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In this study, a comprehensive economic investigation is conducted focusing on the well drilling time and cost. Several updated industrial databases and literature data are taken into account for the development phase and evaluation of proposed models. The models include not only specific correlations dedicated to various zones and depths but also generalized correlations applicable for rough estimation.

The models are derived based on robust multivariable regression looking for minimizing the residuals. According to derived model, Africa has the highest construction cost portion in well drilling and the lowest is related to the United States. Furthermore, the drilling time of different regions is compared. The average accuracy of the cost and time models are found to be 97% and 99% respectively. The proposed model directly estimates both the drilling cost and time to be used in fundamental research and feasibility studies of the geothermal power plants applicable around the world.

Keywords: geothermal well; drilling cost; drilling time; cost correlation

Introduction

In recent years, geothermal power plant is becoming one of the attractive renewable solutions to the energy market. Several studies are following improvements in the design of the geothermal power plants and one of the key components is the geothermal well, which could be used either as the extraction well in terms of the energy source or reinjection well [1, 2].

The high construction cost of geothermal power plants makes it more expensive than power plants that work with conventional fuels. The well drilling cost is one of the major parts the total cost of geothermal construction. Therefore, an accurate cost estimation of this compartment is always a challenge for the feasibility studies of geothermal power plant investments. This is because the actual well drilling costs are not easily available due to confidential matters and proprietary of the data, therefore there is limited data available for the drilling cost. Statistical assessment of drilling costs data present that the majority factor of overall well cost is linked to well depth (around 56%) [3]. Well depth measurement is the elementary step to well drilling cost prediction, but not the only factor affecting drilling expenditures. Well cost also strongly depends on the geological formation. Geological feature specifies rates of penetration, casing strings number and frequency of drilling string failures [4].

Howbeit the drilling procedure is the same in different geographical zones, wells are different in type and complexity level. The Well features defined by the drilling plan, the reservoir location, and the situation faced during drilling. Some drilling site features such as depth, experience of operator and workforce, environmental situation can have significant impact on operator's decision regarding the rig type and contract selection. Other sectors like stuck pipe and mechanical equipment failure are not predictable, however can affect cost and time of drilling remarkably [5]. Present geothermal drilling technologies have developed from a combination of oil and gas and hydrothermal drilling technology as their equipment and materials are similar. So that the modified rigs of the oil and gas industry are applied to drilling geothermal resources [6, 7]. Many factors have an impact on drilling cost and time, such as drilling operation efficiency, operator and labour experiences, drilling rig type, well depth and design, geological conditions, management skill etc.

Rowley et al. [8] considered an advanced drilling system for geothermal well to reduce the drilling cost and increase the penetration rate. Their results showed the rate of penetration enhancement with hydraulic percussion drilling results in reduction in geothermal well drilling expenses. Augustine et al. [9] carried out a comparison of well drilling costs of geothermal plants and the oil and gas industry. In addition, their analysis showed that an additional casing string leads to stepwise rise (around 18%-24%) in the well drilling cost. Mansure and Blankenship [10] applied database Sandia National Laboratory to normalize the geothermal wells costs based on thirty-three wells data and used them to generate cost correlation of geothermal wells as an exponential function of depth. Kaiser [5] developed a framework to model the cost and time of drilling an offshore well which was located in Mexico Gulf. He considered the parameters that have effect on performance of drilling and in a predictive model.

Kennedy et al. [11] at the U.S. Department of Energy conducted a comprehensive overview about geothermal drilling studies in 2010. Shevenell [12] tried to generate the geothermal well drilling cost applying publicly-available data and empirically-derived cost-depth relevance. She estimated the drilling cost according to depth and initial MW power regarding none different sites in Nevada. Thorhallsson and Sveinbjornsson [13] evaluated the drilling time and workday of different activities. They assessed the well cost against the number of workdays required for each section of the drilling. They also applied Monte Carlo simulations for the uncertainties in the workdays, material unit costs, and day rates for the drilling rigs. Amdi and Iyalla [14] investigated applying energy optimization methods to reduce the expenses through the optimum ROP (Rate Of Penetration) prognosis applying real-time drilling data. Mansure and Blankenship [15] did the well drilling cost evaluation and compared the changes in expenses. They compared well construction costs in 2013 and drillings done in the past years. Kipsang [16] defined a model to calculate the material required and total well drilling cost which can be done by determining the casing and time needed for drilling of each part.

Lukawski et al. [17] carried out evaluation of drilling and completion costs of oil and gas wells and compared with geothermal well expense. In addition to well drilling cost, they assessed the economic betterment due to increased drilling experience. Kivure

[18] evaluated the geothermal well drilling cost of a case study to find the most expensive section of geothermal well drilling. Their analysis showed the directional well drilling expense is higher than vertical well geometry at the same well depth. Gul and Aslanoglu [19] did a numerical study of drilling and testing cost of wells to predict the drilling cost. They used the drilling data of twenty wells to estimate of the cost trend of drilling. Okoro et al. [20] considered drilling fluid displacement during the operation of drilling. Their data showed that drilling mud system expense is dependent to cost of mud system formulation. Amorim Jr et al. [21] reviewed and discussed the previous statistical methodology to cost prediction of upcoming oil wells. They used a database from an onshore field in Brazil to show the advantageous of their approach to develop for new drillings.

