The History of the Aquitard-Drainage Model

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ABSTRACT

Pratt and Johnson originally proposed the aquitard-drainage model in their investigation of the first United States occurrence of land subsidence associated with withdrawal of fluids from porous media in the Goose Creek oil field in Texas. The model was immediately challenged, although most subsidence investigators continued to assume that compaction was occurring in fine-grained beds. In the 1960s, direct field measurements of compacting intervals in the San Joaquin Valley, California, confirmed the model's validity for compacting aquifer systems. Today, the model forms the conceptual basis for most physically based methods for predicting subsidence caused by withdrawal of ground water. Measurements of compacting intervals at the Wilmington oil field in California and of sand and clay compressibility in the laboratory, however, indicate that sands may be as compressible as clays at overburden pressures encountered in oil fields.

INTRODUCTION

The aquitard-drainage model attributes land subsidence associated with the withdrawal of ground water from aquifer systems to nonrecoverable compaction of slowly draining interbedded fine-grained layers (Helm, 1975). These layers are known as aquitards (Poland and others, 1972). The model forms the conceptual basis of most theoretical methods that predict land subsidence associated with depressuring of porous media (for example, see Harris and Harlow, 1947; Gambolati and Freeze, 1973; Helm, 1975). This article chronologically reviews the historical development of the aquitard-drainage model and the contributions of Joseph F. Poland and his colleagues to that model (fig. 1). Contributions from both hydrogeology and petroleum engineering are considered here because the conceptual development of the model rests on experience with subsidence associated with both aquifer systems and petroleum reservoirs. This dual treatment gives this review an interesting aspect because the emphasis by some investigators on the compressibility of fine-grained layers in oil fields prompted them to overlook the potential contribution from sands. Later work demonstrated the potential significance of sand compressibility to subsidence associated with petroleum withdrawal. This article follows the terminology adopted by Poland and others (1972), particularly in the usage of

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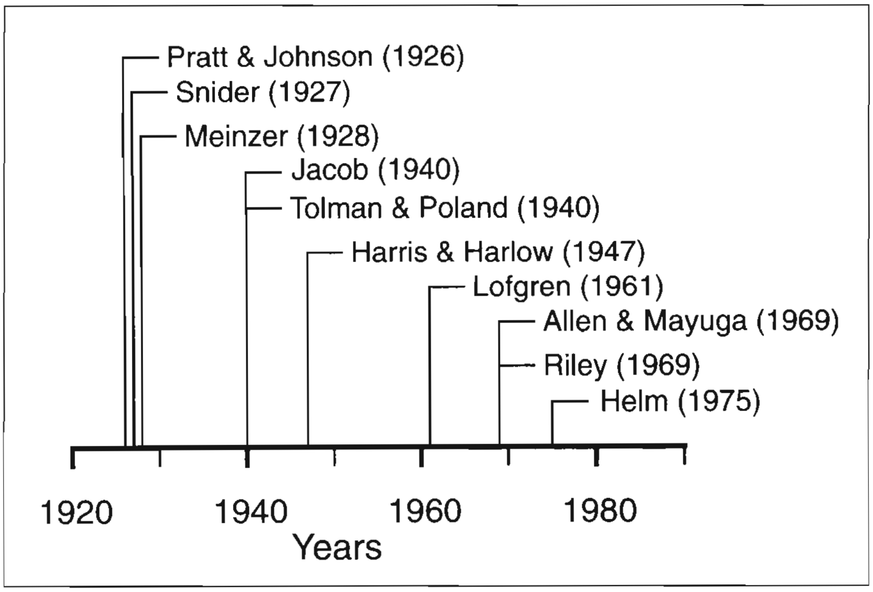

Figure 1. Milepost publications in the history of the aquitard-drainage model.

the term "compaction" to indicate a decrease in volume of sediment under compressive stress.

This review focuses on the historical development in the United States of the aquitard-drainage model. This focus is justified because citations in the American literature indicate the aquitard-drainage model developed without significant foreign influence except for that by Karl Terzaghi. References by Meinzer (1928) to both Terzaghi's principle of effective stress and studies of soil compressibility confirm that Meinzer was influenced by Terzaghi's research. Tolman and Poland (1940) also referred to work by Terzaghi. This general absence of foreign influence is not to imply that foreign investigators were not reaching similar conclusions about the mechanism of land subsidence. For example, Carrillo's (1948) explanation of the mechanism of land subsidence in Mexico City emphasized the role of slowly draining clay layers. Similarly, the historical review by Inaba and others (1969) indicates that Japanese investigators had conducted field studies in subsiding areas in Tokyo before World War II and that these studies revealed the significance of compressible fine-grained layers.

GOOSE CREEK OIL FIELD LAND SUBSIDENCE

The earliest recognition of subsidence associated with fluid withdrawal from porous media was at the Goose Creek oil field, Texas. The field, which is on the northern shore of Galveston Bay, subsided approximately 1 meter from 1917 to 1925. Because much of the land was low-lying, the subsidence converted formerly dry land into tidelands. This led to a legal challenge by the state of Texas, which holds title to all oil beneath tidelands. The litigation prompted an investigation of the cause of the subsidence (Pratt and Johnson, 1926). In their analysis, which concluded that the subsidence was induced by petroleum production, Pratt and Johnson (1926, p. 520) clearly stated the concept of the aquitard-drainage model.

