Evaluation of the bearing capacity of piles in the South Pars field tests using CPT and PDA

Haghighat Mahdiyan[1], Bahram Nadi[2*], Mahmood Vafaeian[3]

1-Phd Student,Department of Civil Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran

2- Assistant Professor ,Departmentof Civil Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran(Correspondence)

3-Full professor,Department of Civil Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran

Abstract

Purpose- The aim of this study is developing a model to determine the bearing capacity of the piles in order to obtain their exact geometric characteristics.

Approach- In the South Pars within the Persian Gulf, a series of field and laboratory tests have been performed by the Oil and Gas Company to find out the soil characteristics and bearing capacity of the piles. In this study, the models are developed for determining the bearing capacity of the pile based on the effective parameters using Genetic Expression Programming (GEP).

Findings- developed models predict the bearing capacity of piles in cohesive and non-cohesive soils. The models depend on the pile length and diameter, pile tip strength and pile friction resistance to determine the pile bearing capacity. The correlation values in both cohesive and non-cohesive soils show good results, which means that the data are well correlated with each other.

Originality/value- So far, no research has been conducted to determine the bearing capacity of piles in offshore areas in Iran using the results of CPT cone penetration test.

Keywords- Piles, Ultimate bearing capacity, GEP, CPT test

1-introduction

Due to the increasing use of offshore structures in our country to extract oil and gas and the high cost of construction and installation of these structures, their sustainability is important that should be used during the operation of this structures(Meyerhof 1951, Mayerhof 1976). One of the most important factors in the stability and strength of offshore structures is their foundation, which are mainly in the form of long metal piles driven into the seabed. Lack of accurate design of piles causes many problems (Terzaghi, Peck et al. 1996). Therefore, it is necessary to determine an exact relationship to determine the bearing capacity of the piles in order to obtain their exact geometric characteristics. Despite the dramatic advances in soil mechanics and geotechnical engineering in recent decades, determining the load-bearing capacity of piles is still difficult (Vesic 1977). For this reason, several researchers in the past decades have tried to provide different theoretical or experimental relationships to determine the bearing capacity (Brucy, Meunier et al. 1991). it is very common today to use the results of in-situ tests to determine the bearing capacity of piles, most of these comparisons are based on the bearing capacity determination relationships presented based on in-situ tests. One of the most detailed studies on the accuracy of bearing capacity determination methods based on in-situ test results was conducted in 1989 by Briaud and Tucker. The two researchers evaluated the methods of determining the load capacity of piles based on the results of in situ tests. In the loading tests performed in this study, the piles were loaded up to four times the allowable load capacity until they reached complete rupture (Briaud, Tucker et al. 1989). The results of studies conducted by Meyerhoff et al. In the field of bearing capacity of piles are known as the most common static methods (Mayerhof 1976). So far, various methods have been published to predict the bearing capacity of piles using CPT results (De Kuiter and Beringen 1979, Bustamante and Gianeselli 1982, Price and Wardle 1982, Eslami and Fellenius 1997, Takesue, Sasao et al. 1998). Determining the bearing capacity of piles directly using CPT and CPTU test results on 102 databases was conducted on 102 databases in 13 countries and 10 sites (USA, Canada, Brazil, Yugoslavia, Australia, Iraq, UK, France, Japan, Taiwan, Norway, Italy, Belgium) by Eslami and Fellenius in 1997. The result of the research led to the production of a relationship to determine the bearing capacity of piles using the results of CPT and CPTU (Eslami and Fellenius 1997). In this regard, a study has been completed by reseaerchers to Assess bearing capacity of piles in sandy soils using CPT results.(Jardine, Chow et al. 2005, Lehane, Schneider et al. 2005, Ebrahimian and Movahed 2017). In 2018, Muoshfeqhi and Eslami conducted a study on final pile capacity criteria and direct methods based on the CPT. CPT studies have been performed on dispersed soils, 42% clay, 35% sandy soils, and 25% mixed soils. PDA[1] and CAPWAP[2] software have been used for dynamic load testing (Moshfeghi and Eslami 2018). The Pile Driving Analyzer (PDA) is the procedure that reflects The strain and acceleration in the pile because of the pile-driving hammer (Long, Bozkurt et al. 1999, Fakharian 2000, Moayedi, Mosallanezhad et al. 2017). Estimating bearing capacity of piles in marine environment can be done through API method. API method is a well-known approach to analyze and estimate bearing capacity of piles in cohesive soils (RP2A-WSD 2000). In 2013, Lacasse *et al.* at the Norwegian Institute of Geotechnics calculated the axial compressive bearing capacity of a number of piles in a case study at three sites with clay, sand, and clay characteristics using five API, ICP, UWA, Fugro, and NGI[3] relationships. Finally, it was concluded that calculating the offshore axial compressive bearing capacity at all three sites, the NGI method is closer to reality (Lacasse, Nadim *et al.* 2013). In 2009, Schneider et

[1] Pile Driving Analyzer
[2] Case Pile Wave Analysis Program
[3] Norwegian Institute of Geotechnics

al evaluated a CPT-based method database for determining the axial capacity of percussion piles in siliceous sands. The results show that the best results are significantly in API and simple alpha methods (Schneider, Xu et al. 2008). In addition to the above methods, in recent years, using Artificial neural network for predicting the behavior of single piles under the effect of axial load based on the results of in situ tests have been proposed. With the advancement of computer science and the invention of machine learning techniques, Artificial neural network has been used with considerable success in modeling various science problems. The main purpose of these methods is to identify patterns between input variables and output values, based on a limited amount of phenomenon data(Lee and Lee 1996, Das and Basudhar 2006, Ardalan, Eslami *et al.* 2009). In models presented with Artificial neural network method to predict the bearing capacity of piles, usually a data set including pile loading tests and geometric characteristics of piles and test results in the vicinity of piles is used to extend the model. Published research confirms the remarkable performance of these methods in modeling the behavior of piles(Cai, Liu et al. 2009, Wang, Moayedi et al. 2019, Pham, Ly et al. 2020).

In this research, the bearing capacity of offshore steel piles hammered in the Persian Gulf (South Pars) is determined using experimental analytical methods and in-situ tests such as CPT and using the results of dynamic pile tests (PDA). These relationships can be calibrated. This can lead to a developed relationship and reduce the cost of offshore projects. In this regard, the relationships in the API regulations are not accurate and in different contexts, the calculation error and its results increase, hence it is necessary to perform calculations and calibrate the models in the context of the Persian Gulf (South Pars). Therefore, it is decided to provide an empirical analytical relationship to determine the axial bearing capacity of the pile in the South Pars seabed and calibrate this relationship according to the PDA results. Also, based on the available data and calibration, the optimization of the best dimensions of the pile is done.

2- methodology

It is noteworthy that in the South Pars within the Persian Gulf, a series of field and laboratory tests have been performed by the Oil and Gas Company to find out the soil characteristics and bearing capacity of the piles. In this study, the test results have been selected as input data and Processing has been done on this data. The main application of this data is as primary data for the Artificial neural network. In order to provide a relation for the bearing capacity of the pile based on the effective parameters by this method.

2-1 site investigation

Iranian Offshore Engineering and Construction Company (IOEC) is planning to develop phases 17 & 18 of the South Pars gas field, offshore Iran, within the Persian Gulf, to allow a gas production of 2000 MMSCFD. The objectives of the proposed development include the provision of geotechnical and engineering services for the South Pars substructures (offshore wellhead platforms and tripod jackets). The main purpose of the soil investigation is to determine the nature and the mechanical properties of the seabed and sub-sea soil layers down to the prescribed depth at the proposed locations. The substructures will be founded on piles and temporary seated on mud mats. To present the geotechnical survey results and laboratory testing carried out at the SPD23, BSP23, FSP23, SPD24, BSP24 and FSP24 locations (Figure 1).

