Geotech Geol Eng (2018) 36:813–826
https://doi.org/10.1007/s10706-017-0355-0

ORIGINAL PAPER

Water Curtain System Pre-design for Crude Oil Storage URCs: A Numerical Modeling and Genetic Programming Approach

Ebrahim Ghotbi Ravandi · Reza Rahmannejad · Saeed Karimi-Nasab · Amir Sarrafi · Amir Raoof

Received: 26 November 2016 / Accepted: 28 August 2017 / Published online: 1 September 2017

Abstract In this paper the main criteria of the water curtain system for unlined rock caverns (URCs) is described. By the application of numerical modeling and genetic programming (GP), a method for water curtain system pre-design for Iranian crude oil storage URCs (common dimension worldwide) is presented. A comprehensive set of numerical simulations is performed using the finite element based commercial software (COMSOL 5.1) where the results are used as database for genetic programming. Describing equations of water inflow to the filled and empty caverns and water production rate of water curtain boreholes are generated using GP. By equating the proposed equations to each other, water curtain system can be pre-designed. Relative error of the generated GP equations shows their ability and accuracy. Applying a standard regression coefficient method, sensitivity analysis of parameters related to water curtain performance and water inflow to the caverns is performed as well. The results help the design of the water curtain system for crude oil storage caverns worldwide.

Keywords Underground storage · Unlined rock caverns (URC) · Water curtain system · Genetic programming (GP) · Numerical modeling

E. Ghotbi Ravandi (✉)
Mineral Industries Research Center, Shahid Bahonar University of Kerman, Kerman, Iran
e-mail: Ghotbi_Ebrahim@yahoo.com

R. Rahmannejad · S. Karimi-Nasab
Mining Engineering Department, Shahid Bahonar University of Kerman, Kerman, Iran

A. Sarrafi
Chemical Engineering Department, Shahid Bahonar University of Kerman, Kerman, Iran

A. Raoof
Earth Sciences Department, Utrecht University, Utrecht, The Netherlands

1 Introduction

1.1 Hydrocarbon Storage in URCs and Hydrodynamic Seepage Control Principle

Underground storage of hydrocarbons (e.g., crude oil) in unlined rock caverns (URCs) to have a safe and stable oil supply is superior to other storage methods due to its safety performance, low cost and being more environmentally friendly. The main issue related to this method is the seepage of stored products, vapors and the associated VOCs to the cavern outside area which can cause serious environmental problems and economical and financial losses. Therefore, seepage control is a prerequisite in underground storage. Seepage control is performed by permeability control (freezing, grouting) and hydrodynamic control (Lu 2010). Hydrodynamic control -which is more economical compared to permeability control-means that there is groundwater present with the pressure higher than the internal storage pressure resulting in a positive groundwater gradient towards the rock cavern. This forces continuous water flow toward the cavern so that the cavern stored products may not escape outside (Haug 2007). The liquid hydrocarbons such as crude oil are not stored under pressure. Vapors VOCs of hydrocarbons can have pressure between 0.5 and 3 bar (10^5 Pa) depending on temperature and oil components (Midtlien 2007). Typically, 75 and 25% of the caverns space is considered for oil and gases respectively (Haug 2007). Aberg (1977) postulated that no leakage will occur if the water pressure gradient toward the cavern is positive and greater than unity. There always some extra groundwater pressure is considered as margin of safety. Positive groundwater gradient causes continuous flow of water into the cavern. The leaking water should not be mixed with the stored products and accumulate at the bottom of the cavern. Therefore, the stored product must be lighter than water and insoluble in water. The polluted and accumulated water is pumped out of the cavern to keep the thickness of the water bed constant (fixed water bed) and treated in water treatment plant for its further use in water supply systems. When the product is pumped out and the level of oil in the cavern decreases an inert gas is replaced under pressure in order to eliminate explosive situations (e.g. replacing O_2 with N_2).

Groundwater level above the cavern has a major impact on the design and performance of hydrodynamic leakage control method and it determines the depth and location of the cavern. The groundwater elevation should be monitored regularly and carefully before and during the construction period as well as the whole storage life using piezometers or observation wells. Groundwater level has to be maintained at its original level therefore the cavern must be equipped with artificial system for supplying water. It can be done by injecting water through water curtain systems above the cavern or using vertical wells. Figure 1 shows the groundwater monitoring, injecting water systems and water curtain systems schematically.

Water curtains are an array of parallel boreholes that are installed over the roof of a cavern and sometimes around the sidewalls if needed (Li et al. 2009). The efficiency and performance of the water curtain is related to the arrangement of boreholes in the system. The geometrical parameters of water curtain systems include the length and spacing of the boreholes, the elevation difference between the boreholes and the cavern crown as well as the pressure (or potential) in the water curtain relative to the storage pressure (Kjørholt and Broch 1992; Wang et al. 2015). Few authors have developed the theory and application of water curtain installations (Kjørholt and Broch 1992; Glamheden and Curtis 2006; Haug 2007; Li et al. 2009; Wang and Tokunaga 2015; Wang et al. 2015; Ghotbi Ravandi et al. 2016). Practical design of water curtain system should be based on a combination of theoretical calculations, experience from existing storages and hydraulic testing at the site (Kjørholt and Broch 1992).

1.2 Water Inflow to the Underground Openings and Tunnels

The prediction of groundwater inflow magnitude into underground openings which is the volume of water, which flows into the opening per unit time and per unit length is an issue in the underground space engineering. Groundwater inflow into an underground opening can cause construction problems as well as environmental impacts such as surface subsidence (Butscher 2012). There are analytical and closed form equations for steady inflow in a horizontal circular tunnel in a fully saturated semi-infinite homogenous and isotropic media which use Darcy equation and mass conversion which is known as Laplace equation as follows (Gulraiz Akhter et al. 2006):

Darcy's law:

$$q_x = -K\frac{\partial H}{\partial x}; \quad q_y = -K\frac{\partial H}{\partial y}; \quad q_z = -K\frac{\partial H}{\partial z} \qquad (1)$$

where q_x, q_y and q_z are specific volumetric flow rate in x, y and z direction respectively. K is hydraulic conductivity and H [L] is hydraulic head, equal to the sum of pressure head $P/\rho g$ [L] head and elevation z [L], with P [$ML/T^2/L^2$].

