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ANALYSIS OF INACCURACY OF DETERMINING A DIRECTIONAL BOREHOLE AXIS***

1. INTRODUCTION

A growing development of directional drilling has been observed in the 21st century. On one hand it is connected with the production of oil and natural gas under the seabed. On the other hand we have to face the environmental protection and economic indices of on-shore drilling. This leads to a considerable reduction of distances between the wells and so possible collisions of the neighboring boreholes. Such cases were observed in practice, therefore when drilling some or a dozen wells on one drilling site or a platform it is necessary to regularly monitor the location of the drilled borehole with respect to its neighbors. For doing so it is necessary to measure basic parameters characterizing the spatial location of borehole axis and make the real time processing of data with the best calculation methods and dedicated computer software. Additionally, the separation coefficient [8] should be determined to avoid collision with the neighboring boreholes.

2. DEVICES DETERMINING THE SPATIAL LOCATION OF BOREHOLE AXIS

Unexpected changes of borehole direction can be encountered while drilling boreholes. This is mainly caused by geologic factors, which frequently have an influence on the direction of drilling. A man can do little about it except minimize the effect by the proper selection of technical, technological and organizational factors [15]. For these reasons attempts were undertaken to work out devices thanks to which the dogleg angle and azimuth could be measured in a borehole. The first successful attempts of measuring the location of borehole axis

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were performed in Texas in the 1820s [14]. Since that time measurement techniques have been developed and improved. A significant acceleration of the development was observed in the 1960s when wedges started to be used on a larger scale for deflecting boreholes, and in the 1970s when skew subs and downhole motors were applied.

There are a few types of devices for measuring the location of borehole axes. Depending on the measuring device the following parameters can be determined [14]:
– angle of deflection of the borehole axis from vertical,
– azimuth of borehole, i.e. deflection of the borehole axis from the north,
– arientation of the drilling tool.

Their operation is based on various physical effects taking place in the Earth crust. Generally, measuring devices can be divided into mechanical, magnetic, gyro and MWD systems.

Downhole inclinometers are the simplest measuring devices determining only the angle of deflection of a borehole axis from vertical. The main part of the device is a needle-indicator. When the needle reaches the end of the string it strikes a paper disk with a single graduation and marks a hole in it [3]. After removing the string to the surface one can read out the dog-leg angle from the disk. In the drilling practice 0–8° and 0–16° graduation disks are applied, though also other options are possible. The first ones give a higher accuracy of measurement, whereas the latter ones are more applicable to wells which are more deflected from vertical.

Presently the downhole inclinometers are used only in vertical wells, where deflections from vertical are searched for.

Magnetic measuring devices [14] are used for measuring the dogleg angle and azimuth of the borehole axis. They make use of the magnetic field of the Earth, therefore measurement is done with respect to the magnetic north, not geographic. This difference, the so-called angle of declination needs to be corrected depending on the localization of the borehole. Magnetic tools cannot be used in cased holes and in a standard downhole string setup. For the sake of minimizing the interferences with the Earth's magnetic field, magnetic tools should be separated from steel elements of the string with, e.g. nonmagnetic collars. The exemplary basic parameters of magnetic inclinometer TYP-E Magnetic Single Shot Instruments are presented in Table 1.

Table 1

Parameters of Magnetic Inclinometer TYPE-E Magnetic Single Shot Instruments

Parameter	Value
Measurement range of dogleg angle [°]	0–90
Accuracy of measurement of dogleg angle [°]	0–20 ±0.2 15–90 ±0.25
Range and accuracy of measurement of azimuth [°]	0–360 ±0.5
Maximum temperature of work [°C]	105
Outer diameter [mm]	27–35
Maximum depth of borehole [m]	4,000
Maximum pressure of work [MPa]	60–90

Gyro inclinometers are similar to the magnetic ones; both they can be used for measuring dogleg angle and azimuth. They only differ in their principle. Gyro inclinometers are based on the angular momentum principle, therefore are insensitive to factors which could disturb the Earth's magnetic field. Accordingly, they can be used in cased boreholes and in standard string setups. Their most important part is a laser gyrocompass powered by a high-speed electric motor. On the surface, the gyrocompass is most frequently oriented to the north, which is used as a reference while making measurements underground.

Gyro inclinometers are very sensitive and should be handled with care. They tend to lose their original direction during measurements, which should be accounted for when processing data [3, 14]. The characteristic of an exemplary gyro inclinometer is presented in Table 2.

