SUBSIDENCE SURVEYING

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SUMMARY Subsidence is measured by comparing levels on benchmarks that are derived by survey levelling techniques fkom surveys taken some time apart. Subsidence is usually expressed as annual rates. In New Zealand the geothermal fields at Wairakei-Tauhara, Ohaaki, Kawerau., Rotokawa, Mokai and Ngawha have extensive benchmark networks that are levelled typically every 2 years. NZ environmental regulatory authorities usually require the geothermal field operator to monitor subsidence as a condition of granting resource consents. With the advent of digital levels and using an adaptation of traditional precise levelling techniques high accuracies are efficiently obtained. Significant potential errors in benchmark elevations can be eliminated or mitigated by using suitable equipment, sound procedures, calibration and equipment checking. Subsidence levelling data is also used for gravity surveys and for designing and setting out geothermal engineering projects. Similar survey techniques are used worldwide for monitoring subsidence due to mining and extraction of water and oil.

1. NEW ZEALAND HISTORY OF SUBSIDENCE LEVELLING

Subsidence was first recognised at Wairakei Geothermal field in the early 1960s. Surveys were first undertaken by the then Lands & Survey Dept. and subsequently mainly by the Ministry of Works and its various successors. Surveys are now usually contracted to private survey companies. A *summary* of developed NZ fields and their subsidence survey history is given in Table 1.

Environmental regulatory authorities require operators to monitor subsidence as a condition of granting a resource consent. These requirements can vary between fields. Field operators may monitor more frequently, intensively or extensively than the consent requires to provide a better understanding of the reservoir and as assurance against plant and equipment damage.

Repeat surveys are usually of two types. A full network survey (Type A) covering all benchmarks (BMs) may be undertaken every 6 years with less extensive Type B surveys undertaken in the intervening period. The Type B surveys usually concentrate on the areas of maximum subsidence and or sensitive structures.

2. SURVEY TECHNIQUES

Subsidence monitoring in NZ is undertaken using survey levelling techniques. Automatic or electronic levels are used to measure elevation differences between levelling staves held on temporary BMs (change points). Using a leapfrog method (typically at 70 metres between change points, depending .on terrain), elevation differences between adjacent BMs are derived. The BM elevation difference is often determined in one direction only (ie not double levelled) so long as the level run forms part of a closed circuit of levelling. Levelling rates of around 1km/hr are achievable in easy country. The levelling routes are designed to maximise the number of circuits thus providing redundancy in the data and to avoid the need for double levelling (on hanging lines). Current procedures are a relaxation of traditional precise levelling techniques. These along with digital levels have resulted in substantial efficiency gains.

In some instances precise theodolite vertical angles and measured slope distances are used to compute elevation differences between BMs. This technique is used to cross rivers, valleys or hilly areas where precise levelling would be impossible or too slow. Vertical angles are usually observed reciprocally and simultaneously, ie two observers observing each others position at the same time. The theodolites are set up adjacent and at a similar level to the two BMs. Observations to levelling staves on the BMs are used to determine the theodolite height above each BM. With *care,* elevation differences approaching precise levelling accuracy can be determined using this technique.

3. DATA ADJUSTMENT

The observed elevation differences are adjusted for circuit misclosure using least squares adjustment software (eg. Star*Lev). If the survey extends over a significant latitude range (5-10km) orthometric corrections are applied to the elevation differences. Selected elevation differences eg. those fiom vertical angles, may be allocated different weights in the adjustment. Adjustment weighting may be a function of (a) elevation difference between

Table 1: NZ Geothermal Field Survey History (Currie; 1998, 2000a, 2000b, 2000c, 2000d, 2001a, 200 lb)

Field	Operator	First Survey	No. of Surveys	Current BMs
Wairakei-Tauhara	Contact Energy	1950	62	960
Ohaaki	Contact Energy	1968	26	1020
Kawerau	Connell-Wagner (for Crown)	1970	21	230
Rotokawa	Mighty River Power	1997	3	110
Mokai	Mighty River Power	1984	3	280
Ngawha	Ngawha Geothermal Resource Company	1984	4	250

BMs (b) number of instrument setups between BMs or (c) distance between BMs. The last is usually preferred. If the survey network is made up of many interlocking circuits then large adjustment residuals may indicate gross errors in the data.

Adjusted elevation differences are related to a selected origin BM. The origin will likely be a BM that has shown historical stability and is probably well outside the area of known subsidence. For first time (baseline) surveys the origin BM will be selected on the best available evidence. Subsequent surveys may indicate a more suitable origin BM requiring a datum shift on earlier surveys. More frequent less extensive surveys (Type B) may use a BM as origin that is checked as apart of the more extensive BM network every 6 years. An extrapolated BM value for this origin may be used in Type B surveys. After a Type A survey the preceding Type B surveys origin may be retrospectively adjusted by a constant amount based on the latest data.

