Glossary of Selected Terms Useful in Studies of the Mechanics of Aquifer Systems and Land Subsidence due to Fluid Withdrawal

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By J. F. POLAND, B. E. LOFGREN, *and* F. S. RILEY

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CONTENTS

SYMBOLS AND DIMENSIONS

Symbol	*Dimensions*	*Description*
c_v	L^2T^{-1}	Coefficient of consolidation.
h	L	Head of water.
h_p	L	Pressure head.
J	FL^{-2}	Seepage stress.
K	LT^{-1}	Hydraulic conductivity.
m	L	Thickness of deposit.
m_v	L^2F^{-1}	Coefficient of volume compressibility of fine-grained sediments (for effective-stress change in range exceeding preconsolidation stress).

Symbol	*Dimensions*	*Description*
n	(1)	Porosity.
p	FL^{-2}	Geostatic stress.
p'	FL^{-2}	Effective stress.
p_a	FL^{-2}	Applied stress.
p_c	FL^{-2}	Preconsolidation stress.
S_s	L^{-1}	Specific storage.
u_w	FL^{-2}	Neutral stress or pressure.
Y_s	(1)	Specific yield.
β_t	L^2F^{-1}	Compressibility of the structural skeleton of the medium, for stress changes in the elastic range of response.
β_w	L^2F^{-1}	Compressibility of water.
γ_w	FL^{-3}	Unit weight of water.

1 Dimensionless.

GLOSSARY OF SELECTED TERMS USEFUL IN STUDIES OF THE MECHANICS OF AQUIFER SYSTEMS AND LAND SUBSIDENCE DUE TO FLUID WITHDRAWAL

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INTRODUCTION

The geologic and engineering literature contains a variety of terms that have been used to describe the processes and environmental conditions involved in the mechanics of stressed aquifer systems and of land subsidence due to withdrawal of subsurface fluids. The usage of certain of these terms in reports by the U.S. Geological Survey research staff investigating mechanics of aquifer systems and land subsidence is defined and explained in this glossary. Several terms that have developed as a result of the Survey's investigations are also defined.

The aquifer systems that have compacted sufficiently to produce significant subsidence in California and elsewhere are composed of unconsolidated to semiconsolidated clastic sediments. The definitions given in this glossary are directed toward this type of sediments; they do not span the full range of rock types that contain and yield ground water. In the definitions of the components of the compacting stresses, the contribution of membrane effects due to salinity or electrical gradients has been discounted as relatively insignificant in the areas studied.

In our research reports, pressures or stresses causing compaction are usually expressed in equivalent "feet of water head" (1 foot of water = 0.433 psi (pounds per square inch)). In this glossary, dimensions involving stresses are listed first in brackets, in the usual convention, and second in parentheses, with stresses expressed in "feet of water."

A Geological Survey committee on redefinition of ground-water terms recently issued a report entitled "Definitions of Selected Ground-Water Terms" (Lohman and others, 1972), to which the reader is referred.

The authors of this glossary appreciate the reviews and improvements of the manuscript suggested by H. H. Cooper, J. G. Ferris, and S. W. Lohman.

TERMS

Aquiclude

An areally extensive body of saturated but relatively impermeable material that does not yield appreciable quantities of water to wells. Aquicludes are characterized by very low values of "leakance" (the ratio of vertical hydraulic conductivity to thickness), so that they transmit only minor inter-aquifer flow and also have very low rates of yield from compressible storage. Therefore, they constitute boundaries of aquifer flow systems.

Aquifer system

A heterogeneous body of intercalated permeable and poorly permeable material that functions regionally as a water-yielding hydraulic unit; it comprises two or more permeable beds separated at least locally by aquitards that impede ground-water movement but do not greatly affect the regional hydraulic continuity of the system.

Aquitard

A saturated, but poorly permeable, bed that impedes ground-water movement and does not yield water freely to wells, but which may transmit appreciable water to or from adjacent aquifers and, where sufficiently thick, may constitute an important ground-water storage unit. Aquitards are characterized by values of leakance that may range from relatively low to relatively high. Areally extensive aquitards of relatively low leakance may function regionally as boundaries of aquifer flow systems.

