.

### 4.2 Coring technique

A standard triple tube coring method was adopted with a 3m long barrel. This type of barrel comprises a thin wall inner "tube" of stainless steel which is slit longitudinally to provide two half tubes ("splits") that can be separated to expose and recover the core. The intention is that the splits remain stationary relative to the stationary core. The splits are therefore located inside (but not attached to) a sampling barrel which in turn is inside the outer barrel which is rotated by the drill rig and has the coring bit at its bottom end.

### 4.3 Sampling technique requirements

As part of the work for the consent applications for the renewal of the Wairakei extraction, samples of conventional core obtained from depths around 90m at Crown Road were tested to determine compressibility. The results were challenged on the grounds that the samples had not been preserved in accordance with good practice. This led to the reference in the consent condition to "properly conserved" samples. A key requirement from Contact was therefore that the procedures for sampling and sample storage and handling should be best possible practice to minimise the risk of testing results being challenged on the basis of sample condition.

For the compressibility testing it was necessary to recover "undisturbed" samples and to maintain those samples as near as possible to the conditions at the time of sampling until they were tested.

Conventional geotechnical practice generally relates to sampling from depths typically less than 100m, normally 20-40m and rarely 100-200m. "Undisturbed" sampling is

generally undertaken in soft-firm soil materials using thin wall push tube samplers. Testing of stronger soil and rock materials is generally undertaken on core samples and does not include compressibility tests.

Key factors with the subsidence at Wairakei-Tauhara are the large thickness of material that may be contributing to the settlement and also the large changes in stresses in those materials arising from the fall in reservoir pressures. It was therefore necessary to determine the compressibility of materials with far greater strength and far lower compressibility than would normally be of concern in conventional geotechnical engineering. Also at the depths from which samples were to be recovered the in-situ stresses are very high.

The sampling technique therefore needed to be able to recover soil and rock samples with a wide range of strength and constrain the sample to minimise expansion under relaxation of the stresses within the sample after it was removed from the ground. It was concluded that none of the conventional geotechnical engineering sampling methods would be suitable.

### 4.4 Undisturbed sampling technique development

The decision was made to explore the concept of replacing the lower section of the inner tube splits in the triple tube barrel with a solid stainless steel tube. Enquiries and a review of manufacturer's literature did not identify any examples of such an approach having been used previously and such tubes did not appear to be offered by manufacturers as standard equipment.

A decision had been made that HQ3 was the optimum diameter for the laboratory test samples. The initial preference was for a relatively long one metre sample tube in the expectation that the middle section of a longer tube would experience less longitudinal extension under the longitudinal stress relaxation resulting from its removal from the ground.

Before designing the sample tube, a review was made of the diameters of the HQ3 coring bit (which produces 61.1mm diameter core) and the standard splits. The requirements for the sample tube were that the inside diameter (ID) had to be sufficiently large for the core created by the bit to pass up through the sample tube into the splits, yet as close as possible to the cut core size to minimize radial relaxation of the sample. At the same time the outside diameter (OD) of the sample tube had to provide sufficient clearance to allow the sampling barrel to rotate around the sample tube allowing it to remain stationary relative to the sample.

While it appeared that theoretically the system should work there were concerns that the sample tube would not have the ability to adjust slightly to accept the core in the manner that splits could, and also that the splits would be bearing on the end of a tube section rather than being continuous for the full length of the barrel. It was therefore decided to trial a range of internal sample tube diameters before committing to a final internal diameter.

It was established that stainless steel tubing with the required target OD was available ex stock but with an ID of 61mm which was less than desirable being smaller than the diameter of the core produced by the bit. A supply of that tubing was obtained and attempts were made to machine out the inside of 1 m lengths of the tubing to 62mm. These were unsuccessful because of difficulties in supporting the cutting tool in position over the 1 m length. However it proved possible to machine out 0.5m lengths and this sample tube length was adopted. The shorter length also made transportation and handling easier and the extrusion of the samples for testing from the tubes was also easier than would have been the case with a 1 m long tube.