In this study, well drilling cost and time are calculated based on the cost data of the QUE$TOR software [22] for different drilling depths and geological features. The well modelling is done in the software and the relevant cost results are calculated for five different continents and regions to compare them economically. The curve multivariable robust regression is applied to develop well drilling cost correlations comparable with literature data. These correlations are generated based on the different drilling and geological conditions in various parts of the World. The available well drilling cost results and data according to other research references are compared with presented correlations trends. Furthermore, the drilling time is compared in diverse parts of the World according to well depth value. The divers cost portions of well drilling cost (equipment, material, construction, design and project management, insurance and certification and contingency expenses) of different regions are compared together. Regarding the considering different locations of the world, as well as this note that there is not a lot of drilling cost and time prediction and data of the well drilling, this study could help operators and investors in their decision and estimation. In addition, this cost results are based on the 2020 database of the QUE$TOR software that shows it is very applicable for researchers and stakeholders. The QUE$TOR is based on the oil & gas industry but as it mentioned prior, because technologies, materials and equipment of geothermal and oil & gas drilling are similar then it can be expanded for geothermal drilling.

Geothermal well drilling

Well drilling cost can vary from country to country, region to region and even well to well according to drilling technologies and available resources. In Europe, electricity generation from geothermal resources is increasing in the both low-medium temperature areas and high-enthalpy regions by utilization of flash and binary geothermal power plants. The capacity of installed direct use of geothermal resources from 1995 to 2020 are shown in Figure 1 [23]. The top ten countries in installing geothermal power plants are displayed in Figure 2 [24]. The geothermal well drilling comprises a wide range of depth from up to 200 m (shallow) to more than 6000 m. Deep geothermal wells apply oil and gas industry drilling technology. Geothermal well drilling generally performs in some step that each steps has a lower diameter than the last one. All of these steps are supported with steel casing that are cemented before starting the following step. The last part applies a perforated un-cemented section that permits fluid to pass into the pipe [25]. The drilling operation from planning, designing to its delivery could be classified into three phases which is illustrated in Figure 3 [16]. The geological formation such as nature, structure and hardness, has direct impact on the drilling speed, the well diameter, required casing strings and, consequently, the well drill time. Deeper wells need larger drilling time and at higher cost. As the drilling cost varies with its time, the cost results of well drilling may vary consequently. The total drilling costs can be declined by reducing the drilling time and speeding up the rate of drilling into the rocks. Well drilling cost and time are dependent on several elements such as environmental situation, drilling, site and well characteristics, geological features, logging and testing time, mechanical failure etc. As construction geothermal power plants are very site-specific, then the drilling cost may vary significantly according to dependent parameters. The drilling cost could comprise between 30% to 70% of total project expenses [26].

There some uncertainties that have considerable impacts on time and cost of drilling. A set of tools (the Decision Aids for Tunneling (DAT)) were expanded to evaluate these uncertainties at MIT [27-29]. The dedicated budget to the research and development may reduce the capital cost by manipulating new technologies for the drilling. Another useful option is the market condition by making the geothermal energy more competitive compared with other renewable energies. Costs reduction at first step could be possible by decline in equipment and methods expenses such as drilling rigs, services, tools. In addition, the drilling cost decreases by prediction of some drilling risks such as technical drilling (lost on hole) and mining risk (seismic) [26].

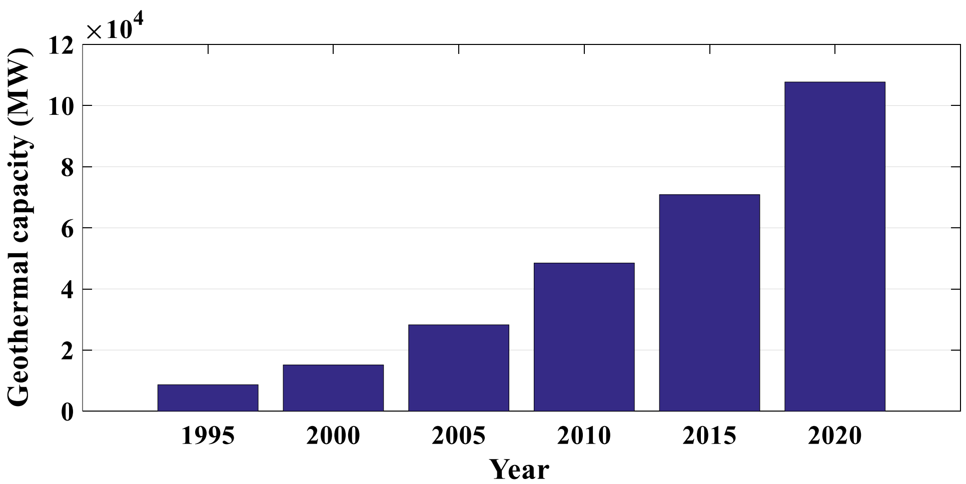

Figure 1. Installed direct use capacity of geothermal resources from 1995 to 2020 [23]

