EFFECTS OF GEOTHERMAL INDUCED SUBSIDENCE

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SUMMARY – Subsidence is a consequence of large scale geothermal development, although the magnitude varies greatly between fields. Subsidence is not unique to geothermal fields: it is common where fluids (oil or water) are drawn fiom aquifers. The greatest subsidence (measured by both area affected and cost of mitigation) arises fiom withdrawal of groundwater for irrigation or municipal use. Geothermal subsidence can be substantial – many metres – but generally has little practical consequence. Wairakei maximum subsidence is about 15 m, but the effects are relatively slight, whereas much less subsidence at Ohaaki means that the Waikato River may inundate adjacent land and structures. Although the subsidence may be relatively large (tens or hundreds of millimetres per year) because it occurs over distances of kilometres, specialised survey techniques are required to measure it accurately.

1. BACKGROUND : SUBSIDENCE, SETTLEMENT AND TILTING

Subsidence is the phenomenon when the whole ground surface moves down, not necessarily evenly. It occurs over wide areas – kilometres or tens of kilometres across.

Settlement is a local effect, when a structure sinks into the soil under self-weight. All structures do this to a greater or a lesser extent. Differential settlement occurs when the structure settles in a non-planar manner. Such settlement causes the greatest structural damage.

Tilting may result from subsidence or fiom local foundation settlement. The latter may be due to differential structure loads or to varying soils under different parts of the structure.

Horizontal deformation may be associated with subsidence, particularly if the rates vary greatly over relatively short distances. It may show as ground cracking or it may only be observable through the effects on long structures such as pipelines, bridges or power lies.

2. NON-GEOTHERMAL SUBSIDENCE

Subsidence is not unique to geothermal fields. It is a natural phenomenon associated with consolidation of strata or other geological events. It occurs over compressible strata when fluid – oil or water – is removed. The mechanism is well described in Robertson (1984), Allis (1990), Fielding et al. (1998) and Galloway (2001).

Non-geothermal subsidence is a widespread and costly phenomenon in the United States. It is estimated that 41,000 square kilometres of the US is affected. 80% of the subsidence is caused by groundwater withdrawal, the areas affected and the extent of the subsidence is increasing as use of groundwater increases.

Most damage from subsidence is due to submergence. Differential subsidence causes changes or reversing gradients in streams, canals, irrigation ditches and sewers. For example, at the south end of San Francisco Bay about 44 square km of former coastal land is now below high tide level due to ground water withdrawal.

Mexico City has experienced substantial damage from widespread but irregular subsidence that has resulted from withdrawal of water by drainage and pumping fiom relatively shallow strata. Subsidence up to 9 m has been measured. However, the area has very weak soils and settlement of buildings occurred before subsidence fiom groundwater withdrawal occurred. The Aztecs noticed settlement of buildings as early as the 1300s. Buildings constructed in the eighteenth and nineteenth centuries have settled so much in the weak soils that the ground stories are now almost below adjacent ground level (Viets et al., 1979). Water well casings have protruded over 5 metres as the ground around them has subsided.

Japan, with extensive low, flat, alluvial plains has experienced significant adverse effects from ground water withdrawal induced subsidence. Over 7000 square km have been affected, with 1200 square km now below sea level. 80 km^2 of Tokyo and 100 km^2 of Osaka are now below mean high tide level.

Northern Italy has been similarly affected. In Modena there has been damage to several buildings and historical monuments. As with Mexico City, the subsidence originates at relatively shallow levels and settlement rates vary greatly over relatively short distances.

Some of the greatest subsidence has occurred over oil and gas fields. The city and port of Long

Table 1: International subsidence examples

Country	Location	Fluid tapped	Vertical max	Vertical now	Period	Horizontal	Ref
USA	Long Beach Wilmington	Oil	710 mm/yr ≈ 9 m total	0 or positive?	1938 - ~1960	3 m	1,8
USA	Lost Hills/ Belridge	Oil	400 mm/yr	400 mm/yr	~ 20 yr		1
USA	San Jose	Ground water	200 mm/yr ≈ 9 m total	~ 0	~ 60 yr		2
Mexico	Mexico City	Ground water	450 mm/yr ≈ 9 m total				7 8. 10
Japan	Tokyo, Osaka,	Ground water			1920 -		8, 10
China	Tianjin	Ground water	2.15 m total	0?	1959 -82		9
Italy	River Po delta	Ground water	300 mm/y	0?			8
Italy	Venice	Ground water	200 mm total	0?			8
Italy	Lardarello	Geothermal	27 mm/y (av)	10 mm/y	63 yr		3
Italy	Travale	Geothermal	25 mm/y	20 mm/y	– 25 yr	10 mm/y	4,5
Mexico	Cerro Prieto	Geothermal	120 mm/y				6

