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Prediction of Penetration Rate of Drilling by Using the Rock Engineering System Approach, Case Study: A Well in the Azadegan Oilfield

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Preliminary communication

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Abstract

One of the criteria in the operational efficiency of drilling is the rate of penetration of the drill bit. Numerous factors affect the rate of penetration. Identification of the effective factors on rate of penetration may lead to a more accurate assessment of drilling time, and as a result, the controlling of operational costs. The concurrent effect of the entire influential factors as well as the differing significance of each of them on the rate of penetration makes the study and optimization of drilling operations much more complicated and difficult. Using the rock engineering systems (RES), the impact of effective operational and geomechanical factors on the rate of penetration has been assessed in this article and a model has been proposed for the prediction of the rate of penetration. Data from one of the wells within the Azadegan oilfield have been used in order to study the impact of effective factors on the rate of penetration. To this end, the effective factors on rate of penetration are initially identified and then an index called "the rate of penetration index (ROPi)" is proposed through the application of the rock engineering systems approach. This index has been calculated at four different depths along the aforementioned well. The results suggested the compliance of penetration rate predictions with field observations. Moreover, porosity and uniaxial compressive strength are the most effective factors on the rate of penetration whereas the weight of drilling fluid has the smallest impact. Finally, a classification for the penetration rate index is presented.

Keywords:
rate of penetration; geomechanical properties; rock engineering systems; Azadegan oilfield

1. Introduction

Hydrocarbon reservoirs are considered one of the main energy generating resources in the world. Since the drilling operations contribute significantly to the costs of exploration and the production of hydrocarbon-based materials, achieving a model that may accurately represent the relationship between the rate of penetration and other effective operational and environmental factors is of major significance in terms of time management and the optimization of the drilling process. This model may represent the drillability of drilled formations and may serve as a tool for the estimation of the rate of penetration in the subsequent wells. The rate of penetration is defined as the rate at which the drill bit is driven into the drilled formation during a certain period. This parameter is expressed in feet per minute or meters per hour. The rate of penetration is affected by a number of parameters that may generally be classified into operational and environmental factors. The need for the optimization of drilling operations has been seriously felt since nearly four decades ago and some models have been proposed for an estimation of the drilling rate. Spear was the first to suggest a comprehensive method for the determination of the techniques for drilling optimization. This study represented the reciprocal empirical correlations between the penetration rate, the weight on bit, the rotary speed of bit, hydraulic horsepower and the drillability of the formation (**Speer, 1958**). In 1965, Bingham proposed the rate of penetration equation based on laboratory data. The threshold weight on the bit is considered insignificant in his equation with the penetration rate merely being a function of the weight applied on the bit and the rotary speed of the bit (**Bourgoyne et al., 1986**). Developing a mathematical model and performing a multi-variable regression analysis on drilling data in 1973, Borgoyne and Young elaborated on the sensitivity

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of penetration rate to the depth, the formation strength, the compression of the formation, the downhole differential pressure, the bit diameter, the weight on bit and the bit rotary speed, bit abrasion and hydraulics. Considering the derived function, the minimum cost of drilling may be achieved when the weight on bit and the rotary speed are kept constant and the hydraulics are used optimally. This model also predicts the drilling time and the abrasion of bits (**Bourgoyne and Young, 1973**). In 1986, Walker et al. attempted to establish relationships between drillability, the penetration rate and the mechanical properties of rocks using the data derived from electrical graphs and the elastic properties of rocks. The suggested equations that linked the penetration rate of roller cone bits to the weight on bit, depth, in-situ compressive strength, porosity and the average particle size of rock. However, the in-situ compressive strength used in the relationships called for data, such as the weight on bit and the internal friction angle which were obtained from drilling data and rock mechanics tests, respectively. One of the main objectives of this model was to represent the effect of rock properties on the drilling rate (**Walker et al., 1986**). While developing a model for the prediction of penetration rate of roller bits in 1988, Onyia suggested the bit design factors, operational conditions and rock mechanics as the effective factors (**Onyia, 1988**). Maidla and Ohara developed a new model in 1991 through the application of drilling data and compared its results with those of the Bourgoyne and Young model. The distinctive feature of their model in comparison to the Bourgoyne and Young model is in the application of uniaxial compressive strength. The objective of this study is the selection of bit, bit bearing, weight on bit and the optimized rotation speed of drilling string with the purpose of minimizing the costs of drilling (**Maidla and Ohara, 1991**). In 2004, Bjornsson et al. applied an expert software system for the selection of drill bits and the penetration rate prediction algorithm to optimize the drilling operations of a vertical well in western Canada. This system accepts the parameters including the travel time of a compression wave, Gamma graph, bit rotation speed, weight on bit, drilling fluid pressure, pore pressure and logging run of a bit from the user and computes the uniaxial compressive strength, the hardness and the abrasiveness of rocks as well as the rate of penetration (**Bjornsson et al., 2004**). In 2010, Rahimzadeh et al. conducted an overall comparison of the models developed for drilling rate within a field in the Persian Gulf. They suggested that the drilling rate equations obtained at different depth intervals were based on the two models of Bourgoyne-Young and Warren. Following this comparison, they developed a new model through the application of neural networks. They reiterated that the result was a decrease in drilling time and costs in the new wells (**Rahimzadeh et al., 2010**). **Basarir et al. 2014** used an adaptive neuro-fuzzy inference system and the multiple regression models for predicting the penetration rate of diamond drilling. In the models, rock properties such as the uniaxial compressive strength, the rock quality designation, and the equipment operational parameters like bit load and rotation are considered. They stated that through the use of the models, the penetration rate of diamond drilling can be predicted effectively.

Moreover, Hankins et al. optimized the operational parameters in 2015 through simulation of the drilling process of one of the drilled wells in order to drill the adjoining wells. Having estimated the drillability of the formation, they optimized the parameters of weight on bit and the bit rotation speed by using this estimation such that it led to the achievement of maximum drilling rate with the minimum possible cost incurred (**Hankins et al., 2015**). **Deng et al. 2016** developed a new prediction model of the rate of penetration considering the combined effect of the main drilling parameters and rock dynamic compressive strength. They claimed that the introduced model is different from others because it replaces the rock static strength with rock dynamic strength and can imitate the real process of rock dynamic crushing by a roller cone bit. The rock drillability index in iron ore oxides was studied by **Inanloo Arabi Shad et al. 2018** using rock engineering systems. This study considers the parameters including Feed (ton force), Rotation (RPM), Rock mass index, Silica percentage, Phosphorus percentage and Iron oxide percentage. The results showed that feed, rotation, rock mass index and iron oxide percent have an important effect on penetration rate.

