Gravimetric monitoring of gas production from the Troll field

Ola Eiken, Statoil, Mark Zumberge, Scripps Institution of Oceanography, Torkjell Stenvold, Norwegian Technical University, Glenn Sasagawa and Scott Nooner, Scripps Institution of Oceanography*

Summary

Three surveys of relative gravity and depth measurements have been carried out over the Troll field during gas production. Due to several improvements in the methodology, precision (intra-survey repeatability measured as standard deviation) has improved from 26 μGal to 11 μGal and 4 μGal in the latest survey. This will improve the reliability of future monitoring, and also opens the range of applications to smaller and deeper fields.

There is no clear subsidence of the seafloor. The estimated average depth change above the reservoir is 0.5 to 0.8 cm, but this is not statistically significant. Time-lapse gravity results show a change, significant at the 80 % confidence level, which is likely due to water influx into the reservoir. The result is in agreement with model expectations, and with time-lapse seismic and well log observations. It demonstrates that the method is useful for constraining dynamic models.

Introduction

The technique of gravity monitoring has gained increasing use in hydrocarbon applications, for observing moving gas-liquid fronts. For the Troll gas reservoir in the North Sea, it is being used for observing water influx (Eiken et al. 2000, Sasagawa et al. 2003), as illustrated in Figure 1. Gravity monitoring is also being used to monitor water injection into the gas cap in Alaska (Hare et al. 1999, Brown et al. 2002, Brown et al. 2003). Time-lapse gravity measurements have previously been published from the Groningen field (Van Gelderen et al. 1999), where a weak signal from water influx was seen. Non-hydrocarbon applications of gravity monitoring include water level changes in hydrothermal reservoirs (e.g. San Andres and Pedersen 1993), changes in volcanic magma chambers (e.g. Rymer and Brown 1986) and CO_2 storage (Nooner et al. 2003).

The giant Troll field in the North Sea, about 90 km north-west of Bergen, consists of thick sandstone units with high porosities and permeabilities, in a tilted fault block geometry. The gas column was initially about 260 m high. Aquifer influx from a large water basin is expected, however, there is little direct information on this during production, as all the wells are clustered near the top of the structure. Pressure decline gives some information, but there are uncertainties related to parameters such as reservoir volume, total porosity and residual gas saturation across the field. To monitor the water influx, one needs field-wide observations, which could be obtained from monitor wells, time-lapse seismic, or gravity data (Tollefsen et al. 2004).

For the fairly shallow, wide and high-porosity Troll reservoir, gravity changes of up to 6 μGal per meter of contact rise can be expected. To detect only a few meters of contact rise, highly precise measurements are needed.

Fig 1: Sketch of the concept.

Method

The offshore environment has some particular technical and operational challenges. Tidal and water density corrections are necessary, wave-generated seafloor accelerations cause a higher noise level than what is common on land, the soft seafloor conditions make it difficult to find stable and repeatable observation locations, and operational costs are generally higher than onshore.

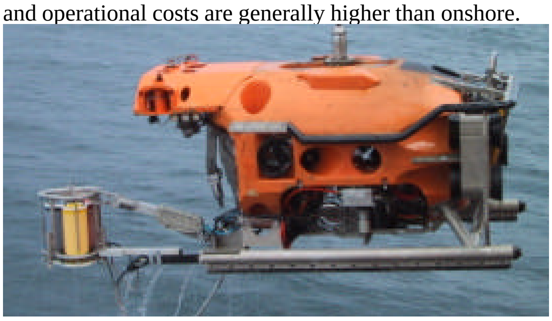

Fig. 2: Instrument and ROV.

For the purpose of offshore gravimetric monitoring, a new technique and instrument has been developed (Sasagawa et al. 2003), shown in Figure 2. Measurements are made at the seafloor, on top of pre-deployed concrete benchmarks as observation points of reference. An instrument with three relative gravity sensors and three pressure gauges is carried by a ROV. Cable connection to the survey ship allows control and data transfer to be done remotely on the ship. Stations are visited sequentially, and typical reading time is 20 minutes, followed by 1-2 hours transit to the next station. Relative gravimeters obtain gravity differences between stations above the field and reference stations outside the field area, which are not influenced by the gas production. The station visits are done in loops to control instrument drift, as in land surveys.

