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Integration of Real-time Data and Past Experiences for Reducing Operational Problems

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Abstract

Oil well drilling operation is a complex process, in which there are always new lessons to be learned during drilling operation. A case-based reasoning (CBR) system is used to provide an intelligent advisory system based on previous experiences. Whenever the process is running smoothly, or is failing, the experiences gained during such episodes are valuable and should be stored for later re-use and prediction. Contributing features are selected for characterizing an episode (case) that is compared to other cases in a case database. In this way, cases are classifed into case classes according to the similarity between a new case and other cases. As most problems during drilling operation are depth dependant, the system keeps all the cases and experiences in each defined depth interval to compose sequences of cases. Our aim is to implement the sequence building for the purpose of predicting problems before they occur. To meet this goal, each sequence is composed of previous, present and next case.

The paper presents a methodology of a semi-automatic case building and case discrimination process to make a robust sequence-based reasoning system. Our approach addresses the task of developing an intelligent system for prediction through sequeces. A CBR platform, developped in our group, was used and employed in the oil well drilling domain. The methodology was applied in one well section in the North Sea and the methodology clearly showed its ability through the good results which were obtained.

Keywords; Oil well drilling, Real-time data, CBR, Sequence-based reasoning, Prediction

Introduction

Drilling a well is associated with different activities such as drilling, circulation, tripping in and out, and reaming. It usually takes a month, but unwanted problems leads to additional time. Encountering problems during drilling is inevitable. Hole cleaning and wellbore restriction is a serious problem in the oil industry. It can lead to delay in the drilling process, increase in drilling cost, and in some cases even abandonment of the well. The prediction of upcoming situations will help to avoid downtime and serious problems which may lead in worst scenarios to abandoning the whole or part of the well section.

Case based reasoning is an approach to solving problems and gaining lessons learned for future use [1]. This technique has been employed in different domains of petroleum engineering. In 2002, Bhushan at al. [2] applied CBR to globally search for reservoir analogues as an important step in planning a new field development. CBR has also been tried in the oil well drilling domain by different groups around the world. One of the first applications of CBR was documented by CSIRO and later refined by Karvis and Irrgang [3]. The technique was applied to derive alternate drilling plans based on previously drilled wells. Each well was represented as one case. Skalle et al. [4, 5] described a system for prevention of unwanted events in the domain of offshore oil well drilling. Mendes et al. [6] presented application of CBR in offshore well design. The intention of their work was to formalize a methodology applied to petroleum well design in the context of case-based reasoning. They also used fuzzy set theory to deal with indexing attributes. Perry et al. [7] described the development of a case-based knowledge repository for drilling optimization. Later, Abdollahi et al. [8] explained the applicability of CBR for diagnosis of well integrity problems to reduce the risk of uncontrolled release of formation fluids through the lifecycle of a well. CBR was also implemented for planning and execution of well interventions. In this regard, Popa et al. [9] presented a specific application of CBR to determine the optimum cleaning technique for sanded/ seized well failures. The number of publications about application of the CBR in oil well drilling indicates that this is a potential method for reducing the cost of drilling by using previous experiences, hidden in reports and/or known by experts. Although, CBR applications are still at its beginning in the oil industry.

A lot of wells are being drilled every day all over the world. Each well may experience both similar and new problems during the drilling operation. On the other hand, getting access to experts for the purpose of solving problem and knowledge acquisition is limited. Consequently, there is a growing need for a semi-automatic method to extract all the valuable experiences to be used for the subsequent drilling operations. The intension of this work is to develop a warning system which predicts a situation that is about to happen. The prediction is done through sequences of cases. Building a sequence database is consequently required and will be presented in detail. A sequence is composed of three cases, at the same depth interval. Our system utilizes all the available data and information to facilitate the decision making process when the drilling operation goes on.

The work presented here has two sides. The first is associated with the methodology of the case building process integrated with a classification routine for re-using and building sequences. Case-based reasoning serves as a main core of our model, and is implemented to utilize experiences and lessons learned from previously stored cases. The second side demonstrates applicability of the method in the oil well drilling domain. Our application is targeted at predicting problems before they occur, with a special focus on hole cleaning issues. It predicts and presents the results to the busy drilling crew through a sequence of cases.

The rest of the paper is structured as follows: In chapter 2 we explain the hole cleaning problem, related to the functionality of our system. Chapter 3 explains the case-based reasoning system accompanied with similarity assessment, used for case matching. Chapter 4 demonstrates our methodology in details. In chapter 5 and 6 results from the study of the methodology applied in oil well drilling is reported. These chapters present how our methodology enhances the prediction process in oil well drilling. The last chapter summarizes and concludes the paper.

Background

Oil well drilling

In oil well drilling, several types of problems can occur. The upmost problem in deviated wellbores (inclination more than 30 degree) is hole cleaning. One of the main causes of the poor hole cleaning is cavings production. It is estimated that this problem costs the oil industry one billion U.S. dollars a year [10]. According to many sources in the industry, hole cleaning problems are responsible for an extra 10 to 15 % of the drilling costs.

The transport efficiency or solids removal rate is low in deviated wellbore sections. Additional solid materials, cavings, may also cause the wellbore restriction as well. Here drill string rotation and adequate flow rate are essential for transporting the materials. The scenario in deviated wells is that solid materials are settling along the wellbore during drilling activity. When the drill string is moved axially, large diameter elements of the drill string, called bottom hole assembly (BHA), such as the drill bit and stabilizers, tend to scrape the solid materials bed, thereby causing the formation of plugs of cuttings which give rise to high over-pulls and pack-offs, and to a continuous need for operations such as backreaming, wiper trips and reduced ROP [11]. If the hole cannot be kept cleaned, repair actions must be done; countermeasures like wiper trips, decreasing the ROP etc. Knowledge of previously successful actions when a problem occurs will help in decreasing the trial and error approach. Hole cleaning has become an increasing concern for horizontal and extended reach wells, especially with the move towards completely openhole lateral sections, and in some cases, openhole build sections through shale cap rocks. It adds complexity to the drilling operation and it is difficult to identify and compensate for poor hole cleaning situations. Therefore, it is imperative to take advantage of the CBR approach in oil well drilling operation, which is very expensive and complex.

Many sensors were introduced to mitigate the number of problems during drilling operation by revealing the current situation. Real-time data from the drilling process and specified indicators are the main source of situation description, which is matched with a past case in order to identify possible problems ahead of the drill bit.

Case-based reasoning

As mentioned, case-based reasoning systems solve new problems by retrieving relevant previous cases and adapting them to fit the new situation[1]. Each case contains data and associated information for properly describing problematic situations. In the work described in this paper, CBR is used to recognize patterns in order to predict an upcoming situation, and to respond to that situation in a proper way.

To get a clear picture of how CBR works, the CBR cycle is illustrated in Figure 1. The CBR cycle consists of four steps; retrieve, reuse, revise and retain [1]. CBR is able to utilize the specific knowledge of previously experienced, concrete problem situations. The design of CBR requires a good portion of cases in the case database. The retrieval task starts with a problem description, and ends when a best matching previous case has been found. A new problem is solved by finding a similar past case, and reusing it in the new problem situation. Sometimes revising the solution is done to adapt the previous solution to the unsolved case. It is important to emphasize that CBR also is an approach to incremental and sustained learning, since a new experience is retained each time a new problem has been solved, making it immediately available for future problems. There are many information sources on the theory of CBR in the literature and for more information we recommend studying the referred papers.

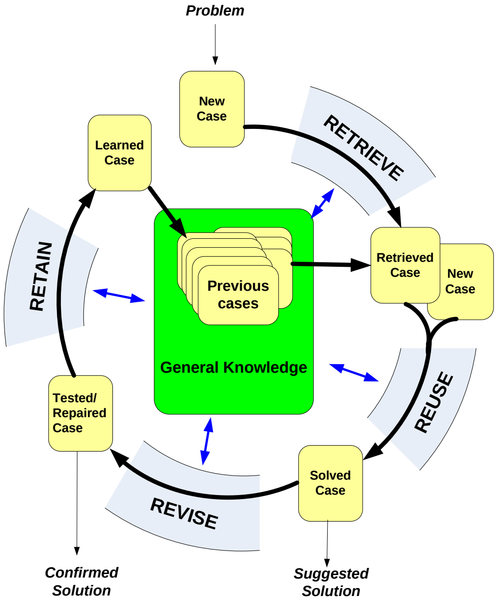


Figure 1: The CBR cycle [1].