Continuity equation:

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} = 0 \qquad (2)$$

For a unit volume where no sink and source present the flow into and out of the control volume must be 0. Combining Eqs. 1 and 2 and considering isotropic media, we get:

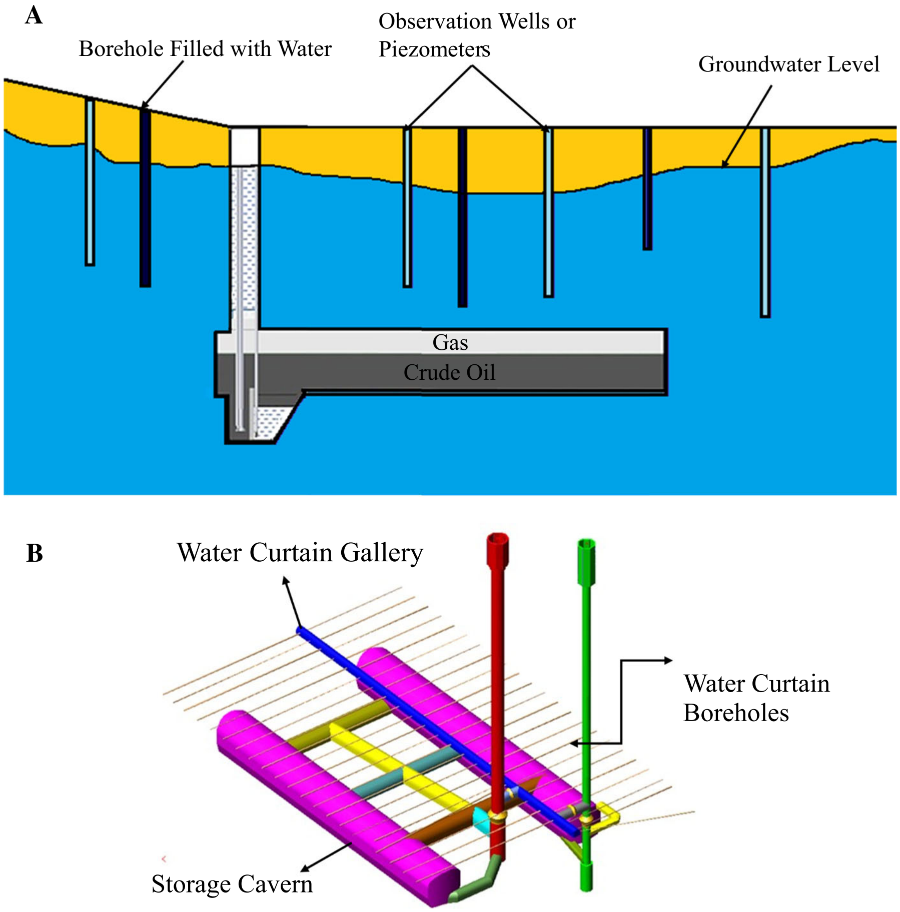

Fig. 1 **a** Groundwater monitoring and injecting water system. **b** Water curtain system. Adopted from Verma et al. (2008)

$$\frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial y^2} + \frac{\partial^2 H}{\partial z^2} = 0 \quad \text{Laplace equation in 3D} \tag{3}$$

$$\frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial y^2} = 0 \quad \text{Laplace equation in 2D} \tag{4}$$

Analytical solutions of water inflow to underground openings are only applicable in rather simple situations, therefore numerical modeling is needed for complex geological situations and distributed hydraulic properties and boundary conditions as well as transient conditions (Butscher 2012). There are some studies calculating tunnel inflow by numerical methods (Finsterle et al. 2003; Butscher 2012) but water inflow to crude oil storage caverns (non-circular geometry and non-constant storage pressure) with water supply systems such as water curtain system and artificial intelligence techniques for prediction of water inflow have not been investigated.

The purpose of this study is to propose a method for water curtain systems pre-design applicable for Iranian crude oil storage URCs (common dimension of storage caverns worldwide) based on the steady water inflow to the caverns and the associated volumetric flow rate that the water curtain system boreholes can produce in different scenarios using numerical modeling (COMSOL) and genetic programming.

2 Validation of Numerical Modeling Using COMSOL with Analytical Method

El Tani (2003) compared the results of most well-known equations for water inflow into circular tunnels presented in Table 1 with the observed water inflow

Table 1 Well known equations for water inflow into circular tunnels (El Tani 2003)

Approximation equation for water inflow	Author(s)
$Q_{MG} = 2\pi k \frac{h}{\ln\left(\frac{2h}{r}\right)}$	Muskat (1937)
$Q_{SL} = 2\pi k \frac{h}{\ln\left(\frac{h}{r}+\sqrt{\frac{h^2}{r^2}-1}\right)}$	Schleiss (1988), Lei (1999)
$Q_{r2} = 2\pi k \frac{1-3\left(\frac{r}{2h}\right)^2}{\left[1-\left(\frac{r}{2h}\right)^2\right]\ln\frac{2h}{r}-\left(\frac{r}{2h}\right)^2}$	Two terms truncated single layer, El Tani (1999)
$Q_{Ka} = 2\pi k \frac{h}{\ln\left(\frac{2h}{r}-1\right)}$	Karlsrud (2001)
$Q_{Le} = 2\pi k \frac{h}{\left(1+0.4\left(\frac{r}{h}\right)^2\right)\ln\frac{2h}{r}}$	Lombardi (2002)

(seepage) into tunnels, for different values of r/h. Where K [L/T] is equivalent hydraulic conductivity, r [L] is tunnels radius, h [L] is the depth of tunnel centerline to the water table. The relative differences of the diverse formulas of Table 1 with the exact (observed) water inflow (Q) are shown in Fig. 2 and are computed with:

$$\Delta = \frac{Q_{ap} - Q}{Q} \tag{5}$$

Q_{ap} is a water inflow approximation.

As Fig. 2 shows, with decreasing r/h, water inflow approximations converge to the exact water inflow. For r/h less than 0.3, the relative differences are negligible.

The results from numerical modeling using COMSOL which uses finite element method to model the transport of single and two-phase fluids in porous media is compared with the Lombardi equation which have the most exact value of water inflow for different values of r/h to investigate the ability of COMSOL modeling. A circular tunnel with 7.5 m radius in the rock with 10^{-10} m/s of hydraulic conductivity is modeled with COMSOL for the values of r/h less than 0.3 (Fig. 3). The results compared with Lombardi equation which are presented in Table 2. As it can be seen from Table 2 the COMSOL results are in a good agreement with the analytical method results.

