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Application of MODFLOW for Oil Reservoir Simulation During the Deepwater Horizon Crisis

by Paul A. Hsieh

Abstract

When the Macondo well was shut in on July 15, 2010, the shut-in pressure recovered to a level that indicated the possibility of oil leakage out of the well casing into the surrounding formation. Such a leak could initiate a hydraulic fracture that might eventually breach the seafloor, resulting in renewed and uncontrolled oil flow into the Gulf of Mexico. To help evaluate whether or not to reopen the well, a MODFLOW model was constructed within 24 h after shut in to analyze the shut-in pressure. The model showed that the shut-in pressure can be explained by a reasonable scenario in which the well did not leak after shut in. The rapid response provided a scientific analysis for the decision to keep the well shut, thus ending the oil spill resulting from the Deepwater Horizon blow out.

Introduction

After discharging crude oil into the Gulf of Mexico for 86 d following the explosion on Deepwater Horizon drill rig, the Macondo well was shut in on the afternoon of July 15, 2010. The shut in marked the start of the "well integrity test," which was planned to last between 6 and 48 h to assess the condition of the well. Of primary concern was whether or not the well casing was damaged during the explosion. If the casing was damaged, the rising shut-in pressure could force oil to leak out of the casing into the surrounding formation and initiate a hydraulic fracture. With continued oil leakage, the fracture would grow and eventually breach the seafloor. The result would be a renewed and uncontrolled flow of oil into the Gulf—a catastrophic development.

Prior to the test, the risk of leakage had been evaluated to develop testing guidelines. Three scenarios were considered. If the shut-in pressure, as measured in the capping stack (Figure 1), was greater than 7500 psi (1 psi = 6.89 kPa), the risk of a leak was low, and the test could proceed for 48 h. This outcome would indicate conditions suitable for keeping the well closed after the 48-h test. By contrast, if the shut-in pressure was less than 6000 psi, major well damage was likely, and the well would have to be reopened within 6 h. If the shut-in pressure was between 6000 and 7500 psi, the risk of a leak was uncertain. Under this scenario, the test could proceed for 24 h, at which point a decision would be made on whether to reopen the well or to keep it closed.

The shut-in procedure for the Macondo well consisted of a series of valve turns, separated by 10-min rest periods, to reduce the oil-discharge rate in a stepwise fashion. When the final turn of the valve was completed and the well was fully shut in, the pressure in the capping stack rose to just above 6600 psi. Although the pressure continued to rise slowly, it became evident that 7500 psi would not be reached. The test result fell squarely in the uncertain middle range.

The impending decision on whether or not to reopen the well after 24 h would carry serious consequences. Reopening the well would once again allow oil to spill into the Gulf of Mexico. Keeping the well closed would risk a more catastrophic spill in the event of a hydraulic fracture-induced breach of the seafloor. A key task was to analyze

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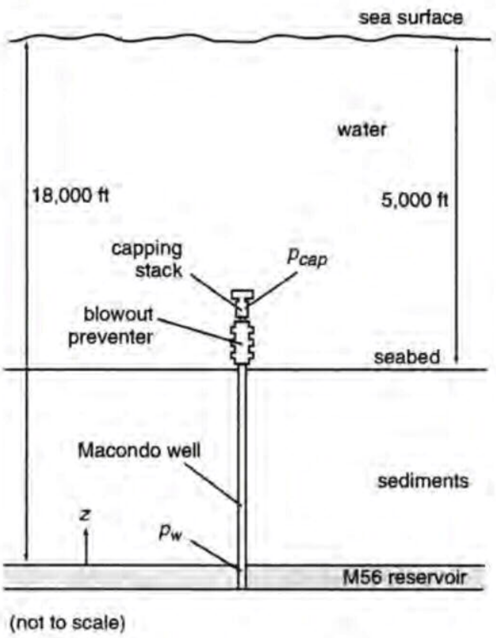

Figure 1. Schematic vertical section showing the M56 oil reservoir, Macondo well, blowout preventer, and capping stack. Note that the diagram is not to scale. The heights of the blowout preventer and capping stack are approximately 50 and 30 feet, respectively.

the shut-in pressure to gain additional knowledge of the well condition. To aid decision making, such an analysis would have to be done within 24 h, that is, prior to the planned termination point of the test under the observed pressure conditions.

This article describes the development of a reservoir model to analyze the shut-in pressure in the Macondo well. The work was carried out by the author while serving on the Government's science team lead by the Secretary of Energy Steven Chu. Some of the data used for model development were provided by BP and were considered proprietary. Therefore, only data from publically available sources are presented here. Such data sources include BP's (2010) investigation report of the Deepwater Horizon blowout, Government press releases (http://www.restorethegulf.gov/news/press-releases), and BP's technical briefings that were made available to the public (http://www.bp.com/sectiongenericarticle.do?categoryId=9034442&contentId=7063846). The 5-month effort to control and eventually "kill" the Macondo well was described in Chapter 5 of the report by the National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling (2011).

