Surface deformation monitoring at geothermal exploitation: a review and case study of Soultz-sous-Forêts and Rittershoffen sites in the Rhine Graben, France

Gilbert Ferhat[1,2]

[1] Earth Physics Institute, UMR7516-CNRS/University of Strasbourg/EOST, 5 rue René Descartes, 67084 Strasbourg Cedex

[2] INSA de Strasbourg, 24 boulevard de la Victoire, 67084 Strasbourg Cedex

gilbert.ferhat@insa-strasbourg.fr

Keywords: levelling, geothermal exploitation sites, surface deformation monitoring

ABSTRACT

The monitoring of surface deformation at geothermal exploitation sites can be performed using terrestrial and/or space techniques. Terrestrial techniques such as gravimetry and leveling provides accurate measurements but at few specific points (e.g. Ferhat et al 2015, 2016; Hinderer et al 2015, 2016). InSAR provides LOS (Line of Sight) temporal variations not directly or easily convertible into horizontal and vertical deformations. We present a review of surface deformation measured at several geothermal exploitation sites. This deformation were in some cases expected, but also accidental. It is shown the importance of terrestrial measurements such as leveling or GNSS stations for capturing correctly surface deformation, and in particular vertical surface deformation. The two geothermal exploitation sites of Soultz-sous-Forêts and Rittershoffen, located in the Rhine Graben, France are presented. At these sites, repetitions of relative gravimetric and levelling measurements are annually performed on large scale (few km).

1. GEODETIC MEASUREMENT OF SURFACE DEFORMATION AT AND AROUND GEOTHERMAL SITES

Repeated leveling has been used in different locations to successfully determine tectonic and anthropogenic vertical movements. Concerning geothermal systems, previous studies have detected active surface deformation above reservoirs using mainly SAR observations and levelling measurements (Massonnet et al 1997, 1998; Lubitz et al 2013; Heimlich et al 2015) or GPS and levelling measurements (Mossop and Segall, 1997).

Repeated leveling was used to quantify subsidence due to magma injection and exploitation of a geothermal field over a Caldera in Eastern California (Howle et al. 2003).

Using 2008-2011 SAR data and leveling data, Lubitz et al. (2013) could map the uplift of the city of Staufen im Breisgau, Germany. This uplift is supposed to be linked to the disturbance of the existing hydro-geological system. This disturbance is thought to be induced by the drilling in 2007 of seven wells for the geothermal heating of the city hall.

Surface deformation occurred in the city of Landau due to anomalies at the geothermal exploitation site. Several cm of uplift are observed by repeated levelling since 2013 performed by local authorities and also by InSAR (Heimlich et al., 2015).

Eysteinsson (2000) combined repeated leveling surveys and repeated gravity measurements (1975-1999) at the geothermal fields on the Reykjanes peninsula (SW Iceland) to estimate total mass change in the geothermal reservoirs.

2. TERRESTRIAL MEASUREMENT AS CONTROL AND TRUE GROUND DEFORMATION

InSAR time series are along the Line Of Sight (LOS) which are a little different for height variations providing by levelling repetitions. Moreover, these height variations may provide a reference state to better interpret surface deformation providing by InSAR data. Direct comparison is not obvious because levelling is performed on a set of discrete points whereas Insar provides information at a pixel scale. Nevertheless, with some assumptions, comparisons are done (see figure 4 of Heimlich et al 2015).

Gravimetric surveys require precise known height and its variations. Gravity changes Δg due to underground mass redistribution must be corrected for any vertical height change h since we have the following relationship:

$$\Delta g = -2\, g0\, h/a \quad +2\pi\, G\rho h \qquad [1]$$

where g0 is the mean surface gravity, a the mean Earth's radius, ρ the mean density of the crust, and G the gravitational constant.

