ANALYSIS OF SUBSIDENCE AT CROWN RD TAUPO; A CONSEQUENCE OF DECLINING GROUNDWATER

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SUMMARY- A recent subsidence bowl that has formed in the Crown-Invergarry Road area of Taupo (Wairakei-Tauhara geothermal field) is interpreted to originate from compaction of a thin elliptical lens of "Post Oruanui Sediments" at about 35 (± 10) m depth, with a minor diameter of about 160m. The local increase in rate of subsidence, which commenced about 1997, but has been more stable since March 2001, is most likely to be caused by a water level decline in the upper-most groundwater aquifer, resulting in drainage of a lens of highly compressible mudstones or embedded cavities. The most likely future scenario predicts that the duration of the anomalous subsidence rates will be another eight years, adding approximately 150% to the existing accumulated subsidence. Since 1997 this has reached a maximum of 0.25 m near the centre (RM59), causing 1.8 mrad tilt at about 80 m radius, and curvatures of +0.05 mrad/m near RM59, and -0.035 mrad/m at the bowl's edge. Predicted accumulated curvatures, using reasonable future scenarios, are generally well below building code tolerances. Properties that are about 100m to 140m from the centre of the bowl will probably experience the greatest extensional curvature effects which may cause minor distortion to rigid structures.

1.0 INTRODUCTION

Subsidence has been known to occur within parts of the Wairakei-Tauhara geothermal field (e.g. Wairakei Valley, Spa Hotel and Rakaunui Road subsidence areas) as a result of drainage of highly-compressible mudstone formations (mostly Upper Huka Falls Formation). This type of subsidence is generally more widespread and gradual (than tomo formation, for example) because of the depth of compaction (typically 100-200 m) and the slow rate of drainage. These Wairakei-Tauhara subsidence bowls have been in existence for many decades and have been well studied (eg Allis 2000, 2001). Rates of subsidence have risen gradually to a peak and then declined (Figure 1). The cause of the subsidence is linked to production-induced pressure decline in steam-filled aquifers underlying the compressible mudstones. The maximum accumulated subsidence in the Wairakei Valley bowl has been about 15 m, and rates reached a peak of 490 mm/yr in the 1970s. Tilts on the eastern side of the bowl (about 200 m radius) peaked in the late 1970s at about 3.8 mrad/yr (0.2°/yr) and horizontal movements peaked at about 150 mm/yr. Surface effects included formation of a pond in Wairakei Stream, appearance of some surface cracks at the outer edges of the bowl (during the 1970s), gradual deformation of drains, steam pipelines and transmission lines (which require regular adjustment) and tilting at the Wairakei Resort swimming pool (Bloomer and Curie, 2001).

The subsidence bowl that has developed at Crown Road in Taupo has quite a different history. In our view, the depth and cause of compaction are also quite different, and here we differ from the SKM (2003) model for the Crown Road bowl which assumes predominantly Lower Huka Falls formation compaction (at ~200m depth) resulting from deep reservoir pressure drawdown.

2.0 CROWN ROAD SUBSIDENCE BOWL

A new subsidence bowl has been developing near the junction of Crown and Invergany Roads since about 1997. It was first recognized after the 2001 levelling survey. Between 1987 and 1997 rates of subsidence on RM59, a benchmark near the centre, had averaged about 11 mm/yr, similar to background rates at other benchmarks in this area (7 mm/yr). Between 1997 and 2001 (~4 years), rates at RM59 increased to *60* mm/yr. For the next two years (2001-2003) rates stayed about the same, fluctuating between about 57 and 77 mm/yr (Energy Surveys, May 2003). Rates therefore appear to have levelled off, and it is inferred that the duration of the Crown Road event is likely to be shorter than the Wairakei event (Figure 1).

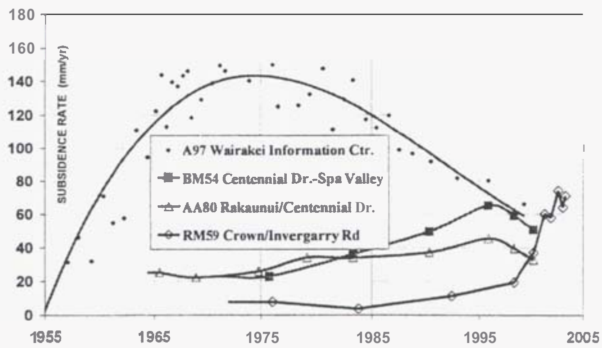

Figure 1. Subsidence rates, in mm/year, for key benchmarks in the main subsidence areas of Wairakei and Tauhara. Rates are plotted at the middle of the time interval between consecutive surveys. Scatter is attributed to uncertainties in survey levels and timing.