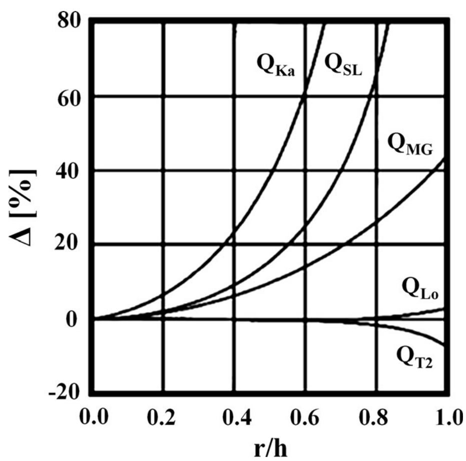

Fig. 2 Relative differences of the approximation by the equation in the Table 1 with the exact water inflow to the tunnels (after El Tani 2003)

3 Genetic Programming

Genetic programming (GP) as an extension of the genetic algorithms (GA) was introduced by Koza (1976). The main difference between genetic programming and genetic algorithms is the representation of the solution. Genetic algorithms create a string of numbers that represent the solution but genetic programming creates computer programs (CPs) in the lisp or scheme computer languages as the solution (Ghotbi Ravandi et al. 2013). GP can be used to find a relationship between input and output data in the form of mathematical expression represented by functions generated in the training (learning) process. If the error rate reached a certain threshold, the training can be stopped and the testing (validation) can be applied to verify the effectiveness of the best function.

Genetic programming uses four steps to solve problems (Ghotbi Ravandi et al. 2013):

1. Generate an initial population of random compositions of the functions and terminals of the problem (computer programs).
2. Execute each program in the population and assign it a fitness value according to how well it solves the problem.

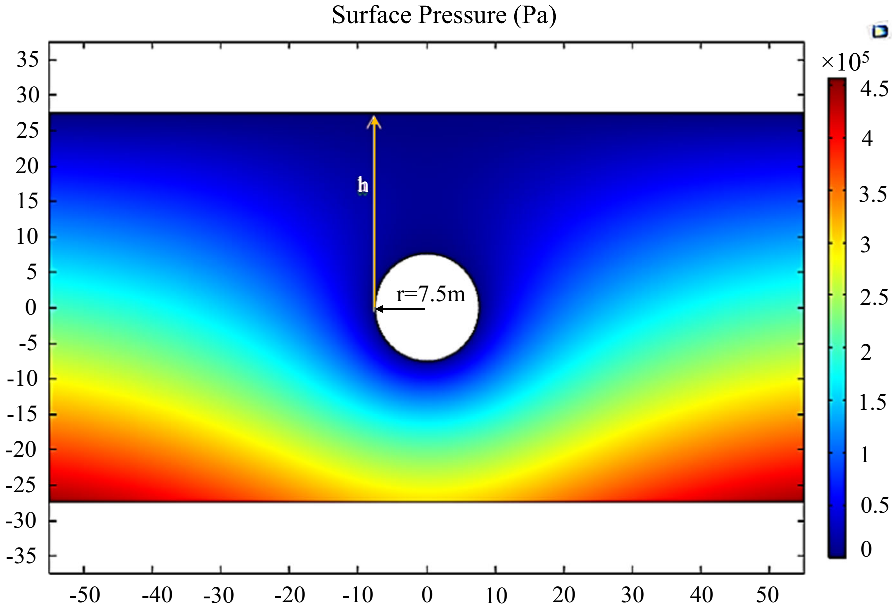

Fig. 3 Numerical modeling of groundwater inflow to the circular tunnel with COMSOL

Table 2 Comparison of the numerical modeling results with the Lombardi equation for different r/h

h	r/h	Lombardi (m^3/s)	Numerical modeling (m^3/s)	Relative error (%)
25	0.3	7.99×10^{-9}	7.75×10^{-9}	3
27.5	0.27	8.42e $\times 10^{-9}$	8.15e $\times 10^{-9}$	3.2
37.5	0.2	1.01e $\times 10^{-8}$	9.64×10^{-9}	4
50	0.15	1.2×10^{-8}	1.14×10^{-8}	5
75	0.1	1.56e $\times 10^{-8}$	1.46×10^{-8}	6.4

3. Create a new population of computer programs by applying the following genetic operations:
   (a) Copy the best existing programs (reproduction).
   (b) Create new computer programs by mutation.
   (c) Create new computer programs by crossover.
4. The best computer program that appeared in any generation (the best-so-far solution), is designated as the result of genetic programming.

Figure 4 shows the genetics programming flow-charts schematically.

4 Methodology

The purpose of this study is to employ genetic programming to generate equations for the estimation of steady groundwater water inflow to the cavern (Iranian crude oil storage URCs) and water volumetric flow rate of boreholes based on the geometrical parameters of water curtain system, hydrogeological properties of the host rocks of the caverns and the crude oil properties including borehole pressure (B_p), borehole spacing (B_s), groundwater level (GW_l) and borehole elevation above cavern (B_e),vertical to horizontal hydraulic conductivity of rock mass (K_z/K_x), gas pressure (G_p) as well as density of oil (O_d) and its height in the cavern (O_h). The groundwater inflow rate to the cavern should be equal to water production rate of the boreholes to have stable groundwater level and water leaking to the cavern can be used as a supply

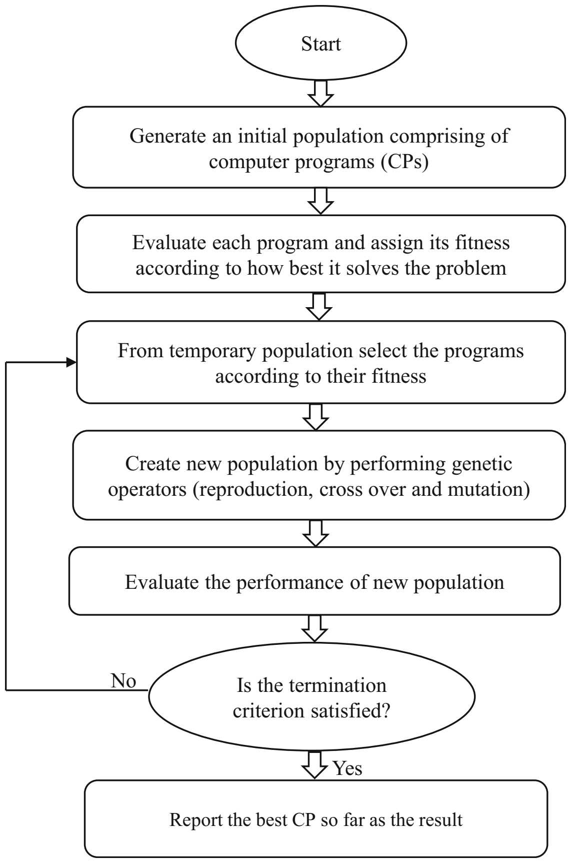

Fig. 4 Genetic programming flowchart (after Ghotbi Ravandi et al. 2013)

