



(12) **PATENT**

(19) NO

(11) **341121**

(13) **B1**

NORWAY

(51) Int Cl.

G01V 9/00 (2006.01)

G01V 1/38 (2006.01)

G01C 13/00 (2006.01)

Norwegian Industrial Property Office

(21)	Application nr.	20150430	(86)	International Filing Date and Application Number
(22)	Date of Filing	2015.04.10	(85)	Date of Entry into National Phase
(24)	Date of Effect	2015.04.10	(30)	Priority
(41)	Publicly Available	2016.10.11		
(45)	Granted	2017.08.28		
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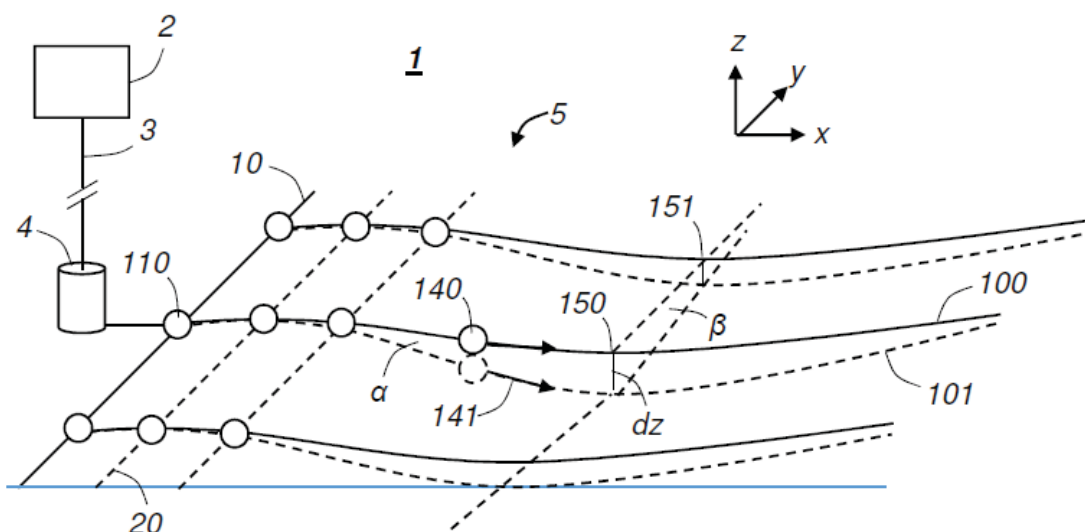
(54) Title **A method and system for measuring subsidence and/or uprise on a field**

(56) References
Cited:

US 2007124079 A1
US 2008123467 A1
US 5417103 A
US 4271696 A
WO 0142818 A1
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WO 2014120932 A1

(57) Abstract

A method for measuring subsidence and/or uprise on a field, comprises the steps of: deploying at least one cable (100) on a solid surface; collecting inline tilt data from numerous tilt sensors deployed along each cable (100); and performing a statistical analysis on the tilt data to determine changes in curvature on the solid surface. Preferably, the statistical method involves computing a cumulative inline and/or cross line tilt, whereby random errors cancel and systematic changes add. In addition, regression and/or interpolation may provide a quantitative estimate of curvature etc.



BACKGROUND

Field of the invention

[0001] The present invention concerns measurements of subsidence or uplift by tilt
5 sensors.

Prior and related art

[0002] Permanent reservoir monitoring (PRM) aims at tracking changes in a subsurface
structure over time, and/or during particular operations such as well treatment or injection.
10 PRM may include microseismic and other geo-mechanical monitoring, and is not
necessarily limited to a production field. For example, subsurface structures used for waste
depositing or long-term storage of CO₂ may be monitored by the same methods and
systems described herein.

