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Hydrodynamic Pressure Gradient Correlation of Some Iraqi Oil Wells

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Abstract

Empirical equation has been presented to predict the optimum hydrodynamic pressure gradient with optimum mud flow rate (one equation) of five Iraqi oil wells to obtain the optimum carrying capacity of the drilling fluid (optimum transport cuttings from the hole to the surface through the annulus).

This equation is a function of mud flow rate, mud density and penetration rate without using any charts or graphs.

The correlation coefficient accuracy is more than 0.9999.

Keywords

Correlation, drilling, pressure gradient, mud flow rate, penetration rate and mud density

Introduction

Saleh [1] has taken the actual data from Iraqi oil fields (five wells) in order to determine the optimum flow rate using graphical solution. Four of the wells are production wells (No.1, 2, 3, 4) and the fifth one is observation well (No.5).

The hydrodynamic pressure gradient of the wells can be expressed by Saleh [4] Using the following equation:

$$\frac{Pbh}{D} = \sum_{i=1}^{J} (\frac{\Delta PT}{L})_i \cdot \frac{Li}{D} \qquad ...(1)$$

And:

$$D = \sum_{i=1}^{J} Li \qquad ...(2)$$

Saleh [1] draws five graphs of five wells by using the relation between the hydrodynamic pressure gradient and mud flow rate to choose the optimum mud flow rate. In the previous studies of Iraqi fields, the empirical equations were not used to find the hydrodynamic pressure gradient, but rather the derivation equations only.

In this study, the empirical equation (one equation) has been performed to predict the hydrodynamic pressure gradient of five wells .Then the optimum mud flow rate can be calculated. Tables (1) and (2) show the range of data (only important data were chosen) and the special information of wells used for this study respectively also table (3) shows the data used for this study.All data are from Saleh[1] .

Previous Investigation

Chien [2] expressed the below equation of pressure gradient:

$$\frac{\Delta PT}{D} = 0.052\rho + 0.052\frac{\Pr(\rho c - \rho)}{[1-(Dp/Dh)^2(Vm - Vs)} + \frac{\Delta P}{D} \qquad \ldots(3)$$

Differentiate Equation (1) with respect to Vm, setting the differential from equal to zero, and then solving it for the optimum annular fluid velocity (Vm)opt.Chien[2] used four models such as Bingham, power-law, Casson and Robertson- Stiff to find the optimum fluid velocity.

Most of researchers focused upon the relation of rheological models and optimum annular flow rate.

H.N. Hall and Howard Thompson [3] show the drilled cuttings velocities computed through estimates of cuttings circulation time from bottom. The observed discontinuity in transport at the transition from laminar to turbulent flow was significant.

Sifferman, T,R. el.[4].concluded that the cutting transport efficiency increases as fluid velocity increases. Also, they found that variables such as particle size, drill pipe rotation, drill pipe eccentricity and drilling rate, at most, only moderate effects on carrying capacity in their experiments.

Thomas, R.P. el.[5]. There Experimental results shows that although increasing rotary speed generally improves particle transport, it more pronounced at lower annular fluid velocities and appears to be negligible at high velocities.

Newitt, D.M. Richarrdson,J.F. and Gleddon, B.J. [6] and Toda, M. et al [7].concluded that pressure losses due to solids –wall friction, pressure losses due to solids – solids collision and pressure losses due to solids – fluid friction can be neglected compared to the total pressure drop.

Lummus J. L. [8]. resulted in a better understanding of the effect of drilling variables and their interactions. He defined the optimized drilling as the "mathematical treatment of the most important controllable drilling variables to develop a comprehensive minimum - cost drilling program". The variables involved in rotary drilling are classified as alterable or unalterable and the variables selected for mathematical optimization are herein described. The alterable variables:

1. Fluid properties such as: fluid density's solid content, viscosity, fluid loss and fluid type.
2. Hydraulic fluid system such as: pump pressure, jet velocity, circulating rate and annular velocity
3. Weight on bit.
4. Rotary speed
5. Bit type and bit size.