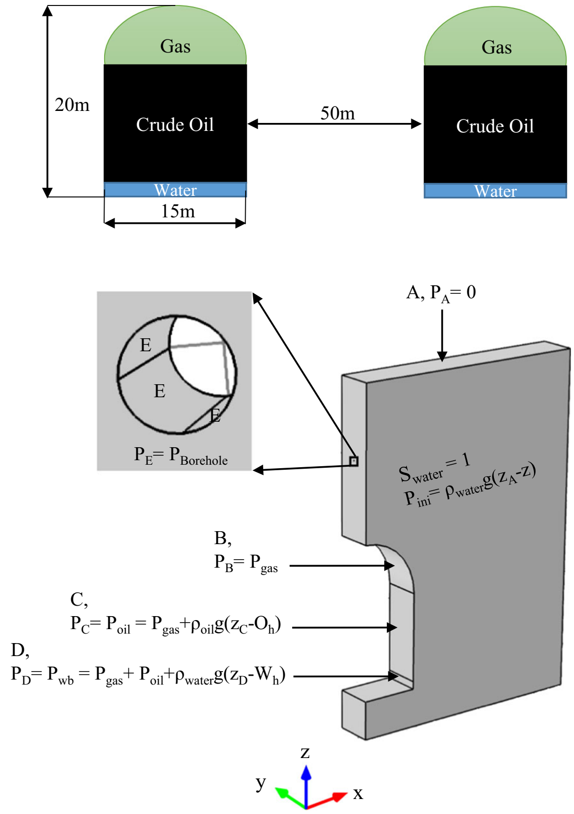

Fig. 5 Scheme of UCRs dimensions and distance as well as initial and boundary condition of numerical modeling: (A) Water table = zero pressure boundary, P = 0. (B) Gas pressure, $P = P_{gas}$. (C) Oil pressure, $P_{oil} = P_{gas} + \rho_{oil} g(z_C - O_h)$. (D) Water bed pressure, $P_{wb} = P_{gas} + P_{oil} + \rho_{water} g(z_D - W_h)$. (E) Borehole pressure P_b. All other boundaries are given as Neumann no-flow boundary conditions ($-n.\rho u = 0$). In the case of empty cavern B = C=D = zero pressure ($P = 0$)

for the water curtain system. Therefore, by equating the two equations and considering given values for some parameters, the water curtain system can be designed. To reach the stated goal three levels including minimum, middle and maximum were considered for each parameter and using full factorial design of experiments all the hypothetical cases were simulated by COMSOL for both the empty cavern and when the oil and gas are within the cavern (i.e., filled cavern). Then steady water inflow rate to the cavern and the borehole steady water production flow rate was evaluated. Cavern dimension and distance and boundary and initial conditions chosen for the simulations are depicted in Fig. 5, where A, B, C, D, E are Dirichlet pressure boundaries. All other boundaries are given as Neumann no-flow boundary conditions ($-n.\rho u = 0$). In the case of empty cavern, B, C and D are zero pressure boundary. Initial condition of the model is hydrostatic pressure of groundwater. Due to the symmetry only half of the cavern was simulated. All the simulations were done by considering the absolute hydraulic conductivity of limestone (10^{-7} m/s). Mesh dependency tests were carried out to insure correct mesh sizes. The quality of modeling mesh and pressure contour for the empty cavern for a specific case (constant borehole pressure, elevation and groundwater level) for three vertical to horizontal permeability ratio and three levels of oil in the filled cavern (full, half and ~empty) where other parameters (e.g., vapor pressure) are constant are shown in Fig. 6. High level of oil (full cavern) means that 75% of cavern is filled with oil (25% of cavern is considered

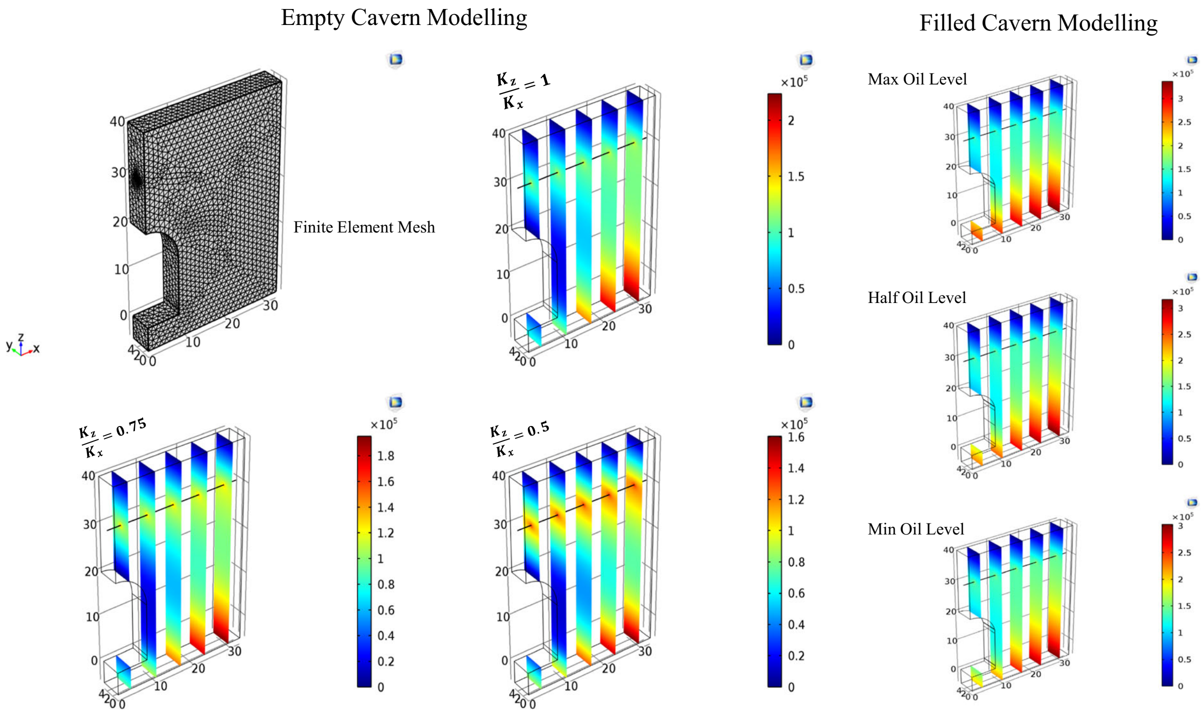

Fig. 6 Pressure contour for the empty cavern modeling for different values of K_z/K_x and filled cavern modeling for different oil levels in the cavern

Table 3 Domain and level of parameters for the empty and non-empty cavern modeling

Variable	Empty cavern domain	Levels of empty cavern	Filled cavern domain	Levels of filled cavern
Gas pressure (bar)	–	–	1–2	3
Oil density (kg/m^3)	–	–	800–950	2
Vertical/horizontal hydraulic conductivity	0.5–1	3	0.5–1	3
Borehole pressure (bar)	1.5–2.5	3	1.5–2.5	3
Borehole spacing (m)	5–20 m	3	5–20	2
Water level above cavern (m)	20–50	3	20–50	2
Borehole elevation (m)	10–45 m	3	10–45	3
Oil height in cavern (maximum level = 1)	–	–	0.01–1	3

for gas and vapors). The level selection of vertical to horizontal hydraulic conductivity carried out from (Domenico and Schwartz 1990). Borehole spacing, pressure and elevation are selected according to the suggestion range provided by previous publications results (Froise 1987; Kjørholt and Broch 1992; Liang and Lindblom 1994; Li et al. 2009; Wang et al. 2015). Vapor pressure of oil is considered based on the Iranian oil type and the storage temperature. Table 3 shows the domain of the selected variables and their levels. Other parameters and some assumptions were considered as follows:

- The rock mass is considered homogenous and anisotropic ($K_x = K_y > K_z$).
- Borehole pressure is always considered more than the gas storage pressure.

