

Prediction of Dewatering Related Settlement in Waihi Township, New Zealand

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Summary :

Between 1995 and 1998, Woodward-Clyde (NZ) Limited (WCNZ) conducted a settlement and rebound study of the Martha Gold Mine and Waihi township. The objective of this study was to support a resource consent application to extend the Martha pit.

Dewatering of the Martha pit has caused the groundwater level in most of the soil and rock layers immediately adjacent to the Martha pit to fall. Lowering of the general groundwater level has resulted in an increase in the level of effective stress within these soil and rock deposits. This increase in effective stress, and four other unrelated factors, has caused some of the soil and rock layers around the pit to consolidate resulting in settlement of the ground surface.

In order to estimate the magnitude of settlement and rebound that is likely to occur in Waihi due to operating and decommissioning the Martha pit, WCNZ completed an extensive program of research, investigation, laboratory testing and modelling. This paper summarises the methodology and results of this work.

While there has been a change in effective stress leading to some consolidation of the ground surface, dewatering of the Martha Pit has not caused any structural distress in the township, and engineering predictions indicate that no distress due to this cause is likely in the future. The magnitude of dewatering related settlement measured in Waihi Township is low compared to that measured in New Zealand and the United States at sites which have been affected by fluid extraction.

1.0 Notation

C	Cohesion.
D	Constrained modulus.
D_C	Constrained modulus of a soil or rock layer during initial consolidation.
D_{UR}	Constrained modulus of a soil or rock layer during unload and reload cycles.
e	Void Ratio.
E	Young's Modulus.
m_v	Coefficient of Compressibility.
s	Estimated settlement
t	Layer thickness
$\Delta \sigma'_v$	Change in effective stress at the centre of a soil or rock layer.
μ	Poisson's ratio
ρ_B	Bulk Density
ϕ	Angle of friction.

Note: $D = 1 / m_v$ *
 $D = E (1 - \mu) / \{ (1 + \mu) (1 - 2\mu) \}$ *
 * After Lambe and Whitman (1979).

2.0 Introduction

Settlement of the ground surface due to the extraction of fluids such as groundwater, oil, gas, and geothermal water has been documented at numerous sites throughout the world.

The extraction of water from the ground, for either water supply or dewatering purposes, has resulted in ground settlement of more than 6 metres in Mexico City (Rivera *et al* 1991) and around 9 metres in the San Joaquin Valley, California (Johnson 1991).

Mine dewatering related settlement has been documented in New Zealand at the Huntly East Coal Mine. During 1983, an area of approximately 7 hectares experienced settlement of up to 800mm (Kelsey, 1985).

Historically, underground mining occurred at the Martha Mine from the late 1880's through to the early 1950's. Old mine records indicate that the underground workings extend to 457m below sea level (BSL). Dewatering of the old mine occurred to the maximum depth of the workings (McAra, 1988).

The Waihi Gold Mining Company Limited (WGC) has operated an open pit mine at the Martha Mine site in Waihi since 1989. Originally Martha Hill outcropped at 160m above sea level (ASL). Resource consents have recently been granted allowing the Martha pit to extend to a depth of 95m below sea level (BSL). The location of the Martha pit is shown on Figure 1.

The Martha pit has been progressively excavated and dewatered over the last ten years and, as at June 1999, the pit excavation extended to a level 10m ASL. Since 1989, the groundwater level has been held at a level 5 to 20 metres below the base of the pit excavation by pumping. This has caused the groundwater level in most of the soil and rock layers adjacent to the pit excavation to fall.

Lowering of the general groundwater level around the pit has increased the magnitude of effective stress within the dewatered zones. This has caused some of the soil and rock layers adjacent to the Martha Pit to consolidate. Monitoring has shown that dewatering of the Martha Pit has not adversely affected buildings or services within Waihi Township. Engineering predictions also indicate that buildings or services are unlikely to be damaged as a result of mine dewatering.

In addition to mine related settlement, four other causes of settlement were identified in Waihi Township:

- i) Natural consolidation settlement of fill and the underlying natural soils;
- ii) Cyclical shrinkage and swelling, of the near surface soils, due to rainfall and changing soil moisture levels;
- iii) Movement or collapse of historic mine workings; and;
- iv) Consolidation of upper soil layers due to reduced water infiltration.

Considerable work was undertaken to evaluate these, and separate their effects from the mine related settlement.

A percentage of the settlement due to mine dewatering is recoverable if the groundwater level is allowed to recover after the pit is decommissioned. As the groundwater level rises, the effective stress levels will decrease, and a proportion of the settlement will be recovered through rebound.

3.0 Study Approach

The settlement and rebound study was conducted in eight stages.

The first stage of the study was a review and analysis of all the available data. This included a review of published and unpublished maps, reports, aerial photographs, historical records and survey data.

The second stage of the study was the development of plans summarising the settlement measured in Waihi Township, and preliminary two dimensional geological, geotechnical and hydrogeological models. During this stage of the study, areas of insufficient data and areas of high or unusual settlement were identified.

