

STUDY OF THE DEPENDENCE OF SEDIMENTARY ROCKS ON EFFECTIVE STRESS BY THE COMPRESSION CURVE METHOD

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Abstract

The article examines the issues of utilizing well data, geophysical methods, and various measurement techniques for studying abnormally high pore pressure (AHPP) in well-explored structures, while in structures with weakly conducted exploration and prospecting works, more modern approaches such as mathematical calculation (compression curve) methods and computer technologies are applied. For this purpose, we attempted to investigate the method of calculating abnormally high pore pressure (AHPP) through the compression curve. Regardless of the way AHPP is studied, these methods are based on the graphical dependence of the physical properties of clay rocks, their burial depth, and environmental conditions. This dependence follows a certain regularity under normal geological conditions. However, under conditions of abnormally high formation pressure (AHFP), this regularity is disrupted, quantitatively and qualitatively affecting pore pressure in rocks. Although normal and abnormal pore pressures of deeply buried clay rocks can be determined from well data and geophysical methods, in areas with poorly developed exploration works, the compression curve method possessing universal characteristics is more appropriate for determining this parameter. This method not only allows analytical calculation of the parameter but also makes it possible to process its results using electronic computing technologies. In studying the compaction of clay rocks, it has been established that in clays with simple mineralogical composition but varying physical properties, the difference in pressures between the fluids within them follows an exponential dependence, extending in a straight-line direction when plotted on a logarithmic scale. In general, in practice, the exponential dependence of porosity, permeability, and specific electrical resistivity of compacted clay rocks on their burial depth is widely recognized. Deviations from the straight-line trend may result from the high degree of mineralization of the water content in clays, or from the increase in temperature with depth. These phenomena usually occur starting from depths of 800–1000 m. If the increase in temperature with depth is uneven, then the compression curve of this dependence can be constructed by selecting points with equal temperatures or by adjusting the values to equivalent temperature points.

Key words: compression curve, abnormally high pore pressure, specific electrical resistivity, clay rocks, fluids, hydrocarbons, volumetric filtration properties, prospective structures.

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Introduction:

It is known that areas with complex geological structures differ from one another by their specific characteristics. One of these features, abnormally high formation pressure (AHFP), in some cases creates problems and difficulties in exploration and prospecting works, as well as complications in drilling operations.

At present, in many oil and gas-bearing basins, including the South Caspian Basin (SCB), hydrocarbon exploration and prospecting are carried out at depths exceeding 4000 meters. Drilling operations conducted at such depths in offshore areas, in addition to unfavorable relief, also encounter numerous geological difficulties such as high formation pressure, high clay content, and other complications resulting in significant additional costs.

Abnormally high pore pressure (AHPP) in well-studied structures can be determined from well data, geophysical methods, and measurement works, while in structures with poorly conducted exploration and prospecting, it can also be identified through more modern approaches such as mathematical calculation (compression curve) methods and computer technologies. For this purpose, we attempt to study the method of calculating abnormally high pore pressure (AHPP) through the compression curve.

The compression curve method is based on the relationship between the difference in pressures exerted on clay layers by overlying strata (lithostatic pressure, σ) and the difference in saturation pressures of fluids within these clay layers.

Regardless of the method by which abnormally high pore pressure (AHPP) is studied, these approaches rely on the graphical dependence of the physical properties of clay rocks on their burial depth and conditions. Under normal geological settings, such dependence follows a certain regularity. However, under conditions of abnormally high formation pressure (AHFP), this regularity is disrupted, quantitatively and qualitatively influencing pore pressure in rocks.

Although normal and abnormal pore pressures of deeply buried clay rocks can be determined by well data and geophysical methods, in areas with poorly developed exploration works, the compression curve method-with its universal applicability-is more suitable for determining this parameter. This method not only enables the analytical calculation of the parameter but also allows processing of its results using electronic computing technologies.

In studying the compaction of clay rocks, it has been established that in clay rocks with simple mineralogical composition and varying physical properties, the difference in fluid pressures within them follows an exponential dependence, which extends linearly when plotted on a logarithmic scale.

