CLASSIFICATION OF LAND SUBSIDENCE BY ORIGIN

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Abstract
Data collected during the last decades allow classification of subsidence into 2 groups: Endogenic, caused by processes originating within the planet; and Exogenic, caused by processes originating near the Earth's surface. Exogenic subsidence can be subdivided into subsidence caused by removal or weakening of support and subsidence caused by an increase in actual or effective loading. Because of interrelationships between natural processes, this classification is only an approximation; subsidence is frequently related to compaction at great depth. Preservation of porosity here can be attributed to the tectonically controlled piezometric head developed prior to or during deposition of overburden. No subsidence will take place as a result of decline of piezometric head developed after aquifers became compacted by overlying sediments.

This concept allows detection of aquifers susceptible to subsidence by consolidation testing; samples of aquifers susceptible to subsidence are capable of consolidation at loadings less than the weight of their overburden.

Introduction
Since the middle of the 20th century, certain forms of land subsidence, related to human activity, have become a widespread, well-recognized geologic hazard (for example, Bolt, et al., 1975). The process has caused large monetary losses (Prokopovich and Marriott, 1983) and, not infrequently, human losses. The future spread of subsidence with growing world population and increasing technological advancement should be anticipated (Prokopovich, 1972). Methodologically, the first two steps in any scientific study are: (1) the accumulation of factual data and (2) proper classification of these data. Several national and international symposia and conferences on land subsidence have occurred during recent decades and a large number of factual case histories of subsidence have accumulated worldwide (Anonymous 1969, 1977; Donaldson, 1983; Poland, in print; Saxena, 1979; etc.).

This information provides a good background for the second step—the classification of subsidence. Such classification can be based on several principles, such as monetary impact of subsidence, magnitude of subsidence, geographic spread of subsidence, etc. From a geologic standpoint, however, the most desirable and scientifically correct classification should be based on the origin of the process, i.e., on its genesis.

The following genetic classification of land subsidence (Fig. 1) was originally proposed at the 24th International Geologic Congress in Montreal, Canada (Prokopovich, 1972), and repeated with minor modification at the International Conference on Evaluation and Prediction of Subsidence (Prokopovich, 1979). In order to promote this classification, regardless of previous presentations, its discussion at the present international gathering seems to be appropriate.
Subsidence and Its Spread

The term "subsidence" is as old as "modern geology." It is generally accepted that geology was "born" with the publication of Charles Lyell's *Principles of Geology* or the Modern Changes of the Earth and Its Inhabitants in the middle 1800's. The word subsidence appears on the first page of this classic volume in the caption to the frontispiece picture of ruins of Serapis' temple in Pozzuoli, Italy. The word was also used in a similar way in many places in the text of the book to indicate, mostly, the results of sea transgressions, rather than actual lowering of land surface. According to the modern definition by Bates and Jackson (1980, p. 624), subsidence is the "sudden sinking or gradual downward settling of the Earth's surface with little or no horizontal motion...."

Such "land subsidence" was rarely mentioned in the geologic literature 50-60 years ago, but has become alarmingly common, particularly after World War II. At the present time, exogenic subsidence has been reported on all continents, in different climatic zones, and is recognized as both a major geological hazard (Bolt, et al., 1975), and a form of pollution (Prokopovich, 1978). What are the reasons for such a "renaissance"? Was land subsidence simply not recognized in the past? Perhaps this is true in some cases, but in general, such an explanation is not sufficient.

Why did our dependable "terra firma" become "terra infirma"? Actually, the recent rapid spread of exogenic subsidence caused by human activity simply reflects the unprecedented growth of world population, growth of affluent societies, and the advancement of technology.
Genetic Classification

According to the classification, all types of subsidence can be divided into two major groups - ENDOGENIC SUBSIDENCE, caused by processes originating within the planet, and EXOGENIC SUBSIDENCE, resulting from forces originating on the Earth's surface and being ultimately related to solar energy. This second group also includes the consequences of ever increasing, frequently poorly planned, human activity. Each of the major groups can be subdivided according to the nature of processes causing the subsidence. The following text contains random, illustrated examples of such divisions and subdivisions.

Classification of endogenic subsidence is rather simple. It can be subdivided into subsidence caused by volcanic activity, folding, faulting, and other endogenic processes.

An excellent example of subsidence caused by volcanic activity is Crater Lake located in Oregon, U.S.A (Fig. 2A). It is generally believed that large volcanic eruptions of the ancient Mount Mazama partially emptied the magma chamber feeding this giant volcano, resulting both in the collapsing of its top and creation of Crater Lake. Another probably more common, but less spectacular type of volcanic subsidence is the collapsing of roofs of lava caves.

A good example of subsidence caused by folding is the Central Valley of California (Fig. 2B). This valley is a giant structural trough, located mostly between two mountain ranges - the Sierra Nevada on the east, and the Coast Ranges on the west. The folding here is probably related to plate tectonics.