These differences, the late commencement of the Crown Road subsidence, plus the shape of the bowl, as determined from repeated surveys on closely-spaced marks, suggested a different source depth and hydrological explanation for this compaction event. An analysis of the local subsurface geology and hydrology with respect to possible compacting layers near **RM59** concluded that the compaction was occurring within a thin lens of highly compressible mudstone, or cavities, in the Post Oruanui Sediments Formation (Bromley, 2003). The lens is estimated to be about **160** m to **200** m in diameter, **10** m to **15** m thick and at about **35** ± **10 m** depth. It is probably capped by a thin, hard-pan. **A** *summary* of the geological information from boreholes surrounding the Crown Rd area, as presented in Table 1, supports this conclusion. The cause of this relatively recent compaction event **was** concluded to be drainage of the lens as a result of a long-term decline in upper groundwater level, accentuated by a deficit in rainfall

Table 1 Geology of Crown –Invergarry Rd area

Formation Name	Age YrsBP	Perm-eability	Crown Rd Predicted Top m-asl	THM1 Actual Top m-asl
Taupo Pumice	2-10k	High	443	454
Post Oruanui Sed.	10-23k	Low	415	430
Wairakei Breccia	23k	High	400	416
Upper Huka Falls	>23k	Low	370	370
Mid Huka Falls		High	325	1313
Lower Huka Falls		Low	225	215
Upper Waiora		Low	175	153
Lower Waiora		High	-225	
Wairakei Ignim.	330k	?	-625	

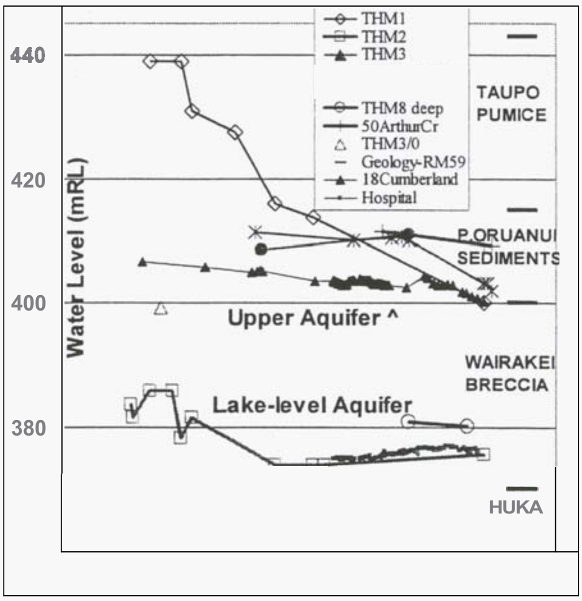

Figure 2. Tauhara water level changes (reduced levels), and predicted geology at **RM59** (Crown Road). These show that ***upper*** aquifer declines since **1995** have probably drained the Post Oruanui Sediments near **RM59**. The lower ***lake-level*** aquifer has remained relatively stable since **1980.**

recharge since **1997.** Evidence fkom historical and recent water level data in nearby bores is shown in Figure **2. A 1996** to **2002** gravity change at **RM59** of **-55** pgal (Hunt et al, **2003) is** also consistent with a local groundwater level decline of about **7** meters.

The decline in upper groundwater level (hosted in the Wairakei Breccia formation) is mostly attributed to discharge from shallow domestic or commercial hot water bores in the northern suburbs of Taupo. Many of these bores have internal down-flowing discharges linking the upper with a lower lake–level aquifer. Other reasons for the decline may relate to reduced shallow recharge or increased natural downflows through fractures. Pressures in the underlying 'lake-level' groundwater aquifer (hosted in the Mid Huka formation) have not decreased over the past **15** years. Neither have the pressures in the deep geothermal aquifer at Tauhara. In fact, they have increased slightly in deep bores TH1 to TH3. ***So,*** there is no evidence that deep geothermal fluid extraction at Wairakei has had a direct effect on the recent subsidence event at Crown Road.

This interpretation differs from the **SKM (2003)** deep geothermal explanation for the Crown Road RM59 local subsidence event, which required:
1) arbitrary thickening of the Lower Huka Falls formation (to about **200m, SKM fig F5);**
2) unsubstantiated local deep pressure drawdown of at least **3** bars between **1980** and **2001 (SKM fig** D12);
3) estimated accumulated subsidence at RM59 between **1950** and **1997** of **0.24m** which was assumed to be all geothermal not tectonic in origin; and
4) an unrealistic step change in deep permeability through a southern 'barrier' during the late **1990's** to account for the delayed acceleration of subsidence.

