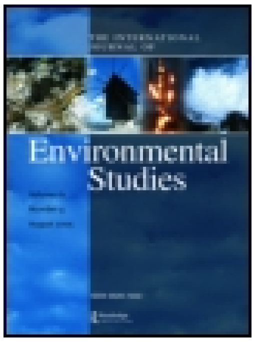

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ARTICLE

Feasibility study and economic analysis of geothermal well drilling

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ABSTRACT
This paper reports a comprehensive survey of well drilling time and cost. The models include both specific correlations on various well types and generalised correlations for rough estimation. The models are derived from robust multivariable regression to minimise the residuals. Africa has the highest construction cost component in well drilling and the United States has the lowest. Data in various regions are compared with European and World average drilling data. Drilling time in Italy is similar to Europe and world averages. The proposed model directly estimates both the drilling cost and time to be used in fundamental research and feasibility studies for geothermal power plants applicable worldwide.

KEYWORDS
Geothermal; well; drilling; cost; correlation; economic

Introduction

The geothermal power plant is an attractive renewable solution in the energy market. Several studies are following improvements in the design of geothermal power plants. One critical component is the geothermal well, which could be used either for extraction or reinjection [1,2].

The high construction cost of geothermal power plants makes them more expensive than conventional power plants. The well drilling cost is one significant part of geothermal construction's total cost. Therefore, accurate cost estimation of this component is always a challenge in feasibility studies for geothermal. The actual well drilling costs are not readily available owing to confidential matters and proprietary data; only limited data are available for the drilling cost. Statistical assessment of drilling costs data suggests that the majority of overall well cost (about 56%) is linked to well depth [3]. Well depth measurement is the elementary step to well drilling cost prediction, but not the only factor affecting drilling expenditures. Well cost also depends on the geological formation. This feature specifies rates of penetration, casing strings number, and frequency of drilling string failures [4].

Although the drilling procedure is the same in different geographical zones, wells are different in type and complexity level. The well features are defined by the drilling plan, the reservoir location, and the situation faced during drilling. Some drilling site features such as

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depth, operator and workforce experience, and the environmental situation can significantly impact the operator's decision regarding the rig type and contract selection. Other contingencies like stuck pipe and mechanical equipment failure are not predictable; but, they can greatly affect the cost and time of drilling [5]. Geothermal drilling technologies have developed from a combination of oil and gas and hydrothermal drilling technology as their equipment and materials are similar. The oil and gas industry's modified rigs are applied to drilling geothermal resources [6,7]. Many factors impact 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 the geothermal well to reduce the drilling cost and increase the penetration rate. Their results showed that the rate of penetration enhancement with hydraulic percussion drilling results in reduced geothermal well drilling expenses. Augustine et al. [9] compared well drilling costs of geothermal plants to those for the oil and gas industry. Their analysis showed that an additional casing string leads to a stepwise rise (about 18%-24%) in the well drilling cost. Mansure and Blankenship [10] applied the Sandia National Laboratory database to normalise costs for geothermal wells, based on data for thirty-three wells, and to generate the 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 located in the Gulf of Mexico. This author considered the parameters affecting the performance of drilling in a predictive model.

Kennedy et al. [11] at the U.S. Department of Energy conducted a comprehensive survey of geothermal drilling studies in 2010. Shevenell [12] tried to generate the geothermal well drilling cost by applying publicly-available data and empirically-derived cost-depth relevance. According to depth and initial MW power, Shevenell estimated the drilling cost regarding nine different sites in Nevada. Thorhallsson and Sveinbjornsson [13] evaluated the drilling time and workday of different activities. These researchers assessed the well cost against the number of workdays required for each drilling section. 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 optimisation 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, by determining the casing and time needed to drill each part.

Lukawski et al. [17] evaluated the drilling and completion costs of oil and gas wells and compared them with the geothermal well expense. In addition to well drilling cost, they assessed the economic betterment resulting from increased drilling experience. Kivure [18] evaluated the geothermal well drilling cost of a case study to find the most expensive geothermal well drilling section; and his analysis showed that the directional well drilling expense is higher than vertical well geometry at the same well depth. Gul and Aslanoglu [19] made 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 the drilling cost trend. Okoro et al. [20] considered drilling fluid displacement during drilling operations. Their data showed that drilling mud system expense depends on the costing of mud system formulation. Amorim Jr et al. [21] reviewed the previous statistical methodology to estimate the cost of prospective wells. These authors used a database from an onshore field in Brazil to show the advantages of their approach to developing new drillings.