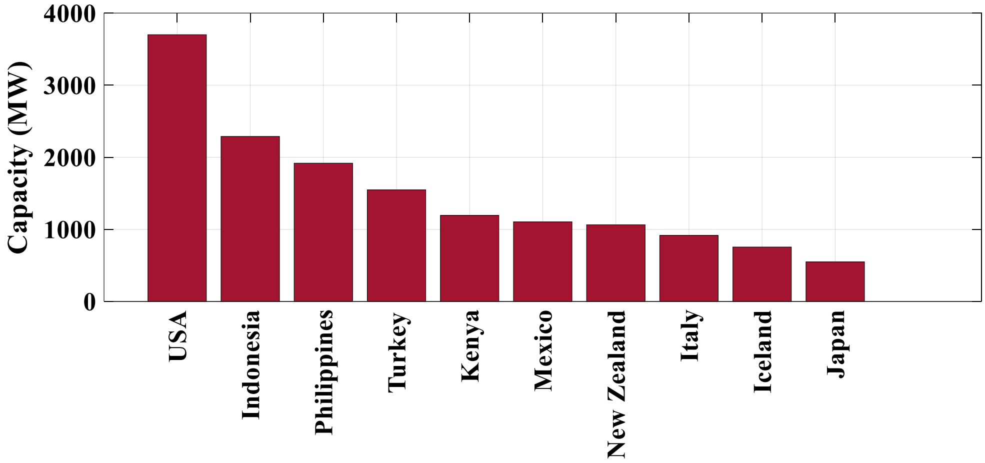

Figure 2. Ten top countries in installing geothermal power plant in 2020 [24]

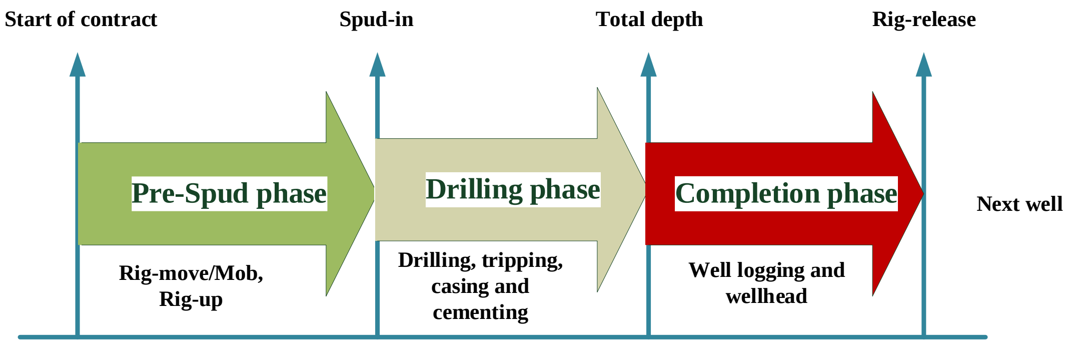

Figure 3. Geothermal drilling phases [16]

Methodology and curve fitting

The cost data are collected based on the well modelling simulation by IHS Markit QUE$TOR software which used using comprehensive and updated (2020, Q1) cost database for various process units including the onshore drilling. The drilling is simulated and the related cost data are estimated for different well depths, well type, geological features, geometry, tubular material etc. The total well drilling cost includes the sum of the equipment, materials, construction process, design and project management, insurance and certification and contingency costs. The equipment cost is the same for all drilling rig types for the same region. The construction cost is the most expensive part of the total well drilling cost. The transportation, drill camp, service logging, cementing, testing and consumables are considered in construction cost.

Curve fitting is performed to specify the best fitted model that compared to the available database. The goal of curve fitting process is finding a function ($f(x_i, y_i)$) based on the input data in which i is the data number. The most compatible and reliable fit is derived by minimization of objective function which is defined in terms of the distance between the derived correlation and variables [30, 31].

In this study, available data have been examined by several correlation forms looking for the most reliable prediction dedicated to the well drilling cost. Various parametric fitting format and approaches are examined and evaluated using the reference data. The examination is done on the basis of the residuals and statistical indexes for the including goodness of fit statistics and confidence intervals on the fitted coefficients. former illustrates how much the fitting is matched with data and the latter shows the exactitude of the coefficients.

In the curve fitting process, according to dissemination of data and points, the weight of fitting is changed based on better matching with data. The Levenberg-Marquardt approach is implemented in MATLAB to evaluate the initial conditions and variables that results in the best fit of data as Jabri and Jerbi was mentioned in their study [32]. Both SSE (sum of squares due to error) and coefficient of determination (R^2) values are considered in the evaluation of models. Furthermore, for each equation, the R-square factor is evaluated which is a statistical measure of how close the data are to the fitted regression line. This evaluation could be done by differentiate, integrate, interpolate or extrapolate of the fitting. The surface model for drilling cost of United States case as a function of well depth and number is shown in Figure 4. The same routine is followed for all other case studies. According to this graph the compatibility of available cost data with fitted graphs are presented. In addition, the drilling time is calculated based on the well depth for different regions of the world. These data are obtained for various drilling rig types and geometries. Some statistical parameters such as range, mean, median and standard deviation are presented in Table 1.