Table 4 An overview of GP runs settings

GP parameter	Q_{Ce}	Q_{Be}	Q_{Cf}	Q_{Bf}
Function set	+, −, ×	+, −, ×, ÷	+, −, ×, exp	+, −, ×, exp
Population size	250	300	250	300
Number of generation	200	250	250	300
Max gens	3	3	4	4

Table 5 Liner regression models for the water inflow to the unit length of the cavern and borehole production flow rate

Equation no,	Linear regression model	R^2	R^2-adj
(7)	$Q_{Ce} = 10K\left(0.158 + 4.22\frac{K_z}{K_x} + 0.337B_p - 0.0348B_s + 0.0183Gw_l - 0.0347B_e\right)$	99.2	99.2
(8)	$Q_{Be} = 100K\left(-2.75 + 3.42\frac{K_z}{K_x} + 2.05B_p + 0.136B_s - 0.187d\right)$	88.8	88.8
(9)	$Q_{Cf} = 10K\left(0.514 - 0.494G_p - 0.000038O_d + 2.97\frac{K_z}{K_x} + 0.317B_p - 0.0286B_s + 0.0194Gw_l - 0.0142B_e - 0.429O_h\right)$	96.8	96.8
(10)	$Q_{Bf} = 100K\left(-1.93 - 0.362G_p - 0.000208O_d + 2.61\frac{K_z}{K_x} + 2.10B_p + 0.121B_s - 0.173d - 0.180O_h\right)$	92.3	92.3

- The minimum groundwater level above the cavern for each gas pressure is considered at least two times more than gas pressure in meters of water (margin of safety).
- Borehole elevation is always less than water table.
- Fixed water bed thickness is considered one meter.
- 25% of the cavern volume is considered for the vapor of crude oil in the case that the cavern is full of oil.
- Boreholes diameter is 64 mm (typical size of borehole diameter).
- The governing equation for the simulation obeys Darcy and Laplace equations.

The standard regression coefficients (SRC) as a sensitivity analysis technique which involves fitting a linear regression to the model response and using standardized regression coefficients as direct measures of sensitivity was implemented for water inflow to the cavern and borehole water production rate of the input parameters to identify which parameters have most and less effects. Insignificant parameters can be neglected from GP input data to have simpler equation.

Genetic programming (GP) was used to generate equations. To reach the stated goal the whole data set was separated into two training and testing set (80 and 20% of whole data sets respectively). The training set was used to evaluate the final or optimum computer programs (CPs) while the testing set was employed to validate the reliability of the GP model. The optimum combination of values for the set of parameters such as population size, number of generations, function set, mutation rate, crossover rate, etc., is achieved by the performance of several trials. The mean absolute error (MAE) between the values evaluated by COMSOL and the values returned by the GP generated equation was used in the modeling evaluation stage as the fitness function. The mathematical form of the MAE is as follows:

$$MAE = \frac{1}{N}\sum_{1}^{N}(q - q_g) \tag{6}$$

where q and q_g are the volumetric rate value obtained by numerical modeling and GP model respectively and N is the number of data. Obviously lower MAE shows the fittest equations. GP was initiated with different randomly generated computer programs for water inflow to the empty and filled caverns and boreholes water production rates (as expression trees) and then evaluated the fitness value of each programs. The programs were evolved by genetic operators in order to produce next generation. Crossover, mutation

