Subsidence Caused by Fluid Withdrawal: The Need for a Systems Approach

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ABSTRACT

Current understanding of the processes induced by fluid withdrawal from a petroleum reservoir or aquifer is incomplete, partly because subsidence processes and related effects are viewed individually rather than as part of a single, complex system. Compaction due to pressure decrease in a reservoir or aquifer causes subsidence of overlying formations and the land surface. This deformation also leads to fracturing. Additional fractures can be created by pressure increases caused by fluid injection. Fracturing can result in upward migration of gas and other fluids, connection between adjacent reservoirs and aquifers, and changes in water composition due to the cross-flow of waters from different aquifers. Land subsidence can reduce the depth to the water table, causing seepage of water and light hydrocarbons floating on the water table into basements of buildings, and uplifting basements resulting in structural damage. Usually these processes and phenomena are studied separately; however, because they are related, they should be jointly investigated. A conceptual outline of the causes and consequences of fluid withdrawal is a preliminary step in developing a more comprehensive systems approach to the phenomena of land subsidence. A comprehensive systems approach requires that new techniques be developed for characterizing mechanical properties and deformation processes of large masses of heterogeneous rocks, monitoring changes in rock properties in the field, and developing hierarchical models of rock deformation.

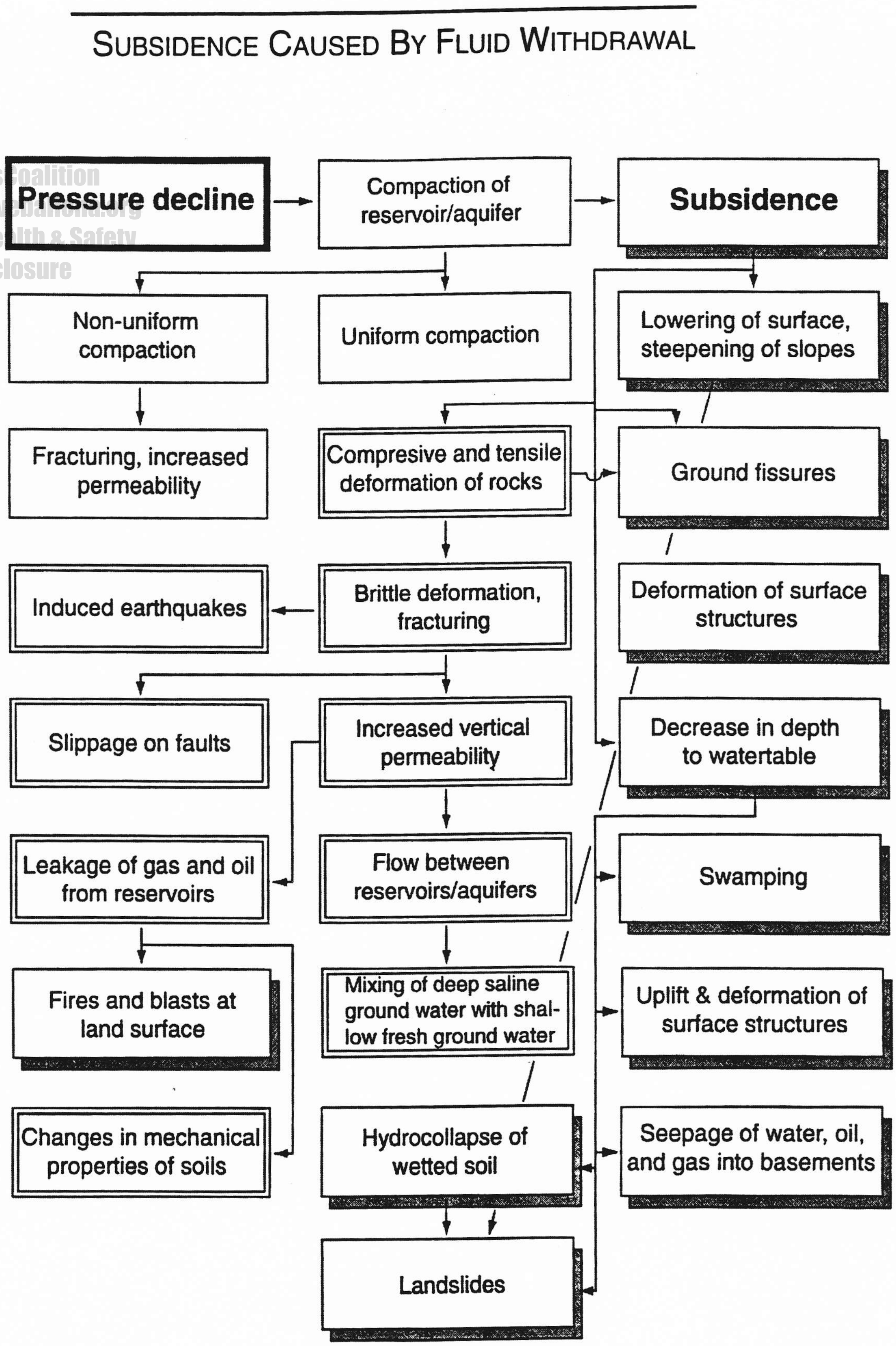

Figure 1. Relation between pressure decline (emboldened box), compaction (single boxes) in reservoirs and aquifers, subsidence-related processes occurring in earth materials overlying reservoirs and aquifers (double boxes), and surface effects of subsidence (shadowed boxes).

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Current understanding of the processes induced by fluid withdrawal from a petroleum reservoir or aquifer is incomplete, partly because subsidence processes and related effects are viewed individually rather than as part of a single, complex system. Compaction due to pressure decrease in a reservoir or aquifer causes subsidence of overlying formations and the land surface. This deformation also leads to fracturing. Additional fractures can be created by pressure increases caused by fluid injection. Fracturing can result in upward migration of gas and other fluids, connection between adjacent reservoirs and aquifers, and changes in water composition due to the cross-flow of waters from different aquifers. Land subsidence can reduce the depth to the water table, causing seepage of water and light hydrocarbons floating on the water table into basements of buildings, and uplifting basements resulting in structural damage. Usually these processes and phenomena are studied separately; however, because they are