In this study, well drilling cost and time are calculated according to the cost data of the QUE$TOR software [22] for different drilling depths and geological features. The well modelling is done in the software, and the relevant cost results are calculated for five different continents and regions to compare them economically. The curve multivariable robust regression is applied to develop well drilling cost correlations comparable with literature. These correlations are generated based on the different drilling and geological conditions in various parts of the world. The available well drilling cost results and data according to other research references are compared with presented correlations trends. Furthermore, the drilling time is compared in diverse parts of the world according to well depth value. The various cost elements of well drilling costs (equipment, material, construction, design and project management, insurance and certification, and contingency expenses) of different regions are compared. There are few published data on drilling costs. This study aims to fill the gap, to assist drilling operators and investors in their planning and estimating tasks. In addition, these cost results are based on the 2020 database of the QUE$TOR software that shows it is very applicable for researchers and stakeholders. The QUE$TOR is based on the oil & gas industry, but as mentioned earlier, because technologies, materials, and equipment of geothermal and oil & gas drilling are similar, it can be extrapolated to geothermal drilling.

Geothermal well drilling

Well drilling costs can vary by country, region, and even by well according to drilling technologies and available resources. In Europe, electricity generation from geothermal resources increases in both low-medium temperature areas and high-enthalpy regions by using flash and binary geothermal power plants. Figure 1 shows the global capacity of installed direct use of geothermal resources from 1995 to 2020 [23]. Figure 2 shows the

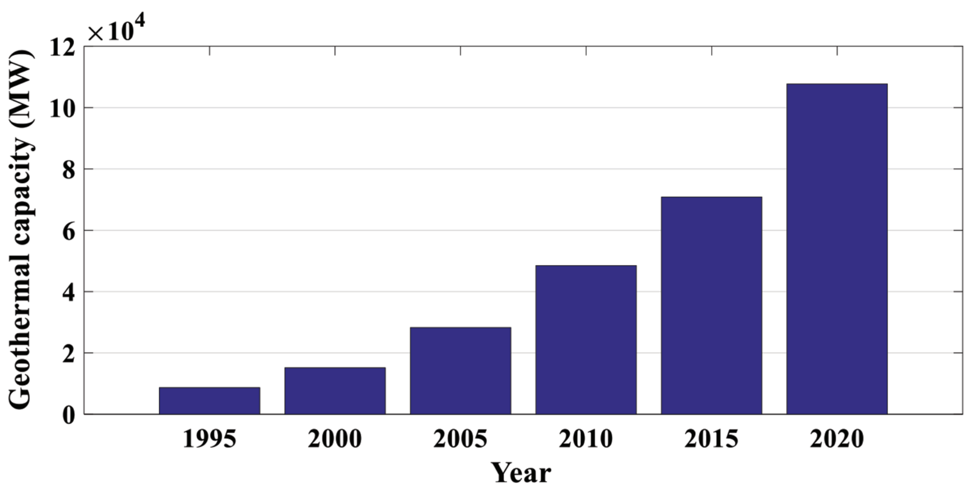

Figure 1. Global installed direct use capacity of geothermal resources from 1995 to 2020 [23].

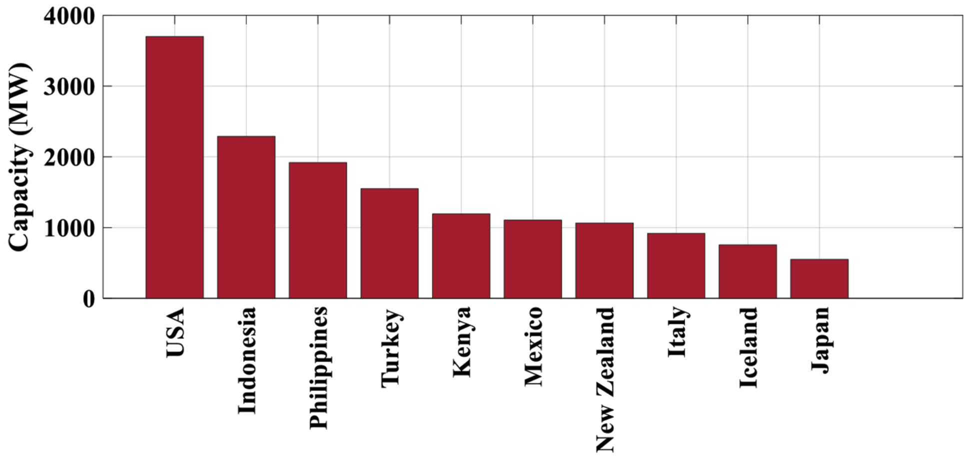

Figure 2. Ten top countries in installing geothermal power plant in 2020 [24].

top ten countries installing geothermal power plants [24]. Geothermal well drilling occurs in a wide range of depths from up to 200 m (shallow) to more than 6000 m. Deep geothermal wells apply oil and gas industry drilling technology.