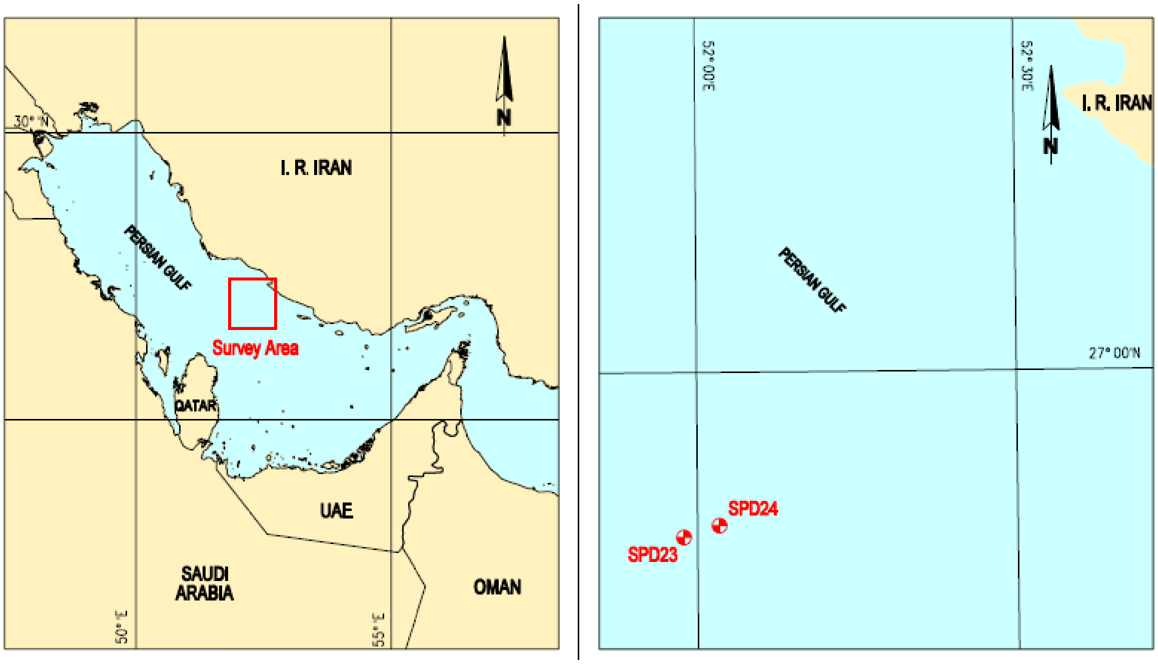


Figure 1 The location of boreholes

2-2 Steps of research

In this research, first, an analytical relationship to determine the bearing capacity of the pile based on the results of CPT test is presented and then this relationship is calibrated based on the results of PDA test. the results of the CPT tests will be used as input data. In determining the carrying capacity extracted by the oil company, the API method has been used to calculate bearing capacity of pile. The American Petroleum Institute provides recommendations for axial load pile design in API entitled "Practical Recommendations for Offshore Platform Design and Construction" based on extensive data from pile load tests that is constantly evaluated and updated(RP 2007, API 2011). In order to calibrate the analytical-experimental relationship of pile bearing capacity based on PDA, it is necessary to have the results of dynamic tests available in Persian Gulf (South Pars). The PDA calculates the amount of load capacity, hammer performance, and stresses created by measuring the force and velocity inside the pile. CAPWAP software was used to achieve the bearing capacity of the pile through PDA testing. The procedure is that the CAPWAP program receives the velocity curve recorded by the PDA and assumes a value for soil parameters in each soil element, such as displacement and damping. Then the received information about the internal movements of the pile (velocity curve at the head of the pile) and the assumption of boundary conditions (soil model parameters) the program calculates the force wave curve at the head of the pile. After calculating the force on the spark plug, the calculated curve is compared with the curve obtained from the PDA device. If the two curves do not match well, the soil parameters will be changed based on experience and engineering judgment, and the force wave curve will be recalculated. This operation is repeated until a good match between the calculated and measured force curves is obtained. Also, in the final stage, in order to optimize the dimensions of the candle, a neural network system is first formed based on the available data and calibration. Then the best dimensions of the candle to satisfy the relations of the regulations are determined. The following is an example of the primary data used in this study as a supplementary explanation.

2-2-1 CPT test

The Cone Penetration Test (CPT) is in wide use for in-situ geotechnical characterization of ground. It involves the measurement of the resistance of ground to steady and continuous penetration of a cone penetrometer equipped with internal sensors. The measurements comprise penetration depth, cone resistance, sleeve friction and, optionally, pore pressure and inclination from vertical. These measurements permit interpretation of ground conditions.

CPT apparatus and procedures adopted by Fugro are in general accordance with the International Reference Test Procedure published by the International Society of Soil Mechanics and Geotechnical Engineering(BSI 1999, ISSMGE 1999). Figure 2 shows an example of the results of

CPT test. It should be noted that the raw results obtained from the CPT test are calibrated by the API method and give the initial data for current study.

2-2-2 PDA test

Dynamic Load Testing or PDA testing, is a fast, reliable and cost effective method of evaluating foundation bearing capacity(Maizir and Suryanita 2018).

Dynamic measurements were made with two strain sensors and two accelerometers bolted to the surface of the pile top. Signals from the sensors were proceeds and stored by pile driving analyzer (PDA).

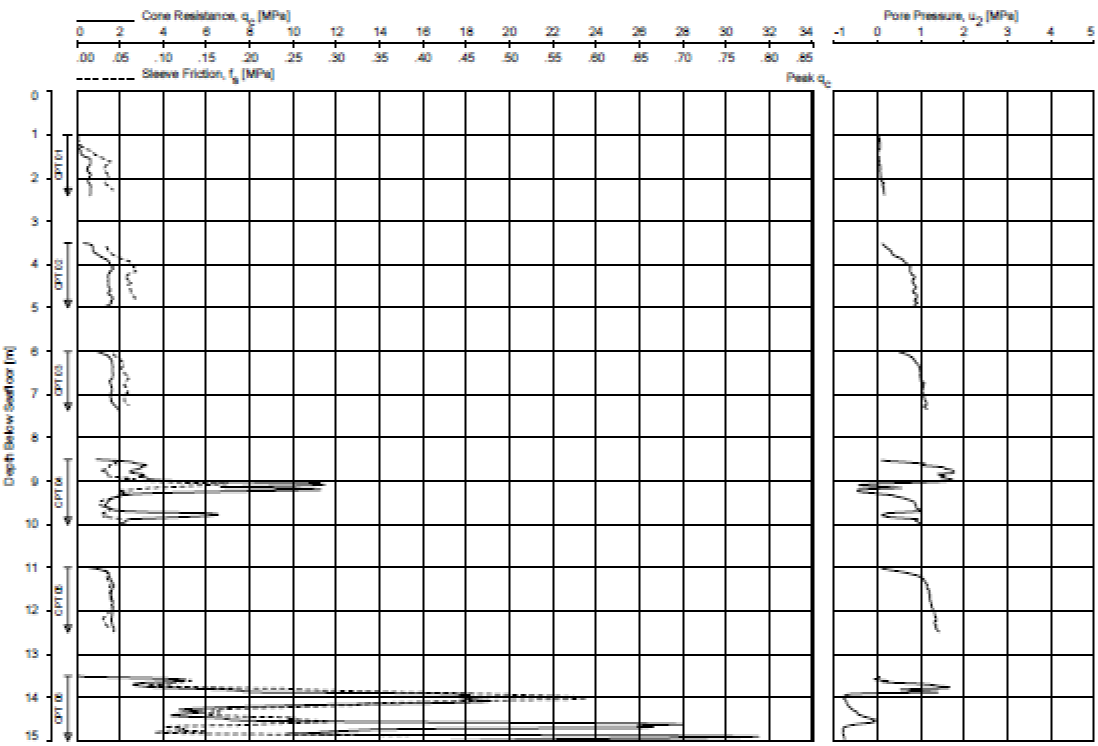


Figure 2 cone penetration test of SPD23

2-2-3 CAPWAP TEST

The preliminary estimates of activated bearing capacity during driving obtained directly from PDA are called CASE Method. Detailed modeling by CASE Pile Wave Analysis Program (CAPWAP) on selected record is required to determine the most representative CASE Method for the tested piles and to verify the activated bearing capacity. CAPWAP combines measured force and velocity data with wave equation analysis to calculate the soil resistance forces acting on the pile(Fakharian 2000).

The CAPWAP analysis software is one of means by which the capacity of a deep foundation can be assessed(Rausche, Likins et al. 2010). Three CAPWAP analyses have been performed on piles at their final penetration for each borehole. Figure 3 shows the results of CAPWAP for FSP 24.