The third stage of the study comprised field investigations and laboratory tests targeted to address information gaps.

The fourth stage of the study was the generation of detailed two dimensional geological, geotechnical and hydro-geologic models, and a detailed analysis of these models in conjunction with the measured settlement and rainfall data. During this stage, a preliminary estimate of the potential settlement and an interim report was completed.

The fifth stage comprised additional field investigations targeted to confirm the extent of the potentially compressible layers, confirm the geotechnical characteristics of key units, and clarify issues identified during stage four of the study.

The sixth stage of the study was the development and refinement of simple one-dimensional geotechnical models. These models were constructed using records of drillholes, readings from groundwater piezometers installed within these drillholes, and laboratory data. The stiffness properties of the different geologic units were refined using the one-dimensional models by comparing predictions of surface settlement made by the models to measured survey data.

The seventh stage of the study was the development of a finite element model along a section through the Martha Mine and Waihi Township. This was achieved using the computer program "Plaxis" (Version 6), the geological, geotechnical and hydrogeologic cross-sections, and geotechnical data from the refined one-dimensional models. Where possible, measured groundwater profiles were used in the finite element models, however, the

maximum number of layers able to be modelled by Plaxis version 6 is ten. Because of this, adjacent geologic units with similar geotechnical properties were modelled as a single layer. The groundwater profiles in these combined layers were initially estimated using field measurements, and then refined by comparing predictions of surface settlement with survey data.

Finally, the refined one dimensional and finite element models were used to predict settlement and rebound due to operating and decommissioning the Martha Mine. By subtracting the predicted rebound from the predicted settlement, an estimate of the permanent ground surface settlement was made.

4.0 Geologic Summary

The near vertical ore-bearing vein systems that originally outcropped on Martha Hill are located within andesite. The andesite is overlain to the east, south and west of the Martha pit by younger ignimbrite, ash, tuff, and alluvial deposits which, in places, are overlain by fill.

For the purposes of the settlement and rebound study, the geological units present at Waihi were grouped into three main deposits according to their geological and geotechnical characteristics. These units were :

- i) Older deposits comprising andesite and altered andesite,
- ii) Younger Deposits comprising ignimbrite, ash, tuff and alluvial deposits, and,
- iii) Man-made Deposits comprising fill.

Figure 2 shows a typical subsurface distribution of the geological units under Waihi Township. Several cross-sections were developed using published maps, field observations and machine drillhole information.

The overall strength of the older deposits is relatively high, and this, together with the fact that they have previously been dewatered, means that they are relatively incompressible.

The overall strength of the younger deposits is highly variable and the unconfined compressive strength of these deposits range from >100 MPa (welded ignimbrite) to <0.1 MPa (alluvium). Most of the younger deposits comprise materials which will consolidate if dewatered or depressurised.

In many locations within Waihi Township, particularly adjacent to historic mine workings and railways, there are man-made deposits of unconsolidated to poorly consolidated fill. In addition, many old swamps have been drained or filled, and the land used for residential development. Most of the man-made deposits are still undergoing post depositional consolidation, or are causing the consolidation of underlying natural deposits independently of the current mine workings.

5.0 Hydrogeologic Summary

The permeability of the materials encountered at Waihi appear to be largely dependant on defect and fracture frequency in the case of welded materials or rock, and on porosity in the case of a soil. For the purposes of the settlement models, the geological units were broken into three groups of comparable permeability :

- i) Highly to moderately permeable. Unaltered andesite and welded ignimbrite fall in to this group. The fractures in these units were generally open and moderately widely to widely spaced in the andesite, and closely spaced in the welded ignimbrite. The boulder alluvium is also highly permeable. This unit comprises cobbles and boulders in a silt, sand and gravel matrix.
- ii) Moderate to low permeability. The geological units that fall into this group are the unwelded to moderately welded ignimbrite, ash and tuff deposits. The fractures in these units are very widely spaced, tight, and poorly interconnected. Some of the silty and sandy alluvial layers had a low to medium permeability and are also included in this group.
- iii) Low permeability. The units in this group include the altered andesite and clay alluvium layers.

Under Waihi township, the presence of an almost continuous layer of low permeability altered andesite, on the surface of the older deposits, separates the older and younger deposits into separate groundwater regimes.

Historic underground mining dewatered the andesite rocks under Martha Hill and Waihi Town via a system of stopes, shafts and drives. This dewatering only drained those overlying younger deposits able to drain through the altered andesite cap into the andesite. Drainage of the younger deposits was, therefore, mainly limited to areas

immediately around the shafts and drives that penetrated the younger deposits.

When historic mining ceased in 1952, pumping stopped and the groundwater levels returned to an elevation close to the ground surface. Re-establishment of the groundwater level within the dewatered younger deposits almost certainly resulted in a partial rebound of the ground surface.

