A re-evaluation of gravity changes in the early stages of exploitation at the Yanaizu-Nishiyama geothermal field, Japan

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ABSTRACT

A 65 MWe power plant was built in 1995 at the Yanaizu-Nishiyama geothermal field, Japan, Annual gravity monitoring surveys in the field began in 1994. Another gravity monitoring survey program was started since 1997 to develop optimal gravity survey methods. The observed gravity change shows a rapid reduction after the beginning of production, and very small decrease after three years of production.

Now the method of Principal Component Analysis (PCA) was employed to expand all the observed gravity changes into the time-space domain. The result is as follows: (1) the 1st component of PCA is hundreds of times larger than the other components, (2) the trend of the temporal factor of the 1st component is obviously different between the former survey part and the latter survey part, (3) the spatial distribution of the 1st component has good correlation with the spatial distribution of gravity values. The result suggests that there is a problem in the calibration factors of the gravimeter that used at the surveys. Considering that calibration measurements were made every year during the latter survey, the calibration factor of the gravimeter used in the former survey should be corrected based on the result of PCA. Numerical simulation based on the observed gravity changes has been carried out to constrain reservoir models. The re-evaluated results suggest that a two-phase zone was expanding in the early stages of exploitation at the field and constrain to revise the reservoir model.

1. INTRODUCTION

Microgravity monitoring is a valuable tool for mapping the redistribution of subsurface mass associated with geothermal exploitation. The approach is as follows: Gravity surveys of the field are performed prior to large-scale development to assess the gravity anomaly distribution in the natural state. Then periodic resurveys are performed and comparisons are made with earlier surveys. The purpose is to detect and characterize changes in the gravity anomaly distribution in and around the field as exploitation proceeds (Hunt, 1995; Sugihara and Ishido, 2008). Of course, results of gravity surveys are difficult to interpret quantitatively in an unambiguous fashion if taken in isolation. One promising possibility is to combine gravity-survey measurements with numerical reservoir simulation studies. The synthesis of the two techniques potentially can provide results that would be unobtainable using either technique alone (Hunt and Kissling, 1994, Ishido et al., 1995).

The use of surface geophysical survey methods, such as microgravity and self-potential (SP), to monitor subsurface changes in geothermal reservoirs arising from production and injection operations is attracting increasing attention as an approach to better understand subsurface changes and to provide additional constraints for history-matching studies used to calibrate proposed predictive reservoir models (Ishido et al., 2015). Ishido et al. (2015) presented the results of history-matching studies based upon SP data and microgravity data taken at the Okuaizu field (Yanaizu-Nishiyama geothermal field). Regarding the microgravity data they referred not the data during the early stages of exploitation but the actually observed data between 3rd and 6th year since the geothermal power station commenced its operation. Generally the largest changes occur in the early stages of exploitation (e.g. Hunt, 1995). In the present paper, we will introduce PCA and re-evaluater gravity changes in the early stages of exploitation at the Yanaizu-Nishiyama geothermal field.

2. DATA

The gravity monitoring survey of the field began in September 1994. The survey area was originally about 15 km2 and covered the production zone and reinjection zone with 83 gravity stations. At these stations, gravity measurements and levelling were carried out every year until 1997. In 1997 the gravity network was expanded by the New Energy and Industrial Technology Development Organization (NEDO) to 138 stations, covering a 30 km2 area. The intention was to develop optimal gravity survey methods and noise reduction techniques for geothermal reservoir monitoring (Takemura et al., 2000, Ohta et al., 2001).

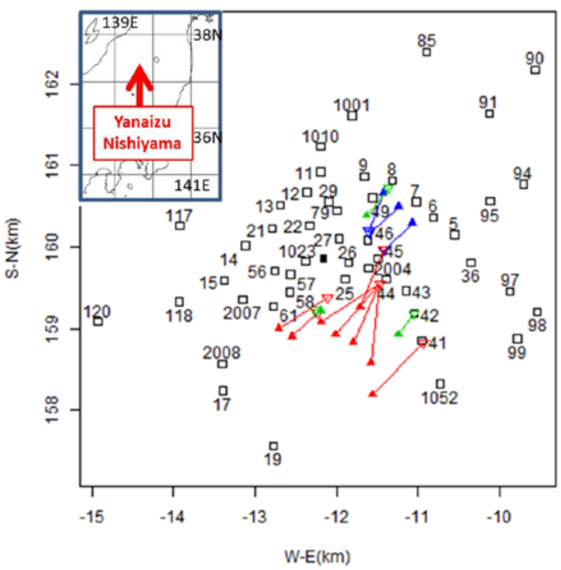

Figure 1: Location of gravity measurement stations. A solid square shows the 65-MW generating capacity Yanaizu-Nishiyama geothermal power station. Red lines are production wells and blue lines are reinjection wells (Saeki, 1999).