References

1. Fielding et al. (1998)
2. Galloway et al. (2001)
3. Dini et al. (1995)
4. Di Filippo et al. (1995)
5. Beinat et al. (1995)
6. Glowacka et al. (2000)
7. Terzhagi (1967)
8. Viets et al. (1979)
9. Quingzhi & Zioujun (1984)
10. Yamamoto and Kobayashi (1984)

Beach subsided at rates up to 710 mm per year (about 40% more than the maximum measured rate at Wairakei). The total subsidence is over 8 m. The major effect has been inundation as the area is flat, relatively low lying and by the ocean: the harbour area is just a few metres above sea level. As horizontal strains are high, there has been substantial damage to pipelines, bridges and other long structures. The 1200-m long Commodore Heins Bridge became inoperable. The Southern Edison power station, at the centre of the subsidence, spends $5M per year on subsidence related costs, primarily pumping and associated work to avoid flooding. Well casings have also been damaged - $20M is one estimate of remedial costs, including raising wellheads to avoid flooding. Recent subsidence at Lost Hills/ Belridge fiom oil removal has been measured as 40 mm in 35 days or about 400 mm per year. That is, similar rates to Wairakei. (Fielding et al., 1998).

3. NEW ZEALAND GEOTHERMAL FIELD SUBSIDENCE

3.1 Wairakei Tauhara Subsidence Rates

Land over the Wairakei geothermal field is subsiding from compaction of underlying strata as those strata drain. Peak measured subsidence rates and total subsidence are very high (over 450 mm per year, totalling 15 m to 2001). Horizontal ground strains, associated with the subsidence, were about 110 mm/y at 250-m radius from the centre of subsidence and about 15 mm/y at 750-m radius (Stilwell et al., 1975). Horizontal movement between 1967 and 2000 is up to 4.3 m. The subsidence has caused some problems with the steam-field operation, particularly during the period of greatest subsidence rates.

Although subsidence occurs over most of the 40 square km of the field, the area of high rates occurs over a relatively limited area. The powerhouse area has negligible subsidence: a few mm per year. Maximum subsidence rates of the highway (SH1) have been up to about 150 mm per year, or a total of about 5 m. The Wairakei Resort Hotel property has subsided up to 4 metres. Tilts are up to about 0.7% at the northern part of the property – closest to the subsidence centre.

Subsidence rates in the Tauhara field (caused by pressure drawdown from Wairakei development) are less, although the total maximum subsidence is about 2 m.

3.2 Ohaaki Subsidence Rates

Maximum subsidence rates at Ohaaki are similar to those at Wairakei, although the total subsidence is much less. Ohaaki has been developed for about 13 years (Wairakei 43 years) and fluid extraction rates are lower. Like Wairakei, the area of major subsidence covers a relatively small area.

As with non-geothermal subsidence, the greatest non-operational adverse effect at Ohaaki results from inundation by the Waikato River, which runs through the field.

Table 2: Subsidence in New Zealand Geothermal Fields

Field	Rate [mm/yr]	Total	Sensitive structures	Effects
Wairakei	>450	>14 m	Long pipelines Steamfield structures Streams Wells Roads	Removing/adding steam main sections Sliding joints in the main drain . Ponding of Wairakei Stream Casing damage Tension cracks
Tauhara	100	2 m	Large buildings	None observed
Ohaaki	500 (>100 mm over an area of 1.5km²)	3 m	Land and structures near the Waikato River Pipelines Wells	Threatened by rising river levels Pipelines stretching and compressing Wells damaged
Kawerau	30 (field) (>10 mm ≈ 5km²) (mill)	>0.8 m 0.35 m	Paper machines	None specific to geothermal subsidence

3.3 Kawerau Subsidence Rates

Subsidence at Kawerau is an order of magnitude less than that at Wairakei, although it started developing at Kawerau about the same time. However, the mass withdrawal rate at Kawerau is much less and deep reservoir pressure changes have been small.