3.0 MODELLING THE CROWN ROAD SUBSIDENCE

Because the shape of the subsidence bowl at Crown Road is well defined, (Figure 3), modelling of the compaction zone that causes the observed surface deformation can be undertaken using the analytical method of Geertsma **(1973).** This assumes radial symmetry and fits the shape of the steepest side of the bowl (southeast from **RM59),** by varying the radius and burial depth of the top of a cylindrical compacting zone. Rates (in mm/yr) are used and a regional trend of **15** to **25 mm/yr** fust subtracted. The best fit is achieved using a compaction zone of 80 m radius at a depth of **32** to **45 m** (Figure **4).** To the northwest of **RM59** the slope of the bowl is slightly lower suggesting that the edge of the compaction zone may be gradational or that the profile of marks is not at right angles to the contours of subsidence. The interpreted depth of compaction is consistent with the prediction of **35** ± **10** m (Bromley, **2003)** based on geology and hydrology. This implicates the young "Post Oruanui Sediments" and not the deeper Huka Falls Formation.

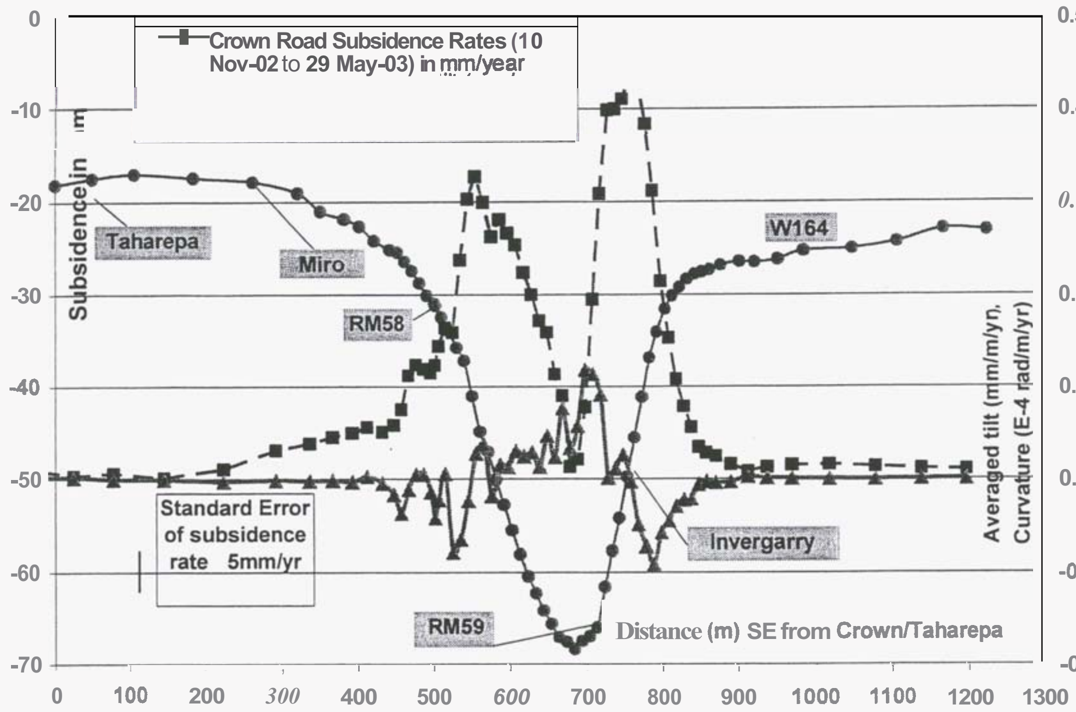

Figure 3. Subsidence profile along Crown Road showing rates (Nov02-May03), tilt magnitudes (3-point average) and calculated curvatures (positive is compressional, negative is extensional).