The first term in right hand side of Eq. 1 is usually called the free air correction and amounts to about – 0.31 µGal/mm; the second term is the effect of an infinite Bouguer slab of density ρ. The sum of the two effects is – 0.2 µGal/mm assuming a mean crustal density of 2670 kg m−3.

Given the typical precision of relative gravimeters (5µGal), a precision a 1-2 cm on the elevation change is required.

3. LEVELING AND GRAVIMETRY MONITORING AT SOULTZ-SOUS-FORETS AND RITTERSHOFFERN GEOTHERMAL EXPLOITATION SITES

In order to monitor the surface deformation around the two geothermal exploitation sites at Soultz-sous-Forêts and Rittershoffen, France. We established a high precision leveling network in May 2014. A large leveling network (about 38 km) surrounding the two sites was observed in May 2014. A small loop (about 3.5 km) around the Rittershoffen site was measured several times in May, June and July 2014. This network is monumented by 43 leveling benchmarks, some theses markers are located close to relative gravimetric sites or some permanent cGPS antennas.

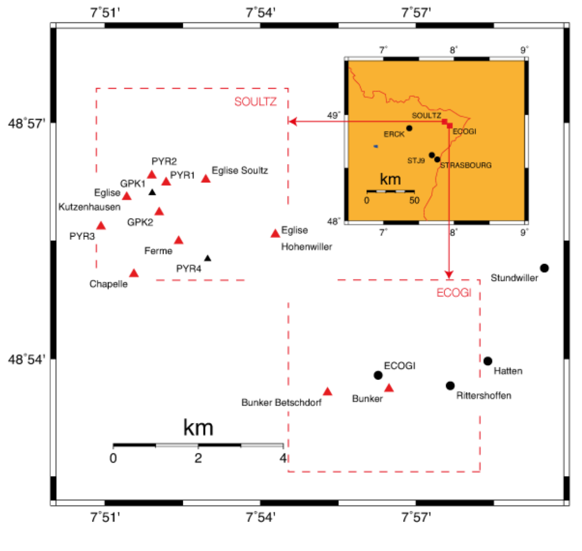

Figure 1: Map of the 6 permanent GPS stations (GPK1, GPK2, PYR4, ECOGI, Rittershoffen, Hatten and Stundwiller) and the micro-gravimetric network of 13 sites (triangles) observed around the two geothermal sites of Soultz-sous-Forêts and ECOGI (Rittershoffen) (NE of France). GPS observations are no more performed at PYR4 site since April 2014).

3.1 Different geodetic techniques for surface deformation monitoring

In order to monitor in the studied area the surface deformation and deep mass redistribution, several geodetic techniques are used:

- Repeated absolute and relative gravimetric measurements (Hinderer et al 2015, 2016)
- InSAR and cGPS measurements (Heimlich et al 2016)
- Leveling observations (this study)

3.2 Leveling network

The leveling network is made of five loops (figure 1). Each loop was observed using a digital level (Leica DNA03 or Trimble DiNi) and standard leveling staff. The leveling lines include some National leveling benchmarks installed by the French Mapping Agency (IGN, Institut National de l'Information Géographique et Forestière) in order to tie the altitudes to the national reference. The loop 5 - surrounding the ECOGI site - was observed several times using the same digital level, but this time using invar staffs. By fixing the altitudes of three leveling benchmarks at IGN values, we computed the altitudes of all other benchmarks. Uncertainties on these altitudes is about 2 to 5 mm.

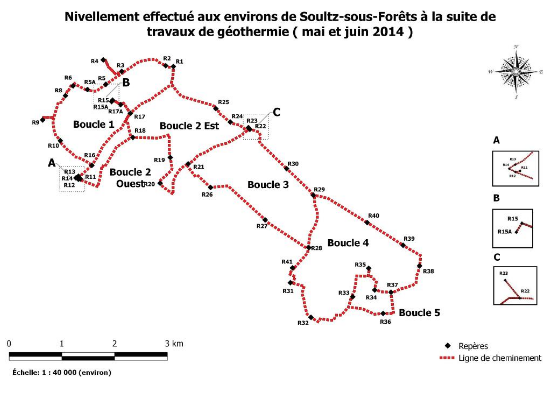

Figure 2: Leveling network around Soultz-sous-Forêts and Rittershoffen co-located in some places with cGPS and gravimetric sites.