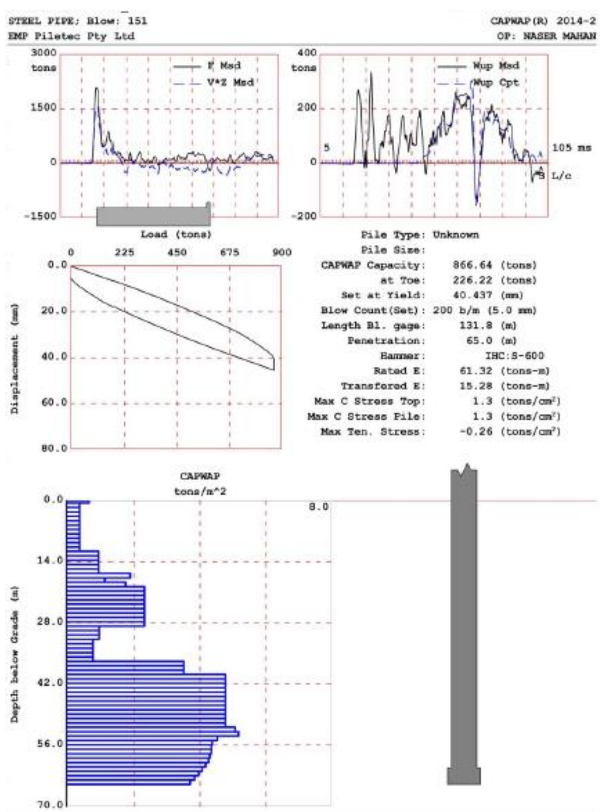


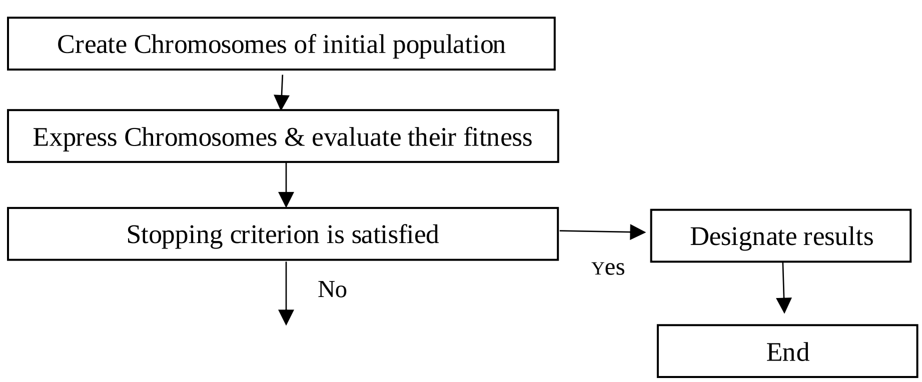
Figure 3 results obtained from CAPWAP for FSP24

Create Chromosomes of initial population

2-3 Genetic Expression Programming (GEP)

Gene expression programming (GEP) was developed by Ferreira (2001) using fundamental principles of the Genetic Algorithms (GA) and Genetic Programming (GP)(Ferreira 2001). The strength of proposed approach includes the simplicity of creating the genetic diversity, a unique and multi-genic nature which allows the evaluation of more complex programs composed of several subprograms. GEP as GA mimics the biological evolution to create a computer program for simulating a specified phenomenon. A GEP algorithm begins by selecting five elements including the function set, terminal set, fitness function, control parameters, and stopping condition. There is a comparison between predicted values and actual values in each subsequent step. When desired results are obtained in accordance with previously selected error criteria, the GEP process is terminated. After the desired fitness score is achieved, the process terminates and then the chromosomes are decoded for the best solution of the problem. The most important advantages of GEP are as follows (Ferreira 2001) : (1) the chromosomes are simple entities and (2) the expression trees are exclusively the expression of their respective chromosomes. It should be noted that the software used to develop this approach is GeneXproTools 4.0 Release 2.

Figure 4 illustrates the GEP modelling process which begins with the random generation of chromosomes of the initial population.



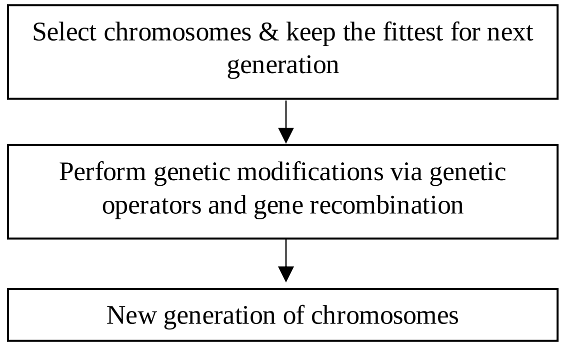


Figure 4 Flow chart of gene expression algorithm

2-3-1 Development of Gene Expression Programming Models

In the present study, GEP has been used to develop models for investigating the axial bearing capacity of piles using CPT data. Therefore, the data used are divided into cohesive and non-cohesive groups based on soil type. Also, the database is divided into two subgroups of training data (including 80% of the data) for model development and experimental data (20% of the data) in order to control the performance of the models. The data are divided into educational and experimental subgroups so that the maximum, minimum, mean and standard deviation values are comparable according to Table 1. A strong representative of the total population, in terms of statistical characteristics, should be obtained for both subgroups based on the random composition of the mentioned subgroups. It should also be ensured that the final models obtained can fully compute Q_t for other cases as well as untrained data.

Table1 Maximum, minimum, mean and standard deviation values of databases

train						test				
	q_c(MPa	f_s(MPa)	L(m)	D(m)	Q_t(KN)	q_c(MPa)	f_s(MPa)	L(m)	D(m)	Q_t(KN)
Cohesionless soil										
Max	3.08	0.14	100.5	1.524	67719	1.951	0.14001	96	1.524	61248

Min	1.34	0.0148	39.2	0.914	8000	1.283	0.0149	30.8	0.0914	6581
Mean	1.87	0.0486	56.07	1.38	25865.67	1.59	0.0618	51.825	1.3715	22837.5
S.D	0.45	0.049	21.56	0.208	19380.16	0.285	0.051	25.79	0.264	22232.26
Cohesive soil										
Max	2.7	0.188	110.5	1.524	82154	2.516	0.154	84.5	1.524	49461
Min	1.16	0.062	31.5	0.914	6684	1.34	0.078	40	0.914	11323
Mean	1.95	0.12	65.86	1.23	30534.68	1.911	0.117	64.25	1.18	246845
S.D	0.35	0.03	23.42	0.25	23668.8	0.363	0.029	18.79	0.23	12573.69

Furthermore, GEP was trained for local loss coefficient prediction with basic arithmetic operators of (+,-,*, /) and several mathematical functions (x^2, x3, $\sqrt{\ }$) as the function set. Different combination of chromosomes structure which was presented in Table 2 were tested. Then the model was run for a number of generations and stopped when there was no significant change in the fitness function value and coefficient of correlation. Accordingly, the models with 30 chromosomes head size of 8 and 3 numbers of genes led to the better results. Besides, one of the important steps in preparing the GEP model is choosing the appropriate set of genetic operators, therefore, a combination of all genetic operators was also tested. Characteristics of optimized GEP models are shown in Table 2.

Table 2. Optimized parameters of GEP models

parameter	setting
Function set	$+, -, \times, /, x^2, x^3, \sqrt{\ }$
Chromosomes	25, **30**, 35
Head size	7, **8**
Linking function	addition

Fitness function	Root mean square error

2-3-2 Performance data

The efficiency of the methods was evaluated using statistical parameters were used, including: correlation coefficient (R), the root mean square error (RMSE). It is worth noting that the RMSE has the same unit of the target parameter (Q_t) which is in terms of KN. The relationships of these statistical parameters are as follows:

Eqs.1
$$R = \frac{\sum_{i=1}^{N}(I_0-\overline{I_0})\times(I_P-\overline{I_P})}{\sqrt{\sum_{i=1}^{N}(I_0-\overline{I_0})^2\times(I_P-\overline{I_P})^2}}$$

Eqs.2
$$RMSE = \sqrt{\sum_{i=1}^{N}\frac{(I_0-I_P)^2}{N}}$$

Where I_0,I_P, $\overline{I_0}$, $\overline{I_P}$, N respectively are: the measured values, predicted values, mean measured values, mean predicted values and number of data samples.

the selection of input models in Artificial neural network can affect the results of the analysis, so it is tried to select appropriate and effective parameters in determining the bearing capacity of the pile in the modeling process. Past studies show that important parameters that can affect bearing capacity include the following: pile length (L), pile diameter (D), pile tip resistance (qc) and friction resistance of the pile (fs).