Subsidence levelling survey elevations are typically accurate to 3mm√km (km measured fiom the survey origin). The accuracy of subsidence rates increases as the time interval between surveys increases. This is one factor considered when intervals between surveys are set.

4. PRESENTATION OF DATA

BM elevations for each subsidence survey are tabulated in spreadsheets or databases. Elevation changes between surveys are converted to subsidence in mm/yr. These changes are contoured with survey software such as SDR MAP. Contour intervals are appropriately set depending on the range of subsidence. Often contours are edited especially on the edge of the contour model where data may be sparse. Hand drawing of contours is still done in some cases where the BM distribution in the network may produce erroneous computer generated contours. Plans of contours showing change in subsidence between epochs are also used. Contour plans usually show sufficient topographical detail (rivers, roads, pipelines) to provide a geographical reference (Allis et al., 2001).

Selected BMs (usually with a long history) are graphed showing subsidence against time. Often graphs include several BMs to illustrate changing subsidence across a field. Sometimes a cross section or profile of BMs are graphed showing subsidence against distance. Several subsidence epochs may be shown on the same graph.

Subsidence graphs may show geothermal net mass withdrawal on a secondary axis to see if any correlation exists.

5. INSTRUMENTATION

From around 1990 digital precise levels (eg. Leica NA3000) that read bar coded staves became available. Digital level accuracies are similar to optimechanical precise levelling equipment (around 1.5mm√km) but are more efficient with the added advantage of elimination of errors resulting from staff misreading or manual recording defects. Precise levelling, by definition, uses invar levelling staves. These provide for negligible temperature related scale errors (1ppm/°C), which are the main source of errors with alloy staves (24ppm/°C), wooden staves (5ppm/°C) or fiberglass staves (10ppm/°C). Precise invar staves are typically in one section of 3 metres in length with the graduated invar strip held in tension inside a wooden or alloy casing. Folding, collapsible or telescoping staves are a source of systematic errors particularly when aged. Precise staves are calibrated for length scale and base errors by a standards laboratory, often using laser measurements, at approximately 5 yearly intervals. During fieldwork the precise level is checked for collimation error (non horizontality of sight) and the stave bubbles checked (to ensure stave verticality) at regular intervals.

6. SURVEYERRORS

Errors that can affect the accuracy of the final BM elevations are either systematic or gross blunders (Whalen et al, 1977). With appropriate field procedures, calibration and checking, most errors can be eliminated or reduced to acceptable limits. Gross errors are summarised as follows:

(a) Levelling staves not on the BM pin.
(b) Misnaming of BM, if this occurs in a baseline survey it may not be discovered until the second survey.
(c) Foresight or forward change plate moved between set ups.
(d) Backsight and foresight observed in wrong order.
(e) Manual recording errors. The use of digital levels has eliminated this error. With older optimechanical levels extra observations (time consuming) were undertaken to detect these errors.

Similarly systematic errors and techniques to mitigate their existence are summarised as follows:

(a) Instrument collimation errors (non horizontality of line of sight). Observe equal sight lengths.
(b) Levelling staves scale error inherent fi-om manufacture. Calibrate by test laboratory. Can also be determined by comparison with calibrated invar staves over a short steep level run.
(c) Levelling staves scale error due to temperature effects. Effect will depend on stave construction material (discussed above in 5.). Measure field temperature and apply correction to observed data.
(d) Levelling stave scale errors due to non-verticality of stave. Stave bubbles regularly checked and staves braced with supporting poles.
(e) Levelling stave zero (or base) error. This constant error can be determined by simply observing each stave fiom the same instrument position. Can be eliminated by always using the same stave to start and finish on the BM in a level run.
(f) Levelling stave joint wear. Not applicable to single section invar staves. Can be determined by measuring the elevation difference between two adjacent points that involves reading across a joint and comparing with that fi-om a single section stave. Difficult and time consuming to apply any resultant error to field data.
(g) Vertical refraction. Can occur in long sloping sight lines especially on hot tarmac surfaces. Keeping sight lines typically more than 0.5m above the ground will reduce the error. This however slows progress on sloping ground as the full length of stave cannot be used.
(h) Slow and imperceptible settling of level tripod or change plate during observation. Can be reduced by careful choice of set up location, firmly set up tripod and well driven suitable change points.

Levelling stave scale errors have the greatest potential impact when the lines levelled have a large elevation difference. Scale errors may well produce levelling circuit miscloses within allowable tolerances (if the same equipment is used) but would result in final BM elevation errors. This may of course lead to erroneous subsidence conclusions.