With our instruments and field procedures, expected vertical precision are:

- 1 mm/1 km with standard rod
- 0.3 mm/1 km for precise leveling using invar rod

2.1 Co-located sites

In order to better understand potential surface deformation, few gravimetric sites are equipped with cGPS, levelling benchmarks. Table 1 gives a list of the sites.

Table 1: List of collocated sites with cGPS, levelling and gravimetric measurements.

Gravimetric Sitenames	Leveling Benchmarks	Permanent GPS
GPK1 Kutzenhausen	R5	Yes
GPK2 Kutzenhausen	R15A and R15	Yes
PYR4	R19	Yes but until April 2014

All the gravimetric sites are equipped with a levelling benchmark (BM).

3.3 Leveling observation procedure

To mitigate refraction effect, sights were limited to 50 m and rod reading were not performed below 50 cm in most cases.

The mean rod reading in 2014 is 1.4 m and mean sight length is 30 m, with a maximum value of 62 m.

3.4 Least square adjustment of levelling data

If we consider a leveling line between two consecutive benchmarks (BM) i, where i varies from 1 to 54 from a BM-begin and ending to the BM-end, then the difference in height is Δhi.

For any leveling lines, we have the observation equation [2]:

$$H_{j\text{-}end} - H_{j\text{-}begin} = \Delta h_i \quad [2]$$

The set of 54 equations can be written as: A X = B

Where X is the vector of unknowns, B is the observed difference heights.

Each observation equation is then weighted inversely proportional to the length between the two BM.

Using three vertical BM provided with their elevations by the French Mapping Agency (R1, R8, R31 see figure 2), we could compute elevations for all the BM. Uncertainties for the estimated elevations vary from 2 to 5 mm.

3.5 Comparisons of different levelling campaigns in 2014, 2015 and 2016

This leveling network has been surveyed in May 2014 and May 2015 and was recently measured in June 2016.

Differences in elevation between consecutive BM have been computed and are less than few mm (Ferhat et al. 2015).

In order to evaluate the effect of the network geometry, we fixed the altitude of the GPK1 benchmark (R5) (Figures 2, 3) and compute the error transmission for all benchmark using 2014 and 2015 leveling observations (Figure 3).

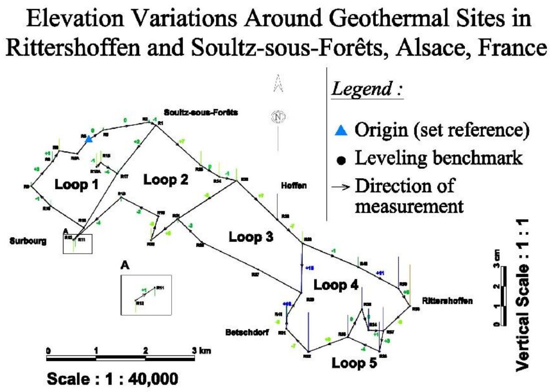

Figure 3: Elevation variations for the period 2014 and 2015 at the Soultz network (Ferhat et al 2016).

Future comparison with 2016 leveling campaigns is about to be analysed.

4. CONCLUSIONS

We present a review of geodetic monitoring of surface deformation at geothermal exploitation sites. The monitoring of surface deformation at geothermal exploitation sites can be performed using terrestrial and/or space techniques. Terrestrial techniques such as gravimetry and leveling provides accurate measurements but at few specific points. The two geothermal exploitation sites of Soultz-sous-Forêts and Rittershoffen, located in the Rhine Graben, France are presented. At these sites, repetitions of relative gravimetric and levelling measurements are annually performed on large scale (few km).