[0003] Subsidence and /or uplift of the seafloor is an issue in many of these applications
15 where fluids are produced, replaced or injected onshore or offshore. For example,
continuous measurement on a production field in order to detect movements in the
overburden is important in understanding the depletion of the underlying subsurface
formation as well as to detect any possible subsidence having an impact on the
infrastructure on the seafloor.

20 [0004] Subsidence or uplift may be monitored by hydro-acoustic methods, measurements
of pressure changes at the seafloor or by tilt-meters. The present invention relates to tilt
measurements.

[0005] In a known PRM-system provided by the applicant of the present invention, sensor
stations are distributed over the reservoir in a large grid connected by cable. Data from
25 each station is transferred to surface by cable in real time. Each sensor station could
include a number of different type sensors. However, a basic system will at least include
seismic sensors. The seismic sensor is preferably a 4-component sensor with a hydrophone
and a 3-component particle velocity or acceleration sensor (accelerometer). A tilt sensor is
often provided to measure the orientation of the 3-component system relative to the
30 vertical. However, these tilt sensors are of a relatively inexpensive type, designed for
different purposes, and typically do not have the required accuracy for tilt measurements in
order to detect subsidence or uplift.

[0006] US 7,028,772 B2 discloses a treatment well tilt-meter system with one or more tilt-meter assemblies located within an active treatment well. The system provides data from the downhole tilt-meters, and can be used to map hydraulic fracture growth or other subsurface processes from the collected downhole tilt data versus time. The system
5 provides tilt data inversion of data from each of the tilt-meter assemblies, and provides isolation of data signals from noise associated with the treatment well environment. The system also provides geo-mechanical modelling for treatment well processes.

[0007] WO 2005/089404 discloses a system with a component array located within the borehole of an active well, in the borehole of a nearby offset well or in multiple shallow
10 boreholes in the surface around the active well. In one embodiment, the system includes a sensor array with at least one tilt sensor, at least one microseismic sensor and a transmitter for transmitting data to a receiver. Received microseismic data are analysed to find a location of a microseismic event, and received tilt-meter data are analysed to ascertain orientation and dimension of a fracture developed during said at least one geophysical
15 process.

[0008] The above systems are commercially available from Pinnacle, a subsidiary of Halliburton, and represent the state of the art. However, the systems require accurate instruments, i.e. tilt-meters, which can withstand the temperature, pressure and chemicals in an active well and/or drilling shallow boreholes. These systems are relatively complex
20 and expensive and are usually deployed as a single instrument or a very limited number of instruments. There is a need for a less costly system for monitoring a solid surface above a subsurface formation.

[0009] US 2007124079 A1 describes reservoir characterization based on observations of displacements at the earth's surface. One method of characterizing a reservoir includes the
25 steps of detecting a response of the reservoir to a stimulus, the stimulus causing a pressure change in the reservoir, and determining a characteristic of the reservoir from the response to the stimulus. The response may be the pressure change that varies periodically over time, or a set of displacements of a surface of the earth.

[0010] US 2008123467 A1 describes seismic sensor systems and sensor station topologies,
30 as well as corresponding cable and sensor station components, manufacturing and deployment techniques. For some embodiments, networks of optical ocean bottom seismic (OBS) stations are provided, in which sensor stations are efficiently deployed in a modular fashion as series of array cable modules deployed along a multi-fiber cable.

[0011] WO 2014120932 A1 describes measuring translational data in a first direction by particle motion sensors contained in an elongated housing of a sensor device provided at an earth surface. The particle motion sensors are spaced apart along a second, different direction along a longitudinal axis of the elongated housing. Rotation data around a third
5 direction is computed based at least in part on computing a gradient of the translational data with respect to the second direction.

[0012] The objective of the present invention is to provide a method and a system for measuring tilt on a field that solves or alleviates at least one of the aforementioned problems and shortcomings.

10

SUMMARY OF THE INVENTION

[0013] This objective is achieved by a method according to claim 1 and a system according to claim 8.

