

## ROBUST SIEVE ANALYSIS USING SIEVE-BY-SIEVE METHOD

***Kouros KHADIVI \* & Shahab HEJRI\*\* & Shapour VOSOUGHI\*\*\****

*\* Senior Reservoir Engineer & Modeler, (Tehran Energy Consultants (TEC),  
Iran, Islamic Republic of, e-mail: khadiv@gmail.com  
ORCID: <https://orcid.org/0000-0002-9495-6163>*

*\*\* Senior Upstream Advisor, Petran Company,  
Iran, Islamic Republic of, e-mail: hejrishahab@gmail.com  
ORCID: <https://orcid.org/0000-0002-6859-0532>*

*\*\*\* Professor of Chemical and Petroleum Engineering, Kansas University  
United States, e-mail: shapour@ku.edu  
ORCID: <https://orcid.org/0000-0002-6234-2175>*

Received: 3 November 2019, Accepted: 23 April 2020

---

### **ABSTRACT**

*Distribution of size of sand grains is an important factor in characterization of unconsolidated reservoirs as well as designing sand control devices. In practice, sand grains are passed through a set of known mesh sizes by mechanical vibration and for a fixed period then the weight of sediments retained on each sieve are measured and converted into the percentage of the total sediment (PTS). This procedure is applied to all core samples and the resulted PTS data are used for characterizing grain size distribution using one of the sieve analysis procedures. The core-by-core method, for example, is one of the conventional methods that PTS data from each core sample are used individually to estimate mean, sorting and other dependent parameters to grain size distribution. In this method, applying a robust statistical method to integrate all PTS data and picking out the most probable size from all cores is a challenge.*

*A new approach is introduced in this paper as sieve-by-sieve method, whereby the grain weight distribution data are classified based on mesh sizes (as bins) and the most probable size in each class is picked out among all cores directly and without any manipulation or averaging.*

*In this paper, the performance of both methods are compared in a homogeneous media and a heterogeneous media. In a homogeneous media, both methods provide comparable results. However, in a heterogeneous media, the core-by-core provides too many distributions which sometimes are not conclusive but the sieve-by-sieve provides the profiles of minimum and maximum weight of retained grains, which facilitates picking out the most probable size among all cores.*

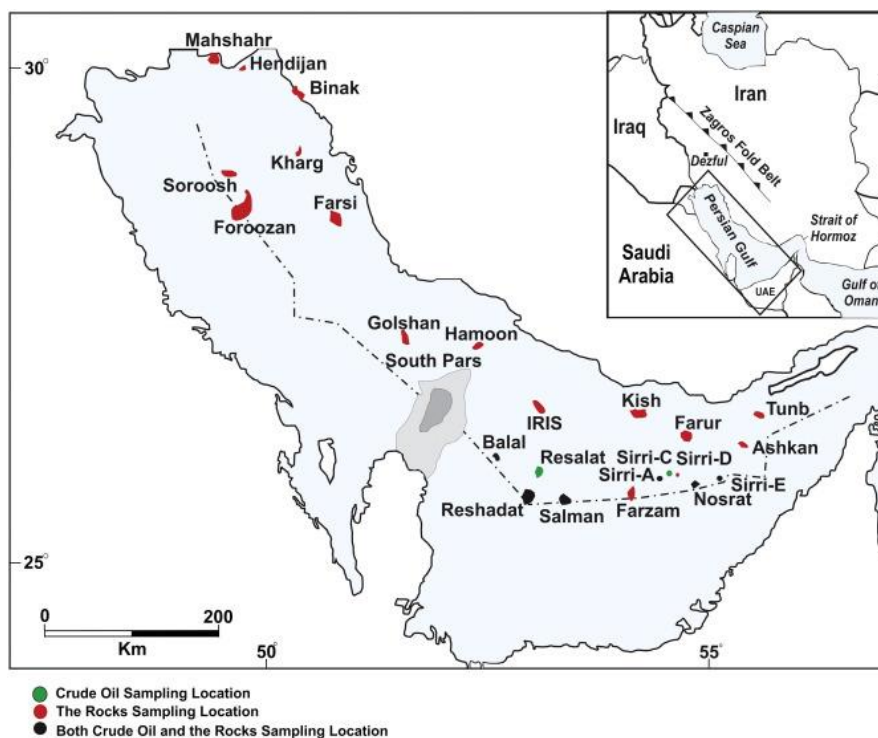
**Keywords:** *Sieve analysis, core-by-core method, sieve-by-sieve method, mean, sorting, the most probable size.*

---

## 1. INTRODUCTION

Burgan Formation is a prolific oil reservoir in Foroozan field in the North West of Persian Gulf (Figure 1). The main reservoirs are Burgan A and Burgan B. It is a siliciclastic reservoir and a member of Lower Cretaceous period. The offshore oil reservoir from Burgan formation has the same geologic characteristics of well-studied formation in the Persian Gulf region common with Kuwait, Saudi Arabia and some other oil-rich countries of the region (Ahlbrandt et al. 2000; Stromenger, et al. 2002; Al-Ajmi and Azim 2003; Mehrabi et al. 2019). The Burgan sands are believed to have been deposited as delta sediments. The Burgan source area began rising during the later Upper Shuaiba time, silt and shale with some occasional thin carbonate beds are inter-bedded over the field and surrounding areas. Due to the rise of the source area at the beginning of Burgan B deposition, a thick layer of sand was deposited, probably as a delta of numerous streams.

**Figure 1:** Location map of Foroozan Field in Persian Gulf (from Sadat and Rabbani 2015).



During Burgan A sand deposition no regression of the sea had happened, but further transgression occurred which resulted in the deposition of silts and clay particles. Even traces of carbonates were deposited during Burgan A sand depositional period. An interbedded sequence of sand, silt and clay particles was the product of rises and falls of the sea during Burgan A time. Some of the beds cover a wide area but some others are very limited in their lateral extent over the field. The deposition of Burgan A was ended with a major transgression of the sea and with the deposition of limestone beds on top of the Burgan A sand known as Dair Limestone. The Dair Limestone member covers the entire area in the field and surrounding areas and it indicates the end of Burgan deposition.

The Burgan is further defined as a sequence of fairly well sorted, medium to coarse-grained sands, usually loosely packed, and with interbeds of shale and silt shale and abundant amber and bituminous matter. The Burgan sandstone is cemented by carbonate and clay. The upper sand stringers in Burgan A are very fine grained sand (silt size) and generally have poorer rock characteristics. The sand grain size generally becomes coarser and exhibits better porosity

and permeability towards the base of Burgan A. The basal portion of the Burgan (Burgan B) consists of medium to coarse, unconsolidated sandstone. Since the Burgan B sand is generally clean and has very coarse grains (it resembles beach sand in most cases), it has on the average higher porosity and permeability than the Burgan A.