related, they should be jointly investigated. A conceptual outline of the causes and consequences of fluid withdrawal is a preliminary step in developing a more comprehensive systems approach to the phenomena of land subsidence. A comprehensive systems approach requires that new techniques be developed for characterizing mechanical properties and deformation processes of large masses of heterogeneous rocks, monitoring changes in rock properties in the field, and developing hierarchical models of rock deformation.

INTRODUCTION

Land subsidence over reservoirs and aquifers from which fluids are withdrawn is a phenomenon known all over the world, including such countries as the United States of America, Mexico, Venezuela, Italy, the former Soviet Union, Italy, Japan, and Kuwait (Saxena, 1979; Johnson, 1991; Chilingarian and others, 1995). Fluid withdrawal causes a chain of interrelated consequences. The immediate result is a decrease in fluid pressure that causes compaction of the aquifer or reservoir and consequent subsidence of overlying formations and the land surface. Bending of rock formations due to subsidence results in compression, extension, and shear, which lead to fracturing of rocks, damage to well bores, and, sometimes, to induced earthquakes. Land subsidence damages surface structures, such as buildings, pipelines, etc. Local subsidence superposed on an unchanged regional ground-water-flow system reduces the depth to the water table. This higher water table can cause water and oil floating on the water to seep into basements, especially if these basements were damaged by subsidence. Further damage can be caused by uplift of basement floors associated with rising water tables.

Rock fracturing allows upward migration of fluids, especially gas. Gas and oil from reservoirs can seep to the surface creating fire hazards. Saline water can contaminate fresh drinking water of the overlying aquifers. Fissures in the ground can very noticeably increase infiltration of surface water into subsurface aquifers and may contaminate ground water. In multireservoir oil/gas fields, fracturing can connect adjacent reservoirs and aquifers and influence production.

The processes causing subsidence and the phenomena resulting from it should be considered parts of a single system. Information on rock properties, geologic structure, and fluid withdrawal parameters should be considered in subsidence investigations. Currently in the oil and gas industry, emphasis is placed on reservoir compaction and subsidence; other facets of the process usually are ignored. A systems approach (fig. 1) allows interrelations among all subsidence issues to be considered. This allows unknown components of the system to be estimated or predicted when information may exist for only some of the components. A systems approach may be crucial to plan fluid production safely, to remediate sites, and to evaluate lawsuits and other litigation. Key details of a legal case may be revealed only if the subsidence process is analyzed in its entirety.