Methodology

Our goal is to develop a predicting system for oil well drilling, mainly to assist the drilling crew to improve their reactions by early awareness. To meet this goal, a new well-established methodology is introduced, as outlined in Figure 2. Hereby, we briefly review the methodology starting from the case building and ending at the sequence building process.

According to the below workflow, the case building includes defining cases, e.g. case's features elicited from measurements, matching between cases, and finally identifying the class of each case. Each case is composed of important groups of features for defining a case. Definition of cases is the crucial component in the case building process and is discussed in more detail in the next section.

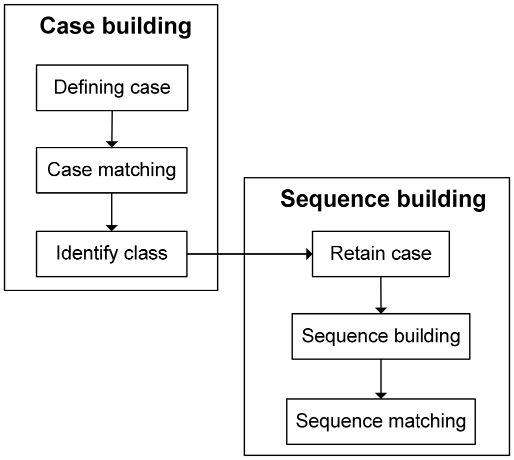


Figure 2: Schematic representation of the methodology.

A case-based reasoning system has been implemented for building the case database and matching between the cases. The ability to categorize cases within the case database allows the identification of the types (classes) of cases that are used for sequence analysis. Cases are categorized in the case database into case classes according to the similarity between a new case and other cases. The benefits from classifying cases can be either finding root causes or using them for sequence building. In order to enable building of sequences, all the categorized cases are kept in a depth-based domain. As can be seen from Figure 2 sequence building is fed directly from the case building process. Where we previously relied exclusively on a single case, sequences now tell us exactly what the next activity will be. In order to determine the applicability of the methodology in oil well drilling, we evaluate the effectiveness of the sequences by measuring the accuracy of their prediction. Each sequence consists of three cases in a raw. An ordering of the cases in a sequence will be previous, present and next case.

In the next sections, the components of the proposed architecture are discussed.

Case structure

A case in CBR must contain information for characterizing episodes, so that whenever a similar episode appears, the most similar case from the case base is matched and retrieved. The Case structure presented by Shokouhi et al. [12, 13] was utilized with some modifications. The case structure accompanied by a case's features is demonstrated in Figure 3. The case structure contains the important features for defining a case. Selecting the adequate factors can provide considerably better case definition for a case retrieval process. Each case comprises: (i) administrative data, (ii) static parameters, (iii) inferred parameters, (iv) indicators, (v) activity determination, and (vi) events recognition. The importance of each feature is dedicated by its weight.

As the drilling operation goes on, a new case is introduced to the system. It means that all of the case's features are captured and after similarity assessment the new classified case is retained in the case base for future use.

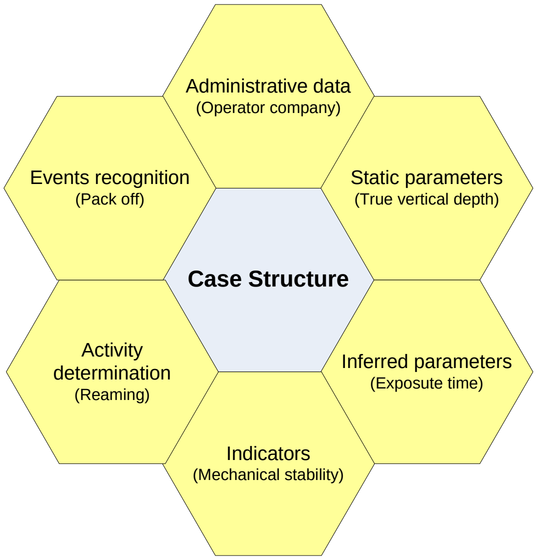


Figure 3: A graphical representation of our case structure (exemplified).

Administrative data

Administrative data are not used in the case matching process. This information describes where and when the problems happen. It helps us to figure out which well sections had likely problematic situations for further analysis and for building cases. Examples of administrative data are operator company, drilling contractor, well identification, field identification, and etc.

Static parameters

Observation factors include drilling fluid and drill string parameters, well geometry, and formation characteristic. These parameters are constant between measurements, i.e. may be altered several times during drilling of a well. Some of static parameters are depth, inclination, mud viscosity, BHA length and so on.

Inferred parameters

Problems generally build up with time, starting with small problems. 'Open Hole Exposure Time' (OHET) is one of the inferred parameters in this study. OHET is the time period when the formation is in contact with drilling fluid, which again may cause a problematic situation during the drilling operation. Higher exposure time can contribute to higher problems [12].

Indicators

While drilling deviated wells the cuttings and also cavings (unintentionally produced materials) tend to accumulate into beds on the low side of the wellbore. When tripping out or tripping in, the drill string with its bottom hole assembly (BHA) tends to scrape and push the wellbore material into piles and thus create restriction in the hole. Therefore, indicators that reveal hole enlargement and cavings production are necessary. In addition, a caliper analysis in the selected well section has shown that the wellbore enlarges during drilling. Caliper while drilling showed a maximum diameter of 10 in, at which the original well diameter is 8.5 in. There can be three main reasons for these enlargements and cavings production, mechanical, chemical and erosion. The Mechanical rock instability can occur because the in situ stress state of equilibrium has been disturbed after drilling. The mud weight may not bring the altered stresses to the original state; consequently, formation may become mechanically unstable.

Borehole breakout is a typical type of wellbore instability induced by compressive rock failure around the wellbore wall due to stress concentration. The failure process around an opening in brittle rock usually describes as spalling or slabbing, and the shape of the failed zone is commonly called "breakout", "dog-ear", or "v-shaped notch" [14]. Problems generally build up with time, starting with the fragmentation of the wellbore wall followed by transfer of the fragments to the annulus and finally if the hole cleaning is insufficient culminate in such difficulties as a tight hole, packing off, filling-of-the-hole, stuck pipe, etc. the ultimate consequences of borehole instability may include having to side-track or losing the hole completely.

In order to determine initial stresses around the borehole, in situ stresses will be transformed with respect to the inclination and azimuth of the borehole. Figure 4 shows the configuration of the borehole accompanied with in situ and transformed stresses. Stresses around the borehole are calculated by equation (4). Plain strain condition is assumed and there is no displacement along the z-axis. Jaeger and Cook's [15] derived the stresses and displacements around a circular hole in a homogeneous medium. Details can be found in this reference. In order to examine the stresses in the rocks surrounding a borehole, it is convenient to express the stresses and strains in cylindrical coordinates.