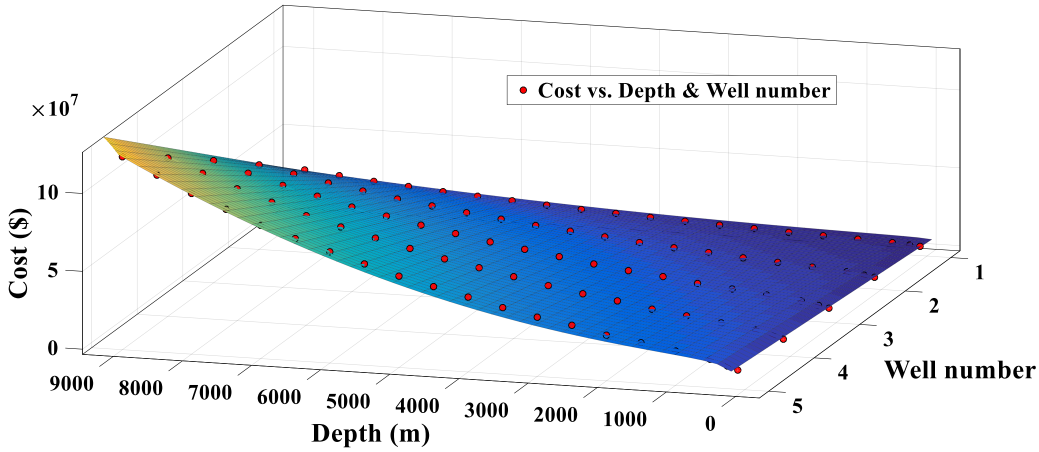

Figure 4. Curve fitting graph based on well depth and number for a case study

Table 1. The statistical parameters of modelling

Zone	Well range (m)	Number of data	Mean ($)	Median ($)	SD ($)	Confidence interval (%)
Italy	$100-9000$	200	3.067×10^7	2.310×10^7	2.441×10^7	± 11
USA	$100-9000$	200	2.632×10^7	1.985×10^7	2.019×10^7	± 10.6
Turkey	$100-9000$	200	2.986×10^7	2.292×10^7	2.275×10^7	± 10.6
Indonesia	$100-9000$	200	3.202×10^7	2.453×10^7	2.442×10^7	± 10.5
New Zealand	$100-9000$	200	3.013×10^7	2.295×10^7	2.292×10^7	± 10.5
Africa	$100-9000$	200	3.288×10^7	2.448×10^7	2.680×10^7	± 11.3
Latin America	$100-9000$	200	3.096×10^7	2.311×10^7	2.381×10^7	± 10.7
Worldwide average	$100-9000$	200	3.068×10^7	2.310×10^7	2.458×10^7	± 11.1

Results and discussion

It has been tried to generate well drilling cost correlations for different parts of the World with different geological and resources conditions to compare the final cost results. The reference database is for the first quarter of 2020 and the extracted correlations are applicable for the studies dedicated to the upcoming geothermal power plant around the world. It has been tried that the generated correlations have the best fit with available data. The logarithmic and non-linear correlation as general form is chosen based on the data [9]. The former studies showed that rising in well drilling cost with well depth is stronger than linear trend [9, 15, 17, 33]. Both regional and worldwide well drilling cost (WDC) coefficients for all considered cases are listed in Table 2. The general form of well drilling cost correlation estimation is as follows:

$$WDC = a.n.log(d) + b.n.d^2 + c \qquad (1)$$

Table 2. Coefficients of well drilling cost equations for all zones

Zone	a	b	c	R^2
Italy average	5.329×10^5	0.2156	9.655×10^5	0.99
USA average	5.05×10^5	0.1715	7.616×10^5	0.98
Turkey average	5.222×10^5	0.1982	1.782×10^6	0.96
Africa average	5.355×10^5	0.2414	1.061×10^6	0.99
Australia average	5.501×10^5	0.1973	1.089×10^6	0.98
Latin America average	5.218×10^5	0.1982	1.977×10^6	0.99
China average	5.547×10^5	0.2378	1.314×10^6	0.95
Indonesia average	5.449×10^5	0.2144	2.123×10^6	0.96
Iran average	5.209×10^5	0.1982	8.594×10^5	0.97
New Zealand average	5.502×10^5	0.1973	1.458×10^6	0.97
Europe average	5.548×10^5	0.2171	8.135×10^5	0.96
Worldwide average	5.255×10^5	0.2181	9.522×10^5	0.96

In above correlations, n is number of wells and d is well depth (m). The R-square value of drilling cost correlations of all cases are high (close to 1) and shows the well compatibility of the generated correlation with points. All drilling cost correlations are generated based on the average data of each region and country. Figure 5 shows the well drilling cost trend of different regions according to well depth change for one well. According to the obtained results, at depths up to 3000 meters, the well drilling cost in

Indonesia is higher than others, however the United States has the lowest drilling cost. Drilling cost of Worldwide average is close to drilling cost in Italy average. At depth higher than 5500 meters, well drilling cost in China is more expensive than other regions and it is close to Africa drilling cost. The well drilling costs of Italy is close to Worldwide even at higher well depths. Drilling cost of Turkey is higher than Worldwide average at lower depths up to 6300 meters and at higher depth it is lower and in general the lowest drilling expenses are related to the United States. These differences at lower depths are less than bigger depths. Other drilling cost trends related to other countries are not shown in this graph, however their extracted cost correlations are presented.