This paper emphasizes the importance of a multidisciplinary systems approach to planning fluid withdrawal and estimating and mitigating subsidence. It draws on our previous work (Gurevich, 1969; Gurevich and others, 1972, 1987; Gurevich and Chilingarian, 1993), but is preliminary. In this paper we (1) present, as fully as possible, all subsidence phenomena, processes, consequences related to fluid removal from aquifers and petroleum reservoirs, and the complete structure of their cause-and-effect relations, and (2) outline media properties and methods of exploration that are necessary to guarantee a successful systems approach to subsidence and related processes and hazards.

Not all statements in this paper are substantiated by published information, empirical data, or calculations. However, while we continue to analyze the subject in more detail for later publication, we hope to initiate discussion of this very important topic among scientists in traditionally disparate fields.

TYPES OF DEFORMATION CAUSED BY FLUID WITHDRAWAL

Deformations of Rocks

Pressure decrease causes compaction of rocks within and immediately above and below a reservoir or aquifer (Geertsma, 1957, 1973). Because pressure change is usually not transmitted a great distance across reservoir or aquifer boundaries, most compaction occurs within the reservoir or aquifer. As a result of compaction, the reservoir or aquifer bottom subsides only slightly, and overlying formations subside to a greater degree.

Structural analysis indicates that in multireservoir oil or gas fields less permeable rocks (cap rocks) between compacting reservoirs can be damaged more than rocks in formations above the shallowest reservoir.

Deformation caused by compaction and subsidence is a complex process. Clastic rock is a medium built of grains. In poorly consolidated, terrigenous rocks, grains have weak bonds. In consolidated, carbonate, metamorphic, and igneous rocks bonds are strong. Deformation begins elastically and is reversible, but soon its potential is exhausted and irreversible, rate- and stage-dependent deformation begins. Very slow deformation is almost plastic; grains have enough time to regroup, breaking and rebuilding bonds here and there. At higher deformation rates, microfracturing and brittle microdeformations become inevitable. At still higher rates, brittle deformation is predominant. The response of rock to stress also is effected by increases in cumulative deformation (deformation stage). Rocks with different mechanical properties follow the sequence of deformation mechanisms differently. Deformation due to pressure decrease caused by fluid withdrawal is rapid compared to geologic processes; therefore, brittle deformation may constitute a very appreciable part of the total process.

Compaction of a reservoir or aquifer is not limited to the rearrangement of constituent grains. In consolidated sandstones, especially in sandstones that are heterogeneous, considerable compaction can create microfractures and macrofractures that might partially neutralize the decrease in permeability caused by compaction.

From the onset of compaction, deformation of overlying formations cannot be considered purely elastic. As has been noted (Gurevich and Chilingarian, 1993), data on well-bore deformation presented by Poland and Davis (1969)