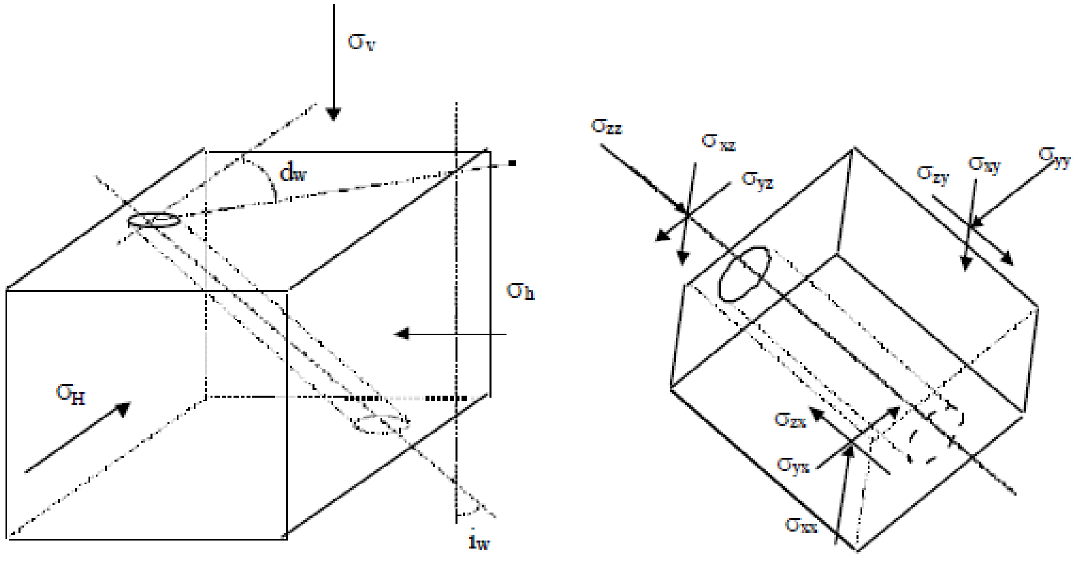
$$\begin{aligned}
\sigma_r &= \left[\frac{\sigma_x^o+\sigma_y^o}{2}\right]\left[1-\frac{R^2}{r^2}\right]+\left[\frac{\sigma_x^o-\sigma_y^o}{2}\right]\left[1-\frac{4R^2}{r^2}+\frac{3R^4}{r^4}\right]\cos 2\theta+\tau_{xy}^o\left[1-\frac{4R^2}{r^2}+\frac{3R^4}{r^4}\right]\sin 2\theta+\frac{p_w R^2}{r^2}\\
\sigma_\theta &= \left[\frac{\sigma_x^o+\sigma_y^o}{2}\right]\left[1+\frac{R^2}{r^2}\right]-\left[\frac{\sigma_x^o-\sigma_y^o}{2}\right]\left[1+\frac{3R^4}{r^4}\right]\cos 2\theta-\tau_{xy}^o\left[1+\frac{3R^4}{r^4}\right]\sin 2\theta-\frac{p_w R^2}{r^2}\\
\sigma_z &= \sigma_z^o-\nu\left[(\sigma_x^o-\sigma_y^o)\frac{R^2}{r^2}\cos 2\theta+4\tau_{xy}^o\frac{R^2}{r^2}\sin 2\theta\right] \qquad (4)\\
\tau_{r\theta} &= \left[\frac{\sigma_x^o-\sigma_y^o}{2}\right]\left[1+2\frac{R^2}{r^2}-\frac{3R^4}{r^4}\right]\sin 2\theta+\tau_{xy}^o\left[1+2\frac{R^2}{r^2}-\frac{3R^4}{r^4}\right]\cos 2\theta\\
\tau_{\theta z} &= (-\tau_{xz}^o\sin\theta+\tau_{yz}^o\cos\theta)\left[1+\frac{R^2}{r^2}\right]\\
\tau_{rz} &= (\tau_{xz}^o\cos\theta+\tau_{yz}^o\sin\theta)\left[1-\frac{R^2}{r^2}\right]
\end{aligned}$$

For cases involving cylindrical or axial symmetry, e.g. stress and pressure analysis around a wellbore, the system of cylindrical coordinates r, θ, z are used, in which the stress components become

Normal stresses: σ_r, σ_θ, σ_z

Shear stresses: $\tau_{r\theta}, \tau_{rz}, \tau_{\theta z}$

In these expressions: σ_x^o, σ_y^o, σ_z^o, τ_{xz}^o, τ_{yz}^o, and τ_{xy}^o are the virgin formation stresses in cartesian coordinates. The σ_r, σ_Θ and σ_z are not principal stresses because the shear stresses are non-zero. The next step will be to determine the maximum and minimum principal stresses.



(a) (b)

Figure 4: (a) A wellbore configuration showing stresses and coordinate systems including in situ stresses (b) stresses in the local wellbore coordinate system around the wellbore [16].

The Mohr-Colomb criterion is commonly used to reveal the unstable parts of the wellbore. With regard to critical mud weight required for staying stable, it is shown by Mohr-Colomb that instability occurs when formation cannot withstand the earth stresses. Using this relationship it is possible to calculate the required support pressures to minimize formation breakout. This criterion needs stress and formation properties around the wellbore.

$$F = \sigma_1 - \sigma_3 \frac{1+sin\varphi}{1-sin\varphi} - 2C_0 \frac{cos\varphi}{1-sin\varphi} \qquad (5)$$

Failure occurs when $F \leq 0$;
where σ_1 , σ_3 are the maximum and minimum principal stresses, φ is the friction angle, and C_0 is the cohesive strength.

Basically, negative value of F points at the unstable part of the wellbore. The positive value explains the possibility of the failure state around the wellbore. It means that intervals with lower F values are sensitive to small changes such as mud weight.

When a hole is drilled into a subsurface rock the horizontal stresses are relieved, and the borehole contracts until the radial stress at its wall is equal to the pressure of the mud column, minus the pore pressure. The load is transferred to a zone of hoop stresses that create tangential shear stresses around the borehole. The hoop stress is maximum at the wall, and decreases with radial distance into the formation (shown in Figure 5). By means of Eq. (4) we will be able to calculate and determine radial and tangential stresses around borehole at plane strain condition. In this study, stresses are calculated around the wellbore, from the wellbore wall into the formation not more than five times greater than the wellbore radius.

Substituting the value R/r=1, 2, 3, 4 and 5 in Equations (4) gives the variation of stresses on the wall of borehole and inside the formation. The Kirsch solution allows calculation of the stresses around the borehole and later will be used for failure analysis.

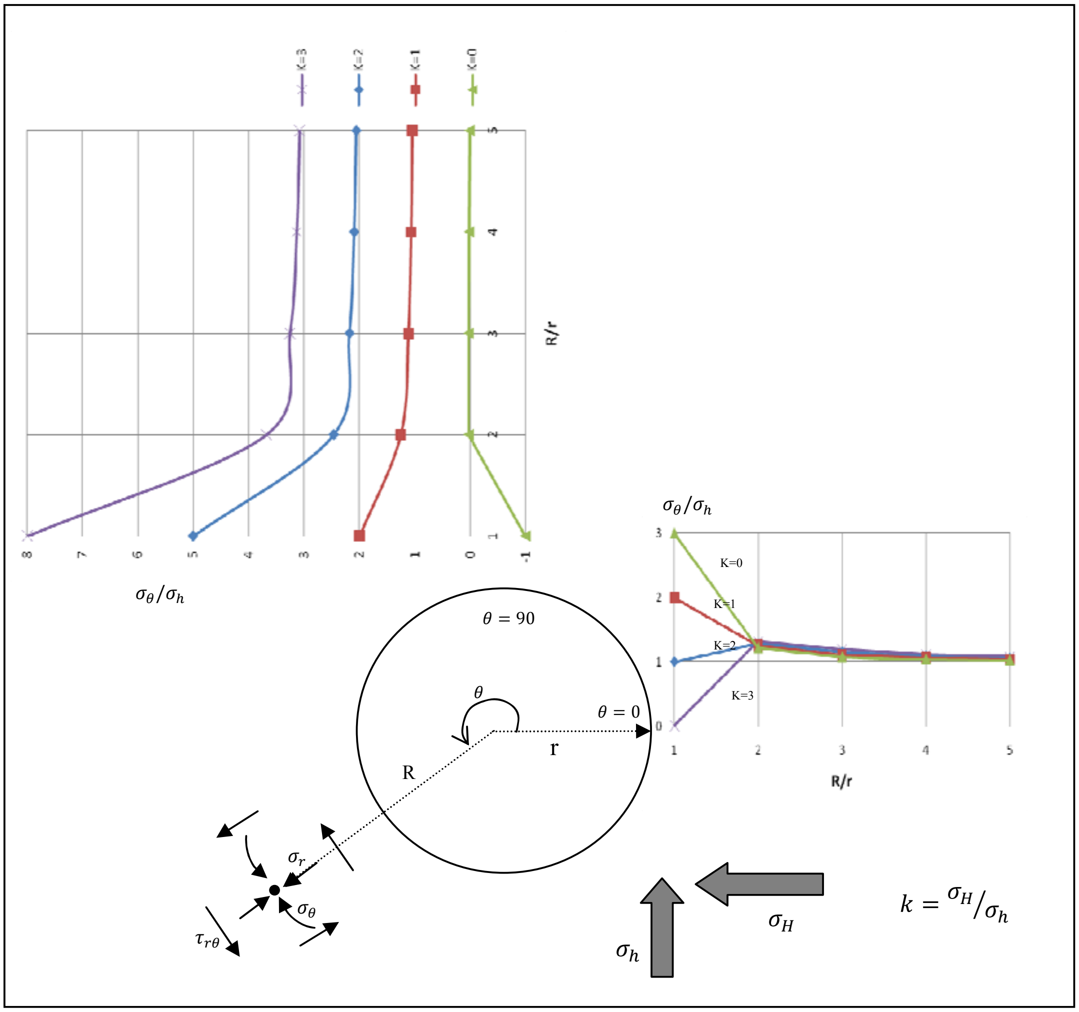


Figure 5: Stresses around a circular hole calculated for various stress ratios and various distance from the borehole wall.