In recent years, numerous efforts have been undertaken in order to present a more precise estimator model by different methods that are still ongoing. **Gan et al. 2019** proposed a novel intelligent model to predict the drilling rate of penetration considering the process properties. A hybrid bat algorithm is suggested to improve the hyper-parameters of support vector regression model. **Ahmed et al. 2019** explored the predictive capabilities of four frequently used computational intelligence techniques in the prediction of the rate of penetration and compared their predictive performance experimentally. The results showed that the least-square support vector regression (LS-SVR) has the best predictive performance in terms of accuracy while the artificial neural network (ANN) has the best testing execution. **Mehrad et al. 2020** used hybrid algorithms for rate of penetration modeling at vertical wells drilled in southwestern Iran. They applied a combination of least-squares support-vector machines (LSSVM) with the cuckoo optimization algorithm (COA), particle swarm optimization (PSO), and genetic algorithms (GA). In their research, mud logging parameters (including depth, mud density, torque, standpipe pressure, equivalent circulating density, weight on bit, revolutions per minute, flow rate, and rate of penetration) and geomechanical parameters (including gamma ray, porosity, density and uniaxial compressive strength) were considered. **Kor et al. 2021** conducted studies with the aim of modifying the Bourgoyne and Young method to predict the rate of penetration in a heterogeneous environment. **Lawal et al. 2021** used antlion optimized ANN (ALO-ANN), ordinary artificial neural network (ANN), multiple linear statistical model (MLSM) and multiple non-linear statistical model (MNLSM) to predict the penetration rate with density, porosity, and point load index as input parameters. It was found that density and point load index have more influence on the penetration rate than on porosity. **Chen et al. 2021** used mathematical programming and optimization-based methods to present and review learning models for data classification. To predict the penetration rate, the coupled simulated annealing-least square support vector machine (CSA_LSSVM) method was applied. Factors affecting the drill penetration rate in this research are drilling mud viscosity filtration, drilling mud composition, weight on bit and bit rotation.

Taking into account the various effective factors on penetration rate in rocks, the immaculate integration of these factors in the drilling schedule is inevitable and may lead to an increase in penetration rate of bit in rock and a subsequent decrease of operational risks (**Karanam & Misra, 1998**). Hence, considering the significance and role of drilling in petroleum projects, this research intends to assess the impact of effective factors on the penetration rate of drilling into rocks with an emphasis on the identification and influence of mechanical parameters. Therefore, the effective factors were initially identified by taking into account the previously conducted studies. The factors considered in this paper are more comprehensive than many previous studies. The 11 factors including weight on bit, bit rotation speed, mud flow rate and mud weight as operating factors and abrasiveness, porosity, density, Young's modulus, compressive strength, tensile strength and rock toughness as geomechanical factors are considered. On the other hand, according to the literature review, one of the less used methods to predict the penetration rate in the petroleum and natural gas drilling industry is the rock engineering systems (RES) method. This method has a high potential for solving complex rock engineering problems. Therefore, in this paper, the RES method is used to predict the penetration rate of drilling. For this purpose, after identifying the factors affecting the penetration rate, the mutual impact of these factors is marked using an interaction matrix. Finally, focusing on one of the wells in Iran's Azadegan oilfield as a case study, a model for estimating the penetration rate using RES method is presented.

2. Rock engineering systems approach

The rock engineering systems were first proposed by **Hudson** (**1992**). The basic and application method of this approach was thoroughly presented in this proposal and thus the system analysis was introduced for the very first time into the field of rock engineering and similar applications. Subsequently, this approach immediately turned into a highly capable tool for the solving of sophisticated rock engineering problems due to its numerous advantages. Moreover, this method has been discussed and applied in diverse subjects other than rock engineering. This method has been applied in environmental studies, waste management, the design of urban sewerage, air pollution slope stability and the design of subsurface structures (**KhaloKakaei & Zare Naghadehi, 2012**). This method is also widely applied in rock engineering. These include slope stability analysis, the design of tunnels and subsurface structures, such as site selection for the construction of the underground plant by **Shang et al.** (**2000**), assessment of the geotechnical risks in the boring of tunnel Athens' underground metro by **Banardos and Kaliampakos** (**2004**), the assessment of instability in tunnels by **Shin et al.** (**2009**), and slope stability analysis by **Zare Naghadehi et al.** (**2011**). **Frough and Torabi** (**2013**) introduced a polynomial for the estimation of TBM (Tunnel Boring Machine) downtimes due to the effect of rock mass parameters. Moreover, Rafiee et al. studied the improvement of rock engineering systems through the application of fuzzy numbers in 2016. They used a semi-numerical expert fuzzy method to code the RES matrix developed based on effective parameters of rock mass in block caving mines (**Rafiee et al., 2016**). Also, Najafi and Rafiee introduced a new coal seam methane drainageability index (CMDI) for pre-drainage techniques in a working mine by using the fuzzy rock engineering system (FRES) (**Najafi and Rafiee, 2019**).

Interaction matrix is used in the identification of critical parameters, effective paths, feedback loops and assessment of engineering selection techniques (**Hudson, 1992**). Interaction matrices are powerful tools in a system approach that compare the mutual impact of effective parameters on each other. The main factors related to the problem are arranged along the leading diagonal of the matrix and the interactions of each pair of factors are represented by other elements. Stages such as the coding of interaction and algebraic operations are applied to the row and columns and the method resumes with graphs as outputs. **Figure 1** presents the interaction between parameters A and B.

According to Hudson, there are five methods for the coding of an interaction matrix. These methods include the binary, expert semi-quantitative (ESQ), based on the slope of graphs of parameters, comparative method based on a direct system approach and the explicit method. The ESQ method has been relatively successful among these methods and widely applied as only one value is deterministically assigned to each interaction. This method is a generalized version of the binary method and consists of five coding scales of 0 to 4 (see **Table 1**) (**Zare Naghadehi, 2013**).

