Appendix E Geology

Analysis of Subsidence and Microseismicity Induced by Montebello Gas Field Pressure Depletion

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EXECUTIVE SUMMARY

The West Montebello Gas Storage Field is located in the City of Montebello, about twelve miles east of Los Angeles. The field was discovered in 1936, and produced oil and gas from several lower Pliocene and upper Miocene sand formations (Stolz, 1939). The 8th zone, lying at a depth of about 7200ft from the surface, has been used for gas storage operations by Southern California Gas Company since about 1956. This is a gentle anticlinal formation elliptical in shape, about 1.5 miles long and 1 mile long (see Figure 1).

Storage operations in the area are currently scheduled for abandonment, and the remaining cushion gas in the 8-1 and 8-2 formations is to be withdrawn. Southern California Gas Company anticipates that this withdrawal will reduce formation gas pressure from a current value of about 1750 psi to a depleted value of about 200psi. Over time, this pressure can be expected to rise slowly as native formation water seeps back into the area. In the interim, however, there is interest to determine what magnitude of surface subsidence and potential microseismicity might be induced by the 1550psi of pressure depletion.

Terralog Technologies has completed a brief geomechanical review of the Montebello field to provide an order of magnitude estimate for surface subsidence and to comment on potential microseismicity. We considered the mechanical properties of the gas storage zone, as indicated by acoustic logs and density logs. We estimate the subsurface compaction and resulting surface subsidence induced by a pressure depletion of 1550psi, using simple analytical equations and conservative assumptions for reservoir parameters. Finally we describe the mechanics and occurrence of microseismic events common to many oil and gas operations, and estimate an upper bound for potential activity at Montebello. Our preliminary review and efforts support the following conclusions:

1. Pressure depletion on the order of 1550psi at the Montebello Field is not likely to induce surface subsidence greater than about 1 inch in magnitude.
2. Any subsidence caused by reservoir compaction at a depth of 7100 feet will be distributed over a lateral extent of about two miles. The resulting differential movement will be extremely small, and will not impact surface roads or structures.
3. Microseismic activity, with magnitude on the order of –1.0 to 1.0, often occurs during injection and extraction operations. Activity of this magnitude can be anticipated at Montebello during depletions operations, and is not significant relative to natural daily seismicity in the Los Angeles area. An upper bound for potential microseismicity would be about M2.

OVERVIEW OF GAS RESERVOIR GEOMECHANICS

The weight of sediments above an oil and gas bearing geologic formation is supported partially by the rock matrix and partially by the pressurized fluid or gas within the rock pore space. When fluid pressure is reduced, more of the load is transferred to the rock matrix and the pressure depleted formation compacts slightly. This subsurface compaction, if it is significant or if the formation is relatively shallow, can sometimes produce measurable surface subsidence. Pressure induced compaction or dilation can also induce small-scale slip (on the order of millimeters) on faults or bedding planes with associated microseismicity on the order of magnitude 1.0 or less. Small-scale deformations and small-scale microseismicity are common to all geologic injection and extraction processes, including oil and gas operations and even shallow groundwater withdrawal and replenishment operations. There are well established geomechanical procedures available to estimate surface subsidence and seismicity risks for specific situations (see for example, Bruno, 1998; 1992).

Surface Subsidence Induced by Pressure Depletion

For most oil and gas formations, the lateral dimensions of the reservoir are large relative to the formation thickness, and therefore most of the compression associated with pressure decline occurs in the vertical direction. The magnitude of this vertical compaction or pressure induced change in formation thickness, ΔH, can be estimated by the following equation:

$$\Delta H \;/\; H = Cm\,\Delta P, \qquad (1)$$

where H is the original formation thickness, Cm is the uniaxial compaction coefficient for the geologic formation material, and ΔP is the change in fluid or gas pressure.

Surface displacements resulting from subsurface compaction may be calculated by applying the nucleus-of-strain equations from continuum mechanics described by Geertsma (1973a,b). For a roughly disk shaped oil and gas bearing formation with compaction coefficient Cm and Poison's Ratio, ν, average radius, R, average thickness, H, and depth of burial, D, the maximum vertical subsidence, S, can be estimated with the following equation (Bruno, 1992):

$$S = 2Cm(1-\nu)[H - (R^2+(D+H)^2)^{0.5} + (R^2+D^2)^{0.5}]\Delta P \qquad (2).$$

The amount of subsidence transferred to the surface by a subsurface source of compaction will depend primarily on the shape and lateral extent of the subsurface compaction zone and the depth of burial. Very shallow and laterally extensive compaction zones will produce subsidence almost equal to compaction, while small and deeply buried compaction zones will produce no measurable surface subsidence. The lateral extent of surface subsidence is also related to the depth of the subsurface compaction zone. Surface subsidence is maximum directly above the compaction source and generally falls off to near zero at a lateral distance equal to about twice the reservoir depth.

Microseismicity Induced by Pressure Depletion

When oil and gas is produced or injected in a reservoir, rock compaction and dilation occurs. The amount of compaction and dilation is related to the pore pressure change and the compressibility of the formation material (as seen in equation 1). Because different materials expand or contract at different rates, there is invariably small-scale slip and shearing within the reservoir and sometimes within the overburden. These microseismic events can be recorded with modern high precision seismic monitoring equipment.