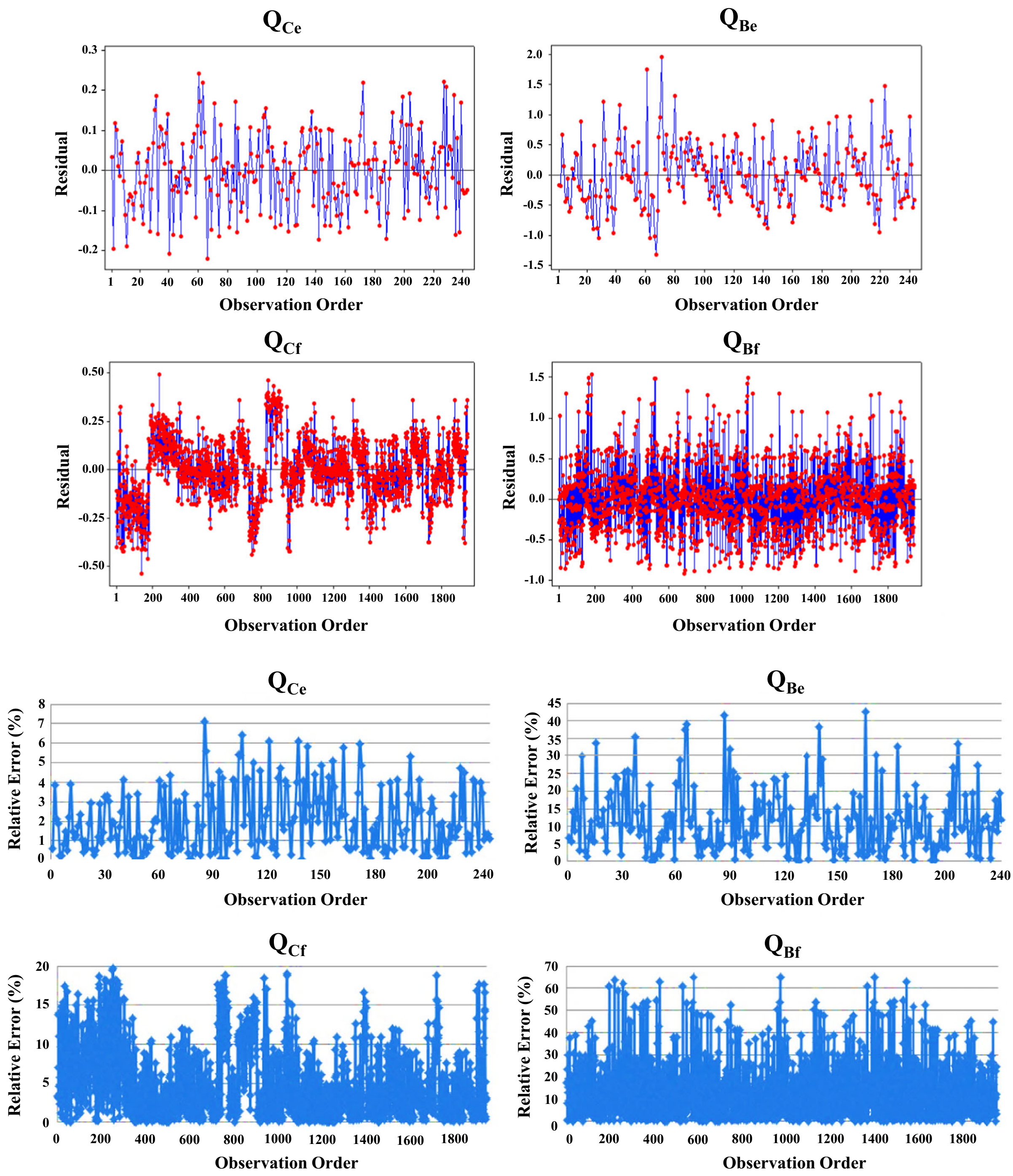

Fig. 7 Residual plot and relative error (%) of the whole data set for the Eqs. 7–10

and reproduction with possibility of 0.9, 0.02 and 0.1 were employed respectively. An overview of the GP runs settings are shown in Table 4. The programs evolving iterated through different generations for every case and the best and simplest generated computer program (CP) in any generation is considered as the final result of GP.

Table 6 SRC for the Eqs. 7–10

Variable	Q_{Ce}	Q_{Be}	Q_{Cf}	Q_{Bf}
G_p	–		0.31	0.11
O_d	–		Insignificant	Insignificant
K_z/K_x	0.97	0.47	0.88	0.40
B_p	0.15	0.53	0.19	0.56
B_s	0.21	0.51	0.22	0.50
Gw_l	0.16	–	0.28	–
B_e	0.3	–	0.18	–
Gw_l-B_e	–	0.57	–	0.79
O_h	–	–	0.22	0.04

5 Result and Discussion

Linear regression model of water inflow across a unit length of the cavern boundary and the borehole production flow rate are represented by the Eqs. 7–10 in Table 5 for both empty and filled cavern in the confident level of 95% ($\alpha = 0.05$). Q_{Ce}, Q_{Cf}, Q_{Be} and Q_{Bf} are water inflow to the unit length of empty and filled cavern and borehole production flow rate for empty and filled cavern in terms of m^3/s respectively, d is difference between groundwater level and borehole elevation above cavern and K is hydraulic conductivity (m/s). All the other parameters were defined previously. Positive sign in the regression model shows the positive effect of variable and negative sign shows the negative effect of variable on the response. It means that increasing a positive variable value (e.g., K_z/K_x or B_p) results in increasing the water inflow to the cavern and borehole water production rate. All of the variables except the oil density are significant (P value is less than α) by the t tests. Residual plot (difference between evaluated flow rate by COMSOL and predicted flow rate by the equations) and relative error of the Eqs. 7–10 are presented in Fig. 7.

$$\text{Relative error } (\%) = \left|\frac{Q_p - Q_o}{Q_p}\right| \times 100 \qquad (11)$$

where Q_p and Q_o are predicted and observed (evaluated) flow rate respectively.

Table 6 shows the sensitivity analysis of the input variables for the Eqs. 7–10 based on the SRC method. The results of Table 6 are as follows:

- The most important parameters in water inflow to the empty caverns are K_z/K_x ratio, borehole elevation above cavern crown and borehole spacing respectively.
- All of the variables have close impact to the borehole water production flow rate for empty cavern but among them the difference between groundwater level and borehole elevation above the cavern are more significant.
- K_z/K_x ratio, gas pressure and groundwater level have most effect in water inflow to the filled cavern respectively.
- Borehole pressure and borehole elevation have less effect in water inflow to the filled cavern respectively.
- Oil density effect on water inflow to the cavern and borehole production rate is insignificant and negligible.
- The difference between groundwater level and borehole elevation above the cavern, borehole pressure and borehole spacing have most meaningful effect on the borehole production rate for the filled cavern respectively.
- Oil height in the cavern has a little effect on the water production rate of boreholes.

The equations presented in Table 7 are the mathematical phrase of the best and simplest generated computer programs (CPs) by GP. Predicted values versus actual values for the training and test sets of GP models as well as relative errors (%) of the Eqs. 12–15 for the data set are shown in Fig. 8.

In the application of the proposed equations the following restriction is better to be taken into account:

- If the borehole is about to located beneath the half of the height of water table above the cavern, the borehole pressure is better to be 0.5 bar more than the gas pressure (e.g., 0.75).
- In the case that $K_z = 0.5 - 0.75\ K_x$, the borehole pressure is better to be 0.5 bar more than the gas pressure.

6 Application of GP Equations to Water Curtain System Pre-design

In this section the application and capability of the proposed GP equations to water curtain system pre-