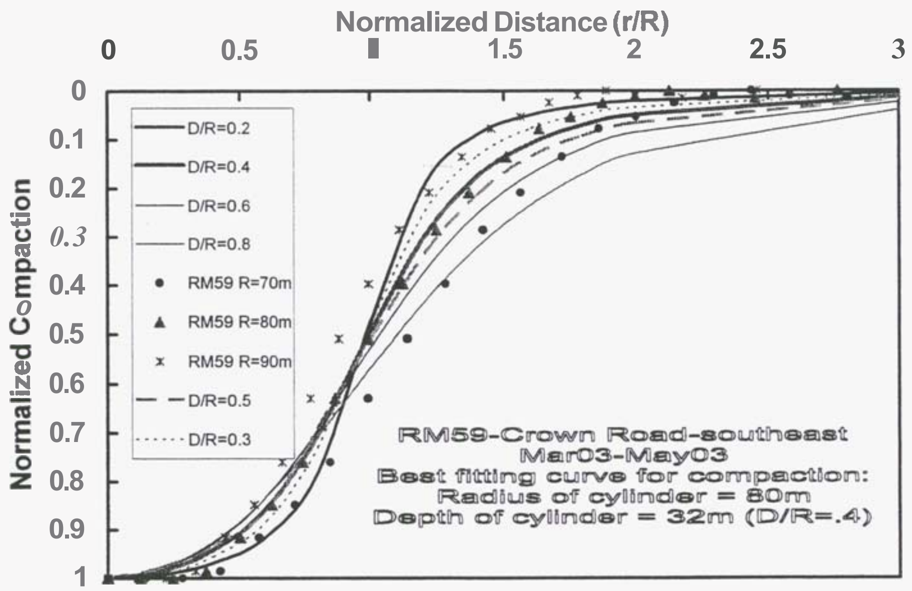

Figure 4. Fit of modelled and observed Crown Rd subsidence bowl shape (south-east of RM59) using the Geertsma (1973) analytical model of a radially symmetric compacting cylinder, of radius R and depth D. Normalised observed level change data are plotted against radial distance, normalised to different cylinder radii R. The best fitting radius is about 80 m and optimum depths vary between 32m and 45m depending on the time period of the subsidence rates.

The source of the 'regional' subsidence of 15 - 25 mm/yr also deserves consideration. These rates have approximately doubled with time across a wide surrounding area of patchy thermal ground, within about 200m to at least 700m of RM59. Without a clearly defined edge to this wider 'regional' component of subsidence it is difficult to determine a source depth. However, the entire area affected is underlain by the layer of Post Oruanui Sediments, 11-17 m thick, as logged in surrounding boreholes. The upper surface of the sedimentary layer is at about 400 m to 430 m. As the piezometric level of the upper groundwater aquifer drops below the level of the mudstones (see Figure 2), these mudstones will drain and could compact as a sheet.

So the mechanism for the 'regional' rate increase may be the same as that for the local subsidence bowl at Crown Road, except that the local feature is compacting more rapidly because of a difference in effective compressibility. This difference might be due to local cavities or to very soft thermal clay lenses interlayered with the mudstone sediments and capped by silicified sands. Drilling logs from THMl and Invergany Road domestic bores reported poor core recovery and drill bit drops (cavities) within the Post Oruanui Sediments sequence. This supports the conclusion that lateral heterogeneity within this layer could account for the different compaction rates.

Fluctuations in shallow groundwater level, typically of about ±1 m, are caused by variations in rainfall recharge (Bromley, 2003). This may locally influence changes in subsidence rates with time, as the effective stress on the draining and compacting formation changes. Likewise, lateral undulations in the upper or lower surface of the compressible layer could locally affect the timing of changes in subsidence rate. Channelling of recharge water could also occur.

4.0 EFFECTS OF CROWN ROAD SUBSIDENCE

Whether the cause of the 'regional' subsidence is shallow or deep, the effects on structures of near-uniform subsidence occurring across a wide area will not be significant, because the changes in tilt and curvature are negligible. However, the effects of the localised subsidence bowl centred at RM59 may become noticeable with time because of the higher tilt rates and curvature (change in tilt with distance). To assess the potential effects of Crown Road subsidence on nearby properties, the survey data set of levels determined by Central Surveys on a neighbouring property was combined with those of Energy Surveys (2003) for three repeated surveys: November 2002, March 2003 and May 2003. To make the surveys compatible, polymer stave scale corrections were applied to some of the data.

Contour maps of subsidence and derived rates were prepared by gridding all the data at 20 m intervals and contouring using Kriging. Figure 5 shows the subsidence rates in mm/yr between November 2002 and May 2003. The centre of the area of maximum subsidence *(65* mm/yr) is located 17 m northwest of RM59, about 70 m northwest of Crown-Invergarry Road junction. Comparison of the November 2002 to March 2003 rates with the March 2003 to May 2003 rates shows that the pattern of compaction is not completely uniform in time, probably because of heterogeneity in the compacting layer or because of local differences in timing of the shallow groundwater drainage effect. However, the location of the shoulder, or edge, of the anomalous subsidence bowl, where well defined along Crown and Invergarry Road curbing, (see Figure 3) has not shifted with time; this suggests that it is laterally constrained by a relatively sharp change in formation properties (effective compressibility and/or permeability) rather than by laterally diffusing pressure changes from a localised downflow of groundwater.