Geological study of Burgan reservoirs shows that there are several unconsolidated sand layers in these reservoirs (Mehrabi et al. 2019). A common problem in unconsolidated reservoirs like Burgan reservoir is sand migration to the wellbore (Al-Awad et al. 1999; Zivar et al. 2019). In fact, it is because of poor cementation between sand grains whereby sand grains can slip and move over each other and migrate from sand body to the wellbore then travel through the production tubing. Sand production is a harmful phenomenon because of severe erosion through production tubing, wellhead, choke, and clogging of production lines. In addition, it causes premature water breakthrough in waterflooding process (Nassir et al. 2015). The visual observation of cores and daily production reports of nearby field confirmed this problem. Thus, it was considered in the mitigation program and designing well completion for new wells (Khadivi and Vossoughi 2005). Slotted liner and Screener are two types of sand control devices, which restrict sand migration and settle them beyond the casing (Dong 2016; Shahsavari and Khamnehchi 2018; Mahmud et al. 2019; Wang et al. 2019).

Design of mesh size of a sand control device (i.e. gravel pack, screener or slotted liner) requires information about the most probable size of sand grains. There are several techniques for selecting the mesh size of a sand control device. The most widely used sizing criterion provides sand control when the median grain size of the gravel-pack sand,  $D_{50}$ , is no more than six times larger than the median grain size of the formation sand,  $d_{50}$  (Penberthy and Shaughnessy, 1992). In the other side, the size of the holes can be half of the smallest grain diameter but should not be smaller than 70% of the smallest grain diameter as this design becomes conservative and restricts productivity. Therefore, mesh size impacts significantly on the economic and productivity of wells. As such, our goals for this study are,

- To find the variability scheme through these formations and relate it to sand size distribution and,
- To find the most probable size of sand grains among all cores to be used for robust design of sand control devices.

In order to address above objectives, sieve analysis is used as a tool to obtain distribution of size of sand grains, which is an important factor in characterization of unconsolidated reservoirs as well as designing sand control devices.

## **2. SIEVE ANALYSIS**

Grain size is one of most fundamental property of sediment particles, which influences on the entraining, transporting and depositing of sand particles. Sieve analysis is a method to obtain the dominant grain size of sediment particles (Folk and Ward, 1957). Sand grain sizes are most generally measured by sieving. The basic principle of this technique is as follows (ASTM and AASHTO) whereby a sand sample of known weight is passed through a set of sieves of known mesh sizes. The sieves are arranged in downward decreasing mesh diameters. The sieves are mechanically vibrated for a fixed period. The weight of sediments retained on each sieve is measured and converted into the percentage of the total sediment (PTS). The percentage of the retained sample in every stage are added with the previous stage to obtain a new parameter named Cumulative Percentage of the Total Sediment (CPTS). This procedure is applied to every core sample and reported individually. This method is quick and sufficiently accurate for most purposes.

An important objective to conduct sieve analysis is to obtain sorting or the degree of scatterness. Sorting is tendency for the grains to fall in one class of grain size (see Appendix for formula). Cumulative curve is a useful presentation of data because many sample curves can be plotted on the same graph and differences in sorting become apparent. The closer a curve approaches the vertical the better sorted it is, as a major percentage of sediment occurs in one class. Significant percentages of coarse and fine end-members show up as horizontal limbs at the ends of the curve. Sorting can be expressed by statistical methods as well. The simplest of these is the measurement of the central tendency of which there are three commonly used parameters: median, mode, and mean. The median grain size is that which separates 50% of the sample from the other; the median is the 50 percentile. The mode is the largest class interval. The mean is variously defined, but a common formula is the average of the 25 and 75 percentile.

## **2.1 Conventional Sieve Analysis: Core-by-Core Method**

Grain size distribution is normally investigated by sieve analysis based on statistical parameters and probability of occurrence for each core plug (McGlinchey Donald 2005). A conventional method of sieve analysis is based on core-by-core analysis. PTS data are used to estimate dominant size of sands, which potentially can migrate from the sand bodies to the wellbore. Statistical methods are applied to every single core data to acquire a measure of central tendency (including median, mode, and mean); a measure of the degree of scatterness or sorting; kurtosis, the degree of peakedness; and skewness, the lop-sidedness of the curve. Various formulae have been defined for these parameters (Folk and Ward, 1957). Eventually, statistical analysis is performed on the grain weight distribution of cores then the most probable size is picked out from the whole core data (Fuller et al. 2019). However, applying a robust statistical method to integrate all PTS data and picking out the most probable size from all cores is a challenge. In the other words, PTS data cannot be added or averaged because they are ratio numbers and have been resulted from different references. However, this method is simple to apply in homogenous reservoir where distribution is like a unimodal distribution (e.g. clean sand reservoirs) but it is difficult to get conclusive results in the heterogeneous reservoirs (e.g. shaly sandstone) where distribution is a kind of bimodal distributions.

In summary, lack of a robust averaging method over PTS data and handling variability of grains size are two shortcomings of the core-by-core method. To address above challenges, a new approach is presented in the next section whereby variability of grain size is incorporated into the averaging process simultaneously.

## **2.2 New Sieve Analysis Method: Sieve-by-Sieve Method**

Variability of the grains size across the perforated interval is a challenge which can be addressed by studying depositional environment. The weighted average method could be a solution to integrate all data; however, lack of relevant data to account for the representative volumes of sand bodies is a new challenge. Another solution for this problem would be developing an integrated method through scaling up from core-level to whole-core-level while heterogeneity of grains size is preserved. The benefit of this method is applying sieve analysis once and just on the whole core instead of multiple analysis on the entire core samples. In the other words, instead of multiple averaging on the core data to achieve a unique value as the most probable grain size, cores are combining together and grain size distribution is analyzed once on the whole core. Although this idea may not be practical in the lab but it is possible by the mathematical calculation and applying a novel method of sieve-by-sieve method. All cores indeed are assumed parts of a whole core, which have been sampled and sieved in several steps. In addition, contrary to the core-by-core method, which is based on PTS (ratios) data, the sieve-by-sieve method is based on the weight of retained grains, which is an addable parameter. In this method, the weight data are classified based on the mesh sizes (as bins). Such classification

allows us to compare the corresponding data of all cores and pick out the most probable size in each class directly without any manipulation or averaging. The sieve-by-sieve method is simple and robust because it does not use any complicated statistical calculation or averaging method.