Reactive shales can interact with water and fail, leading to washouts. To check chemical effects, pore pressure diffusion and ion diffusion, which is usually a slower process, and osmotic effect [17], are implemented. When drilling in shale, drilling problems may be reduced by the use of muds that inhibit reaction between drilling fluid and formation. The formation of this instability is a direct consequence of changes in pore pressure that occur due to water and solute influx into the shale [16].

Water movement due to osmotic effects is controlled by the ratio between the water activities of the mud and the pore fluid. The water activity is inverse proportional to the solute concentration in the fluid. Pure distilled water has a water activity of unity.

Fluid dynamic in the annulus can be a source of further caving, addresses hydraulic erosion. Drilling muds are non-Newtonian fluid that can generate high shear forces at the borehole wall. This effect is obviously all the more intense as the flow rate is high and the annulus narrow (in front of the drill collars for example). Risk of hydraulic erosion can be assessed by the Metzner number (MTZ) which is simply an adaption of the Reynolds number to non-Newtonian fluids in an annulus [18].

Activity recognition

Drilling a well section, i.e. a part of the drilled hole, typically in the range of 500-2000 meters long, may take several days. Generally speaking, drilling operation includes different activities such as

- *Drilling:* The process of making a new hole.
- *Connection:* The process of adding a drill pipe to the drillstring.
- *Tripping In/Out:* The act of running the drillstring into/ out of the hole.
- *Circulating:* Pumps are turned on with pipe turning slowly and/or some pipe reciprocation and/or no weight on bit.
- *Reaming:* Return to total depth with pumps on, pipe rotating and/or weight on bit.
- *Backreaming:* Return back from total depth with pumps on, pipe rotating and/or weight on bit.

Real-time data include observed data collected from sensors. They cannot explain the situation alone. But they need to be interpreted in such a way that they can be understandable and informative. Some of these data are implemented to distinguish what kind of activity goes on when a case occurs. Based on the different parameters, such as rotation of the drilling bit, pumping the drilling fluid from the drill pipe and back through the annular, and positioning of the drilling bit and traveling block, activities are interpreted.

Table **1** shows typical drilling parameters and variations for determining the drilling activities. It also explains how to distinguish between different activities on the basis of real-time data. As can be seen, when the rotation and pumping are on, hook load is equal to weight of drill string minus WOB, and with position decreasing, the activity will be inferred as drilling.

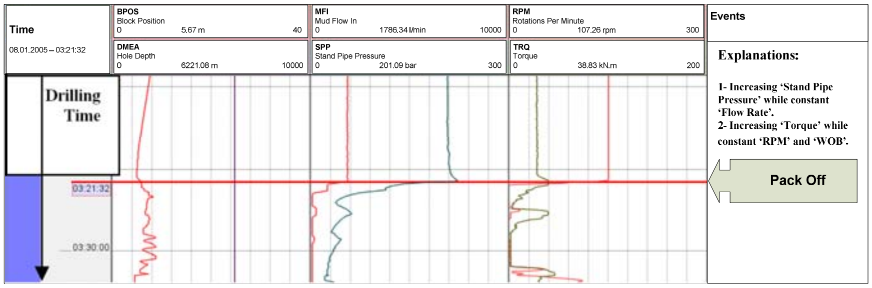
Table 1. Definition of the most frequent occurring drilling activities Where: B= weight of the travelling block, WODS=weight of drill string. Definitions of symbols are: ✓=active parameter, ×= inactive, ↑= moving up and ↓=moving down.

Parameter Activity	Rotating	Pumping	Block movement	Hook load
Drilling	✓	✓	↓	WODS - WOB
Tripping in (RIH)	×	×	↓	WODS - friction
Tripping Out (POOH)	×	×	↑	WODS + friction
Reaming	✓	✓	↓	WODS - (WOB + friction)
Backreaming	✓	✓	↑	WODS + (WOB + friction)
Connection	×	Either	×	B
Circulating	×	✓	×	WODS

Event recognition

If hole cleaning is insufficient, it culminates in difficulties such as tight hole, packing off, stuck pipe, etc. The ultimate consequences of poor hole cleaning may include side-track or losing the hole completely. Accumulation of beds of solids (cuttings, cavings, and weight material) at a given depth is a common source of packoff and tight spot.

In this section 'pack off' is exemplified. Figure 6 shows a snapshot from one of the system's screens, where a 'pack off' event is interpreted from real time data. Observed data collected from sensors, like flow rate and stand pipe pressure, cannot explain the situation alone. They are more useful for case classification and for finding the root cause when combined. In the Explanations (right part of the figure), 'Flow rate' is the pump rate of drilling fluid for transportation of produced material from the bottom of the hole to the surface. 'Stand Pipe Pressure' is the pressure measured at the surface which may increase due to any obstacle inside the hole. Increasing of the 'Stand Pipe Pressure' will indicate a 'pack off' situation while the variables such as 'Flow Rate' are constant.



Explanations:

1- Increasing 'Stand Pipe Pressure' while constant 'Flow Rate'.
2- Increasing 'Torque' while constant 'RPM' and 'WOB'.

Figure 6: 'Pack off' recognition from observed data [12].

Due to the high cost of a drilling operation, the need for real-time data and measurements has become greater than ever. Interpretations of available data are essential for providing safe and low cost drilling. The acquired data consist of drilling rate, hook load, pump pressure, flow rate, depth, torque, rotary speed, weight on bit, etc. Some small problems, such as took weight, tight spot, pack off, etc. can be detected by monitoring some parameters. Torque and drag programs are indicative for the small problems which may develop into big problems later.

Because no hole is truly vertical, and because the drill string is flexible, the rotating drill pipe bears against the side of the hole at numerous points. The frictional resistance thus generated may require considerable extra torque than otherwise required to turn the bit. Similarly, considerable frictional resistance to raising and lowering the pipe may occur, a problem referred to as drag [19]. Drag is defined as the excess in hook load over the free handling load. Increase in drag may be caused by bit balling, sever dog legs, deviated holes, differential sticking, and extra volume of cuttings influx into the wellbore. Tight spot is a sudden increase in hook load while tripping out at constant speed. Likewise, took weight is a sudden decrease in hook load while tripping in at constant speed. It means that hook load will be lower than the real weight of drill strings.

Torque vibrations are continuously monitored at the drilling rigs. Torque usually increases gradually with depth due to increased wall-to-wall contact of drillpipe and wellbore. A drastic increase in torque may serve as an additional pressure indicator.

Case matching

Two different mechanisms are used to compute the values of similarity between a new problem case and a case in the case base. Linear similarity is used for those features that have numeric values. Semantic similarity is being used for direct or indirect match of symbolic feature values. It is relying on concepts abstraction. Linear and direct symbolic similarity measurements are used for case matching within the plain CBR platform (for more information see [12]).

Basic similarity among cases, a solved case and an unsolved case, is computed by the following equation.

$$sim(C_{IN}, C_{RE}) = \frac{\sum_{i=1}^{n}\sum_{j=1}^{m} sim(f_i, f_j) \times relevancefactor_{f_j}}{\sum_{j=1}^{m} relevancefactor_{f_j}} \qquad (6)$$

C_{IN} and C_{RE} are the input and retrieved cases, n is the number of findings in C_{IN}, m is the number of findings in C_{RE}, f_i is the i^{th} finding in C_{IN}, f_j the j^{th} finding in C_{RE}.

Two different mechanisms are used to compute the values of similarity between a new problem case and a case in the case base. Linear similarity is used for those features that have numeric values. Semantic similarity, relying on concepts abstraction, is being used for direct or indirect match of symbolic feature values. The latter, indirect match, is used when the model based module is utilized.

The linear approach explicitly computes the values of similarity according to the minimum and maximum values of each concept. The maximum and minimum of each feature give an interval, and the values of the two cases are compared on this scale, giving a value of 0 if the difference between the values is the same as the difference between the minimum and the maximum, and a value of 1 if the values are the same.

For symbolic concepts:

$$sim(f_1, f_2) = \begin{cases} 1 & if\ f_1 = f_2 \\ 0 & if\ f_1 \neq f_2 \end{cases} \qquad (7)$$

For linear concepts:

$$sim(f_1, f_2) = 1 - \left|\frac{f_1 - f_2}{Max - Min}\right| \qquad (8)$$

The relevance factor is a number that represents the weight of a feature for a stored case. The relevance factor of each feature was defined according to the feature's importance for the case description.