Generally, in geothermal well drilling each step has a lower diameter than the last one. All of these steps are supported with steel casing and cement, one at a time. The last part applies a perforated un-cemented section that permits fluid to pass into the pipe [25]. The drilling operation, from planning and designing to its delivery, could be classified in three phases illustrated in Figure 3 [16]. The geological formation – its nature, structure, and hardness – directly impacts the drilling speed, the well diameter, required casing strings, and consequently, the well drill time. Deeper wells need longer drilling time and they have a higher cost. The drilling cost varies with the time taken for the task. The total drilling costs can be reduced by shortening the drilling time and speeding up the rate of drilling into the rocks. Well drilling cost and time depend on many 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, the drilling cost may vary significantly according to dependent parameters. The drilling cost could comprise between 30% to 70% of total project expenses [26].

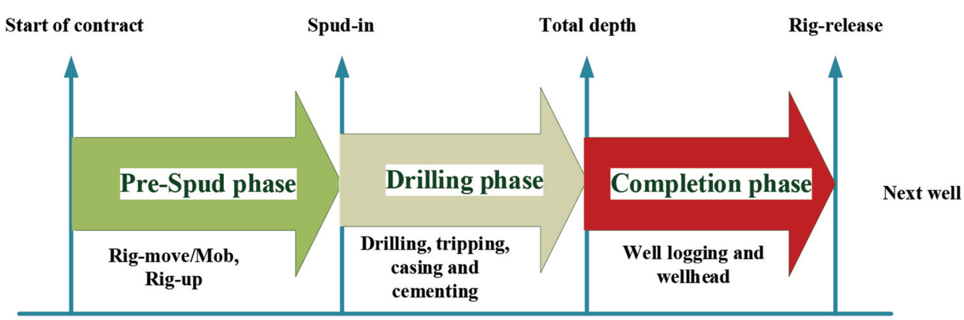

Figure 3. Geothermal drilling phases [16].

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

Methodology and curve fitting

The cost data are collected based on the well modelling simulation by IHS Markit QUE $TOR software, using a comprehensive and revised (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 costs.

Curve fitting is performed to specify the best-fitted model compared to the available database. The curve fitting process aims to find 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 minimising objective function, which is defined in terms of the distance between the derived correlation and variables [30,31].

This study has examined available data by several correlation forms looking for the most reliable prediction dedicated to the well drilling cost. This study has examined and evaluated various parametric fitting formats and approaches using the reference data. The examination is done based on the residuals and statistical indexes, including the goodness of fit statistics and confidence intervals on the fitted coefficients. The 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 the 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 result in the best fit of data, as Jabri and Jerbi noted in their study [32]. Both SSE (sum of squares owing to error) and coefficient of determination (R^2) values are considered in assessing models. Furthermore, for each equation, the R-square factor is evaluated: a statistical measure of how close the data are to the fitted regression line. This evaluation could be done by differentiating, integrating, interpolating, or extrapolating the fitting. Figure 4 shows the surface model for the United States case's drilling cost as a function of well depth and number. The same routine is followed for all other case studies. The graph in Figure 4 presents the compatibility of available cost data with fitted graph. In addition, the drilling time is calculated based on the well depth for different

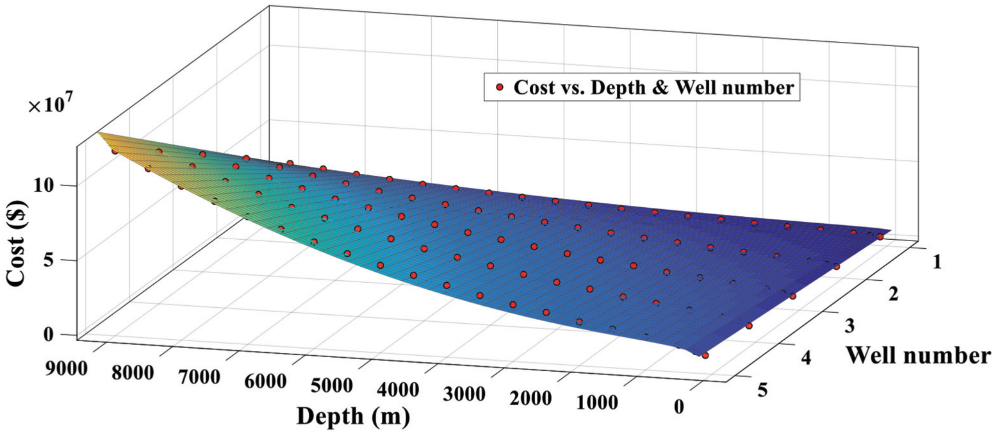

Figure 4. Curve fitting graph based on well depth and number for the United States.

