油井压裂过程中 岩石破裂压力计算公式的理论研究

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摘要　根据多孔介质的双重有效应力概念,研究了油井压裂过程中岩石破裂压力的计算问题,提出了一个新的综合计算公式。该公式参数取不同的数值,可预测不同类型岩石的破裂压力。应用新公式还分析了现有公式的应用范围,指出:H－W公式只能计算非渗透岩石的破裂压力,因而给出了破裂压力的上限值;H－F公式只能计算高渗透岩石的破裂压力,因而给出了破裂压力的下限值。新公式可预测任何渗透状况岩石的破裂压力,它包括了早期提出的2个计算公式,并把渗透性岩石和非渗透性岩石完全统一起来。

主题词　油井　压裂　岩石　破裂压力　计算方法　理论　研究

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在油井压裂设计过程中,根据有关理论公式事先预测岩石破裂压力,对成功进行压裂作业有很大帮助。影响岩石破裂压力的因素很多,井筒周围的地应力及其分布、地层岩石的性质是其主要影响因素。破裂压力的理论计算公式必须充分反映这些因素。本文以形成垂直裂缝的情形为例,首先对现用破裂压力计算公式存在的问题进行了分析,然后给出了一个新的通用理论计算公式。

一、现用公式介绍

目前压裂设计过程中广泛使用的破裂压力计算公式有2个[1-2]。

1. Hubbert－Willis(H－W)公式

$$p_b = 3\sigma_h - \sigma_H + \sigma_t - p_o \quad (1)$$

该式适用于非渗透性岩石。

2. Haimson－Fairhurst(H－F)公式[3]

$$p_b = \frac{3\sigma_h - \sigma_H + \sigma_t - 2\eta p_o}{2(1-\eta)} \quad (2)$$

该式适用于渗透性岩石。式中η取值范围为$0\leqslant\eta\leqslant 0.5$。当$\eta\to 0$时,岩石即趋向于非渗透性岩石,此时,(2)式变成

$$p_b = \frac{1}{2}(3\sigma_h - \sigma_H + \sigma_t) \quad (3)$$

由此可见,当地层由渗透性岩石趋向于非渗透性岩石时,H－F公式并未收敛到H－W公式。事实上,在渗透性岩石和非渗透性岩石之间并不存在一个明确的界限,描述它们性质的公式应是统一的。但H－F公式和H－W公式之间却存在着很大的差异。对于非渗透性岩石,孔隙压力$p_o=0$,用(1)式和(3)式计算的破裂压力竟相差1倍多。可见现用的破裂压力计算公式之间存在着极大的矛盾。

二、岩石有效应力

上述公式是建立在Terzaghi有效应力基础之上的,而Terzaghi有效应力只适用于像土壤这样的疏松介质,对于像岩石这样的致密介质,应用Terzaghi有效应力会带来一定的偏差[4-5]。严格地讲,岩石存在2个有效应力[7]:本体有效应力和结构有效应力。

1.本体有效应力(σ_{eff}^{p})　本体有效应力决定岩石的本体变形。其公式为[6-7]

$$\sigma = \sigma_{eff}^{p} + \phi p_o \quad (4)$$

2.结构有效应力(σ_{eff}^{s})　结构有效应力决定岩石的结构变形(包括岩石的破坏和断裂)。其公式为[7]

$$\sigma = \sigma_{eff}^{s} + \alpha p_o \quad (5)$$

α视岩石的胶结状况而定,其值介于φ和1之间。对于胶结程度较低的点接触疏松土壤介质,$\alpha\to 1$;对于胶结程度较高的岩石,$\alpha\to\phi$。当$\alpha=1$时,(5)式即变成Terzaghi方程

$$\sigma = \sigma_{eff}^{T} + p_o \quad (6)$$

有效应力概念是由 Terzaghi于 1923年最早提出的[5],并在实践中发挥过很好的作用,目前 Terzaghi方程仍广泛应用于许多科学领域中。但(6)式仅是(5)式的一个近似公式,且仅适用于胶结程度较低的点接触疏松类介质。

三、新公式建立

1. 地应力在井筒周围井壁上产生的最小周向应力[1]

$$\sigma_\theta = 3\sigma_h - \sigma_H \tag{7}$$

2. 井筒内压在井壁上形成的周向应力[1]

$$\sigma_\theta = -p_i \tag{8}$$

3. 渗入井筒周围地层中的流体在井壁上产生的附加周向应力[3]

$$\sigma_\theta = (p_i - p_o)\alpha\frac{1-2\nu}{1-\nu} \tag{9}$$

井壁上总的最小周向应力为上述 3个应力之和。

根据(5)式,井壁上最小周向结构有效应力

$$\sigma^s_{eff,\theta} = 3\sigma_h - \sigma_H - p_i + (p_i - p_o)\alpha\frac{1-2\nu}{1-\nu} - \phi p_i \tag{10}$$

