Introduction

Seafloor gravity and subsidence surveys are a mature reservoir monitoring technology that has been successfully utilized in ten hydrocarbon production fields in the Norwegian continental shelf. In some cases, gravity-subsidence is the only geophysical 4D technology used for managing the reservoirs. In others, like Ormen Lange, seismic surveys and gravity-subsidence surveys are interleaved for cost efficiency and to exploit the complementarities between both data types (Vatshelle et al., 2017).

While time-lapse gravity changes at the seafloor are sensitive to aquifer influx and hydrocarbon depletion, seafloor subsidence provides lateral information on pore compaction and pressure depletion through the reservoir. Field cases demonstrate that the lateral distribution of subsidence can be used to identify undrained compartments (Statoil ASA, 2015). Røste et al. (2017) show that subsidence measurements can be used to calibrate the geomechanical model and hence provide an improved interpretation of seismic time-shifts in the overburden.

At Ormen Lange, Shell uses time-lapse changes in gravity to invert for mass changes in the reservoir, providing valuable constraints for dynamic reservoir modelling. Seabed subsidence data is used as an indirect measurement of compaction throughout the reservoir. 4D seismic provides the vertical resolution required to interpret these datasets in three dimensions.

Subsidence measurements can either be acquired in joint gravity-subsidence surveys, or in standalone surveys (Hatchell et al., 2019). The survey method uses water pressure measurements at the seafloor as a starting point. Once the required tide corrections are applied, the method reaches accuracies of 2 - 5 mm, depending on the field conditions. This accuracy is the best that can be obtained with any method (Hatchell et al. 2017). Notably, the accuracy is much better than the specified accuracy of the pressure sensors used in the survey, which is typically 10 cm for a pressure sensor rated for 1000 m of water. This is because the surveying method relies on repeatability and linearity rather than absolute sensor accuracy.

The output of the core sensing elements in pressure sensors are always dependent on both pressure and temperature. The temperature dependency is corrected for by means of an independent thermometer incorporated to the sensor and a calibration equation in the sensor firmware. The calibration equations have a reduced number of parameters that are fitted in large ranges of pressure and temperature, sufficient to match the specified accuracy of the sensor (e.g. 10 cm). Imperfections of the calibration equation can have systematic dependencies with temperature and pressure, that can potentially result into systematic errors in subsidence measurements in fields where temperature at the seafloor changes systematically between seafloor locations, as is the case of Ormen Lange.

There is a second complication introduced by temperature: when sensors are exposed to fast temperature changes, there is a delay between the temperature observed by the pressure sensing element and the dedicated thermometer. This deteriorates the temperature calibration for some time after the sensor has moved through the varying temperatures in the water column. This means that a high-quality temperature measurement is only obtained after tenths of minutes of measurement, which is a problem in offshore surveys performed by costly vessels.

In this abstract, we present a patented solution that eliminates the two abovementioned temperature-related issues. We first review the principles of the surveying technology and then review subsidence results from older data vintages at the Ormen Lange field. Then, we present the new solution put in place in 2016 and use the results from the time-lapse 2016-2018 at Ormen Lange to demonstrate that temperature-induced effects from data are removed, and that measurement time can now be largely reduced.
The marine 4D gravimetry and subsidence method

Seafloor subsidence data can either be acquired standalone (Hatchell et al., 2019) or in combined gravity-subsidence surveys as in the case of Ormen Lange (Vatshelle et al., 2017). A sensor frame is used for the measurements, containing three pressure sensors, together with three gravimeters for combined surveys. The acquisition method is the same in both types of surveys, and we will here disregard gravity measurements for simplicity.

At each field, water pressure is measured with the sensor frame at a number of stations defined by semi-permanent concrete platforms placed at the seafloor. The top surface of the platforms is circular with a diameter of approximately 1 m. The role of the platforms is to guarantee time-lapse repeatability in the measurement location. They are left on the seafloor during the field lifetime and can be retrieved at the end of production.

During a survey, a vessel is positioned sequentially above the concrete platforms, and a remotely operated vehicle (ROV) deploys the sensor frame to perform measurements on top of each of them. The number of platforms depends on the field size and the magnitude of the lateral variations of the expected subsidence signal. The duration of a survey ranges from a few days to a few weeks.