4- Discussion and Results

4-1 GEP based developed models

The expression trees of the GEP models are shown in Figure.5 for bored piles in cohesive soils and Figure.6 for driven piles in non-cohesive soils. As mentioned earlier, one of the advantages of the GEP techniques is that the relationship between model inputs and the corresponding outputs is automatically formulated in a mathematical equation that is accessible to the users. The expression trees of the models are easily translated into mathematical formulations which are given in Eqs.3 and 4 for driven piles in cohesive soils and non-cohesive soils, respectively.

Eqs.3 $$\mathrm{Q_u} = \left(0.64\frac{\mathrm{L}}{\mathrm{D}^4}\right)(\mathrm{f_s} + \mathrm{L}) + (3.77 - \mathrm{f_s})^{1.5}(\mathrm{q_c}^3 - \mathrm{D}^3)^3 + 38.25\mathrm{L}^{1.5}\mathrm{D}$$

Eqs.4

$$Q_u = -((q_c + 6.12)^3 - q_c L)(q_c - 6.12D + 6.59) + (3.5 - 2L)^2 + (DL(q_c + L) + (7.13D)(L + 7.13)(2.43f_s + 7.13D)$$

Where, $\mathrm{Q_u}$ is in terms of KN, q_c and f_s is in terms of MPa, D and L is in terms of m.

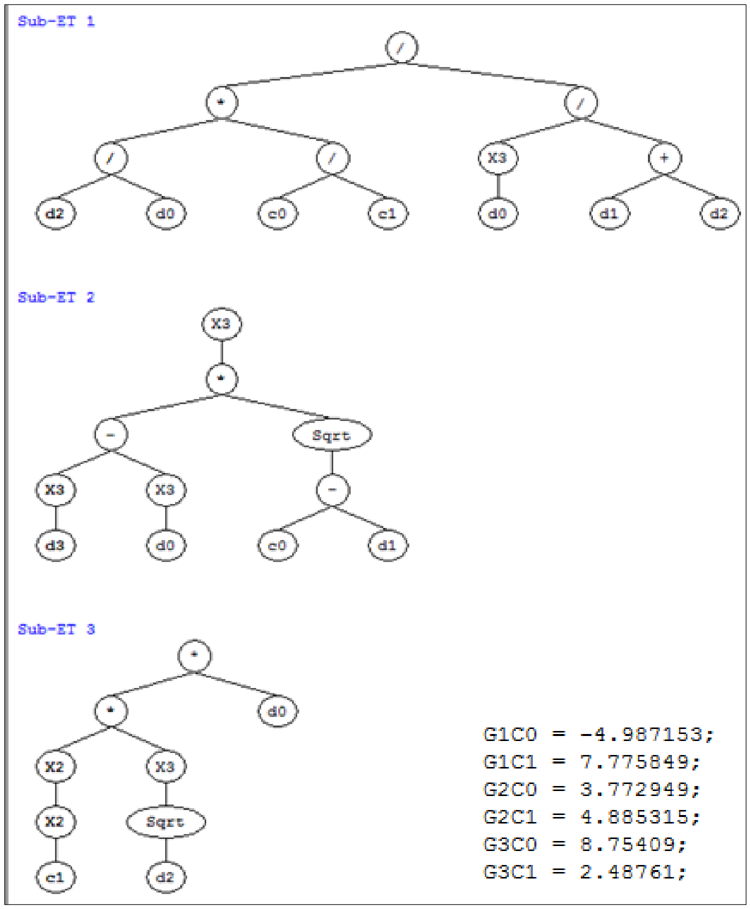


Figure 5 Expression tree (ET) of the GEP model formulation for driven piles in cohesive soils

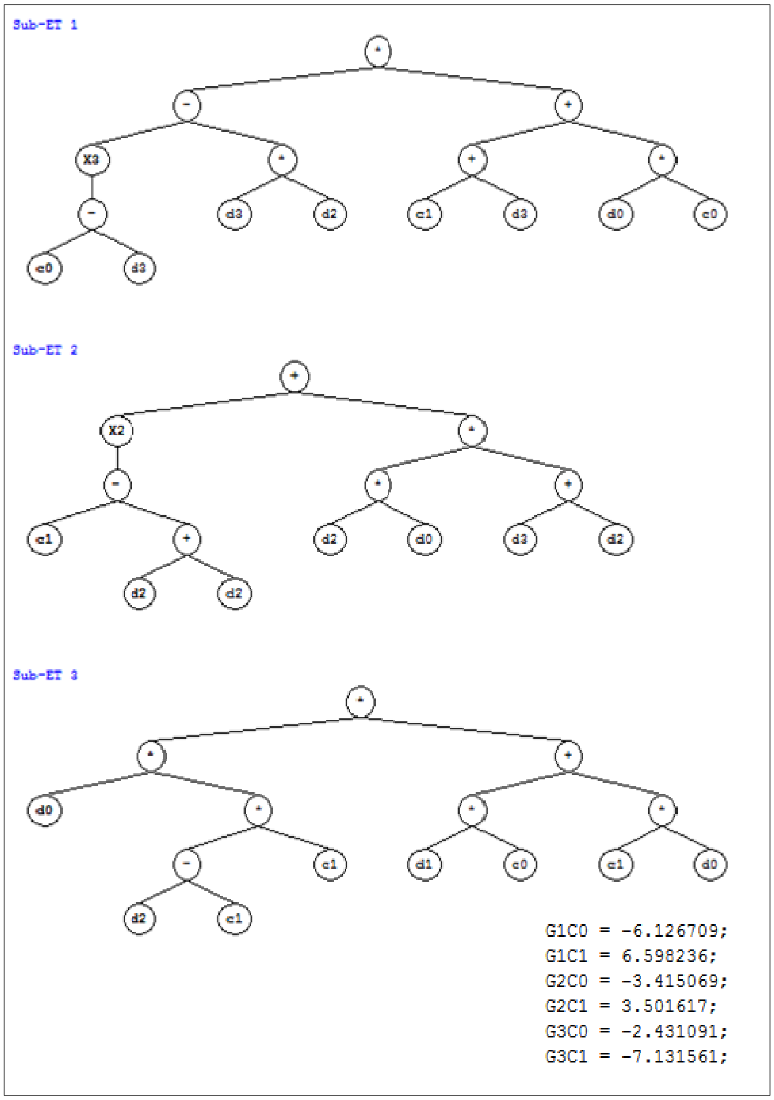


Figure 6 Expression tree (ET) of the GEP model formulation for driven piles in non-cohesive soils

These models indicate the prediction of pile bearing capacity in cohesive and non-cohesive soils. In this case, the model depends on the pile length and diameter, pile tip strength and pile friction resistance to determine the pile bearing capacity. The results of the analysis of gene expression programming models in the models are given in Table 3. According to the results shown in Table 3, it can be seen that the correlation values in both cohesive and non-cohesive soils show good results, which means that the data are well correlated with each other. On the other hand, it can be seen that the correlation values of the input data with the target function in non-cohesive soils are higher than in cohesive soils.

Table 3 Statistical parameters of the GEP models

Models	R^2	RMSE	R^2	RMSE
	train		test	
Cohesive soil	0.91	0.071	0.84	0.054
Non-cohesive soil	0.99	0.029	0.98	0.011

In order to evaluate the accuracy and performance of the developed models, these models have been validated based on experimental data. The predicted values of Q_t versus the measured values for the training and testing data subset are shown in Fig.7 and 8 for cohesive soils respectively and Fig.9 and 10 for non-cohesive soils. Therefore, the proposed models can predict the ultimate axial bearing capacity of the pile. According to Fig.7 and 8, in the proposed model for cohesive soil, the values of R2 and RMSE are 0.91 and 7.1% for training data and 0.84 and 5.4% for testing data, respectively. Also, according to Fig.9 and 10, in the proposed model for non-cohesive soil, the values of R2 and RMSE are 0.99 and 2.9% for training data and 0.99 and 1/1% for testing data, respectively.