The Reservoir Model

The Macondo well was drilled into an oil reservoir known as M56, which consisted of three oil-producing sand layers. The top of the reservoir was penetrated by the well at a depth of approximately 18,000 feet below sea surface (Figure 1). Water depth was approximately 5000 feet. The combined thickness of the three oil-producing sand layers was approximately 90 feet. The initial reservoir pressure was 11,850 psi, which is significantly above hydrostatic due to overpressure conditions typical of the sediments in the Gulf of Mexico. The reservoir temperature was approximately 240 °F (116 °C). As the bubble point of the oil in the reservoir was approximately 6500 psi, the reservoir was believed to be under single-phase (liquid oil) condition.

The equation of oil flow in the reservoir is given (after Matthews and Russell 1967, 7, equation 2.12) by

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} = \frac{\phi \mu_o c}{k} \frac{\partial p}{\partial t} \tag{1}$$

where p is the pressure, ϕ the porosity, μ_o the oil viscosity, c the system compressibility, k the permeability, x and y the Cartesian coordinates in the horizontal plane, and t is the time. The system compressibility is computed (after Matthews and Russell 1967, 135, note 1) as

$$c = (1 - S_w)c_o + S_w c_w + c_f \tag{2}$$

where S_w is the water saturation, c_o the oil compressibility, c_w the water compressibility, and c_f is the effective formation (or pore) compressibility. Because the water saturation is relatively low, the flow of water is neglected. Nonetheless, the effect of water compressibility is included in Equation 2.

In applying Equation 1 to the reservoir, the following conditions are assumed:

1. Flow of oil is under single-phase and isothermal conditions.
2. Reservoir properties (permeability, porosity, and compressibility) are homogeneous.
3. Permeability and viscosity are independent of pressure.
4. Permeability is isotropic.

Additional assumptions are given by Matthews and Russell (1967). These are standard in the analysis of pressure buildup and flow tests in oil wells, and include assumptions that the reservoir is horizontal, the fluid compressibility is small and constant, and that pressure gradients within the reservoir are sufficiently small for Darcy's law to apply.

When the reservoir model was initially developed during the 24-h period after the Macondo well shut in, the author had no information on the lateral extent of the M56 reservoir. However, an estimate of the volume of oil in the reservoir had been provided by BP. Therefore, the bulk volume of the reservoir containing the oil was estimated as

$$V_b = \frac{V_o B}{\phi(1 - S_w)} \tag{3}$$

where V_o is the volume of oil in the reservoir (known as "volume of original oil in place") and B is the formation volume factor. By petroleum industry convention, V_o is

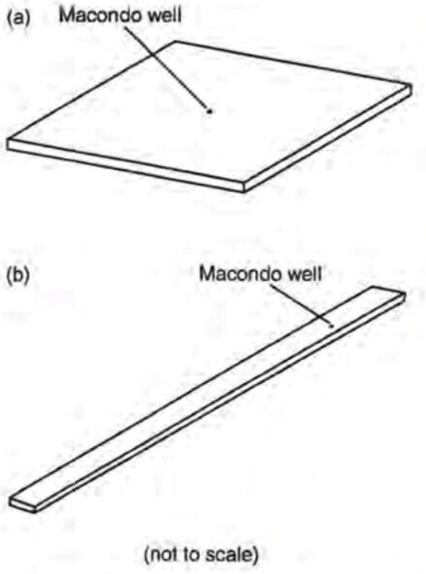

Figure 2. Oblique view of the M56 oil reservoir as implemented in the (a) initial model and (b) revised model.

given for surface conditions (60 °F and 14.7 psi). When a quantity of oil is brought from the reservoir to the surface, the change in temperature and pressure and the release of gas bubbles actually cause the oil volume to decrease. The formation volume factor B is the ratio of the oil volume under reservoir conditions to the volume under surface conditions. Therefore, the product $V_o B$ in Equation 3 gives the volume of original oil in place under reservoir conditions.

Next, the area of the M56 reservoir was estimated by dividing V_b by the combined thickness of the three oil-producing sand layers. In effect, the model represented the three sand layers by a single model layer. To develop the initial model, the M56 reservoir was assumed to occupy a square area with impermeable boundaries on all sides. The Macondo well was assumed to be in the center of the square (Figure 2a). Such a conceptualization was deemed adequate as the model would initially be used only to simulate the first 6 h after shut in. During this period, pressure recovery occurred in the close vicinity of the well, and the shut-in pressure was insensitive to the location of the reservoir boundaries.