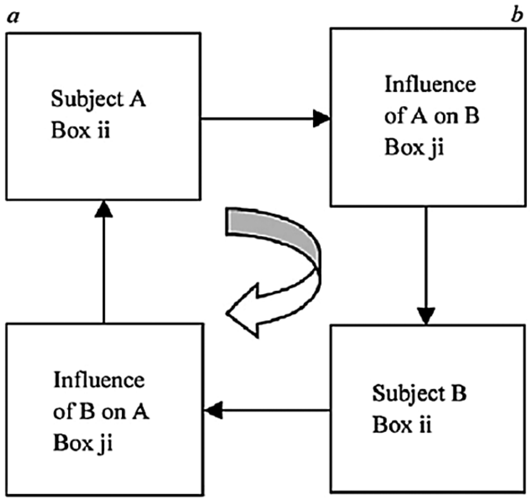


Figure 1: Concept of Interaction Matrix for a system consisting of variables A and B (**Hudson, 1992**)

Table 1: Description of contract ranks in the ESQ interaction matrix (**Hudson, 1992**)

Interaction Between Parameters	Value
No	0
Poor	1
Medium	2
Strong	3
Critical	4

3. Case study

The case study considered for this research comprises one of the wells in the Azadegan oilfield. Discovered in 1997, the Azadegan oilfield is one of the largest oilfields of Iran, and also one of the largest in the world. This oilfield lies within an area of 20 km by 60 km running parallel to the border of Iran and Iraq, only 80 km west of the city of Ahwaz. The confirmed reserve of this oilfield is estimated at 33 billion barrels. The aforementioned well is located in the northern field of Azadegan. With an approximate area of 460 km^2, this field forms part of the Azadegan oilfield that is situated in the southwest of Iran and it is mainly encapsulated within the Hawizeh marshes (**Jadbavi, 2012**). **Figure 2** presents the location of Azadegan oilfield as well as the layout of the wells drilled in this field. The well represented in this study has been delineated in this figure.

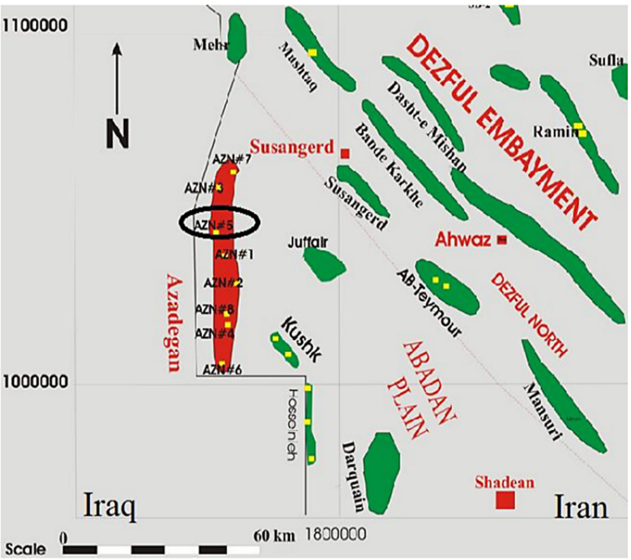


Figure 2: Location of the study area and the considered well

4. Effective factors on rate of penetration

It is necessary to identify the entire effective factors derived from various drillings in order to predict the rate of penetration. Taking into account the conducted studies, data related to the reservoir range of 2,660 m to 3,587 m drilled using a PDC bit and an 8.5 inch core barrel are of acceptable comprehensiveness. Thus, this section of the reservoir has been considered for data collection. A number of 676 data items have been collected. The average data of each parameter in various depths is presented in **Table 2**.

This set of data consists of two series of operational and geomechanical factors. Weight on bit, bit rotation speed, flow rate and mud weight are operational factors, whereas abrasiveness, porosity, density, Young's modulus, compressive strength, tensile strength and toughness of rock are identified as geomechanical factors.

- Weight on Bit: is one of the most effective factors on the rate of penetration. Regardless of bit type, the pull down applied to the bit must be to the extent that exceeds the compressive strength of formation rocks. Field tests suggest that the increase in rate of penetration is directly related to an increase of weight on bit (**Irawan et al., 2012**).
- Bit Rotation Speed: this parameter is also highly effective on the penetration rate. Studies suggest a direct relationship between the rate of penetration and rotation speed in soft formations as opposed to hard ones (**Eren and Ozbayoglu, 2010, Rashidi et al., 2010**). Applying speeds exceeding the optimum rotation speed has no effect on the rate of penetration in hard formations (**Nguyen, 1996**).
- Mud Weight: the rate of penetration decreases due to an increase in the weight, viscosity and solid content of the drilling fluid while it may be increased through increased filtration. The viscosity of the drilling fluid plays an essential role in controlling reduced drill string friction and the residual hydraulic horsepower in the bit nozzle. Based on the studies, an increase in viscosity would result in a lower rate of penetration, even when the cuttings are completely removed (**Lummus, 1970**).
- Mud Flow Rate: removing cuttings from the bottom of the borehole and from the borehole to the surface

Table 2: Well Classified Data

Data			Sample 1	Sample 2	Sample 3	Sample 4
Depth (m)			2728	3113	3371	3574
Parameter						
	Operational factors					
P1	Weight on Bit (kN)		48.9	60.9	64.5	46.7
P2	Bit Rotation Speed (rpm)		120	119	120	120
P3	Mud Weight (kg/m^3)		1310	1281	1278	1279
P4	Fluid Flow Rate(m^3/h)		79.28	79	78.3	79.18
	Geomechanical factors					
P5	Rock Density (g/cm^3)		2.33	2.55	2.61	2.69
P6	Porosity		0.23	0.08	0.047	0.025
P7	Uniaxial Compressive Strength (MPa)		44.23	87.3	78.39	110.24
P8	Tensile Strength (MPa)		8.13	12.76	12.77	16.74
P9	Rock Toughness (kg/mm^2)		121.6	233.9	182.3	276.1
P10	Rock Abrasiveness Constant		0.28	0.8	2.3	3.96
P11	Static Young's Modulus(GPa)		8.51	18.49	21.37	24.74

is one of the most important roles of the mud flow rate. An increased flow rate along with an increased weight on bit may result in clearance of a borehole and improved conditions, and a subsequent increase of penetration rate.