However, the paper mill situated over the middle of the field has sensitive machinery: tolerances for setting up the machines are about lmm across the 7-m wide rolls. Hence relatively small tilts require re-levelling of the machines. Stilwell et al (1975) identified this as an important issue possibly limiting further development of the field.

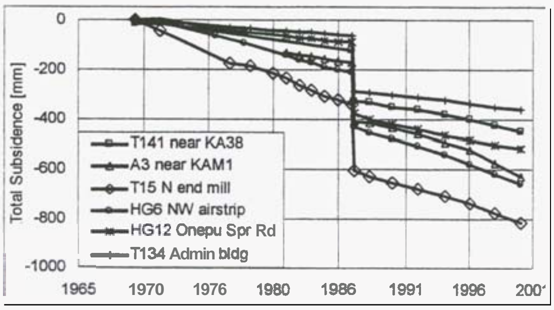

Figure 1: Kawerau geothermal field cumulative subsidence

The marked effect of the 1987 Edgecumbe earthquake is apparent on Figure 1. The subsidence during the earthquake was similar to all geothermal subsidence up to that time. Damage from the earthquake was substantial – not from the subsidence, but from the seismic shaking.

4. TYPICAL EFFECTS

Subsidence per se may not cause any damage and may only be observable using precise survey techniques. However, relatively slight subsidence may cause major problems in flat low-lying areas near a water body. Around 200-mm of subsidence at Venice in Italy has caused significantly increased flooding at high tide with consequent risk of damage to buildings.

Effects, and more particularly the cost of remediation, are hard to evaluate. In one case, estimates of economic losses ranged from 'nominal' to US$100M (Viets et al, 1979).

4.1 Inundation

Effects are seen most dramatically near the sea or lakes. In the United States, the cost to remedy this subsidence is very high with most of the cost' (85%) going to construction of levees. Other costs include pumps, water well repairs, re-grading sewers and relocating and lengthening bridges (Galloway et al., 2001).

Costs fiom flooding during an extreme storm event – the risk of which is increased by subsidence – may be very high. Predictions of such costs in the Houston-Galveston area are many billions of dollars.

4.2 Building and Structure Effects

Building codes typically provide limits on building deformations. These are based on movements of floors and beams under loads. If sags are excessive, building components will distort, leading to reduced function (doors will stick, for example) and unsightliness (cracks in wall linings). Long spans may also cause excess dynamic deflection, which may cause discomfort for occupants – even though strength may not be compromised. 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%.**

If a building subsides at the same rate as the supporting soil (as distinct fkom settling), the effect may not be noticed. Similarly, if a building tilts uniformly, damage is unlikely to occur and the tilt may not be noticed. Exceptions include tall buildings and structures such as pools. In a pool the surface of the water remains level, so if the pool tilts, freeboard will be less at the down tilting side. In the extreme case, the pool would overflow.

Apart fkom these particular cases of tilting, 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 – cracking of components, leakage, unsightliness, etc.

Despite buildings at Wairakei being in areas of significant tilt (about 0.7% or 1:140), little damage is obvious. Examples are the 'log cabin' at the Wairakei Resort (built before 1958) and the Information Centre.

4.3 Well Effects

Subsidence **has** caused damage to oil, water and geothermal wells. Water wells have been pushed out of the ground as the ground subsides. At Mexico City, some wells protrude ftom the ground by over **5** metres.

4.4 Tauhara, Wairakei and Ohaaki Subsidence Effects

Inundation: The most serious effect at any of the three fields is possible inundation **of** the Ohaaki Marae fkom the nearby Waikato River. Other land and structures are similarly affected. The Wairakei Stream, where it passes through the area of maximum subsidence at Wairakei, has formed a small lake.

Effects on Station Operation: Structures, Pipelines, Drains, Wells: The operations of the Wairakei and Ohaaki steam-fields have been affected by subsidence. In both cases the powerhouse is located in an area of low subsidence and has not been adversely affected.