Table 2

Parameters of Precision Gyro Inclinometer TCX-5B

Parameter	Value
Measurement range of dogleg angle [°]	0–50
Accuracy of measurement of dogleg angle [°]	±0.1
Range and accuracy of measurement of azimuth [°]	0–360 ±4
Maximum temperature of work [°C]	85
Outer diameter [mm]	40
Maximum depth of borehole [m]	≤2500
Maximum pressure of work [MPa]	150

The Measurement While Drilling (MWD) systems are used for measurements in the vicinity of the bit while drilling, and the obtained results are transmitted to the surface in real time. The signal is most frequently sent by small changes of mud pressure or rarely by remote systems. The special build of the device transmitting the signal to the surface with pressure impulses evokes a slight difference in the mud flowing through the bit, causing a positive or negative difference of pressures on the surface. Pressure sensors on the surface armature receive impulses and send them to the computer, where they are processed and transformed into the final result in the form of the location of the borehole axis. The pressure systems used for transmitting data are most efficient and are most popular in the field practice. However, they also have their limitations. The transmitting medium must be a non-compressible fluid, data transmission is slow, advanced signal processing techniques have to be involved to eliminate distortions and noises. Besides, communication with downhole equipment is limited. It sometimes happens that data cannot be retrieved or processed. In this case data obtained during measurement can be recuperated after the setup is removed to the surface as the MWD/LWD systems are equipped with a programmable computer memory. The azimuth can be measured with a gyroscope, whereas the dogleg – with accelerometer.

The MWD systems are most advanced devices making use of the newest technological achievements shortening the time of measurement and accelerating the time of performing the well. However, proper MWD service is very expensive. The Logging While Drilling (LWD) service measures the location of the borehole and also other parameters of drilled layers, e.g. gamma radiation, resistivity, neutron density, equivalent mud weight on the bottom of the borehole, downhole temperature etc. [3, 14].

3. METHODS OF DETERMINING THE LOCATION OF DIRECTIONAL BOREHOLE AXES

With the advancement of methods enabling the efficient deflection of boreholes, there were also worked out measuring systems and mathematical models determining the position of directional boreholes. The 3D position of the borehole should be determined while drilling [7, 9]. Importantly, the actual location of the borehole should be referred to the planned trajectory. In the case of deep directional boreholes there are used MWD systems which give, e.g. parameters of borehole deflection from vertical and azimuth at various depths of the drilled well. Then, its trajectory is measured with one of the analytical methods. Neither the dogleg angles not the azimuth between neighboring boreholes are known, therefore the calculation methods are based on certain assumptions [1, 6, 11].

One of the following major methods is used for determining the borehole trajectory:

- average angle method,
- balanced tangential method, i.e. modified tangential method,
- radius of curvature method (RCM),
- minimum curvature method.

In the average angle method the dogleg and azimuth in the lower and upper measuring point are arithmetically averaged, therefore it is assumed that the borehole axis trajectory is tangent to the average dogleg angle and azimuth (Fig. 1) [1, 4, 5, 7, 12].

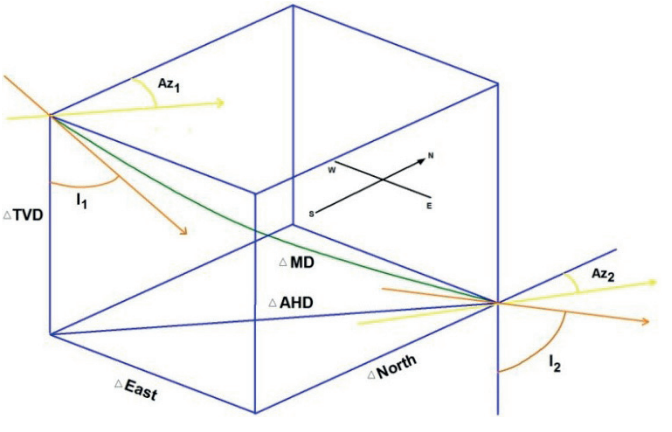

Fig. 1. Schematic of parameters describing the borehole axis

The change of location of borehole axis between two measuring points is calculated from the equations:

$$\Delta North = \Delta MD \cdot \sin\left(\frac{I_1 + I_2}{2}\right) \cdot \cos\left(\frac{Az_1 + Az_2}{2}\right) \quad (1)$$

$$\Delta East = \Delta MD \cdot \sin\left(\frac{I_1 + I_2}{2}\right) \cdot \sin\left(\frac{Az_1 + Az_2}{2}\right) \quad (2)$$

$$\Delta TVD = \Delta MD \cdot \cos\left(\frac{I_1 + I_2}{2}\right) \tag{3}$$

where:

ΔMD – the distance between measuring points [m],

I_1, I_2 – borehole dogleg angle in the upper and lower measuring point [°],

Az_1, Az_2 – borehole axis azimuth in the upper and lower measuring point [°].

