Workshop on

4D Gravity Monitoring of Reservoirs and Aquifers

Through the Support of the Gravity and Magnetics Committee

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W-4: 4D GRAVITY MONITORING OF RESERVOIRS AND AQUIFERS

Thursday afternoon, September 27, 2007

Organizers: Yaoguo Li and Alan Herring

Through the Support of the Gravity and Magnetics Committee

Recent advances in gravimeter technology and the emerging need for characterizing the dynamic changes of subsurface systems have led to increased application of micro-gravity method in time-lapsed monitoring, also known as 4D gravity. Various groups have applied 4D gravity to ground water aquifers of small scales to large oil and gas reservoirs with noticeable success. However, specifics of the technology are still being developed and data sets are rarities. Huge potential in both research and application lies ahead. This workshop aims to bring together the researchers, practitioners, and users of 4D gravity from academia and ground water and petroleum industries to present and discuss the emerging technology. The goal is to provide a forum for presentation of the state-of-art of instrumentation, field survey methods, and data interpretation. With this backdrop, the workshop hopes to facilitate the interaction between different groups and foster rigorous discussion on the future direction of the technology.

There are seven invited presentations covering topics ranging from instrumentation, GPS positioning, and case histories in petroleum and ground water applications.

Application of absolute and relative gravity measurements to detect time lapse gravity changes

Tim Niebauer, Jeff Macqueen, Derek Van Westrum, Fred Klopping, Daniel Aliod, Ethan Mann, Micro-g LaCoste Inc, Lafayette, Colorado, USA; Chris Nind, Scintrex Ltd, Concord, Ontario, Canada; Olivier Francis, European Centre for Geodynamics and Seismology, Walferdange, Luxembourg;

Gravity meters are commonly used to map spatial changes in the earth's gravity, achieving resolution of parts per billion on microgravity surveys. The application of gravity surveys to monitor change and recent improvements in gravity instrumentation are summarized. The use of absolute gravity to track the progress of a waterflood in Prudhoe Bay, Alaska, provides a 4D Gravity case history. The surface gravity change caused by the injection of water into the gas cap is measured annually and compared to the expected change calculated from the reservoir simulation. Monitoring injected products using non-intrusive, inexpensive surface 4D Gravity measurements provides an effective "early warning system" for injection and sequestration projects. A recent Borehole Gravity survey in Hanford, Washington, demonstrates the ability to measure bulk densities using a Borehole Gravimeter. The applications include geotechnical studies at waste disposal sites, bridges and structures, locating and monitoring thief zones in reservoirs, and grade control in iron mines. Recent and ongoing improvements in borehole gravity instrumentation will result in the introduction of a new borehole gravity meter during 2008 that can be used in smaller boreholes with larger deviations from vertical. Gravity meters can be used in a stationary or monitoring mode to look for high frequency signals associated with seismic motion. Gravity meters provide an excellent way to measure the acceleration of the ground at frequencies from 10Hz and lower which is a natural complement to existing seismometers that typically cover frequencies from 1Hz and above. A double integration of the gravity signal provides a direct measure of the vertical position of the crust of the earth at the point of the gravity meter. The measurements provide a huge dynamic range of motion ranging from nominal seismic noise that with amplitude of about 1 micron to very large centimeter amplitudes caused by earthquakes. The ground shaking in Luxembourg before and after the January 13, 2007, earthquake in Japan was recorded on a long period seismometer, a superconducting gravity meter and a new gPhone gravity meter. The match between the seismometer data and the gPhone data during the earthquake is excellent. The gPhone continued to record the arrivals of Rayleigh waves for much longer than the seismometer. The portable gPhone gravity meter provides the means to record earth movements along active fault zones and other critical locations continuously, using breaking waves and small earthquakes for signal sources.

Time-lapse gravity monitoring of an aquifer storage recovery project in Leyden, Colorado

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We present a case study on using time-lapse relative micro-gravity surveying to monitor an aquifer storage and recovery project. An abandoned coalmine is being developed into an underground water reservoir in Leyden, Colorado. Excess water from surface sources is injected into the reservoir during the winter and then retrieved for use in the summer months. Efficient operation of the storage-recovery process requires knowledge of water concentration and movement within the mine workings as well as in the host geologic units. Three relative micro-gravity surveys were carried out to monitor the process over the course of ten months during the initial water injection stage. We present the survey design, data acquisition and errors, and results. We show the importance of forward modeling and inversion in recover parameters and understanding the extent of water movement in the subsurface during the monitoring experiment.

Use of Absolute Gravity Measurements for Long-Term Groundwater Monitoring in the Española Basin, New Mexico

Allen H. Cogbill, Los Alamos National Laboratory, Los Alamos, NM
John F. Ferguson, University of Texas at Dallas, Richardson, TX

We present results of 35-month project using absolute gravity measurements to monitor groundwater in the Española Basin, an arid to semi-arid region in northern New Mexico. Over 100 permanent gravity stations were established over approximately 7,000 km2 in the basin. A-10 absolute gravity meters, manufactured by Micro-g LaCoste, Inc., were used to monitor long-term gravity changes in the groundwater basin. More than fifty A-10 sites were established; other gravity sites have been established by reference to the primary A-10 sites using Scintrex CG-3M and CG-5 relative gravimeters. Geodetic-quality GPS surveys were used to directly measure any possible elevation changes at the gravity sites. At good sites, away from regions where we expect changes due to groundwater removal, reproducibility of the A-10 measurements is ±4 μGal.