[0014] In a first aspect, the invention concerns a method for measuring subsidence and/or
15 uprise on a field. The method comprises the steps of: deploying at least one cable on a solid surface; collecting inline tilt data from numerous tilt sensors deployed along each cable; and computing a cumulative tilt as a sum of collected tilt data. According to the invention the cumulative tilt determines changes in curvature on the solid surface, and the cumulative tilt is a cumulative cross-line tilt from tilt sensors disposed along one cross-line
20 extending perpendicular to several essentially parallel cables.

[0015] In one embodiment, the cumulative tilt is a cumulative inline tilt from tilt sensors disposed along one cable.

[0016] This embodiment may further comprise the step of adding several cumulative inline tilts.

25 [0017] In an alternative embodiment, the method further comprises the step of adding several cumulative cross-line tilts.

[0018] In all embodiments above, the steps may be repeated at predetermined intervals.

[0019] The method may further comprise the step of performing a regression analysis on the tilt data in order to obtain an estimate of a curvature on the solid surface.

30 [0020] The sign of tilt data may be conserved to provide a difference between subsidence and uplift.

[0021] In a second aspect, the invention concerns a system using the method described above. The system comprises several cables with seismic stations arranged at regular

intervals. Each seismic station comprises a tilt sensor and the cables are arranged essentially parallel in an array. Moreover, each seismic station is connected through the array, a base station and an umbilical to a control unit. According to the invention the control unit is configured to compute a cumulative tilt as a sum of collected tilt data to
5 determine changes in curvature on the solid surface. The solid surface may be a seafloor above a subsurface formation to be monitored.

[0022] Further features and advantages will become apparent from the detailed description below.

10 BRIEF DESCRIPTION OF THE DRAWINGS

[0023] The invention will be explained by means of examples and reference to the drawing, in which:

Figure 1 illustrates basic principles of the invention.

15

DETAILED DESCRIPTION

[0024] Figure 1 shows a system 1 comprising a control unit 2 providing power and two-way communication to a seismic array 5 through an umbilical 3 and a base station 4. The seismic array 5 is deployed at a solid surface, e.g. a seafloor, and comprises cables 100
20 running essentially in the horizontal direction denoted x. A cable 10 on the surface essentially perpendicular to the cable 100, i.e. in the direction denoted y, connects the cables 100 to the base station 4.

[0025] Each cable 100 provides several seismic stations 110, 140 with power and communication. Seismic stations 110, 140 are placed along the entire length of each cable 100, but most of them are omitted from figure 1 for clarity of illustration. The direction
25 along cables 100 is termed inline, and the horizontal direction perpendicular to the cables is termed cross-line. Typically, the inline distance between sensor stations 110, i.e. along the cables 100, are 50 m. The cross-line distance, i.e. between cables 100, is typically in the range 200-500 m. For simplicity of illustration, all cables 100 run in the x-direction.
30 Dashed lines 20 through the sensor stations 110 in the y-direction are not physical connections, but illustrate that the seismic array 5 may be mapped to a polygonal mesh representing the solid surface. If desired, e.g. for computational purposes, the quadrilateral

mesh may be represented by a triangular mesh in a known manner. In either case, the seismic stations 110 or 140 are located at corners of the mesh.

[0026] Figure 1 also illustrates consequences of subsidence such that the cables 100 sink to new positions illustrated by dashed lines 101. More particularly, a point 150 on the solid surface subsides a distance dz in the vertical direction z . The shift dz at vertex 150 will shift an adjacent seismic station 140 downward, e.g. to the position illustrated by the dotted circle below seismic station 140. The shift dz also increases the tilt 141 in the inline direction at seismic sensor 140 by an angle α . A corresponding downward shift is shown at vertex 151 of the grid, and a change of tilt in the cross-line direction y is illustrated by an angle β .