7. BM DESIGN AND LOCATION

A variety of different types of BMs are used. BMs on structures (eg. Power House floors or pipe supports) are usually a 10-25x70mm diameter stainless steel domed top pin grouted into and just proud of the structure surface. Freestanding BMs may also be placed near the structure to determine any relative structural and country subsidence. Freestanding BMs specifically installed for subsidence monitoring are usually one of two types viz:

1. Poured in situ concrete (typically 400mm dia and 600mm deep) with a stainless pin, name tag and suitably placed marker post.
2. Assembled fiom prefabricated components comprising a 700mm long rod welded onto a base plate of 200mm dia. with a stainless tip all hot-dipped galvanized. This is placed and backfilled then topped with a 400x400x100 concrete slab collar. One or two layers of "U or C" shaped building blocks are placed on the collar and finished with a steel lid set just below ground level. The base of the BM rod is some 1100mm below ground level and independent of the concrete assembly.

Care is taken in placement of BMs to avoid damage fiom erosion, future construction and ongoing public activities. The determining factors for BM survival include thoughtful location, quality of mark, clearly visible marking (painted post and BM tag), location diagrams, horizontal coordinates (sufficient for location) and education of local landowners and area operators. After a number of monitoring surveys BMs become valuable assets.

Once subsidence patterns are identified other existing or new marks may be included in the BM network. For convenience BMs are usually located on roadsides, tracks or along fence lines. They are placed at spacings (typically 300-500m) such that any measured changes can be determined as typical subsidence or local BM disturbance. The subsidence BM network may be part of the original control survey network established in the early stages of an engineering project. The network of field BMs will usually be connected to the national framework of BMs.

BMs are often also used for gravity, topographic and cadastral surveys. BMs are usually coordinated (N & E), sometimes relatively coarsely to 0.5m, for the purpose of plotting and future location prior to a subsidence survey. BMs are sometimes also used as horizontal monitoring marks.

8. USING OTHER DATA FOR SUBSIDENCE ANALYSIS

NZ has one of the best cadastral survey systems in the world. In cadastral surveys measurements for elevation are not usually taken. National standards require a dense framework of quality survey marks. In geothermal areas where sparse or no elevation data exists there is the potential to resurvey old cadastral marks to detect significant horizontal changes. Horizontal vectors of movement between well spaced surveys (tens of years) can be used to determine probable subsidence patterns. DSIR (1988) undertook a similar exercise in the Rakanui Rd. area in Taupo to investigate subsidence where only one BM existed..

In areas of long standing civil structures (eg, concrete kerbs, drains, buildings and transmission lines) subsidence patterns and magnitude can be determined by resurveying engineering design or "as built" data.

These techniques will however only provide total subsidence data and not show how subsidence has changed.

Damage in geothermal fields is more likely to be a result of horizontal changes (that occur as a consequence of subsidence) rather than from vertical changes. However horizontal monitoring surveys have only been undertaken infrequently in some NZ fields. Horizontal vectors can be inferred if the subsidence pattern and magnitude is known. However precise calculation requires knowledge of the geometry of the compaction zone (especially depth). Horizontal surveys are relatively expensive to undertake with costs directly proportional to the number of marks surveyed (unlike precise levelling). Positional accuracies of 5-10mm are achievable with suitable equipment and procedures.

9. OTHER SUBSIDENCE SURVEY TECHNIQUES

9.1 GPS

Although GPS is not used in NZ for subsidence monitoring it may have future potential. GPS vertical accuracies (from differential mode operation) are 2-3 times inferior to precise levelling. The cost of a levelling survey using GPS is proportional to the number of BMs surveyed whereas the cost of conventional precise levelling is proportional to the levelling distance. For this reason the close spacing of BMs along a route (greater than approximately 70 metres) incurs minimal extra cost in a precise levelling survey, once the BMs are installed. For high accuracy, differential GPS requires a number of control (or fixed) suitably positioned BMs. Stability assumptions may have to be made on some peripheral BMs to achieve this.

The cost of high accuracy GPS equipment is much higher than precise levelling equipment. If in the future GPS equipment becomes cheaper and a lower accuracy could be tolerated (eg. in areas of high known subsidence) then GPS may become viable. Use of GPS has the advantage of producing horizontal coordinates and hence three dimensional deformation monitoring would be possible. GPS horizontal coordinates are to a similar or higher accuracy than those derived by conventional means. Conventional levelling would still be required in areas of poor or no GPS reception eg. Power houses.