In general, in practice, the exponential dependence of porosity, permeability, and specific electrical resistivity of compacted clay rocks on their burial depth is widely recognized. Deviations from the linear trend may occur due to the high degree of mineralization of water within clay rocks or as a result of increasing temperature with depth. These phenomena usually begin to manifest at depths of 800–1000 m in clay rocks.

Calculation of Abnormally High Pore Pressure in Clay Rocks by the Compression Curve Method

If the temperature increase with depth is uneven, then the compression curve of this dependence can be constructed by selecting points with the same temperature or by reducing their values to equivalent temperature points.

For this purpose, let us consider the following calculation method. Suppose that the quantity x at three points possesses the same property and lies along a straight-line trend. Let us assume that these parameters are equal to the value of temperature at point 1. The pore pressures of fluids at points 1 and 2 are equal to p . Let us determine the pressure at point 3 (p^3). To do so, we first take into account the coordinates of these points.

For point 1	$1 - [\lg x_1; (\sigma_1 - p_1)]$
For point 2	$2 - \left\{ \left[\lg x_2 \pm \frac{\alpha(x) \Gamma(h_2 - h_1)}{2,3} \right]; (\sigma_2 - p_2) \right\}$
For point 3	$3 - \left\{ \left[\lg x_2 \pm \frac{\alpha(x) \Gamma(h - h_1)}{2,3} \right]; (\sigma - p_a) \right\} [11]$

$\alpha(x)$ – the temperature coefficient of the physical quantity x ;
 Γ – the average value of the geothermal gradient within the interval h_1-h_2 ;
 H, h_1, h_2 – the depths of points 3, 1, and 2;
 $\sigma, \sigma_1, \sigma_2$ – the average normal stress at the depths h, h_1 , and h_2 .

Then, the straight-line equation passing through points 1 and 2 should be as follows:

$$\frac{\lg x \pm \frac{\alpha(x)\Gamma(p-p_1)-\lg x_1}{2,3}}{\lg x \pm \frac{\alpha(x)\Gamma(h_2-h_1)-\lg x_1}{2,3}} = \frac{(\sigma-p_a)-(\sigma_1-p_1)}{(\sigma_2-p_2)-(\sigma_1-p_1)} \quad (1)$$

Taking the slope coefficient into account, this equation can be reduced to a more convenient form:

$$p_a = \sigma - \frac{\lg x \pm \frac{\alpha(x)\Gamma(h_2-h_1)-\lg x_1}{2,3} b(x)}{k(x)} \quad (2)$$

To calculate the other parameters, this linear equation can be transformed into the following form:

$$b(x) = \frac{\lg x_1(\sigma_2 - p_2)}{(\sigma_2 - p_2) - (\sigma_1 - p_1)} - \frac{\lg x \pm \frac{\alpha(x)\Gamma(h_2 - h_1)}{2,3} (\sigma_2 - \sigma_1)}{(\sigma_2 - p_2) - (\sigma_1 - p_1)}$$

$$k(x) = \lg \frac{x_2}{x_1} \pm \frac{\frac{\alpha(x)\Gamma(h_2 - h_1)}{2,3}}{(\sigma_2 - p_2) - (\sigma_1 - p_1)}$$

Thus, in order to determine abnormally high pore pressure in clay rocks using the compression curve method, it is essential to calculate the quantities $b(x)$ and $k(x)$, taking into account their regional conditions [6]. For regions with relatively simple geological structures, these coefficients can be calculated using equation (3). They can also be estimated through geophysical diagrams and the curve showing the variation of clay rock densities with depth. However, in regions with complex geological structures, it is more appropriate to determine these coefficients through geophysical methods and, in most cases, by directly measuring the formation pressures (abnormal and normal) of horizons predominantly composed of clay rocks.

A number of measurements have confirmed that, in collectors within clay rocks, the formation pressure is generally equal to the pore pressure.

It is known that, in several hydrocarbon (HC) fields located in the Baku Archipelago zone, the formation pressures in collectors are lower than the pressures in clay layers at the same depth. The results of pore pressure measurements conducted in wells drilled in most of the producing fields of the Baku Archipelago show that their values deviate by $\pm 5-6\%$ from the values calculated by the compression curve method.