Identifying class

Knowledge from operation and from experts is presented in the form of cases that summarize the drilling experience. A classification algorithm is implemented to organize the cases for predicting of the upcoming action. Cases are classified into several classes solely on the basis of their descriptions. In order to make cases usable by sequences, all cases are classified into certain classes by our case-based reasoning system. The retrieval process is responsible for identifying the class. A current case is then compared to others in the case base where each case is composed of several features and an associated action. Whenever there is no matched case for a new case, the new case is categorized into a new class after having been revised by experts. The classification algorithm was presented in another paper in greater detail [20].

Sequence building

A new case is made and compared to previously retained cases. The new case will be kept for later re-use as part of the CBR cycle. Afterwards, the new case is retained and will constitute a sequence. A sequence includes three cases representative of past, present and succeeding situation. For sake of clarity a simple example of the sequence building is reported in Figure 7. Assume, there are 5 cases for one interval; case 1, case 2, case 3, case 4, and case 5. According to our definition there are 3 sequences (shown in Figure 7). The first sequence consists of case 1, case 2 and case 3. Over time, a new case, e.g. case 4 is introduced to the system where the second sequence is composed of case 2, case 3 and case 4. The third and last sequence is created upon the case 5 is made. Thereby, sequence 3 consists of case 3, case 4 and case 5. The main advantage of the system is of predictability based on the previous and current situation of each sequence.

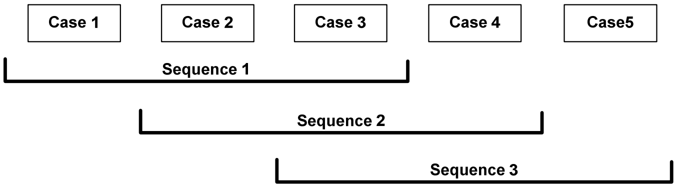


Figure 7: Sequence building routine, exemplified by five cases.

Sequence matching

A case has finally got a two-dimensional vector, where the first dimension is the activity code such as drilling, tripping in, tripping out, etc. The second dimension is the class code. For example, D4 represents a case with drilling activity, classified into class 4. We use codes to identify cases. Hence all the cases can be used for pattern recognition. The coding system enables a simple sequence matching process. The CBR model will then match the pattern with the other cases in the sequence base. As mentioned before, each sequence is composed of three cases; previous, present and next case. In this way, a sequence database is created and is used for sequence matching.

The quality of a prediction algorithm is generally judged by the results it produces on a certain test set for which the true classification is a priori known. Whenever both the activity code and class code for the succeeding case of two sequences (a new and retrieved sequence) are not the same, the prediction is failed. Leave-one-out cross-validation was used, and the single most similar sequence was used to check predictability of the sequence that was taken out. Leave-one-out cross-validation is a standard test procedure for statistically evaluating the accuracy of a method based on a set of data. The sequence matching routine is run for each sequence. The matching results are presented in section 5.

Evaluation of the methodology in oil well drilling

Figure 8 demonstrates the implementation of the methodology described in section 3 in oil well drilling. When a new well is drilling, a new case is made. As mentioned all the case's features including activity code are collected. A new case is compared to other cases in the case database shown in the lower part of Figure 8. The new case is also classified based on the available cases in the case database. Since most of the problems during the drilling operation are related to the formations being drilled [21], classified cases will be kept into the depth-based intervals for later re-use and prediction. In addition, the cases are used to build the sequence database. Our database includes two types of sub-database; the case database and the sequence database. The first one, case database, is used for the case matching purpose. The second type, sequence database is thus used for the sequence matching process. As we already explained in the previous part, each sequence has three cases; past, present and succeeding case. The system is able to predict the succeeding situation based on the past and the present case. Therefore, the result of the sequence matching process is labeled as prediction.

Valuable explanations are deduced from cases and sequences. Knowing about the background of an interval will facilitate decision making and also cautiousness of the drilling crew. In brief, the explanation of problems and patterns recognition is another benefit of sequence analyses.

To evaluate the model, the methodology is applied in the oil well drilling. Due to the number of parameters, influencing hole cleaning operation and the complex mechanisms involved, the phenomenon has not yet been fully understood [22]. In fact, hole cleaning problems were chosen to be investigated by means of our methodology. We will investigate a well section located in the North Sea for application part of the research.

Well location: In this work an 8½ inch well section drilled in the North Sea was chosen. The various reservoir zones have different permeabilities and rock strengths. The lithology of the area consists of a relatively uniform claystone package down to the reservoir sands. The claystone is interbedded with sand and limestone stringers and does not have faults.

An analysis of azimuthal caliper data showed that the hole in general is enlarged in shale. The caliper analysis also showed that when drilling hard calcite cemented sandstones at very low ROP, additional erosion is taking place in the shale above the stringer. This is caused by mechanical and hydraulic wear around stabilizers, and increased exposure time when drilling into hard stringers at low ROP.

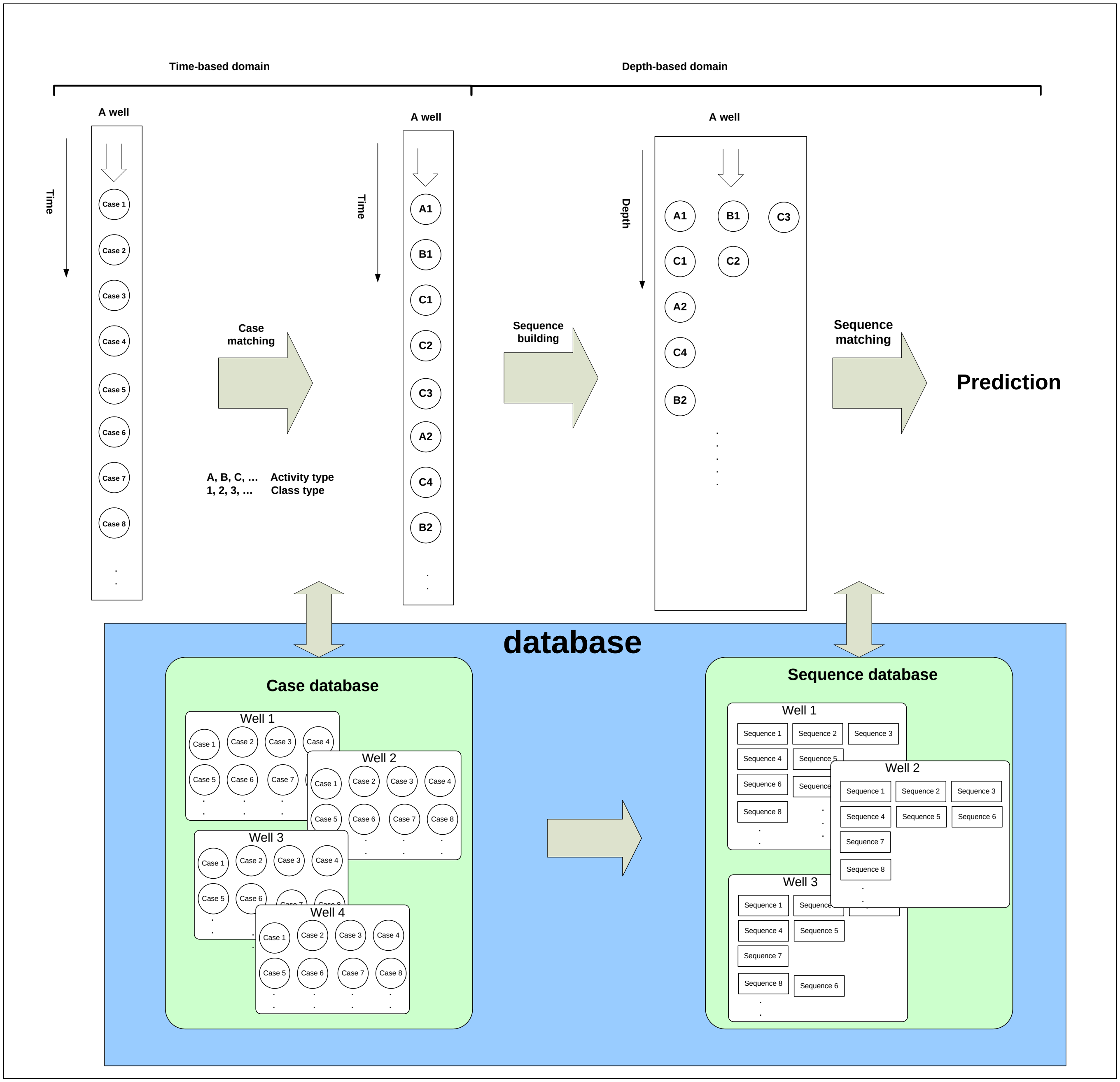
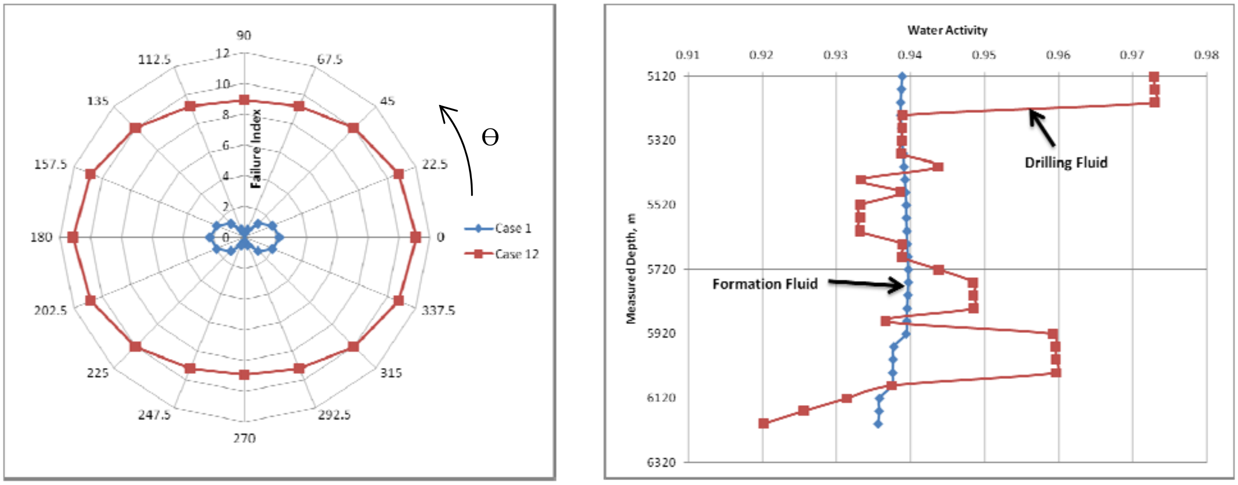