The unalterable variables (uncontrolled) such as: weather, location, rig conditions, corrosive gas, bottom hole temperature, depth, round trip time formation characteristics, hole problems, water availability and crew efficiency.

Correlation (This Study)

The following general relation of hydrod-dynamic pressure gradient is assumed:

Hydrodynamic Pressure Gradient

$$= f(\rho, \Pr, Qm) \qquad \ldots(4)$$

The chaos of these important parameters is due to their direct effect on hydrodynamic pressure gradient, and these parameters are designed at the beginning of drilling.

Hydrodynamic pressure gradient

$$\propto (\rho, \Pr, 1/Qm) \qquad \ldots(5)$$

Table (3) shows data of sixty nine points used to write the following correlation equation in this study by using statistical program. Non-linear model will be chosen to develop the following equation:

$$\frac{Pbh}{D} = a_1 + a_2*\rho + a_3*Pr + a_4/Qm + a_5*\rho^2 + a_6*Pr^2 + a_7/Qm^2 \quad \ldots(6)$$

Where:

a_1= 1.833331 a_2= - 0.299532

a_3= - 0.063143 a_4= - 0.825984

a_5= 0.020372 a_6= 0.002062

a_7 =187.782992

Statistical Analysis

Naji Tawfik. and Rashid Al – Salihi, [9] and W.H. Aleen, [10].

The relative deviation error in percent from the data:

$$APRE = \frac{1}{N}\sum_{i=1}^{N} Ei \quad \ldots(7)$$

Where: **Ei** is the relative deviation in percent of an estimated value from the compute value:

$$PRE = \left[\frac{Xest - Xcal}{Xcal}\right]\times 100 \quad i = 1,2,\ldots N, \quad \ldots(8)$$

The average absolute percent relative error is given as:

$$AAPRE = \frac{1}{N}\sum_{i=1}^{N} |PRE| \quad \ldots(9)$$

The minimum and maximum values to know the range of error for this correlation are given as:

$$E_{min} = \min_{i=1}^{N} |PRE| \quad \ldots(10)$$

$$E_{max} = \max_{i=1}^{N} |PRE| \quad \ldots(11)$$

Standard deviation (Sx) is the measure of the data dispersion around zero deviation as follows:

$$Sx = \frac{1}{N-1}\sum_{i=1}^{N} PRE^2 \quad \ldots(12)$$

Correlation coefficient (r) is the degree of success in reducing the standard deviation as follows:

$$r^2 = 1 - \left\{ \frac{\sum_{i=1}^{N}\left[(X\,est - X\,cal)_i\right]^2}{\sum_{i=1}^{N}\left[(X\,cal - \overline{X})_i\right]^2} \right\} \quad \ldots(13)$$

Where

$$\overline{X} = \frac{1}{N}\sum_{i=1}^{N} (X\,cal)_i \quad \ldots(14)$$

Results and Discussions

Fig(1) presents the relation between the calculated hydrodynamic pressure gradient Saleh [1] and the estimated hydrodynamic pressure gradient of this study by using Eq(6). Most of the data points are close to the perfect line 45^o (0.79 rad.).

Table (4) shows the comparison of average percent relative error between the Saleh [1] calculations and this study correlation for the hydrodynamic pressure gradient with very small different between them for all data.

The correlation coefficient for this study of Eq (6) presents high value of 0.9999 with the lowest value of standard deviation of 0.9380 as shown in table (5).

Fig (2) shows the histogram distribution of calculated (Saleh [1]) and the correlation value of hydrodynamic pressure gradient. It also shows the behavior similarity of this study and Saleh [1].

Fig(3)presents the average percent relative error (APRE) for this study from ∓ 3%.