当最小周向结构有效应力达到岩石的拉伸应力强度 σ_t 时,岩石即产生裂缝,此时

$$\sigma^s_{eff,\theta} = -\sigma_t \tag{11}$$

于是,由(10)式和(11)式得岩石的破裂压力公式

$$p_b = p_i = \frac{3\sigma_h - \sigma_H + \sigma_t - \alpha\frac{1-2\nu}{1-\nu}p_o}{1+\phi-\alpha\frac{1-2\nu}{1-\nu}} \tag{12}$$

令 $\xi = \frac{\alpha}{2}\frac{1-2\nu}{1-\nu}$,则(12)式变成

$$p_b = \frac{3\sigma_h - \sigma_H + \sigma_t - 2\xi p_o}{1+\phi-2\xi} \tag{13}$$

由于 $0\leqslant\alpha\leqslant 1$, $0\leqslant\nu\leqslant 0.5$,因此 $0\leqslant\xi\leqslant 0.5$。$\alpha$、$\phi$和 ξ 统称为岩石的性质参数,即岩性参数。

四、公式分析

公式(13)是岩石破裂压力的一个综合计算公式,对于非渗透性岩石,$p_o = 0$,由于 $\alpha\to 0$, $\phi\to 0$, $\xi\to 0$,(13)式计算结果与 H-W公式的计算结果一致。对于渗透性极高的疏松介质,$\alpha\to 1$,则(13)式变成 H-F公式。

由此可见,(13)式是一个通用的岩石破裂压力计算公式,而 H-W公式和 H-F公式则分别是描述非渗透性岩石和高渗透性岩石两种极限状态的岩石破裂压力计算公式。(13)式可预测任何渗透性状况的岩石破裂压力,而 H-W公式和 H-F公式则只能分别预测二种极限状态下的岩石破裂压力,即岩石破裂压力的上限值和下限值。至此,争论多年的岩石破裂压力公式终于得到了统一。

H-W公式和 H-F公式在预测岩石破裂压力时之所以产生矛盾,是因为在建立这 2个公式时完全采用了 Terzaghi有效应力。采用双重有效应力,将得到正确的岩石破裂压力计算公式。

五、计算举例

某井层的地层应力条件为: $\sigma_h = 30$MPa, $\sigma_H = 40$MPa。岩石参数: $\alpha = 0.10$, $\phi = 0.50$, $\nu = 0.23$, $\xi = 0.035$。若 $p_o = 12$MPa, $\sigma_t = 5$MPa,则由 H-W公式计算的非渗透性岩石的破裂压力 $p_b = 55$MPa;由 H-F公式计算的岩石破裂压力 $p_b = 28.06$MPa。令 $\xi = 0$,则由 H-F公式计算的所谓"非渗透性岩石"的破裂压力

$$p_b = \frac{1}{2}(3\sigma_h - \sigma_H + \sigma_t) = 27.5\text{MPa}$$

由(13)式计算的岩石破裂压力 $p_b = 37.87$MPa。

由计算结果可看出,H-W公式给出了岩石破裂压力的上限值(55MPa),即不渗透状况下的岩石破裂压力;H-F公式则给出了岩石破裂压力的下限值(28.06MPa),即高渗透状况下的岩石破裂压力;而由(13)式计算的岩石破裂压力(37.87MPa)介于上、下限破裂压力之间。精心确定或适当调节岩性参数,(13)式可更准确地预测井筒条件下的岩石破裂压力,为石油开发提供更可靠的依据。用 H-F公式计算的所谓"非渗透性岩石"的破裂压力(27.5MPa)是不正确的,因为它比极高渗透性岩石的破裂压力还低。H-W公式和 H-F公式都是特定条件下的破裂压力计算公式,其中的岩性参数(ξ)不能再进行调整。如果仅令 $\xi\to 0$,试图让 H-F公式预测非渗透岩石的破裂压力,将得到完全错误的结果,这是因为公式(13)所描述的岩石性质由 ξ 和 ϕ 两个参数共同决定,单独改变其中一个参数将得到十分离奇的结果。

六、结论

H-W公式和 H-F公式是目前广泛应用于油井压裂设计过程中的 2个岩石破裂压力计算公式。H-W公式适用于非渗透性岩石,H-F公式适用于高渗透性岩石,而对处于中间过渡状态岩石的破裂压力,它们都无法进行预测。它们之间存在着不能统一的矛盾,矛盾的起因在于推导二式采用了