Trials were undertaken by two drilling contractors (as part of geotechnical investigations for other projects) with sample tubes with IDs of 61 and 62mm. The trials indicated that sample tubes with an ID of 62mm were effective but those with the as received 61mm were not. Later in the project it was possible to order tube with both the desired ID (62mm) and OD (66mm) which could be simply cut to length.

### 4.5 Performance of coring and undisturbed sampling

Almost full core recovery was achieved with the triple-tube coring barrel; the exception being core loss in some sections of hydrothermal eruption material and in very weak highly hydrothermally altered clay materials. In these sections the poorer core recovery was achieved despite attempts by the drillers using shorter core runs (down to 0.25m in places) and changing weight on the bit and speed of bit rotation.

The sample tubes recovered were typically full and there was no difficulty in extruding samples suitable for the specialist triaxial testing except again in some of the very weak or highly altered materials.

After completion of the geotechnical investigation boreholes, a decision was made by the geohydrologists to install four additional monitor holes in the Tauhara area, two of which could be reasonably close to geotechnical investigation boreholes where poor core recovery had been experienced. Attempts were made in those holes to sample the materials not recovered in adjacent holes using the triple tube sampler.

A thin wall push tube sampler was manufactured from the same tubing as used for the triple tube barrel sampler (66mm OD and 62mm ID). It was possible to target the thin wall tube sampling to predetermined depths using the geological profile established in the previous hole at the location. In one hole the ground conditions proved too hard to push in the thin wall sampler but in the other five thin wall sample tubes were obtained in a 10m length of borehole.

### 4.6 Logistics of core processing

The project presented two particular challenges not normally experienced in geotechnical investigations. These were the 24 hour – 7 day core recovery and the sheer quantity of core being recovered. There was also the requirement to provide best practice protection of the core and factual investigation reports that were comprehensive, robust and would not be challenged.

Contact already had a core storage facility and routinely produced very high quality wooden boxes for core and cutting samples. However with the anticipated 4000m of core it became apparent that manufacturing the traditional core boxes would not keep up with core production rate and would be very expensive.

A Contact staff member with experience in the plastic industry suggested the use of plastic core trays produced by rotational moulding. A tray design was prepared which accommodated 5 m of core with dividers between the 1m core lengths and was designed to stack without resting on the core. The trays were relatively flexible and a plywood sheet with handles was used to support the tray during transporting between locations. Some 800 trays were used and proved extremely effective convenient and economical.

The existing core store was extended and new racks built to take the core trays.

### 4.7 Core logging and routine testing

A consultant was engaged to provide full time geotechnical technician presence on site in shifts while coring was in progress. Core was transferred from the stainless steel splits into uPVC splits after which a geotechnical log was produced and samples removed for on-site geotechnical tests (point load test, pocket shear vane or pocket penetrometer).

After testing, those samples were returned to the splits. At the same time samples for off site geotechnical tests were removed and placed in plastic bags. Sampling for both on site and off site tests was undertaken at predetermined intervals and when significant changes in material properties were observed.

High quality photographs were taken of the core using a properly set up lighting and camera arrangement. Examples of these photographs are shown in Figures 3 and 4.

After logging, photography and removal of samples for offsite testing, the core was fully enclosed in the uPVC splits which were taped together before being encased in heavy duty lay flat polyethylene tube for long term storage.

In addition to the geotechnical logging, core was inspected at regular intervals by geologists who classified the materials in geologic terms and extracted samples for laboratory testing.

### 4.8 Logistics for undisturbed samples

Where coring runs contained sample tubes, these were separated from the adjacent core and the ends sealed with wax after an inspection to check that the sample tube was full.

The sealed tubes were then packed into partitioned wooden boxes with packing and a screwed on lid before being transported by car the 300 km to The University of Auckland where the testing was undertaken.

## 5. LABORATORY TESTING

Four types of laboratory testing were undertaken on samples recovered during the investigations:

### 5.1 Routine geotechnical consistency and classification tests

Conventional geotechnical laboratory tests were undertaken to characterize the materials and to assist in decisions on which of the undisturbed samples should be subjected to specialist testing. These tests included density, moisture content, Atterberg Limits and PSA (particle size distribution) test as appropriate to the material type.

