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An Improved Differential Strain Analysis Method for Super Deep Wells

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Abstract: The deeper a reservoir is, the smaller diameter the drilled full diameter cores have. It is difficult to conduct in-situ stress experiments with conventional methods if the diameter of the full diameter cores is less than 6.0 cm, especially for cores abundant in natural fractures. In this paper, based on conventional Differential Strain Analysis (DSA) methods and wave velocity anisotropy methods, we developed an improved Differential Strain Analysis (DSA) method that is specially designed for small full diameter cores. The improved method, combined with the paleomagnetic core reorientation tests, can predict magnitude and orientation of in-situ stress. Results from the improved method are very close to those obtained from conventional Differential Strain Analysis. The improved method was applied to carbonate cores in Tahe Oilfield, which has a depth up to 6000 meters and has cores with a diameter from 5.5cm to 6.0 cm. The experimental results with the improved method show good consistence with the field-monitored ones, which shows that the improved method is reliable and practical.

Keywords: In-situ stress, laboratory test, wave velocity anisotropy, improved DSA method, super deep reservoir.

1. INTRODUCTION

Many in-situ stress testing technologies have been developed with the development of rock mechanics [1], but strictly speaking, there is not a direct testing method. Laboratory experiment is the main approach to predicate orientation and magnitude of in-situ stress. As known to all, the testing samples are cores in the laboratory, so cores' size and physical properties are important to the laboratory experiments.

For non-directional cores, it is necessary to conduct paleomagnetic core reorientation experiment [2], but the final results should be confirmed by integrating with wave velocity anisotropy experiments, differential strain analysis experiments or kaiser effect of acoustic emission experiments.

There are two main laboratory experiments on magnitude of in-situ principal stress, as follows:

(1) Kaiser effect of acoustic emission test. Acoustic emissions (AE) are transient elastic waves created by sudden changes of inner stress state in the solid under a mechanical load [3, 4]. It is important to determine the Kaiser point accurately, but for many cores, the Kaiser point may be ambiguous and is hard to determine with AE tests. At present, there is no effective method [5] for this challenge. Cores may be subject to multiple geologic processes after rock formation generation. There are different views on whether cores memorize the in-situ maximum stress only at geologic period or in-situ stress at different periods.

(2) Conventional Differential Strain Analysis (DSA) method. The magnitude and the orientation of in-situ principal stress can be predicated by Differential Strain Analysis experiments. The theory of Differential Strain Analysis (DSA) is rigorous and already proven [6, 7], but more than six foil strain gages are needed in experiments, and all gages must have conformability. Due to the experimental difficulty, high workload, and low experimental efficiency, conventional Differential Strain Analysis (DSA) experiment has been restricted in application at times [8].

The main objective of this study is to introduce an improved Differential Strain Analysis (DSA) for deep or super deep wells. This method is designed for cylindrical cores whose diameter is between 5.0cm and 7.0cm, and height is 6.0cm. Combined with paleomagnetic core reorientation method and wave velocity anisotropy method, the improved method can predict the orientation and magnitude of in-situ principal stress. We compared the results predicted by the improved Differential Strain Analysis (DSA) with the ones predicted by the conventional Differential Strain Analysis (DSA) and compared the experimental results from the improved method and field monitored results. The comparison shows that the improved Differential Strain Analysis (DSA) method is reliable and practical.

2. EXPERIMENTAL PROGRAM

2.1. Experimental Philosophy

The full diameter cores that were drilled from deep or super deep reservoir have small diameter between 5.0 cm to 6.0 cm, while the diameter of general full diameter cores is between 9.5cm to 11.0cm. If Kaiser effect of acoustic emission test is used, at least 4 standard cores (diameter is 2.5cm, length is 5.0cm) must be drilled from the same full

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Once the initial direction of full diameter cores before drilling in actual reservoirs was obtained, the actual orientation of in-situ horizontal principal stress can be determined with two experiments together.