Gravity stations were observed approximately every six months over the course of the project. Systematic changes in both gravity and station elevation were observed at a number of sites. On the basis of our observations, we can delineate three areas which appear to have systematic changes in storage. We conclude that the use of high-accuracy absolute gravity measurements, in conjunction with precise observations of station elevation, can provide useful information for evaluating groundwater storage changes over long time periods.

Time-lapse seafloor gravity measurements for reservoir monitoring

Mark Zumberge and Glenn Sasagawa, Scripps Institution of Oceanography, University of California, San Diego, Ola Eiken and Håvard Alnes, Statoil ASA, Trondheim, Torkjell Stenvold, The Norwegian University of Science and Technology, Trondheim*

Measurements of variations in gravity with time can reveal evolving density structure beneath the surface. Production of oil or gas from a reservoir is normally accompanied by replacement of the withdrawn fluid by water or subsidence of the overburden (or both). Modern gravity meters are capable of sensing changes of a few parts per billion of the Earth's gravity field. Depending on the porosity and depth of the reservoir, this sensitivity can reveal sub-meter changes in the height of a reservoir's gas-water contact.
Our group has developed the instrumentation required to observe relative gravity changes on the sea floor with a precision of 3 microGal (3×10^{-8} m/s^2). In addition, simultaneously collected pressure records provide information on measurement heights precise to a few mm. We have surveyed five North Sea fields to date; the number of measurement sites in each field ranges from 21 to 84. We have repeated surveys at two of the sites separated by three years or more. Based on these observations we can now confirm the level of data quality and detect time variations that we interpret as sub-surface density changes caused by gas withdrawal in one case and gas injection in another.

See workshop section of SEG conference CD for full text.

Global Positioning System (GPS) Methods and Results for 4-D Gravity Surveys

John E. Seibert, Seibert & Associates LLC, Anchorage, Alaska

Time-varying density changes in subsurface reservoirs can be monitored using 4-D surface gravity measurements. These measurements depend on precise surveying of gravity station elevation and position, or precise re-positioning of the gravity meter at each survey station. This presentation will discuss the need for precise surveying and provide examples from the on-going North Slope of Alaska gas-cap water-injection monitoring project.

See workshop section of SEG conference CD for full text.

The successes and challenges of 4D seismic and their implications for 4D gravity

Martin J. Terrell, ExxonMobil Exploration Company

No abstract available.

Organizers' note:
Time-lapse seismic is a mature reservoir surveillance technology proven to improve reservoir characterization, increase oil recovery, and decrease operating costs. This presentation discusses a case history covering the modeling-based workflow to use the 4D seismic anomalies to update the reservoir simulation model and identify new drilling opportunities. Although successfully applied in many production settings, 4D seismic has challenges in certain rock and fluid physics scenarios, and can be cost-prohibitive in certain production scenarios, providing opportunities for 4D gravity monitoring. Future opportunities for novel applications of 4D gravity and opportunities for collaboration with 4D seismic are offered. Throughout the talk, links will be made between the technical and commercial aspects of geophysical reservoir monitoring using time-lapse seismic and time-lapse gravity methods.

Lockheed Martin Ventures Development of Unique Borehole Gravity Sensor

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Lockheed Martin has launched a program to develop a miniature absolute gravity sensor – small enough to insert into production tubing, if desired, and accurate enough for time lapse monitoring of oil-gas interfaces, and perhaps even oil-water interfaces… the sort of information prized for guiding reservoir management. Parallel efforts focus on minimizing interruption of normal operations and on maximizing utility of data provided by the new technology.

Sensor heads deployed in sequential mode provide in-situ measurement of plumb gravity one location at a time, while pairs of sensor heads with fiber-optic link operate in differential mode providing in-situ measurement of differences in plumb gravity across a reservoir.

The program draws upon expertise of their Energy and Gravity Security Systems group located in Niagara Falls, NY ("Niagara" is part of Lockheed's Electronic Systems Division) and their Advanced Technology Center located in Palo Alto, CA ("ATC" is part of Lockheed's Space Systems Division).

Niagara holds over 35 years experience in design and deployment of moving-base gravity gradiometer and stable platform technology. Fielded systems routinely demonstrate sub-µGal/m performance.
ATC is a proven world leader in fiber-optic interferometry and precision pointing and control technologies. Having demonstrated pico-meter level displacement measurements, their compact integrated optic gauge defines a new state-of-the-art in metrology.

This poster introduces unique attributes of the sensor, identifies potential applications, and highlights benefits by way of conceptual oil recovery examples.