### 5.2 General Geological Tests

In addition the geologists removed samples of core for petrographic testing which included methylene blue tests (for smectite content) and X Ray Diffraction (XRD) tests (for clay abundance).

### 5.3 Compressibility Testing

At the commencement of the investigation a primary requirement had been for laboratory testing to establish the compressibility of the materials for input to the 3D ABAQUS finite element subsidence analysis. This testing would be undertaken in a specialized triaxial test which would return samples to the stress state present in the ground and then determine the compressibility under reduced fluid pressure. Testing of this type had been undertaken by University of Auckland for Contact in 2004 on samples taken from core recovered at Crown Road from depths around 90m. However it was necessary to build special equipment to match the HQ3 sample size and with sufficient strength to resist the high pressures required to replicate confining pressures for depths up to 800m. A detailed description of the testing programme and its results is presented by Pender (2010).

### 5.4 Mineralogical Analyses

Mineralogical analyses and scanning electron microscopy was undertaken by University of Auckland on selected samples to seek to determine any correlations between differences in mechanical properties and differences in mineralogy and morphology. The aim was also to seek to understand the processes that had lead to a high degree of geothermal alteration observed in materials recovered from near the centre of some of the subsidence bowls. A detailed description of those tests and the results and conclusions is presented by Lynne et al. (2011).

## 6. INSITU TESTING AND MONITORING

The possibility and justification for in-situ testing and monitoring was examined. Consideration and was given to the following:

### 6.1 In Situ Permeability

The permeability values used in the reservoir models are not measured values but have been determined by back analysis using a large amount of data from well tests which measure injection and extraction rates and fluid pressure.

The project peer reviewer requested that attempts should be made to measure in-situ permeability using packers and Lugeon Test procedures which are generally applied in boreholes with normal ground water temperatures and pressures to depths up to 100m.

After discussions with suppliers, two possible systems were identified: a single packer system (SWIPS) and a HOT (High Operating Temperature) double packer system. Both systems had advantages and disadvantages including risks to hole stability. While it was possible to obtain rubber packers capable of withstanding the predicted ground temperatures, there was no experience in carrying out such tests in geothermal conditions and doubts as to the ability maintain a sealed off section for testing. Eventually after a workshop involving Contact staff and the two suppliers the HOT system was selected.

The packer system was deployed in only one borehole. After it proved impossible to lower it to the selected test depth because of some obstruction, it was partially withdrawn and one test was completed successfully at a higher level, indicating no take and very low permeability. On withdrawing the packer equipment it jammed in the hole and part of the equipment was lost and considerable additional work was required to bypass the bore around the lost equipment.

A subsequent review concluded that the potential value from the testing did not justify the significant risks and costs involved and no further attempts were made.

### 6.2 In-situ pore fluid pressure monitoring

Subsidence bowls as experienced at Wairakei and Tauhara are due to differences in compression of columns of soil within and outside the bowl area. This compression is a product of the compressibility of the soil and the amount of pore fluid pressure reduction. The differential subsidence can therefore be the consequence of one of two factors (or a combination of those). Those factors are the possible existence within the bowl area of a different geological profile or different materials (with greater compressibility), and the possibility of a greater reduction of pore fluid pressures within the bowl, possibly due to localized vertical drainage paths.

Without any detailed investigations establishing the soil profile and compressibility of the soil materials inside and outside the bowls or measurements of in-situ pore fluid pressures inside and outside the bowls it was not possible to conclude whether the subsidence bowls were due to one or other of these factors or a combination.

The geotechnical drilling and testing programme was designed to determine whether there were differences in geological profile and soil compressibility sufficient to explain the differential subsidence. However, as a contingency in the event of the drilling not identifying such differences, enquiries were made to establish the feasibility of installing pore fluid measurement devices that could be left in situ, would survive in an aggressive geothermal high temperature and pressure environment for a substantial period, and record in-situ fluid pressures in low permeability materials.

While in-situ monitoring of pore water pressures in low permeability materials is routinely undertaken in geotechnical investigations those measurements are made at shallower depths and in non aggressive cool groundwater. None of the equipment used in conventional geotechnical engineering was suitable for use in geothermal conditions.