REFERENCES

Eysteinsson, H.: 2000, Elevation and gravity changes at geothermal fields on the Reykjanes Peninsula, SW Iceland, *World Geothermal Congress*, Kuyshu, Japan, May 28 – June 10, (2000).

Ferhat, G., Patoine, V., Clédat, E.: Leveling network for surface deformation monitoring along Soultz-sous-Forêts and Rittershoffen geothermal sites, France. *European Geothermal Workshop*, Karlsruhe, Germany, 15-16 October 2014.

Ferhat, G., Lopez-Barraza, M. I., Clédat, E.: Vertical surface deformation monitoring during 2014 and 2015 using precise leveling around Soultz-sous-Forêts and Rittershoffen geothermal exploitation sites, Rhine Graben, France. *European Geothermal Workshop*, Strasbourg, France, 19-20 October 2015.

Ferhat, G., Lopez Barraza, M. I, Clédat, E., Hinderer, J., Calvo, M., Abdelfettah, Y., Hector, B., Riccardi, U., Bernard, J.-D.: Leveling and hybrid gravimetry monitoring applied to geothermal sites of Soultz-sous-Forêts and Rittershoffen, Rhine Graben, France. *Proceedings of the Joint International Symposium on Deformation Monitoring*, March 30- April 1st, 2016, Vienna, Austria, (2016).

Heimlich, C., Masson, F., Schmittbuhl, G. Ferhat, Geodetic measurements for geothermal site monitoring at Soultz-sous-Forêts and Rittershoffen deep geothermal sites, *Proceedings of the European Geothermal Congress 2016*, Strasbourg, France, (2016)

Hinderer, J., Calvo, M., Abdelfettah, Y., Hector, B., Riccardi, U., Ferhat, G., Bernard, J.-D.: Monitoring of a geothermal reservoir by hybrid gravimetry; feasibility study applied to the Soultz-sous-Forêts and Rittershoffen sites in the Rhine graben, *Geothermal Energy*, 3:16 (2015)

Hinderer, J., Calvo, M., Abdelfettah, Y., Ferhat, G., Riccardi, U., Hector, B., Bernard, J.-D., Littel, F.: Hybrid gravity monitoring of a geothermal reservoir. *Proceedings of the European Geothermal Congress 2016*, Strasbourg, France, (2016).

Howle, J. F., Langbein, J. O., Farrar, C. D., Wilkinson, S. K.: Deformation new the Casa Diablo geothermal well field and related processes Long Valley caldera, Eastern California, 1993-2000, *Journal of Volcanology and Geothermal Research*, 127, (2003), 365-390.

Lubitz, C., Motagh, M., Wetzel, H.-U., Kaufmann, H.: Remarkable Urban Uplift in Staufen im Breisgau, Germany: Observations from TerraSAR-X InSAR and Leveling from 2008 to 2011. *Remote Sensing.* (2013), 5(6):3082-3100.

Massonnet, M., Holzer, T., Vadon, H.: Land subsidence caused by the East Mesa Geothermal Field, California, observed using SAR interferometry, *Geophysical Research Letters*, Volume 24, Issue 8, (1997), 901–904.

Massonnet, M., Holzer, T., Vadon, H.: Correction to «Land subsidence caused by the East Mesa Geothermal Field, California, observed using SAR interferometry, *Geophysical Research Letters*, Volume 25, Issue 16, (1998), 3213.

Mossop, A., Segall, P.: Subsidence at The Geysers Geothermal Field, N. California from a comparison of GPS and leveling surveys. *Geophysical Research Letters*, 24, (1997).

Acknowledgements

This work has been conducted under the framework of the LABEX ANR -11-LABX-0050_G-EAU-THERMIE-PROFONDE, and it is supported by funding from the state managed by the French National Research Agency as part of the Investments for the Future program and by the Région Alsace.