Figure **6** is a contour map of the calculated gradients (tilt changes per year, in the direction of maximum change) as determined at each grid point, from the interpolated grid of level changes. The values range from 0 to 0.5 mm/m/yr (–0.5 mrad/yr or 0.05 %/yr). The most reliable contour values occur along Crown and Invergarry Roads where there is sufficient density of data to accurately differentiate tilt changes. Elsewhere, contours are more uncertain, but the zone of higher tilt values (> 0.2 mm/m/yr) probably forms an annulus surrounding the central zone of maximum subsidence. This annulus has a minimum radius of about 80 m, but is probably in the shape of an ellipse.

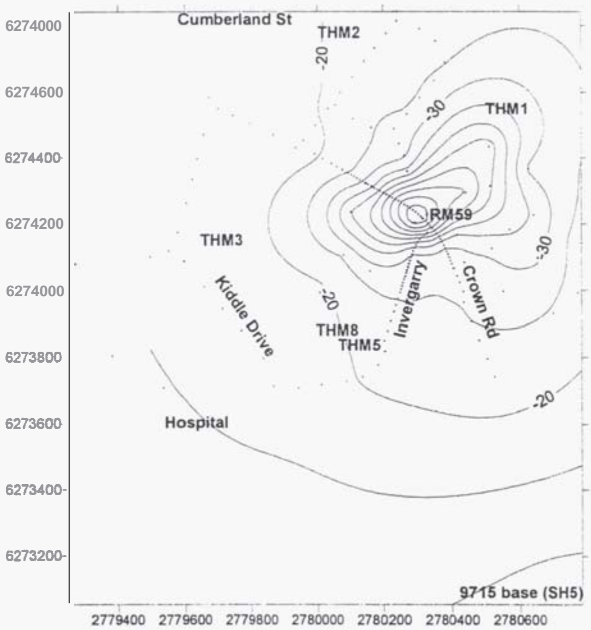

Figure 5. Crown-Invergarry Rd subsidence rates Nov 2002-May 2003. Crosses show benchmark locations. RM59 is near the centre of the bowl. Map is oriented north, and NZ Map Grid coordinates are shown.

Consideration of tilt rates (with time) is important when considering aspects of drainage such as storm water drains, sewers, guttering, or pools, however, the most important factor for assessing the likelihood of damage to rigid structures in buildings is the curvature or accumulated change in gradient across such structures. This is the second derivative of the measured subsidence values. Figure 3 shows these values along the Crown Road profile. Surface curvature (negative=extensional) is linearly related to surface strain rate (Allis and Barker, 1982). Figure 7 shows a contour map of the calculated maximum curvature at each grid point in mm/m/m/yr (~mrad/m/yr). To calculate a maximum curvature or angle deflection, the length of a rigid structure is specified, and the rates integrated over the duration of the subsidence event. The maximum extensional curvature of up to -0.01 mm/m/m/yr occurs at the 'outer' edge of the bowl about 100 to 140 m from the centre, as shown along Crown and Invergany Roads (Fig.3). With more detailed data, these contours would probably show a narrow annulus surrounding the bowl, linking the areas of maximum data density. An 'inner' zone of maximum positive curvature (which can cause buckling) occurs within about 30m of the centre, near RM59. (This coincides with fractured and displaced roadside curbing).

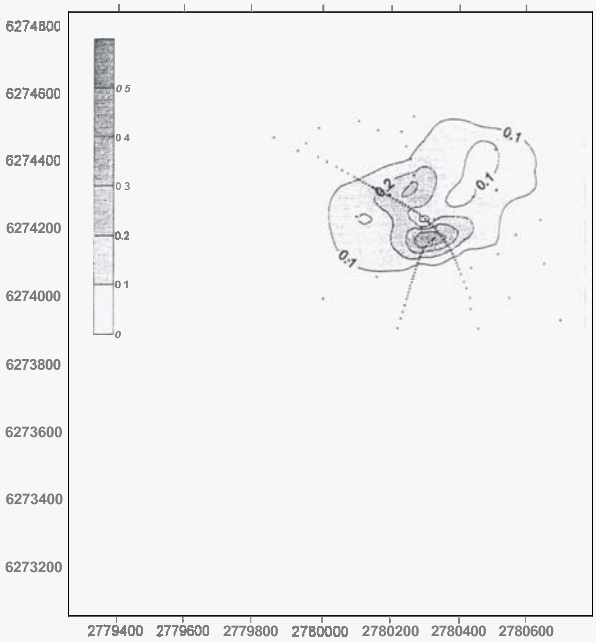

Figure 6. Crown-Invergarry Rd contour map of the magnitude of the subsidence gradient or tilt (mrad/yr), calculated at each grid point from interpolated subsidence rates (fiom figure 5).