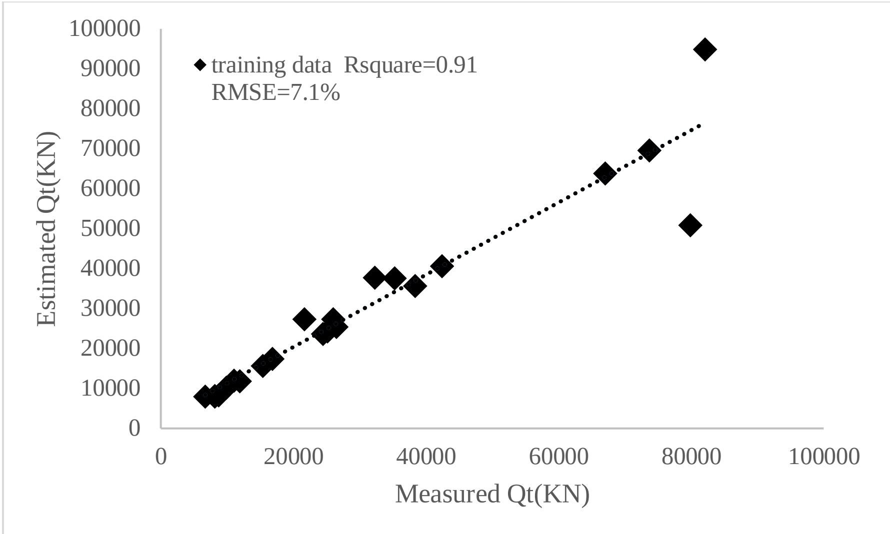


Figure 7 Performance comparison of GEP driven piles model and CPT based methods in cohesive soils for training data

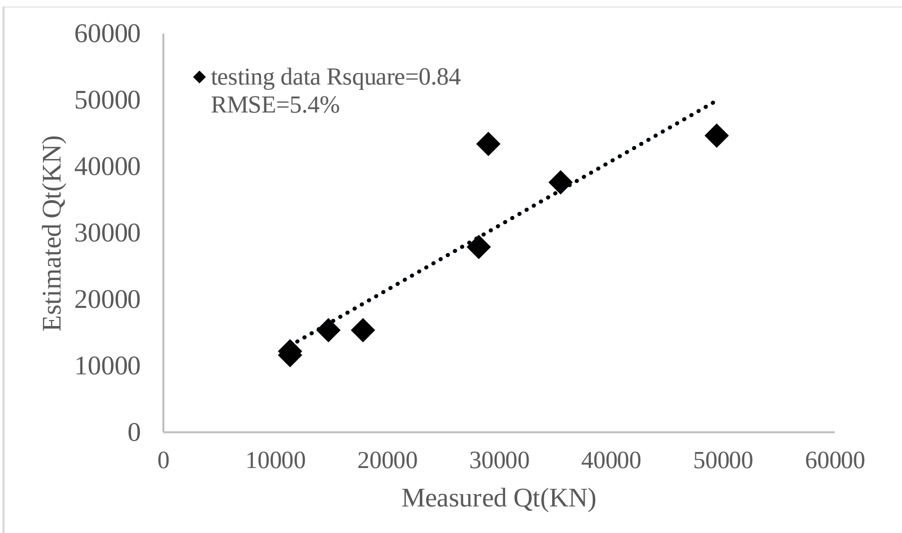


Figure 8 Performance comparison of GEP driven piles model and CPT based methods in cohesive soils for testing data

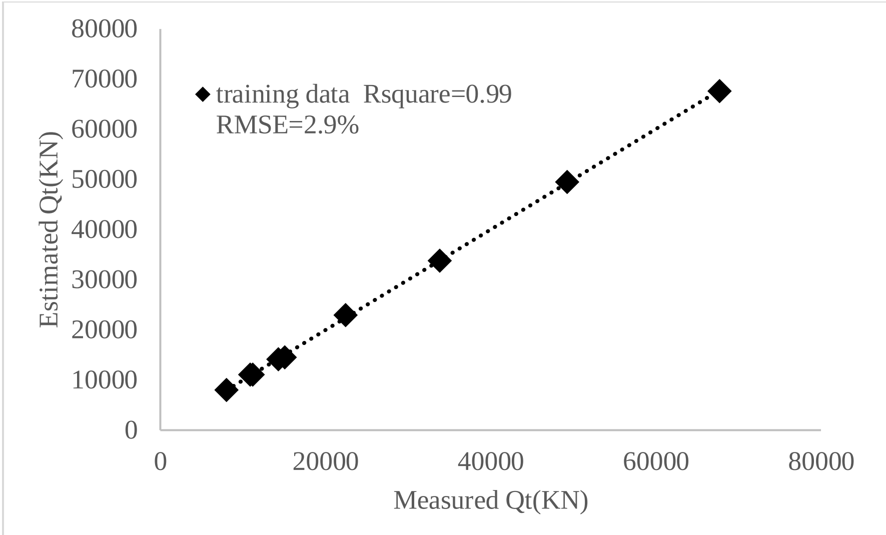


Figure 9 Performance comparison of GEP driven piles model and CPT based methods in non-cohesive soils for training data

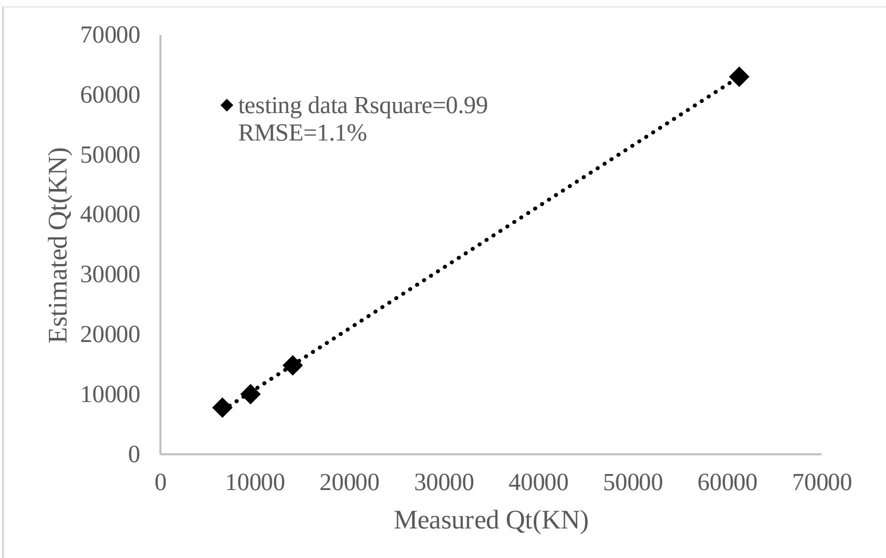


Figure 10 Performance comparison of GEP driven piles model and CPT based methods in non-cohesive soils for testing data

4-2 Calibration based on PDA results

The present study is to determine the axial bearing capacity of piles in the South Sea region of Iran and is based on real data collected from the Persian Gulf region and South Pars Square. The type of piles under evaluation in this study are steel piles with one end closed and the focus of the research is on the offshore area. Inspired by existing analytical methods, an analytical relationship is established to determine the compressive axial bearing capacity of tubular metal piles in the Persian Gulf region and then the resulting relationship is calibrated using the results of PDA field tests. The results of this type of calibration are according to Figures.11 to 14. After calibration, the predicted values of Qt versus the measured values for the training and test data subset are shown in Figures 11 and 12 for cohesive soils, respectively and Figures 13 and 14 for non-cohesive soils, respectively. Therefore, the proposed models can predict the ultimate axial bearing capacity of the pile. According to Figures 11 and 12, in the proposed model for cohesive soils, the values of R2 and RMSE are 0.91 and 1.2% for training data and 0.92 and 1.25% for testing data, respectively. Be. Also, according to Figures 13 and 14, in the proposed model for non-cohesive soils, the values of R2 and RMSE are 0.99 and 1.9% for training data and 0.99 and 1% for testing data, respectively.