Water pressure measurements made at each site, together with reference water pressure recorded continuously at fixed locations during a survey, allow accurate relative depth determinations, which are crucial for correcting gravity for any seafloor subsidence. Fixed location water pressure records also improve the precision of water tide corrections, compared to using astronomical tide models. Field-wide monitoring of subsidence can also constrain reservoir compaction determination, which is useful for the dynamic reservoir model, and potentially for the safety of field installations (e.g. platforms, pipelines, wells) if the subsidence becomes large.

Data

So far, surveys have been carried out over the Troll field during 1998, 2000 and 2002. The current n et consists of 68 locations, of which 7 are outside the reservoir and serve as references to which changes above the field can be compared.

The average distance between stations is 2-3 km. This was chosen as a compromise between survey cost of this large area and lateral resolution. The distance from the seafloor to the gas-liquid contact is about 1250 m, so there is a potential for improving the resolution with denser station spacing. However, in view of the typical 1 km grid block size in flow simulation models, the pattern of wells in the field, and the most likely distribution of future secondary drainage points, the observation density is probably adequate.

During the 2002 survey, 119 individual occupations of 68 seafloor benchmarks were made. Of these, 38 were repeat visits made to estimate drift and survey precision. Data files contain time series of 1s samples of gravity, together with pressure, tilt and several instrument parameters for each sensor. Noisy periods, typically encountered during leveling procedures or biological disturbances, were removed. Corrections for tilt and instrument temperature were performed automatically. Windowed averages of the time series were used to generate a single gravity value for each observation. These values were further corrected for tides and repeat data misfits were minimized by making a drift correction with up to 4th order terms. The time-lapse data also allowed for scale factor calibrations of the sensors. Finally, averages were extracted for stations with more than one visit within a survey.

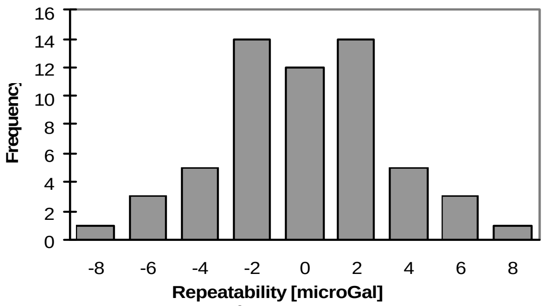

Figure 3: Distribution of gravity repeatability errors in the 2002 survey, based on 38 repeat measurements at 20 stations (deviations from station means).

Intra-survey accuracy is estimated by comparing repeated measurements at a site during one survey. Observed standard deviations were reduced from 26 µGal in 1998 to 11 µGal in 2000 and 4 µGal in 2002. The distribution of repeat site differences for the latest survey is shown in Figure 3. While drift generally was a significant source of error in the first survey, we now believe we have better estimates of the drift. Improvements in accuracy have come from changes in instrumentation, instrument handling, measurement procedures, recording software, and data processing.

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Seafloor subsidence

Similar to gravity, relative depth precision can be estimated from repeat measurements (repeatability). Standard deviations have improved from 1.4 cm in 1998 to 0.7 cm in 2000 and 0.6 cm in 2002. The most significant reason for the improved precision has been better control on the spatial variations in the water tides across the field.

Time-lapse depth measurements have additional uncertainties related to the settlement of benchmarks, gauge calibration, seasonal water density variations and the determination of zero-level at reference stations outside the field. Time-lapse uncertainties at individual stations are estimated to be about 2 cm, which is in agreement with the observations. Above the field, the observed subsidence is close to zero. On average there is an increase in relative water depth of 0.5 cm between 2000 and 2002 and 0.8 cm in the period 1998-2002, but this is less than the uncertainty in this estimate. Hence, there is no statistically significant subsidence. This is in accordance with GPS measurements at the Troll A grounded platform, but not with the pre-production prognosis.

Due to the large width of the Troll field compared to the overburden thickness (ratio about 10:1), most if not all of the reservoir compaction may be transferred to seafloor subsidence. This may indicate that either the compressibility of the reservoir is much less than determined from laboratory core plug measurements, or there is a significant time-delay in compaction mechanisms (Hettema et al. 2002).