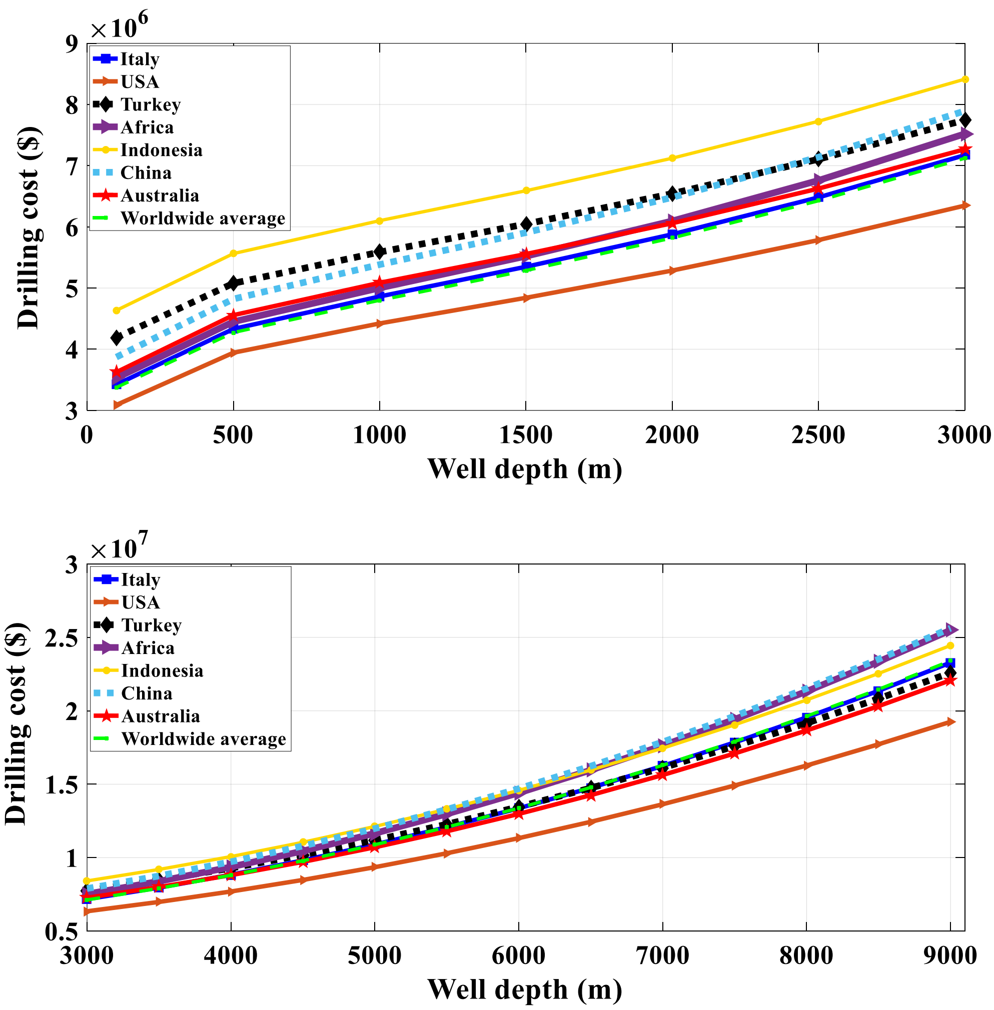

Figure 5. Drilling cost vs. well depth in different regions

Figure 6 shows the well drilling cost of Italy and Turkey based on QUE$TOR drilling cost. In addition, the available well drilling cost in some European countries based on other references [16, 17, 19, 26] are illustrated in this graph. It can be seen that the QUE$TOR well drilling costs of Italy and Turkey are in the middle range of other available well drilling costs in Europe. Also, the well drilling cost estimation of the GEOELC report is close to the presented model. The well drilling cost of the Kizildere geothermal power plant which was presented by Zorlu, shows good compatibility with the presented model for Turkey. The points related to the well drilling cost of Italy, Germany, Iceland and Kipsang model are close to the well drilling cost model based on QUE$TOR. The well drilling cost of the USA model according to QUE$TOR and others performed well drilling expenses [10, 12, 17, 19, 25, 34] in different regions of the USA are presented in Figure 7. It can be seen that some points are exactly compatible with the presented model. Also, some cost drilling points are too much higher than others and presented model which because of lots of effective elements in well drilling costs which related to site-specific features. The cost data are scattered according to different cases and regions, but the majority of them are in the range of the presented QUE$TOR model. The presented well drilling cost model trend and some drilling cases in Australia and Kenya as well as other regions [17, 19] are shown in Figure 8. The point related to the Kenya case is close to the presented QUE$TOR model. The points related to non-US wells are scattered in different ranges but most of them are close to the predicted model line. As it can be found, at lower depths in all cases, the presented model calculated higher drilling cost which is related to pre-drilling costs that is considered within presented models. Consequently, these models include the majority of pre drilling and drilling expenses.

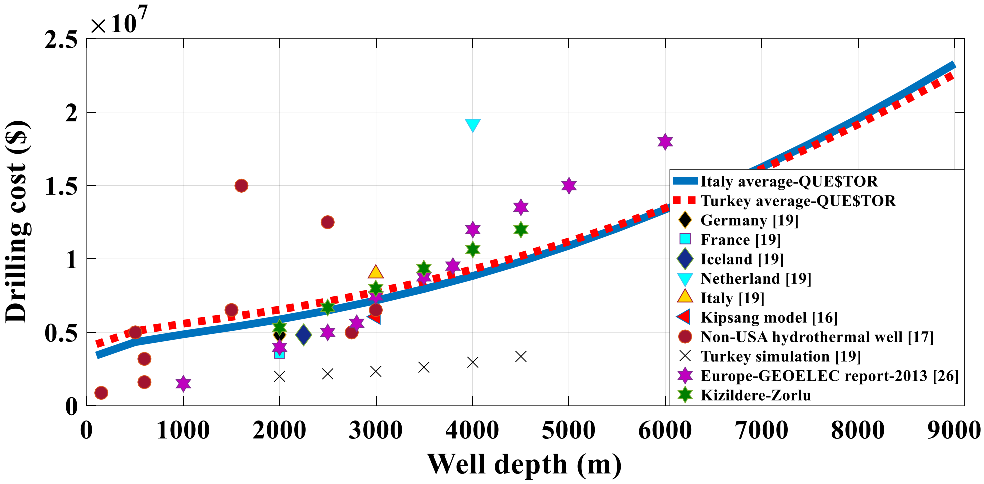

Figure 6. Evaluation of the proposed drilling cost model with European references