Data from piezometers, installed prior to mine dewatering recommenced in 1989, shows that the groundwater level in 1988 was close to the ground surface in all layers.

Piezometric and survey data indicates that the present day limit of groundwater draw-down (and mine related settlement) is approximately 700 metres north, 2000 metres east, 1200 metres south and 400 metres west of the Martha pit. Within the andesite, these limits appear to correspond with the location of major structural faults.

Piezometric data indicates that the water level in the andesite rock immediately adjacent to the Martha pit has been drawn down to a level similar to the dewatering pump intake in the old Waihi No.7 shaft. The groundwater level measured in piezometers within andesite layers generally rises as the distance from the pit increases. Piezometers installed within altered andesite indicate that the piezometric pressure within this unit is variable and the unit is only locally drained via the historic underground workings.

Piezometers within the ignimbrite, ash, tuff and alluvial layers indicate that the groundwater level within the younger and man-made deposits follow a separate regime to the underlying older deposits.

The welded ignimbrite layer appears to have been dewatered to a level which is controlled by the units exposure in the Martha pit wall. Some recharge of this unit appears to occur via infiltration from overlying layers, and through outcrops of welded ignimbrite in the beds of streams.

Piezometers in the pumiceous ignimbrites, ash and tuff layers, that underlie the welded ignimbrite, indicate that the groundwater levels within these units are variable and are only drained locally.

Piezometers in the fill, alluvium and boulder alluvium layers, analysed in conjunction with rainfall data and six-

monthly survey data, indicate that the groundwater level in these layers is controlled by :

- i) the lowest level of the unit concerned exposed in the Martha pit wall,
- ii) rainfall recharge, and,
- iii) under-draining of the surface boulder alluvium by the welded ignimbrite layer.

6.0 Geotechnical Summary

Review and analysis of historic, survey, rainfall, geological and geotechnical data identified five physical processes that produce settlement of the ground surface within Waihi Township. In most areas at least three of these causes of settlement occur simultaneously. The five settlement processes which were identified are :

- i) Natural consolidation settlement of fill and the underlying natural soils;
- ii) Cyclical shrinkage and swelling, of the near surface soils, due to rainfall and changing soil moisture levels. At some locations, seasonal shrink and swell of ± 20 mm has been measured;
- iii) Movement or collapse of historic mine workings such as the Milking Cow block cave;
- iv) Consolidation of upper soil layers due to reduced water infiltration. This reduced infiltration is due to a combination of :
 - El Nino weather patterns and a lower than average rainfall over the five or six years prior to the study;
 - the installation of sewage and storm water reticulation systems in Waihi township since the mid 1980's;
 - the clearing or modification of streams; and;
 - the local removal of vegetation.
- v) Dewatering of the present day Martha Mine.

Settlement caused by i, ii and iii frequently results in differential settlement and damage to settlement intolerant structures. The consequences of settlement causes iv and v are usually regional, more subtle in nature, and therefore less destructive.