### **3. RESULTS AND DISCUSSION**

Among 200 core samples across Burgan formation, 17 core samples were selected for sieve analysis which 4 of them falls in the Burgan A and the rest (17 samples) from Burgan B (Nemati, et al., 2003). Cores have not been sampled across the reservoir sections consistently. Most of cores are from Burgan B and a few of them are from Burgan A. In addition, distribution of samples is not uniform. In Burgan B, samples have been taken more or less from the entire reservoir section; however, a few samples have been taken from top of Burgan A with no sample from the base of this reservoir. Inadequacy and non-uniformity of samples create uncertainties in representativeness of samples in Burgan A.

Conventional core analysis (CCAL) tests were undertaken to acquire grain density, porosity and permeability data. The CCAL results are discussed to better understand porous media then sieve data are examined using core-by-core and sieve-by-sieve methods to see the privilege of sieve-by-sieve methods against core-by-core method.

#### **3.1 Conventional Core Analysis (CCAL)**

Comparing average grain density data shows that the nature of both reservoirs predominantly is sand. An average grain density of 2.64 g/cc in Burgan A against 2.61 cc/gr in Burgan B confirms poor carbonate content and cementation in Burgan B.

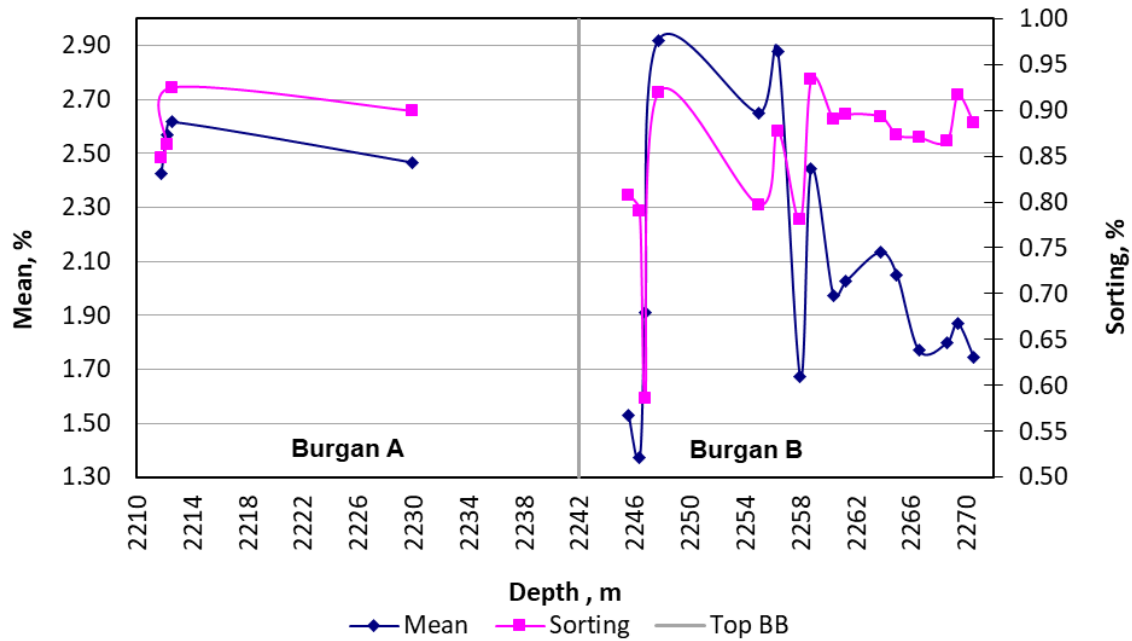
Figure 2 is an exhibition of sorting and mean of all core samples from Burgan A and Burgan B formations (see Appendix for formula). No significant correlation is seen between these two parameters.

As mentioned before, Burgan A is a sandstone formation mixed with shale, silt and bituminous matter, which have been cemented by carbonate and clay. However, the available mean and sorting data (4 samples) show minor variations in Burgan A, thus in any analysis based on such data, it is considered a homogenous reservoir. Burgan B, in contrast, consists of medium to coarse, unconsolidated sandstone and generally clean sands with higher porosity and permeability than Burgan A. However, variations of mean and sorting parameters in Burgan B are much wider than Burgan A, so in any analysis based on these data, Burgan B resemble a heterogeneous reservoir.

In the lower part of Burgan B, the mean profile decreases in a stepwise fashion. This is a typical representation of fining downward (or coarsening upward) behavior, which is common in the clastic reservoirs (Van Wagoner, et al., 1990; Emery and Myers, 1996).

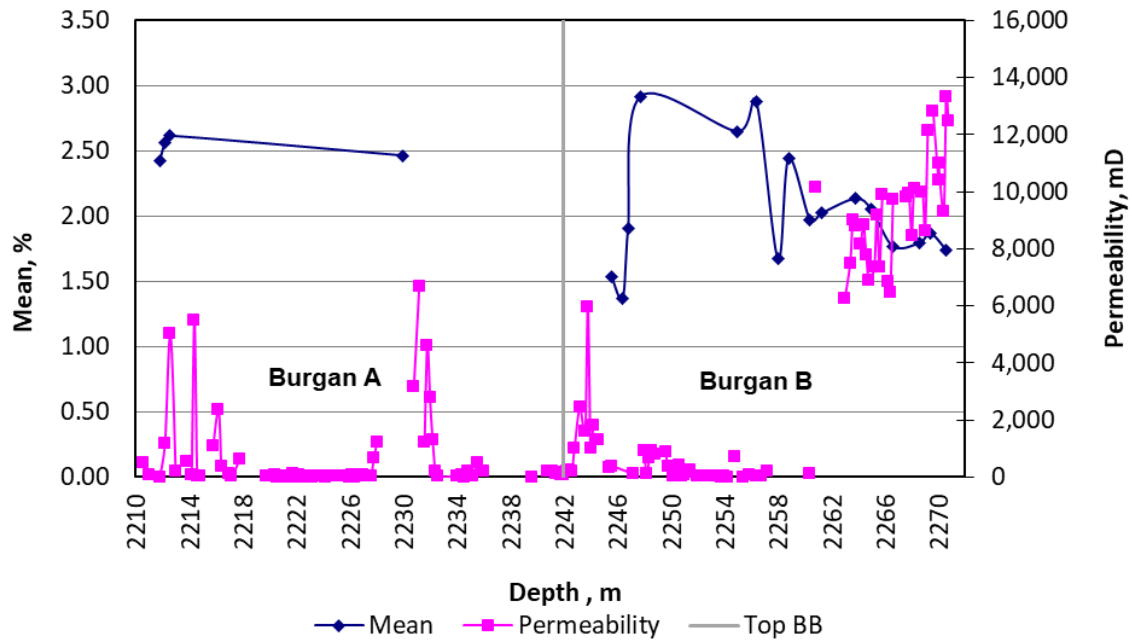
The sorting remains almost constant at the base of Burgan B, which means in spite of decreasing grain sizes (or mean), the relative amount of different grain sizes (or sorting) remains relatively constant. Considering a high degree of sorting (0.9) in this zone, a high permeable zone in this zone is expected.