In 2002 we carried out an additional microgravity measurements (Sugihara, 2002: Sugihara and Ishido, 2008), however, no microgravity measurements were carried out in ten years since then. Recently another microgravity measurements were planned and relocatable points were selected out of the 138 gravity observation points (Figure 1). Past observed data were reviewed for the selected points and a gap is recognized between the 1994-1996 data and the 1997-2000 data (Figure 2).

Changes in gravity that took place in and around the production and reinjection areas between 1997 and 2000 were well documented and published by the R & D program (e.g. NEDO, 1998, 2001, 2002, 2003). The data between 1994 and 1996, however, have not been published sufficiently. Adachi (2010) indicated the gap between 1996 and 1997 around the injection area.

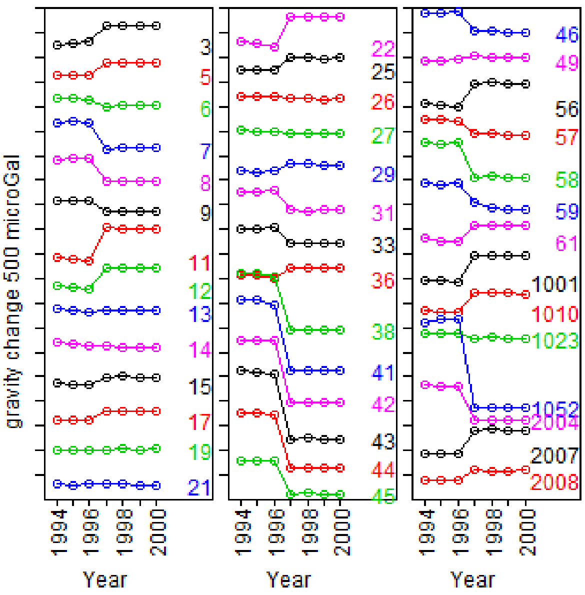

Figure 2: Gravity changes versus time. The data were compiled from NEDO(1998) and NEDO(2001).

3. PRINCIPAL COMPONENT ANALYSIS (PCA)

Principal component analysis (PCA) is a technique usually applied first to find statistical feature of a data set. With PCA, we find generally a few components that can recover a large part of the variations of many variables (Kaizu, 1999). Fukuda et al.(1996) extended the observed gravity changes into two components. Savage (1988) extended the leveling data into two self-coherent sources and the second source is explained as an artifact of systematic error in the leveling.

PCA is known as empirical orthogonal component analysis. We can find a common cause as a component with large eigenvalue in PCA. PCA was employed the data shown in Figure 2. The eigenvalue of the 1st component was determined to be hundreds of times larger than the eigenvalue of the 2nd component, which indicates that the observed variations can be represented by a single coherent source. Figure 3 shows the spatial factor of the 1st component by contours on a geographic map. This figure is quite familiar to us it looks similar to topography of the area. Plotting altitude versus value of spatial factor at each point we can see good correlation between topography and spatial factor (Figure 4). Similarly it is recognized the good correlation between gravity value and spatial factor.

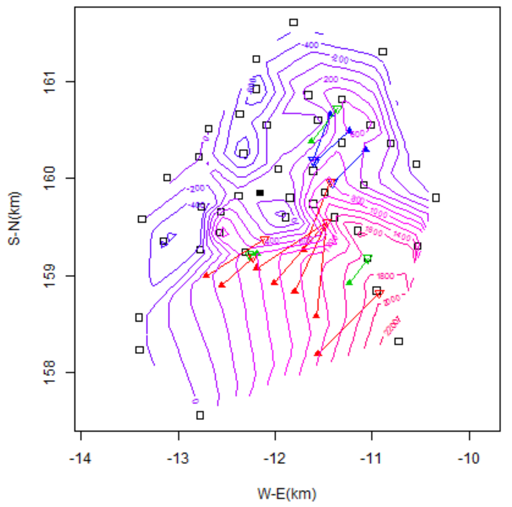

Figure 3: The spatial factor of the 1st component by contours on a geographic map.