Typical cases of subsidence related to faulting are numerous grabens or down-faulted blocks of the Earth's crust, such as the famous Rhine Valley in Europe. In the United States, "horst and graben" topography is particularly well developed in the Basin and Range Province in Nevada, Arizona, and partially, in California (Fig. 2C).

By definition, all forms of endogenic subsidence are natural processes not related to human activity. On the contrary, many forms of exogenic subsidence are directly caused by human activity. The impact of this subsidence will increase with increasing world population and advancing technology. This subsidence is actually a surficial expression of compaction ("consolidation") of material at depth due to removal of support (for example, oxidation of organic particles, melting of ice, etc.), weakening of support (for example, hydrocompaction), or an increase in actual or effective loading. Good examples of subsidence due to an increase in actual loading are collapses of karst cavities due to dewatering of unconfined aquifers. Such dewatering results in both increased grain-to-grain pressure due to the loss of buoyancy and increased weight of water-coated particles (Poland and Davis, 1969). Typical examples of subsidence due to an increase in effective loading are subsidence related to piezometric decline of confined aquifer systems and subsidence due to withdrawal of crude oil and natural gas. Selected examples of these forms of subsidence are shown in Fig. 3.

Interaction of Exogenic and Endogenic Processes

The presently accepted definition of land subsidence and its genetic classification should be considered as only a "first approximation" and may raise several new, hard-to-answer questions. For example, determination of vertical displacement of a point is usually made by comparing its surveyed elevations. "Absolute" elevations are based on mean sea level, which is not a constant. During Pleistocene glaciation, much ocean water
Fig 2. Selected examples of endogenic subsidence due to (A) volcanism (Crater Lake collapse caldera in Oregon, U.S.A.); (B) folding (Central Valley (V), located between the Coast Ranges (C) and the Sierra Nevada (S), California, U.S.A.); and (C) faulting (horst and graben topography - Basin and Range province, Nevada, U.S.A.).
Fig. 3. Examples of exogenic subsidence due to 
(A) removal of support (collapsed underground lignite mines, North Dakota, U.S.A., courtesy of the U.M. Region of the USSR); (B) weakening of support (hydrocompaction sink in the San Joaquin Valley, California, U.S.A.); (C) increase of actual loading (collapse of preexisting karst cavity due to dewatering for gold mining - loss of buoyancy and increased grain to grain stress, South Africa, courtesy of Dr. C. A. Bezuidenhout); and (D) increase of effective loading (withdrawal of crude oil; dry dock in Long Beach Harbor, California, U.S.A., courtesy of U.S. Navy).
was bound in continental ice caps and global sea levels were well below their present position. Melting of continental ice released large volumes of water and raised sea levels, submerging near-shore lowlands. If such flooding is considered to be a form of exogenic subsidence, we can expect a global acceleration of this process because of the melting of polar ice due to a growing "greenhouse" effect resulting from increasing levels of carbon dioxide and other pollutants in the Earth's atmosphere.

A more basic complication of genetic classification is the existence of intimate interrelationships between natural processes. As a general rule, exogenic processes are controlled by an endogenetic framework. For example, studies of subsidence caused by overdraft of confined aquifer systems in California indicate the important function of tectonic movement in this process. Since the subject is discussed in detail by Prokopovich (1983, 1983A), it is only briefly outlined in the following text.

Subsidence in the California San Joaquin Valley is mostly caused by an overdraft of a deeply seated sub-Corcoran aquifer system, and is a surface expression of consolidation of sediments of this aquifer at depth. In both the laboratory and nature, a series of equal increments of increased loading in the same material will result in progressively less compaction. Graphically, such a relationship follows an exponential decay curve. Hence, at a certain loading the original porosity of the material will be reduced to a point from which no notable further compaction will take place. Two terms, "stable depth" and "stable field," were used by Prokopovich (1976) to express these concepts. Depending upon the composition of sediments and other geologic factors, the "stable depth" below which additional compaction of sediments is practically nil, may vary. Theoretically, the amount of potential subsidence exponentially decreases with depth, and near-surface deposits are the most susceptible to compaction-related subsidence.

Surprisingly, most of the available facts on compaction of aquifers in areas affected by major subsidence contradict this assumption and indicate that most compaction actually occurs at a relatively great depth. The contradiction can be explained by past tectonic movements, which created piezometric head, which compensated for some of the loading of newly deposited overburden and thus prevented "normal" consolidation of aquifer systems (Fig. 4).

Prediction of Susceptibility of Aquifers to Subsidence
The theoretical considerations described above may be used for relatively simple and inexpensive detection of aquifer systems susceptible and not susceptible to compaction due to an increase in effective loading, i.e., systems capable and not capable of causing land subsidence.

