Optimization of Dogleg Severity in Directional Drilling Oil Wells Using Particle Swarm Algorithm

(Short Communication)

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Abstract

The dogleg severity is one of the most important parameters in directional drilling. Improvement of these indicators actually means choosing the best conditions for the directional drilling in order to reach the target point. Selection of high levels of the dogleg severity actually means minimizing well trajectory, but on the other hand, increases fatigue in drill string, increases torque and drag, particularly in the rotation mode. Therefore the aim is to define the index in an optimal range which meets both requirements. Particle swarm algorithm was used for optimization the dogleg severity. The final measured depth and directional well pattern were considered as an objective function and Build & Hold, respectively. Then the fatigue caused by the stresses exerted on the drill string, evaluated by modified Goodman equation simultaneously. The relationship between path parameters and the obligation to reach a target point in directional wells, converts the problem into a constrained optimization problem. Comparing the proposed directional drilling path in a drilled well in the Ahwaz oilfield with the responses obtained from the particle swarm algorithm indicated that the particle swarm algorithm is converged in finding the shortest path, and on the other hand, it decreases the time of using directional drilling equipment due to the selection of the proper dogleg severity. Note that it is likely to add other constraints to the optimization process which indicates the particle swarm algorithm efficiency in solving these problems.

Keywords: Dogleg severity, Optimization, Particle swarm algorithms, Fatigue

Introduction

The optimization in drilling was applied for the first time in 1967. Although this method was not used at all due to its available capacity, but it markedly resulted in reduced drilling cost. With a more scientific look at the industry, experts realized that the development and advancements of the equipment to achieve expected goals which were largely economic ones are not enough and optimization of drilling parameters can have prominent role in increasing speed of drilling and consequently in reducing the costs. Optimization weight on bit, rotary drill speed, drill and wells hydraulics as well as improving drilling mud and drills type, are some of measures that helped so much to improve the drilling process.

Improving various parameters of directional drilling due to its wide applications, were also affected by and always has been under consideration. Planning 3D well trajectories by using cubic function [1] and improving drilling trajectory by using different methods such as nonlinear dynamical systems [2] and multi-objective optimization method [3], were among the measures that have been performed for optimization of this type of drilling. Interdependency on various parameters of drilling as well as development of modern and intelligent methods in optimization, resulted in focusing the expert on these new techniques such that speaking of today's so smart drilling methods. Path optimization of a 'S' shape well using genetic algorithms (GA), performed by Shokir et al [4] also production optimization strategy based on GA[5] are among these measures.

In the recent decades, evolutionary methods have been applied as an optimum tool in various fields of sciences, such as economics and engineering. Ease of use

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and wide range of application as well as the ability to obtain acceptable solutions, are among the reasons for the popularity of these methods. One can mention Particle Swarm Algorithm, which is derived from the collective motion of fishes in the face of danger or birds motions in searching for food. In this paper, using this algorithm, optimization of the dogleg severity as one of the most important directional drilling indices in a well of " Build & Hold " pattern will be considered (Figure 1), the difference is that the mechanical parameters of drill string that are affected by the dogleg severity such as shear stresses, bending stresses and torque and drag of the drill string are considered in the optimization process. Remarkable note in this optimization is that other lateral parameters that somehow have influence on well path can be involved in this process.

Dogleg severity

Usually the dogleg severity indicates deflection amount of oil or gas well per hundred feet which is in two dimensions and is one of the most important parameters for directional drilling. In fact optimization of this index means selecting the best directional drilling conditions to achieve the target point. Choosing large values for the dogleg severity actually means decreasing drilling path but on the other side results in increased fatigue of the drill string, increased torque and drag force, especially in case of rotational drilling and eventually increased the possibility stuck of the drill string or creation key seat. Therefore, the objective is that the mentioned index can be defined in such an optimal range which satisfies both requirements.

The relation between the dogleg severity and final measured depth through the well path equations provides the possibility to select the final measured depth as the objective function to optimize it.

Equations in build & hold Pattern

Build & Hold pattern is one of the most commonly used patterns in directional drilling patterns as shown in Figure 1. In this pattern, there are three variables with two degrees of freedom as follows: kick of point (KOP), dogleg severity, maximum well angle. Relationships between these parameters are possible from relations 1 to 5[6].

$$DLS = \frac{18000}{\pi R} \quad (1)$$

$$\alpha = arc\cos\frac{R-X}{d} - arc\cos\frac{R}{d} \quad (2)$$

$$d = \sqrt{(D_3 - D_1)^2 + (X - R)^2} \quad (3)$$

$$MD_{EOB} = D_1 + \frac{100\alpha}{DLS} \quad (4)$$

$$MD = MD_{EOB} + \frac{D_3 - D_2}{\cos\alpha} \quad (5)$$

In proposed drilling programs the horizontal displacement amount X and also true vertical depth, D_3 until reaching to target point are known.