It is assumed in the tangential method that the dogleg angle and azimuth are constant between neighboring measurement points, and the tangential in the lower point is the borehole trajectory. Therefore, the trajectory of the borehole axis is measured on the basis of the dogleg angle and azimuth at the lower measuring point [4, 6, 11, 12].

The change of localization between two measuring points is calculated from the formulae:

$$\Delta North = \Delta MD \cdot \sin(I_2) \cdot \cos(Az_2) \tag{4}$$

$$\Delta East = \Delta MD \cdot \sin(I_2) \cdot \sin(Az_2) \tag{5}$$

$$\Delta TVD = \Delta MD \cdot \cos(I_2) \tag{6}$$

where denotations as above.

This method is rarely applied as the obtained result is burdened with considerable error. The faster are the angles increased or decreased, the bigger is the error [4, 13].

The Balanced Tangential Method treats the first half of the distance between measuring points as tangent with the upper point, and the remaining part as tangent with the lower measuring point [5].

The change of location is calculated from the following equations:

$$\Delta North = \frac{\Delta MD}{2}\left(\left(\sin I_1 \cdot \cos Az_1\right) + \left(\sin I_2 \cdot \cos Az_2\right)\right) \tag{7}$$

$$\Delta East = \frac{\Delta MD}{2}\left(\left(\sin I_1 \cdot \sin Az_1\right) + \left(\sin I_2 \cdot \sin Az_2\right)\right) \tag{8}$$

$$\Delta TVD = \frac{\Delta MD}{2}\left(\cos I_1 + \cos I_2\right) \tag{9}$$

where denotations as above.

The dogleg angle and azimuth in the upper and lower measuring point are known in the radius of curvature method. On this basis a borehole trajectory is selected in a 3D space. It has the shape of an arch on the side of the cylinder, passing through both measuring points [4, 11, 12]. It assumes that the borehole trajectory is a smooth arch linking the neighboring measuring points.

A change of location between the neighboring measuring point is calculated from the formulae:

$$\Delta North = \Delta MD \cdot \sin\left(I_2\right) \cdot \cos\left(Az_2\right) \quad (10)$$

$$\Delta East = \Delta MD \cdot \sin\left(I_2\right) \cdot \sin\left(Az_2\right) \quad (11)$$

$$\Delta TVD = [(180 \cdot (\Delta MD) \cdot (\sin(I_2) - \sin(I_1))] : \pi(I_2 - I_1) \quad (12)$$

where denotations as above.

In the minimum curvature method based on the dogleg angle and azimuth of two neighboring measuring points we determine the oval arch linking the points. The arch lies on the surface of the sphere. This method is most frequently used in the drilling practice. Its graphical representation is illustrated in Figure 2.

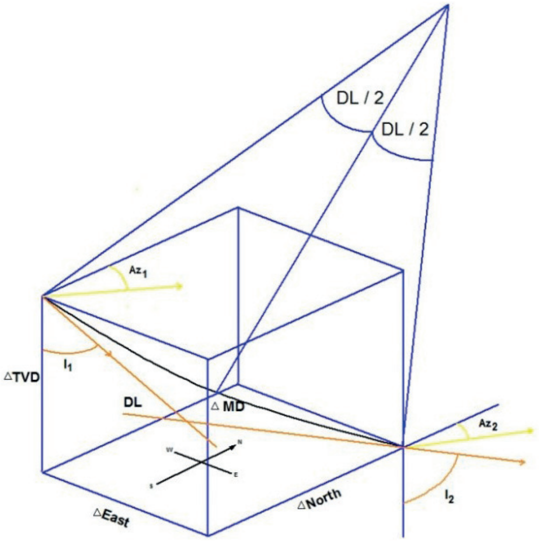

Fig. 2. Schematic of parameters describing the dogleg severity

The minimum curvature method involves the intensity of spatial deflection of a borehole axis, i.e. Dogleg Severity (DLS), i.e. a measure of the dogleg angle and azimuth in reference to a unit of length of the borehole for calculating the shifting of the dogleg in horizontal and vertical planes [10]. The change of the location is calculated from the formulae:

$$\Delta North = \frac{\Delta MD}{2}\left(\left(\sin I_1 \cdot \cos Az_1\right) + \left(\sin I_2 \cdot \cos Az_2\right)\right) RF \quad (13)$$

$$\Delta East = \frac{\Delta MD}{2}\left(\left(\sin I_1 \cdot \sin Az_1\right) + \left(\sin I_2 \cdot \sin Az_2\right)\right) RF \qquad (14)$$

$$\Delta TVD = \frac{\Delta MD}{2}\left(\cos I_1 + \cos I_2\right) RF \qquad (15)$$

$$RF = \frac{2}{DL} \cdot \tan\frac{DL}{2} \qquad (16)$$

$$\cos DL = \cos(I_2 - I_1) - \sin I_1 \cdot \sin I_2 \cdot \left(1 - \cos\left(Az_2 - Az_1\right)\right) \qquad (17)$$

where DL – angle of spatial curvature of borehole axis [°] (remaining denotations as above).

4. EXEMPLARY CALCULATIONS

Although the mathematical assumptions are simple, the manual calculation of the borehole location at each measurement point is time-consuming and practically impossible with the ongoing drilling of the well. For the sake of creating a spatial model of the well which would account for all measurement errors, computer software is used. In this way the computations are made and a real-time spatial model is generated, thus minimizing the risk of possible calculation errors. The needed pieces of information are obtained quickly, especially when the drilling jobs are performed in a close vicinity of an existing well.

One of the computer programs used for determining directional borehole trajectories is COMPASS, part of Landmark package (Halliburton) [1].

The software used in this paper calculated the spatial location of the directional boreholes for four described methods of determining directional wells localization. The accuracy of calculations realized for particular methods was exemplified on three wells having different profiles, which could be generally divided into two groups: 2D wells (two-dimensional, increase/lowering of deviation angle) and 3D (three-dimensional, increase/lowering of dogleg angle and azimuth).

Generally, the selected wells are [16]:

- 2D type:
  - 2.1 – borehole with a long radius of curvature, one interval of the dogleg angle increase,
  - 2.2. – borehole with an interval of increase and decrease of the dogleg angle;
- 3D type:
  - Built & Turn borehole, long radius of curvature, sections with a change of azimuth and dogleg angle.

Tables 3–5 illustrate data from wells designed for the sake of comparing results obtained for various measurement methods.

Table 3

Data from borehole 2.1

Measured depth [m]	True vertical depth [m]	Built [°/30 m]	Turn [°/30 m]
0.00	0.00	0.00	0.00
800.00	800.00	0.00	0.00
2370.70	1800.00	1.72	0.00
4370.80	1800.00	0.00	0.00

Table 4

Data from borehole 2.2

Measured depth [m]	True vertical depth [m]	Built [°/30 m]	Turn [°/30 m]
0.00	0.00	0.00	0.00
500.00	500.00	0.00	0.00
604.42	590.56	15.00	0.00
1124.82	909.44	0.00	0.00
1229.24	1000.00	−15.00	0.00
1729.24	1500.00	0.00	0.00

Table 5

Data from borehole 3.1

Measured depth [m]	True Vertical Depth [m]	Built [°/30 m]	Turn [°/30 m]
0.00	0.00	0.00	0.00
800.00	800.00	0.00	0.00
900.00	898.60	5.00	0.00
1300.00	1281.79	0.00	0.00
1500.00	1473.39	0.00	−5.00
1700.00	1664.99	0.00	−7.00
1800.00	1760.79	0.00	0.00
1900.00	1856.59	0.00	5.00
2000.00	1952.38	0.00	7.00
2100.00	2048.18	0.00	10.00
2500.00	2291.04	5.00	10.00
2800.00	2325.87	0.00	10.00
2830.00	2328.13	4.67	0.00
3630.00	2356.00	0.00	0.00

The 3D pictures of borehole trajectories generated by Landmark/COMPASS software are presented in Figures 3–5.