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	$\pm$ 11
USA	100 – 9000	200	2.632×10^7	1.985×10^7	2.019×10^7	$\pm$ 10.6
Turkey	100 – 9000	200	2.986×10^7	2.292×10^7	2.275×10^7	$\pm$ 10.6
Indonesia	100 – 9000	200	3.202×10^7	2.453×10^7	2.442×10^7	$\pm$ 10.5
New Zealand	100 – 9000	200	3.013×10^7	2.295×10^7	2.292×10^7	$\pm$ 10.5
Africa	100 – 9000	200	3.288×10^7	2.448×10^7	2.680×10^7	$\pm$ 11.3
Latin America	100 – 9000	200	3.096×10^7	2.311×10^7	2.381×10^7	$\pm$ 10.7
Worldwide average	100 – 9000	200	3.068×10^7	2.310×10^7	2.458×10^7	$\pm$ 11.1

regions of the world. These data are obtained for various drilling rig types and geometries. Table 1 shows some statistical parameters such as range, mean, median, and standard deviation.

Results and discussion

The present work has tried to generate well drilling cost correlations for different parts of the world with different geological and resource 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 prospective geothermal power plant around the world. The generated correlations appear to have the best fit with available data. The logarithmic and non-linear correlation as a general form is chosen based on the data [9]. Previous studies showed that a rise in well drilling cost with well depth is more potent than a linear trend [9,15,17,33]. Table 2 lists both regional and worldwide well drilling cost (WDC) coefficients for all considered cases. The general form of well drilling cost correlation estimation is as follows:

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

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 the above correlations, n is the number of wells, and d is well depth (m). The R-square value of drilling cost correlations for all cases is high (close to 1) and shows the well compatibility of the generated correlation with points. All drilling cost correlations are generated based on each region's average data 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 metres, Indonesia's well drilling cost is higher than others; but, the United States has the lowest drilling cost. The worldwide average drilling cost is close to the drilling cost in Italy's average. At a greater depth than 5500 metres, well drilling cost in China is more expensive than in other regions, and it is close to African drilling cost. Italy's well drilling costs are close to worldwide, even at higher well depths. The drilling cost for Turkey is higher than the worldwide average at lower depths up to 6300 metres and, at greater depth it is less, and in general, the lowest drilling expenses are related to the United States. These differences at shorter depth are less than in deeper wells. Other drilling cost trends related to other countries are not shown in this graph; but, their extracted cost correlations are presented.

Figure 6 shows Italy and Turkey's well drilling cost based on QUE$TOR drilling cost. In addition, the available well drilling cost in some European countries based on other references [16,17,19,26] is illustrated in this graph. It appears that the QUE$TOR well drilling costs of Italy and Turkey are in the middle range of other available well drilling costs in Europe. 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 shows good compatibility with Turkey's presented model. The points related to the well drilling cost of Italy, Germany, Iceland, and the Kipsang model are close to the well drilling cost model based on QUE$TOR.

Figure 7 shows the well drilling cost of the USA model according to QUE$TOR and other performed well drilling expenses [10,12,17,19,25,34] in different regions of the USA. It can be seen that some points are exactly compatible with the presented model. Some cost drilling points are very much higher than others because of many practical elements in well drilling costs related to site-specific features. The cost data are scattered according to different cases and regions, but are mostly in the range of the presented QUE$TOR model.

Figure 8 shows the trend of the well drilling cost model, some drilling cases in Australia and Kenya, and other regions [17,19]. The point related to the Kenya case is