Effects of mechanical parameters

In directional drilling of oil and gas wells, drill string is influenced by various forces such as tension, compression, drag and torque and etc. These forces are very much affected by the well path. The combinations of these forces, particularly in the curved sections of wells as well as in case of rotational drilling due the generation of oscillating forces cause fatigue in the drill string. Figure 2 obviously shows that how the choice of a path which results in reducing these forces can decrease damages to the drill string. Torque and drag amounts as well as bending stress [7] can be calculated by the related relationships.

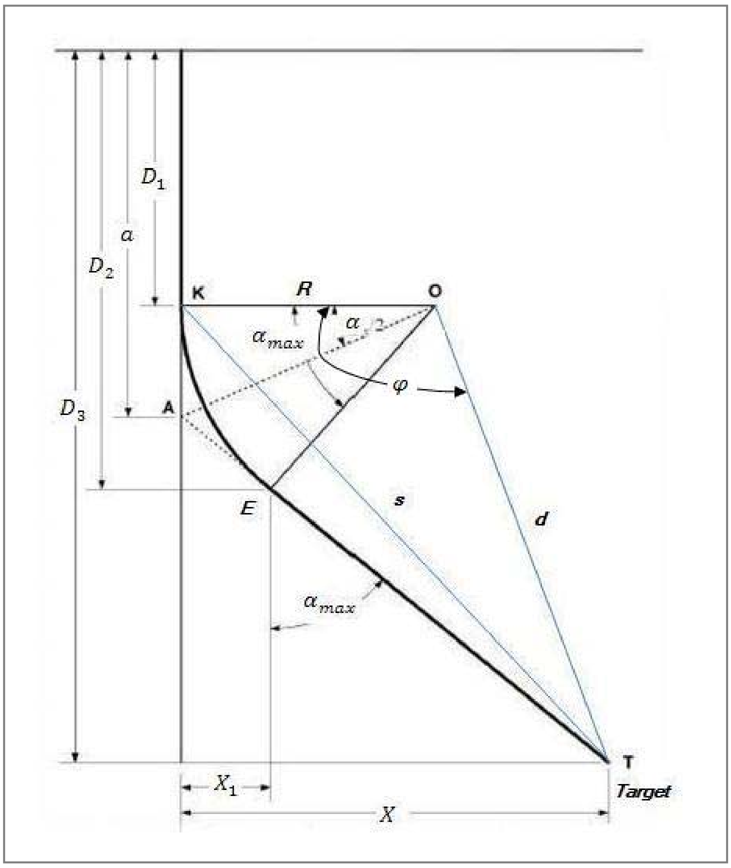

Figure 1: Well profile

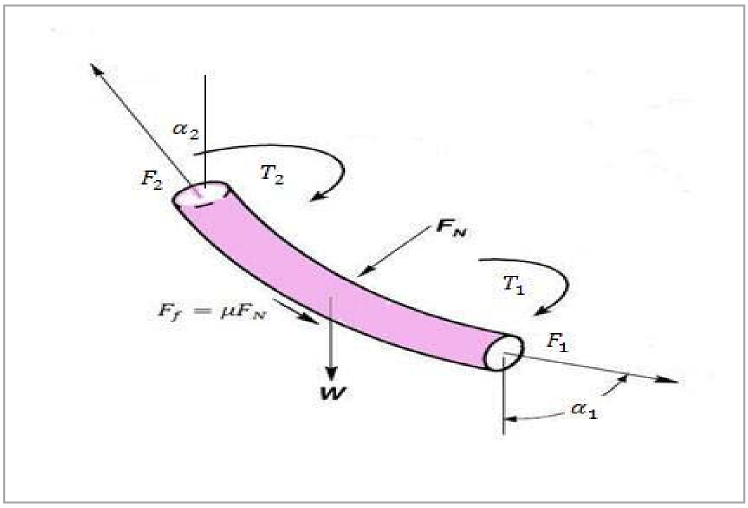

Figure 2: Drill string in curved section

Drill string fatigue

Despite of considerable progress that has been made in the drilling industries, fatigue failure of the drill string is still the largest contribution in imposed damages. Putting drill pipes into the curved sections of well in directional drilling causes bending stresses in the drill string. Amount of the stress depends on the well deformation trend. This trend of variations is expressed by the parameter of the dogleg severity. It means that the more dogleg severity, the more bending stress will be applied to the pipes. The pipes which are in curved path may be under tension or compression. Studies show that when the drill pipes are under tension, dogleg severity must have the less severe.

Rotation of the drill string in the curved path of the well put all sections of drill string under tensile and compressive loads effects in every rotation. Repeating these rotations, ultimately causes fatigue in the drill string (Figure 3).

Concerning that in curved section of the well, the drill string will be simultaneously affected by bending, torsion and tension forces, Von Mises stress [8] are used to obtain the ultimate stress amount.