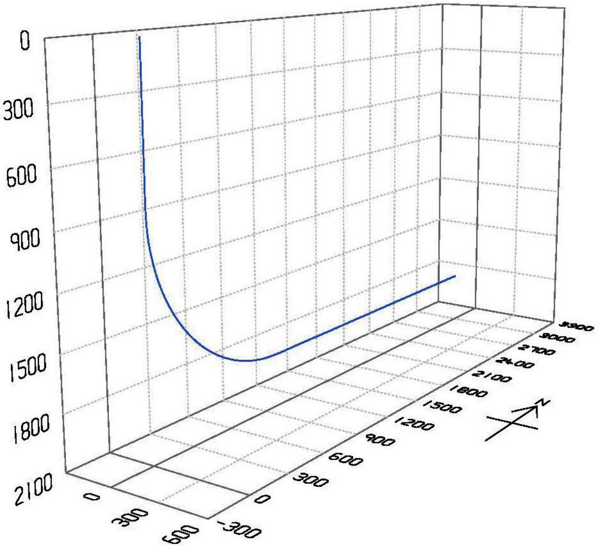

Fig. 3. Trajectory of borehole 2.1 axis, 3D picture

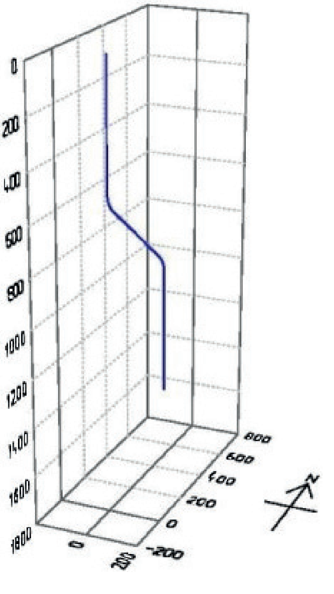

Fig. 4. Trajectory of borehole 2.2 axis, 3D picture

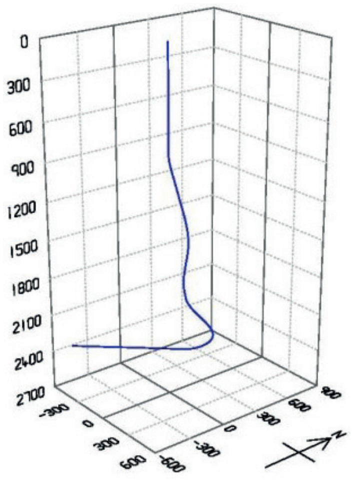

Fig. 5. Trajectory of borehole 3.1 axis, 3D picture

5. COMPARATIVE ANALYSIS OF DATA

Figures 6–12 are an illustration of the differences between the planned values and values obtained with the use of four analyzed methods of determining the position of the selected directional boreholes.