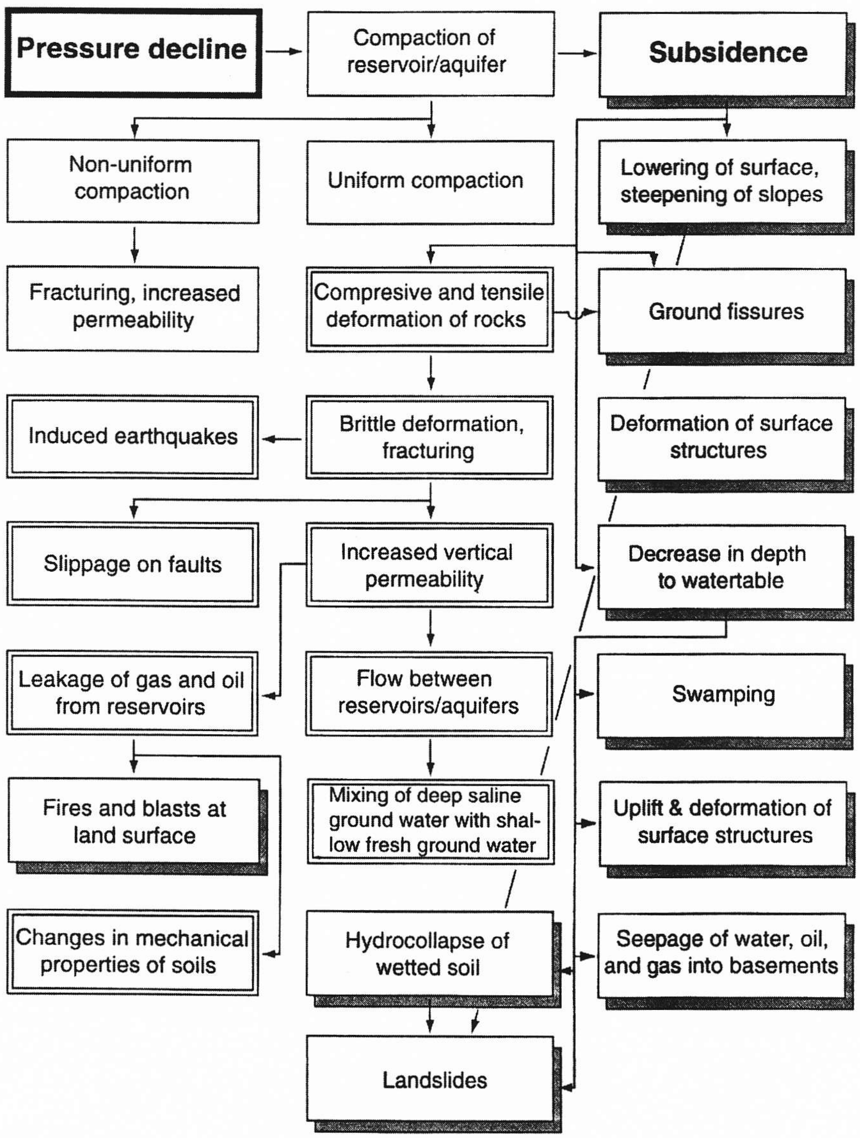

Figure 1. Relation between pressure decline (emboldened box), compaction (single boxes) in reservoirs and aquifers, subsidence-related processes occurring in earth materials overlying reservoirs and aquifers (double boxes), and surface effects of subsidence (shadowed boxes).

suggested that subsidence begins gradually in beds immediately overlying the reservoir or aquifer whereas land surface and shallow formations are unaffected. During this process, different rock beds and thin strata can separate, opening existing bedding joints and creating new ones (Gurevich and Chilingarian, 1993). Gradually, the deformation process expands upward. Therefore, from the very beginning of subsidence, deformation is not uniform in a vertical section and contains elastic, plastic, and brittle components in proportions that change with time and with the rate and total amount of deformation.

Compaction and subsidence also depend on the permeability of reservoir or aquifer rocks. In poorly permeable rocks, pressure decrease is uneven. Pressure decrease is greatest in the immediate vicinity of producing wells and lessens rapidly with distance from the well, especially early during fluid withdrawal. The bulk strength of rock formations overlying a compacting reservoir or aquifer provides lateral support (bridging effect) that prevents them from settling immediately. Land subsidence begins when horizontal extension of the pressure depletion zone becomes approximately five times greater than the thickness of the above-lying formations (Kotov and others, 1971). Subsidence, therefore, does not take place in the initial stage of fluid production, but deformation due to the initial pressure decrease can still occur. Local pressure decrease in the fluid changes compression of the rock grains in the depleted volume of reservoir or aquifer. The overburden weight is not yet active because of the bridging effect, but increase in grain volume caused by decreased fluid pressure can produce additional stress at grain contacts (effective stress) and cause some rearrangement and microfracturing. Pressure decreases of more than 100 kg/cm^2 are common during oil and gas production and consequent increase in effective stress may be substantial. Because grains of different minerals have different elastic moduli and because grain packing varies, differential stresses that theoretically could develop at grain contacts might break bonds between grains and create microfractures. This preliminary deformation could increase the amount of sand removed during initial production of the fluid and, thus, reduce rock stress around the well bore and somewhat loosen the rock. Processes active during the early stages of fluid production prepare the reservoir or aquifer rocks for compaction, which begins as soon as pressure depletion zones reach the size necessary to activate the overburden. This nonuniform deformation probably contributes to localization of fracturing during the full-scale compaction-subsidence process.