After paleomagnetic core reorientation tests and wave velocity anisotropy tests for rock distribution characteristics were done, the orientation of in-situ maximum horizontal principal stress in Tahe Oilfield is found among NE 45° and NE 94°. The details are shown in Table **4**.

Table 4. Results of In-situ Stress Orientation of the Carbonate Reservoir in Tahe Oilfield

Well NO.	Depth of Cores(m)	θ (NE, °)
TPX1	6548.87-6549.03	91.7
TPX2	6492.09-6492.2	50.6
TPX3	6844.39-6844.54	65.4
TPX4	6362.99-6363.14	60.5
TPX5	6158.44-6158.55	81.1
TPX6	6274.38-6275.53	78.2
TPX7	6828.73-6828.9	80.1
TPX8	7005.99-7006.22	72.2
TPX9	6211.21-6211.42	65.0

3.2. Magnitude of In-situ Principal Stress

When cores were drilled from reservoir, the degree of unloading is different in different directions because three-dimensional principal in-situ stresses are different from each other. The micro-fracture strain relative to degree of unloading are formed when in-situ stress is released. When a constant confining pressure is preloaded, strain recovery is different in the three directions of three principal in-situ stress, so the direction of maximum strain represents the orientation of in-situ maximum stress before the core was drilled from the reservoir.

Three strain curves of principal in-situ stress were obtained by improved Differential Strain Analysis (DSA) tests in the paper. Some strain curves of TPX1 well to TPX6 well are shown in Fig. (**5**). Vertical in-situ stress was calculated from density logging according to equation (1). The maximum and minimum of horizontal in-situ stress of the carbonate reservoir in Tahe Oilfield are shown in Table **5**.

$$\begin{aligned}\sigma_v:\sigma_H:\sigma_h &= [\mu(\varepsilon_H+\varepsilon_h)+(1-\mu)\varepsilon_v] \\ &:[\mu(\varepsilon_v+\varepsilon_h)+(1-\mu)\varepsilon_H] \\ &:[\mu(\varepsilon_v+\varepsilon_H)+(1-\mu)\varepsilon_h]\end{aligned} \quad (1)$$

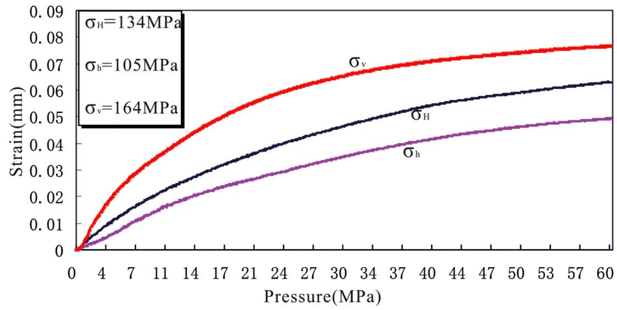
4. COMPARISON BETWEEN EXPERIMENTAL RESULTS AND FIELD MONITORED RESULTS

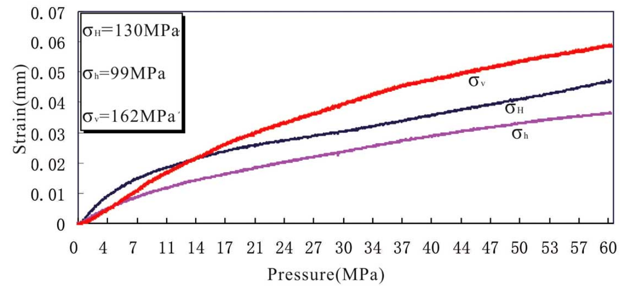
4.1. Comparison of Orientation

The orientation of the acid fracture in Tahe Oilfield was monitored by micro-seismic. Accordingly, the orientation of in-situ maximum horizontal principal stress can be obtained from the monitoring results. Due to natural fractures and faults, monitored orientation is distributed in a wide range, with 71% among NE 45° and NE 90°. The monitored results show that there are 15 wells with the acid fracture orientation among NE 0° and NE 45°, 70 wells with the orientation among NE 45° and NE 90°, and 13 wells with the orientation among NE 90° and NE 180°. Most monitored orientations are distributed among NE 45°and NE 90°. Most results from experiments are among NE 45° and NE 90° as well. Orientations of in-situ maximum horizontal principal stress by experiments fundamentally match the field monitored results.