Figure 8: Case-based reasoning is used to retrieve a case similar to a new case in a time-based domain. They create sequences of cases in a depth-based domain. For each case, a combination of letters and figures represents activity and class type respectively.

Mechanical and chemical instability

A failure index has been defined in Eq. (5) and exemplified here for two different intervals; 5120 - 5160 m and 5560 - 5600 m. Figure 9a shows the value of the failure index around the wellbore. The failure index was calculated in different points around the wellbore with respect to Θ. The value depends on the inclination and azimuth of the wellbore. In the first interval, the wellbore is next to unstable situation for $\Theta = 90$ and 270 degree. It shows a case where a wellbore is initially stable. However, as water and solute are exchanged between the wellbore and the formation a region of instability develops. As mentioned in chapter 3, larger values of failure index will result in more stable boreholes. It is desirable to match the activity of the drilling fluid with the water activity in the shale. Otherwise, the shale adsorbs water and hence the pore pressure within the shale is increased. This could lead to wellbore instability. But for the second interval the failure index varies between 11.5 and 9 around the wellbore. These kinds of analyses provide a useful indication of the weak places around the wellbore.

Another phenomenon that provides delayed instability is chemical instability. Water activity of the drilling fluid is required to be identical to the water activity of the formation fluid. Figure 9b illustrates water activity profiles of drilling fluid and formation fluid. Water activity depends on the type and amount of dissolved ions. Lower water activity of the drilling fluid compared to water activity of the formation fluid is beneficial for borehole stability since that increases the effective support of the drilling fluid on the borehole wall. Due to this chemical effect the failure index for case 1 moves towards instable situation, meaning the negative value of the failure index. In short, the failure indices determined in different points around the wellbore are included in the case's features. The value of the failure index is used for case comparing with respect to the sign of the failure index.



(a) (b)

Figure 9: (a) Failure index exemplified for case 1 and case 12 around the wellbore (b) water activity profile of drilling fluid and formation fluid of the studied well.

Activity and event recognition

Figure 10 shows typical drilling operations for 1120 m open hole length section in the mentioned well section. It depicts the usual drilling operation in bit measured depth (MD) and time scale. Several events such as pack off occurred frequently due to poor hole cleaning and wellbore restriction. The section starts from 5120 m and ends at 6240 m measured depth. The previous casing depth was at 5120 m. There is no point in making a case in the depth above 5120 m with respect to the wellbore restriction. Every 40 meters has been chosen for data analysis and case building length.

According to the time and depth, the whole drilling operation was digitized into 163 cases, marked with numbers from 1 to 163. In order to provide a good classification and later employing the right repair actions based on previous experience, it was decided to divide cases into groups with respect to their operational activities. In this study drilling, reaming, tripping in (RIH), tripping out (POOH) and circulating are the most frequent activities. The number of cases made based on their activities are: 29 for drilling activity, 33 for tripping in, 43 tripping out, 21 for reaming and backreaming, 35 for circulating, and 2 for miscellaneous activities. For each case all the features were provided and 163 cases were introduced to the system. Each case is compared to other cases which belong to the same group in terms of activity type.

The following chapter will discuss the results only for the drilling activity. Surface and downhole data are logged typically every 5 second. These data are continuously evaluated and interpreted to identify events in the ongoing operation. All the interpreted events were tagged, and are shown in Figure 11. The tagged events are pack off, tight spot, took weight, torque vibration and increased torque, hard formation and hard stringer. They can happen due to many reasons such as presence of mobile formations, hydration of shales, presence of cuttings or cavings and mud cake.

These problems are common and manageable in drilling operation. But if the severity or quantity of the mentioned problems increases it may turn into more serious problems which require extra time to fix. With time, the problems may even lead to giving up the well section partially or completely. Drilling through alternating hard /soft intervals caused hole enlargement and directional changes, resulting in taking weight while RIH. After RIH (Run in Hole), packing off problems were continued for 43.5 hours. The well packed off completely and was given up. The bottom part of this section (bottom at 6221m MD) was given up due to hole cleaning issues, and sidetracked from 5608 m MD.

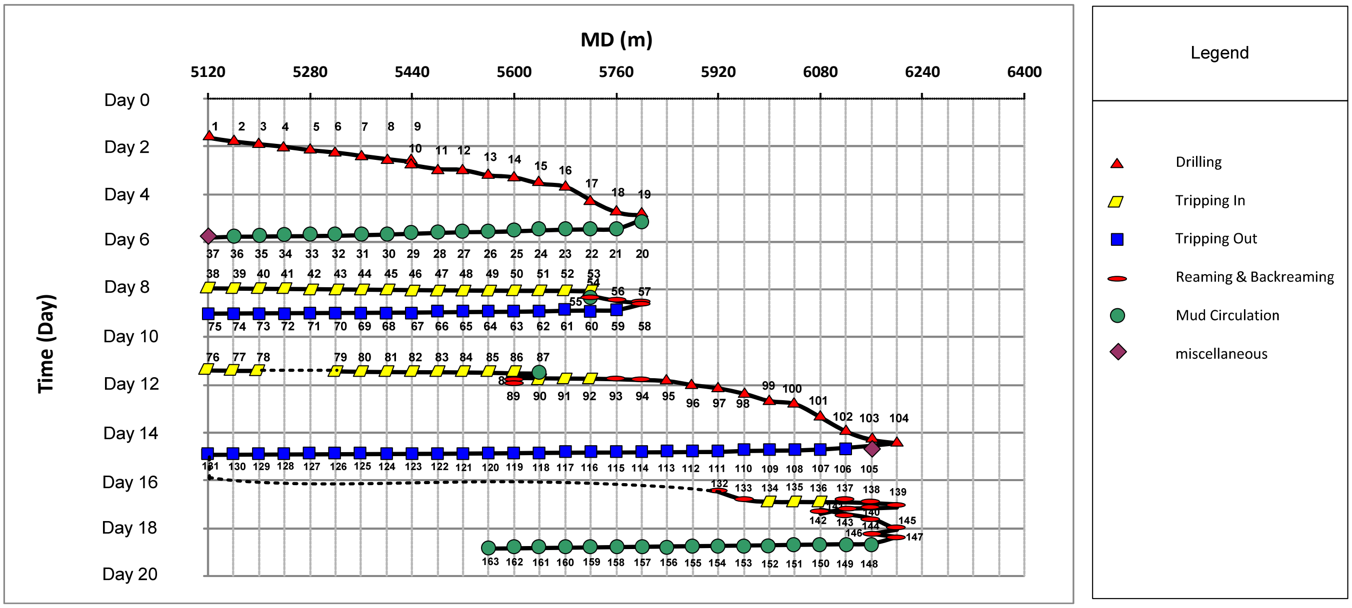


Figure 10: Digitized cases in a bit depth vs. drilling time plot. Cases were made in different activities.