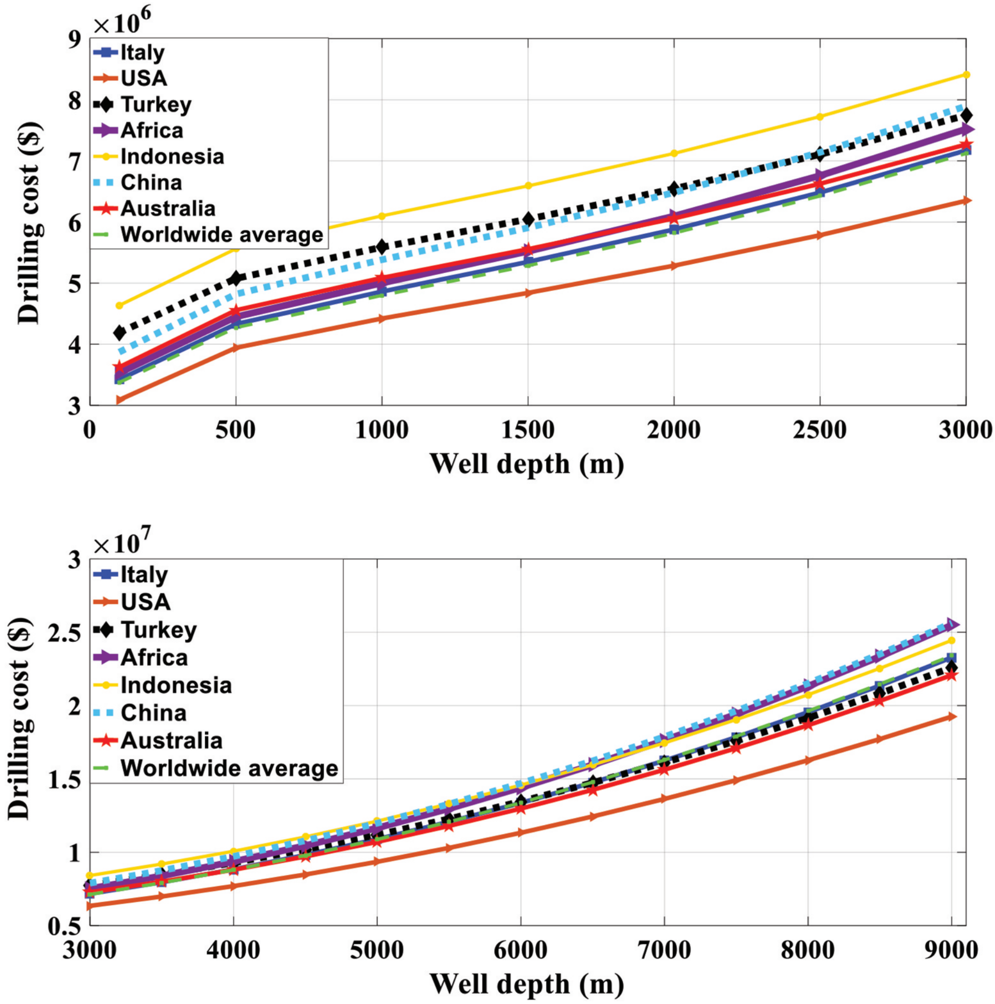

Figure 5. Drilling cost vs. well depth in different regions.

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 may be seen, at lower depths in all cases, the presented model calculated higher drilling cost, which is related to pre-drilling costs that are considered within presented models. Consequently, these models include the majority of pre-drilling and drilling expenses.

Figure 9 shows the cost portion of well drilling expenses for different regions in various continents. Based on the obtained results, the construction section is the most significant part of drilling costs in all areas, about 50% to 56% of drilling expenses. Africa has the highest construction portion in well drilling – 56%. The lowest is that of the United States (50%). Moreover, Australia's material cost is higher than others, which is about 29% of full drilling costs, and the lowest is the cost in Africa. The lowest drilling cost portion is relevant to insurance and certification expenses (less than 1%). It is apparent that the design and project

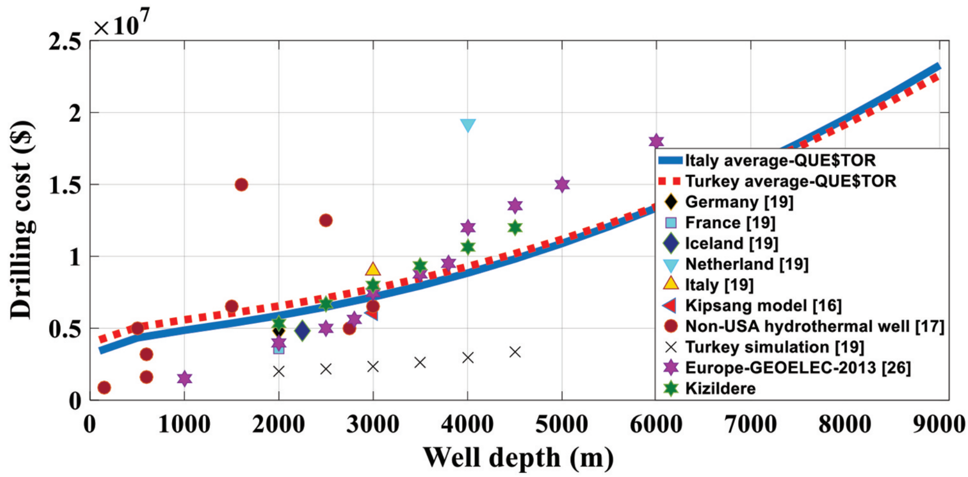

Figure 6. Evaluation of the proposed drilling cost model with European references.

