ENVIRONMENTAL ASPECTS OF OIL AND GAS PRODUCTION

J. O. Robertson
Earth Engineering, 3708 La Canada Road, Fallbrook, CA 92028, USA

G. V. Chilingar
Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, USA

L. F. Khilyuk
Russian Academy of Natural Science, U.S.A. Branch

B. Endres
101 S. Windsor Blvd., Los Angeles, CA 90004, USA

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Contents

Summary

The present paper on the environmental aspects of oil and gas production and natural gas storage reservoirs consists of the following items: (1) subsidence, (2) gas migration and (3) toxic and/or flammable emissions. These issues are interactive and should be evaluated prior to extraction of fluids (oil, gas and water) from the subsurface reservoirs. Ignoring these issues could result in substantial legal liability upon the oilfield operators and upon those responsible for the public safety due to damage to the public sector. The writers would like to stress that oil and gas production can be conducted safely if proper precautions are used.

1. Subsidence Associated with Fluid (Gas, Oil and Water) Production

Subsidence caused by withdrawal of fluids (ground water, oil and gas) has been observed and studied for more than a hundred years (Poland and Davis, 1969; Strehle, 1989). Some of the earliest best known examples of subsidence due to ground water withdrawal are Osaka, Japan (first noted in 1885), London, England (first noted in 1865), and Mexico City, Mexico (first noted in 1929). One of the earliest examples of subsidence caused by withdrawal of oil is Goose Creek Oil Field, Texas, USA (first noted in 1918), described by Pratt and Johnson (1926). Thus, the phenomenon of subsidence is well known and thoroughly studied by many investigators up to now. It is physically obvious and fully recognized that subsidence is caused by compaction of reservoir rocks due to an increase of effective stress due to a reduction of fluid pore pressure. Pratt and Johnson in 1926 also indicated one more factor, which is important in formations with loose sands and other unconsolidated granular sediments, i.e., extraction of sand.

Subsidence due to fluid withdrawal occurs when: (1) reservoir fluid pressures are lowered, (2) reservoir rocks are compactable and/or are unable to effectively resist deformation upon the transfer of load from the fluid phase to the grain-to-grain contacts, and (3) the overburden lacks internal self-support and the formations can easily deform downward (see Donaldson and Chilingarian, 1997, p. 253).

The principal lithological and structural characteristics of the subsiding areas include the following:

(1) Sediments are unconsolidated and lack appreciable cementation.
(2) Porosity of the sands is high (20 to 40%).
(3) The sediments are of Miocene age or younger.
(4) Producing formations are located at a shallow depth (300 to 1000 m).
(5) The aquifer is thick (more than 30 m).
(6) Overburden is composed of structurally weak sediments.
(7) Tension-type faulting, often with a graben is present.
(8) Sands are interbedded with clays, fine silts and/or siltstones, and shales.
(9) Pore pressure is greatly reduced by production.
(10) Overburden is composed of structurally weak rocks.

1.1. Mechanics of Subsidence

Subsidence over formations producing oil, gas and/or water, is caused by the reduction of pore (fluid) pressure within the producing formation through the removal of fluids in the pores:

P_e (effective, grain-to-grain stress) $= P_t$ (total overburden stress) $- nP_p$ (pore or fluid pressure)
P_e

However, Rieke and Chilingarian in 1974 proved experimentally that coefficient n is equal to one.

The concept of the shale-compaction process can be explained by a mechanical model which is composed of a perforated round metal plate and the enclosing cylinder which contains a metal spring and water (Figure 1). In this analogy, the spring represents the compressible clay particles, the water represents the fluid in the pore space, and the size of the perforations in the metal plate determines the permeability.