It is Possible to use a simple computer program to extract the optimum mud flow rate (optimum Qm) . The program can calculate the hydrodynamic pressure gradient (Eq(6)) by increasing the mud flow rate (Qm) as the input data (suggest data such as 100,150,200,...etc) in the computer program. It is known if mud flow rate is increased, the hydrodynamic pressure gradient decreases. When the hydrodynamic pressure gradient reaches a point which starts to increase or the previous value equal or increase with the present value (with accuracy such as 1E-4), the point that precedes the previous value represents the optimum mud flow rate.

Conclusions

1. Hydrodynamic pressure gradient of five Iraqi drilling wells have been estimated from equation (6). this equation has high correlation coefficient of 0.9999.
2. Equation (6) can be used for all mud flow rate, mud density and penetration rate instead of using many charts.
3. The importance of Equation (6) is to estimate the hydrodynamic pressure gradient by the directly using of the practical field factors.

Nomenclatures

AAPRE = average absolute percent relative error, (%), Eq.(9)

APRE = average percent relative error, (%), Eq. (7)

D = total depth of the well, (ft)

E_{max} = maximum absolute percent relative error, (%), Eq.(11)

E_{min} = minimum absolute percent relative

F = function

J = number of sections along the annulus.

L = length, (ft)

Li = length of the i^{th} section of annulus, (ft)

N = number of variables

Pbh/D = hydrodynamic pressure gradient, (psi/ft)

Pr = penetration rate, (ft/hr)

PRE = percent relative error, (%) Eq.(8)

Qm = mud flow rate, gal/min.

r = correlation coefficient, Eq.(13)

S_X = Standard deviation, Eq. (12)

Vm = average fluid velocity,ft/min.

$(Vm)_{opt}$ = optimum fluid velocity, ft/min.

Vs = particle slip velocity, ft/min.

$\bar{X}$ = average value of x_{exp}, Eq.(14)

X_{cal} = calculated value of X (Pbh/D)

X_{est} = estimated value of X (Pbh/D)

ρ = mud density, (ib/gal).

ρ_c = drilled cutting density, (ib/gal).

ΔPt = total pressure drop, (psi).

Subscripts

cal calculated from Saleh [1]

est estimated from correlation (this study)

max maximum

min minimum

SI Metric Conversion Factors

atm × 1.013 250* E + 05 = Pa

Psi × 6.894 757 E + 00 = kP

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Table 1, Range of data

Depth, ft	1325	to	3027
Mud density , ib/gal	9.66	to	10.41
Penetration rate, ft/hr	6.56	to	24.6
Pbh/D , psi/ft	0.45986	to	0.577299
Qm (suggestion) , gal/min	100	to	2000

Table 2, Selected information of wells. Saleh[1]

	Well NO.				
	1	2	3	4	5
Formation type	Limestone	Anhydrite	Marle &Siltstone	Anhydrite	Limestone
Depth, ft	1896	1407	3027	1906	1325
Mud density , ib/gal	10.41	9.58	10.41	8.75	9.66
Penetration rate, ft/hr	6.56	7.87	24.60	6.56	9.84
Applied mud flow rate, gal/min	385	400	570	460	265

Table 3, Data used for this study (five drilling wells). Saleh[1]