According to Figure 4, the stress values of represent mean stress and stress amplitude respectively which are equal to following values.

$$\sigma_a = \sigma_b$$
$$\sigma_m = \sigma_{von} = \sqrt{3\tau^2 + (\sigma_{axial})^2} \quad (6)$$

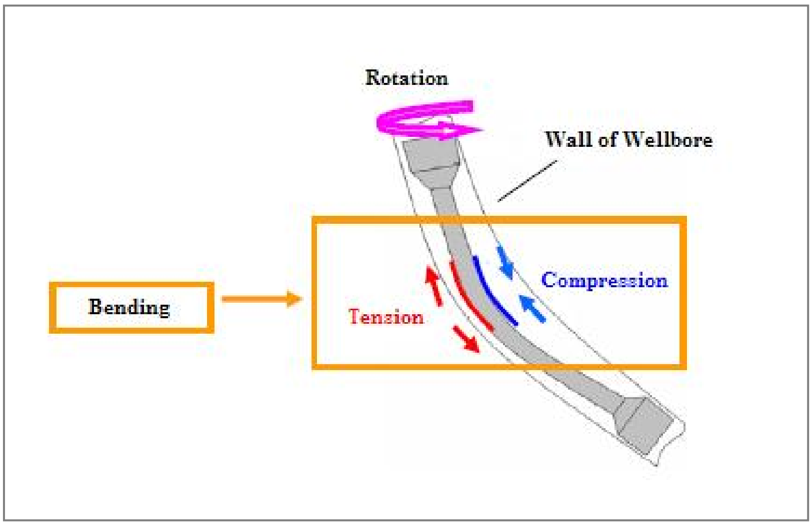

Figure 3: Forces exerted to drill string in curve section

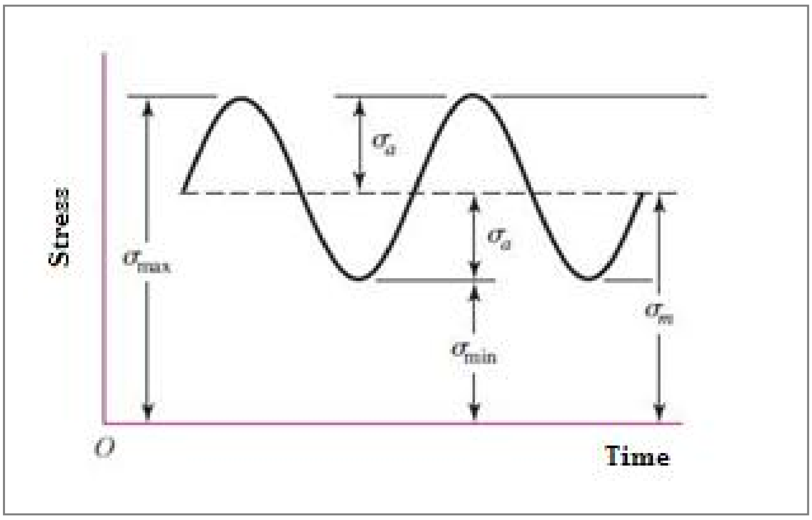

Figure 4: Stress-Time relation, fluctuating stress[8]

Shear stress τ is due to the torque applied to the drill string and axial stress σ_{axial} is due to the drill string tension. To assess fatigue failure, modified Goodman equation [8] is being used:

$$\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_{ut}} = \frac{1}{n} \quad (7)$$

Particle swarm algorithm

Collective motion of particles is a population-based optimization method and the self-adaptive search [9] inspired by the social behavior of bird flocking or fish schooling. Because of the simplicity of use and also the ability to quickly convergence to acceptable solutions, it has received much attention. This algorithm was introduced by Kennedy and Eberhart in 1995 [10]. By studying and simulating the behavior of birds for finding food, they tried to create some sorts of computational intelligence that do not need special personal abilities. Although their initial goal was not to create an optimum model, the results of their efforts lead to create a robust algorithm for optimization.

All particles have a fitness value which is evaluated by fitness function. The fitness function is also referred to as "cost function" or "objective function". Also, particles have a non-zero initial velocity. In this model, particles or individuals follow a simple behavior [9] emulating their success and the success of neighboring particles. By collecting these simple behaviors, they explore optimized range or area of search space. The principle is based on the fact that in every moment, every particle adjusts itself in the search space with regard to the best place ever been in and the best place in the whole its neighborhood. In fact, this method with combining local search method (particle personal experience), and global search (experienced neighbors), looks for optimal solution in the search space. In initial stage of the algorithm, a random population of particles with different positions and speeds will be generated. Then particles velocities and their positions are updated through relations 8 and 9 respectively.

$$V_i(k+1) = WV_i(k) + C_1 r_1\big(P_i(k) - X_i(k)\big) + C_2 r_2\left(P_g(k) - X_i(k)\right) \quad (8)$$

$$X_i(k+1) = X_i(k) + V_i(k+1) \quad (9)$$

The particle swarm algorithm can be written as follows:

1- Defining variables and set their range (the search space)
2- Creating a random initial population in the search space by various positions and velocities
3- Evaluating each particle by the objective function with respect to the number of variables
4- Comparing the evaluated value with the best particle position, if the new value is better, the best position of the particle is selected as the new one.
5- Comparing the best position of the particle through the evaluation of the objective function with the best global position, if this value is better it will replace the best global position.
6- Changing the speed and position of particle according to equations 8 and 9
7- Repeating steps 2 to 6 until as the stop criteria is satisfied (Figure 4). These criteria can be a good fitness and/or a certain numbers of repeated stages.