A comparison of results obtained from direct depth manometer measurements of abnormally high pore pressure with those measured through the compression curve shows that the application of this method in practice would be appropriate in poorly studied exploration areas. This, in turn, could help prevent complications related to pore pressure during drilling operations.

It should be noted that if the parameters are determined only in individual wells and in a limited number, the error of pore pressure values obtained by this method in regions with complex geological structures will be high [3]. Therefore, by utilizing statistical data from well-studied neighboring structures with the same geological structure, it is possible to estimate the mentioned parameter for prospective structures. If the practical measurement values are calculated through the method described above, the difference and error between them can be clarified (as presented in Table 1) [1].

It is known that, in the compression curve equation, the slope coefficient Kx is related to the compaction intensity of sedimentary rock densities Vx , which in turn represents the free terms of the equation described in this dependence, and its value is determined when the effective stress is equal to zero. These coefficients, namely Kx and Vx , vary depending on whether the wells are located in the

crest or in the flanks of the structure. These parameters can be used to identify the gas–water contact and the locations of tectonic faults.

To predict the geometric dimensions of the water-saturation zone, it is first necessary to thoroughly study geophysical, drilling, and core materials.

According to observations carried out in the VII horizon of the aforementioned field, during the production period, the volumetric filtration properties (VFP) of clays in the crest of the structure increased from 1.4–1.5 to 1.8–2.0 in the flanks as depth increased. A second piece of evidence proving the variation of rock densities is the change in mechanical drilling rate in wells drilled in the crest of the structure.

Table 1.

No	Deposit	Well No	Horizon and measurement interval	Interval, measured for- mation pres-	Interval, res- ervoir pres- sure (atmos-	K(x)	B(x)	Reservoir pressure measured by	ϕ , - difference
1	San-gachal sea	600	VII3500	30,4/0,08	33,44	0,00	-0,44		
2		600	VII4000	33,2/0,08	36,52	0,00	-0,40		
3		610	VII4000	33,7/0,08	37,07	0,00	-0,42		
4		453	VII3500	31,3/0,08	34,43	0,00	-0,43		
5		453	VII3800	33,98/0,0	37,38	0,00	-0,46		
6	Duvanni sea	273	V 3535	35,7/0,10	42,12	0,00	-0,49		
7		273	V 3570	35,9/0,10	43,08	0,00	-0,36		
8		273	V 3520	35,4/0,10	42,48	0,00	-0,61		
9		301	V 3383	31,0/0,09	38,75	0,00	-0,68		
10		33	V 3943	44,2/0,11	48,62	0,00	-0,71		
11		341	V 3830	33,4/0,09	40,08	0,00	-0,33		
12		89	VII396	35,0/0,08	42,00	0,00	-0,56		
13		89	VII 3980	35,2/0,08	44,00	0,00	-0,62		
14		89	VII 3972	35,0/0,08	42,0	0,00	-0,45		
15		89	VII3995	34,4/0,09	39,65	0,00	-0,53		
16		89	VII4000	35,7/0,08	39,27	0,00	-0,39		
17		89	VII4055	35,9/0,08	39,49	0,00	-0,45		
18		97	VII4658	38,8/0,08	46,56	0,00	-0,64		
19		87	VII4251	37,0/0,08	46,25	0,00	-0,69		
20		87	VII4280	37,1/0,08	44,521	0,00	-0,7		
21		87	VII 4302	37,3/0,08	41,03	0,00	-0,71		
22		87	VII 4301	37,5/0,08	42,19	0,00	-0,53		
23		87	VII4350	37,6/0,08	42,49	0,00	-0,66		
24	Rilla sea	14	V3100	43,1/0,13	48,27	0,00	-0,37		
25		21	V3000	36,0/0,12	40,43	0,00	-0,41		
26		9	V 4400	26,6/0,06	37,24	0,00	-0,58		
27		23	V 4400	28,0/0,06	36,4	0,00	-0,55		
28		25	VH 5730	71,1/0,12	78,14	0,01	-0,80		
29		31	VII 5654	74,0/0,13	80,66	0,01	-0,78		

The dependence of rock compaction on effective stress is determined by the compression curve. In the compression curve equation, Kx is the slope coefficient of the curve and depends on compaction intensity, while Bx is a free parameter and depends on effective stress (graphical example from Fentl).