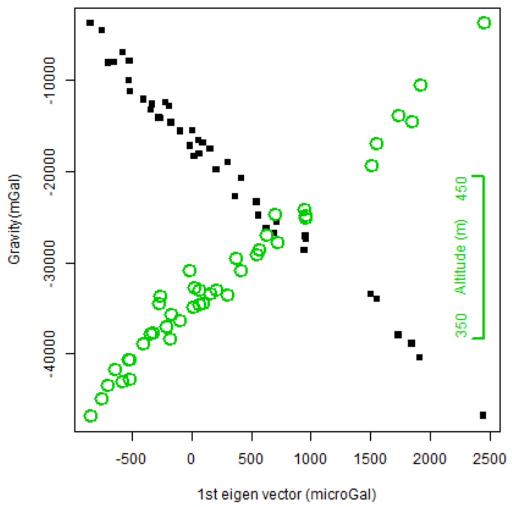

Figure 4: Correlation between gravity value and the spatial factor of the 1st component.

4. DISCUSSION

4.1 Calibration factor of gravimeter

In gravity measurements, a discrepancy among the scale constants of gravimeters used is one of the most essential, important but inevitable problems (Nakagawa et al., 1977). A CG3M gravimeter was used during the gravity survey 1997-2000, and calibration measurements were also made every year (NEDO, 2001). A LaCoste G gravimeter was used during the survey 1994-1996, however, calibration data is absent (NEDO, 1998). Usually a table of calibration factors is given for each LaCoste G gravimeter by manufacture. A number is given for such range that measured in the Yanaizu-Nishiyama field. It is unlikely that no change in calibration has occurred since it was manufactured. Roughly there is linear relation between the true values and the observed values using a poor calibrated meter. Assuming calibration factors PCA was employed to the dataset. Assuming 1.058 to be a calibration factor the results are plausible: (1) the smallest 1st eigenvalue was obtained (Figure 5a), (2) temporal change of 1st component is less step-like (Figure 5b), (3) gravity change smoothly at each point (Figure 6).

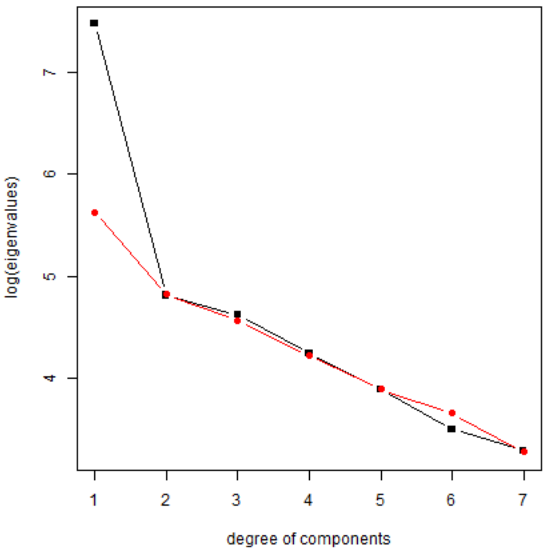

Figure 5a: Eigenvalues found for the principal mode representation. for two cases: (1) original data (black) and (2) revised calibration constant data (red).

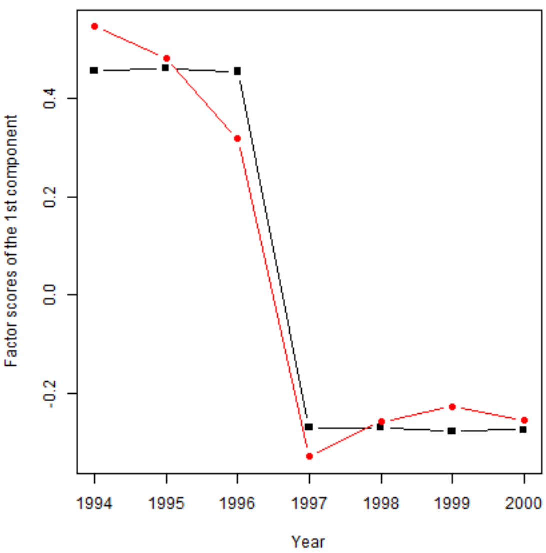

Figure 5b: Temporal change of 1st component for two cases: (1) original data (black) and (2) revised calibration constant data (red). As the factor scores are normalized, components of them show proportional to the temporal factor by a plot as a function of time represented by the first component.