Table 7 Computer programs (CPs) generated by GP

Equation no.	Description	GP equation	R^2	R^2-adj
(12)	Q_{Ce}	$10K\left(\frac{K_z}{K_x}\left(4.454-0.065\frac{K_z}{K_x}^2+0.009\frac{K_z}{K_x}^3\right)+0.25B_p+0.009GW_l - 0.0179B_e+0.2663\frac{K_z}{K_x}B_p-0.0314\frac{K_z}{K_x}B_s - 0.0056\left(B_pB_s-\frac{K_z}{K_x}B_p^2\right)+\frac{K_z}{K_x}^2B_p\left(0.03475+0.009\frac{K_z}{K_x}-0.009B_p\right) + 0.0056\frac{K_z}{K_x}B_pGW_l-0.0112\frac{K_z}{K_x}B_pB_e-0.1036\right)$	99.66	99.65
(13)	Q_{Be}	$98.5K\left(\frac{0.2052}{d}\left(\frac{3.02((B_p+9.491)(\frac{K_z}{K_x}+B_p)-8.276)}{B_s}+B_p\left(\frac{K_z}{K_x}+8.403\right)\left(\frac{K_z}{K_x}+0.8964\right)-8.556\right) - \frac{1}{B_s}\left(\left(0.07215\left(B_p+B_sd+\left(7\frac{K_z}{K_x}+B_p\right)\left(4\frac{K_z}{K_x}^2+\frac{K_z}{K_x}-5.08\right)\right)\right)+7.028B_p\right) - 0.1492B_p\left(\frac{K_z}{K_x}+0.8964\right)\left(\left(\frac{\frac{K_z}{K_x}}{B_s}-0.8063\right)\left(\frac{K_z}{K_x}-\frac{B_p}{B_s}+0.815\right)-7.792\right)+0.8516\right)$	98.74	98.73
(14)	Q_{Cf}	$10K\left(\left(\frac{5.669\frac{K_z}{K_x}B_s\exp(\exp(\exp(\exp(O_h-3.863))))\left(0.31\frac{K_z}{K_x}+O_h+2.808\right)(G_p-B_p+O_h-11.47)}{10^5} - 1.007\frac{K_z}{K_x}(GW_l+O_h-5.081) - 0.001009\frac{K_z}{K_x}(G_p-B_p+3.323)\left(5.056\frac{K_z}{K_x}+4.947GW_l-2O_h + B_e(O_h+6.639)+\exp(O_h)\left(O_h-\frac{K_z}{K_x}+13.75\right)+55.87\right) - 0.2177\frac{K_z}{K_x}(G_p-4.803GW_l+2.248)+0.2072\right)*(0.1414O_h+0.7788)\right)$	98.96	98.95
(15)	Q_{Bf}	$98.5K\left(0.272+0.2783B_s-0.294d-0.01962\exp\left(\frac{K_z}{K_x}\right)\exp(O_h) + B_p\left(0.3332\frac{K_z}{K_x}+0.6685\exp\left(\frac{K_z}{K_x}\right)\right) + 0.00981\left(d^2-dG_p\exp\left(2\frac{K_z}{K_x}\right)-B_s^2\right) + 0.0003819\left(G_p^2\exp\left(G_p+3\frac{K_z}{K_x}\right)-B_pd\exp(B_p) + B_p^2(B_s+7.519)\left(B_s-d-\exp(O_h)+\frac{K_z}{K_x}B_s\right)\right)\right)$	99.3	99.29

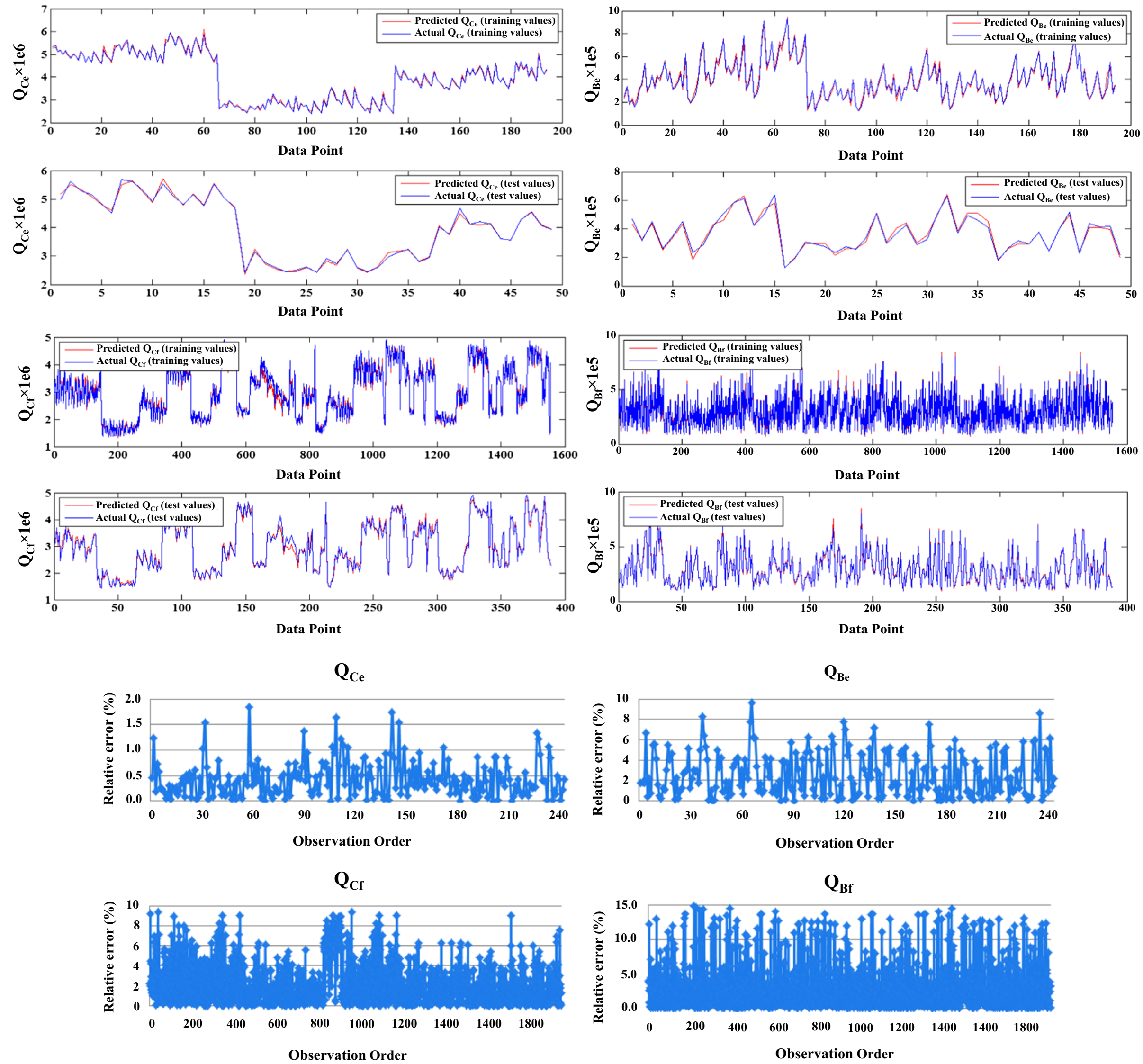

Fig. 8 Predicted values versus actual values of GP output for the training and test sets as well as relative percent error of the Eqs. 12–15

design is shown by an example. For a cavern which is filled with oil, the required borehole pressures (B_p) and borehole elevation above the cavern crown (B_e) are needed while the other parameters including hydro-geological properties of rock mass, properties of hydrocarbons and geometrical parameters of bore-holes are considered as given and known values according to Table 8. Since water production volumetric rate of the boreholes and water inflow rate to the caverns should be equal to have stable and constant groundwater level, the results of the Eqs. 14 and 15 (Q_{Cf} and Q_{Bf}) should be equal. By equating these two equations, the required unknowns can be obtained. By choosing borehole pressure equal to 1.415×10^5 Pa (1.415 bar) and borehole elevation above the cavern crown equal to 20 m, the both two equations result (Q_{Cf} and Q_{Bf}) would be 1.35×10^{-6} m^3/s. It should be noted that the Eq. 14 is for 1 m length of the cavern, therefore its value should be multiplied by borehole spacing (5 m).