Bending of rock layers in addition to lateral displacements produces cross-bedding fractures, increases the aperture of faults, and causes slippage along faults. Earthquakes induced by fluid withdrawal or injection are a well-known phenomenon (McGarr, 1993). Lateral displacement due to subsidence causes earthquakes (Lee, 1979; Kosloff and others, 1980). Analyzing subsidence-induced earthquakes at the Wilmington, California, oil field, Richter (1958), Mayuga (1965) and Kovach (1974) noted that slippage occurred along nearly horizontal planes.

Fracturing increases cross-bedding permeability and, thus, creates or enhances vertical connectivity of adjacent reservoirs or aquifers.

Surface Deformation

Deformation due to compression and extension at and near the land surface causes fissures in the soil and damages buildings, pipelines, and other structures. Subsidence of 15 to 20 ft or more may cause swamping of subsurface structures. Regional water tables that approximately parallel the land surface can remain at nearly the same altitude after local subsidence lowers the land surface. The effect is to decrease the depth to water. If the water table rises (relative to land surface) higher than the bottom of a building, the uplift pressure on the structure is noticeably increased. If a basement is in heterogeneous soils or rocks, uplift may not be uniform, causing a distorting stress (fig. 2) and consequent damage to the structure. This damage can be combined with damage from deformation of the land surface. Raised water tables (relative to land surface) can saturate previously dry soils. In arid areas especially, this can lead to hydrocollapse, which can be considerable in loessal soils, and additional deformation of surface and subsurface structures.

Shallower water tables, especially during heavy rains when additional water table rise occurs, can cause water to leak into basements through damaged walls. If light oil, gasoline, or other hydrocarbons are floating on the water table, these contaminants can seep into the damaged basement creating serious hazards and fire danger. The authors observed domal deformation of floors of and seepage of crude oil into the underground garage of a multistory apartment building in the Fairfax area of Los Angeles.

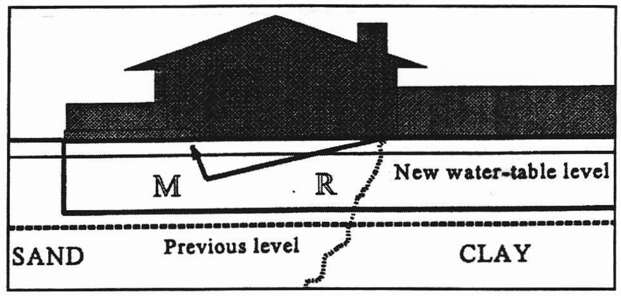

Figure 2. Illustration showing the effect of water table rise in heterogeneous soil. The basement of the building is partly in sand, partly in clay. Uplift due to a shallower water table after subsidence initially affects the part of the basement that is surrounded by sand. Therefore, the buoyancy force provides a rotating/bending moment (M) (equal to the buoyancy force multiplied by the action radius, R) that can damage the building.

Deformation in the Case of Heterogeneity in Rock Properties

Lateral heterogeneity of a reservoir or aquifer can cause hydraulic compartmentalization that can significantly affect deformation associated with subsidence in the following way. Hydraulic compartmentalization is most often caused by heterogeneous lithology and sealing faults. In a reservoir or aquifer divided into hydraulically separate compartments, fluid can be withdrawn from one compartment without affecting pressures in adjacent compartments. Because pressure decrease occurs only on one side of a seal, compaction and subsidence occur only on one side of the seal. This can create great stress in a fault zone and can cause a noticeable and sudden slip along sealing faults. Much greater surface damage can result from this kind of differential subsidence than from uniform subsidence due to compaction in a regionally uniform reservoir or aquifer.