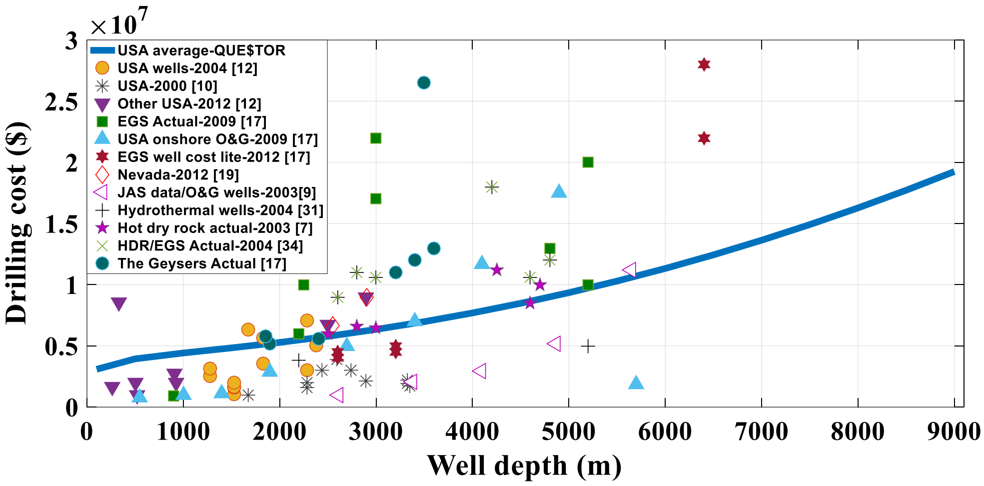

Figure 7. Evaluation of the proposed drilling cost model with USA literature data

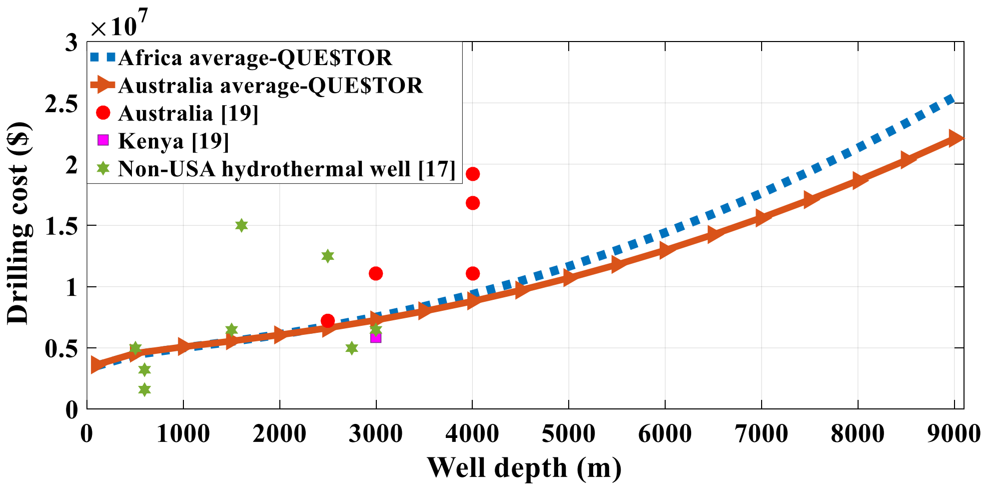

Figure 8. Evaluation of the proposed drilling cost model with literature data for Africa and Australia

Figure 9 displays the cost portion of well drilling expenses for different regions in various continents. Based on the obtained results, the construction section is the biggest part of drilling costs in all areas which is about 50% to 56% of drilling expenses. Africa has the highest construction portion in well drilling compared with others which is 56% and the lowest is related to the United States (50%). Moreover, material cost in Australia is higher than others which is about 29% of whole drilling costs and the lowest is relevant to Africa. In all considered regions, the lowest drilling cost portion is relevant to insurance and certification expenses (less than 1%). Also, it can be seen that the design and project management costs have the highest amount in the United States and Africa which is 7% and after them, China has the highest design and project management costs (about 4%).

Figure 10 shows the drilling time in different parts of the world against well depth. According to extracted drilling data of QUE$TOR, the average drilling time of vertical geometry is calculated for different regions. It can be found that the highest drilling time is related to Africa and the lowest related to the United States. Drilling time in Italy is similar to Europe and world averages. There may be several problems during the drilling wells that can cause interruption of the drilling activities and make drilling time longer. It is hard to specify all drilling aspects and factors, especially when available data are few, scattered and incomplete, but by some statistical data could extend the models. The drilling time of different geometries (vertical, horizontal and deviated) against well depth in Europe and Worldwide are presented in Figure 11. It can be found that the drilling time of vertical well is longer than other geometries and deviated geometry has lowest drilling time.