Despite large subsidence and tilts of various steam-field structures, damage has been relatively slight and the repairs required are straightforward. The steam vents at Wairakei are near the edge of the subsidence bowl but no damage has occurred – this **is** to be expected, as the structure is squat and stiff. Separation Plants 1 and **2** at Ohaaki have tilted significantly; about **3%** across and 1% along SP1, for example. The result has been minor spalling of concrete at joints.

The effects are most noticeable on long structures, such as pipelines, drains and power lines. Stretching **and** compression **of** pipelines in both fields has made it necessary to remove sections **of** pipe – in areas of compression – to realign the pipeline with its supports or to prevent over-rotation of bellows-type expansion joints. In other areas, sections of pipe have been added. This is a continuing process as subsidence continues. Curvature of the pipelines has not required remedy (Figures 2 and **3).**

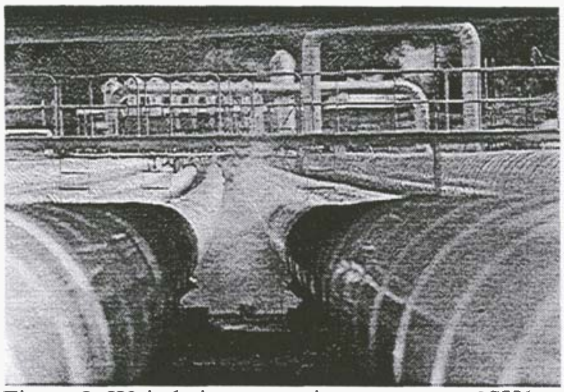

Figure **2:** Wairakei steam mains, upstream of SH1 bridge

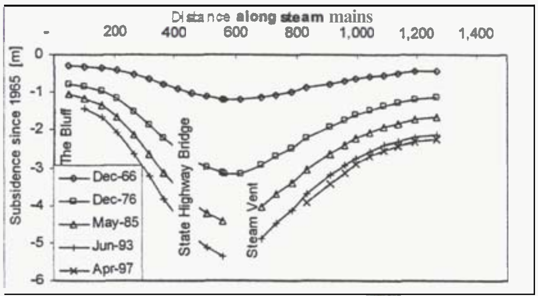

Figure **3:** Wairakei steam mains subsidence

The concrete, separated water drainage channel at Wairakei has been damaged by compression at the edge of the subsidence bowl (Figure **4).** It has been repaired and the effect mitigated by incorporating sliding joints where the drain **drops** down to the Wairakei Stream. Repairs were first carried out in 1967, **an** additional joint was constructed in 1979; since then no further work **has** been required.

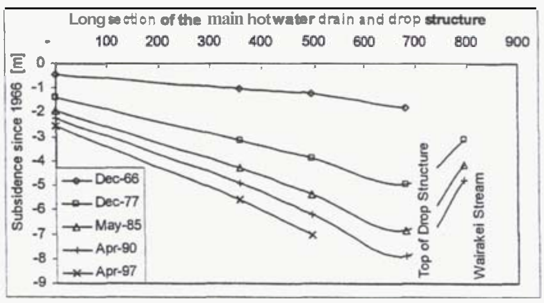

Figure **4:** Wairakei main drain subsidence

Recent horizontal movement is not obvious, but vertical curvature of the drain is apparent as submergence and re-emergence of the central dividing wall. The lower horizontal sections of the drop structure tilt back into the slope. Both effects are consistent with the measured subsidence.

Wells at Wairakei and Ohaaki have been damaged in greatest subsidence areas, as the compression of the draining aquiclude has been transferred into the well casings. In some cases resulting in well abandonment. (Bixley and Hattersley 1983).

Power pylons: Two high-voltage transmission lines cross the area of maximum subsidence at Wairakei. (Figure 5). The subsidence of some of the pylons has been extreme. Tilts of some of the pylons have required remediation as the lines are over-tensioned - causing insulators to rotate beyond operational limits. The tilt of Pylon 4, at the edge of the maximum subsidence is about 2.9% across the line and about 2.7% along the line. For the 24-m high pylon, this translates to about one metre horizontal movement at the top.