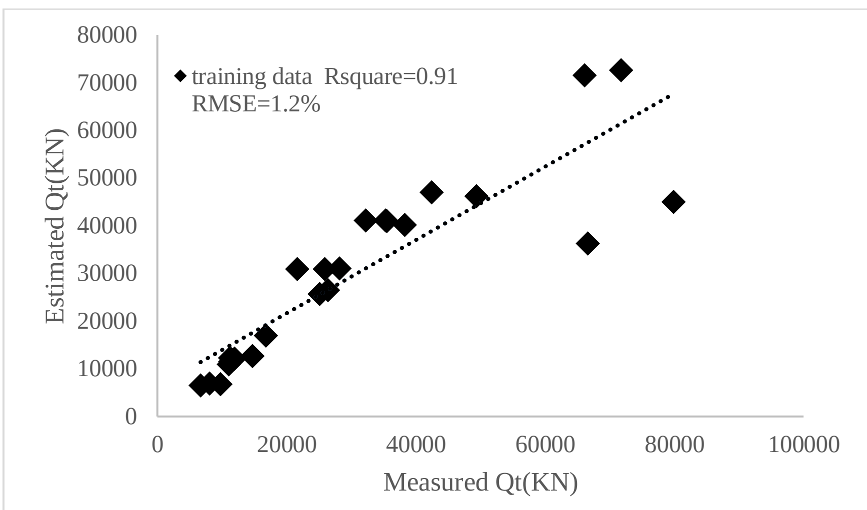


Figure 11 Calibration Performance comparison of GEP driven piles model and PDA based methods in cohesive soils for training data

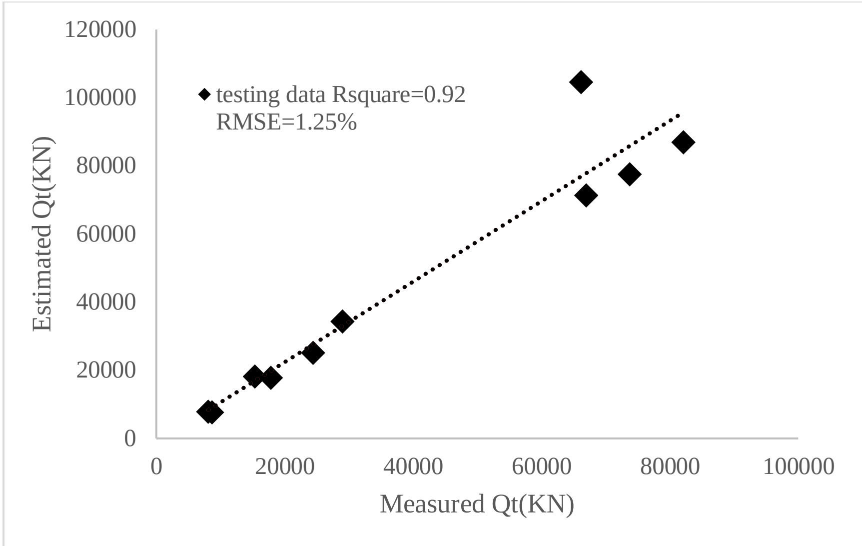


Figure 12 Calibration Performance comparison of GEP driven piles model and PDA based methods in cohesive soils for testing data

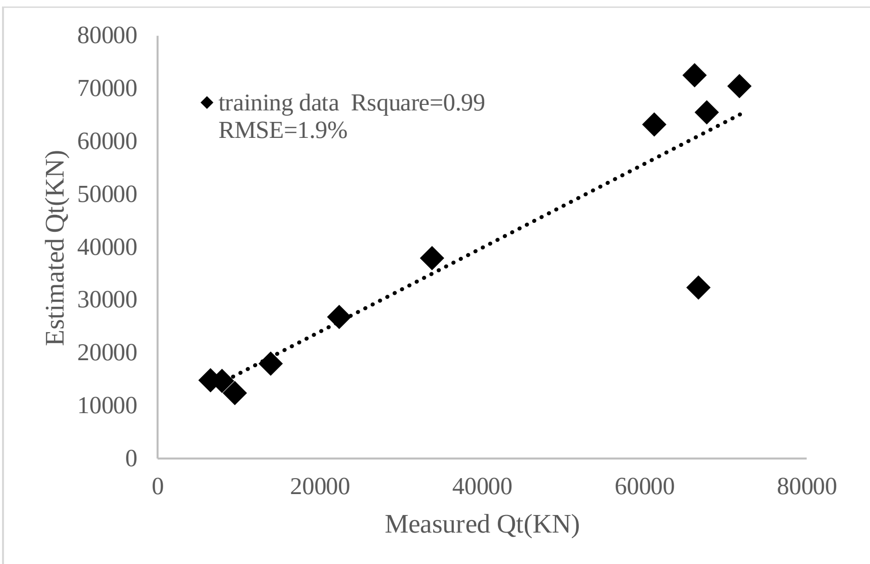


Figure 13 Calibration Performance comparison of GEP driven piles model and PDA based methods in non-cohesive soils for training data

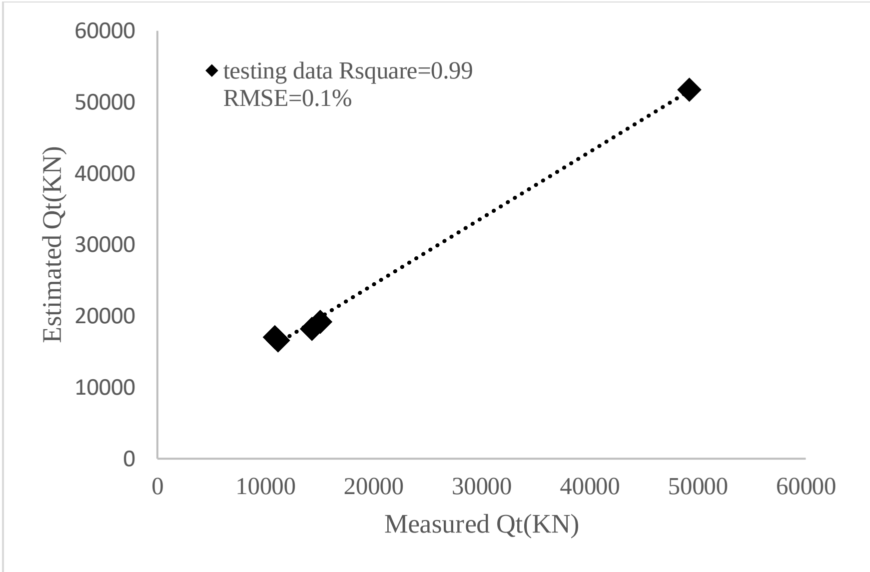


Figure 14 Calibration Performance comparison of GEP driven piles model and PDA based methods in non-cohesive soils for testing data

4-3 Optimization the dimensions of driven piles

To use the GEP in optimization as a fast analyzer, it is necessary to first train the network based on a series of random input-output pairs. Obviously, the operation of the network must be controlled, so that the accuracy of the outputs is within acceptable limits. After training the network and in the stage of structural optimization, there is no need to re-analyze the structure, but in the countless iterations that occur, the GEP acts as a fast analyzer. In the present study, an attempt has been made to optimize the length and diameter of the piles. For this purpose, optimization plots are presented according to the following figures. evaluation of the plots in Figures 15 to 19 show that for different values of f_s and q_c the optimize value of length-to-diameter ratio is approximately 40, when the length to diameter ratio of the pile is in the range of 19 to 75.