Such detection can be achieved by one-dimensional consolidation testing of undisturbed core from the studied sediments. Routinely, consolidation testing is conducted on samples initially prestressed by loading equal to the weight of overlying sediments. For detection purposes, however, the initial testing should start with loading equal to approximately one-fourth to one-third of the weight of the overlying sedimentary column. The following testing should be carried out with increasing load increments, approaching, reaching, and exceeding the weight of overburden.

Interpretation of changes in the trend of consolidation-loading graphs will theoretically indicate the susceptibility of tested samples to consolidation under an increase in effective loading, i.e., susceptibility of the system to subside due to a decline in piezometric pressure. The
Fig. 4. Theoretical relationship between susceptibility to compaction and piezometric head of an aquifer. A. Older alluvium aquifer capped with a clay bed in an intermountain basin before deposition of overburden. B. The aquifer is compacted by the weight of overburden. C. Folding creates a confined aquifer in older alluvium prior to or during the deposition of overburden. D. Piezometric head partially compensates for the weight of overburden deposited after or during folding. Compaction of the aquifer is less than in case B. Decline of piezometric head under such conditions will result in subsidence. E. Folding occurred after the deposition of overburden; the aquifer is compacted by weight of overburden. No subsidence will be caused by a decline of piezometric head under such conditions.
idealized interpretation of compaction graphs is illustrated in Fig. 5. In the figure, compaction is shown not as the usual semilogarithmic plot, but as a Cartesian compaction-loading graph (Fig. 5, graph A). The loading scale is modified to indicate both the loading and the depth in an assumed basin. Graph A illustrates a "normally compacted" (consolidated) condition not modified by piezometric pressure.

A theoretical graph of laboratory consolidation of a sample taken at point "X" is shown in Fig. 5, graph C. Due to natural loading, the first three loadings (L1, L2, and L3) of the sample will cause no consolidation. (Actually, minor consolidation due to rebound will occur during this initial loading.) However, consolidation will occur at the
loadings $L_4$, $L_5$, $L_6$, etc., which exceed the weight of material capping sample "X". The confined aquifer system described in this testing was completely "precompacted" by the load of overburden, and the terrain is not susceptible to subsidence due to decline in piezometric head.

In the case shown in Fig 5, graph D, notable laboratory consolidation of the sample started at the loading $L_2$, which is smaller than the calculated load of overburden at the depth of the sample. Such compaction (consolidation) patterns indicate deposits that are not completely pre-consolidated by the weight of overburden and, hence, are susceptible to compaction as a result of an increase in effective loading. Land subsidence due to a decline in piezometric head can be expected in such a basin.

Further interpretation of consolidometer testing may provide important geological data on the magnitude and timing of tectonic movement. The method is probably also applicable to forecasting subsidence in oil and gas basins.

Conclusions
All predictions of future changes in global population indicate its rapid increase in the forthcoming decades. Such an increase will unavoidably be associated with growing demand for water, crude oil, gas and other natural resources. Hence, a future acceleration of development of aquifer systems and depletion of oil and gas fields appears to be unavoidable.

Agriculture, one of the main water users in the world, is already well-developed in many humid areas. Its future growth, needed to feed growing global populations, will most likely concentrate in warm, semiarid and arid regions. Experience obtained in California, Arizona, New Mexico, Texas, and elsewhere demonstrates the enormous agricultural potential of semiarid and arid regions. Such regions are particularly attractive to agriculture because of an abundance of sunshine, a long growing season and the absence of damaging precipitation.

Water in such regions may be obtained either locally, from underground sources, or by importation via long conveyance canals. Development of available ground water is, in the short run, less expensive than importation which requires construction of dams, canals, and pumping plants, i.e., large capital investments. Due to regional aridity, the recharge of available local ground water will soon be more than offset by pumping, resulting in an overdraft. Flat terrains, the choice lands for agricultural use, are usually associated with structural basins, which are frequently vulnerable to subsidence. The association of irrigation canals and subsidence is, therefore, not an accident. Proper understanding of origin and extent of subsidence is, therefore, mandatory for correct data-gathering, planning, and design of new, and rehabilitation of old, engineering projects. Genetic classification allows relatively easy "fingerprinting" of subsidence, while the concept of an endogenic framework of exogenic subsidence seems to allow relatively inexpensive detection of aquifer systems susceptible and nonsusceptible to subsidence. This concept may also be applied to predictions of possible amounts of future subsidence. The same approach will also probably be applicable to oil and gas fields.

Geologic interpretation of consolidometer testing may also be helpful in understanding the past tectonic history of an area. For example, such an evaluation allowed tracing of a generalized map of Holocene uplift in the west-central portion of the San Joaquin Valley (Prokopovich, 1983). Knowledge of the existence of such neotectonic movement is important for proper survey of land subsidence.
References
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