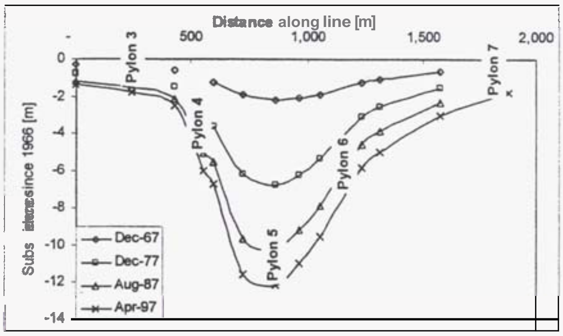

Figure 5: Subsidence along Whakamaru HT line

Roads: Roads constructed to normal New Zealand standards are intrinsically flexible structures. Roads undergo wear under normal use, requiring maintenance. Wear includes compaction of the pavement leading to loss of crossfall (drainage problems) and unevenness (ride problems). Repairing such defects is part of normal road maintenance. Unevenness is a local effect that occurs over distances of tens of metres, so is unlikely to be affected by the subsidence rates and tilts recorded. But it may result from ground strains causing soil cracking that is reflected up into the pavement.

Historically, there have been tension cracks in the pavement of State Highway 1 near the steam mains overbridge (Stilwell et al, 1975). Anecdotal evidence is that subsidence has not required extensive maintenance, despite total subsidence of about 5 metres and tilts of several per cent over the 40 years of Wairakei operation (Figure 6).

Lateral movement of the steam-mains bridge has been up to 40 mm per year, with subsidence of 100 mm per year. Relative horizontal strains south of the bridge are about 10 mm per 100 m per year. Pavement cracking is still occurring adjacent to the steam mains bridge: new surfacing placed about 1994 requires further remediation in 2001. Damage appears as narrow depressions diagonally across the highway, parallel to the bridge abutments. The cause may be sub-surface cracking. The direction of measured horizontal movement is towards the centre of subsidence and approximately perpendicular to the line of the highway.

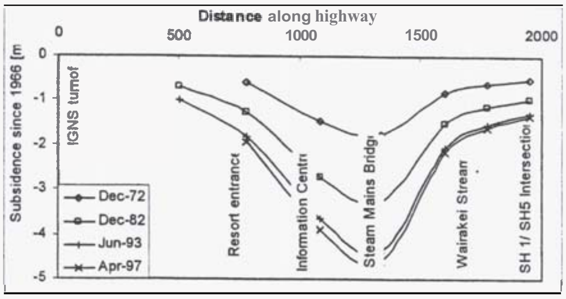

Figure 6: Subsidence of S.H.1 at Wairakei

Swimming pools: The pool at the Wairakei Resort shows signs of tilting – the freeboard is less in the northwest comer. This is consistent with geothermal subsidence in the area a tilt of about 0.7% to the north over 35 years. The pool was built before 1958, as shown by aerial photographs of that date.

Geothermally induced tilt in the AC Baths area is generally to the northeast, typically around 0.001% per year. Assuming a constant rate for 40 years, the tilt is about 20 mm over the diagonal of the Lido pool. Interestingly, the tilt of the shallow arm of the pool is in the opposite direction: the pool is shallower (higher) in the northeast comer. That is, tilt – if any – must be due to causes other than areal subsidence. Tilt of the 20-m pool is in the same direction as the area wide subsidence, but many times greater.

5. CONCLUSIONS

Ground subsidence caused by fluid withdrawal is a worldwide phenomenon. The major cause is withdrawal of groundwater for municipal or irrigation use. Withdrawal of oil has caused similar subsidence, as has withdrawal of geothermal fluids. The consequences can be significant in low-lying areas where drainage systems are altered causing damage and requiring remedial measures costing several hundred million dollars in the US alone. It can also cause damage to wells and to long structures – where horizontal strains arise from the subsidence.

The magnitude of geothermal development induced subsidence varies widely, but can be greater than that caused by groundwater withdrawal. The resultant effects are poorly correlated with the subsidence magnitude. At Wairakei and Ohaaki, with some of the greatest measured subsidence rates, repairs to steam-field structures have been necessary. This is considered a normal operational requirement. Flooding has occurred close to water bodies.

6. ACKNOWLEDGEMENTS

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