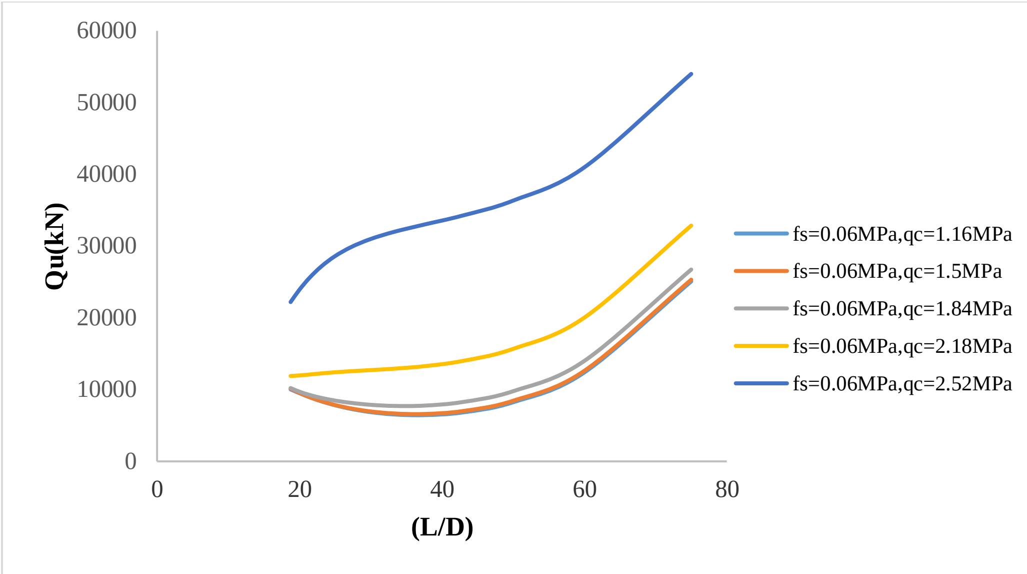


Figure 15 Optimal values of length to diameter ratio of piles for fs = 0.06MPa and different values of qc

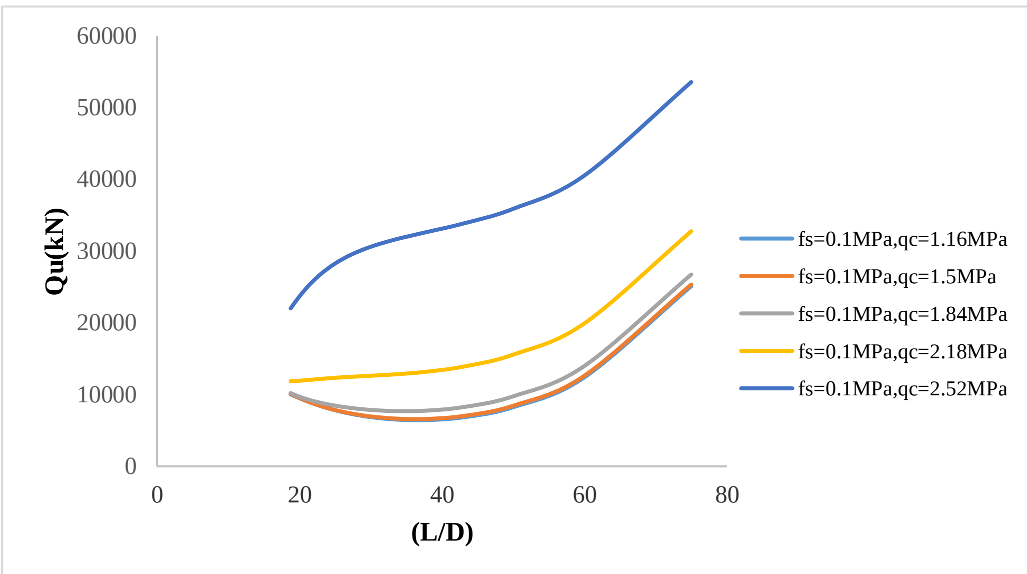


Figure 16 Optimal values of length to diameter ratio of piles for fs = 0.1MPa and different values of qc

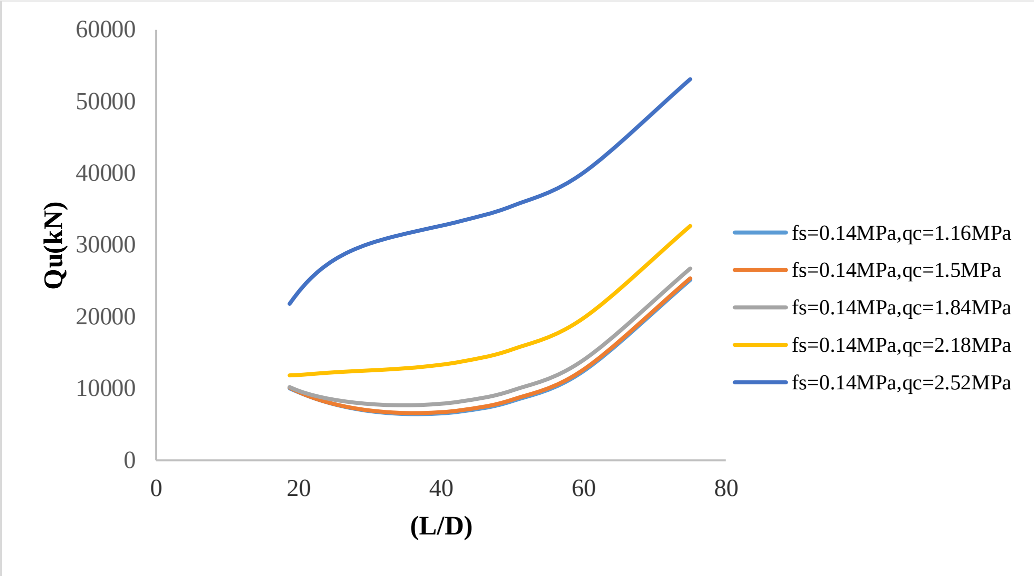


Figure 17 Optimal values of length to diameter ratio of piles for fs = 0.14MPa and different values of qc

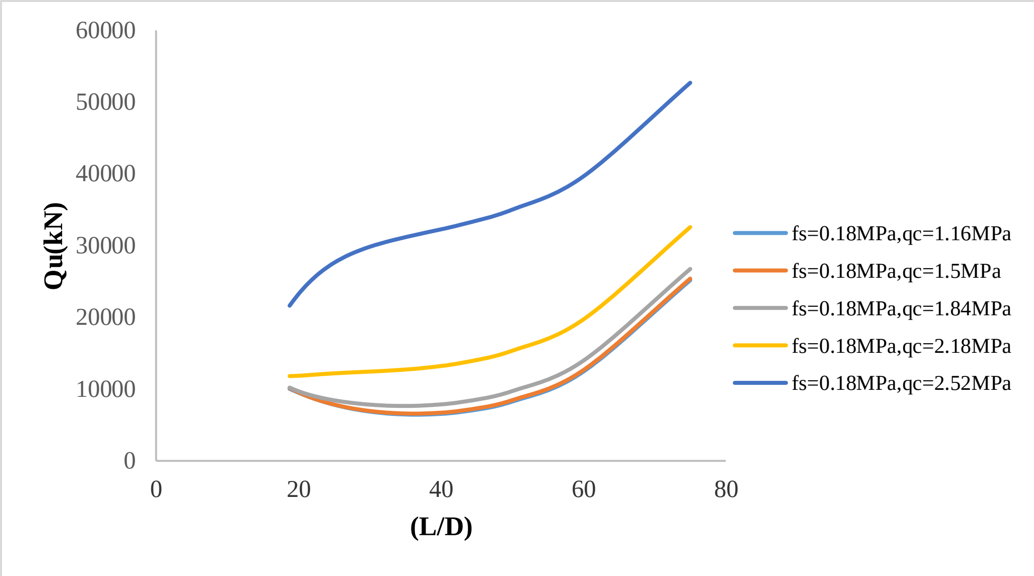


Figure 18 Optimal values of length to diameter ratio of piles for fs = 0.18MPa and different values of qc

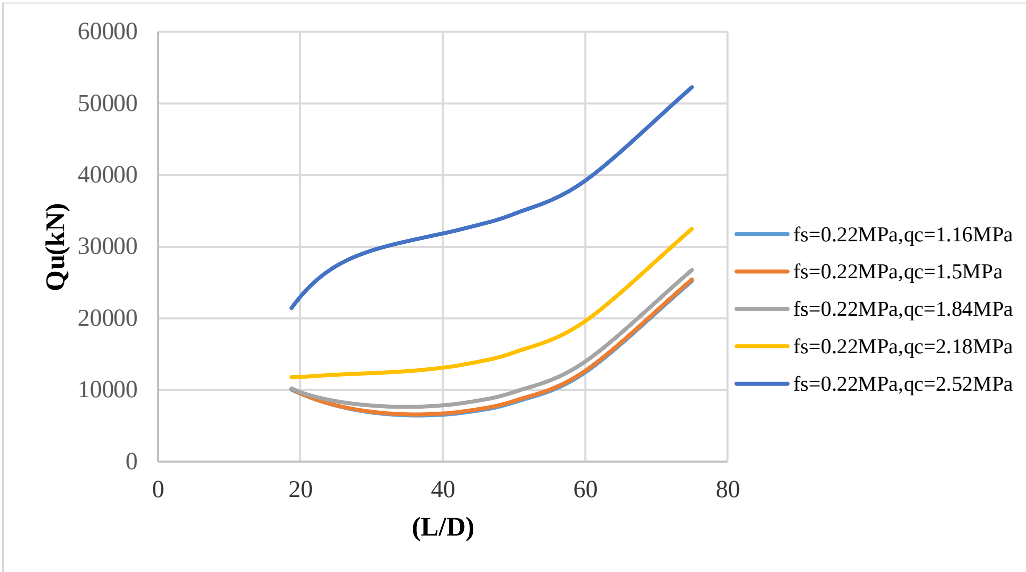


Figure 19 Optimal values of length to diameter ratio of piles for fs = 0.22MPa and different values of qc