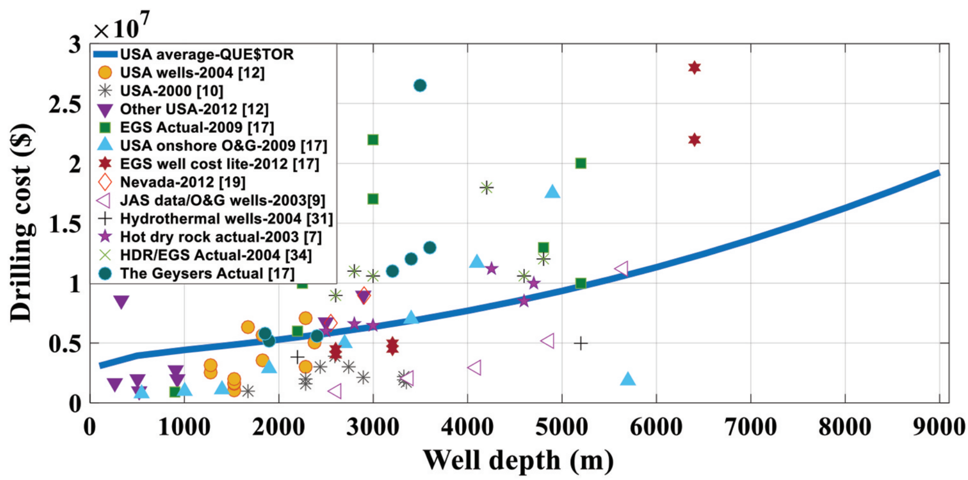

Figure 7. Evaluation of the proposed drilling cost model with USA literature data.

management costs are the highest in the United States and Africa, which is 7%, and after that, 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 appears 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 factors, especially when available data are few, scattered, and incomplete, but some statistical data could extend the models. Figure 11 shows the drilling time of

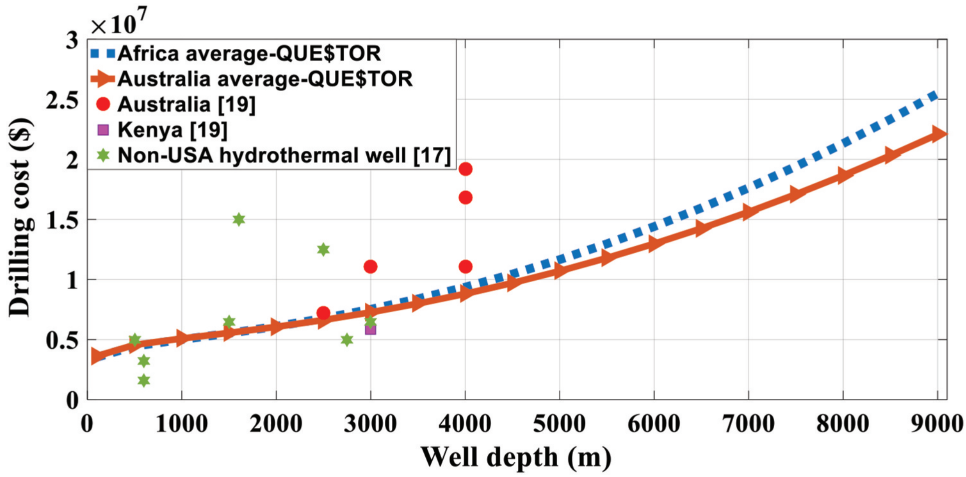

Figure 8. Evaluation of the proposed drilling cost model with literature data for Africa and Australia.

different geometries (vertical, horizontal, and deviated) against well depth in Europe and worldwide.