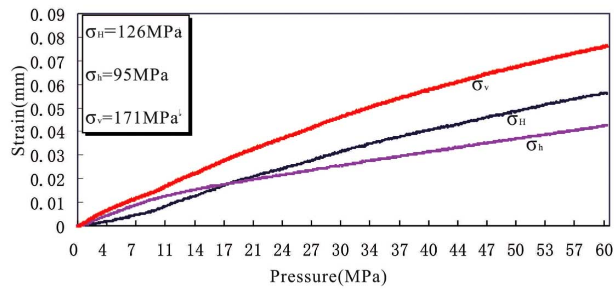
Table 5. Stress of the Carbonate Reservoir in Tahe Oilfield by The Improved DSA

Well NO.	Depth of cores(m)	σ_v		σ_H		σ_h		σ_h^{com} (MPa)	Error(%)
		Magnitude(MPa)	Stress gradient (MPa/m)	Magnitude(MPa)	Stress gradient (MPa/m)	Magnitude(MPa)	Stress gradient (MPa/m)		
TPX1	6548.87-6549.03	164.0	0.025	134.0	0.0205	105.0	0.0160	103.45	1.5
TPX2	6492.09-6492.2	162.0	0.025	130.0	0.020	99.0	0.0153	97.1	2.0
TPX3	6844.39-6844.54	171.0	0.025	126.0	0.0184	95.0	0.0139	95.49	0.5
TPX4	6362.99-6363.14	159.0	0.025	133.0	0.0209	100.0	0.0157	98.65	1.4
TPX5	6158.44-6158.55	157.0	0.025	129.0	0.0209	97.0	0.0158	98.6	1.6
TPX6	6274.38-6275.53	154.0	0.025	126.0	0.0201	91.0	0.0145	92.08	1.2
TPX7	6828.73-6828.9	170.0	0.025	142.0	0.0208	97.0	0.0142	102.6	5.5
TPX8	7005.99-7006.22	175.0	0.025	141.0	0.0201	115.0	0.0164	108.3	3.0
TPX9	6211.21-6211.42	155.0	0.025	129.0	0.0208	94.0	0.0151	95.6	1.7
Average stress gradient			0.025	/	0.0203	/	0.0152	/	/





a. TPX1 well ***b. TPX2 well***



c. TPX3 well ***d. TPX4 well***

e. TPX5 well ***f. TPX6 well***

Fig. (5). Strain curves of three principal stress of TPX1 well to TPX6 well.

4.2. Comparison of Magnitude of In-situ Minimum Horizontal Principal Stress

In-situ minimum horizontal stress can be obtained from fracturing, which is a direct method. The magnitude of in-situ minimum horizontal stress with this method is the most accurate, so this method is widely applied. According to the acid fracturing operation curve, a pressure decline curve at the well head can be obtained when stopping the pump more than half an hour during the process of acid fracturing. In-situ minimum horizontal principal stress can be predicated by the pressure decline curve and the depth of the reservoir. The acid fracturing operation curve of TPX3 is shown in Fig. (**6**). The depth of the reservoir is between 6784.04m and 6881.0m. Accordingly, the magnitude of minimum horizontal principal stress is about 95.49 MPa, while the magnitude of minimum horizontal principal stress is 95.13MPa at the depth of 6844.39 m to 6844.54 m by laboratory tests. The very small difference of stress predicted by the two methods shows that the improved DSA method is reliable and practical.