> *Under such circumstances, the removal of oil and water from the sands is not followed by a free flow of water into the pore spaces from distant localities, because the compact nature of the clays, which completely surround and isolate the sand lenses, prevent [sic] such ready flow of water. The pore spaces are therefore occupied by water draining in more slowly from the adjacent clays; and it is a well-known fact that the draining of clays causes them to become more compact. This, in turn, would permit subsidence of the overlying surface.*

Although the subsidence was associated with petroleum production, Pratt and Johnson (1926) speculated that the slow drainage of water from the clays was the specific mechanism that caused compaction and subsidence.

Snider (1927) challenged Pratt and Johnson's (1926) proposed mechanism of subsidence at Goose Creek. He speculated that removal of oil, gas, and water caused cavities to form in the subsurface and that the subsidence was caused by collapse of the cavities. Snider dismissed clay compaction as the mechanism of subsidence Snider (1927, p. 729 first paragraph; p. 734 second paragraph).

> *...but the explanations given (by Pratt and Johnson, 1925) as to the mechanism of the subsidence are not considered satisfactory. The hypothesis is advanced that the oil, gas, and water occupied space in addition to the normal pore space of the sands, and their removal created cavities which were the direct cause of the subsidence.*
>
> *Clay retains water very tenaciously. It is difficult to press water even from a wet mud, and it is very doubtful that pressures involved would do it.*

AQUIFER-SYSTEM COMPRESSIBILITY

The significance of compressibility of confined aquifer systems was recognized in the 1920s. Previously, estimates of the potential yield from confined aquifers assumed aquifers were incompressible. Meinzer's pioneering research on free-flowing wells in the Dakota Sandstone, however, indicated that aquifer compression was an important source of water (Meinzer and Hard, 1925; Meinzer, 1928). He concluded that the compression was occurring in the sand and cited several lines of evidence to support his hypothesis, including Snider's (1927, p. 269) conclusion that the mechanism of subsidence at Goose Creek was seated in the sand layers.

> *...Snider (1927) accepts that the subsidence was caused by the removal of oil, gas, water, and sand but shows that...drainage from the clay strata interbedded with the producing sands cannot have been effective in causing shrinkage and subsidence.*

Theis (1935), with the aid of friend and mathematician Clarence Lubin (Clebsch, 1993), extended Meinzer's concept of elastic compressibility of aquifers to derive the relation between the lowering of the piezometric surface and discharge of a pumping water well. Theis followed Meinzer's conclusion that the compressibility effects occurred within the sand layers, although Theis also included a term in his storage coefficient for water compressibility. Jacob (1940) placed Theis' equation on a more fundamental basis by deriving from first principles of physics the differential equation that describes the flow of ground water in an elastic confined aquifer. Although Jacob (1940, p. 574) did not reveal the source of his insight, he recognized the significance of the elastic compressibility of clay beds and stated aspects of the aquitard-drainage model.

> *...the chief source of water derived from storage "within" an artesian aquifer is probably the contiguous and intercalated clay beds (or shale-beds, in a sandstone aquifer) and that because of the low permeability of the clays (or shales) there is a time lag between the lowering of pressure within the aquifer and the appearance of that part of the water which is derived from storage in those clays (or shales).*

Because Jacob (1940) considered the deformation of the clay beds to be elastic, he stopped short of stating the aquitard-drainage model.

SANTA CLARA VALLEY LAND SUBSIDENCE

Following the subsidence in the Goose Creek oil field, the next major episode of subsidence in the United States was on the south end of San Francisco Bay in the Santa Clara Valley of California. Subsidence, which amounted to 1.25 meters, was recognized during the 1932–1933 releveling of benchmarks that had been first leveled in 1912.

Discrepancies in an earlier releveling in 1920 had been incorrectly attributed to survey error. Although the subsidence was quickly attributed to ground-water withdrawal based on its areal correlation with water level decline (Tibbetts, 1933), the mechanism was misidentified. Tibbetts (1933, p. 204), although correctly identifying the clay beds as the seat of the deformation, incorrectly attributed the deformation to desaturation of the clay beds.

> *The change in volume of the formerly saturated clay which has now been drained (by pumping) should account for the settlement...*

Joseph F. Poland, who had enrolled as a graduate student at Stanford University in 1931, initiated an investigation with his professorial adviser, Charles F. Tolman, of ground-water problems in the Santa Clara Valley. Their investigation (Tolman and Poland, 1940, p.33) unambiguously stated the aquitard-drainage model and used it to explain the observed subsidence.

> *...the pressure in the sand layers is reduced in direct proportion to the lowering of water level and this pressure-difference allows the water in the clay to drain into the sand layers...*

Their mechanism drew heavily on laboratory investigations by Terzaghi (1927), but they also cited field correlations that indicated the compaction was indeed occurring in clay beds (Tolman and Poland, 1940, p. 33).