Time-lapse gravity changes

The 2002 gravity data were corrected for the (small) observed depth changes, using a gradient of 2.22 µGal/cm, and for produced gas in the time period 2000-2002 using measured and estimated pressure drop and reservoir thickness as mapped from seismic data. After adjusting the zero-levels of different surveys (using stations outside the field), time-lapse gravity changes can be estimated. The observed scatter between the reference stations is in agreement with single-vintage estimates, and clearly the older vintages limit the time-lapse repeatability most. For the 2002-2000 differences (all stations and including the time-lapse signal), observed scatter is 12 µGal, slightly better than accuracy estimates based on single-survey accuracies.

Single-station time-lapse changes between 2000 and 2002 are shown in Figure 4. The uncertainty is too high to support any conclusions for single locations, but there is a majority of gravity increases, as can be seen from the map. For the average of all stations above the reservoir, a time-lapse increase in gravity is observed at an 80 % confidence level.

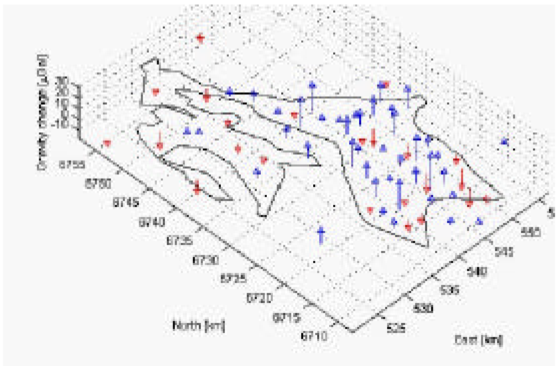

Figure 4: Time-lapse gravity changes 2002 – 2000. In this perspective plot, the rim of the hydrocarbon reservoir is drawn. Blue arrows are gravity increases, red are decreases, and a station is located at the tail of each arrow.

The gravity changes may be inverted to estimate rises of the gas-liquid contact, assuming all water is coming from far away (thus water deficit in the aquifer is insignificant) and assuming porosity and saturation change values in the water-flushed zone are identical to those of the reservoir model. This contact-rise map can be compared against other types of data (time-lapse seismic, repeated well logging and permanent pressure gauges) and with the flow simulation model, which gives a consistent history. Combining complementary sets of data gives together a model for the reservoir performance.

The data can also be used to estimate total water influx, independent of the geometry of the reservoir. This can be put into a material balance equation, as for example formulated by Dake (1994):

Underground withdrawal	=	Gas expansion	+	Water expansion/ pore compaction	+	Water influx

While the first two terms can be determined from production and extrapolated pressure data, gravity data can directly yield the water influx, and the subsidence data can constrain pore compaction values.

Discussion

It is too early in the field's life to test the agreement between gravity, seismic and well observations and the production data. The high accuracy in the latest gravity survey gives increased expectations for this technology in future monitoring. If a similar accuracy is obtained in the next survey as in 2002, time-lapse accuracy of less than 10 µGal (95 % confidence interval) will allow a vertical resolution of 1-2 m in the gas-water contact height, which compares favorably with both seismic and well log measurements.

The large and fairly shallow Troll reservoir with its large aquifers is an almost ideal candidate for gravity monitoring. With the latest accuracy improvements, the method will be applicable to much smaller and deeper fields as well. In such cases, vertical resolution will be less. However, the strength of the method, like field-wide data coverage and a direct measure of mass change is maintained. We therefore expect that gravity monitoring will find increasing applications in the years to come.

In comparison, methods of measuring the gravity gradient have recently been improved (DiFrancesco and Talwani 2002). However, to obtain a similar sensitivity to gas-liquid changes, accuracies well below 1E is needed. This still seems to be beyond the capabilities of the technique at present.

Conclusions

The first time-lapse gravity measurements at Troll show a change, which is likely to have been caused by water influx. The results are in agreement with expectations and with time-lapse seismic and log observations. As the signal is still close to the noise level, future surveys will provide a better constraint on the reservoir dynamics, and will test the measurements at well calibration points. Combined with well and seismic monitoring, such a complementary monitoring program is an attractive solution.

Precision in the relative gravity measurements has improved significantly, and the 4 μGal standard deviation observed in the latest survey will give better time-lapse resolution in future surveys. This also opens possibilities for monitoring smaller and deeper fields using this technique.

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Acknowledgments

We thank Statoil for permission to publish the methodology, and the Troll partners Statoil, Shell, Norsk Hydro, Total and ConocoPhillips for showing results. Håvard Alnæs contributed to the onboard data analysis.