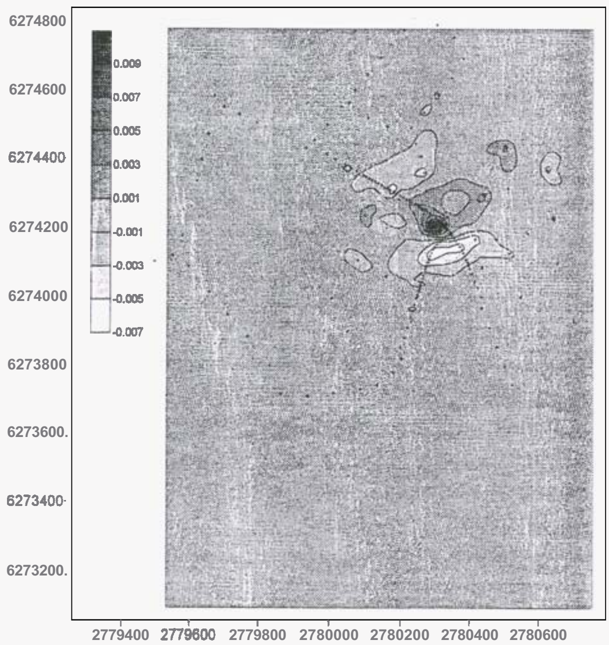

Figure 7. Crown-Invergany Rd subsidence curvature rates (mrad/m/yr), Nov02-May03. These are maximum calculated curvatures **(-ve** = extension), at 20m spaced grid points, from interpolated subsidence rates. Deformation to rigid structures occurs in areas of maximum curvature (+ve or −ve).

Table 2 (Scenario One) lists the observed maximum values of subsidence, tilts and curvature rates in the 'narrow annulus' and compares them with 'typical' values for properties at about 140m to 200m from the centre, and also surrounding 'regional' values (>500m radius). The curvature effects on a 30 m long rigid structure (oriented perpendicular to the slope) are calculated by integrating the observed rates over the period fi-om 1997 to 2003, when rates were rising for 4 years and then approximately constant for 2 years.

5.0 PREDICTED EFFECTS OF FUTURE SUBSIDENCE

Accurate prediction of subsidence trends with time is very difficult during the early stages of an event, but becomes progressively more reliable once rates have reached their maximum and begun to decline. **As** at Wairakei (Allis, 2001), models can be used to match the observed history of subsidence, and pressure changes, by adjusting parameters such as effective permeability, compressibility and thickness of the compacting layer. These models can then be used to extrapolate trends into the future. Near RM59, Crown Road, the history of subsidence and pressure change is not yet sufficient to be able to make reliable future predictions. However, in Table **2,** two scenarios have been constructed as an attempt to illustrate a 'likely' prediction and a longer duration 'pessimistic' prediction. For Scenario Two ('likely') it is assumed that the present rates continue for another two years, then decline linearly over the next six years. This assumption follows the overall shape of the rate changes observed at Wairakei (Figure 1) but scales the duration back by a factor of about 0.25 to account for the relatively shallow origin and thinner compaction zone. For Scenario Three (pessimistic) the present rates are presumed to continue for another 10 years and then decline linearly over the following 40 years. The future duration of the 'event' is therefore 50 years. This coincides with the nominal lifetime of new buildings.

For the most likely scenario, the future accumulated tilt under new structures (built in 2003), at a distance of about 80 m fi-om RM59, would amount to a maximum of 2.5 mm/m (1:400 or 0.25%). The maximum accumulated curvatures would occur near RM59 (+0.07 mrad/m of compressive deformation) and at about 100 m radius fi-om RM59 (-0.05 mrad/m of tensile deformation).

6.0 BUILDING AND STRUCTURE EFFECTS

The curvature predictions detailed in Table 2 should be considered in conjunction with building codes which provide acceptable limits on building deformations. Bloomer and Currie (2001) summarize

Table 2. Crown Road subsidence bowl, observed and predicted rates.