- Rock density: since rock density is linear to the strength of rock and has an inverse relationship to the rate of penetration, hence the more compact and dense the rock is, the higher the horsepower required for drilling by the rotary drilling system and the smaller the rate of penetration will be (**Kahraman et al., 2000**).
- Porosity: most variations in rate of penetration are due to the variations in porosity. Rocks of high porosity, such as sandstones or shales, demonstrate lower resistance to drilling compared to carbonated or low porosity rocks. Studies conducted on the impact of porosity on the drillability of rocks suggest a linear (**Thuro, 2002**) and non-linear (**Onyia, 1988**) increase in the rate of penetration due to increased porosity.
- Toughness: the higher the scale of rock toughness, the lower the life span of bits and rate of penetration. According to **Gstalder and Raynal** (**1996**), the increase in toughness of soft and medium results in a decreased rate of penetration, but this declining trend is not obvious in hard rocks.
- Abrasiveness: silica content or generally, the quartz content is used to determine the abrasiveness of rocks. The more abrasive the rock, the lower the bit life span and rate of penetration. Qualitative and quantitative indices have been proposed, the most important of which are the RAI (Rock Abrasiveness Index) and CAI (Cerchar Abrasivity Index), among others.
- Uniaxial Compressive Strength: this is the most crucial strength parameter for rocks and is one of the most important factors affecting the rate of penetration and rock drillability (**Andrews et al., 2007**). The increase in the compressive strength results in a decreased rate of penetration (**Nguyen, 1996**).
- Tensile Strength: tensile strength in drilling engineering represents the boundary resistance of particles and matrix. Thus, the increase in resistance and bonding between the particles and matrix results in an increase in the tensile strength of rock. Bonding and extreme cohesion of particles and matrix leads to the augmented abrasiveness of rock and ultimately a decrease in the rate of penetration (**Ersoy & Waller, 1995**). **Kahraman et al.** (**2000**) suggested that tensile strength has an inverse linear relationship to the drillability of rocks.
- Young's Modulus: rate of penetration is linearly reduced in soft and medium rocks as the modulus of elasticity increases, but this declining trend is not perceptible in hard rocks with low weight on the bit (**Gstalder & Raynal, 1996**). Moreover, having performed numerous tests, **Kahraman et al.** (**2000**) suggested that the increase in modulus of elasticity leads to a lower rate of penetration and lower drillability of rocks.

5. Analysis of interaction between the factors using the rock engineering system approach

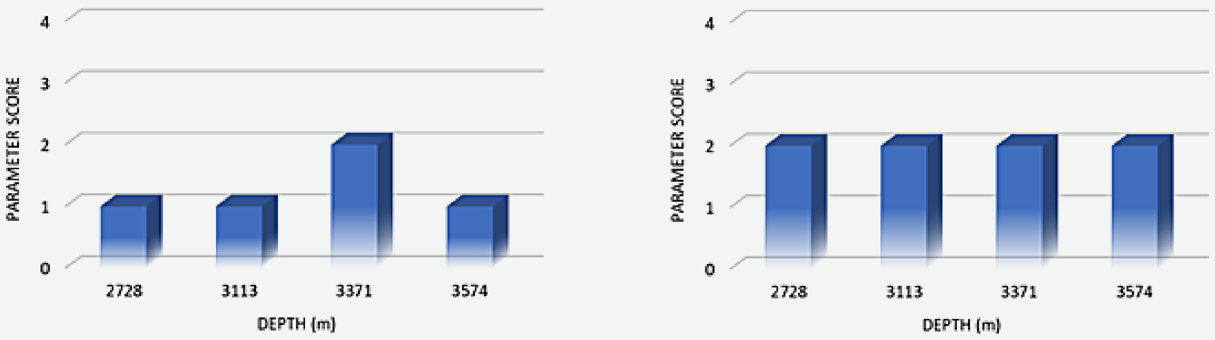
In order to study the rate of penetration in the aforementioned well, the well was divided into four different depth sections based on variations of the geomechanical characteristics per depth. It is noteworthy that various factors simultaneously affect the rate of penetration, but taking into account the already conducted studies, the most

Table 3: Rating of effective factors on rate of penetration

Parameter	**Symbol**	**Rating**				
		Zero	**1**	**2**	**3**	**4**
Weight on Bit (kN)	P1	<31.1	31.1-62.3	62.3-102.3	102.3-155.7	>155.7
Bit Rotation Speed (rpm)	P2	<60	60-110	110-160	160-210	>210
Mud Weight (kg/m^3)	P3	>2434	1954-2434	1473-1954	993-1473	<993
Fluid Flow Rate (m^3/h)	P4	<45.42	45.42-68.13	68.13-136.27	136.27-204.41	>204.41
Density (g/cm^3) **(Onyia,1988)**	P5	>3	2.6-3	2.2-2.6	1.8-2.2	<1.8
Porosity (%) **(Onyia,1988)**	P6	<7	7-14	14-20	20-26	>26
Uniaxial Compressive Strength (MPa) **(Bieniawski, 1976)**	P7	>225	85-225	50-85	25-50	<25
Tensile Strength (MPa) **(Singh et al,1989)**	P8	>15	10-15	5-10	2-5	<2
Rock Toughness (kg/mm^2) **(Gstalder and Raynal, 1996)**	P9	>250	200-250	150-200	100-150	<100
Rock Abrasiveness (CAI factor) **(Cerchar, 1973)**	P10	>6	3-6	1-3	0.3-1	<0.3
Young's Modulus (GPa) **(Gstalder and Raynal, 1996)**	P11	>70	40-70	20-40	10-20	<10