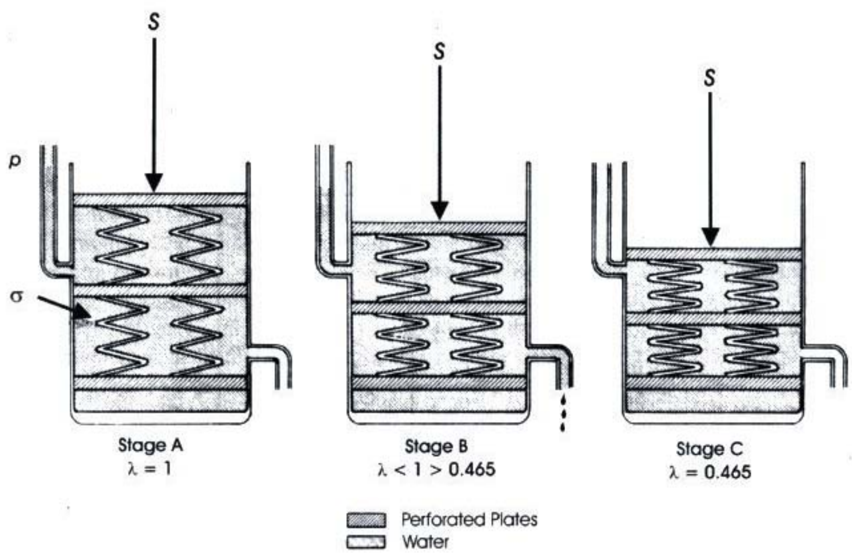

Figure 1. Schematic representation of compaction. σ = grain-to-grain strength. S = axial component of total stress (overburden pressure), and p = fluid pressure, $\sigma = S - p$. Stage A) initial pressure system. Stage B) some water is allowed to escape; springs now carry a greater part of applied load. Stage C) compaction equilibrium; load is supported jointly by springs and the water pressure, which is hydrostatic. $\lambda = p_p / p_t = p / S$, where p_p = pore pressure and p_t = total pressure. (Modified after Terzaghi and Peck, 1948: in Hottman and Johnson, 1965, p. 718 and in Rieke and Chilingarian, 1974, fig. 51, p. 93.)

Using this model, clay saturated with water can be treated mathematically as a two-phase continuum. The hydrated clay may be envisioned as clean clay plates in mechanical contact with each other with the water wetting the clay-particle surfaces and filling the pore space between the particles. If the mechanical model were sealed in such a manner that no fluid could escape through the plate, then the total applied pressure to the system would be carried by the fluid and none by the spring (Figure 1A). The compressibility of the spring is assumed to be so great that the strains produced in the fluid and in the cylinder walls are negligible in comparison (Taylor. 1948). Figure 1B shows that if the fluid is allowed to escape through the perforations, then the overburden pressure is carried both by the spring and the fluid. As the fluid escapes, the plate sinks lower and lower, compressing the metal spring. The length of time required for the spring to pass from one state of compaction to the next depends on how rapidly the water escapes; this is determined by the size of the perforations in the plate or permeability of the rock. Equilibrium is reached at a point where none of the overburden stress is borne by the fluid (Figure 1C); however, any additional applied loads cause the plate to further compact the spring, expelling additional fluid. In this manner the clay layers are thought to be compacted under the weight of the overlying sediments.

In the spring analogy for compaction, the following relationship (static equilibrium) must exist at any particular time:

$$F_\mathrm{t} = F_\mathrm{e} + F_\mathrm{p} \qquad (1)$$

where F_t is the total overburden force applied to the system, F_e is the effective force carried by the spring, and F_p is the force applied to the fluid. If these forces are divided by the total cross-sectional area, A, of the enclosing cylinder through which the fluid flows, then:

$$P_\mathrm{t} \text{ or } \sigma_\mathrm{t} = F_\mathrm{t}/A \qquad (2)$$

$$P_\mathrm{e} \text{ or } \sigma_\mathrm{e} = F_\mathrm{e}/A \qquad (3)$$

$$P_\mathrm{p} \text{ or } \sigma_\mathrm{p} = F_\mathrm{p}/A \qquad (4)$$

where P_t or σ_t is the total stress applied to the system, P_e or σ_e is the effective stress and P_p or σ_p is the pore pressure carried by the fluid. Thus, Eq. (1) can be rewritten as:

$$\sigma_\mathrm{t} = \sigma_\mathrm{e} + \sigma_\mathrm{p} \quad \text{or} \quad P_\mathrm{t} = P_\mathrm{e} + P_\mathrm{p} \qquad (5)$$

As expressed in Eq. (5), the total stress, P_t, normal to any plane in the skeletal structure consists of two components: (1) the pore fluid pressure, P_p; and (2) the effective stress component, P_e, which is “effectively” carried by the skeletal structure. The spring analogy in the lab often fails to agree with the actual compaction of clay in the field as the pressure conditions are often not uniform throughout the thickness of the clay mass as they are in the smaller test cylinder. In compacting a saturated clay sample with water at a given pressure, the water pressure at its surface is atmospheric (0 psig), whereas at short distances inside the clay sample the water pore pressure is equal to $P_\mathrm{t} - P_\mathrm{e}$.

1.2. Models of Subsidence

There are several different theoretical and semi-empirical approaches regarding the prediction of subsidence over producing formations. In particular, Poro-elasticity and Terzaghi's approach will be illustrated in the following.