All the minimum horizontal principal stress obtained from acid fracturing operation curves are shown in Table **5**. A good match between experimental results and field monitored results show that the improved Differential Strain Analysis (DSA) method is reliable and practical.

5. CONCLUSIONS

In this paper, we designed an improved differential stain analysis for in-situ stress measurement for small full diameter cores from deep or super deep wells. With the improved method, we combine wave velocity anisotropy method and palaeomagnetic core reorientation method to

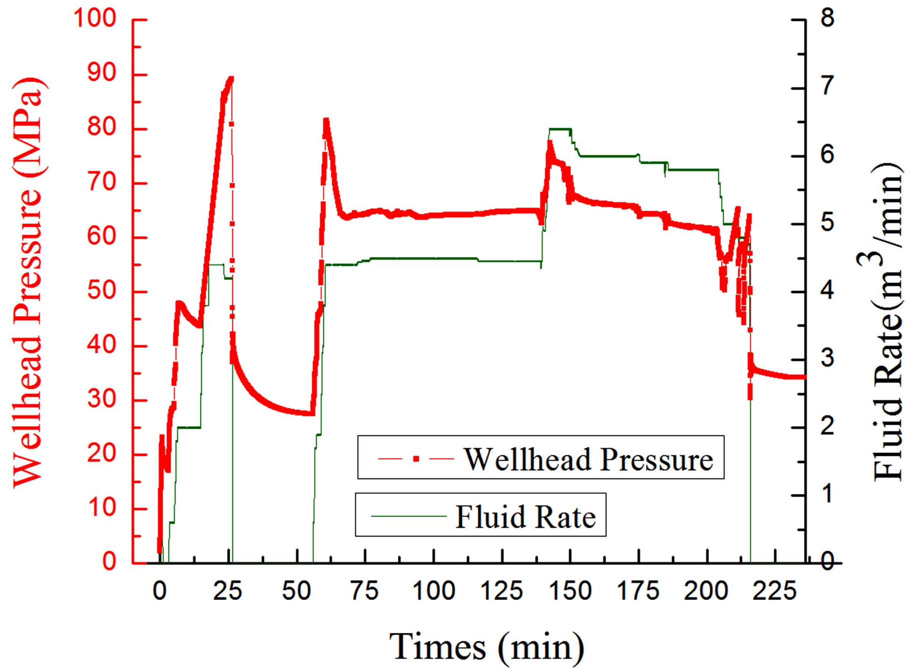


Fig. (6). Acid fracturing operation curve on TPX3 well in the carbonate reservoir.

develop a suit of improved experimental program on in-situ stress measurement with small diameter cylindrical cores.

Using the improved experimental program, we measured magnitude and orientation of in-situ stress of the carbonate reservoir in Tahe Oilfield. The results show that the orientation of maximum horizontal principle stress mainly distributes among NE 45°-90°, the gradient of vertical principle stress is 0.025 MPa/m, the gradient of horizontal maximum principle stress is 0.020 3MPa/m, and the gradient of minimum horizontal principle stress is 0.015 2MPa/m.

The good match between experimental results and field-monitored results shows that the improved experimental program is reliable and practical.

LIST OF SYMBOLS

σ_v = In-situ vertical principal stress, Pa

σ_H = In-situ horizontal maximum principal stress, Pa

σ_h = In-situ horizontal minimum principal stress, Pa

ε_v = Principal strain of vertical direction, dimensionless

ε_H = Principal strain of horizontal maximum principal stress direction, dimensionless

ε_h = Principal strain of horizontal minimum principal stress direction, dimensionless

μ = Poisson's ratio of rock, dimensionless

σ_h^{com} = In-situ horizontal minimum principal stress computed from acid fracture operation curve, Pa

θ = Orientation of maximum horizontal principal in-situ stress,°

CONFLICT OF INTEREST

The authors confirm that this article content has no conflicts of interest.

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