Natural felt earthquakes (> M3) in the Los Angeles area occur on deeply buried faults in stiff basement rock, with hypocenters on the order of 10 miles beneath the surface. This contrasts with oil and gas operations that are only on the order of 1 mile beneath the surface. Therefore shallow seismic events, such as those that might be associated with oil and gas or water injection and extraction, are much lower in magnitude for two reasons. First, seismic magnitude increases with fault size; deep faults can be large while shallow faults and the associated area influenced by gas operations are relatively small. Second, seismic magnitude increases with rock stiffness; deep sediments are generally compacted and stiff while shallow sediments are relatively soft.

Microseismic activity on the order of magnitude minus 1.0 to plus 1.0, however, is common in active oil and gas reservoirs. To provide some perspective on these values, consider the relative slip associated with a magnitude 0.5 seismic event. An approximate relation between the shear slip on a small fault and a seismic event may be expressed as (Scholz, 1990):

$$\mu \mathbf{Ad} = \mathbf{10^{(1.5M + 16.05)}} \qquad (3)$$

where μ is the material shear modulus (dyne/cm^2), **A** is the fault area (cm^2), and **d** is the amount of fault slip (cm). If we assume a typical value for sedimentary rock of μ = 2E11 dyne/cm^2 and solve equation (3) for the fault area and slip induced by a seismic event of magnitude **M=0.5**, we obtain the following relationship:

$$\mathbf{Ad = 3.2E05\ cm^3} \qquad (4)$$

For example, this would be equivalent to a 10m x 10m zone slipping by about 3 mm. Slip of this magnitude is not sufficient to be felt at the surface nor sufficient to cause damage to subsurface wells penetrating these slip zones. In fact, due to natural tectonic stressing in the area, larger magnitude seismic events on the order M1 occur on a daily basis throughout Southern California.

SUBSIDENCE ESTIMATE FOR MONTEBELLO FIELD

Equations (1) and (2) can be applied to establish a conservative (maximum) estimate of subsidence which might be induced above the Montebello Field due to pressure depletion. This requires estimates or assumptions for the mechanical properties of the formation material, including the compaction coefficient and Poisson's ratio, and the geologic setting for the formation, including its average depth, thickness, and lateral extent. Table 2 below presents a summary of assumed and calculated formation properties for the gas storage zones at Montebello.

Table 2. Assumed Montebello Gas Storage Zone Formation Properties

Formation Property	Variable Name	Value
Depth to top of gas storage zone	D	7200 ft (2190 m)
Total formation thickness	H	220 ft (67 m)
Maximum formation radius	R	4000 ft (1220 m)
Compaction coefficient	Cm	2.68E-7/psi (3.89E-11/Pa)
Poisson's Ratio	ν	0.20
Shear Modulus	μ	1.40E6 psi (9.6E9 Pa)
Maximum Pressure Depletion	ΔP	1550 psi (6.9E6 Pa)
Compressional Velocity	V_c	11,500 ft/s (3500 m/s)

The formation mechanical properties are estimated from sample acoustic velocity logs and density logs (included in Appendix A) across the 8-1 and 8-2 gas storage formations. The average compressional wave velocity measured in wells MGS 13-20 and MGS 17-9 is about 11,000 ft/s to 12,000 ft/s, or approximately 3500m/s. The average bulk density measured in well MGS 11-16 over the gas formation is about 2.1 gm/cm^3 (2100 kg/m^3). For an elastic material, the uniaxial compaction coefficient, Cm, is related to bulk density, ρ, and the compressional wave velocity, V_c, through the expression:

$$Cm = 1\ /\ (\rho V_c^2) \qquad (5).$$

Then the compaction coefficient can be estimated for the gas bearing formations at Montebello to be approximately:

$$Cm \sim 1 / [2100\mathrm{kg/m^3} \times (3500\mathrm{m/s})^2] = 3.89\mathrm{E}{-11}/\mathrm{Pa} = 2.68\mathrm{E}{-7} / \mathrm{psi} \qquad (6).$$

Equations (5) and (6) assume that the formation material behaves elastically, and that the large-strain "static" rock deformation is equal to "dynamic" rock deformation controlling very small-strain compressional velocity in the rock. In fact, several researchers have documented that static compressibility factors are generally higher than dynamic compressibility factors (see for example, Montmayeur and Graves, 1986, and Eissa and Kazi, 1988). When dynamic compressibility is in the range of 1E-6/psi to 1E-7/psi, the observed differences can be accounted for by scaling the dynamic compressibility value by an additional safety factor of about 2 to arrive at the static compressibility that should control compaction and subsidence.

Next we require estimates for the formation size and depth. Figure 1 presents a structural contour map and a cross section map for the 8th zone at Montebello. Gas is stored at Montebello in the 8-1 and 8-2 formations lying at depths from about 7100 ft to 7500 ft. The gas formation is anticlinal, and roughly elliptic in shape with a maximum radius of about 4000 ft and a minimum radius of about 2000 ft. Reservoir thickness varies from about 200 feet to 220 ft. Equation (2) may therefore be applied to estimate maximum surface subsidence by using the minimum burial depth (D=7100ft), the maximum average radius (R=4000ft), and the maximum formation thickness (H=220ft).