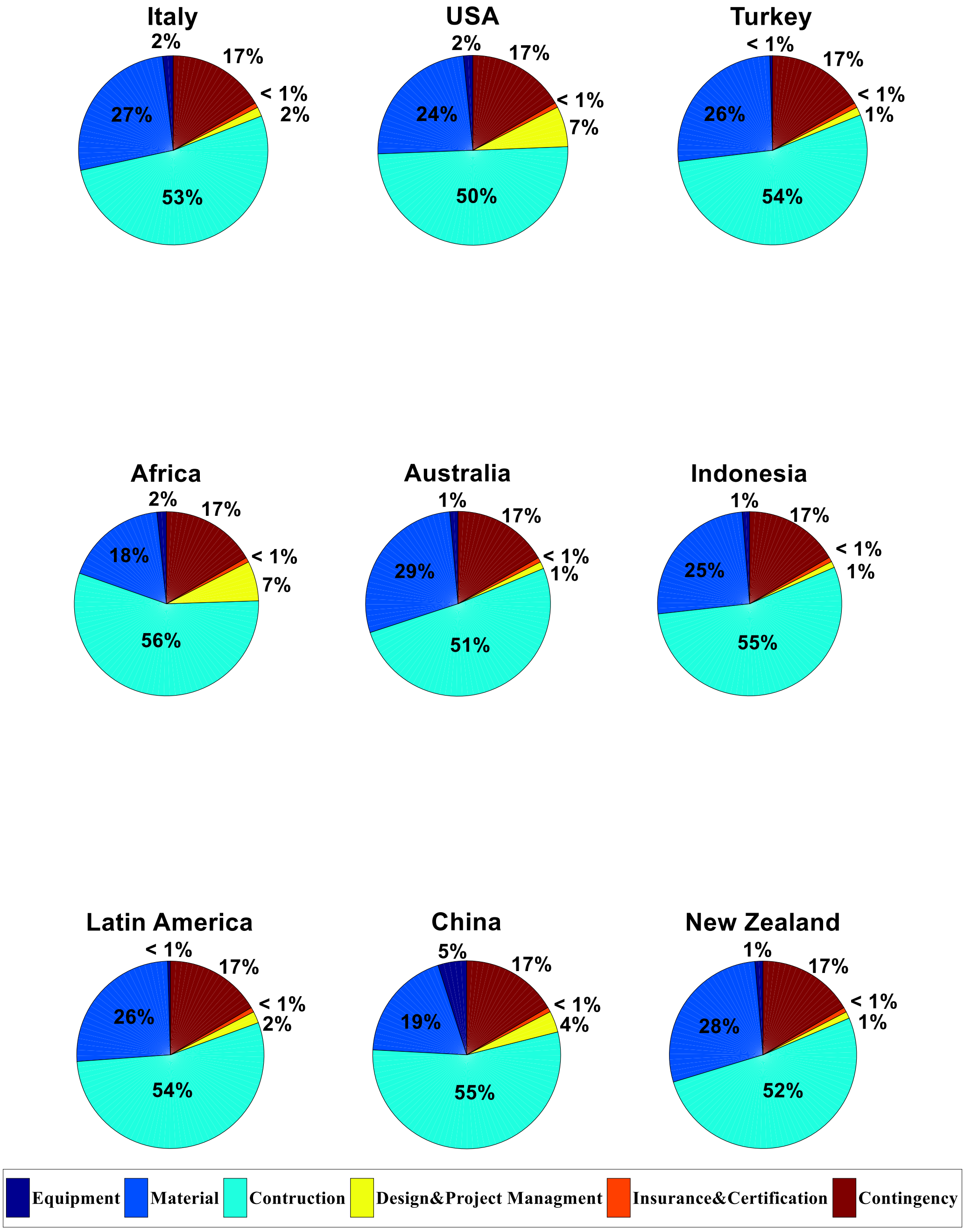

Figure 9. Cost portions of well drilling expenses for different regions of the world