The estimated oil-discharge rate from the Macondo well had been revised several times after the Deepwater Horizon explosion. On June 15, 2010, the Government's Flow Rate Technical Group estimated that the oil-discharge rate was between 35,000 and 60,000 barrels per day (bpd; 1 barrel = 0.159 m^3). However, by the time of the Macondo well shut in, some members of the Government's science team believed that the oil-discharge rate was closer to 60,000 bpd than 35,000 bpd. In the reservoir model, the oil-discharge rate was initially assumed to be a constant 55,000 bpd throughout the period from explosion to shut in.

In summary, the mathematical formulation of the reservoir model consists of solving equation 1 for a well discharging at a constant rate from a reservoir bounded by impermeable sides. After 86 d of oil discharge, the shut-in procedure was simulated by six uniform step decreases in oil-discharge rate to reach zero discharge after 1 h. In effect, the model simulated the scenario in which the well had perfect integrity and there was no leakage after shut in. The objective was to compare the simulated pressure with the observed pressure inside the capping stack during the 6 h after shut in.

MODFLOW Implementation

The U.S. Geological Survey model MODFLOW (Harbaugh et al. 2000) was used to simulate oil flow in the M56 oil reservoir. Although MODFLOW was originally designed to simulate the flow of groundwater in aquifers, it can actually be used for simulating flow of oil in reservoirs under single-phase and isothermal conditions. The fluid flow equation solved by MODFLOW is analogous to Equation 1, and can be written as

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{S_s}{K}\frac{\partial h}{\partial t} \tag{4}$$

where h is the hydraulic head, S_s the specific storage, and K is the hydraulic conductivity. For simulating oil flow, these three quantities are computed as

$$h = \frac{p}{\rho_o g} + z \tag{5}$$

$$K = \frac{\rho_o g k}{\mu_o} \tag{6}$$

$$S_s = \rho_o g \phi c \tag{7}$$

where ρ_o is the oil density, g the gravitational acceleration, and z is the vertical elevation above a reference datum, taken to be the top of the oil reservoir. In effect, Equation 5 defines an oil head instead of a water head as the simulated quantity in MODFLOW, and Equation 6 defines a hydraulic conductivity for oil flow, using oil properties. The actual property values are proprietary data and cannot be presented here.

The M56 oil reservoir was represented by a single model layer discretized into 117 rows by 117 columns of cells. The central cell, containing the Macondo well, had a horizontal dimension of 0.8 feet × 0.8 feet. Away from the well, the cell size increased gradually to a maximum dimension of 100 feet × 100 feet. Discharge from the well was simulated using the Well Package of MODFLOW. The down-hole pressure in the well (p_w, i.e., pressure at the reservoir depth) was computed by solving for p in Equation 5:

$$p_w = \rho_o g h_w - z \tag{8}$$

where h_w is the simulated (oil) head in the cell containing the well. The pressure in the capping stack (p_{cap}) was computed by subtracting from p_w the pressure exerted by

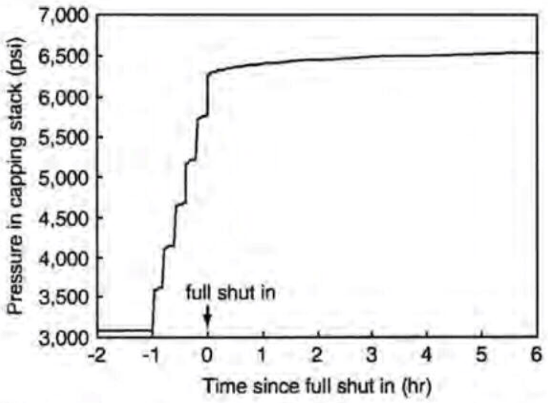

Figure 3. Simulated pressure in the capping stack of the Macondo well. Start of the shut-in process occurs at time = −1 h. Full shut in occurs at time = 0 h. The line shows the simulated pressure calculated by the initial model. The simulated pressure closely matched the observed pressure data, which are not shown due to their proprietary nature.