> *Land sinking is also more pronounced in the vicinity of deep wells which tap a larger number of aquifers and which drain a greater thickness of clay than shallow wells.*

Tolman and Poland (1940, p. 33) also addressed the issue of recoverability of the subsidence, that is, the proportion of the compaction that was elastic.

> *Whether or not the volume recovery is complete, partial, or nil depends largely on whether the structure and mineralogic composition of the clay has been changed by compaction. We know that the change of clay into shale by compaction due to geologic processes is irreversible.*

They presciently noted that issue would be resolved by future recoveries of water level in the aquifer system (Tolman and Poland, 1940, p. 33).

> *Further measurements of ground-level compared with recovery of water-level should show whether this action in the non-indurated alluvial deposits of the Santa Clara Valley is partially or completely reversible: in other words, whether with complete recovery of water-level in wells the ground-surface level will rise to the original position or to some intermediate level.*

Subsequent periods of water level recovery conclusively showed that most of the compaction in the Santa Clara Valley was permanent (Poland and Ireland, 1988).

WILMINGTON OIL FIELD LAND SUBSIDENCE

Subsidence above the Wilmington oil field in Long Beach, California, was the next significant land subsidence to occur in the United States (Holzer, 1990). The subsidence, which began in 1937, posed a hazard to port and naval facilities in the harbor at Long Beach. The subsidence ultimately reached 8.8 meters, accumulated rapidly, and prompted several efforts to predict its ultimate value. One of the earliest predictions was by Harris and Harlow (1947). They assumed that compaction was occurring in shales and used Terzaghi's theory of consolidation to predict the ultimate amount of compaction. Their application of consolidation theory to the Wilmington subsidence problem was the first quantitative application of the aquitard-drainage model to a subsidence problem. They predicted that subsidence would reach about 2.7 meters.

Ironically, subsequent oil well–collar surveys, which documented compaction as a function of depth and lithology, revealed that 67.7 percent of the compaction in the oil field had occurred in sands and only 32.4 percent had occurred in shales (Allen and Mayuga, 1969). Thus, Harris and Harlow (1947) had underestimated the significance of sand-bed compressibility. The importance of sand-bed compressibility at overburden pressures comparable to those encountered in oil fields has been corroborated by laboratory studies. These studies have demonstrated that sands that undergo shattering of individual grains may be at least as compressible, if not more compressible, than clays (Roberts, 1969).

FIELD AND RESEARCH INVESTIGATIONS: MECHANICS OF AQUIFERS PROJECT

In 1954, a U.S. Geological Survey (USGS) effort under the supervision of Joseph F. Poland began actively studying land subsidence in the San Joaquin Valley, California, as part of a federal and state interagency committee. The USGS efforts were formalized under the Mechanics of Aquifers Project, which was organized in 1956 and headed by Poland (Bull and Miller, 1975). The project sponsored both field monitoring and research, some of which bore directly on the aquitard-drainage model.

Documentation of the stratigraphic intervals in aquifer systems that were compacting was an early contribution of the project. The documentation was achieved by installing vertical strainmeters, known as vertical extensometers, in boreholes (Lofgren, 1961). These devices continuously monitored the total compaction of sediments next to the borehole. By installing multiple vertical extensometers at different depths, one could determine the compaction occurring in different depth intervals. These extensometers provided the first direct field confirmation in the United States that compaction, comparable to land subsidence, was concentrated in the depth intervals experiencing large head declines.

Later, Riley (1969) combined the extensometer records with hydrographs to produce stress-strain diagrams for the compacting interval. Riley developed a methodology to estimate the average vertical permeability and average elastic and inelastic compressibilities of the fine-grained strata from these records. This was the first field-based method to estimate aquitard-drainage model parameters. Riley's (1969) insight provided the basis for Helm's (1975, 1976) one-dimensional simulations of compaction that permitted the aquitard-drainage model to be used reliably as a predictive tool for subsidence.

The impact of Riley's (1969) and Helm's (1975, 1976) quantification of the aquitard-drainage model is described in the summary of the 1971 Geological Society of America Penrose Conference on the role of aquitards in multiple aquifer systems (Witherspoon and Freeze, 1972, p. 23).

> *The subsidence work of Francis Riley and more recently of Don Helm,...brought home to the participants a realization of the importance of maximum past consolidation pressure, and the concepts of reversible and permanent compaction to our understanding of the nature of formation compressibility and storage.*

CONCLUSION

Pratt and Johnson (1926) originally proposed the concept of the aquitard-drainage model in their investigation of the first United States occurrence of land subsidence associated with fluid withdrawal from porous media in the Goose Creek oil field. Although the concept was immediately challenged, most investigators of land subsidence associated with either petroleum or ground-water withdrawal assumed that compaction was occurring in clay beds. The validity of this assumption for subsidence associated with ground-water withdrawal was established by direct field measurements of compacting intervals in subsiding parts of the San Joaquin Valley in the 1960s. Field measurements in the Wilmington oil field, however, established that sands may be as compressible as clays at overburden pressures encountered in oil fields. Today, the aquitard-drainage model is the conceptual basis for most physically based predictive models of subsidence associated with ground-water withdrawal.

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