The values of Kx and Bx may vary depending on whether wells are located in the crest or the flanks of structures. These parameters can be used to identify the boundaries of gas–water contacts and faults.

In large-amplitude structures, it is possible to predict the water-saturation zone, the height, and the configuration of the structure before drilling operations, based on the specific features of the structure itself.

Assessment of Oil–Water Contact Displacement in Large-Reserve Fields and Determination of Its Position Across a Wide Area

It is known that the limitation of geological data obtained from oil and gas fields, the diversity of field types, and the incompleteness of theoretical foundations reduce the efficiency of their development. Therefore, the study of oil and gas fields, the investigation of factors affecting their natural characteristics, and, on this basis, the modeling of the natural properties of the reservoir and the reservoir regime are of great importance. These factors are as follows:

1. The occurrence conditions of oil and gas fields at great depths;
2. The phase state of hydrocarbons in reservoirs;
3. The properties of oil under reservoir conditions;
4. The dependence on the mentioned factors and the investigation of this relationship;
5. The intrusion of shale interlayers into producing reservoir-collectors, the displacement of formation waters, and the provision of reliable forecasts in this regard, etc.

Another natural characteristic of reservoirs occurring at great depths is the determination of the geometric dimensions of the water-saturated area in the distribution of external waters accumulated in shale interlayers and, in some cases, entering reservoir-collectors from more permeable layers [3].

Experience shows that during the development of oil and gas fields (when reservoir pressure decreases in the exploitation period), in local zones far from the oil-bearing contour, more precisely in the arch and near-arch areas of the field, significant water-saturated zones can be encountered. A number of researchers note that the reasons for the inflow of these waters into the production object are through shale layers acting as screens and/or shale interlayers present in the oil-bearing objects. During the natural development of reservoirs, the intensive decrease of reservoir pressure is most often observed in the arch part of the field. However, in the flanks of these fields and near the oil–water contact lines, the decrease in reservoir pressure has been relatively smaller. When the field begins to be developed, usually the exploitation starts with wells drilled into the arch part of the reservoir, which strongly influences the intensification of water inflow from the shale interlayers located in and around the arch of the field.

In addition to direct methods of determining the distribution area of water encroachment in hydrocarbon reservoirs, the following indirect methods can also be used:

a) To determine the geometric dimensions of the water-encroached zone and to make forecasts in this regard, the study of well logging data, shales in drilling, and core samples is of primary importance.

Studies carried out on the above-mentioned fields show that in the VII horizon, considered more productive in these reservoirs, the specific electrical resistivity of shales increases from 1.4–1.5 in the arch part of the structure to 1.8–2.0 in the flank parts.

One of the factors confirming the change in rock density is that the drilling rate in wells drilled in the arch part of the reservoir is higher compared to the drilling rate in wells drilled in the flanks. For example, in the Bulla-Deniz field, the mechanical drilling rate in the arch part of the reservoir is approximately 1–3 m/hour, whereas in the wells drilled on the flanks of the structure this indicator is 0.6–1.0 m/hour [4].

For the prediction of water-encroached zones in large-scale structures before drilling, it is of great importance to study the proportionality between the configuration of the reservoir and its height, together with the properties of hydrocarbons, as well as to identify heterogeneity along the reservoir section.

In the absence of internal contour wells, the study and industrial assessment of oil and gas reservoirs requires the determination of the spatial position of the oil–water (gas–water) contact.

The displacement of the oil–water contact at different hydrodynamic depths in the various flanks of the structure, that is, the displacement of the reservoir in structural plan to some degree, has been observed in many fields of the world. The asymmetric position of reservoirs has long been known in Absheron [6].