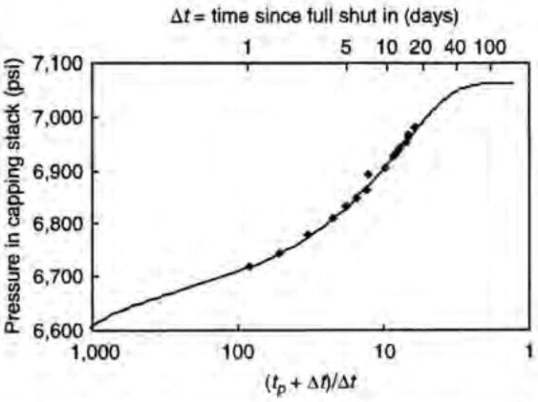

Figure 4. Horner plot (the petroleum industry's equivalent of a Theis recovery plot) of shut-in pressure in the capping stack of the Macondo well, where t_p is the period of oil discharge, which is 86 d, and Δt is elapsed time since full shut in. The line shows the simulated shut-in pressure calculated by the revised model. The diamond symbols show pressure readings that were announced in Government press releases and in BP technical briefings. These pressure readings are a subset of the observed shut-in pressure data, which are not shown in their entirety due to their proprietary nature.

the column of oil in the well from the reservoir to the capping stack:

$$p_{\text{cap}} = p_{\text{w}} - \rho_{\text{o}} g H \tag{9}$$

where H is the distance from the reservoir to the capping stack (about 13,000 feet).

Simulation Results

Figure 3 shows the simulated pressure in the capping stack from 2 h before full shut in to 6 h after full shut in. The simulation used reservoir and fluid property values provided by BP. Due to the time constraint, calibration was not attempted. The step-like rises in pressure from time = −1 h to time = 0 h simulate the pressure response to successive turns of the valve to choke back the oil-discharge rate. After full shut in was achieved with the final valve turn, the simulated pressure began to level off at about 6600 psi.

The simulated shut-in pressure closely matched the observed shut-in pressure, which cannot be shown in Figure 3 due to the proprietary nature of the data. The close match provided a reasonable scenario of a well with full integrity (i.e., no leakage after shut in). Although the possibility of a leak could not be ruled out, the decision was made by senior Government officials to extend the shut in beyond 24 h, with reevaluation of that decision at regular intervals (initially every 6 h, then every 12 h, and finally every 24 h). An intense surveillance effort, using reflection seismic surveys, sonar surveys, and visual observations by video cameras in remotely operated vehicles, monitored for signs of leakage from the well. At the first detection of leakage, the well would be immediately reopened.

As shut in continued beyond 24 h, additional shut-in pressure data were used to update the reservoir model. After about 2 d of shut in, it became apparent that the initial model needed to be revised. Analysis of the pressure data using a Horner plot (the petroleum industry's equivalent of a Theis recovery plot, see Matthews and Russell 1967, chapter 3) indicated that the M56 oil reservoir would be more appropriately modeled as a long, narrow channel (Figure 2b) instead of a square. Consultation with geologists on the Government science team supported this conceptualization, as the sedimentary history of the Gulf Coast in the vicinity of the Macondo well suggested that the oil-producing sands composing the M56 reservoir are submarine channel fills (Posamentier 2003).

The model was revised by adjusting the width and length of the reservoir channel, the location of the Macondo well, the reservoir permeability (k), and the formation compressibility (c_f) in order for the simulated shut-in pressure to match the observed shut-in pressure. The updated values of k and c_f remained in the respective ranges typical of reservoir sands, but cannot be reported here due to their proprietary nature. The oil-discharge rate was revised from 55,000 to 50,000 bpd, based on new analyses by teams of scientists from Sandia, Los Alamos, and Lawrence Livermore National Laboratories. All other model parameters were kept the same as before. This calibration was carried out repeatedly on a near-real-time basis, as observed pressures become available every 24 h. As shown in Figure 4, the pressures simulated by the revised model (line) closely match the observed pressures (diamond symbols) through August 1, 2010, approximately 17 d after shut in.

As shut in continued, the ability of the revised model to simulate the observed shut-in pressure and the absence of leakage detection from the monitoring effort provided increasing support for the Macondo well having full integrity. The Macondo well remained shut until August 3, 2010, when mud was injected into the well to start the "static kill" operation. This was followed 2 d later by cementing of the production casing. Finally, in mid-September, the annulus space in the well was cemented after BP finished drilling a relief well that intercepted the Macondo well. On September 19, 2010, Admiral Thad Allen, the National Incident Commander for the Federal Government's response to the Deepwater Horizon oil spill, announced that the Macondo well was "effectively dead."

Closing Comment

While geoscientists often work on projects with timelines that extend over months or years, a crisis situation requires rapid response to provide scientific analysis for decision making. In the response to the Deepwater Horizon oil spill, the time for scientific analysis was often a matter of hours. Providing such rapid response required a high level of coordination among scientists, engineers, and emergency response officials, ready access to data, and the ability to mobilize personnel and resources on the fly to deal with critical scientific and technical issues. Modeling the shut-in pressure in the Macondo well using MODFLOW was one among many innovative efforts that contributed to ending the Deepwater Horizon oil spill.

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