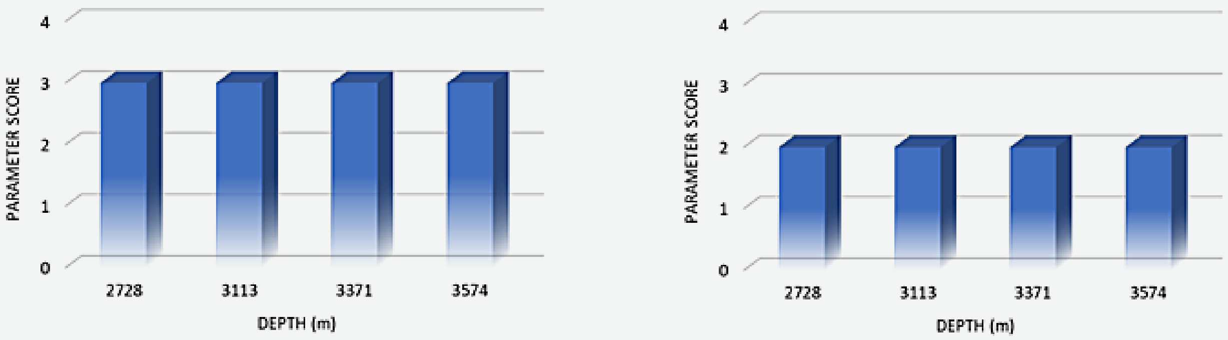
important of those factors have been utilized in this research. Developing a data bank of all the above mentioned factors calls for three classes of references including well log plots, mud logging and daily drilling reports.

Following the introduction of effective factors, this section introduces a scale for their classification. Each classification scale consists of five categories to which a score of zero to four may be allocated with respect to the drilling conditions. The better the drilling condition and penetration rate, the higher the allocated score. The rating of these factors was carried out according to **Table 3**. Based on this table, as shown in **Figure 3**, the rating of effective factors has been done along the well at four different depths. In this figure, for example, the parameter of weight on bit at depths of 2,728.0 m, 3,113.0 m and 3,574.0 m is 48.9, 60.9 and 46.7 kN, respectively



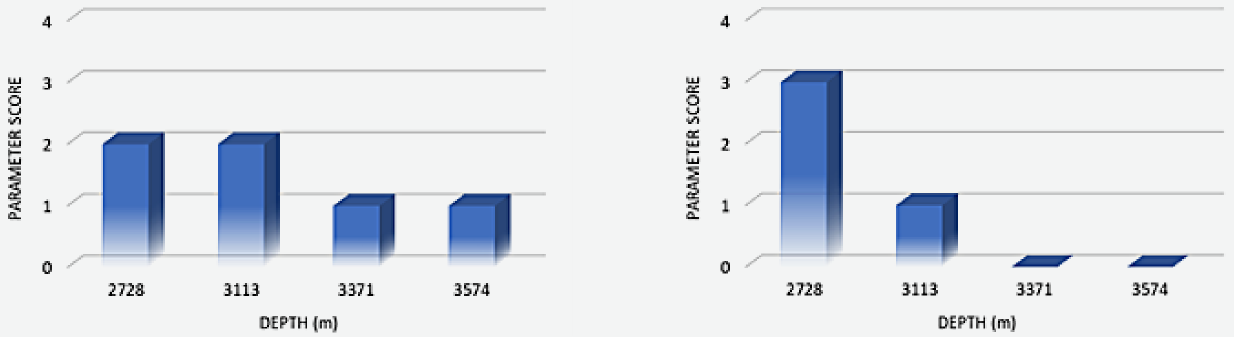
A) Weight on bit (kN)

B) Bit rotation speed (rpm)



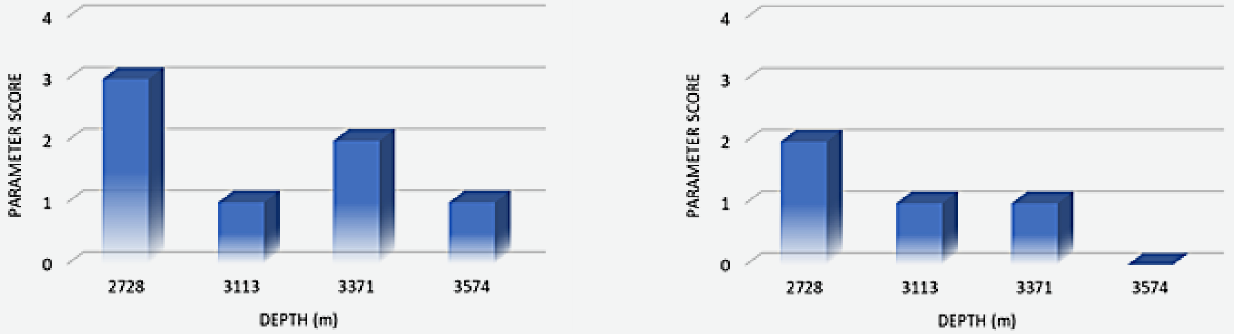
C) Mud weight (kg/m^3)

D) Fluid flow rate (m^3/h)



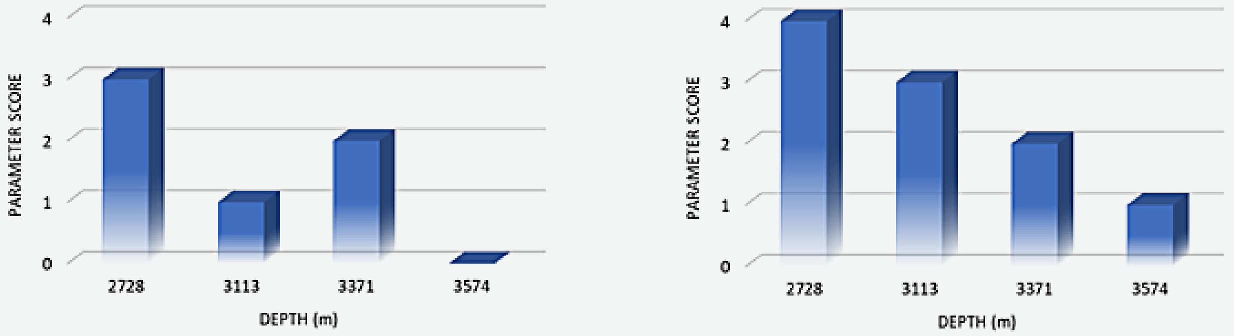
E) Rock density (g/cm^3)

F) Porosity (%)



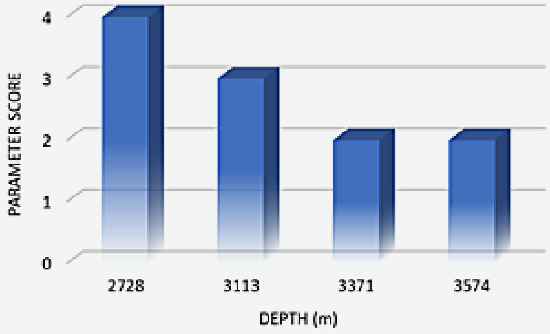
G) Uniaxial compressive strength (MPa)

H) Tensile strength (MPa)



I) Rock toughness (kg/mm^2)

J) Rock abrasiveness (CAI factor)



K) Modulus of elasticity (GPa)

Figure 3: Rating of effective factors at four different depths

(according to **Table 2**). According to **Table 3**, since these values are in the range of 31.1 to 62.3, they are awarded a score of 1. At a depth of 3,371 m, the parameter of weight on bit is 64.5 kN. Since this parameter is in the range of 62.3 to 102.3, at this depth a score of 2 is assigned to the weight on bit. The other parameters are scored in the same way in **Figure 3**.