To determine the spatial positions of oil–water and gas–water contacts, the existence of wells drilled in various parts of the reservoir inside the contour, in the transition zone, and outside the contour is essential. At the initial stage of exploration, such wells may often be absent. Moreover, under complex geological conditions, especially in offshore fields and particularly in the deep parts of the sea, drilling such wells beyond the contour creates numerous difficulties [2].

The preservation of the structure of an oil reservoir in accordance with its form is possible only under a balance of influencing factors. In practice, in many cases, the structure of the oil reservoir shifts toward one of its flanks (or down-dip), i.e., remains in a suspended state. In practice, studies conducted in productive layer reservoirs show that such reservoirs are usually observed in the flanks (down-dip) of the structure where formation waters of different densities are present [5].

It is known that in the flank where the density of formation water is relatively lower, the level of the water column is higher compared to the opposite flank, and as a result, the additional (excess) pressure generated is balanced (compensated) by the pressure of the liquid column formed by the joint presence of oil and water in the other flank with higher-density formation water. Consequently, the reservoir takes a suspended position toward this flank.

This condition can be explained in the graph as follows: if the reservoir pressure at point A1 in the flank with relatively lower formation water density consists of the sum of the pressures created by the water columns at heights RA, hv, and ΔhA, then the pressure RV at point V1 is equal to the sum of the pressures created by the water column at height ΔhV with relatively higher density and the oil column at height hV (Fig. 2) [3].

Under the condition RA = RV, the following equation is obtained:

$$\frac{gh\gamma_1 + g\Delta\gamma_H}{10} = \frac{gh_b\gamma_b + g\Delta h_b\Delta\gamma_H}{10} \quad (1)$$

Here, g is the acceleration due to gravity; γ_1, γ_2 are the water densities in different flanks of the structure (g/cm^3); γ_H is the oil density under reservoir conditions (g/cm^3); hV is the height or vertical distance from the oil–water contact in the subsided flank of the reservoir to the closing isohypse (the difference between the structure’s amplitude and the reservoir height), in meters.

From this, the displacement of the reservoir (vertical distances along the flanks) due to the variation in formation water densities is expressed as follows:

$$\Delta h = h_b \frac{\gamma_2 - \gamma_1}{\lambda_1 - \gamma_H} \quad (2)$$

Thus, if under static conditions the pressures at all points of the AV horizontal section are equal to each other, then this situation will be valid at points S and D taken on the horizontal plane:

$$P_A - \gamma_1 h_b \neq P_B - \gamma_2 h_B \quad (3)$$

Since $\gamma_1 < \gamma_2$, the reduced pressure at point C ($PC = PB - \gamma_2 h_B$) will be higher than the pressure at point D ($PD = PB - \gamma_2 h_B$), i.e., the reservoir will always shift toward the flank with higher-density formation water (3).

Thus, the main factor causing reservoir displacement is the unequal distribution of formation waters with different densities within the structural boundary (the presence of formation waters with varying densities in different flanks and depressions), which generates a hydrodynamic gradient. This gradient can be used to estimate the approximate magnitude of reservoir displacement and, more precisely, to determine its direction, which in turn allows for more effective exploration, especially at the early stage, by preventing the drilling of non-productive wells.

In the absence of out-of-contour wells (i.e., when wells exist only within the oil- and gas-bearing part of the reservoir), a method is proposed for determining the spatial position of oil–water contacts. This method is based on the correlation established for the first time in the South Caspian Basin between pore pressures in clays and reservoir pressures in collectors.

Conclusion:

The methodological proposals presented above form the fundamental principles for predicting and modeling the unusual natural characteristics of oil reservoirs within the Productive Series, which in turn makes it possible to increase the efficiency of exploration and development operations. The proposed methods allow for the prediction of hydrocarbon (HC) properties, the geometrization of waters migrating from clay caps and interlayers into producing reservoirs, and the assessment of oil–water (gas–oil–water) contacts as well as the directions of reservoir displacement. In practice, these approaches have mainly been applied to the prediction of oil and gas occurrence and the efficient recovery of hydrocarbons at great depths.

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