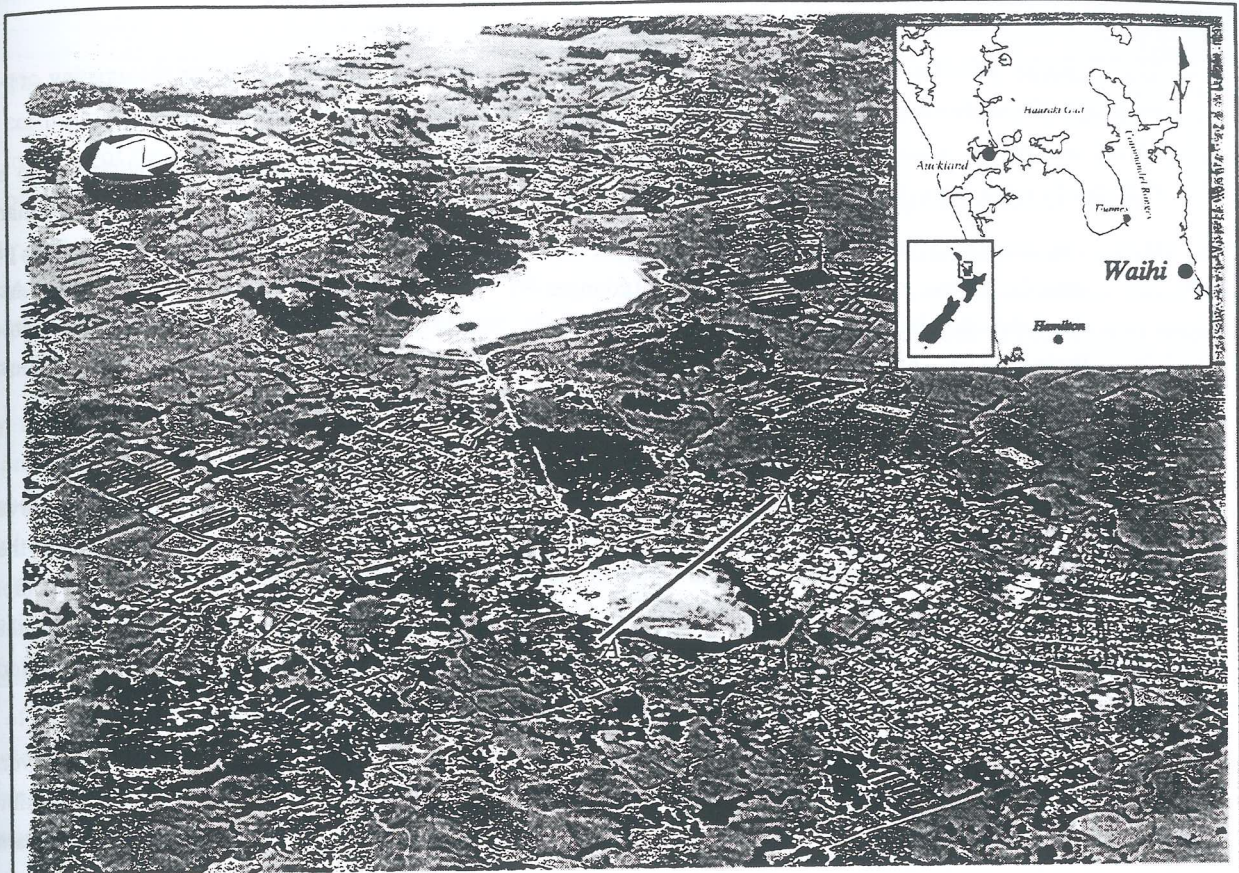


FIGURE 1
Location Plan

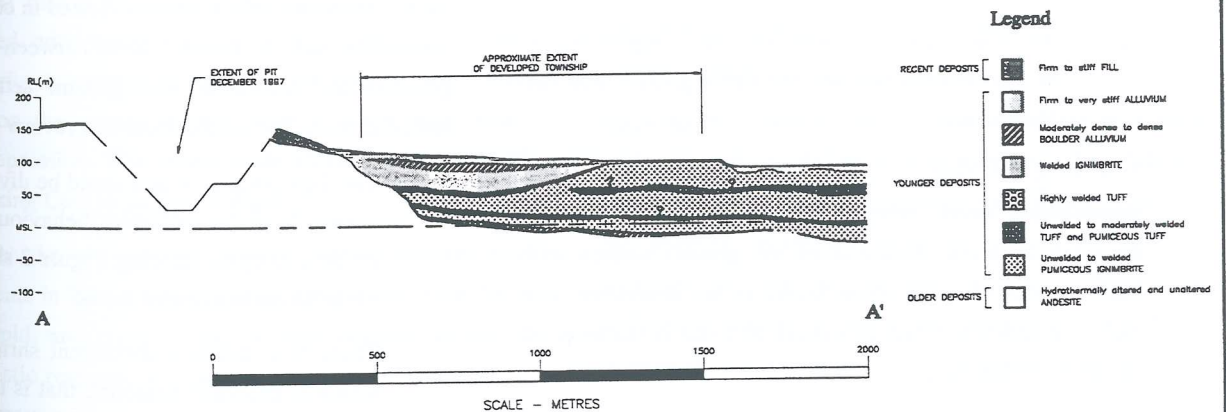


FIGURE 2
Typical Geological Cross Section A-A'
(Refer to Figure 1 for location)

The results of the geological and geotechnical investigations, observation of laboratory tests, analysis of survey monitoring results, and the analysis of laboratory tests results are summarised below :

- i) The calculated pre-consolidation pressures of the ignimbrite, tuff, ash, and alluvial layers (younger deposits) underlying Waihi Township suggest that these layers had not undergone significant consolidation during historic dewatering.
- ii) Many of the unwelded to poorly welded ignimbrite samples tested in the laboratory exhibited low to moderate consolidation characteristics up to a critical pressure. Once this critical pressure is exceeded the samples exhibit moderate to high consolidation characteristics. Observations of laboratory tests indicate that this critical pressure appears to reflect the collapse strength of pumice within the material, and welding of the material, rather than preconsolidation of the material;
- iii) The pumiceous ignimbrite and tuff layers are brittle and compressible once critical pressures are exceeded;
- iv) Some of the welded ash layers are brittle and moderately compressible once critical pressures are exceeded;
- v) In places, the alluvium and fill layers are highly compressible;
- vi) Most of the near surface cohesive alluvial soils are susceptible to cyclical shrink and swell;
- vii) The consolidation coefficient of compressibility (m_v) is between two and ten times greater than the rebound m_r .

Following the eventual pit closure, and recovery of the groundwater level, rebound of the ground surface is expected to occur. Rebound of the ground surface will occur as the effective stress levels in the dewatered soil and rock layers decrease as a result of a rise in the level of the groundwater table.