The estimated calibration constant, 1.058, is quite large. Why has it been overlooked? In gravity measurements, a discrepancy among the scale constants of gravimeters used is important especially when a difference of gravity values among the measuring stations is large. The range of gravity values, however, is relatively small in the Yanaizu-Nishiyama area. At a base observation point measurements were made many times and temporal variations due to tidal effect could be observed. In 1994-1996 tidal correction was made using Longman's (1959) formula (amplification factor = 1.16), which is widely used for gravity surveys (NEDO, 1998). In Japan, however, 1.20 is more suitable for the amplification factor (Nakagawa et al., 1977). The difference between 1.16 and 1.20 might cancel the error due to calibration problem.

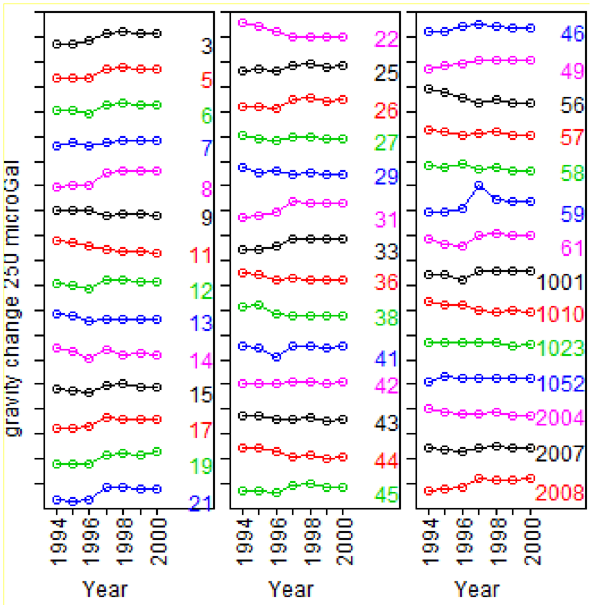

Figure 6: Calibration constant was corrected. Gravity changes versus time.

4.2 Re-evaluated gravity changes in the early stages of exploitation at the Yanaizu-Nishiyama geothermal field

Now we can re-evaluate gravity changes in the early stages of exploitation (1994-1996) at the Yanaizu-Nishiyama geothermal field using the new calibration factor. Spatial pattern of gravity changes around production zone and/or reinjection zone are observed (Figure 7). Some short-wavelength patterns, however, were also observed.

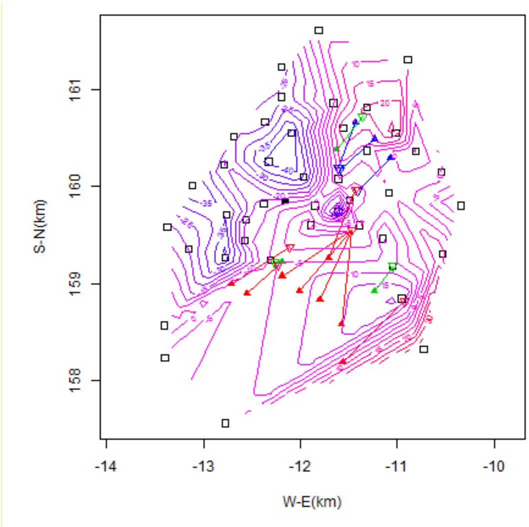

Figure 7a: Re-evaluated gravity changes 1994-1995.