**Figure 2:** Comparing profiles “sorting” and “mean” with depth.

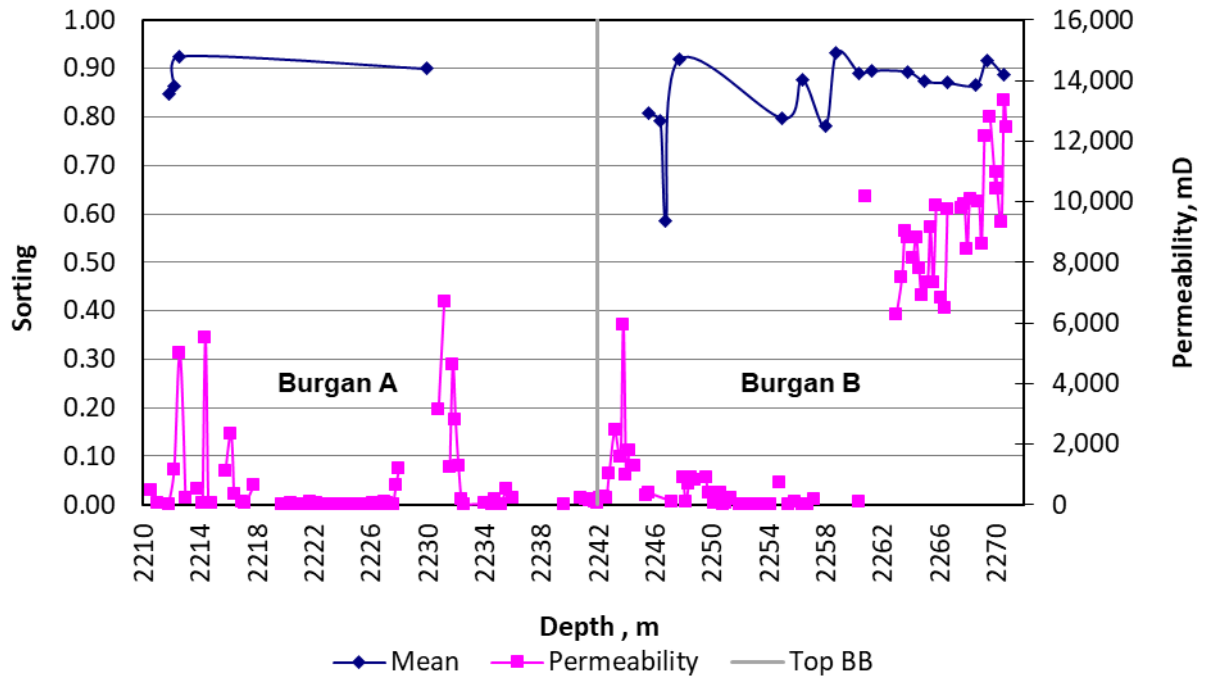


In order to investigate dependency of mean and sorting parameters with formation permeability, the profiles of permeability and mean are presented in Figure 3, while the profiles of permeability and sorting are presented in Figure 4. Permeability and sorting shows a better correlation than permeability and mean. Increasing permeability in the base of Burgan B is attributed to the well sorted grains, uniformity of clean sand grains and poor cementation factor.