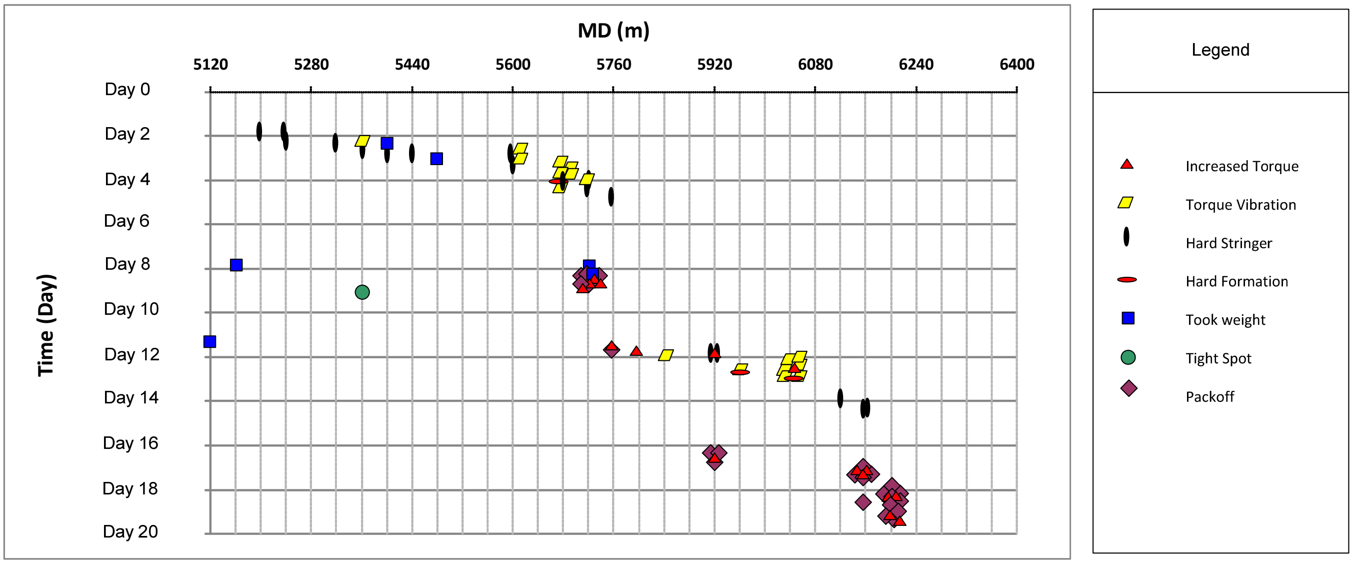


Figure 11: Event recognition in the studied well section.

Results and discussion

Case analyses

The near bit continuous inclination showed small directional changes both when drilling into, and when exiting hard calcite cemented formations. Changes in azimuth cannot be measured. Presence of ledges results in a stiffer and less flexible BHA when different stabilizers were positioned within different intervals of stringers. It is of critical importance how these stringers are drilled in order to avoid tripping problems. Cuttings and material will easily accumulate in hole enlargements. The problem may occur even if hole cleaning has been efficient. These mechanisms do not hinder the BHA from being pulled smoothly out of the wellbore. However, when running back into the wellbore, the bit may easily hang up in these zones due to enlarged hole and ledges. The face of the bit also plays an important role. When starting to circulate drilling fluid and rotate the drill string, cuttings accumulations pack off around stabilizers positioned in gauge calcite cemented sandstones where the flow area is marginal.

Classification results themselves are not the aim of this paper. It is therefore sufficient to explain the classification results for one of the activities. The results for cases with drilling activity including lessons learned are explained. We then classified the cases mentioned in the previous part into five classes. These classes are soft formation, hard stringer, normal condition, hard formation and reactive formation respectively. Most of the cases were classified in class 2, in which hard stringer i.e. a relatively small portion of harder earth formation, has been encountered. Detailed study reveals that the lithology of the area consists of a relatively uniform claystone package down to the reservoir. The claystone is interbedded with sandstone and limestone stringers. Instantaneous reduction in rate of drilling occurs while drilling through hard stringers. Hard stringers can make directional changes when entering and exiting the hard stringer. Washouts are created in softer formation in front of stringers due to mechanical and hydraulical wear around large outer-diameter (OD) components. Thereafter, produced materials easily accumulate in such hole enlargements. During the RIH and POOH activities some kind of events such as took weight and tight spot will occur. In some cases best-practice are available. Otherwise former experiences from matched cases are used. Our methodology may return either cases without any problems or cases with some problems that have to be solved.

The following items were observed when drilling in alternating layers of hard calcite cemented formations and softer shale:

- The softer shale will erode and hole enlargement take place
- Stick slip and possible whirl occurring when drilling very hard formations at high WOB and low RPM resulting in tool failure, tripping and increased erosion of the formation
- Calcite stringers are in gauge
- Micro ledges are generated when entering and exiting the stringers at low angle of attack between the wellbore/bit and the hard stringers
- Shoulders are generated in the transition zone of enlarged shale and gauge hard stringer
- The BHA will be stiffer and less flexible when stabilizers positioned in different stringer intervals
- Bit may easily take weight in entry/exit points
- Cuttings will accumulate in hole enlargements
- Pack off may easily occur when mobilizing cuttings by means of rotation and circulation
- Directional changes performed just after long gauge calcite cemented sections may further increase risk of taking weight when running in hole

The drill string is pulled out of the hole and run into the hole for several reasons. For example, the bit has dulled and must be replaced by a new one to drill efficiently. Once the job is done, the drill string is run again into the hole to continue the drilling activity. But sometimes the RIH activity may take several hours and several repair activities are necessary. Out of 163 cases 33 cases belong to this group. In this study cases with different severity of problems were made. Some cases have experienced took weight while RIH. In addition, it was found that when pulling the BHA out of the wellbore, the pressure drop from the piston effect can be quite significant.

Sequence analyses

The ordering of problem cases is important for prediction of succeeding case. When a case was made and the class of the case was defined, the case is maintained in the depth-based domain. All the 163 cases are presented in Figure 12. For each interval we may have several cases. As can be seen in Figure 12, at least there are three cases in each interval. Every three-case on each interval is considered as a sequence. It means that each sequence is composed of three cases. Some of the sequences are exemplified in Figure 12. The maximum number of cases and sequences are nine and seven respectively. They are shown in 5600 m and 5720 m intervals. It is necessary to emphasize that the sequences are made whenever three cases are available. Having three cases depends on the operation, i.e. when and how many times drill bit could pass each interval. As can be seen from Figure 12, there is no sequence ordering up from starting depth to the bottom of the well section. The operation time controls the sequences ordering.

Moreover, on the right side of Figure 12 the distribution of formation characteristics are shown. Formations are characterized into five subgroups; sandstone, siltstone, claystone, limestone and coal bed. They are depth-dependent features in our case structure and they have a great influence on the hole cleaning and wellbore restriction issues.

In the following section two different types of conclusion will be presented. Firstly, the operation with some explanations and lessons learned from a detailed study of the sequences and reports, and secondly, the accuracy of the sequence retrieval process is presented and discussed.

Brief explanations of the operation: The wellbore was drilled from 5120 m MD to 5845 m MD. The drill string was pulled out to the 9 5/8” casing shoe. The drill string was run back in hole. While entering/exiting a sequence of hard calcite cemented sandstone formation at 5757 m MD, problems taking weight were encountered. Circulation and rotation of the drill string was initiated. While trying to pass the area, stalling and pack off events took place. The MWD signal was lost during the efforts to ream the area. After reaming the area, the mud weight was increased from 1.57sg to 1.59 sg, and a 0.9 sg pill was pumped. Next, drilling continued from 5845 m to 5850 m MD. Still no signals were being transmitted from the Power- Drive.

Later, while RIH activity the drill string took weight at 5760 m MD. This was the same depth as in previous run. However, with circulation and rotation, the area that had previously been reamed, could now easily be passed. Drilling continued until 6068 m MD where very hard formation was encountered. At 6075 m MD, the MWD tool failed again while drilling a hard stringer with excessive levels of stick slip. The hole was drilled to 6221 m MD with no MWD signals received at surface. It was then decided to pull out of the hole to replace the MWD tool. No problems were encountered when pulling the drill string out of the hole.