Poro-elasticity approach

The poro-elasticity approach proposed by Geertsma (1973) suggested the following formula for calculating a component of the stress tensor, σ_{ij}:

$$\sigma_{ij} = 2G\left[e_{ij} + \frac{\nu e \delta_{ij}}{(1-2\nu)}\right] - (1-\beta)P\delta_{ij} \tag{6}$$

where:

σ_{ij} = stress component, related to the bulk stress system

e_{ij} = strain component

$e = \sum e_{ij}$ = dilatation or relative volume change of the bulk material

G = bulk shear or rigidity modulus

ν = Poisson's bulk ratio

P = pore-fluid pressure

β =.ratio of rock matrix compressibility to the bulk compressibility

δ_{ij} = Kronecker's delta

This approach can only be used for elastic, reversible deformations. The majority of deformations due to natural and engineering processes, however, contain irreversible components that often prevail.

Terzaghi's Approach

Terzaghi's model (1943) introduced a different approach, the effective stress concept. The effective stress concept was first empirically formulated on the basis of laboratory experiments. This approach assumed that the load, L (overburden pressure), applied to a unit of fluid-filled soil or rock, is supported by the solid frame (grain-to-grain stress, σ_e or P_e) and the pore pressure increase, ΔP. The support provided by the solid frame, within this scheme, was also called effective-stress σ_e or P_e. Effective stress does not correspond to any actual stress in a rock, but is the stress in the model medium and is an average stress (a computed value) on a horizontal plane:

$$\sigma_\mathrm{e} = L - \Delta P \tag{7}$$

In the Terzaghi's model, physical meanings of measured values are quite definite: L represents a new, additional load applied to a physical body in mechanical equilibrium and ΔP is the elastic response of the pore fluid to the total (elastic, reversible, and plastic, irreversible) deformation of the specimen. It is assumed that effective stress, σ_e, is the stress in the solid frame under these conditions, whereas actually it is the stress in the model medium (Gurevich and Chilingarian, 1993).

In Terzaghi's equation ($\sigma_e = L - \Delta P$), although ΔP is called the pore pressure, it actually represents the pressure change. It is an elastic response of the pore water to deformation of a sample, caused by the applied load and not the total pore pressure itself. In the laboratory, the height of a specimen is, usually, about one inch (2.54 cm). Thus the hydrostatic pore pressure, before load application, is negligible in such a specimen and the excess pressure above the hydrostatic pressure was taken for the whole pressure value. Numerically, mathematically this was correct, but physically it was not, leading to unavoidable confusion. Thus, the excess pore pressure and additional stress in the solid frame support the load.

Later, Terzaghi's concept was extended to the relation between the total load (including the weight of rock column) and the total pore fluid. Whereas in the previous model fluid pore pressure existed only dynamically, in the course of the deformation process in this extended case pore fluid pressure exists even at equilibrium. At equilibrium, pore fluid pressure due to its gradient provides buoyancy of grains, which results in the reduction of their weight (see Rieke and Chilingarian, 1974). However, owing to the fact that grain contacts are not point contacts, the relation:

$$\sigma_e = L - P \qquad (8)$$

where the total value of pressure P is used, is possibly incorrect for the majority of cemented rocks (Jaeger. 1979; Gurevich, 1980). Equations (7) and (8) are physically different.

In a dynamic situation, hydrostatic uplift and elastic response act together. Thus, the physical meaning of the effective stress concept being applied to deformations of rocks in situ is rather obscure physically and often leads to confusion. This is especially true because the effective-stress concept completely ignores both the nature of deformations and mechanical properties of rocks that are deformed. This concept does not take into account the fact that, not just a small piece, but rather a large mass of rocks is being deformed as a single unit. Thus, when deformation cannot be reduced to a one-dimensional model, some additional problems arise. For example, the generation of a vertical tension and strain of rocks in the course of subsidence of formations above a compacting reservoir is not compatible with the effective-stress concept: the overburden weight is not fully transmitted to the reservoir but, nevertheless, compaction continues (Gurevich and Chilingarian, 1993). Additional problems with the effective-stress concept arise because of heterogeneity of the rock mechanical properties, and the presence of fractures. Owing to heterogeneity, some scale effects arise and should be taken into account (Bell and Dusseault, 1990: Enever et al.. 1990; Ito et al., 1990; Li, 1990; Ratigan, 1990).