Modeling

In mathematical, optimization means minimizing or maximizing a function for certain variables. In this case the variables are called optimal variables. On the other hand in search space the aim is to find number of x that the function such as $f(x)$ should be maximized or minimized, although for finding the answer some constraints should be considered. In this paper, choosing the best dogleg severity is the purpose, not necessarily the highest or the lowest one. So the measured depth considered as an objective function so that the dogleg severity is one of the variables in this function and the final purpose is to minimize this function according to the well path, the drill string and operational constrains. This function is written as follows:

$$f(x) = MD = D_1 + \frac{100\alpha}{DLS} + \frac{D_3 - D_1 - R\sin\alpha}{\cos\alpha} \quad (10)$$

According to the Build & Hold pattern, there are three variables that are as follows:

- KOP
- Dogleg severity
- Maximum well angle

But these variables are related to each other according to the well path relationships, so there are two degrees of freedom in this pattern. Thus the number of variables in this problem is two that are the KOP and the dogleg severity. But the third variable, maximum well angle can be considered as a constraint.

In order to determine the initial population of particles, the range of variables must be specified. But due to the range of start of KOP is different to dogleg severity, also in order to create the initial population, both variables are defined in two separate vectors and then the initial population will be formed with their combination in a matrix. Therefore each particle will have two properties that are KOP and dogleg severity. The range of KOP can be considered in two ways:

- From true vertical depth of base casing point to the true vertical depth of next casing point. (For example, from casing point of 13 $\frac{3}{8}$ to casing point of 9 $\frac{5}{8}$). But according to relationships of well path, because of non- compliance of the maximum well angle range, there is the possibility that the solution of problem becomes incorrect. Therefore we can define constraints to this range such that the resulting solutions become acceptable. This can be done by imposing constraints on the maximum well angle of the hole. For example, we can stipulate that the angle of the hole will not be more than a certain limit or value.
- Using trial and error, and controlling the desired depth and maximum well angle one can obtain the desired range for the KOP.

In both of the above methods, changes are on lower bound.

Range of the dogleg severity is completely optional and its range according to conditions of each well (size &shape) can be different.

The initial population is evaluated according to the objective function (final measured depth). Measured depth is obtained by equation (5) and after evaluating all of the particles with respect to the initial population, the best particle (having the best KOP, and the best of dogleg severity) will be selected. Then, according to Equations (8) and (9), speed and position of particles will be found and after that re-evaluation by objective function and repeating stages by required numbers of iterations will be done to satisfy the condition, then the best particle (best General) will be selected. It is worthy to say that in this approach, convergence is toward the best solution and in the practical example that will be discussed later, it is so evident.

In the last iteration, the condition of satisfying the fatigue reliability is being evaluated by following it in each step. At the end, Optimum conditions for both modes are attained:

1- The shortest path regardless satisfaction of the fatigue requirement.

2-The shortest path regarding to the condition of fatigue criteria. For considering the fatigue criteria the equation (7) must be satisfied regarding to maximum applied stresses to the drill string. According to the well profile and mechanical properties of the drill string mentioned before, the variables and constraints can be summarized in Table 1.

Case study

According to the research subjects mentioned before, we now come to optimization of well path and directional drilling parameters such as the dogleg severity.

The optimization will be done on the Ahvaz well No.359, with hole size 12 $\frac{1}{4}$. Characteristics of well, drilling mud properties and bottom hole assembly were obtained and used from daily drilling reports presented in Table 2.

Table 1: Variables & Constraints used for modeling

Variables	Constraints
KOP,DLS,INC	Constraints related to well path such as HD, Target TVD, …. Constraints related to drill string mechanical properties such as maximum tensile strength). Constraints related to operational condition such as max well angle.

Table 2: Characteristics of well and drilling mud properties

Well Description		Mud Properties	
Field	Ahvaz	Mud Weight	145 PCF
Well Number	359	M.F.Viscosity	55
Hole Size	12 ¼ in	Solid	45%
Shoe 13 3/8	1893.5 m	θ_{300}	67
Flow Rate	520 Gpm	θ_{600}	117
Pressure	2800 Psi	PV	49
ROP Average	1.3 m	YP	19

Table 3: proposed directional drilling program

Section Calculated on 225.85								
	DEPTH	ANGLE	AZIMUTH	TVD	N/S	E/W	SECTION	DOGLEG
0	0	0	0	0	0	0	0	0
1	1909	1.5	226	1908.78	-17.97	-17.97	24.99	0.02
2	2185.14	38.32	225.85	2163.97	-81.73	-84.30	117.42	4
3	2683.54	38.32	225.85	2555.00	-296.98	-306.04	426.45	0

Table 4: Ranges of variables

Variable	Lower Limit	Upper Limit
KOP	1909	2555
DLS	1	7

With regard to the proposed directional drilling program, this program according to the Table 3 will be under local coordination. Also, ranges of variables regarding topics are presented in the section of modelling and also drilling problems in neighbouring Ahvaz field as well as field data, all are considered in Table 4.