It may be seen that the drilling time of a vertical well is longer than other geometries and deviated geometry has the lowest drilling time. Vertical and mildly deviated wells are known as conventional wells, which are more common than horizontal because of relatively more cost-effective drilling operations. Vertical wells operate downward; horizontal wells drill from the side. A deviated well defines a well with an inclination other than zero degrees from vertical. Generally, deviated drilling improves the reservoir exposure and access of the resources in maximum ways. The deviated well drilling is known as slant or directional drilling. Engineers can better access the reservoir by performing the drilling at a deviated angle. Drilling of the horizontal and high-angle wells is similar to drilling for a directional well; but, horizontal and high-angle wells are more complex. In a horizontal well, the reservoir drills at a high angle. The differences in drilling techniques and methods are caused by drilling complexity and the drift's higher build rate and angles. Angle-build rate is the main factor in the classification of the horizontal wells. These wells are not exactly horizontal, but they are generally at an angle more prominent than 80° from vertical; deviated wells generally operate more than about 10° from vertical [35].

The time data are simulated by the same tool of QUE$TOR fitted in the form of Equation (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 is about 0.99 for all cases.

$$T = a.d^b + c \tag{2}$$

Conclusion

In this study, the well drilling cost in different regions of the World is considered by QUE $TOR software related to cost data from 2020. Various conditions are considered in cost

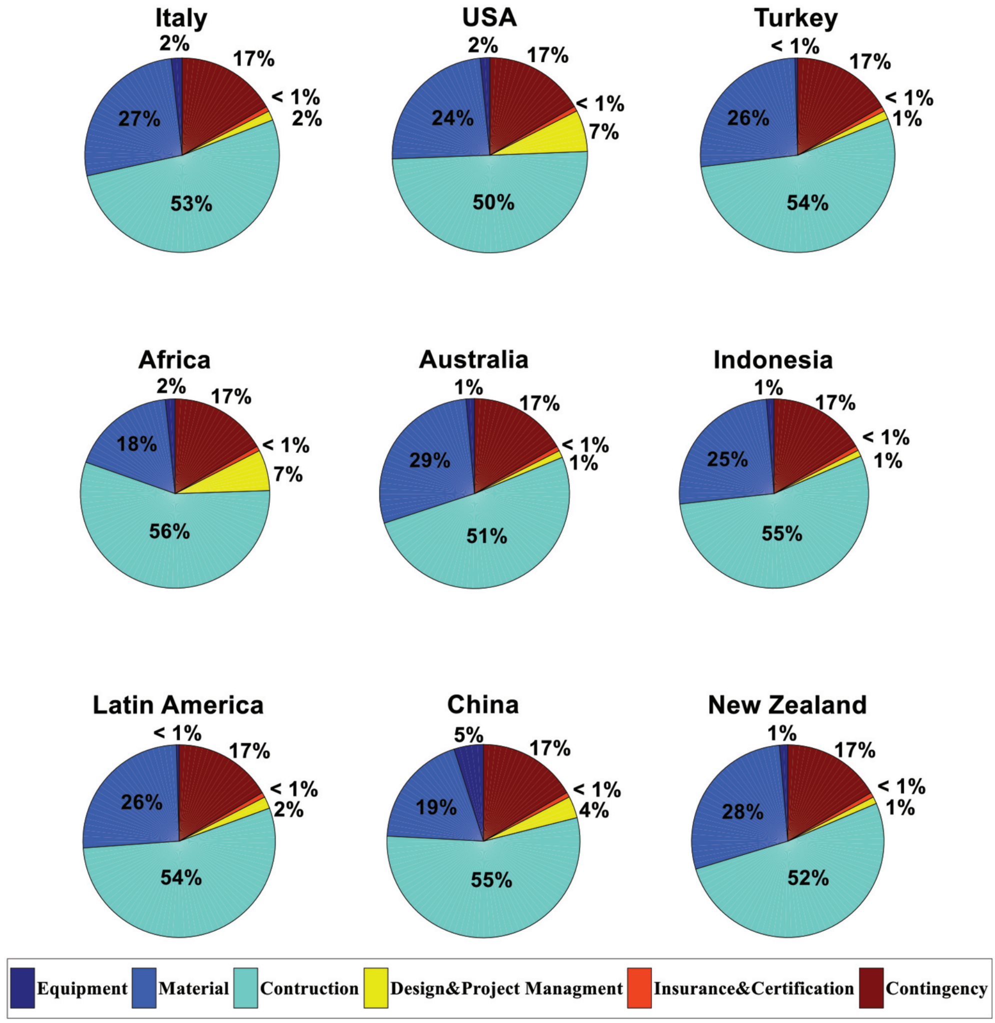

Figure 9. Cost component of well drilling expenses for different regions of the World.

Table 3. Coefficients of Equation (2) for all zones and geometries.