5- Conclusions

Investigating the CPT laboratory results and using it in numerical analysis using GEP in this study, the bearing capacity of offshore steel driven piles in the Persian Gulf (South Pars) were determined using experimental analytical methods and in-situ tests such as CPT. thus, the models calibrated using the results of piles Dynamic tests (PDA). Also, based on the available data and calibration, the optimization of the best dimensions of piles was performed. GEP has been used to develop models to evaluate the axial bearing capacity of piles using CPT data. Effective parameters in determining the pile ultimate loading capacity include pile length (L), pile diameter (D), pile tip resistance (qc) and friction pile resistance (fs). In this research, different models are defined under two scenarios, once for cohesive soils and once for non-cohesive soils. in the recent study developed models predict the bearing capacity of piles in cohesive and non-cohesive soils. In this case, the models depend on the pile length and diameter, pile tip strength and pile friction resistance to determine the pile bearing capacity. The correlation values in both cohesive and non-cohesive soils show good results, which means that the data are well correlated with each other. In the proposed model for cohesive soil, the values of R2 and RMSE are 0.91 and 7.1% for training data and 0.84 and 5.4% for testing data, respectively. Also, in the proposed model for non-cohesive soil, the values of R2 and RMSE are 0.99 and 2.9% for training data and 0.99 and 1.1% for testing data, respectively. After calibration using PDA results in the proposed model for cohesive soil, R2 and RMSE values are 0.92 and 1.25% for training data and 0.91 and 1.2% for testing data, respectively. furthermore, by calibration using PDA results in the proposed model for non-cohesive soil, R2 and RMSE values are 0.99 and 1.9% for training data and 0.99 and 1 for testing data, respectively. The results show that for different fs and qc the optimal value of the length to the diameter ratio of the pile is about 40, when the length to diameter ratio of the pile is in the range of 19 to 75.

References

1. API, R. (2011). "2GEO (2011) Geotechnical and foundation design considerations." American Petroleum Institute, Washington, DC, USA.

2. Ardalan, H., et al. (2009). "Piles shaft capacity from CPT and CPTu data by polynomial neural networks and genetic algorithms." Computers and Geotechnics **36**(4): 616-625.

3. Briaud, J.-L., et al. (1989). Axialy loaded 5 pile group and single pile in sand. Congrès international de mécanique des sols et des travaux de fondations. 12.

4. Brucy, F., et al. (1991). Behavior of pile plug in sandy soils during and after driving. Offshore Technology Conference, Offshore Technology Conference.

5. BSI, E. (1999). "1015-11, Methods of test for mortar for masonry-Part 11: Determination of flexural and compressive strength of hardened mortar." British Standards Institution (BSI).

6. Bustamante, M. and L. Gianeselli (1982). Pile bearing capacity prediction by means of static penetrometer CPT. Proceedings of the 2-nd European symposium on penetration testing.

7. Cai, G., et al. (2009). "Assessment of direct CPT and CPTU methods for predicting the ultimate bearing capacity of single piles." Engineering Geology **104**(3-4): 211-222.

8. Das, S. K. and P. K. Basudhar (2006). "Undrained lateral load capacity of piles in clay using artificial neural network." Computers and Geotechnics **33**(8): 454-459.

9. De Kuiter, J. and F. Beringen (1979). "Pile foundations for large North Sea structures." Marine Georesources & Geotechnology **3**(3): 267-314.

10. Ebrahimian, B. and V. Movahed (2017). "Application of an evolutionary-based approach in evaluating pile bearing capacity using CPT results." Ships and Offshore Structures **12**(7): 937-953.

11. Eslami, A. and B. H. Fellenius (1997). "Pile capacity by direct CPT and CPTu methods applied to 102 case histories." Canadian Geotechnical Journal **34**(6): 886-904.

12. Fakharian, K. (2000). A Case Study On the Application of Pile Driving Analyzer (PDA) And CAPWAP Analysis to Bearing Capacity of Piles. The Tenth International Offshore and Polar Engineering Conference, International Society of Offshore and Polar Engineers.

13. Ferreira, C. (2001). "Gene expression programming: a new adaptive algorithm for solving problems." arXiv preprint cs/0102027.

14. ISSMGE, I. (1999). "International reference test procedure for the cone penetration test (CPT) and the cone penetration test with pore pressure (CPTU)." Report of the ISSMGE Technical Committee **16**.

15. Jardine, R., et al. (2005). ICP design methods for driven piles in sands and clays, Thomas Telford London.

16. Lacasse, S., et al. (2013). Reliability of API, NGI, ICP and Fugro axial pile capacity calculation methods. Offshore Technology Conference, Offshore Technology Conference.

17. Lee, I.-M. and J.-H. Lee (1996). "Prediction of pile bearing capacity using artificial neural networks." Computers and Geotechnics **18**(3): 189-200.

18. Lehane, B., et al. (2005). The UWA-05 method for prediction of axial capacity of driven piles in sand. International Symposium on Frontiers in Offshore Geomechanics, Perth, Western Australia.

19. Long, J. H., et al. (1999). "Value of methods for predicting axial pile capacity." Transportation research record **1663**(1): 57-63.

20. Maizir, H. and R. Suryanita (2018). Evaluation of axial pile bearing capacity based on pile driving analyzer (PDA) test using Neural Network. IOP conference series: earth and environmental science. IOP.

21. Mayerhof, G. (1976). "Bearing capacity and settlemtn of pile foundations." Journal of Geotechnical and Geoenvironmental Engineering **102**(ASCE# 11962).

22. Meyerhof, G. (1951). "The ultimate bearing capacity of foudations." Geotechnique **2**(4): 301-332.

23. Moayedi, H., et al. (2017). "Evaluation of maintained load test (MLT) and pile driving analyzer (PDA) in measuring bearing capacity of driven reinforced concrete piles." Soil Mechanics and Foundation Engineering **54**(3): 150-154.

24. Moshfeghi, S. and A. Eslami (2018). "Study on pile ultimate capacity criteria and CPT-based direct methods." International Journal of Geotechnical Engineering **12**(1): 28-39.

25. Pham, T. A., et al. (2020). "Prediction of Pile Axial Bearing Capacity Using Artificial Neural Network and Random Forest." Applied Sciences **10**(5): 1871.

26. Price, G. and I. Wardle (1982). A comparison between cone penetration test results and the performance of small diameter instrumented piles in stiff clay. Proceedings of the 2nd European symposium on penetration testing, Amsterdam.

27. Rausche, F., et al. (2010). Static and dynamic models for CAPWAP signal matching. Art of foundation engineering practice**:** 534-553.

28. RP2A-WSD, A. (2000). "Recommended practice for planning, designing and constructing fixed offshore platforms–working stress design–." American Petroleum Institute, Washington Dc.

29. RP, A. (2007). 2A-WSD, recommended practice for planning designing and constructing fixed offshore platforms-working stress design, Washington: API Publishing Services.

30. Schneider, J. A., et al. (2008). "Database assessment of CPT-based design methods for axial capacity of driven piles in siliceous sands." Journal of Geotechnical and Geoenvironmental Engineering **134**(9): 1227-1244.

31. Takesue, K., et al. (1998). Correlation between ultimate pile skin friction and CPT data. Geotechnical Site Characterization.

32. Terzaghi, K., et al. (1996). Soil mechanics in engineering practice, John Wiley & Sons.

33. Vesic, A. S. (1977). "Design of pile foundations." NCHRP synthesis of highway practice(42).

34. Wang, B., et al. (2019). "Feasibility of a novel predictive technique based on artificial neural network optimized with particle swarm optimization estimating pullout bearing capacity of helical piles." Engineering with Computers: 1-10.