KOP can be considered from 13 $\frac{3}{8}$ casing point, 1893.5m, but regarding to geological considerations, depth of 1909 was selected as KOP. The dogleg severity range is completely optional, but it should satisfy the problem conditions. According to field data, the dogleg severity range between 1 and 7 degrees per hundred feet was considered. According to the given information, the horizontal displacement until target point (9 $\frac{5}{8}$casing point) is equals to 426.45. Also, in terms of fatigue, it is sufficient to satisfy the equation (7).

To start optimizing, the initial population of 200 is considered. Other parameters of particle swarm algorithm are obtained based on trial and error and repetition. According to initial population, dispersion of solutions will be in form of Figure 5. After optimization (coding with MATLAB software) two solutions were obtained for the both cases.

1- Shortest path with respect to the path parameters. As presented in table 5.
2- Shortest path considering the applying fatigue condition and mechanical parameters (See table 6).

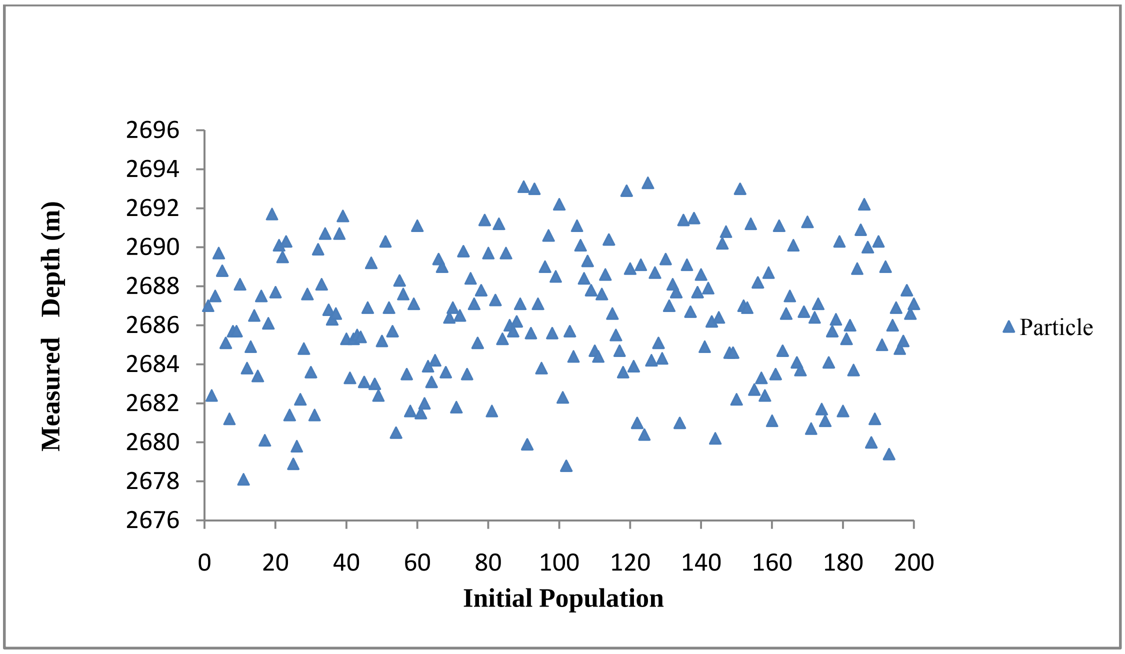

Figure 5: Dispersion of solutions in search space. *It shows the possible of reaching to target base on population.*

Table 5: Shortest path with respect to the path parameters

Section Calculated on 225.85								
	DEPTH	ANGLE	AZIMUTH	TVD	N/S	E/W	SECTION	DOGLEG
0	0	0	0	0	0	0	0	0
1	1909	1.5	226	1908.78	-17.97	-17.97	24.99	0.02
2	2052.17	34.91	225.85	2042.87	-48.07	-49.62	69.09	7
3	2676.65	34.91	225.85	2554.97	-297	-306.05	426.47	0

Table 6: Shortest path with considering fatigue criteria and mechanical parameters.