Settlement developed during operation of the Martha pit is unlikely to be fully recovered for two reasons :

- a) Most of the younger alluvial and man-made deposits are normally consolidated. Soil stresses, as a result of dewatering the Martha pit, are

anticipated to exceed the existing pre-consolidation pressure in some locations.

- b) The final lake level is anticipated to be around RL 104 m ASL. This represents a permanent lowering of the groundwater table around the pit and Martha Hill by between 0 and 30 metres. As a result, the original effective stresses in the ground will not fully recover to pre-existing conditions.

7.0 Settlement Monitoring Data

WGC has measured a network of 180 survey pins, on a six-monthly basis, since dewatering of the Martha pit commenced in 1989. This network comprises surface settlement marks which were installed throughout the township before major excavation or dewatering of the pit commenced.

In addition, several close order survey networks have been established around buildings which exhibit cracks, or properties whose occupants or owners claim have been damaged by mine activities.

The close order survey networks comprised a combination of piezometers and closely spaced survey pins. Survey pins were installed at a spacing less than 50 metres across properties and around buildings. Deep seated and near surface survey pins were installed to separate mine related settlement from the other causes of settlement which were known to be present in Waihi.

Six-monthly pit contour plans, and the corresponding survey monitoring data, were reviewed in conjunction with piezometer data to identify links between pit operations, groundwater movement and ground settlement in the township area. The results from this review indicated that:

- i) The Township of Waihi could be divided into seven zones of similar settlement behaviour demonstrated by the survey monitoring. Figure 3 shows the extent of the seven settlement zones
- ii) There is a moisture dependent shrink-swell cycle, which is generally seasonal, that is unrelated to the mining operations;
- iii) It was observed that ground movements occur rapidly, and many of the younger deposits exhibit a near-elastic response to changes in the groundwater level.

- iv) The periods of greatest settlement usually correspond with pit wall cutbacks that result in a lowering of the exposure of younger deposits in the pit wall.
- v) To date, the measured settlement has not been consistent, or symmetrical, around the Martha pit. The complex geology surrounding the pit is considered to be the main reason for this.

Survey results indicated that settlement Zones 1 and 2 were probably unaffected by mine dewatering related settlement. In Zones 1, 2 and 3, settlements appear to be predominantly controlled by cyclic variation of the soil water content, with some settlement due to mine dewatering in Zone 3.

Settlement within Zones 3 to 7 is due to a combination of any 5 of the causes of settlement previously discussed in the geotechnical summary. Of Zones 3 to 7, Zone 3 is the zone least affected by mine dewatering and Zone 7 is the zone most affected by mine dewatering.

Settlement in Zones 4 to 7 appears to be primarily due to changes in the groundwater level caused by present day mining activities. Survey data indicates that considerable seasonal fluctuations are also present in these zones. The settlement in Zone 7 is primarily due to the combined effects of mine dewatering and stress redistribution within the Milking Cow block cave.

The Milking Cow is an historic block cave feature. Old mine records indicate that this underground excavation is over 300 metres deep, and was extensively mined and backfilled with waste soil and rock between 1910 and 1945. Prior to present day mining, the Milking Cave was visible on the ground surface as a 20 metre deep water filled depression. The approximate location and extent of the Milking Cow is shown on Figure 3

To date, the six-monthly survey results indicate that settlements in Zones 4 to 7, due to mine dewatering, have been rapid, and many of the younger deposits exhibit a near-elastic response to changes in the groundwater level. These movements are expected to be partially recovered when the pit is decommissioned and the pit-lake reaches its final level.

In all settlement zones, differential settlement, unrelated to mine dewatering, can be expected due to the local occurrence of unconsolidated alluvium, fill or rock

outcrops, which respond differently to changes in load, rainfall recharge and surface water conditions.

8.0 One Dimensional Geotechnical Models

Once the soil property data had been collated and analysed, and the soil and rock characteristics identified, work focused on the development of geotechnical models which could be used to estimate settlement and rebound of the ground surface due to operating and decommissioning the Martha pit.

Preliminary one dimensional geotechnical (POD) models were initially constructed for several drillhole locations using :

- a) borehole logs;
- b) geotechnical laboratory data; and
- c) measured piezometric levels.

For all one-dimensional models, the following equation, originally developed by Terzaghi during the 1930's, was used to estimate the settlement of each layer :

$$s = m_v \times t \times \Delta\sigma'_v \quad (\text{Lambe \& Whitman, 1979})$$

The estimated settlements, for all the layers encountered in a drillhole, were summated to provide an estimate of the ground surface settlement.

The values of m_v used in the POD models were selected based on the layer material types, and the mid-layer effective stress, both before and after dewatering. Estimates of the material properties were obtained from the results of laboratory tests.

Once the POD models had been constructed, an estimate of settlement was made using piezometric readings taken in December 1995. These predictions were then compared to the average settlement measured around the drillhole locations by the six monthly surveys. The average difference between the actual and estimated settlement due to mine dewatering was found to be approximately 30%.