	Vertical			Horizontal			Deviated		
Zone	*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

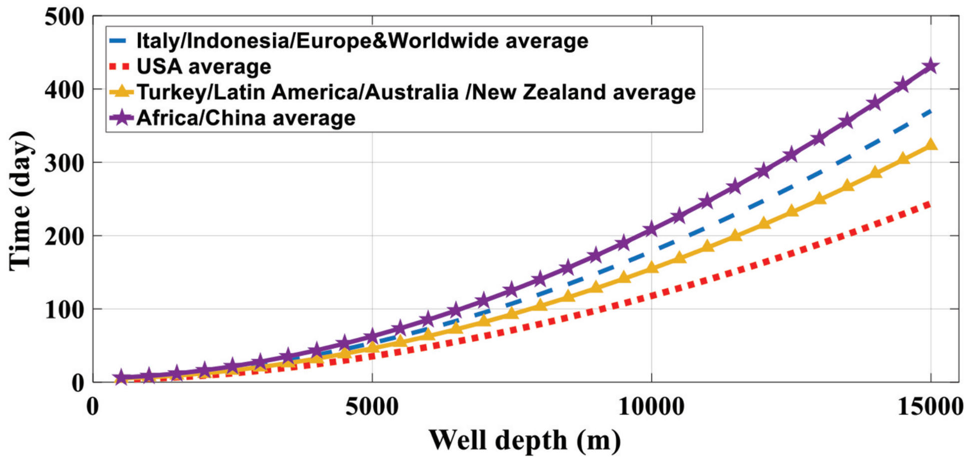

Figure 10. Drilling time vs. well depth in different regions.

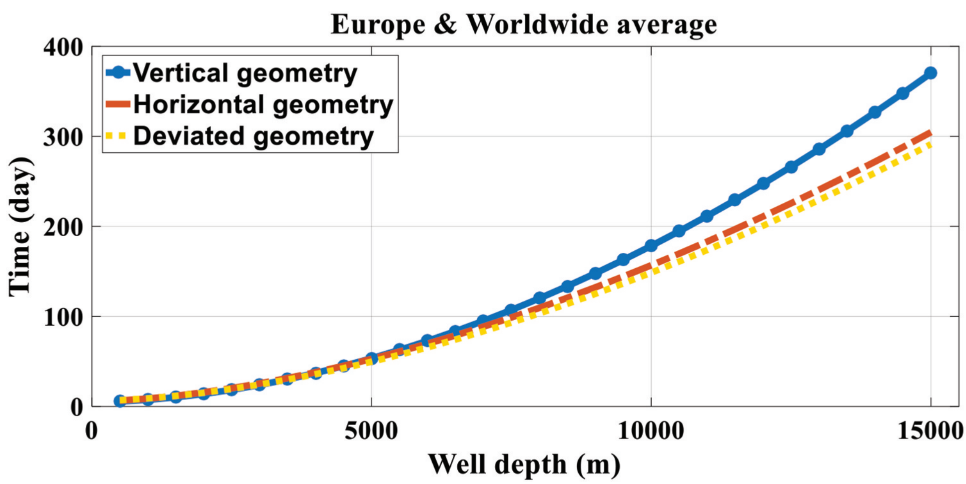

Figure 11. Drilling time of different geometries for Europe and Worldwide average.

calculations, such as well geometry, depth, region, and geological features for different locations. After data collection, the well drilling cost correlations based on the available data are extracted by applying the robust surface modelling approach. The research has attempted to consider different regions and continents to understand well drilling cost difference better. The available well drilling cost data from other references are collected to compare with the presented models. The results showed good compatibility with other data. There are some scatter data, but normally well drilling costs vary for many reasons. The extracted cost correlations in this study are reliable as the presented models are compatible with QUE$TOR cost data with the minimum R-square value of 0.95 for all cases. The drilling time data are also calculated in QUE$TOR, and correlations related to well drilling time of different regions and geometries are generated.

It is evident that the construction section is the biggest part of drilling costs in all areas. Africa has the highest construction portion in well drilling, 56%, and the lowest is for the United States (about 50%). Moreover, Australia's material cost is the highest, about 29% of full drilling costs, and the lowest is for Africa. The lowest drilling cost portion is relevant to insurance and certification expenses (less than 1%). The design and project management costs are greatest in the United States and Africa, 7%, and the next costly country is China, about 4%. QUESTOR calculates well drilling time according to well depth in different countries. It is evident that the longest drilling time is for Africa and the shortest for 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 the shortest drilling time.

Nomenclature

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

Disclosure statement

No potential conflict of interest was reported by the author(s).

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