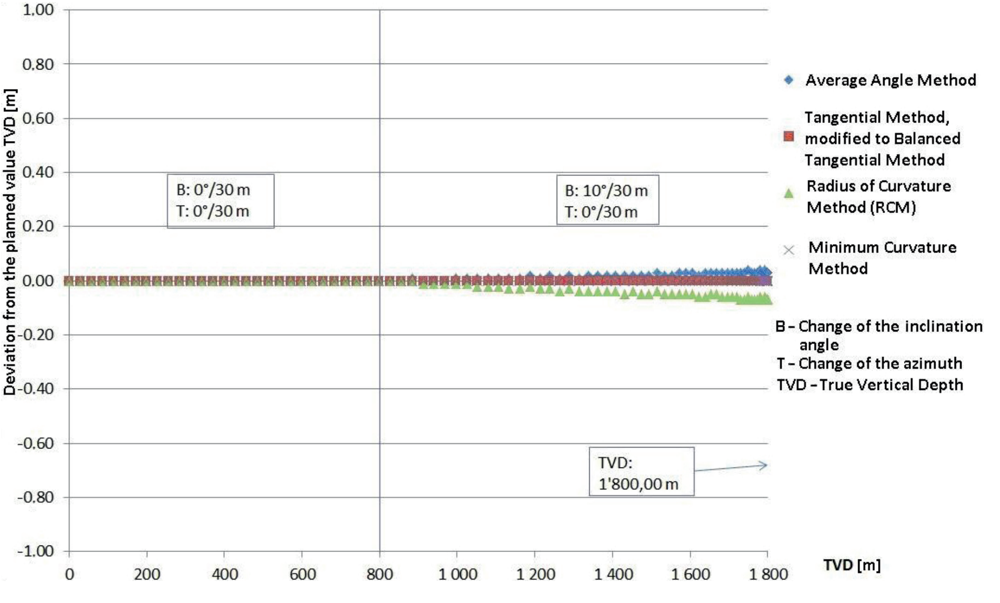

Fig. 6. Borehole 2.1, deviation from the planned value

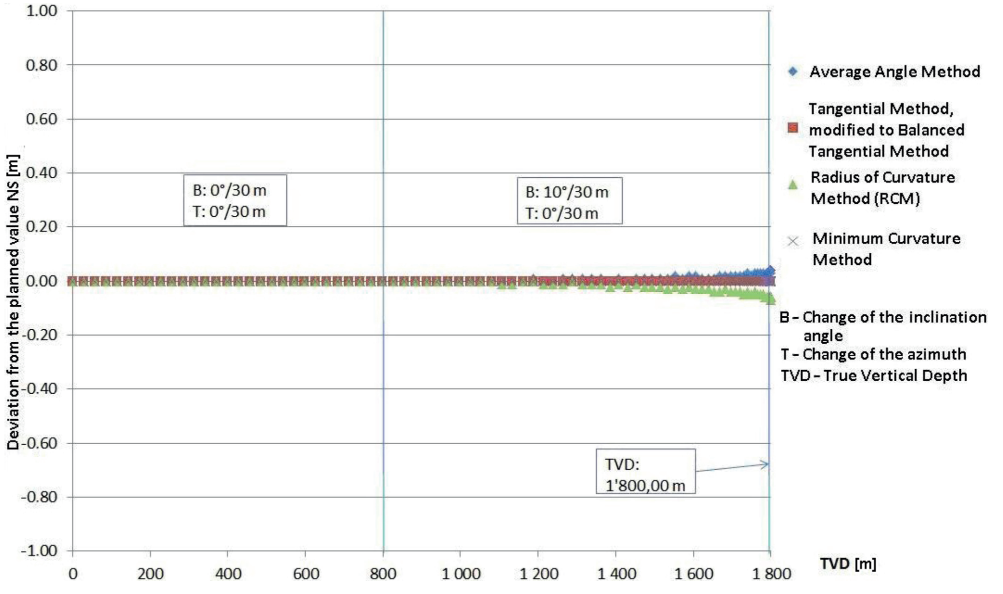

Fig. 7. Borehole 2.1, deviation from planned NS value

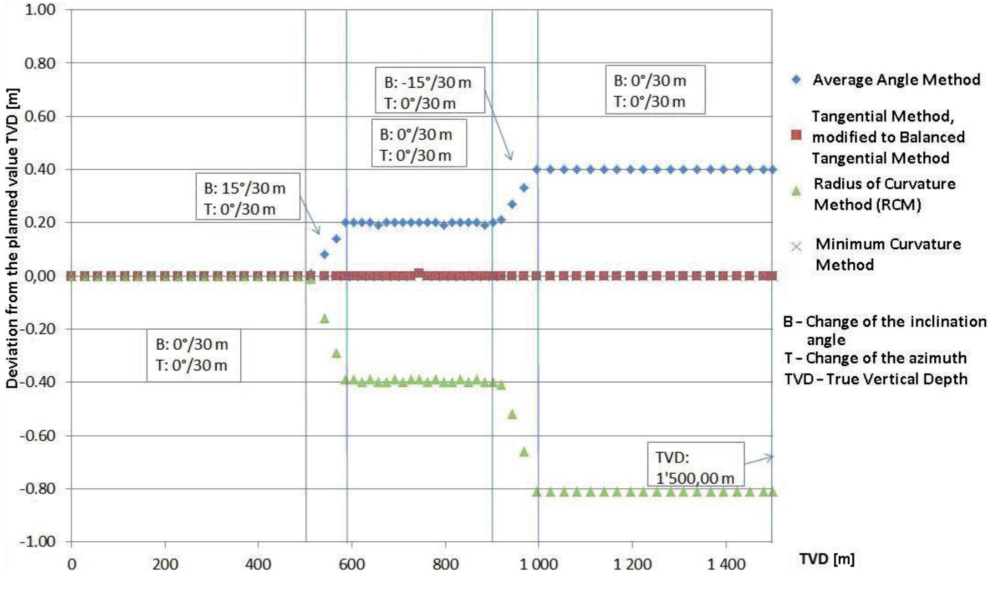

Fig. 8. Borehole 2.2, deviation from the planned value

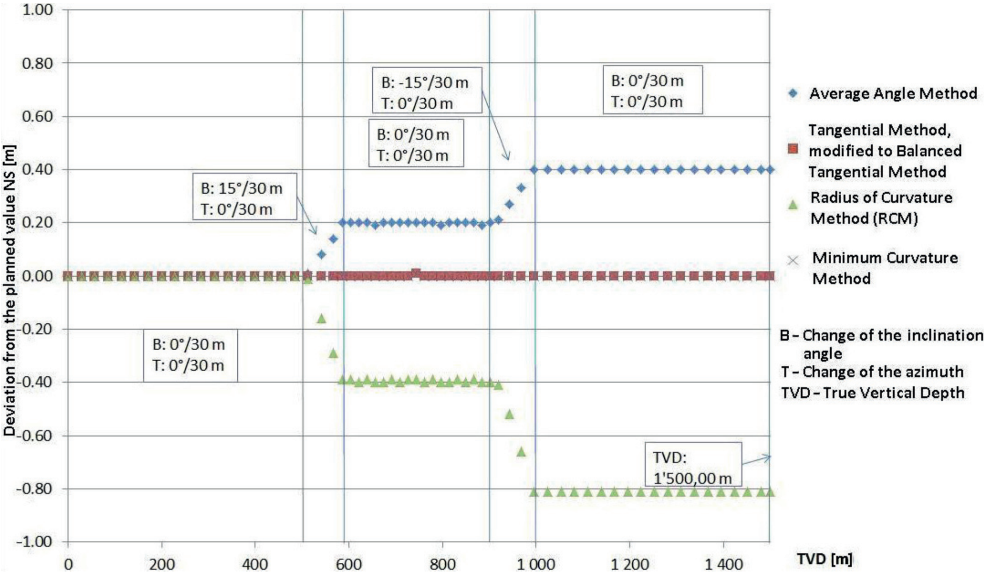

Fig. 9. Borehole 2.2, deviation of NS

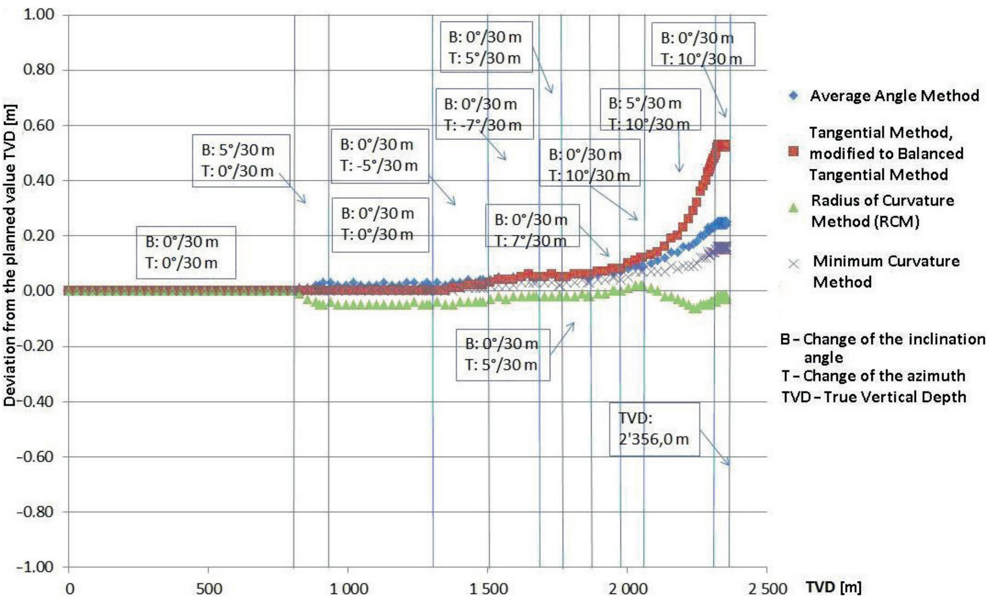

Fig. 10. Borehole 3.1, deviation from the planned value

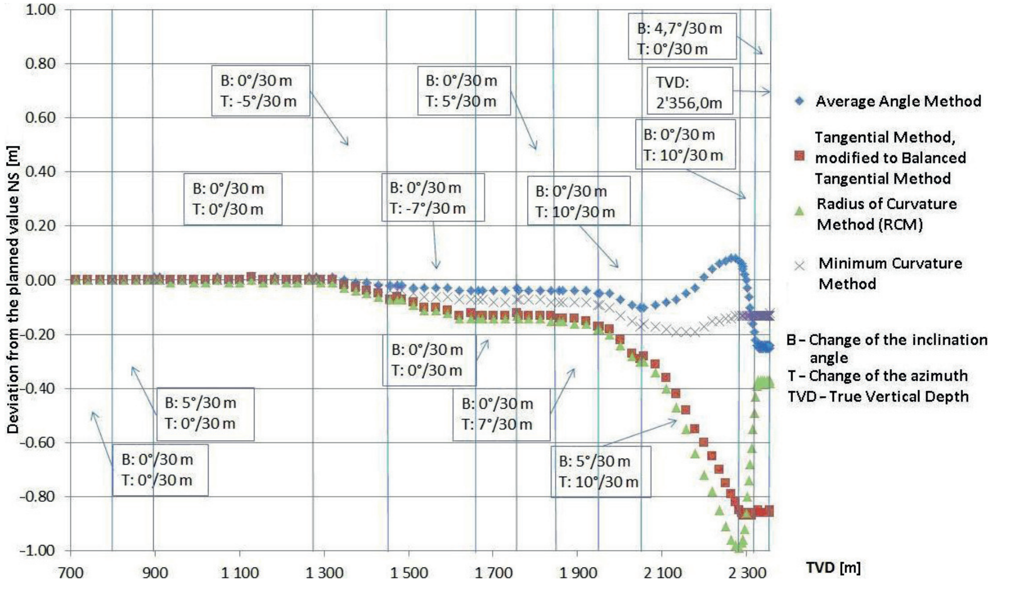

Fig. 11. Borehole 3.1, deviation of NS

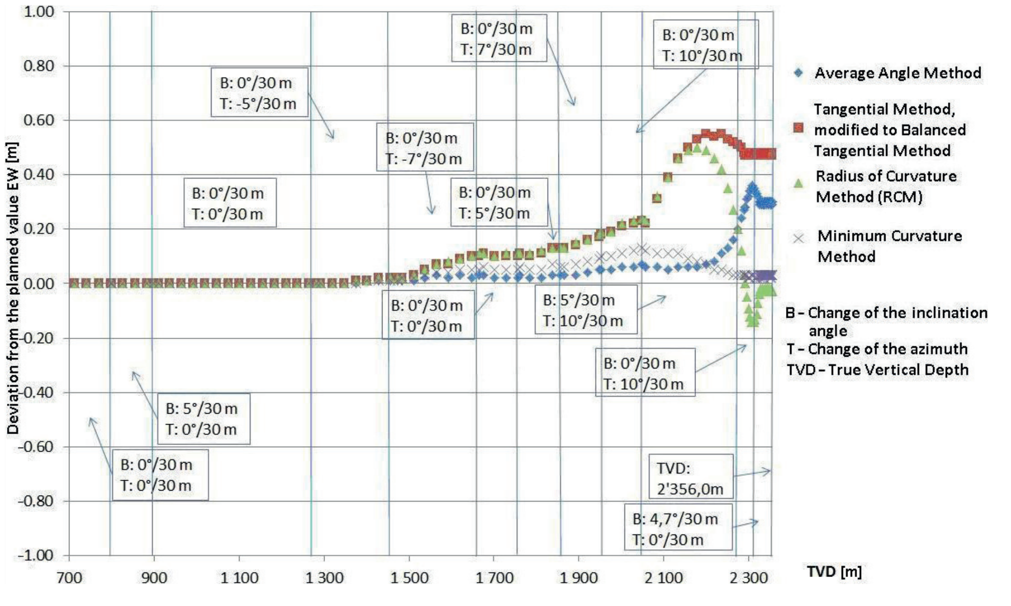

Fig. 12. Borehole 3.1, deviation of EW

6. CONCLUSIONS

For boreholes located in a 2D space (Syant and S-type) the minimum curvature method and radius of curvature method do not show any errors. The biggest errors were observed in the balanced tangential method.

For 3D boreholes (Built & Turn) none of the methods was error-free. The least deviations from the planned values were observed for the radius of curvature method.

All methods reveal the highest error values in the intervals of increase/decrease of dogleg angle or change of azimuth. In sections of constant dogleg angle and azimuth, error values continued from the preceding intervals, but they did not increase.

The higher was the intensity of the growth of the dogleg angle or azimuth, the bigger errors were reported for all methods.

In all calculation methods the differences in the depth of the borehole (TVD) were biggest at the end of the interval of the dogleg angle and/or azimuth.

The inaccuracy of determining the trajectory of directional boreholes was caused by the class of the devices measuring length, dogleg angle and azimuth and the applied methods of determining the spatial position of the borehole axis.

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