Another source of confusion is the disagreement on whether or not compressibility of sediments and rocks obtained from compaction tests in the laboratory and those in situ differ. There is a dependence of compressibility on loading history and according to some investigators the measured degree of compaction in situ is lower than those predicted from laboratory tests. Radioactive bullet surveys in the Groningen gas field showed that the actual compaction values were three times lower than the amount predicted (Mess, 1979). It is also important to know, whether uniaxial or hydrostatic compaction equipment was used in the laboratory. For example, the writers observed that when using hydrostatic compaction apparatus, the compressibilities of unconsolidated sands are often about twice as high as those obtained when using uniaxial compaction apparatus.

The effective-stress concept is attractive because of its simplicity. It is believed to work well in simple cases when deformation is a one-dimensional compression. Rieke and Chilingarian (1974) relied heavily on uniaxial compaction apparatuses because they believed that "as the overburden load becomes large enough, the pressures are probably uniaxial".

The overburden pressure, P_t, is equal to the specific weight of the overlying water-saturated rock (γ_b) multiplied by depth (D):

$$P_\mathrm{t} = \gamma_\mathrm{b} D \tag{9}$$

The effective stress, P_e, continuously increases with decreasing porosity (ϕ) and is a function of either porosity or the remaining fluid content:

$$P_\mathrm{e} = f\left(\phi\right) \quad P_\mathrm{e} = f\left(S_\mathrm{g}, S_\mathrm{w}, S_\mathrm{o}\right) \tag{10}$$

where S_g = gas saturation, S_w = water saturation and S_o = oil saturation, (saturations expressed as percent of pore space).

$$S_\mathrm{g} + S_\mathrm{w} + S_\mathrm{o} = 100\% \tag{11}$$

During sedimentation, the stresses ($P_\mathrm{e}, P_\mathrm{t}, P_\mathrm{p}$) attain temporary equilibrium with different degrees of support assumed by the rock-matrix skeletal structure and the fluids occupying the pores ($P_\mathrm{t} = P_\mathrm{p} + P_\mathrm{e}$). Gravitational stress (mass of the overburden) is transmitted vertically through the grain-to-grain contacts. Hydrostatic stress from the mass of the interstitial water above the compacting rocks is transmitted through the water column. Another stress that aids grain redistribution is the viscous drag caused by movement of water downward and toward producing wells.

There are several types of recoverable and non-recoverable deformations that may occur in response to the unbalance of the $P_\mathrm{t}, P_\mathrm{p}$ and P_e. Increase in the grain-to-grain stress can result in recoverable elastic and visco-elastic (time dependent) deformation of the grains or the grains may permanently deform by structural yield (crushing under the increased load) and plastic deformation of shape.

Compaction in natural environments is accompanied by other processes and occurs at a much slower rate (Gurevich, 1969, 1980). Compaction in nature depends both on the acting overburden or tectonic load and on rock strength. Continual tectonic movements influence the rock strength. These movements sporadically break grain contacts and, thus, result in the rearrangement of grain packing and compaction without additional load. Periodic changes in temperature, seismic waves, and other factors have the same impact on compaction. Shaking (seismic waves) facilitates compaction. These mechanisms of compaction are missing in the laboratory tests. In situ loading and compaction are sometimes six to eight orders of magnitude slower than in the laboratory tests. This means that molecular processes of slippage along the grain-crystal boundaries also play a more significant role in nature than when measured in the laboratory.

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Biographical Sketches

John O. Robertson, Jr, Ph.D., has more than 40 years' experience in the area of petroleum and environmental engineering. Dr. Robertson has co-authored 10 books and 30 articles in leading scientific journals. He has been awarded three gold medals and many international honors for his work. He has served as president of Heart Enginnering Inc. for the past 25 years.

George V. Chilingar, Ph.D., is a professor of civil and petroleum engineering. He is an author of 65 books and 500 articles in the field of petroleum engineering and geology. Dr. Chilingar has received more than 100 medals and awards from various countries and organizations, including foreign membership in the Russian Academy of Sciences. During his career, he was chief of petroleum and chemicals laboratory at Wright Patterson Air Force Base, Dayton, Ohio, and senior advisor to the United Nations. He is the Director of Dr. Rudolf W. Gunnerman Energy and Environment Laboratory in the University of Southern California.

Leonid F. Khilyuk, Ph.D., is a consultant in mathematical modeling of environmental processes and former chairman of the Department of Computer Sciences and Applied Mathematics in the Kiev Technological University. He has more than 100 publications worldwide in mathematical modeling of environmental processes, control theory, probability, and statistics.

Bernard Endres, Ph.D., is an environmental consultant specializing in the fields of oil and gas migration, geological site characterization, and evaluation of chemicals and gas constituents relating to source identification within the earth's geological structure. His scientific publications have included the environmental hazards associated with oil and gas migration, and evaluation of regulatory compliance.