[0027] For useful subsidence measurements, vertical displacement less than 10 cm should be detectable. Thus, 50 m between seismic stations in the inline direction corresponds to an angle $\alpha < \arctan(10^{-2}/50) = 0.2^\circ$. Similarly, a cross-line spacing of 200 m corresponds to $\beta < 0.06^\circ$, and a cross-line spacing of 500 m corresponds to $\beta < 0.02^\circ$.

[0028] It is possible to detect subsidence by mapping a polygonal mesh to the solid surface, e.g. the seafloor above a formation, and monitoring the mesh in a time-lapse sequence. In this case, tilt sensors within the seismic stations 110, 140 could provide spatial derivatives in the x and y -directions. If each tilt sensor is able to detect tilt changes less than 0.06° and the spacing of the cables 100 is less than 200 m, then the edges of the mesh are easily determined. In addition or alternatively, the corners of the mesh may be determined by pressure sensors capable of detecting pressure changes less than approximately $10^{-1}\text{m}/(10\text{ m/bar}) = 0.01\text{ bar}$.

[0029] However, the tilt sensors within the seismic stations 110, 140 are generally not designed with the accuracy discussed above. Similarly, some or all seismic stations 110, 140 may lack pressure sensors with the required sensitivity and/or means to filter noise in pressure data due to waves on the surface.

[0030] However, it may be possible to use statistical analysis to cancel out presumed stochastic variations in accuracy of the tilt sensors already present in the seismic stations 110, 140. If so, it will also be possible to provide those seismic stations 110, 140 that do not already have tilt sensors with relatively inexpensive tilt sensors, typically based on MEMS accelerometers.

[0031] Returning to figure 1, it is seen that the tilt 141 at sensor 140 is changed due to the greater curvature in the x - z plane after subsidence, i.e. after the downward shift dz at

vertex 150. Thus, if tilt is measured as a deviation from the horizontal direction as indicated by arrow 141, the sum of all tilts in the x-z plane taken along the dotted line 101 will be greater than the same sum taken along the solid line 100. Furthermore, this assumption holds even if a real cable 100 deviates from the x-z plane, i.e. curves slightly in the x-y plane. In other words, a sum of deviations in the inline direction is equivalent to a sum in the x-direction. Depending on the implementation of the tilt sensors, this difference may or may not obviate a scalar product between a measured tilt and a unit vector in the x-direction, or a similar trigonometric computation, to obtain the tilt direction in the x-z plane. The sum of tilts along one cable 100 will be termed a cumulative inline tilt in the following.

[0032] From figure 1 it is also apparent that similar changes in curvature due to subsidence occur at the cable 100 running through vertex 151, and in other cables. A sum of cumulative inline tilts of several or all cables 100 is expected to be an even better measure of change of curvature, i.e. presence of subsidence, as the summed tilt difference grows systematically if the solid surface has subsided, while random inaccuracies in the tilt sensors continue to cancel each other.

[0033] A similar argument applies to the cross-line direction. The angle β implies a greater tilt in the y-z plane, which is equivalent to the cross-line direction. The sum of tilts along one cross-line 10, 20 is termed a cumulative cross-line tilt, and a sum of cumulative cross-line tilts of several or all cross-lines 10, 20 is expected to provide a better indication of subsidence than each individual cumulative cross-line tilt.

[0034] In short, the sum of cumulative inline tilts, possibly added to the sum of cumulative cross-line tilts, provides a fast and accurate indication of the presence of subsidence. Obviously, the presence of an uprise could be determined in the same manner.

[0035] Alternatively or additionally, there may be a desire to map the solid surface by means of inexpensive tilt sensors rather than just determine the presence of subsidence or uplift as discussed above. It is readily seen that regression analysis or known interpolation techniques can be employed inline and cross-line to obtain estimates for edges of the polygonal mesh, and hence quantitative estimates for curvature etc., using the ideas discussed above.