Section Calculated on 225.85								
	DEPTH	ANGLE	AZIMUTH	TVD	N/S	E/W	SECTION	DOGLEG
0	0	0	0	0	0	0	0	0
1	1909	1.5	226	1908.78	-17.97	-17.97	24.99	0.02
2	2110.27	36.32	225.85	2096.27	-62.09	-64.06	89.22	5.19
3	2679.61	36.32	225.85	2555.00	-296.98	-306.02	426.43	0

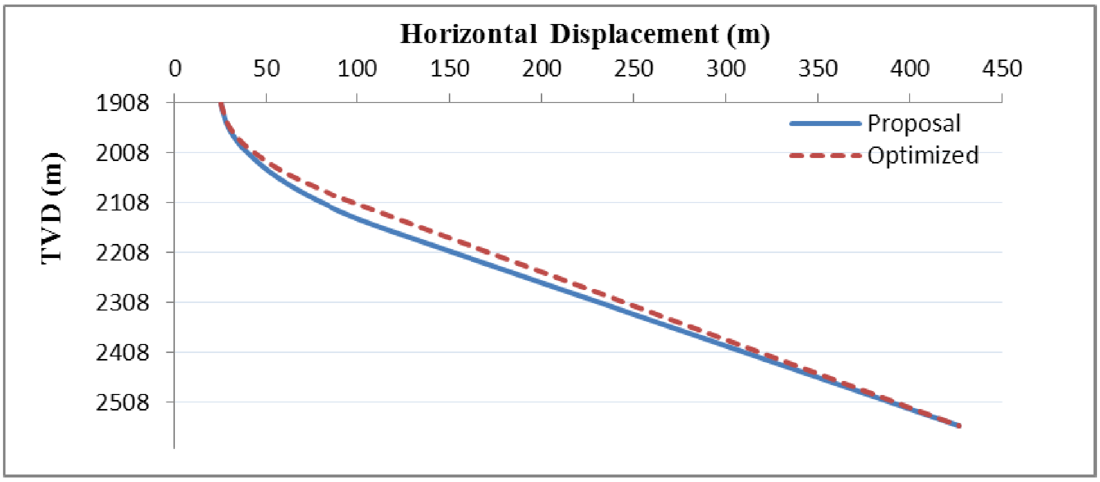

Figure 6: Comparison between proposed & optimized well path

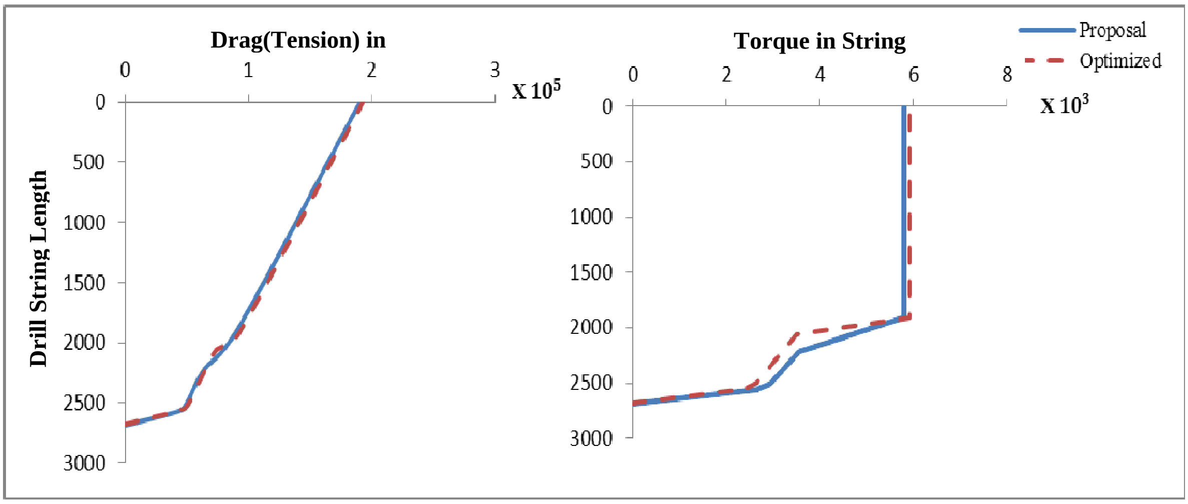

Figure 7: Torque & Drag in drill string, comparison between proposed & optimized well path. *In this case difference is negligible so choosing the proposed well path due to its lower drag and torque is not considered as an advantage.*

Discussion on the results and conclusion

By comparing Table 5 and 6 it was concluded that the measured depth was less in the case that just drilling path parameters had determining role; in this case the dogleg severity is the highest possible value. Also in this case, the safety factor due to fatigue regarding to maximum applied stress to the drill string is below 1. In the other words, the fatigue condition is not satisfied. However, by comparing Table 3 and 6 it was realized that not only the fatigue criteria is satisfied, but also the final measured depth is less than the proposed program. Although this difference was not significant but, it shows the strength of the optimization algorithm in shallower depths and it is evident that at the more final measured depth of the well, this difference will be greater.