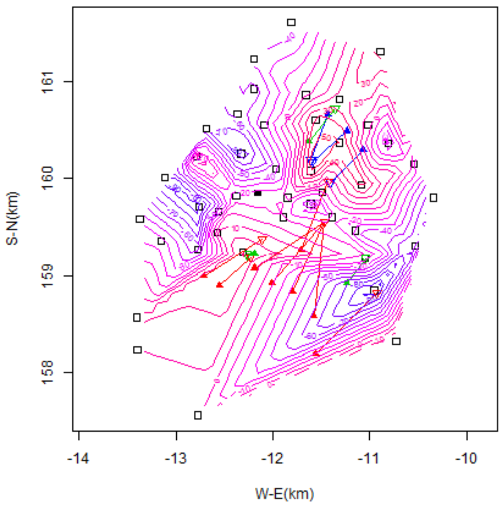

Figure 7b: Re-evaluated gravity changes 1994-1996.

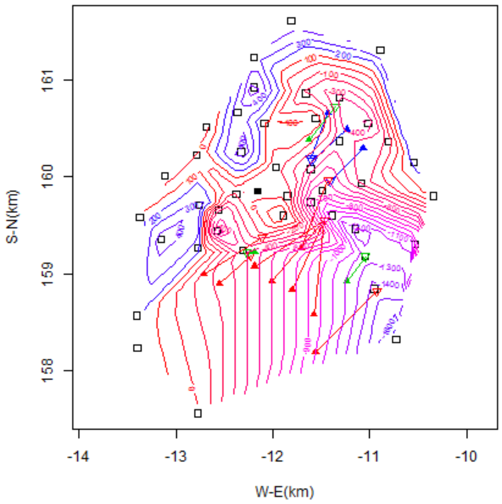

Figure 7c: Re-evaluated gravity changes 1994-1997.

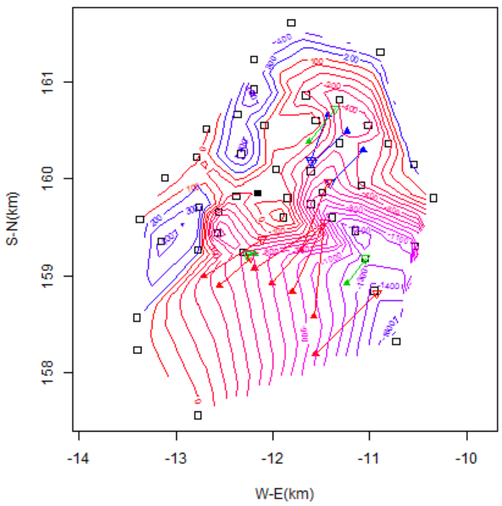

Figure 7d: Re-evaluated gravity changes 1994-2000.

The spatial factor specifies the configuration that is maintained throughout time; only the amplitude of the pattern as a whole is governed by the temporal factor. That is, in a given mode each particle moves coherently with every other particle, and the ratio of the amplitudes of any two particular particles remains fixed (Figure 8). The short-wavelength patterns are also seen in Figure 8. Most of them should be artificial. We just multiplied with the new calibration constant to the processed values. Strictly the observations must be reduced using standard precise gravity techniques again. All of the observation points were visited at least three times over each survey. One base station was occupied more than two times within a day. The looping technique was used to minimize instrument drift errors and to identify tares (jumps). Most of the non-natural short-wavelength patterns will be disappeared after reprocessing using the standard techniques, such as the looping. Regarding the long-wavelength pattern we can infer now (Figure 9). ,

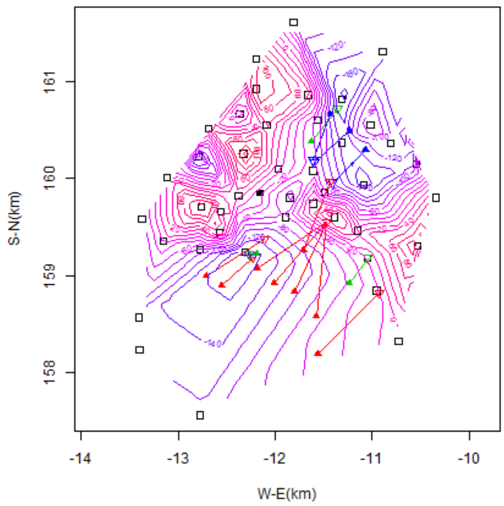

Figure 8: The spatial distribution of the 1st component factor of the re-evaluated gravity changes during 6 years. Elements of 1st eigenvector and contour.