[0036] So far, the basic observed variable, i.e. tilt, has been described as deviation from a horizontal plane, i.e. the x-y plane in figure 1, for ease of explanation. However, conventional tilts, i.e. deviation from a vertical, work equally well, as displacing all angles

by 90° or $\pi/2$ changes the sums, but does not change the basic ideas. Furthermore, any basic variable measuring the different curvature of inlines 100 and 101 and/or the cross-lines can be used without changing the basic ideas of obtaining cumulative sums inline and/or cross-line, and then summing the cumulative sums. Thus, the term 'tilt' as used
5 herein should be understood as any such basic variable that can be derived from tilt sensor measurements, and is not limited to angular deviation from a horizontal as in the previous example.

[0037] The direction of tilt must of course be preserved in order to detect a difference between subsidence and uplift, whereas a sum involving squared basic variables may be
10 employed if only subsidence or only uplift are of interest. Also, partial sums may be used if some part of the solid area is prone to uplift and other parts are prone to subsidence. Selecting suitable basic variables and constructing appropriate sums are considered well within the capabilities of one skilled in the art knowing the present disclosure and knowing the application at hand.

15 [0038] Thus, while the invention has been described by way of examples, the scope of the invention is determined by the accompanying claims.

Claims

1. A method for measuring subsidence and/or uprise on a field, comprising the steps of:
deploying at least one cable (100) on a solid surface;
5 collecting inline tilt data from numerous tilt sensors deployed along each cable (100);
computing a cumulative tilt as a sum of collected tilt data **characterised by** the
cumulative tilt determines changes in curvature on the solid surface and that the
cumulative tilt is a cumulative cross-line tilt from tilt sensors disposed along one cross-
line (10, 20) extending perpendicular to several essentially parallel cables (100).
10
2. The method according to claim 1, wherein the cumulative tilt is a cumulative inline tilt
from tilt sensors disposed along one cable (100).
3. The method according to claim 2, further comprising the step of adding several
15 cumulative inline tilts.
4. The method according to claim 1, further comprising the step of adding several
cumulative cross-line tilts.
- 20 5. The method according to any preceding claim, further comprising the step of repeating the
steps at predetermined intervals.
6. The method according to any preceding claim, further comprising the step of performing a
regression analysis on the tilt data in order to obtain an estimate of a curvature on the solid
25 surface.
7. The method according to any preceding claim, wherein a sign of tilt data is conserved to
provide a difference between subsidence and uplift.
- 30 8. A system (1) using the method according to any preceding claim, comprising several
cables (100) with seismic stations (110, 140) arranged at regular intervals, each seismic
station (110, 140) comprising a tilt sensor and the cables being arranged essentially
parallel in an array (5);

wherein each seismic station (110, 140) is connected through the array (5) a base station (4) and an umbilical (3) to a control unit (2) **characterised** in that the control unit (2) is configured to compute a cumulative tilt as a sum of collected tilt data to determine changes in curvature on the solid surface.

5

9. The system according to claim 8, wherein the solid surface is a seafloor above a subsurface formation to be monitored.

Krav

1. Fremgangsmåte for å måle innsynkning og/eller heving på et felt, omfattende trinnene:
å utplassere minst én kabel (100) på en fast overflate;
5 å samle inn inline helningsdata fra tallrike helningssensorer plassert langs hver kabel
(100);
å beregne en kumulativ helning som en sum av innsamlede helningsdata,
karakterisert ved at den kumulative helningen bestemmer forandringer i krumning på
den faste overflaten, og at den kumulative helningen er en kumulativ tverrlinjahelning fra
10 helningssensorer anordnet langs en tverrlinje (10, 20) som strekker seg perpendikulært på
flere hovedsakelig parallelle kabler (100).
2. Fremgangsmåte som angitt i krav 1, hvor den kumulative helningen er en kumulativ inline
helning fra helningssensorer anordnet langs én kabel (100).
15
3. Fremgangsmåte som angitt i krav 2, videre omfattende trinnet med å legge til flere
kumulative inline helninger.
4. Fremgangsmåte som angitt i krav 1, videre omfattende trinnet med å legge til flere
20 kumulative tverrlinjahelninger.
5. Fremgangsmåte som angitt i et av de foregående kravene, videre omfattende trinnet med å
gjenta trinnene med forutbestemte intervaller.
- 25 6. Fremgangsmåte som angitt i et av de foregående krav, videre omfattende trinnet med å
utføre en regresjonsanalyse på helningsdataene for å fremskaffe et estimat av en krumning
på den faste overflaten.
7. Fremgangsmåte som angitt i et av de foregående krav, hvor et fortegn av helningsdata
30 bevares for å tilveiebringe en forskjell mellom innsynkning og heving.
8. System (1) som bruker fremgangsmåten som angitt i et av de foregående krav, omfattende
flere kabler (100) med seismiske stasjoner (110, 140) anordnet med jevne mellomrom,