Stations are located both above and surrounding the hydrocarbon field. The latter ones are called zero-level stations. They are placed in locations where no production-induced vertical seafloor deformation is expected. That allows using those stations as a reference in time-lapse computations (Agersborg et al., 2017).

In a subset of stations, tide gauges are deployed during the whole survey as a means for correcting raw pressure measurements for tides and other oceanographic effects. Pressure data taken at the concrete platforms corrected in this way are converted into a measurement of station depths.

Recently, Hatchell et. al (2019) showed that it is possible to incorporate subsidence surveying into OBN campaigns, as another option for improving the cost efficiency of the method.

Subsidence monitoring at the Ormen Lange field

The Ormen Lange field is located in the Møre basin on the Norwegian continental shelf. The reservoir lies at an approximate depth range of 2600 - 2900 m below sea level, and water depths range between 300 and 1100 m. The reservoir covers an area of approximately 44 × 8 km.

Seafloor geodesy has been monitored at Ormen Lange by using two technologies. The first one is based on a network of seafloor autonomous monitoring transponders that utilize acoustic and pressure measurements (Dunn et al., 2016). These record pressure data in a continuous mode and provide cost-efficient data harvesting but suffer from a limited accuracy at the level of 10 cm due to sensor drift. The second is the survey method presented in this abstract. A total of 120 concrete platforms are deployed at Ormen Lange.

At each survey, stations are visited at least twice, with an average of close to three times. This allows computing single-measurement repeatability as an estimator of acquisition and processing uncertainties. Repeatability is found to be 5 mm and 4.3 mm in 2012 and 2014 respectively. Figure 1 shows the bathymetry at Ormen Lange and the subsidence measured between 2012 and 2014.
The water temperature challenge

The water column at Ormen Lange features an abrupt thermocline at a depth of 500 m separating a shallower, saltier Atlantic water mass at some 7 °C and a deeper, fresher water mass at some -1°C. This means that for the 12 southernmost stations (Figure 1), pressure measurements are taken at temperatures some 8 °C higher than at the rest of the 120 locations. In order to prevent any temperature-induced systematic effect, the southern part of the field was treated independently in the processing, by relying only upon the zero-level stations that are placed in that region. That meant effectively splitting the field in two and diminished the statistical power of the processing in the south.

In 2016, the patented Temperature Stabilized Pressure measuring system (TSP) was introduced in the sensor frame. In this system, the ambient temperature of the sensors is stabilized to 0.01 °C. This effectively reduces any temperature dependency on pressure measurements. As a demonstration, Figure 3 shows the subsidence values measured at the zero-level stations between the 2016 and 2018 surveys, both featuring the TSP system. Note that the measurements cluster around the expected null value within the complete depth range, spanning 800 m in seafloor depth. The average uncertainty estimate for this field is 5 mm, with some larger spread expected in the zero-level stations due to their geographical dispersion.

Figure 1 Seafloor depth (left) and subsidence measured in the 2012-2014 time-lapse at the Ormen Lange field (right), from Vatshelle et al. (2017).

Figure 2 Seafloor subsidence measured in the 2016-2018 at the zero-level stations at the Ormen Lange field as a function of station depth.
As an additional key development, the data acquired in the two surveys demonstrates that the TSP allows for a significant reduction of measurement times without impacting the data quality. Reducing measurement time from 20 minutes to 5 seconds does only deteriorate the repeatability from 4.5 to 5.3 mm in the data collected in 2018. This is an important development for reducing the duration of subsidence monitoring surveys, and hence their cost in standalone applications like those in Hatchell et al. (2019).

Conclusions

At Ormen Lange, subsidence data is used to indirectly measure reservoir compaction throughout the reservoir.

The large range of water depths and temperatures introduces additional challenges when utilizing the survey method to measure seafloor subsidence on the field. The introduction of the TSP system mitigates uncertainties derived from sensor temperature sensitivity and allows to largely reduce measurement time in applications where only subsidence (and not gravity) data is acquired.

When the TSP is utilized, data from the whole Ormen Lange field can be jointly processed, and a consistent accuracy of 5 mm is obtained for stations spanning a total of 800 m in water depth.

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