However a specialist device manufactured by Opsens in Canada was identified that had been developed for aggressive high temperature environments in the oil and gas industry. The device utilizes interferometer technology and fibre optic cable and appeared suitable for use in geothermal conditions. The devices are relatively expensive and would require to be installed in dedicated boreholes each of which would be able to accommodate a maximum of two devices.

Once the geotechnical drilling and testing had identified localized differences in material properties in the subsidence bowls sufficient to explain the formation of the bowls, there was no justification for installation of the Opsens devices.

## 7. DESCRIPTION OF DRILLING PROGRAMME

A total of nine boreholes were drilled for the geotechnical programme with a total depth of 4,390m and depths ranging 157 to 804m. The locations are indicated in Figure 1 and were constrained in many cases by topography, access and site development, and the proximity to other geothermal wells and public areas. The boreholes were drilled with three objectives:

- Monitor holes (2 of the 9) which were for long term pressure monitoring in the Middle Huka Falls formation as required by consent conditions and extended only to the monitoring level. These holes were cored and sampled only where this was not significantly more expensive than advancing the holes with a tri-cone bit.
- Hybrid holes (3 of the 9) which had the same objective as Monitor holes but were drilled as deep as possible (but not to the Waiora) and cored and sampled for their full depth, after which the lower sections were grouted and the borehole converted to a monitoring well.
- Geotechnical holes which extended into the Waiora Formation geothermal reservoir and were cored and sampled over their full depth.

The intention in deciding borehole locations was to, as far as possible, locate holes near the centre of each subsidence bowl and outside but as close as possible to each bowl.

Because of the major cost and time involved in the drilling the aim was to gather as much information as possible and to recover and preserve full core wherever possible and to take a generous number of samples for specialist and routine testing. As a consequence a total of 3920m of core was recovered including 269 samples (0.5m long) for specialist testing. The number of onsite classification tests undertaken was 1563 and 456 samples were subject to routine laboratory testing.

## 8. FINDINGS OF THE DRILLING AND TESTING

The investigations disclosed that near the centre of each of the subsidence bowls drilled there was either a localized geologic deposits not found at similar levels outside the bowl or evidence of localized hydrothermal alteration of the persistent strata in the area of the bowl.

Thus at Crown Road a localized hydrothermal eruption breccia is present between 35 – 200m depth. This has a strongly altered hydrothermal clay matrix and is considered a new formation; Crown Breccia. Figure 3 shows section of core from borehole THM16 at Crown Road indicating a ‘cavity’ (defined by a sudden drop in the drill string) recorded during the drilling and anomalously soft material.




**Figure 3: Section of core from Crown Road Bowl**

At the Spa Sights bowl altered materials were observed within the 270m thick Huka Falls Formation

At the Geyser Valley Bowl at Wairakei alteration was noted within the 155m thick Huka Falls Formation and also within a 100m thick layer of tuff breccia in the Waiora Formation. Figure 4 shows core from the Waiora Formation at almost the same elevation in the two boreholes at Wairakei. The upper box is from THM14 outside the bowl while the lower is from WKM15 inside the bowl, the latter showing evidence of hydrothermal alteration.

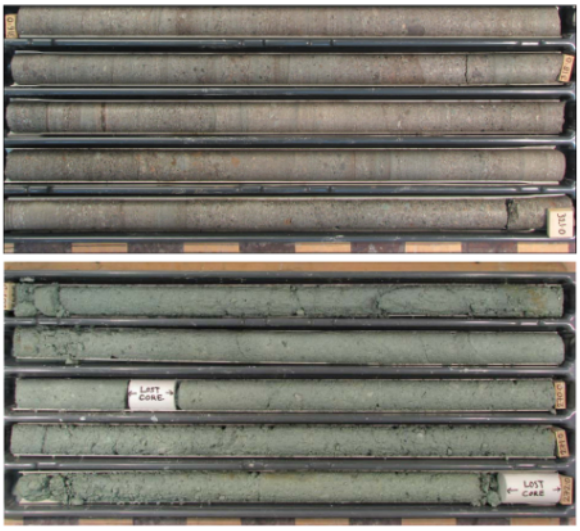


**Figure 4: Sections of core from Geyser Valley – Outside the bowl (top) and inside the bowl (bottom).**

In each case the presence of soft altered materials was initially indicated by poor core recovery and from logging of the recovered materials. The anomalous high compressibility of the materials was subsequently confirmed by specialist laboratory testing.