hver seismiske stasjon (110, 140) omfatter en helningssensor, og kablene er anordnet hovedsakelig parallelt i en oppstilling (5);

hvor hver seismiske stasjon (110, 140) er forbundet gjennom oppstillingen (5), en basestasjon (4) og en navlestreng (3) til en styreenhet (2),

- 5 **karakterisert ved** at styreenheten (2) er konfigurert til å beregne en kumulativ helning som en sum av innsamlede helningsdata for å bestemme forandringer i krumning på den faste overflaten.

- 10 **9.** System som angitt i krav 8, hvor den faste overflaten er en havbunn over en undergrunnsformasjon som skal overvåkes.

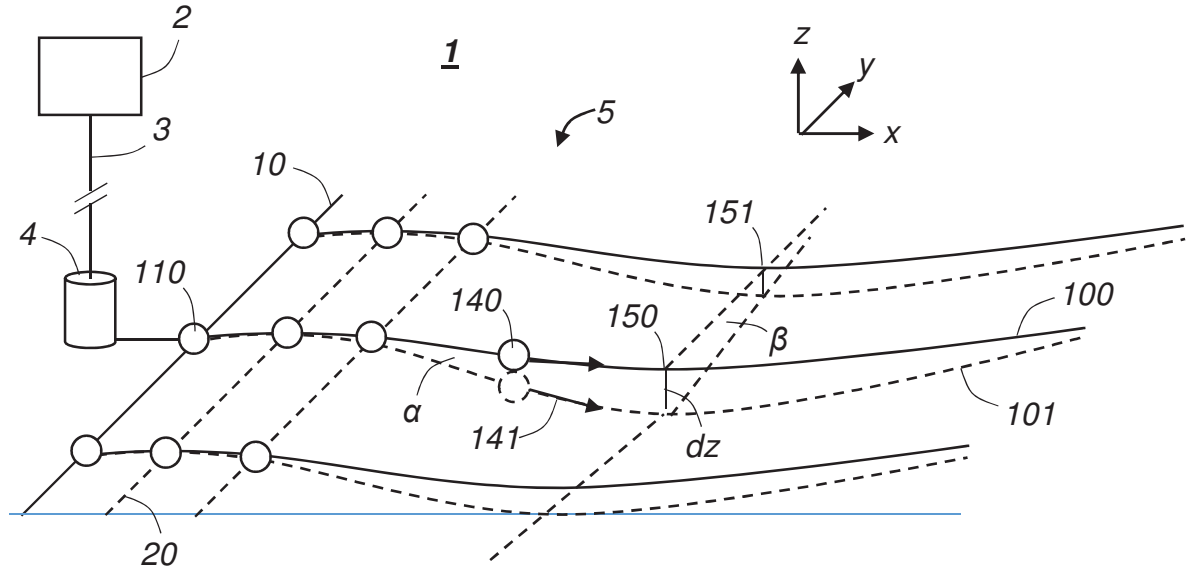


Fig. 1