Case No.	Qm, gal/min	Pbh/D, psi/ft	ρ, ib/gal	Pr, ft/hr
1	100.000	0.5553330	10.410	6.560
2	100.000	0.5248800	9.580	7.870
3	100.000	0.5735020	10.410	24.60
4	100.000	0.4853680	8.750	6.560
5	100.000	0.5276230	3.660	9.840
6	150.000	0.5526360	10.410	6.560
7	150.000	0.5138320	9.580	7.870
8	150.000	0.5690950	10.410	24.60
9	150.000	0.4665940	8.750	6.560
10	200.000	0.5513890	10.410	6.560
11	200.000	0.5098780	9.580	7.870
12	200.000	0.5676160	10.410	24.60
13	200.000	0.4633030	8.750	6.560
14	200.000	0.5330560	3.660	9.840
15	250.000	0.5505350	10.410	6.560
16	250.000	0.5078590	9.580	7.870
17	250.000	0.5665440	10.410	24.60
18	250.000	0.4619740	8.750	6.560
19	300.000	0.5500250	10.410	6.560
20	300.000	0.5066380	9.580	7.870
21	300.000	0.5664550	10.410	24.60
22	300.000	0.4612680	8.750	6.560
23	300.000	0.5375840	3.660	9.840
24	400.000	0.5496300	10.410	6.560
25	400.000	0.5052400	9.580	7.870
26	400.000	0.5658740	10.410	24.60
27	400.000	0.4605550	8.750	6.560
28	400.000	0.5469220	3.660	9.840
29	500.000	0.5491470	10.410	6.560
30	500.000	0.5044690	9.580	7.870
31	500.000	0.5660530	10.410	24.60
32	500.000	0.4602170	8.750	6.560
33	500.000	0.5609960	3.660	9.840
34	600.000	0.5491380	10.410	6.560
35	600.000	0.5039850	9.580	7.870
36	600.000	0.5672710	10.410	24.60
37	600.000	0.4600370	8.750	6.560
38	700.000	0.5491150	10.410	6.560
39	700.000	0.5036570	9.580	7.870
40	700.000	0.5687570	10.410	24.60
41	700.000	0.4599380	8.750	6.560
42	800.000	0.5489590	10.410	6.560
43	800.000	0.5034220	9.580	7.870
44	800.000	0.5686420	10.410	24.60
45	800.000	0.4598860	8.750	6.560

Table 3, Data use for this study (five drilling wells) (continue). Saleh[1]				
Case No.	Qm, gal/min	Pbh/D, psi/ft	ρ, ib/gal	Pr, ft/hr
46	900.000	0.5489660	10.410	6.560
47	900.000	0.5032480	9.580	7.870
48	900.000	0.5710700	10.410	24.60
49	900.000	0.4598630	8.750	6.560
50	1000.000	0.5489250	10.410	6.560
51	1000.000	0.5031160	9.580	7.870
52	1000.000	0.5729180	10.410	24.60
53	1000.000	0.4598600	8.750	6.560
54	1250.000	0.5487720	10.410	6.560
55	1250.000	0.5028960	9.580	7.870
56	1250.000	0.5753300	10.410	24.60
57	1250.000	0.4599700	8.750	6.560
58	1500.000	0.5494640	10.410	6.560
59	1500.000	0.5027710	9.580	7.870
60	1500.000	0.5737500	10.410	24.60
61	1500.000	0.4600830	8.750	6.560
62	1750.000	0.5492910	10.410	6.560
63	1750.000	0.5026980	9.580	7.870
64	1750.000	0.5743210	10.410	24.60
65	1750.000	0.4603990	8.750	6.560
66	2000.000	0.5496250	10.410	6.560
67	2000.000	0.5026550	9.580	7.870
68	2000.000	0.5772990	10.410	24.60
69	2000.000	0.4611720	8.750	6.560