Terzaghi有效应力。本文根据多孔介质的双重有效应力概念,推导出的新公式可预测任何渗透状况岩石的破裂压力,把渗透性岩石和非渗透性岩石的预测公式完全统一了起来。

符 号 说 明

p_b—— 井筒破裂压力, MPa;
p_i—— 井筒内压, MPa;
p_o—— 岩石孔隙中的流体压力,即孔隙压力, MPa;
σ—— 岩石正应力, MPa;
σ_h—— 地层的最小水平主应力, MPa;
σ_H—— 地层的最大水平主应力, MPa;
σ_t—— 岩石的单向拉伸应力强度,即破裂应力, MPa;
σ_θ—— 井壁上周向应力, MPa;
σ^p_{eff}—— 本体有效应力, MPa;
σ^s_{eff}—— 结构有效应力, MPa;
$\sigma^s_{eff,\theta}$—— 周向结构有效应力, MPa;
σ^T_{eff}—— Terzaghi有效应力, MPa;
ν—— 泊松比,无因次;
ζ—— 孔隙弹性常数,无因次;
ϕ—— 岩石孔隙度,%;
ϕ_c—— 岩石触点孔隙度,%。

参 考 文 献

1 王鸿勋,张琪主编.采油工艺原理(修订本).北京:石油工业出版社,1989-07.205~215

2 Detournay E, Carbonell R. Fracture-Mechanics Analysis of the Breakdown Process in Minifracture or Leakoff Test. SPE Production & Facilities, August 1997:195~199

3 Haimson B, Fairhurst C. Initiation and Extension of Hydraulic Fractures in Rocks. SPEJ, Sept. 1967.310~318

4 Lade P V, Boer R De. Concept of Effective Stress for Soil, Concrete and Rock. Geotechnique, Vol. 47, No. 1, Mar. 1997.61~78

5 耶格 J C,库克 N G W著,中国科学院工程力学研究所译.岩石力学基础.北京:科学出版社,1981-07.268~272

6 Biot M A. Theory of Elasticity and Consolidation for a Porous Anisotropic Solid. J Appl Phys, 1955, 26 182~185

7 李传亮,孔祥言,徐献芝,李培超著.多孔介质的双重有效应力.自然杂志,1999,21(5):288~292

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(上接第 53页)

Hydrodynamik. Akademische Verlagsgesellschaft. Leipzig. 1927

3 Goldstein S. The Steady Flow of Viscous Fluid Past a Fixed Spherical Obstacle at Small Reynaud Numbers. Proc Royal Soc. London Ser. A, 1929, 12(3): 54~58

4 Гончаров, В. Н. Основы динамики русловых потоков, Гидрометеоиздат, Ленинград, 1954

5 Allen H S. The Flow of Viscous Fluid at Small Reynauds Numbers. Phil Mag., 1900, 5(2): 323~329

6 窦国仁.泥沙运动理论.南京水利科学研究所,1963

7 Rouse H. Elementary Mechanics of Fluids. 1946

8 岳湘安.液固两相流基础.北京:石油工业出版社,1996

9 Gu Dazhi, Tanner R I. The Drag on a Sphere in a Power-Law Fluid. Journal of Non-Nowtonian Fluid Mechanics, 1985, 17.1~12

10 岳湘安.牛顿与非牛顿液、固两相流的本构理论及其垂直管流[博士学位论文].中国科学技术大学,1993

11 岳湘安,郝江平,陈家琅.固体颗粒在宾汉流体中的阻力系数和沉降速度.石油钻采工艺,1993,15(1):1~8

12 刘永建,孙维林.球形岩屑在赫-巴流体中的沉降速度.石油钻采工艺,1990,12(3):42~48

13 Batchelor G K. Sedimentation in a Dilute Dispersion of Spheres. Jour. Fluid Mech., 1972,(52): 77~90

14 Hawksley P G. The Effect of Concentration on the Settling of Suspensions and Flow Through Porous Media: In Some Aspects of Fluid Flow. Edward Arnold Co., London, 1951,(4): 114~135

15 McNown J S, Malaika J. Effect of Particle Shape on Settling Velocity at Low Reynaud Numbers. Trans Amer. Geophys. Union, 1950,31(1): 74~82

16 Mcnown J S. Particles in Slow Motion. La Houille Blabche, 1951, 6(5): 701~722

17 吉良八郎. Hydraulical Studies on the Sedimentation in Reservoirs. Memories of Faculty of Agri., 1963(12): 191~200

18 Schulz S F, Wilde R H, Albertson M L. Influence of Shape on the Fall Velocity of Sedimentary Particles. M. R. D. Sediment Series Missouri River Div. U S Corps of Engrs., 1954(5): 161~176

19 Swanson V F. Influence of the Fall Velocity of Sedimentary Particles. Trans Soc Mining Engrs. 1967(3): 160~187

20 钱宁,万兆惠.泥沙运动力学.北京:科学出版社,1983

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analyzed.