Table 8 Parameters of numerical modeling and their values for GP equations test

Parameter	Value
$K_x = K_y$	10^{-8} m/s
K_z/K_x	0.85
Gas pressure (G_p)	1 Bar (10^5 Pa)
Borehole spacing (B_s)	5 m
Groundwater level (GW_l)	30 m
Oil height in the cavern (O_h)	1 (maximum level)
Oil density (O_d)	900 kg/m^3

7 Conclusions

This study provides a description of underground storage of hydrocarbons using water curtain systems. Several mathematical relations are presented using genetic programming (GP) for the prediction of steady water inflow to the empty and filled cavern as well as volumetric flow rate provided by water curtain boreholes. The database used for GP was gathered using numerical modeling (COMSOL 5.1). For this purpose the influencing parameters on water inflow rate to the cavern and borehole water production rate including vertical to horizontal hydraulic conductivity of rock mass (K_z/K_x), borehole pressure (B_p), borehole spacing (B_s), groundwater level (GW_l) and borehole elevation above cavern (B_e), storage gas pressure (G_p) and as well as density of oil (O_d) and its height in the cavern (O_h) were considered in different levels and all possible cases was simulated to evaluate water inflow to the cavern and borehole water production rate. The controlling parameters and water flow rates were considered as input and output for GP respectively, to generate the equations. By equating the GP equations to each other and solving them for unknowns the water curtain system can be designed. Correlation coefficient and relative percent error of the suggested equations shows the ability of numerical modeling and genetic programming in design of water curtain systems. Sensitivity analysis were done to investigate the effect of water curtain parameters using standard regression coefficients (SRC). It was found that oil density has negligible effect on water inflow to the cavern and vertical to horizontal hydraulic conductivity ratio and the difference between groundwater level and borehole elevation have most effects on the water inflow rate to the cavern and borehole flow rate respectively. Since the dimension of the caverns are common, the proposed equations and the obtained results can be used in preliminary design of water curtain system of unlined crude oil storage caverns worldwide.

Acknowledgements The authors would like to thank Iranian Oil Terminals Company for financial support.

References

Aberg B (1977) Prevention of gas leakage from unlined reservoirs in rock. In: Proceedings of the international symposium on storage in excavated rock caverns. Stockholm, Sweden, pp 399–413

Butscher C (2012) Steady-state groundwater inflow into a circular tunnel. Tunn Undergr Space Technol 32:158–167. doi:10.1016/j.tust.2012.06.007

Domenico PA, Schwartz FW (1990) Physical and chemical hydrogeology. Wiley, New York

El Tani M (1999) Water inflow into tunnels. In: Proceedings of the World Tunnel Congress ITA-AITES, Oslo, pp 61–70

El Tani M (2003) Circular tunnel in a semi-infinite aquifer. Tunn Undergr Space Technol 18:49–55. doi:10.1016/S0886-7798(02)00102-5

Finsterle S, Ahlers CF, Trautz RC, Cook PJ (2003) Inverse and predictive modeling of seepage into underground openings. J Contam Hydrol 62–63:89–109. doi:10.1016/S0169-7722(02)00174-2

Froise S (1987) Hydrocarbon storage in unlined rock caverns: Norway's use and experience. Tunn Undergr Space Technol 2:265–268. doi:10.1016/0886-7798(87)90033-2

Ghotbi Ravandi E, Rahmannejad R, Feili Monfared AE, Ghotbi Ravandi E (2013) Application of numerical modeling and genetic programming to estimate rock mass modulus of deformation. Int J Min Sci Technol 23:733–737

Ghotbi Ravandi E, Rahmannejad R, Karimi-Nasab S, Sarrafi A (2016) Sensitivity analysis of effective parameters on water curtain performance for crude oil storage in Iranian URC using the 2k factorial design and numerical modeling. Tunn Undergr Space Technol 58:247–256. doi:10.1016/j.tust.2016.06.001

Glamheden R, Curtis P (2006) Excavation of a cavern for high-pressure storage of natural gas. Tunn Undergr Space Technol 21:56–67. doi:10.1016/j.tust.2005.06.002

Gulraiz Akhter M, Ahmad Z, Khan KA (2006) Excel based finite difference modeling of groundwater flow. J Himal Earth Sci 39:49–53

Haug SM (2007) Storage of oil and gas in rock caverns below the groundwater table-general design development. In: Underground constructions for the Norwegian oil and gas industry. Norwegian Tunnelling Society Publication 16, pp 19–25

Karlsrud K (2001) Water control when tunnelling under urban areas in the Oslo region. NFF Publication, vol 12, pp 27–33

Kjørholt H, Broch E (1992) The water curtain—a successful means of preventing gas leakage from high-pressure,

unlined rock caverns. Tunn Undergr Space Technol 7:127–132. doi:10.1016/0886-7798(92)90042-G
Koza J (1976) Genetic programming: on the programming of computers by means of natural selection. MIT Press, Cambridge
Lei S (1999) An analytical solution for steady flow into a tunnel. Ground Water 37:23–26. doi:10.1111/j.1745-6584.1999.tb00953.x
Li Z, Wang K, Wang A, Liu H (2009) Experimental study of water curtain performance for gas storage in an underground cavern. J Rock Mech Geotech Eng 1:89–96. doi:10.3724/SP.J.1235.2009.00089
Liang J, Lindblom U (1994) Analyses of gas storage capacity in unlined rock caverns. Rock Mech Rock Eng 27:115–134
Lombardi G (2002) Private notes
Lu M (2010) Rock engineering problems related to underground hydrocarbon storage. J Rock Mech Geotech Eng 2:289–297. doi:10.3724/SP.J.1235.2010.00289
Midtlien NO (2007) Cavern storage excavation-store. In: Underground constructions for the Norwegian oil and gas industry. Norwegian Tunnelling Society Publication 16, pp 47–56
Muskat M (1937) The flow of homogeneous fluid through porous media. McGraw Hill, New York, pp 175–181
Schleiss AJ (1988) Design of reinforced concrete-lined pressure tunnels. Int Congr Tunn Water Madr 2:1127–1133
Verma KSRK, Vijaya Bhaskar K, Elangovan S (2008) Underground storage—a summary on first Indian cavern for LPG storage. World Tunnel Congress 2008—underground facilities for better environment and safety—India, pp 1024–1036
Wang S, Tokunaga TK (2015) Capillary pressure—saturation relations for supercritical CO_2 and brine in limestone/dolomite sands: implications for geologic carbon sequestration in carbonate reservoirs. Environ Sci Technol 49:7208–7217
Wang Z, Li S, Qiao L (2015) Design and test aspects of a water curtain system for underground oil storage caverns in China. Tunn Undergr Space Technol Inc Trenchless Technol Res 48:20–34. doi:10.1016/j.tust.2015.01.009