**Figure 3.** The profiles of permeability and mean grain size with depth in Burgan A & B.

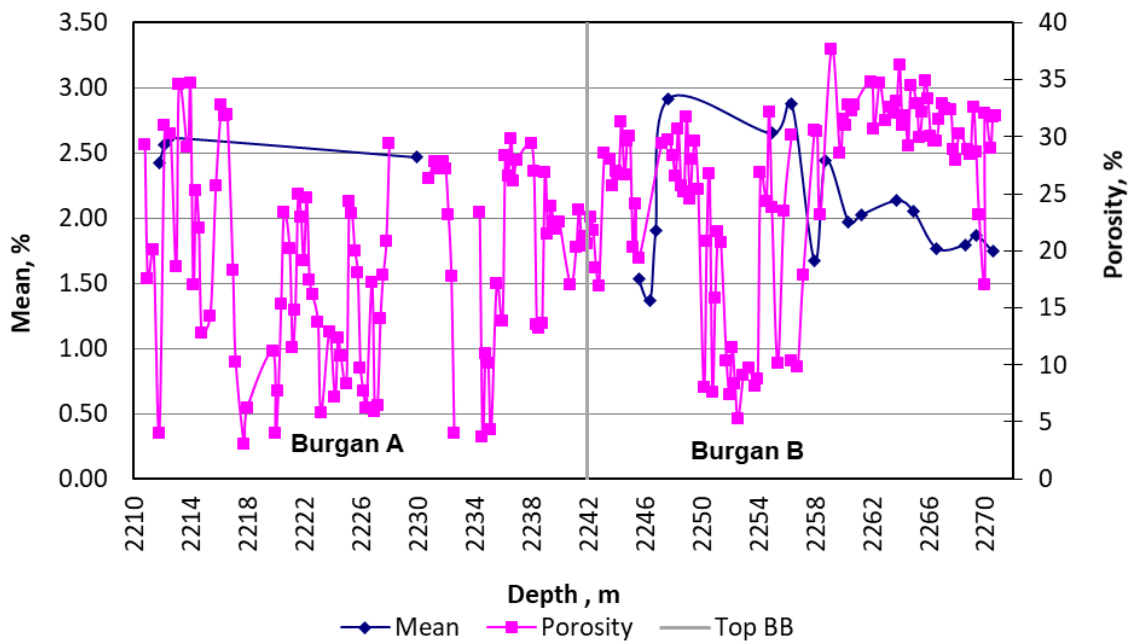


**Figure 4:** The profiles of permeability and Sorting with depth in Burgan A & B.

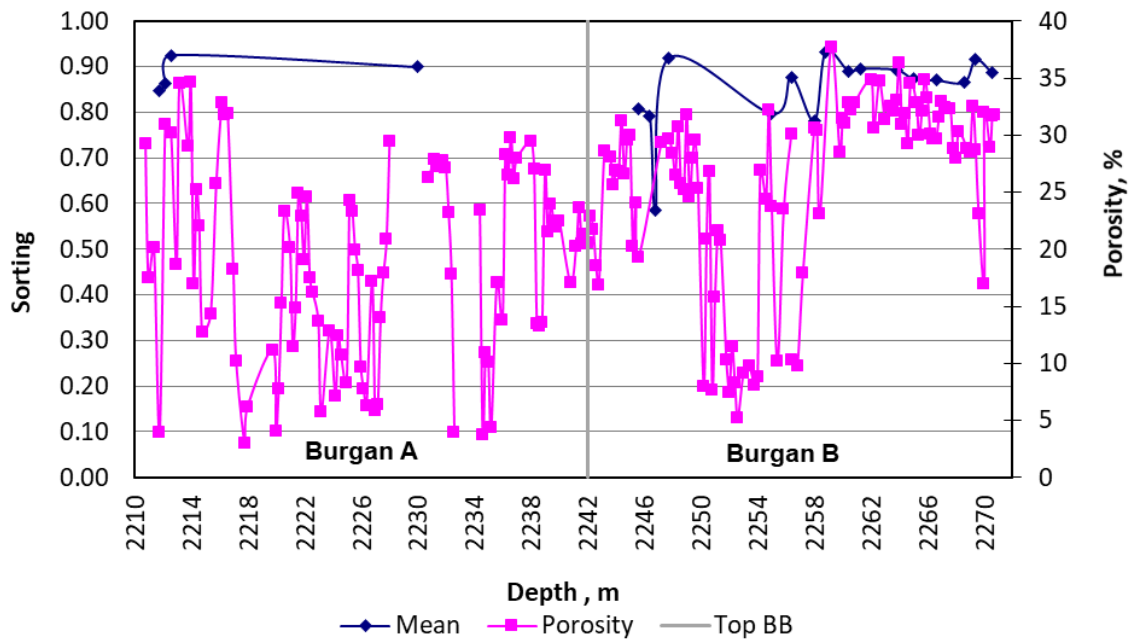


The profiles of mean and sorting are compared with porosity in Figures 5 and 6, respectively. Correlation of porosity and sorting specially in Burgan B is seen clearly in Figure 6; however, no correlation exists between porosity and mean grain size.

**Figure 5:** The profiles of porosity and mean grain size with depth in Burgan A & B.

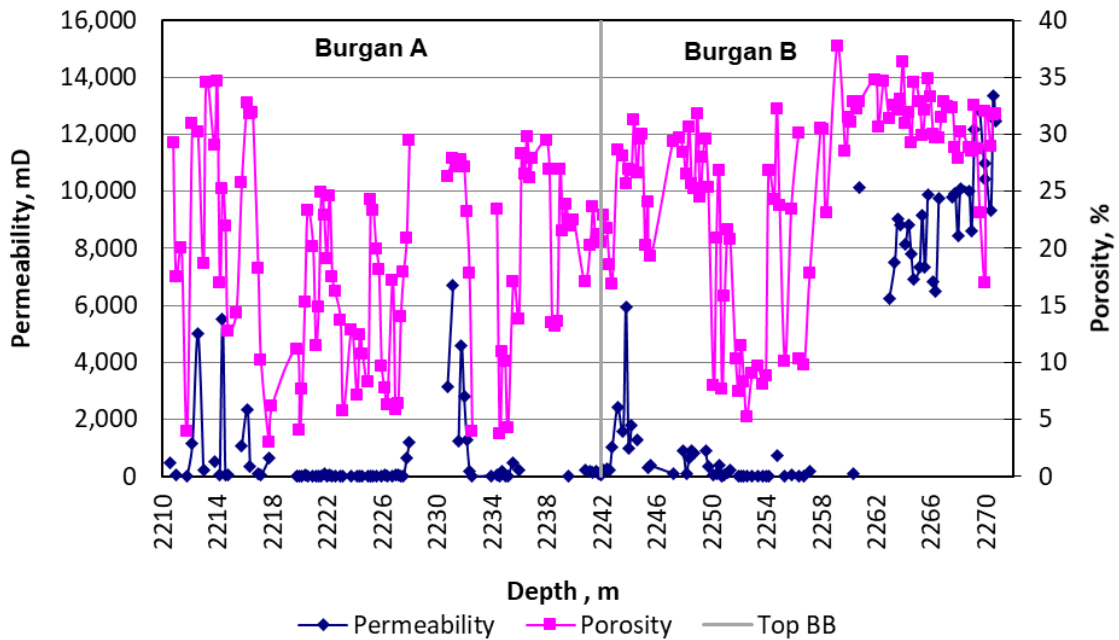


**Figure 6:** The profiles of porosity and sorting with depth in Burgan A & B.



As shown in Figure 7, a nice correlation is seen between porosity and permeability along the depth in Burgan A and B. This correlation is confirmed in the next cross plots as well. Figure 8 and Figure 9 show porosity-permeability cross plots in Burgan A and Burgan B reservoirs, respectively.

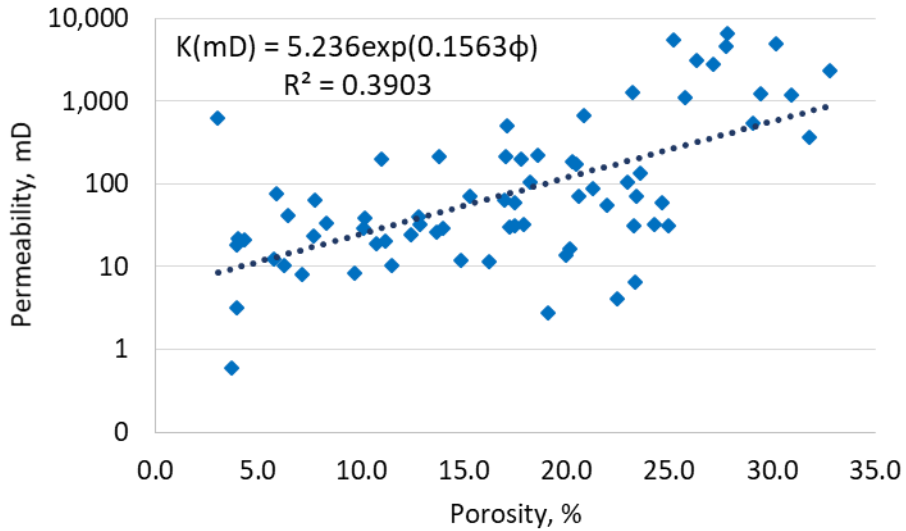
**Figure 7:** The profiles of porosity and permeability with depth in Burgan A & B.