In directional wells, end of build or the point where the wells reaches to maximum angle, is important by two reasons: switching drilling state from sliding to rotary state, which this causes improving the drilling conditions and also providing the possibility to use rotary assemblies, by which the time needed to use of directional drilling assemblies is also decreases and in fact this is actually means reducing costs. By comparing table 5 and 6 it can be understood that more dogleg severity, the less depth needed to reach maximum well, and that means, choosing the more dogleg severity has more positive impacts. In this case, the fatigue safety factor is reduced (negative impact). Therefore choosing optimal path (Table 6) between the two modes (Tables 5 & 3) creates optimal conditions. Comparing optimum path (Table 6) and the proposed one (Table 3) indicates that the in optimum path achieving to the maximum angle occurs at a depth of 2110.27m while in the proposed path, achieving to the maximum angle takes place at a depth of 2185 m. The 75- meters difference between these two cases shows that regarding to the average drilling speed, extracted from daily drilling reports, that equals to 1.3 meters per hour, in case of using rotary drilling assemblies, the time duration of using directional drilling assemblies is reduced to 58 hours. The proposed and optimized well paths with respect to the fatigue condition satisfaction of the drill string were shown in Figure 6.

Figure 7 shows tensile (drag) force and the torque applied to the drill string for the both cases of proposed and optimized path. Comparison of these two paths indicates that there are not meaningful differences between the cases and existing difference is negligible so choosing the proposed well path due to its lower drag and torque is not considered as an advantage. However, with increasing drilling measured depth, this difference may be more pronounced. In this case, depending on the considered priorities, optimal path will be selected. This means that the optimal path can be selected based on the lowest drag and torque.

With looking at the optimization process it can be discovered that in this process, there is no limit on the size of the hole and it means that the particle swarm optimization algorithm can be easily used in the dogleg severity optimization in other hole size. In smaller holes due to the wider range of the dogleg severity changes, because of stiffness of drill string, choosing optimal path will be done with more options, and robustness of particle swarm algorithm will be more evident. In the other words, the greater range of path variables, the greater efficiency of proposed algorithm. In Figure 8, the shortest well path, comparing with the proposed path, is shown. The more dogleg severity, the shorter drilling path. It means that for finding the shortest drilling path, the trend is towards more dogleg severity. Convergence of particle swarm algorithm which results to find the shortest path is shown in Figure 9. In this figure, the highest, the mean value, and the lowest measured depths at each step are shown. Remarkable note in this chart is that if the maximum measured depth being also considered as criterion then after 130 iterations again the solution approach to the shortest drilling path.

At the end, it is pointed that the higher dogleg severity, the lower maximum well angle and it is of advantages of the greater dogleg severity since by reducing the maximum well angle we have less problems in drilling affairs. Comparing Tables.3, 5 and 6, clearly shows this claim. Maximum well angle in terms of measured depth of the well is shown in Figure 10 and the slope of this chart represents the dogleg severity.

In this paper by choosing measured depth as an objective function, the suitable amount of the dogleg severity has been obtained. In this process well path and drill string constraints applied simultaneously with fully operational look.

In optimized well path the final angle is 2 degrees less than proposed well path, this can be better for drilling operational. The measured depth and curve section in optimum case was less. Thus by considering the speed drilling in drilling well, the time of using directional drilling equipment can be decreased by 58 hours. Also about using particle swarm algorithm we can imply to its convergence for achieving the optimal solution.

The important point is that instead of choosing optimized path based on the fatigue of drill string, choosing optimized path can be done based on the other conditions such as the smallest of torque and drag. This is especially very important in wells extended reach.

Acknowledgements

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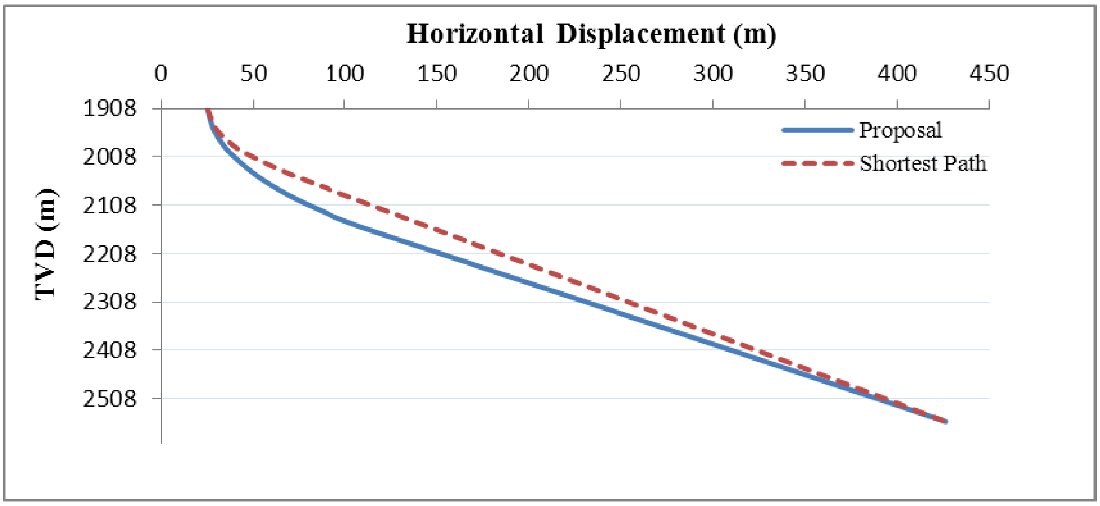