Table 4, Hydrodynamic pressure gradient estimated correlation for this study

Case No.	Calculated hydrodynamic pressure gradient(psi/ft), (Saleh,[1])	Estimated hydrodynamic pressure gradient(psi/ft), (this study)	Deviation % Estimated hydrodynamic pressure gradient (APRE)	Pbh/D(estimated) - Pbh/D(calculated) (Psi/ft)
1	0.555333	0.557735	0.432453	0.002402
2	0.524880	0.514002	- 2.072468	- 0.010878
3	0.573502	0.578067	0.796000	0.004565
4	0.485368	0.470196	- 3.125784	- 0.015172
5	0.527623	0.547815	3.826934	0.020192
6	0.552636	0.552088	- 0.099111	- 0.000548
7	0.513832	0.508356	- 1.065765	- 0.005476
8	0.569095	0.572421	0.584402	0.003326
9	0.466594	0.464550	- 0.438031	- 0.002044
10	0.551389	0.550379	- 0.183233	- 0.001010
11	0.509878	0.506646	- 0.633847	- 0.003232
12	0.567616	0.570711	0.545298	0.003095
13	0.463303	0.462841	- 0.099812	- 0.000462
14	0.533056	0.540459	1.388767	0.007403
15	0.550535	0.549709	- 0.149992	- 0.000826
16	0.507859	0.505977	- 0.370630	- 0.001882
17	0.566544	0.570042	0.617386	0.003498
18	0.461974	0.462171	0.042672	0.000197
19	0.550025	0.549411	- 0.111554	- 0.000614
20	0.506638	0.505679	- 0.189306	- 0.000959
21	0.566455	0.569744	0.580620	0.003289
22	0.461268	0.461873	0.131229	0.000605
23	0.537584	0.539492	0.354857	0.001908
24	0.549630	0.549206	- 0.077109	- 0.000424
25	0.505240	0.505474	0.046247	0.000234
26	0.565874	0.569539	0.647619	0.003665
27	0.460555	0.461668	0.241681	0.001113
28	0.546922	0.539286	- 1.396101	- 0.007636
29	0.549147	0.549172	0.004575	0.000025
30	0.504469	0.505440	0.192400	0.000971
31	0.566053	0.569505	0.609774	0.003452
32	0.460217	0.461634	0.307901	0.001417
33	0.560996	0.539252	- 3.875901	- 0.021744
34	0.549138	0.549187	0.008838	0.000049
35	0.503985	0.505454	0.291478	0.001469
36	0.567271	0.569519	0.396293	0.002248
37	0.460037	0.461648	0.350281	0.001611
38	0.549115	0.549215	0.018212	0.000100
39	0.503657	0.505482	0.362445	0.001825
40	0.568757	0.569548	0.138992	0.000791
41	0.459938	0.461677	0.378072	0.001739

Table 4, Hydrodynamic pressure gradient estimated correlation for this study (continue)

Case No.	Calculated hydrodynamic pressure gradient(psi/ft) from Saleh, [1]	Estimated hydrodynamic pressure gradient(psi/ft) (this study	Deviation % Estimated hydrodynamic pressure gradient (APRE)	Pbh/D(estimated) - Pbh/D(calculated) Psi/ft
42	0.548959	0.549246	0.052335	0.000287
43	0.503422	0.505514	0.415512	0.002092
44	0.568642	0.569579	0.164747	0.000937
45	0.459886	0.461708	0.396227	0.001822
46	0.548966	0.549277	0.056567	0.000311
47	0.503248	0.505544	0.456238	0.002296
48	0.571070	0.569609	- 0.255826	- 0.001461
49	0.459863	0.461738	0.407823	0.001875
50	0.548925	0.549304	0.069123	0.000379
51	0.503116	0.505572	0.488140	0.002456
52	0.572918	0.569637	- 0.572690	- 0.003281
53	0.459860	0.461766	0.414544	0.001906
54	0.548772	0.549363	0.107688	0.000591
55	0.502896	0.505630	0.543739	0.002734
56	0.575330	0.569695	- 0.979353	- 0.005635
57	0.459970	0.461825	0.403256	0.001855
58	0.549464	0.549408	- 0.010206	- 0.000056
59	0.502771	0.505675	0.577679	0.002904
60	0.573750	0.569740	- 0.698833	- 0.004010
61	0.460083	0.461870	0.388368	0.001787
62	0.549291	0.549443	0.027662	0.000152
63	0.502698	0.505710	0.599251	0.003012
64	0.574321	0.569775	- 0.791462	- 0.004546
65	0.460399	0.461905	0.327073	0.001506
66	0.549625	0.549471	- 0.028055	- 0.000154
67	0.502655	0.505738	0.613399	0.003083
68	0.577299	0.569803	-1.298404	- 0.007496
69	0.461172	0.461933	0.164949	0.000761

Table 5, Statistical accuracy of the hydrodynamic pressure gradient of this study