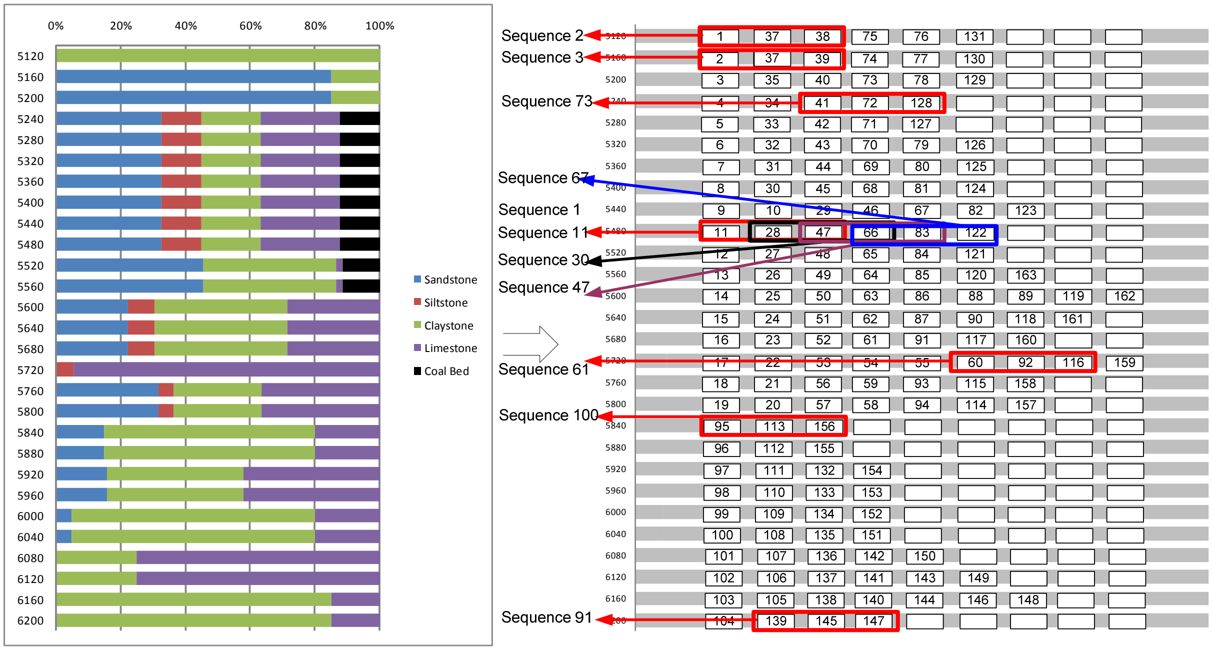


Figure 12: Formation characteristics for the studied well section (left) and a depth-based domain starts from 5120 m and ends in 6240 m including all the cases and exemplified sequences (right).

In run #3, the drill string was run in hole to a depth of 5970 m MD. Weight was taken while entering/exiting calcite cemented sandstone. When starting to circulate and rotate the drill string, the hole started packing off. Several pack off incidents occurred while reaming the area, which resulted in lost circulation. Reaming continued for a while after circulation was lost. The drill string was then run further into the hole. The drill string took weight again when exiting a long interval of very hard calcite formation. When starting to circulate and rotate, the drill string repeatedly packed off and the string had to be worked free with significant over-pull. As a result of severe drilling problems and near stuck incidents, the drill string was pulled back and an open hole sidetrack was performed.

Accuracy: 107 sequences were made out of 163 cases. Sequence matching was applied on these 107 sequences. Results are concluded and shown in Figure 13. Each sequence was compared with the previously made sequences to find the similar one if there exist one in the sequence database. As there are not so many sequences in the sequence database, therefore all sequences with no match are considered as new sequences. They are marked as not available (N/A). 44 % of the sequences were marked not available (N/A) during the sequence matching routine. In interpreting these results, the rational judgment is that unavailable sequences should not reflect the ability of our system because they are not originally present, in our sequence database.

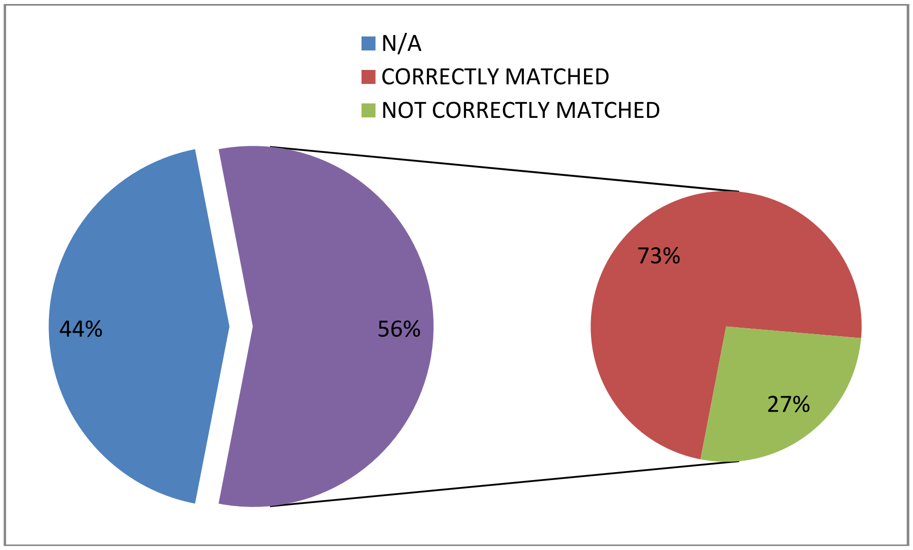


Figure 13: Accuracy of the sequence matching process.

Figure 13 presents the accuracy of sequence matching process for different sequences. It shows that matches were found for 56 % of the sequences. Out of 56 % of the sequences with matches available in the sequence database, 41 % and 15 % were retrieved correctly and incorrectly respectively. Now we just assess only the available sequences by upgrading from 56 % to 100 % because it will be more tangible in a sense. We can see from the results that 73 % were matched correctly and 27 % were not. It should be noticed that 73 % is remarkable which can improve the oil well drilling dramatically.

Conclusion

A lot of wells are being drilled every day. It is crucial to drill a hole faster and safer. To avoid the repetition of mistakes or any problems that happened in the past, a CBR system is a suitable tool in this business. This paper describes the development of a new methodology for the assessment of hole cleaning episodes. The paper illustrates what benefits our methodology can provide in the real world for predicting succeeding action to warn the busy drilling crew.

The CBR and classification approaches were successfully integrated. The paper describes a machine learning approach which starts with case discretization of cases and accumulates experiences via comparison of cases in the case database. This methodology has two main characteristics. First, it categorizes cases in the case database into case classes. Case classes are dynamically updated if it is necessary. If there is no matched case, a new class is considered and the new case is the first member of the new class. Second, when new problems are successfully classified and reported, the solution from a similar situation with the same kind of problems can be reused.

Predicting succeeding action was the main goal of this work. To meet this goal, each classified case is retained in the depth-based domain to constitute a sequence. Each sequence consists of three cases; previous, present and next case. We managed to make 163 cases and 107 sequences and categorized them with respect to the operational activity. This system is addressed as an advisory system which warns the drilling crew. The accuracy of correctly retrieved sequences was 73 %. It has been shown promising results in oil well drilling. The accuracy of prediction can be improved by enhancing the raw data from which cases were constructed, and enhancing the casebase through cases from more well sections. The results obtained from one well section show the feasibility and effectiveness of the methodology under realistic conditions.

This research work describes how to retrieve situations similar to a new case by using the case's features. Pattern recognition is a potential output of this work which needs to be tested out on different well sections. In this study each sequence is composed of three cases. An interesting extension would be to increase the number of cases in each sequence in order to improve the accuracy of the prediction.

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Nomenclature

r	wellbore radius, L,
R	near wellbore radial position, L
σ_h	minimum horizontal stress, m/Lt^2
σ_H	maximum horizontal stress
σ_r, σ_θ, σ_z	radial, hoop, and axial stress, m/Lt^2
$\tau_{r\theta}$, τ_{rz} , $\tau_{\theta z}$	shear stress component, m/Lt^2
σ_1 , σ_3	principal stresses, m/Lt^2
k	stress ratio
φ	friction angle, radians, °
C_0	cohesive strength, m/Lt^2
C_{IN} , C_{RE}	the input and retrieved cases
n	the number of findings in C_{IN}
m	the number of findings in C_{RE}
f_i	the ith finding in C_{IN}
f_j	the jth finding in C_{RE}

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