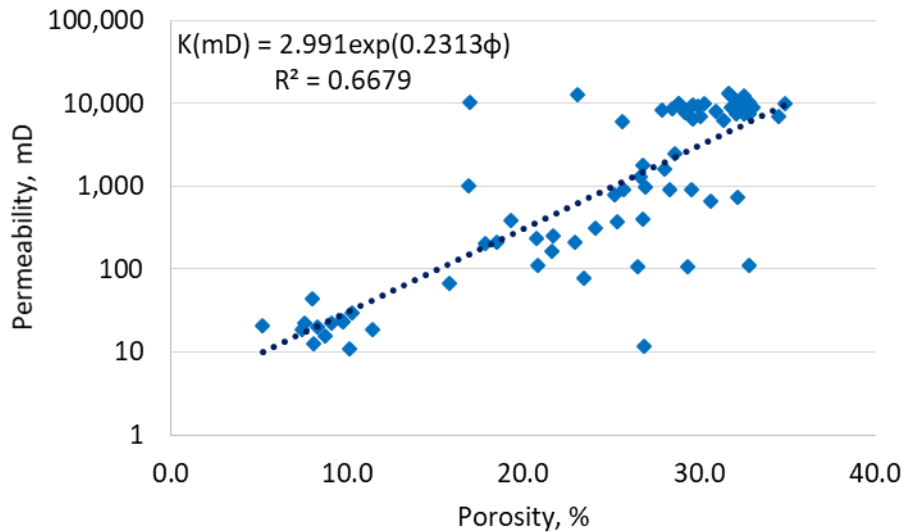


Comparing permeability data and the fitted functions in both reservoirs (Figure 8 and 9) shows better rock quality (permeability) in Burgan B than Burgan A. This is confirmed by comparing the correlation coefficient ( $R^2$  values) data as well, which is higher in Burgan B (Figure 9).

**Figure 8:** Cross plot of porosity-permeability in Burgan A Formation.



**Figure 9:** Cross plot of porosity-permeability in Burgan B Formation.



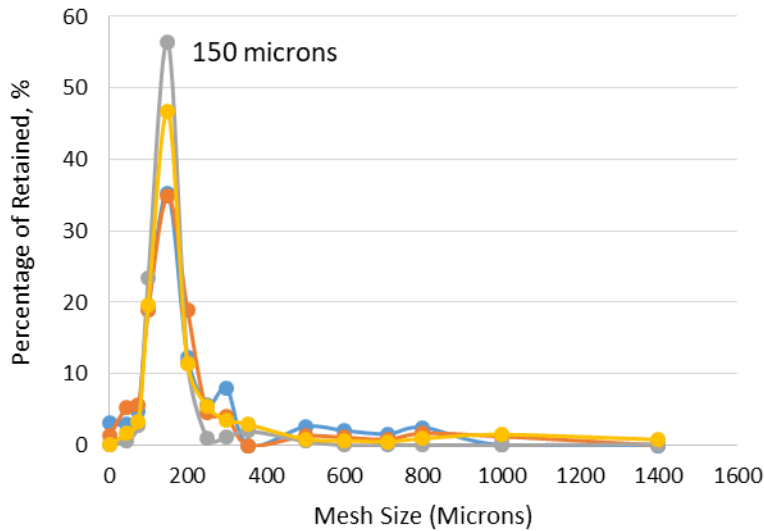
Improving permeability, porosity and sorting properties at the base of Burgan B (Figure 4 and Figure 6) attribute existence of a clean and loose sands with minimal cementation. This is an important conclusion as the most probable location of sand production is identified.

**3.2 Sieve Analysis**

Estimating dominant grain size is crucial for designing sand control devices. This requires integrating the most probable grain size of all core samples. Figure 10 presents distribution of grain sizes of 4 core samples from Burgan A. Figure 10 indeed is a representation of conventional sieve analysis using core-by-core method. Meanwhile, the weight of retained grains of all 4 core samples on every sieve are added together to obtain distribution of the

retained grain sizes using sieve-by-sieve method. Figure 11 presents minimum and maximum distributions of the weight of retained grains of all core samples using sieve-by-sieve method.

**Figure 10:** Conventional sieve analysis using Core-by-Core Method in Burgan A.



**Figure 11:** New sieve analysis method based on the Sieve-by-Sieve Method in Burgan A.

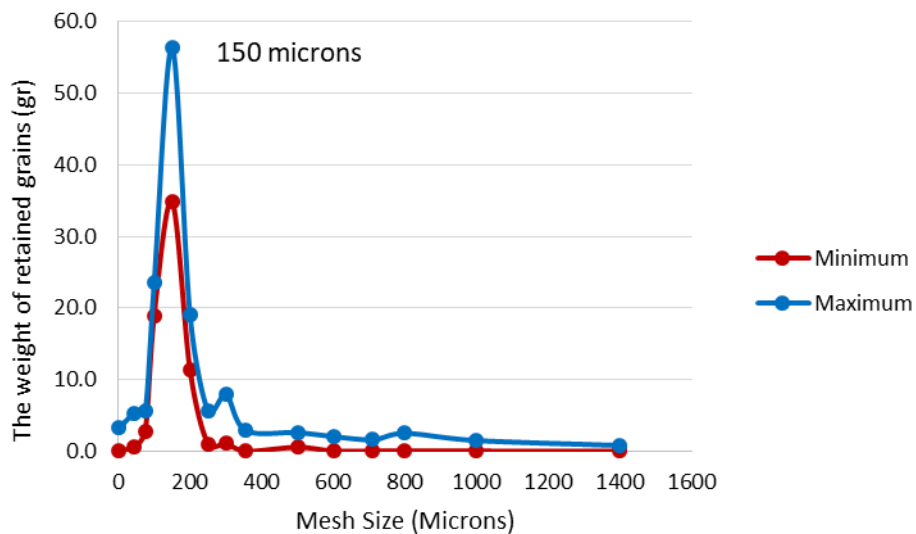
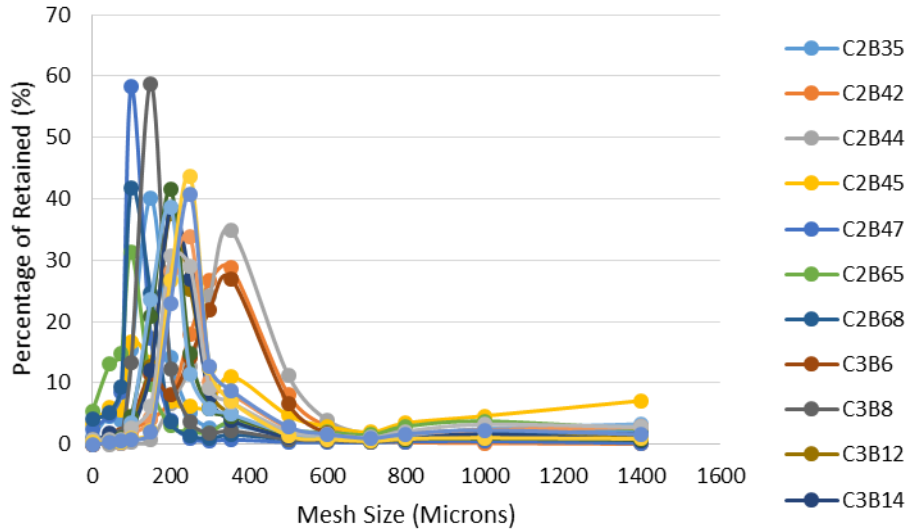