Operational and geomechanical factors were considered in the interaction matrix in order to come up with a model to estimate the rate of penetration using RES. Taking into account the effective factors, their interaction and mutual impact on each other has therefore been included in this matrix. Based on **Table 4**, the comments of 10 pundits from among academic and industry ex-

Table 4: Mean Interaction Matrix

													∑C
	P1	2.2	0.3	0	0	0	0	0	0	1.3	0.3	3.8	7.9
	1.3	**P2**	0.2	0.3	0	0	0	0	0	1.5	0	3.9	7.2
	1.6	1.1	**P3**	2.3	0	0	0	0	0	0	0	2.1	7.1
	1.2	1.4	1.3	**P4**	0	0.2	0.1	0.1	0	0.6	0	2.9	7.8
	1.9	2.2	1.5	1.4	**P5**	2.1	2.1	2.3	2.2	1.8	2.4	2.8	22.7
	2.1	2.3	1.3	2	3.1	**P6**	3.3	3	2.4	1.9	2.8	3.4	27.6
	2.6	2	0.8	1.3	1.8	1.3	**P7**	3.3	2.4	2	2.5	3.3	23.3
	2.2	2.1	0.7	0.5	1.4	1.2	3.1	**P8**	2	1.8	2	3.1	20.1
	1.7	2.6	0.5	0.3	1.2	1.1	2.2	2.3	**P9**	3.1	2.1	3.4	20.6
	1.5	2.6	0.7	0.5	0.8	0.8	1.4	1.2	2.1	**P10**	1.1	3.2	15.9
	2	2.1	0.3	0.9	1.3	1.6	2	1.7	1.5	1.1	**P11**	2.8	17.3
	1.1	0.9	0.6	0.8	0	0	0	0	0	0	0	**P12**	3.4
∑E	19.2	21.5	8.2	10.3	9.6	8.3	14.2	13.9	12.6	15.1	13.3	34.7	
P1: Weight on Bit, P2: Bit Rotation Speed, P3: Mud Weight, P4: Mud Flow Rate, P5: Density, P6: Porosity, P7: Uniaxial Compressive Strength, P8: Tensile Strength, P9: Toughness, P10: Abrasiveness, P11: Young's Modulus, P12: rate of penetration (ROP) C: Cause, E: Effect													
	Operational Factors				Geomechanical Factors							ROP	

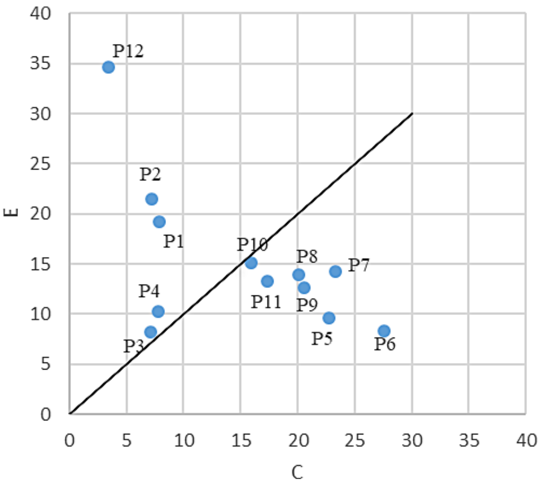


Figure 4: Cause-Effect Plot

perts have been utilized instead of sufficing with an individual opinion. In other words, mean interaction matrix (MIM) has been applied. Each element of the matrix presented in **Table 4** is calculated from the average of the 10 pundits' opinions. In addition to the 11 factors represented, a twelfth factor i.e. the rate of penetration has also been incorporated into the leading diagonal of this matrix. The interaction column crossing the last cell demonstrates how operational and geomechanical factors affect the rate of penetration. Accordingly, the row crossing the same cell represents the impact of penetration rate on the system. Coding of the matrix has been carried out through the ESQ method and the sum of all row ordinates termed cause C and the sum of all column ordinates termed effect E have been calculated for each individual factor.

When the sum of numerical values of each row (cause) and sum of numerical values of each column (effect) are plotted as coordinates, they form a cause-effect plot. The cause-effect plot represents the dominance or subordination of a factor in the system. The C=E line determines the dominance or subordination of each factor. The histogram of interaction intensity also reveals the most interactive factors in the system.

Figure 4 presents the cause-effect plot. As illustrated in **Figure 4**, the more a variable that lies on the C=E line is plotted closer to the C axis, the more dominant that variable (factor) may become, thus inflicting more impact on the system, and similarly, the more a variable that lies on the C=E line is plotted closer to the E axis, the more subordinate it becomes and is more susceptible to the system. This figure is helpful in understanding the role of each factor within the system. Based on **Figure 4**, it may be concluded that geomechanical factors have maximum effects on the system and operational factors are the most subordinate and are most affected by the system. This figure illustrates that parameter P1 (weight on bit) and P2 (bit rotation speed) are more subordinate and parameter P6 (porosity) and P7 (uniaxial compressive strength) are more dominant. It can be also seen that parameter P12 or rate of penetration (ROP) is totally affected by the system.