The resulting order of magnitude estimate for maximum surface subsidence, with an additional factor of 2.0 to account for uncertainty in the static compaction coefficient, can then be obtained from equation (2) as follows:

$$S = 4(2.68\mathrm{E}{-7}/\mathrm{psi})(1-0.2)[220\mathrm{ft} - ((4000\mathrm{ft})^2+(7100\mathrm{ft}+220\mathrm{ft})^2)^{0.5} + ((4000\mathrm{ft})^2+(7100\mathrm{ft})^2)^{0.5}](1550\mathrm{psi}) = 0.037\ \mathrm{ft} = 0.44\mathrm{in}$$

Surface subsidence on the order of 1 inch, distributed over a lateral extent of about 2 miles, is relatively insignificant. Differential surface movement on the order of 1 inch in 1 mile, or a slope of about 1E-5, will have no impact on surface roads or structures.

MICROSEISMICITY ESTIMATE FOR MONTEBELLO FIELD

Potential microseismicity induced by pressure depletion in a formation can be estimated by considering slip that might be induced on a known or hypothetical fault near the reservoir. This generally requires a geomechanical model for the reservoir to simulate induced stresses and strains on specific fault locations (see for example, Bruno et al, 1998). It is possible, however, to make conservative assumptions regarding the maximum slip that might be induced in the vicinity of the field to provide order of magnitude type estimates for maximum potential microseismicity. Applying equation (1) and the reservoir parameters provided in Table 2, we estimate a maximum subsurface compaction of about $\Delta H = .091$ft (2.8cm). Let us assume that this compaction is not accommodated by elastic deformation of the overburden, as is normally the case, but rather by complete slip on a hypothetical fault bounding one side of the reservoir (an extreme assumption applied here for illustrative purposes only). For example, assume that a fault 220ft high by 4000ft long (8.17E8cm^2 area) slips by an average displacement amount of 1.4cm. Equation (3) can be rearranged to estimate the seismic magnitude for slip of this given magnitude occurring on a fault of this given surface area as follows:

$$M = 0.67\log_{10}(\mu A d) - 10.7 = 0.67\log_{10}[(9.6E10)(8.17E8)(1.4)] - 10.7 = M2.6$$

This is a conservative upper bound on seismicity that might be induced by depletion operations at Montebello, assuming material fails in a completely brittle manner instantaneously along an entire edge of the reservoir. In fact the formation material is relatively soft and can be expected to deform slowly and aseismically during pressure drawdown. Actual microseismic activity induced by depletion is not likely to exceed about magnitude 1.0.

DISCUSSION AND CONCLUSIONS

The West Montebello Oil Field has produced oil and gas since 1936, and has been used for gas storage for more than 40 years. The gas storage zone formation material is relatively consolidated and the formation is relatively deep (7200ft). Future pressure depletion should not exceed about 1550psi. These combined factors suggest that reservoir compaction and associated surface subsidence will be small.

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REFERENCES

Bruno, M.S., DeWolf, G., and Foh, S. (2000): Geomechanical analysis and decision analysis for delta pressure operations in gas storage reservoirs, Proc. AGA Operations Conf., Denver, CO, May 7-9.

Bruno, M.S., Dusseault, M.B., Balaa, T.T, Barrera, J.A., (1998): Geomechanical analysis of pressure limits for gas storage reservoirs, *Int. J. Rock. Mech. Min. Sci.*, V35, No. 4, 1998, pp. 569.

Bruno, M.S., (1998): Identifying Source Mechanisms Responsible for Subsidence Through Inversion of Measured Surface Displacements, Current Research and Case Studies of Land Subsidence, J. Borchers (ed), Land Subsidence, Case Studies and Current Research, Special Pub. No 8, Association of Engineering Geologist, 1998, pp. 441-450.

Bruno, M.S. (1992): Subsidence-Induced Well Failure, *SPE Drilling Engineering*, June, 1992, pp. 148-152.

Eissa, E.A. and Kazi, A. (1988): Relation between static and dynamic Young's Modulus of rocks, Int. J. Rock Mech. Min Sci., Vol. 25, No. 6, pp 479-482.

Montmayeur, H. and Graves, R.M. (1986): Prediction of static elastic / mechanical properties of consolidated and unconsolidated sands from acoustic measurements: Correlations, SPE15644 presented at 61st SPE Ann. Tech. Conf., New Orleans, LA, October 5-8, 1986.

Scholz, C.H.: The Mechanics of Earthquakes and Faulting, (Cambridge Univ. Press, 1990), pp. 177-179.

Stolz, H.P.(1939): West Montebello Oil Field and Application of the State Gas Law, Calif. Div. of Oil and Gas Summary of Operations, California Oil Fields, Vol. 25.

FIGURE 1. MONTEBELLO OIL FIELD MAP

APPENDIX A: WELL LOGS