Next, the values of material stiffness (m_v) used in the POD models were refined so that the difference between the measured and estimated settlement was less than 10%.

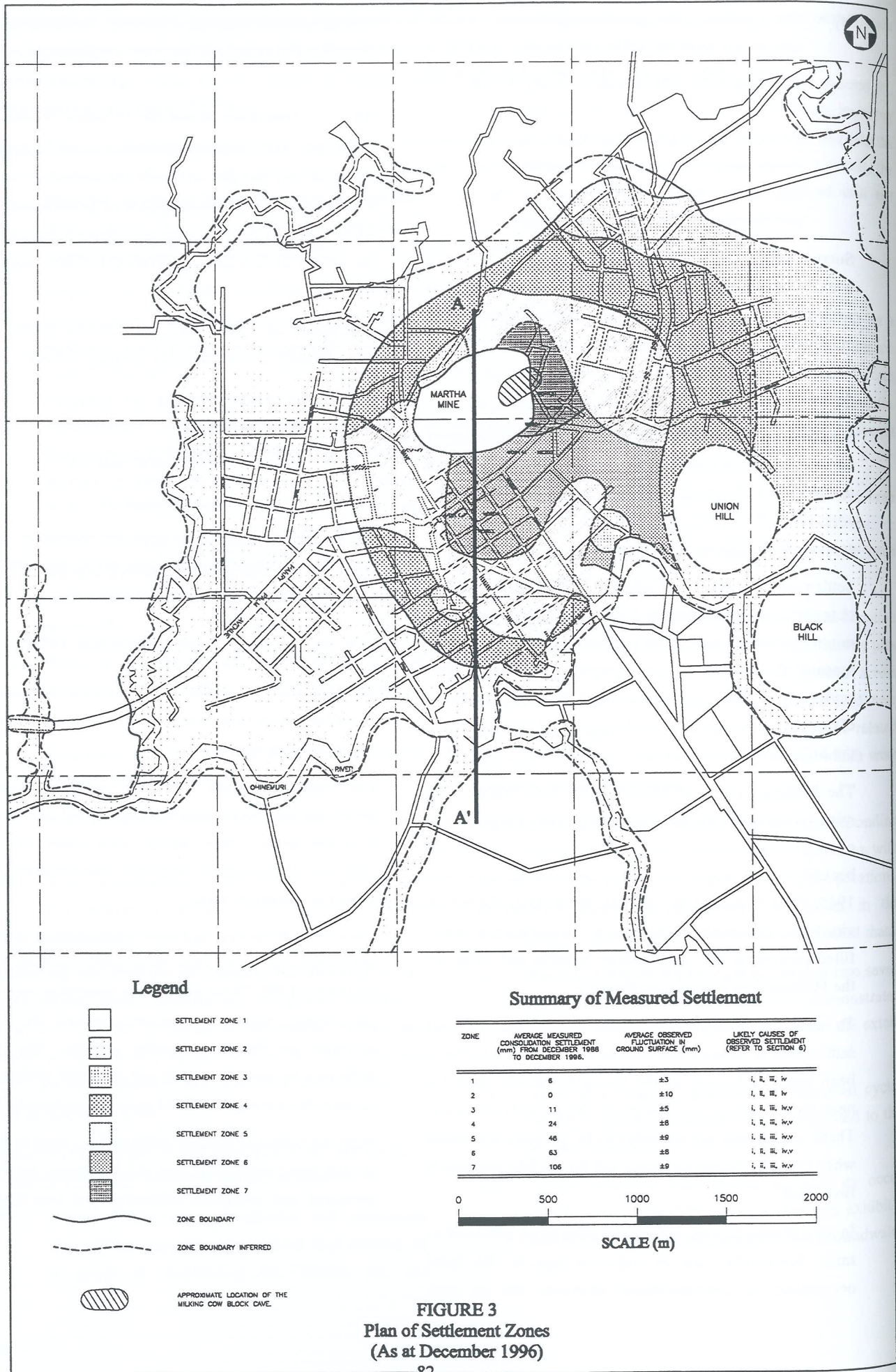


FIGURE 3
Plan of Settlement Zones
(As at December 1996)

Refinement of material stiffness, in general, was limited to an adjustment of $\pm 20\%$ and concentrated on those layers that most significantly influenced the total settlement. The exception to this was when laboratory data from adjacent drillholes indicated that a sample anomaly had occurred. The refined models were known as the refined one-dimensional (ROD) models.

A second calibration was undertaken using the ROD models and additional survey and piezometric data measured in May 1996. The May 1996 piezometric data was keyed into the ROD models to obtain an estimate of settlement. These predictions were then compared to the measured settlement. Differences between the estimated and measured settlements were less than 10%, indicating that reliable models had been constructed. A summary of the material stiffnesses used in the one dimensional settlement models is presented in Table 1.