Nishi and Ishido (2012) tried to incorporate the SP observations into a simple numerical reservoir model. This amounts to a history-matching study. After a few tens repetition of parameter adjustments and natural-state and exploitation simulations, they reached a final model MINC1 and three variants of the final model: "MINC2", "MINC3" and "POROUS". Although all of these models have the same common features, the formations representing the upper, main and deep reservoirs are assumed to be "MINC" double-porosity media for the "MINC1", "MINC2" and "MINC3" models and to be equivalent porous media for the "POROUS" model.

Referring the NEDO(2003) Ishido et al. (2015) discussed that the calculated gravity changes for the "MINC1" and "MINC2" models are in the range of long-wavelength micro-gravity decline actually observed between 1997 and 2000. Referring the re-evaluated data the MINC1 model is in the range of long-wavelength decline actually observed between 1994 and 2000 also.

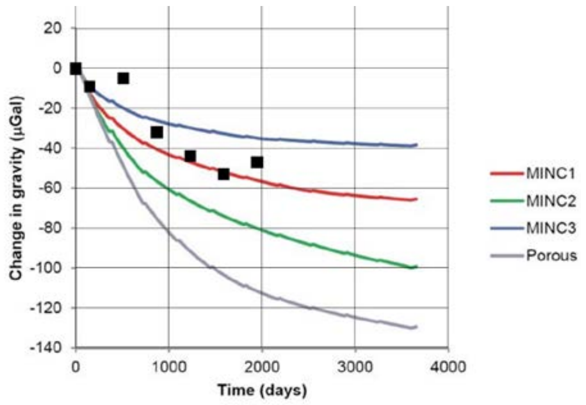

Figure 9: Re-evaluated temporal variations plot of microgravity at "CENTER" station. Four lines show temporal changes in gravity calculated using gravity postprocessor for four geothermal reservoir models (Ishido et al., 2015).

4.3 Applicability of PCA to other geodetic data at Yanaizu-Nishiyama geothermal field

PCA is a procedure for resolving data sampled simultaneously at a network of observing stations into a superposition of several modes each of which is time and space separable and applied to geodetic analysis (e.g. Savage, 1988). At Yanaizu-Nishiyama geothermal field many kinds of geodetic measurements were made. Adding to the microgravity data shown in previous part other microgravity surveys were made as follows. Seasonal gravity measurements were carried out at the field-wide observation network. Relatively frequent gravity measurements once every two to three weeks at several stations for more than two years revealed a correlation between seasonal changes in gravity and water-table depth at some stations. Continuous measurements of groundwater-table depth in 10 shallow wells and of water saturations in the unsaturated zone between 30- and 250-cm depths at one location also were carried out to identify causes of fluctuations in gravity results In support of the yearly gravity survey, leveling surveys are conducted at all gravity stations. The leveling data are used to correct the gravity measurements for any changes in elevation. Some of the leveling data were used to infer the distribution of volume change within the Okuaizu reservoir (Vasco et al., 2002).

4.4 Applicability of PCA to SP monitoring data

PCA is applicable to non-geodetic data, that is, SP. Regional SP variations can cause errors in the determination of the SP "datum" to which measured changes are referred. In order to overcome the datum problem Yasukawa et al. (2005) proposed "relative" SP procedure, which is obtained assuming that the average SP among monitoring points at each moment is always zero. PCA, however, is more useful than the method to characterize the behavior of each observation point from the statistical point of view.

5. CONCLUSIONS

Annual gravity monitoring with levelling surveys at 83 gravity stations were made since September 1994, about a half year before production began at the Yanaizu-Nishiyama geothermal field. In 1997-2000 another gravity survey was conducted nine times since 1997 with these gravity stations and 53 additional stations in the study area. PCA was employed to expand all the observed gravity changes into the time-space domain. The eigenvalue of the 1st component was determined to be hundreds of times larger than the eigenvalue of the 2nd component, which indicates that the observed variations can be represented by a single coherent source. The source is explained as an artifact of systematic error in the calibration constant of the gravimeter which was used during the early stage survey. The calibration factor was corrected based on the result of PCA. The re-evaluated results suggest that a two-phase zone was expanding in the early stages of exploitation at the field and constrain to revise the reservoir model.

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