Details of the specialist test results on compressibility and a commentary on the geotechnical properties of the materials are provided by Pender (2010) and discussions of the mineralogy and morphology of the altered and unaltered materials and possible mechanisms for the alteration is presented by Lynne et al. (2011).

The compressibility parameters obtained from the specialist testing were used as input to the ABAQUS 3D Finite Element analyses which were able to replicate the observed subsidence patterns and provide predictions of future subsidence for various extraction and re-injection scenarios.

## 9. CONCLUSION

The geotechnical investigations described in this paper involved the recovery of materials of various consistencies ranging from soft soils to hard rocks to depths of 800m in geothermal conditions. New techniques were developed to recover high quality undisturbed samples for specialist triaxial testing to determine material compressibility at the high levels of stress acting on them in the field.

The scale of the investigations and the complexities arising from undertaking geotechnical sampling in geothermal conditions presented logistical and technical challenges which are described in the paper.

The investigations identified anomalous geological features beneath the subsidence bowls. Testing of materials from those features demonstrated high relative compressibility which allowed the formation of the bowls to be replicated in 3D Finite element analyses. This provided a factually-supported explanation for the formation of the bowls and the ability to determine the future development and control of those bowls with various scenarios for the extraction and re-injection of geothermal fluid.


## ACKNOWLEDGEMENTS

The success of the investigations reported was the result of close collaboration between and innovative suggestions from a large number of parties. Particular acknowledgement is made to Beca Consultants that project managed the investigations and developed the investigation scope and procedures; Boart Longyear who undertook the drilling; GNS who undertook geological logging and special tests; the Contact Geothermal Resources team who undertook the well design and geothermal testing; EMS who provided project management of the overall subsidence analysis project; Griffiths Drilling Co who provided specialist geotechnical drilling advice; Opus International Consultants who undertook the geotechnical logging and core processing plus routine on and off site geotechnical tests; and the University of Auckland staff who undertook the specialist triaxial and mineralogical testing.

The development and execution of the investigations was peer reviewed by Dr Richard Davidson of URS Denver.

Finally the permission of Contact Energy to present this paper is acknowledged.


## REFERENCES


Bromley C, Currie S., Ramsay G., Rosenberg M., Pender M., O'Sullivan M., Lynne B., Sang-Goo L., Brockbank K., Glynn-Morris T., Mannington W., and Garvey J. Tauhara Stage II Geothermal Project: Subsidence Report *GNS Science Consultancy report 2010/151 February 2010(2010)*

Glynn-Morris T., King T., and Winmill R., Drilling History and evolution at Wairakei, *Geothermics 38 1 30-39 (2009)*

Lynne, B., Pender M and Glynn-Morris T. Scanning electron microscopy and compressibility measurements: A dual approach providing insights into hydrothermal alteration and rock strength at Tauhara Geothermal field, New Zealand. *New Zealand Geothermal Workshop 2011* Auckland New Zealand (2011)

O'Sullivan M.J, Yeh A., and Mannington W.I., A history of numerical modeling of the Wairakei geothermal fluid *Geothermics 38 No 1 155-168 (2009)*

O'Sullivan M.J, Yeh A., and Clearwater E. Three-dimensional model of subsidence at Wairakei-Tauhara. *The University of Auckland - Appendix 10 GNS Science Consultancy report 2010/151 February 2010 (2010)*

Pender, M., Triaxial testing on core from the Wairakei-Tauhara geothermal field *The University of Auckland – Appendices 8 and 9 GNS Science Consultancy report 2010/151 February 2010 (2010)*

Rosenberg M.D., Ramirez L.E., Kilgour G.N., Milicich S.D., and Manville V.R. Tauhara Subsidence Investigation Project: Geological Summary of Tauhara Wells THM12-18 and THM21-22 and Wairakei Wells WKM14-15 *GNS Science Consultancy Report 2009/309 December 2009(2009)*