9.2 Electronic total station traversing

With the advent of electronic total stations (ie. combination of theodolite and electronic distance meter) there is the potential to use precise vertical angles and slope distances to determine elevation differences (Kozlowski 1997). The method has significant efficiency advantages in hilly country where precise levelling is slow (eg some Asian geothermal fields). Sight lengths can be typically 100 metres or more with no need to balance individual back and fore sights between change points. However these should balance between BMs. A matched pair of sighting poles (2-2.5m long) incorporating a survey reflector and a precise sighting target are used. The method is not affected by thermal expansion of the poles. As with precise levelling, the method is independent of the instrument height as only a difference in level between change points is determined. Ample ground clearance on sight lines can be maintained reducing refraction effects. The method could be used to compute approximate BM coordinates fiom observed data.

However the instrumentation is expensive (3 times precise levelling equipment) and is heavier to carry in the field. The availability of suitable data collection software may need addressing before the method gains wider acceptance.

9.3 Synthetic Aperture Radar

This method of subsidence measurement utilises interferometric analysis of SAR (synthetic aperture radar) data collected by (amongst others) the European Space Agency remote sensing satellites. SAR was first introduced in 1974 for topographic mapping. The method has the advantage of not requiring ground access. Many data points can be measured at a small incremental cost. A 20x20m data grid was used in the Californian Lost Hills and Belridge oilfield SAR survey project (Fielding et al., 1998) where subsidence rates of 400mm/yr were measured. No estimation of the systems accuracy was made.

The Californian Landers earthquake in 1992 was mapped by SAR (Massonnet et al 1993) which showed that agreement with terrestrial survey methods of 35mm was achieved. Accuracies of 10mm using artificial targets were reported with an ultimate accuracy at the mm level claimed.

The character of the ground surface being measured may be a limitation to the methods usefulness. Without further research it is not known if suitable satellite "scenes" would be available for NZ. Any likely cost saving over conventional methods cannot yet be assessed. The technique is still under development and partly sponsored by NASA.

10. CONCLUSIONS

Geothermal subsidence has been monitored in NZ since the early 1960's using precise levelling techniques. Digital instrumentation, PC based adjustment software and streamlined procedures have resulted in great efficiency gains in the last 10 years. Potential systematic and gross errors are eliminated or mitigated by using appropriate techniques. Along with suitable equipment and sound procedures, the installation and maintenance of suitable BMs is a key to successful monitoring results. New techniques potentially offer some advantages including three dimensional monitoring of all data points, more rapid surveying in hilly country, frequent remote sampling of many points and access to difficult areas. New technology will only be accepted when it is cost effective.

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12. REFERENCES

Allis, RG., and Zhan, X. (2001) Update of Subsidence of Wairakei-Tauhara Geothermal System. *Report for Contact Energy, August 2001*

Currie, S.A., (1998) Ohaaki Power Station: Subsidence Levelling Survey. *Report for Contact Energy, February 1998.*

Currie, S.A., (2000a) Kawerau Geothermal Field, Subsidence Levelling Survey. *Report for Connell Wagner, February 2000.*

Currie, S.A., (2000b) Ngawha Geothermal Field, Subsidence Levelling Survey. *Report for Ngawha geothermal Resource Company, April 2000.*

Currie, S.A., (2000c) Rotokawa Geothermal Field, Subsidence Monitoring Survey. *Report for Mighty River Power, November 2000.*

Currie, S.A., (2000d) Wairakei Geothermal Field Ground Movement Survey. *Reportfor Contact Energy, January 2000.*

Currie, S.A., (2001a) Mokai Geothermal Field, Subsidence Monitoring Survey. *Report for Mighty River Power, Feb. 2001.*

Currie, S.A., (2001b) Wairakei and Tauhara: Precise Levelling and Horizontal Survey. *Reportfor Contact Energy, July 2001.*

DSIR, (1988) Assessment of development impacts and reservoir resources of Tauhara Geothermal Field. *Reportfor Waikato Valley Authority.*

Fielding, E.J., Blom, RG., Goldstein, RM. (1998) Rapid Subsidence over oil fields measured by SAR Interferometer. *Geophysical Research Letters,* Vol.25, p3215-3218.

Kozlowski, J (1997) Electronic Total Stations are levels too. *Trigonometric workshop notes.*

Massonnet, D., Rossi, M, Carmona,C., Adranga, F., Peltzer, G., Feigl, K., and Rabaute, T. (1993) The displacement field of the Landers earthquake mapped by radar interferometry. *Nature,* Vol 364 p. 138-142.

Whalen, C.T., Balazs, E.I., (1977) Test Results of First order Class 3 levelling, *Surveying and Mapping,* p 45-58.