Table (5) - Statistical accuracy of the hydrodynamic pressure gradient of this study.	
Average relative error , %	0.0210
Average absolute relative error , %	0.5579
Minimum absolute relative error , %	0.0046
Maximum absolute relative error, %	3.8759
Standard deviation, %	0.9380
Correlation coefficient (r)	0.9999

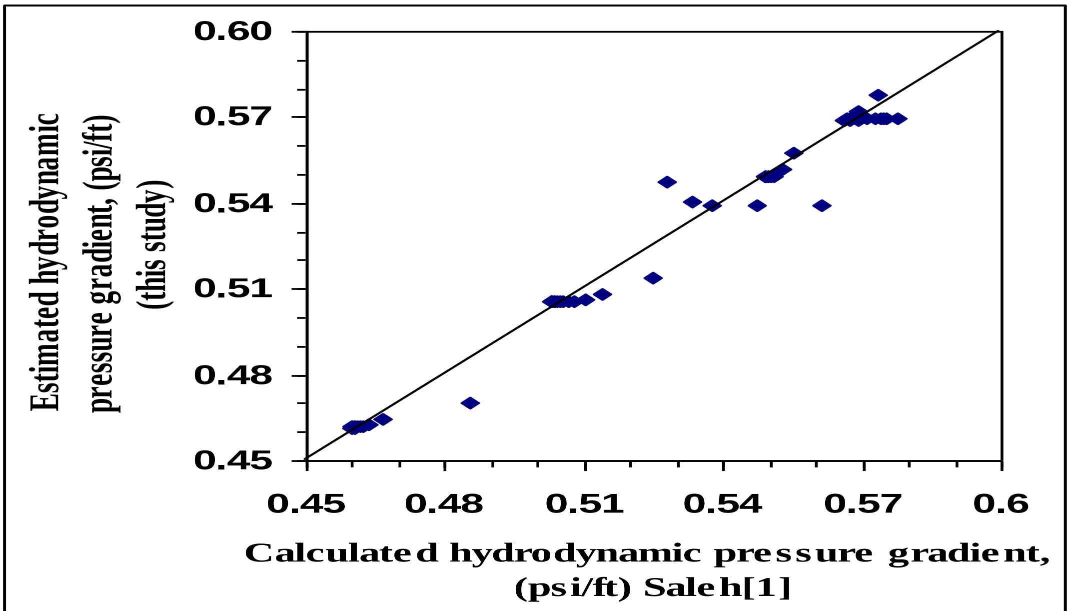

Fig. 1, Cross plot of hydrodynamic pressure gradient, (psi/ft) Saleh[1]