Calculating the sum of E+C, a histogram of interaction intensity may be plotted for each factor. **Figure 5** presents a histogram of interaction intensity. This figure illustrates that the uniaxial compressive strength and porosity enjoy the most interaction in the system such that a slight variation in them inflicts a great effect on the system behavior. Variations of penetration rate at differ-

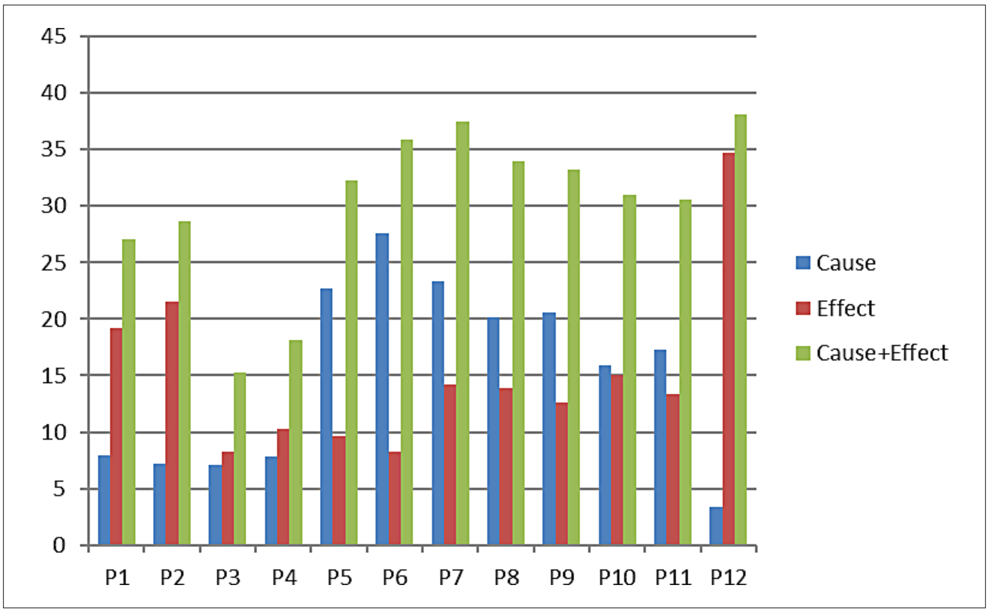


Figure 5: Histogram of Interaction Intensity of Factors

ent depths due to these two factors also indicate the same fact. Also, it can be seen that parameters P3 and P4, i.e. the Mud Weight and Fluid Flow Rate, respectively, have a minimal interaction in the system. In general, as the mud density increases, the hydrodynamic pressure in the well increases, and thus the differential pressure acting on the bottom of the well increases, so the rate of penetration decreases due to the chip hold down effect.

6. Estimation of the rate of penetration index

The rate of penetration index (ROPi) at each depth represents the rate of penetration for that particular depth. In other words, with more favorable conditions for drilling at that particular depth, the value of rate of penetration index would be higher. To calculate the rate of penetration index, equation (1) is used at four different depths of the well. In this equation, i represents factor 1 to 11, P_i is the score for ith factor and P_{max} is the maximum score allocated to each factor. According to **Table 3**, the P_{max} value is assigned to be 4. Moreover, a_i is the weight coefficient of each factor derived from equation (2) (**Mazzoccola & Hudson, 1996**). **Table 5** represents the calculation of *ROPi*.

$$ROPi = \sum_{i=1}^{n} a_i \frac{P_i}{P_{\max}} \tag{1}$$

$$a_i = \frac{(C_i + E_i)}{\left(\sum_i C_i + \sum_i E_i\right)} (\%) \tag{2}$$

Where C_i and E_i are the cause and effect of ith factor, respectively. For example, a_1 for the first factor (P1), based on the data in Table 4, is calculated as follows:

$$a_1 = \frac{(7.9 + 19.2)}{(180.9 + 180.9)} \times 100 = 7.49(\%) \tag{3}$$

As the table suggests, depths of 2,728.0 m and 3,574.0 m have the highest and lowest penetration indices, respectively.

For validation purposes, the results of rate of penetration index obtained through the RES method and the actual rate of penetration measured at this particular well are presented in **Table 6**.

The results suggest that the predictions carried out at depths of 2,728.0 m, 3,113.0 m and 3,574.0 m through the RES method are totally consistent with field observations. However, following the comparison made at depth of 3,371 m, it was determined that the derived rate of penetration index is slightly different to the actual value at this depth which may be due to the low internal friction angle of the rock and the subsequent low strength at a depth of 3,371.0 within the study area. This indicates the need for the incorporation of more rock parameters to achieve a more accurate estimation. This entails further data, such as compressional wave travel time, shear wave travel time, dynamic Young's modulus, water absorption, pore pressure, etc. so that their effect may be incorporated into the interaction matrix.

Finally, based on the studies conducted in this paper, the data and field experiences and the results obtained in **Table 6**, a classification for the *ROPi* is proposed. This classification is presented in **Table 7**. Accordingly, the penetration rate at depth 3,574.0, is very low; at depths of 3,371.0 and 3,113.0, it is low and at depths of 2,728.0, it is moderate.

The analysis and obtained results in this paper are based on data from only one well. Therefore, this work can be considered a preliminary communication. It is necessary to process the data from at least a few other

Table 5: Calculation of Rate of Penetration Index (ROPi)