Figure 8: Comparison between proposed & shortest well path

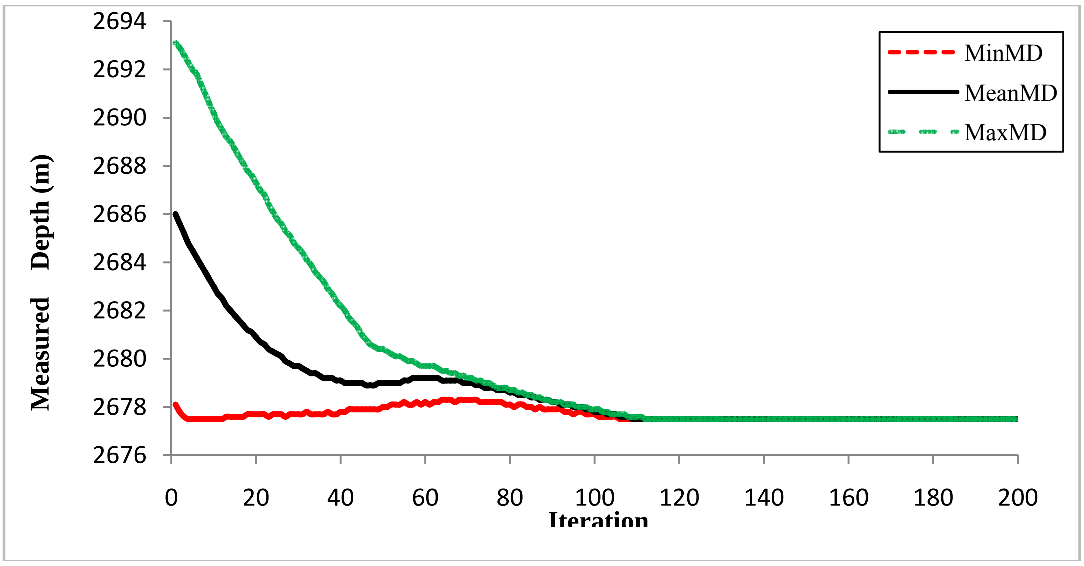

Figure 9: the highest, the mean value, and the lowest measured depth at each step. *Convergence of particle swarm algorithm which results to find the shortest path is completely evidence.*

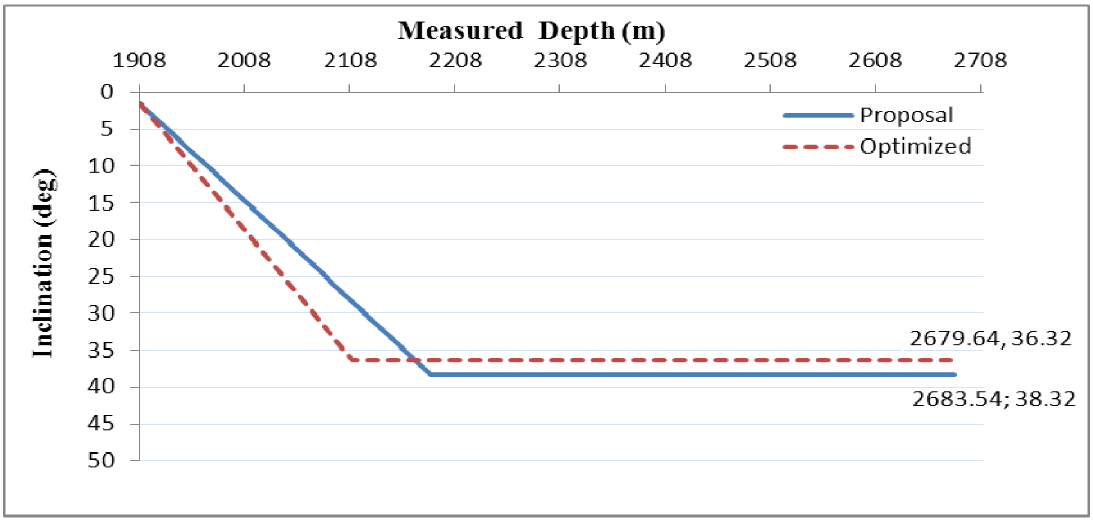

Figure 10: Maximum well angle measured depth, *the slope represents the dogleg severity.*

Nomenclature

C_1, C_2	Positive acceleration constants in PSO
D_1	TVD to KOP
D_2	TVD to EOB
D_3	TVD to target
n	Safety Factor
r	Random Number (0,1) in PSO
R	Radius of Curvature
s_e	Endurance Limit
s_{ut}	Ultimate Tensile Strength
V	Velocity of Particle in Search Space
W	Inertia Weight in PSO
X	Position of Particle
α	Inclination
σ_a	Stress Amplitude
σ_b	Bending Stress
σ_m	Mean Stress
σ_{axial}	Axial Stress
σ_{von}	Von Mises Stress
τ	Shear Stress
DLS	Dogleg Severity
EOB	End of Build
INC	Inclination
MD	Measured Depth
MD_{EOB}	MD at end of build
TVD	True Vertical Depth

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