Figure 10 represents a strong leptokurtic histogram, which implies a very well sorted sand grain sizes in Burgan A. The most probable size based on this histogram is definitely 150 microns ( $\phi=2.737$ ). Similar conclusion is derived from Figure 11 using sieve-by sieve method.

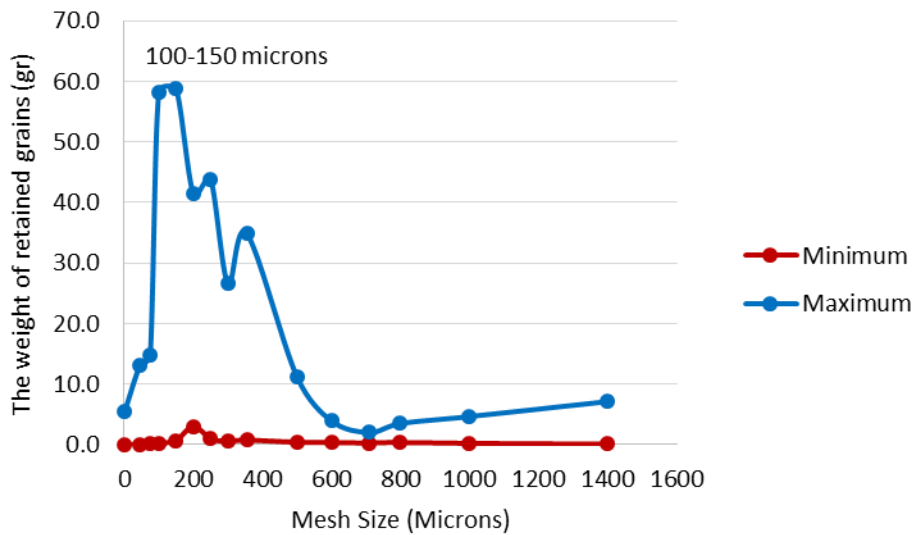
Figure 12 presents histograms of sand grains of 17 samples in Burgan B. Combining all histograms to get a representative distribution from all samples is not a straight forward task using core-by-core method. However, sieve-by-sieve method readily provides minimum and maximum distributions of the weight of the retained grains of all core samples as shown in

Figure 13. In fact, the sieve-by-sieve method exhibits a reliable averaging method to obtain a representative histogram of all samples. The shapes of distributions do not really look a unimodal histogram; thus, the mode of “maximum” histogram is chosen as the most probable size of sand grains in Burgan B, which is 100-150 microns ( $\phi= 2.74-3.32$ ). Selecting a single mesh size among this range depends on the availability and economic of a sand control device as well as productivity of well.

**Figure 12:** Conventional sieve analysis using Core-by-Core Method in Burgan B.



**Figure 13:** New sieve analysis method using Sieve-by-Sieve Method in Burgan B.



#### **4. CONCLUSIONS**

Sieve analysis is a useful and simple tool to characterize unconsolidated sandstone formations. Sorting and mean are two important parameters that can be integrated with CCAL data for reservoir characterization. Statistical parameters can also be used for determination of distribution of size of sand grains. All results provide an insight about possibility of sand migration and the most probable location of sand production.

The study presented here indicates that permeability and porosity exhibit some correlations with sorting but not with mean values of sand grain sizes. Conventional sieve analysis based on core-by-core method, attempts to obtain a mean sand size for the whole formation thickness. This method of study produces inherent uncertainties due to smoothing and reduction of data. A new approach was introduced in this paper as sieve-by-sieve method, whereby the weight of retained grains data were classified based on mesh sizes (as bins) and the most probable size in each class is picked out among all cores directly and without any manipulation or averaging.

As results, the performance of both methods were compared in Burgan A & B. The sorting data show less variability as seen in Burgan A (a homogeneous media) but they show some extends of variability in Burgan B (a heterogeneous media). Improving permeability, porosity and sorting properties at the base of Burgan B attribute existence of a clean and loose sands with minimal cementation. Both methods provide comparable results in terms of the most probable size of 150 microns ( $\phi=2.737$ ) in Burgan A. The core-by-core provides too many distributions in Burgan B, which are not conclusive but the sieve-by-sieve provides the profiles of minimum and maximum weight of retained grains, which facilitate picking out the most probable size of 100-150 microns ( $\phi= 2.74-3.32$ ).

#### **5. Acknowledgements**

We thank the management and director of petroleum department of PetroIran Development Company for permission to publish this paper.