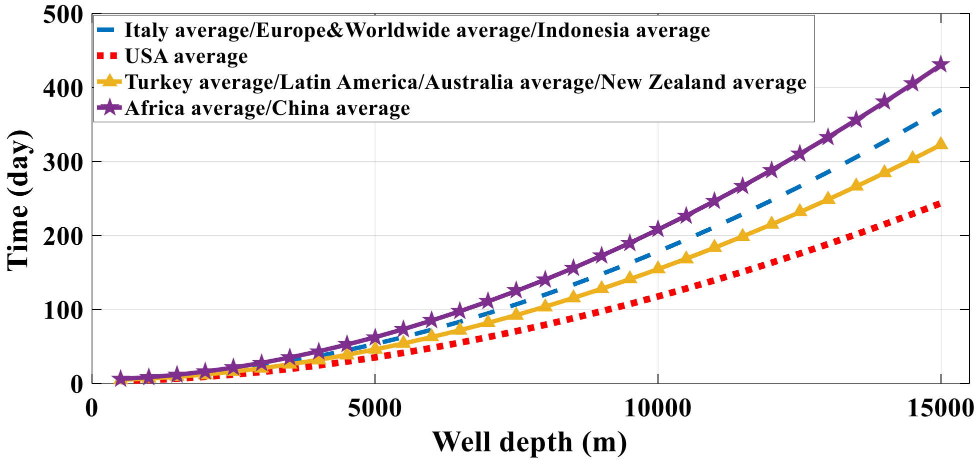

Figure 10. Drilling time vs. well depth in different regions

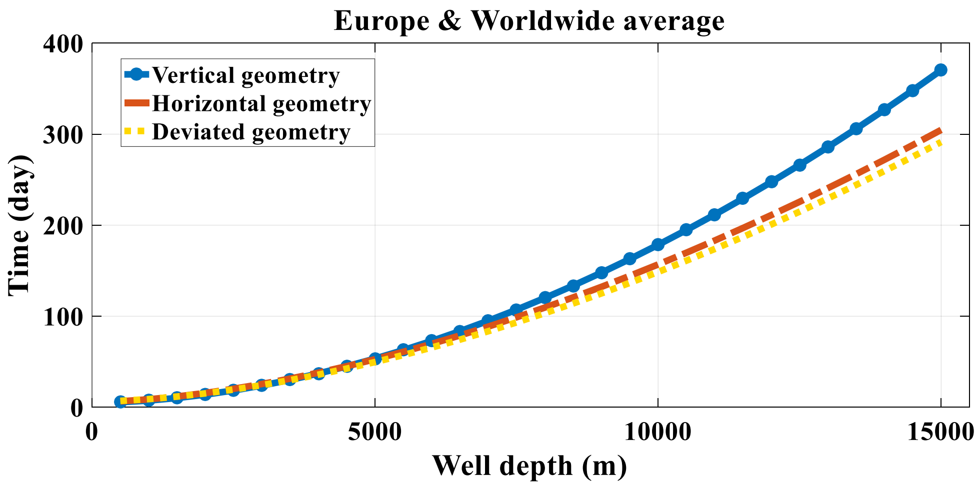

Figure 11. Drilling time of different geometries for Europe and Worldwide average

The time data are simulated by the same tool of QUE$TOR fitted in the form of Eq. 2 and the related coefficients are listed in Table 3 for various geometries (vertical, horizontal and deviated) and zones. The R-Square value for these correlations are about 0.99 for all cases.

$$T = a.d^b + c \quad (2)$$

Table 3. Coefficients of Eq. 2 for all zones and geometries

Zone	Vertical			Horizontal			Deviated		
	a	b	c	a	b	c	a	b	c
Italy	7.86×10^{-6}	1.836	4.853	2.856×10^{-5}	1.681	5.576	2.021×10^{-5}	1.712	6.198
USA	5.541×10^{-6}	1.829	3.075	1.523×10^{-5}	1.706	3.818	1.246×10^{-5}	1.72	4.049
Turkey	5.757×10^{-6}	1.854	4.627	2.065×10^{-5}	1.701	5.018	1.529×10^{-5}	1.726	5.412
Africa	9.879×10^{-6}	1.828	5.53	2.756×10^{-5}	1.703	6.775	1.808×10^{-5}	1.742	7.583
New Zealand	5.757×10^{-6}	1.854	4.627	2.065×10^{-5}	1.701	5.018	1.529×10^{-5}	1.726	5.412
China	9.879×10^{-6}	1.828	5.53	2.756×10^{-5}	1.703	6.775	1.808×10^{-5}	1.742	7.583
Indonesia	7.86×10^{-6}	1.836	4.853	2.856×10^{-5}	1.681	5.576	2.021×10^{-5}	1.712	6.198
Latin America	5.757×10^{-6}	1.854	4.627	2.065×10^{-5}	1.701	5.018	1.529×10^{-5}	1.726	5.412
Australia	5.757×10^{-6}	1.854	4.627	2.065×10^{-5}	1.701	5.018	1.529×10^{-5}	1.726	5.412
Europe average	7.86×10^{-6}	1.836	4.853	2.856×10^{-5}	1.681	5.576	2.021×10^{-5}	1.712	6.198
Worldwide average	7.86×10^{-6}	1.836	4.853	2.856×10^{-5}	1.681	5.576	2.021×10^{-5}	1.712	6.198

Conclusion

In this study, the well drilling cost in different regions of the World is considered by QUE$TOR software which is related to cost data of 2020. Various conditions are considered in cost calculations such as well geometry, depth, region and geological features for different locations. After data collection, by applying the robust surface modelling approach, the well drilling cost correlations based on the available data are extracted. It has been tried to consider different regions and continents to have a wider understanding of well drilling cost difference. The available well drilling cost data from other references are collected to compare with presented models. The results showed a good compatibility with other data. There are some scatter data but it is normal as well drilling cost can vary because of many influential factors. The extracted cost correlations in this study are reliable as presented models are so compatible with QUE$TOR cost data with the minimum R-square value of 0.95 for all cases. Also, the drilling time data are calculated in QUE$TOR and correlations related to well drilling time of different regions and geometries are generated. Based on the results, the construction section is the biggest part of drilling costs in all areas. Africa has the highest construction portion in well drilling compared with others which is 56% and the lowest is related to the United States (about 50%). Moreover, material cost in Australia is higher than others which is about 29% of whole drilling costs and the lowest is relevant to Africa. In all considered regions, the lowest drilling cost portion is relevant to insurance and certification expenses (less than 1%). Also, it can be seen that the design and project management costs have the highest amount in the United States and Africa which is 7% and after them, China has the highest design and project management costs (about 4%). In addition, well drilling time according to well depth is calculated by QUE$TOR in different countries. It can be found that the highest drilling time is related to Africa and the lowest related to the United States. Drilling time in Italy is similar to Europe and world averages. Furthermore, the drilling time of vertical well geometry is longer than other geometries and deviated geometry has lowest drilling time.

Nomenclature

a, b, c	Coefficients
d	Well depth, (m)
n	Number of well
T	Time, (day)
WDC	Well drilling cost

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