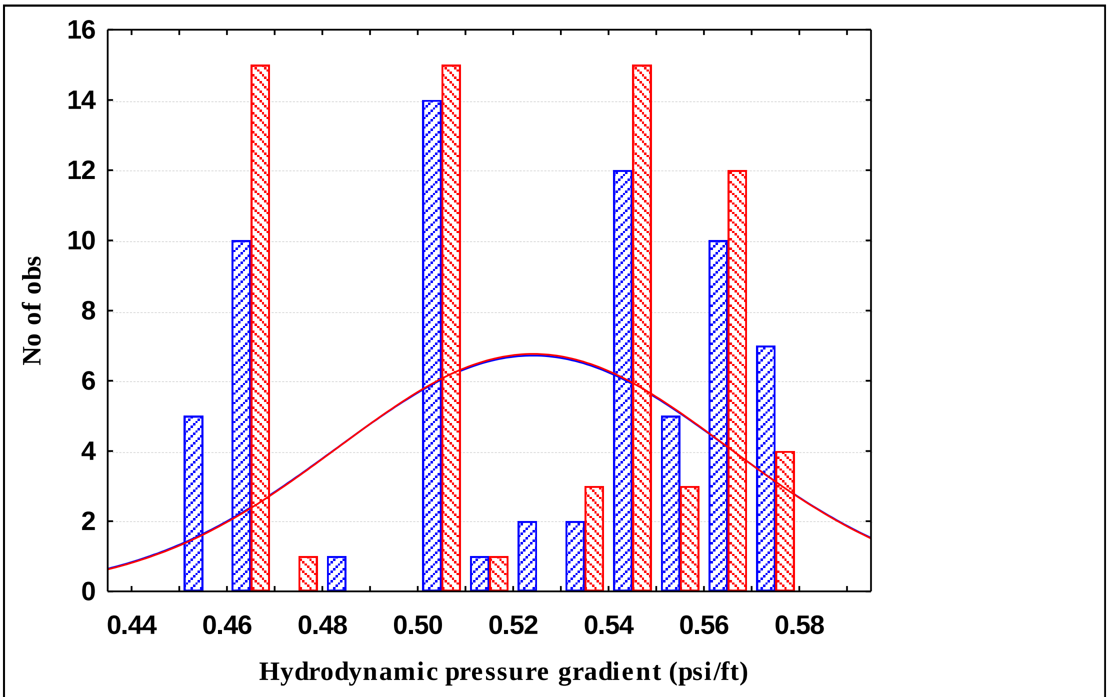

Fig. 2, Histogram distribution of calculated and correlation values of hydrodynamic pressure gradient

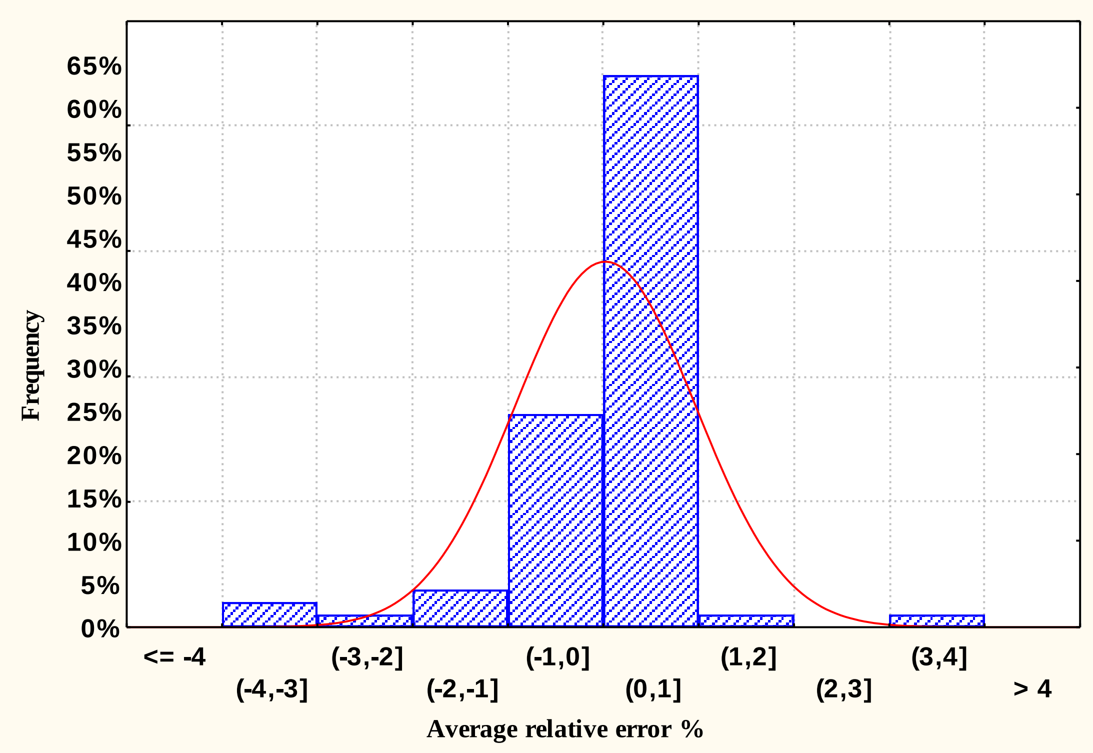

Fig. 3, Error distribution of hydrodynamic pressure gradient correlation (this study)