CROSS-BEDDING FLOW

Seepage of oil and gas to the surface is a widespread and well known phenomenon (Link, 1952; Hovland and Judd, 1988; Clarke and Cleverly, 1991). Cross-bedding fracturing enhances old migration paths and creates new paths that hydraulically connect reservoirs or aquifers in the vertical section and the surface. Oil and more particularly gas can leak upward from a reservoir. If such migration occurred naturally, prior to fluid extraction (such as in the area of the La Brea tar pits in Los Angeles), migration may intensify after production begins. Vertical migration of hydrocarbons and, sometimes, leakage though damaged wells frequently creates a series of smaller pools above the major reservoirs. Fracturing induced by subsidence may increase leakage from these pools. Therefore, seepage can increase even though pressure in major reservoirs decreases dramatically. Gas, due to its low density, can migrate upward through substantially opened fractures and damaged wells even from reservoirs containing gas at less than hydrostatic pressure (Gurevich, 1969; Gurevich and others, 1993).

In areas subject to earthquakes, seeping hydrocarbon gases can affect mechanical properties of soil. Depending on the chemical and biochemical processes initiated by gas, the soil may become mechanically stronger, or may become more easily liquefied during vibrations caused by an earthquake.

Fractures can connect two or more reservoirs in an oil or gas field. The authors observed a California field where adjacent reservoirs became connected hydraulically as a result of deformation that occurred in the course of production.

FIELD EXPLORATION

Lithology, degree of lithification, arrangement of rocks of different lithology (bedding relations, etc.), and tectonic deformation determine the mechanical properties of rocks. Geologic analysis of a rock volume that contains a reservoir or aquifer from the viewpoint of deformational properties and the consequent translation of geologic data into mechanical data, are the basis for prediction of deformation due to fluid withdrawal or injection. Deformational behavior of rocks and formations should be examined and analyzed with respect to stress rates and deformation. Stresses that change slowly compared to the potential rate of grain rearrangement can produce plastic deformation of the rock. Faster stress change will cause brittle deformation and fracturing. Initial stresses in rock, caused by overburden weight and tectonic stress, will strongly affect distribution of stresses and the deformation produced by subsidence.

Deformation within a homogenous geologic stratum depends on the mechanical properties of that stratum and the adjacent strata. For example, the presence of a rock with very low shear strength (thin layer of a clay, mudstone, a rock rich in mica, etc.) can cause slippage in this weak layer at much lower shear stress than in the case of a relatively uniform formation. Most deformation would occur in this thin weak layer and the rest of formation would suffer only minor shear deformation. The presence of rocks with low shear strength should be investigated thoroughly.

Fracture distribution and dimensions (aperture, length, height) depend on tectonic structure, (anticline, flexure, fault zone), stress regime, secondary mineralization, and weathering, and, therefore, on geologic history. A major part of subsidence deformation can occur on existing macrofractures and microfractures, leaving blocks of unfractured rock nearly intact.

Geologic formations are complex, discrete bodies that can be represented only approximately as continuous media. To understand deformation of large volumes of rock with varying lithology, deformational models at multiple scales must be developed. Also, a "dictionary" should be developed to translate three-dimensional geology into a three-dimensional description of mechanical properties. This dictionary could be used as a basis for developing a hierarchical chain of deformational behavior models that mimics changes in deformational mechanisms as cumulative deformation increases and as deformation rates vary.

MONITORING

The following characteristics should be monitored simultaneously with study of their interrelations.

- Surface vertical and horizontal deformations by leveling surveys, satellite (Global Positioning System) techniques, and other similar techniques.
- Deformations in well bores by existing techniques (i.e., logging the position of radioactive bullets).
- Changes in the permeability of reservoir or aquifer rocks either indirectly through changes in productivity or directly by measuring permeability of cores obtained from new well bores.
- Microseismic activity recorded at several automatic microstations for locating microearthquakes to monitor and predict deformation and also to use as a warning for effects on production.
- Gas seepage and gas composition by automatic detectors positioned at probable seepage locations (fault zones, flexures, zones of extension due to subsidence).
- Position of the water table and other piezometric surfaces.

- Composition of water from producing and observation wells.

The set of monitoring techniques and monitored parameters would be different for shallow aquifers than for deep oil or gas reservoirs, which can have great pressure decreases. The set of monitored parameters would vary on a case-by-case basis.