Subject heading Yanchang Oil Field stimulation operation (Dilatancy deconsolidation) field testing

EVALUATION ON CALCULATION METHODS OF SOLID PARTICLE SETTLING VELOCITY IN FLUID

by Wu Ning, Zhang Qi, Qu Zhanqing

Abstract Calculation of subsidence rate and resistance coefficient of solid particles in fluid affect the relevant technological design on the spot directly. At present, drift flow model is usually adopted in the calculation of solid & fluid multiphase flow. Subsidence rate of solid phase in motionless fluid is the basis of drift flow model. So it is necessary to know the subsidence dynamic characteristics of solid particles in motionless fluid. The paper systematically describes correlation equations of subsidence rate and resistance coefficient for subsidence and interference subsidence rate of particles shape and boundary conditions.

Subject heading solid grain liquid settling velocity resistance force coefficient calculation method

A THEORETICAL STUDY ON ROCK BREAKDOWN PRESSURE CALCULATION EQUATIONS OF FRACTURING PROCESS

by Li Chuanliang, Kong Xiangyan

Abstract Based on the dual effective stress concept of porous media formation, the calculation method for rock breakdown pressure is studied in the paper, and a new composite calculating formula is provided. It is possible to predict breakdown pressure for different types of rocks if different parameters are used in the formula. The application scope of currently used equations is analyzed by using of new formula. The H- W equation can only be used to calculate the breakdown pressure of non- permeable rock; therefore it gives the upper limited value of breakdown pressure. The H- F equation can be used to calculate the breakdown pressure of high permeability rock, therefore, it gives the lower limited value of breakdown pressure. It is available to predict the breakdown pressure of any kinds of rocks by the new calculation formula. It consists of previous two calculation equations, and totally combines the calculation of non- permeable rock and that of permeable rock in one.

Subject heading oil well fracturing rock fracturing pressure calculation method theory research

HYDRAULIC FRACTURING APPLICATION STUDY FOR STIMULATION OF MARGINAL AND LOW PERMEABILITY RESERVOIRS

by Ding Yunhong, Chen Zuo, Chen Guoqiang, Wang Song

Abstract A related hydraulic fracturing stimulation technology is supplied in this paper to decrease operating cost and improve productivity of low permeability reservoir in which there are not enough data and the reservoir geology condition is complex. While running the technology, the whole well formation interval is fractured orderly in steps, the formation is recognized during the fracturing operation at different step, and improves the overall level of hydraulic fracturing technology by use of previous study result. This technology has been used in No. 52 oil bearing block of Shengli Wangbei Oil Field. The result shows the way to deeply study formation is very effective, which is an inverse way to know the formation condition. In this way, many difficult developing reservoirs in which they are marginal and low permeability reservoirs can be developed in a high efficiency manner. Therefore it offered a lower cost and more operative method to develop above related reservoirs in the future.

Subject heading marginal oil field low permeability reservoir hydraulic fracturing optimization design technology research application

PERFORATION OPTIMIZATION DESIGN FOR OPERATION OF LIMITED ENTRY FRACTURING TECHNOLOGY

by Zhang Shicheng, Wang Shigui, Zhang Guoliang, Zhang Youcai, Dong Jianhua

Abstract Limited entry fracturing technology is a chief method used to stimulate low permeability muti- layer reservoirs. The key point is how to optimize perforation process for different layers. Perforations are determined according to the formation thickness in conventional way. Then the fracturing fluid and sand volume is calculated proportionally based on the number of perforations. Therefore, the influence of characteristic nature of different layer on the operation scale and perforations is not considered. It is also not considered that the well bore; the perforations and the friction affect fluid entry volume in different layer during operation. A mathematic model to calculate limited entry volume changes with time, formation characteristic and perforations has been set up. Combining the model above and the model of fracture geometry can carry out the optimization design. The field test of 22 wells in Daqing Chang- huan shows a better production improvement.

Subject heading limited entry fracturing perforation project optimizing design

THE APPLICATION OF ENVIRONMENT SCANNING ELECTRON MICROSCOPE IN OBSERVATION OF CORE BEFORE AND AFTER EXPOSED TO ACID

by Li Suzhen, Wang Xugang, Cheng Xingsheng, Jiang Tian

Abstract Sandstone matrix acidizing is a very effective stimulation method to remove the damage nearby the wellbore in sandstone reservoir The study on acid/rock reaction and mechanism of secondary damages to formation is the basis of optimizing acid system and acidizing design. The Environmental Scanning Electron Microscope (ESEM) plays an importance