	Scenario One (observed)			Scenario Two (likely)			Scenario Three (pessimistic)		
	Measured: 1997-May2003			Predicted 2003- 2011			Predicted 2003- 2053		
Duration of rates (yrs):	Rising 4, constant 2			Constant 2, falling 6			Constant 10, falling 40		
	Maximum	Typical	Regional	Maximum	Typical	Regional	Maximum	Typical	Regional
SUBSIDENCE			assumed		North			North	
location:	RM59	RM58	SH5	RM59	Invergarry	Kiddle Dr	RM59	Invergarry	Kiddle Dr
Total subsidence (m)	0.248	0.095	0.04	0.35	0.175	0.075	2.1	1.05	0.45
Rates 2002-3 (mm/yr)	70	35	7 *	70	35	15	70	35	15
HORIZONTAL MOVEMENT									
Predicted from best fitting model of compacting cylinder:160m diameter, at ~32m depth, centred 17m NW of RM59.									
radius from RM59:	~80m	~140m	>500m	~80m	~140m	>500m	~80m	~140m	>500m
Horizontal rates (mm/yr)	15	7	0	15	7	0	15	7	0
Accum. Movement (m)	0.05	0.02	0	0.08	0.04	0	0.45	0.21	0
TILTS									
radius from RM59:	~80m	~140m	>500m	~80m	~140m	>500m	~80m	~140m	>500m
Peak Tilt rate (mm/m/yr)	0.5	0.1	0	0.5	0.1	0	0.5	0.1	0
Accumulated tilt(mm/m)	1.77	0.35	0	2.5	0.5	0	15	3	0
Accumulated tilt as ratio	1:560	1:2800		1:400	1:2000		1:66	1:333	
CURVATURE (+or-)									
Outer(-), radius-RM59:	~100m	~200m	>500m	~100m	~200m	>500m	~100m	~200m	>500m
Rate mm/m/m/yr	-0.01	-0.004	0	-0.01	-0.004	0	-0.01	-0.004	0
Accum. -Curv. mm/m/m	-0.035	-0.014	0	-0.05	-0.02	0	-0.3	-0.12	0
Inner(+), radius-RM59:	~30m	~200m	>500m	~30m	~200m	>500m	~30m	~200m	>500m
Rate mm/m/m/yr	0.014	0.004	0	0.014	0.004	0	0.014	0.004	0
Accum. +Curv. mm/m/m	0.050	0.014	0	0.07	0.02	0	0.42	0.12	0
Curvature Effects on 30m Buildings (differences in mm/m or mrad tilt change)									
Accum.-Curv./30m	-1.06	-0.43	0	-1.5	-0.6	0	-9	-3.6	0
Accum.+Curv./30m	1.49	0.43	0	2.1	0.6	0	12.6	3.6	0

*Note: levels were measured relative to BM9715(SH5), then corrected to Aratiatia datum using a rate of 7mm/yr

the situation: "Typical criteria are to limit deflections to span/500 to span/150 (0.2% to **0.7%**). Such sags will result in slopes at the support – for a simply supported beam – of about 0.6% to 2.1% (**6** to 21 mrad). Problems usually only occur when parts of a building move down at different rates. That is, the building foundation or floor does not remain in one plane. This leads to distortion and consequent loss of serviceability".

In the case of a rigid structure, 30 m long, the accumulated future curvature (or change in slope) for the most likely scenario ranges fiom -1.5 to 2.1 mad, at the worst locations (–100 m and –30 m radius). To calculate the accumulated effect on existing buildings, add scenarios one and two. Horizontal strain rates can also be estimated by multiplying the curvature rates by -40m compaction depth (Allis and Barker 1982). The curvatures are much less than the implied building code limits of 6 to 21 mrad (depending on construction type). Even in the pessimistic scenario of a 50 year event duration the worst negative curvature effects could be accommodated by appropriate designs. Likewise, appropriately designed storm-water and sewer service lines should cope with the predicted maximum tilts and level changes in Table 2.

7.0 DISCUSSION

Predictions of accumulated curvature (causing extensional or compressional strain and deformation) are more useful as indicators of possible damage effects than tilt (or "differential subsidence") which has been used in the hazard maps of the SKM (2003)' report to Taupo District Council, and as a basis for LIMS reports on property titles.