## REFERENCES

- AASHTO The Voice of Transportation. T0 27. (2006). <https://store.transportation.org/?AspxAutoDetectCookieSupport=1>.
- ASTM International-Standards Worldwide. (2006). ASTM C136-06. <https://www.astm.org/Standards/C136.htm>
- AHLBRANDT, T. S., POLLASTRO, R. M., KLETT, T. R., SCHENK, C. J., LINDQUIST, S. J., FOX, J. E., REGION 2 assessment summary – Middle East and North Africa, U.S. Geological Survey Digital Data Series 60, USGS, 2000.
- AL-AJMI, H., AND Z., AZIM, S. A (2003). Sequence stratigraphy, depositional environment and reservoir geology of Arabian Reservoirs in Kuwait, AAPG International Conference, Barcelona, Spain.
- AL-AWAD MUSAED N.J., EL-SAYED ABDEL-ALIM H., DESOUKY SAAD EL-DIN M., (1999). Factors Affecting Sand Production from Unconsolidated Sandstone Saudi Oil and Gas Reservoir, Journal of King Saud University - Engineering Sciences, Vol. 11, Issue 1, 1999, pp 151-172. [https://doi.org/10.1016/S1018-3639\(18\)30995-4](https://doi.org/10.1016/S1018-3639(18)30995-4)
- Dong Changyin, Zhang Qinghua, Gao Kaige, YangKangmin, Feng Xingwu, Zhou Chong, Petroleum Exploration and Development, Vol. 43, Issue 6, Dec 2016, pp 1082-1088. [https://doi.org/10.1016/S1876-3804\(16\)30126-4](https://doi.org/10.1016/S1876-3804(16)30126-4)
- EMERY, D., and MYERS, K. Sequence Stratigraphy: Oxford, Blackwell Science, 297 p, 1996.
- FOLK, R. L. and WARD, W. C (1957). Brazos river bar [Texas]; a study in the significance of grain size parameters, J. of Sedimentary Research, v. 27, n. 1, p. 3-26.
- Fuller Michael, Palisch Terry, Fischer Christine, (2019). Sieve Distribution vs Sand Retention: The Impact of Mono-Sieved Gravel on Sand Control, SPE-196139-MS, presented in the SPE Annual Technical Conference and Exhibition, 30 September - 2 October, Calgary, Alberta, Canada.
- KHADIVI, K. and VOSSOUGHI, S., (2005). Foroozan Full Field Study, Final Report, Vol. II, Reservoir Characterization II, Document No. FE1000000RERS904201, PEDCO, NIOC.
- KRUMBEIN, W. C. (1934). Size frequency distributions of sediments. J. of Sedimentary Petrology. 2 (4). doi:10.1306/D4268EB9-2B26-11D7-8648000102C1865D.
- MAHMUD HISHAM B., VAN HONG, L., LESTARIONO, Y., 2019. Sand production: A smart control framework for risk mitigation, Petroleum, In Press. <https://doi.org/10.1016/j.petlm.2019.04.002>
- MCGLINCHEY, D., (2005). Characterisation of bulk solids by, p231, CRC Press.
- MEHRABI, H., ESRAFILI-DIZAJI, B., HAJIKAZEMI, E., NOORI, B., MOHAMMAD-REZAEI, H., (2019). Reservoir characterization of the Burgan Formation in northwestern Persian Gulf, J. of Petroleum Science and Engineering, Vol 174, pp 328-350, March 2019. <https://doi.org/10.1016/j.petrol.2018.11.030>.
- NASSIR, M., WALTERS DALE, A., YALE DAVID P., CHIVVIS, R., TURAK, J., (2015). 3D Modeling of Sand Production in Waterflooding by Coupled Flow/ Geomechanical Numerical Solutions, IDARMA-2015-426, presented in 49<sup>th</sup> U.S. Rock Mechanics/Geomechanics Symposium, 28 June-1 July, San Francisco, California.
- NEMATI, M., ESFAHANI, M. R., HASHEMI, S. M., KAZEMZADEH, E., KAMALI, M. R. (2003). Sieve Analysis Results, Report No. 7745/5540, Research Institute of Petroleum Industry (RIPI), NIOC.

- PENBERTHY, W.L. Jr. and SHAUGHNESSY, C.M. (1992). Sand Control, Vol. 1, 11-17. Richardson, Texas: Monograph Series, SPE.
- SADAT, M. Z., & RABBANI, A. R., (2015). Organic geochemistry of crude oils and Cretaceous source rocks in the Iranian sector of the Persian Gulf: An oil–oil and oil–source rock correlation study, *International Journal of Coal Geology*, Vol 146, 1 July 2015, pp 118-144. <https://doi.org/10.1016/j.coal.2015.05.003>
- SHAHSAVARI, M. H., and KHAMEHCHI, E., (2018). Optimum selection of sand control method using a combination of MCDM and DOE techniques, *Journal of Petroleum Science and Engineering*, Vol. 171, Dec 2018, pp 229-241. <https://doi.org/10.1016/j.petrol.2018.07.036>
- STROHMENGER, C. J., DEMK, T. M., MITCHELL, J. C., PATTERSON, P. E., LEHMAN, P. J., AL-SAHLAN, G., AL-ENEZI, H., (2002). Sequence stratigraphy of the Burgan and Maudud formations (Lower Cretaceous, Kuwait): Reservoir distribution and quality in a carbonate-clastic transition, AAPG Annual Meeting, Houston, Texas.
- TRASK PD. (1932). *Origin and Environment of Source Sediments of Petroleum*. Gulf Publishing Company: Houston.
- VAN WAGONER, J. C., MITCHUM, R. M., CAMPION, K. M., and RAHMANIAN V. D., Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: concepts for high-resolution correlation of time and facies: *AAPG Methods in Exploration* 7, 55 p, 1990.
- WANG, C., PANG, Y., MAHMOUDI, M., HAFTANI, M., SALIMI, M., FATTAHPOUR V., NOURIA A., (2019). *Journal of Petroleum Science and Engineering*, In Press, <https://doi.org/10.1016/j.petrol.2019.106608>
- ZIVAR, D., SHAD, S., FOROOZESH, J., SALMANPOUR, S., (2019). Experimental study of sand production and permeability enhancement of unconsolidated rocks under different stress conditions, *Journal of Petroleum Science and Engineering*, Vol. 181, Oct 2019, 106238. <https://doi.org/10.1016/j.petrol.2019.106238>.

**Appendix**

All equations used in this paper are presented here. Grain-size statistical parameters and graphic representations are given in phi units. The Krumbein (1934) proposed a logarithmic transformation of mesh size in millimeters into whole integers according to the following formula;

$$\phi = -\log_2(d), \tag{Eq. 1},$$

where  $d$  is the grain diameter in millimeters.

The statistical parameters like sorting and mean are defined based on the graphical cut off  $\phi_{16}$ ,  $\phi_{25}$ ,  $\phi_{50}$ ,  $\phi_{75}$  and  $\phi_{84}$  (Folk and Ward, 1957). A common formula to estimate sorting has been proposed by Trask (1932) as

$$Sorting = \sqrt{\phi_{25}/\phi_{75}} \tag{Eq. 2}$$

where  $\phi_{25}$  and  $\phi_{75}$  represent the 25<sup>th</sup> and 75<sup>th</sup> percentiles of the grain size distribution in phi units. The mean parameter is calculated using the graphical cut off  $\phi_{16}$ ,  $\phi_{50}$ , and  $\phi_{84}$  (Folk and Ward, 1957),

$$Mean = \frac{\phi_{16} + \phi_{25} + \phi_{84}}{3}. \tag{Eq. 3}.$$

**Nomenclature**

**PTS** Percentage of the Total Sediment

**CPTS** Cumulative Percentage of the Total Sediment

$d$  The grain diameter in millimeters

Greek letters

$\phi$  Phi, a logarithmic transformation of mesh size in millimetres