TECHNIQUES TO BE DEVELOPED

Some new techniques are needed to improve understanding of subsidence-related processes to allow collection of field data at monitoring locations and to improve prediction capability.

- Often, reservoir pressures are maintained by waterflooding or gas injection to reduce the possibility of subsidence in urban and industrial areas during oil and gas production. Beyond the protected areas, pressure decrease and subsidence can occur and can be substantial enough to cause earthquakes. Pressure increase in underground gas storage reservoirs (usually abandoned oil fields) due to gas injection can lead to the same result. In seismically active zones there is a danger that these small earthquakes could trigger a major earthquake; therefore, it is necessary to develop techniques for (1) indirect and direct measurement of stress in heterogeneous rocks during subsidence, (2) evaluating tensile and shear strength of heterogeneous formations (as opposed to the methods used in a homogenous rock bodies), (3) measuring changes in rock strength during deformation, and (4) maintaining and reducing stress to a level below the formation strength to avoid earthquakes.
- Geologic media and their behaviors are very complex. Laboratory experiments and tests do not reproduce in-situ compaction or subsidence processes and cannot simulate them accurately. Deformation rates in the laboratory are much greater than in situ and, therefore, deformation mechanisms are different in the laboratory than in nature. Laboratory tests are conducted using uniform samples, whereas in-situ processes often occur in complex heterogeneous media where redistribution of pressure, stress, and deformation significantly affects material response (Gurevich, 1987). Correlation of empirical statistics of in-situ deformation with geologic and physical characteristics is necessary to determine more realistic parameters for simulation models. This will increase the accuracy of predictions of, for example, subsidence, fracturing, induced earthquakes, and gas seepage. Correlations between geologic characteristics and deformation parameters could be made on the basis of a complete cause-and-effect geological/physical model of deformation processes. A set of geologic characteristics selected as analogs to physical values of this model, together with hydrodynamic parameters of the fluid withdrawal or injection can be used for correlation techniques. Data on many reservoirs or aquifers should be used to provide reliable results and develop geologic indices for accurate prediction of subsidence and its consequences.
- Improved models and sets of models for simulating and predicting subsidence should be developed, continuing the current trend of evolution of subsidence simulation models.

Total relative deformation of rocks during subsidence is small. Therefore, it is difficult to reliably establish the mechanism responsible for deformation by mathematical modeling because adjusting numerical values of parameters and coefficients is merely a data-fitting process that does not reveal incomplete or incorrect models of the mechanisms involved. More attention should be paid to developing adequate understanding of deformation mechanisms and processes in huge masses of rock with heterogeneous geologic and mechanical properties. As a result, more realistic, complete, and accurate models of in-situ deformation will be developed.

Deformation and mechanisms of deformation are not uniform in time and space. Initially, pressure depletion occurs only around producing wells. Due to small lateral size of these zones (the lower the permeability, the smaller the lateral size), initially there is no subsidence, but deformation and predeformational changes in rock strength do occur. As depletion zones spread over the larger area of reservoir or aquifer, compaction becomes noticeable and subsidence begins, but due to rock strength changes around producing wells during the initial period, later deformation is not uniform. As has been mentioned, there is also evidence that deformation due to subsidence begins at depth and can cease to be elastic even before surface deformation occurs.

The complete deformation model, therefore, may be based on a "sliding" model of deformation mechanisms such that at each particular physical point (i.e., a grid cell in a mathematical model), the deformation law (algorithm in a mathematical model) should change from linearly elastic to nonlinearly elastic to plastic to brittle depending on the critical value of certain deformation parameters. Such a model, although complex, should describe real deformation processes more accurately. If the distribution of types of deformation mechanisms acting concurrently is statistically uniform, another approach can be suggested. Integrating the effects of all deformational mechanisms involved could yield a composite model with a generalized mechanism. Parameters of this model may be made dependent on the rate and total amount of deformation to provide necessary flexibility for this "bulk" model. Models of these two types may bridge the gap between current models of deformations in a laboratory samples and in huge volumes of rocks in situ.

To select an optimal simulation approach, hierarchical systems of models can be developed (Gurevich, 1989). Partial simulations of separate elements of the total process make it possible to select best approximations of the actual process and to simplify simulation of the total process without losing accuracy.

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