Subsidence in the Crown-Invergany Road area is expected to have some effect on nearby properties, particularly those at the centre and around the edges of the local 'subsidence feature, that is, within about 200m of RM59 (see Figure **8** for a perspective view). The most likely scenario is that the event will last about eight years more, and will add a **maximum** of 0.35 m to the existing 0.25 m subsidence (since 1997) at RM59. Accumulated tilt is expected to add a maximum **2.5** mrad to the existing **1.8** mrad, along a narrow band approximately 80m to 120m fiom the centre of the subsidence feature. Accumulated curvatures at the centre and edges of the feature are also expected to add about 150% to the existing (1997-2003) deformation. Effects on building structures are expected to be minor and within existing building code tolerances. The predicted area of minor effects, as shown in Figure **7**, is only about 0.2 km^2 compared with the SKM predicted hazard zone area for this bowl of about 1.5 km^2. (SKM fig **4**-16). This **has** implications for many of the property owners with subsidence notifications in the form of LIMS reports on their property titles.

Although there have been a few local cases of cracks appearing in rigid concrete slabs, driveways and roadside curbing, there are no unequivocal examples

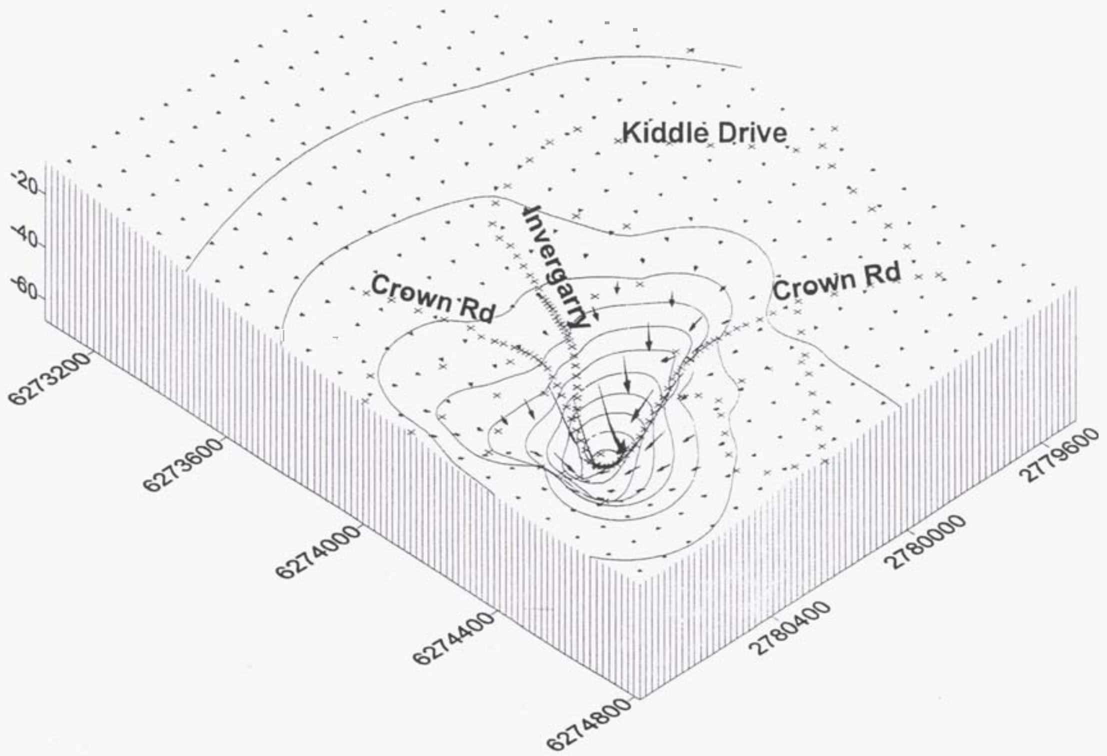

Figure 8. Perspective view **of** Crown/Invergarry Road subsidence bowl **to** the **SW** (from Mt Tauhara), with rates at **5mm/yr intervals** and tilt vectors. Note the period is Nov02 to Mar03 and the vertical scale is 10 to **70** mm/yr.

(to date) of subsidence-induced damage to buildings on Invergany Road properties that lie within the narrow zone of maximum curvature. This provides some reassurance, and supports the prediction that deformation, if it proceeds as expected, is unlikely to cause significant damage to appropriately designed structures in this area.

It is recommended that accurate levelling of existing benchmarks be continued to establish trends in subsidence rates and improve long-term forecasting. Some detailed profiles (20 m intervals) would assist with mapping areas of maximum curvature.

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