Table 1

Summary of Material Compressibility.

Material Type	m_v , (m ² /MN) Calculated from Consolidation Test Results.	m_v , (m ² /MN) Calculated from Triaxial test Results.
Fill	0.02 to 0.27	---
Alluvium	0.02 to 7.65	0.01 to 0.23
Boulder Alluvium Matrix	0.01 to 0.08	0.02 to 0.22
Weathered Welded Ignimbrite	0.01 to 0.05	---
Welded Ignimbrite	---	0.00005 to 0.00017
Moderately Welded Pumiceous Ignimbrite	0.005 to 0.10	0.0002 to 0.0085
Unwelded Pumiceous Ignimbrite	0.006 to 0.035	0.002 to 0.013
Moderately Welded Tuff	---	0.0006 to 0.0054
Slightly Welded Tuff / Ash	0.012 to 0.24	0.0014 to 0.019
Unwelded Tuff / Ash	0.01 to 0.25	0.0006 to 0.065
Altered Andesite	---	0.0003 to 0.057

The ROD models were used to predict settlement and rebound of the ground surface at the drillhole locations due to operating and decommissioning the Martha pit. These

predictions were made by feeding an estimate of the appropriate groundwater levels and rebound stiffness into the ROD models. The reload stiffnesses were estimated from the laboratory test results and are summarised in Table 2 in the form of Reload Compressibility Ratios.

Table 2

Summary of Virgin / Unload : Reload Compressibility Ratios

Material	Compressibility Ratio (Virgin m_v / Unload : Reload m_v)
Fill	3 to 9
Alluvium	3 to 7
Boulder Alluvium	3 to 6
Welded Ignimbrite	1
Ash and Tuff	3 to 5
Pumiceous Ignimbrite	3 to 5
Altered Andesite and Andesite	1

9.0 Finite Element Models

A preliminary finite element model (PFE model) of a section through Martha pit and Waihi township was initially constructed using Plaxis and :

- i) Geological cross-section A-A (refer to Figure 2);
- ii) Material data from the refined one dimensional geotechnical models; and
- iii) The groundwater draw-down cones for May 1996.

The selection of the material stiffness, to be used in the finite element models, was very difficult due to the variation in geotechnical properties between adjacent drillholes.

Initially, the average layer stiffness was calculated using all the one-dimensional settlement models. Estimating material stiffness using this method resulted in finite element models which gave an estimate of settlement which was within 40% of the survey results.

A second value of the material stiffness was based on the one-dimensional settlement models of drillholes WC202 and WC206 only. This method gave an estimate of settlement which was generally within 20% of that measured by survey methods.

Table 3 summarises the finite element model material input parameters. For the purposes of the PFE model, a

Mohr-Coulomb type model was selected to represent the behaviour of all material types.

The complex sequence of inter-bedded tuff, ash and pumiceous ignimbrite units; that underlie the welded ignimbrite, is modelled by two layers in the finite element model. This simplification was possible because these units have similar geotechnical and hydrogeologic properties, and appear to have a compatible level of dewatering.

A simplification of the geology was unavoidable, as the maximum number of different layers able to be analysed by Plaxis version 6.31, is ten.

Predictions of settlement made by the PFE model were compared to the settlements measured during May 1996. In general, the difference between the predicted and measured settlement was less than 20%.

Table 3

Material Properties Used in the Refined Finite Element Models

Layer Name	C (kPa)	ϕ ($^{\circ}$)	ρ_B (t/m ³)	D_c (MPa)
Andesite	80,000	50	24.0	38,000
Altered Andesite	3,000	42	22.0	300
Moderately Welded Pumiceous Ignimbrite, Ash & Tuff	300	42	16.0	2500
Unwelded to moderately welded Ash & Tuff	200	34	17.0	150
Highly Welded Ignimbrite	120,000	46	22.5	10,000
Boulder Alluvium	10	34	20.0	800
Alluvium	10	28	16.5	20
Fill	10	28	15.0	4.5

Using the PFE model as a base, the two-dimensional groundwater level within the altered andesite, pumiceous ignimbrite and ash layers (initially estimated / interpreted and considered the most variable set of input data) was adjusted to reduce the difference between predicted and measured settlement. This model is referred to as the Refined Mohr-Coulomb Finite Element Model (RM-CFE model).

The RM-CFE model predicted settlements that were generally within 8mm (approximately 10%) of that actually measured.

Finally, more sophisticated material models, that have the ability to model inelastic consolidation and rebound of soil and rock, were constructed. Using the RM-CFE model as the base, a Preliminary Advanced Finite Element model (PAFE model) was developed using advanced mathematical models to model soil and rock behaviour.

Both the RM-CFE model, and the RAPE model, were used to predict maximum settlement due to mine dewatering. This prediction was made by feeding the predicted maximum groundwater draw-down profiles into the finite element models. In general, the magnitude and pattern of settlement predicted by the two models was very similar.