Factors Indexes	P_i	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11
Weight of factor (%)	$a_i = \frac{(C_i+E_i)}{\left(\sum_i C_i + \sum_i E_i\right)}(\%)$	7.49	7.93	4.23	5.00	8.93	9.92	10.36	9.40	9.18	8.57	8.46
Score of P_i	P_i	1	2	3	2	2	3	3	2	3	4	4
	$\frac{P_i}{P_{Max}}$	0.25	0.5	0.75	0.5	0.5	0.75	0.75	0.5	0.75	1	1
	$a_i \times \frac{P_i}{P_{Max}}$	1.87	3.97	3.17	2.50	4.47	7.44	7.77	4.70	6.89	8.57	8.46
Rate of Penetration Index	$ROPi = \sum_{i=1}^{n} a_i \frac{P_i}{P_{max}}$	59.81						**Depth: 2,728 m**				
Score of P_i	P_i	1	2	3	2	2	1	1	1	1	3	3
	$\frac{P_i}{P_{Max}}$	0.25	0.5	0.75	0.5	0.5	0.25	0.25	0.25	0.25	0.75	0.75
	$a_i \times \frac{P_i}{P_{Max}}$	1.87	3.97	3.17	2.50	4.47	2.48	2.58	2.35	2.28	6.43	6.35
Rate of Penetration Index	$ROPi = \sum_{i=1}^{n} a_i \frac{P_i}{P_{max}}$	38.45						**Depth: 3,113 m**				
Score of P_i	P_i	2	2	3	2	1	0	2	1	2	2	2
	$\frac{P_i}{P_{Max}}$	0.5	0.5	0.75	0.5	0.25	0	0.5	0.25	0.5	0.5	0.5
	$a_i \times \frac{P_i}{P_{Max}}$	3.74	3.97	3.17	2.50	2.23	0	5.18	2.35	4.59	4.29	4.23
Rate of Penetration Index	$ROPi = \sum_{i=1}^{n} a_i \frac{P_i}{P_{max}}$	36.26						**Depth: 3,371 m**				
Score of P_i	P_i	1	2	3	2	1	0	1	0	0	1	2
	$\frac{P_i}{P_{Max}}$	0.25	0.5	0.75	0.5	0.25	0	0.25	0	0	0.25	0.5
	$a_i \times \frac{P_i}{P_{Max}}$	1.78	3.97	3.17	2.50	2.23	0	2.59	0	0	2.14	4.23
Rate of Penetration Index	$ROPi = \sum_{i=1}^{n} a_i \frac{P_i}{P_{max}}$	22.70						**Depth: 3,574 m**				

Table 6: Applicability (validity) assessment of *ROPi*

Actual Rate of Penetration (m/h)	Calculated *ROPi*	Depth (m)
8.52	59.81	2,728
6.22	38.45	3,113
6.46	36.26	3,371
3.72	22.70	3,574

Table 7: Classification of Range of the Rate of Penetration index (ROPi)

Range of the Rate of Penetration index (%)	Description
0-25	Very low
25-50	Low
50-75	Moderate
75-90	High
90-100	Excellent

wells and from other depths until the classification of rate of penetration index can be generally applicable.

7. Conclusions

The identification of drilling media and the properties of in situ rock mass, as well as the estimation of penetration rate significantly contribute to the selection of a drilling rig. The effective factors on drilling have been identified in this study and the most important factors have been singled out from among them, based on previous studies, in order to predict the rate of penetration. The mean interaction matrix was analyzed and the weight of effective factors on the penetration rate was calculated, and in the end, the rate of penetration index was analyzed. The conclusions of this study are as follows:

- A number of 11 effective factors on the rate of penetration were assessed. The weight of these factors was calculated in general and not specifically for this research. Therefore, the results of this research may be applied in similar studies.
- Among the effective factors, porosity and uniaxial compressive strength were computed at four different depths using the rock engineering system.
- Compressive strength has the greatest influence on the rate of penetration, whereas mud weight has the lowest effect on the rate of penetration.
- As the mud density increases, the hydrodynamic pressure in the well increases, and thus the differential pressure acting on the bottom of the well increases, so the rate of penetration decreases due to the chip hold down effect.
- Considering the porous medium and the highly influential role of porosity on the other properties of rock, it is considered a very important factor in this well. Moreover, the factors of bit rotation speed and mud weight are the most and least susceptible to the system, respectively. Consequently, the desirable rate of penetration during drilling may be achieved to a great extent through control of the bit rotation speed.
- Depths of 2,728m and 3,574m recorded the highest and lowest rate of penetration index values, respectively. It may be concluded that the rate of penetration decreases with an increase in depth, and given the slight range of variation along this particular well, the effect of geomechanical factors on penetration rate at deeper depths becomes more evident.
- The results proved that except for one case, the predicted *ROPi* are thoroughly consistent with field observations, which approve the capability of the proposed methodology.
- A classification for the rate of penetration index (ROPi) is provided that can qualitatively indicate the penetration rate.

Symbols

List of Symbols

Description	Symbol
Effect	E
Cause	C
Point of Each Parameter	P
Weight Coefficient	a
Rate of Penetration Index	ROPi

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SAŽETAK

Predviđanja mehaničke brzine bušenja korištenjem stijensko-inženjerske metode, analiza slučaja bušotine s naftnoga polja Azadegan

S obzirom na to da su čimbenici koji izravno utječu na troškove izrade bušotina, vrijeme i operativna učinkovitost imaju veliku važnost tijekom bušenja. Jedan od kriterija operativne učinkovitosti bušenja jest mehanička brzina bušenja (engl. *rate of penetration*, ROP). Velik broj čimbenika utječe na mehaničku brzinu bušenja. Njihova identifikacija omogućuje točnu procjenu vremena bušenja, a time i kontrolu operativnih troškova. S obzirom na istodobno djelovanje navedenih čimbenika, kao i specifičnosti njihova pojedinačnog djelovanja na ROP, analize i optimizacija operacija bušenja vrlo su složene i teške. U ovome je radu vrednovan utjecaj operativnih i geomehaničkih čimbenika na ROP korištenjem stijensko-inženjerske metode (engl. *rock engineering system*, RES), temeljem čega je predložen model predviđanja mehaničke brzine bušenja. Podatci korišteni u radu dobiveni su iz jedne bušotine s naftnoga polja Azadegan (Iran). Do sada su početno utvrđeni čimbenici koji utječu na ROP te je, korištenjem RES metode, predložen tzv. indeks ROP (ROPi). Navedeni je indeks za ranije spomenutu bušotinu izračunan za četiri različite dubine. Dobiveni rezultati upućuju na poklapanje predviđene brzine bušenja i stvarnih terenskih podataka. Također, rezultati su pokazali da na mehaničku brzinu bušenja najveći utjecaj imaju šupljikavost i jednoosna tlačna čvrstoća, dok gustoća isplake ima najmanji utjecaj. U radu je također prikazana klasifikacija indeksa ROP.

Ključne riječi:
mehanička brzina bušenja, geomehanička svojstva, stijensko-inženjerska metoda, naftno polje Azadegan

Author's contribution

Hamidreza Saeedi (M.Sc.): contributed in the following terms: formal analysis, resources, and writing - original draft. **Seyed Esmaeil Jalali** (Associate Professor): conceptualization, methodology, and supervision. **Mehdi Noroozi** (Assistance Professor): investigation, project administration, and writing - original draft. **Somayeh Behraftar** (Ph.D.): writing - review & editing.