The main difference between the two finite element models was the prediction of settlement within 100 metres of the pit crest. The RM-CFE model predicted approximately 300mm of movement at the pit crest while the RAPE model predicted approximately 150mm. Within Waihi Township, both models predicted approximately 100mm of settlement at a distance 150 metres from the pit crest reducing to 10mm at a distance 1100 metres from the crest of the pit. The results of the finite element modelling are summarised in Table 4.

A prediction of ground surface rebound due to future recovery of the groundwater levels was made using the RAPE model. The RAPE model was used to predict rebound as the RM-CFE model does not have the ability to directly model inelastic rebound.

An estimate of the nett long-term ground surface settlement was made by subtracting the predicted rebound from the maximum settlement.

Due to a lack of survey data near the pit crest, and variability of the fill layer, a detailed knowledge of the site, and engineering judgement, was relied upon to select the finite element model which gave the best prediction of settlement near the pit crest.

Discussions with the WGM surveyors suggested that the predictions made by the RM-CFE model were probably more realistic than those made by the RAPE model. For this reason, the predictions of long-term settlement presented in Table 4, are made using the RM-CFE model.

Upon completion of the geotechnical modelling, a comparison of the predictions made by the ROD, RAPE and RM-CFM models was made.

Table 4
Predicted Settlement and Rebound.

Node Number	Distance Between the Node & Pit Crest (m)	Estimate of Maximum Settlement using the RM-CFE Model (mm)	Estimate of Maximum Settlement using the RAFE Model (mm)	Estimate of Rebound using the RAFE Model (mm)	Estimated Long Term Settlement of the Ground Surface (mm)
629	0	301	153	34	267
663	50	196	122	8	188
697	100	182	114	12	170
731	150	105	95	18	87
765	200	88	81	25	63
799	220	82	79	27	55
833	260	85	86	38	47
867	320	86	81	47	39
901	330	92	84	51	41
935	450	80	72	37	43
969	480	75	68	32	43
1003	520	67	62	27	40
1037	700	37	40	20	17
1071	800	28	31	14	14
1105	825	27	30	13	14
1139	975	17	23	4	13
1137	1075	10	11	4	6
1207	1125	2	2	0	2
1241	1313	>1	>1	0	>1
1275	1500	>1	>1	0	>1
1309	1600	0	0	0	0
1343	1700	0	0	0	0
1377	1800	0	0	0	0
1411	1900	0	0	0	0
1445	2000	0	0	0	0

Predictions made using the refined finite element and one dimensional models were of the same order, and were generally within 20% of each other. The finite element models usually predicted less movement of the ground surface than the one dimensional models.

10.0 Conclusions

- 1) The magnitude of dewatering related settlement is low compared to that measured at other sites in

New Zealand and the United States. Monitoring has shown that dewatering of the Martha Pit has not adversely affected buildings or services within Waihi Township.

- 2) The geology and hydrogeology of Martha Mine and Waihi Township is extremely complex with closely inter-bedded layers, confined hydrogeologic systems and perched water tables.

- 3) The measured settlement, to date, has not been consistent, or symmetrical, around the Martha pit. The complex geology surrounding the pit is considered to be the main reason for this.
- 4) Settlements, in each of the seven settlement zones identified to date, are attributed to a combination of five processes of consolidation. Only one of the five processes of consolidation is directly related to current mine dewatering.
- 5) Graphs showing actual settlement against time indicate a progressive, staged settlement that occurs as the pit geometry is altered, exposing the younger geologic deposits in the Martha pit wall at a lower elevation. This allows dewatering of the younger deposits to develop to the level of the units exposure in the pit wall.
- 6) To date, settlements have occurred rapidly, and many of the younger deposits exhibit a near-elastic response to changes in the groundwater level. These movements are expected to be partially recovered, due to rebound, as the pit-lake reaches final level. Full recovery of settlement is not expected due to the altered groundwater regime and unrecoverable consolidation of the affected geologic units.
- 7) Acceptable levels of differential settlement and tilt are predicted by the finite element models.
- 8) Understanding of the following was essential for the successful prediction of settlement at Waihi:
 - Identification and quantification of all the causes of settlement present in Waihi.
 - Thorough research of historic mine features, both above and below the ground surface, and property use histories.
 - Detailed understanding of the geology and hydrogeology of Waihi.
 - Detailed understanding of the soil and rock geotechnical characteristics.
 - Excavation and dewatering history of the Martha Pit.
 - A summary of the measured settlements.
 - Historic Rainfall and weather patterns for Waihi Township.
 - Most importantly, how all the above were related, or connected, to each other.
- 9) Due to the complexity of the issues, it was imperative that thorough field observations and note keeping was undertaken. An understanding of the problem took several months to develop, and seemingly unimportant details were often later found to be a crucial component of the problem.
- 10) Finite element modelling proved essential when estimating differential settlement and tilt.
- 11) Engineering models are only as reliable as their input data.

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