Coefficient of volume compressibility $[L^2F^{-1}]$, (L^{-1})

The compression of a lithologic unit, per unit of original thickness, per unit increase of effective stress, in the load range exceeding preconsolidation stress. Symbol m_v. (Modified after Terzaghi and Peck, 1948, p. 64.)

Compaction

"Decrease in volume of sediments, as a result of compressive stress, usually resulting from continued deposition above them" (American Geological Institute, 1957, p. 58). In this glossary, compaction is defined as the decrease in thickness of sediments, as a result of increase in vertical compressive stress, and is synonymous with "one-dimensional consolidation" as used by engineers. The term "compaction" is applied both to the process and to the measured change in thickness.

Compaction of sediments in response to increase in applied stress is *elastic* if the applied stress increase is in the stress range less than preconsolidation stress, and is *virgin* if the applied stress increase is in the stress range greater than preconsolidation stress.

Elastic compaction (or expansion) is approximately proportional to the change in effective stress over a moderate range of stress, and is fully recoverable if the stress reverts to the initial condition. Elastic changes occur almost instantaneously in permeable sediments and, for stresses less than preconsolidation stress, with relatively small time delay in strata of low permeability.

Virgin compaction has two components: an inelastic component that is not recoverable upon decrease in stress and a recoverable elastic component. Virgin compaction of aquitards is usually roughly proportional to the logarithm of effective stress increase. In aquitards (fine-grained beds) virgin compaction in response to a manmade increase in applied stress beyond the preconsolidation stress is a delayed process involving the slow expulsion of pore water and the gradual conversion of the increased applied stress to an increased effective stress. Until sufficient time has passed for excess pore pressure to decrease to zero, measured values of compaction are less than ultimate values. In virgin compaction of aquitards, the inelastic component commonly is many times larger than the elastic component. In coarse-grained beds, on the other hand, the inelastic component may be small compared to the elastic component.

Compaction, residual

Compaction that would occur ultimately if a given increase in applied stress were maintained until steady-state pore pressures were achieved, but had not occurred as of a specified time because excess pore pressures still existed in beds of low diffusivity in the compacting system. It can also be defined as the difference between (1) the amount of compaction that will occur ultimately for a given increase in applied stress, and (2) that which has occurred at a specified time.

Compaction, specific, $[L^3F^{-1}]$

The decrease in thickness of deposits, per unit of increase in applied stress, during a specified time period.

Compaction, specific unit, $[L^2F^{-1}]$, (L^{-1})

The compaction of deposits, per unit of thickness, per unit of increase in applied stress, during a specified time period. Ultimate specific unit compaction is attained when pore pressures in the aquitards have reached hydraulic equilibrium with pore pressures in contiguous aquifers; at that time, specific unit compaction equals gross compressibility of the system.

Compaction, unit

The compaction per unit thickness of the compacting deposits. Usually computed as the measured compaction in a given depth interval during a specified period of time, divided by the thickness of the interval.

Consolidation

In soil mechanics, consolidation is the adjustment of a saturated soil in response to increased load, involving the squeezing of water from the pores and a decrease in void ratio (American Society of Civil Engineers, 1962). In our reports, the geologic term "compaction" is used in preference to consolidation, except to report and discuss results of laboratory consolidation tests, made in accordance with soil-mechanics techniques.

Excess pore pressure, $[FL^{-2}]$, (L)

Transient pore pressure at any point in an aquitard or aquiclude in excess of the pressure that would exist at that point if steady-flow conditions had been attained throughout the bed.

Expansion, specific, $[L^3F^{-1}]$

The increase in thickness of deposits, per unit of decrease in applied stress. Specific expansion is a net specific expansion if compaction is continuing in parts of the interval being measured.

Expansion, specific unit, $[L^2F^{-1}]$, (L^{-1})

The expansion of deposits, per unit of thickness, per unit decrease in applied stress. Specific unit expansion is a net value if compaction is occurring in parts of the interval being measured during the period of decrease in applied stress.

Hydraulic diffusivity, $[L^2T^{-1}]$

The ratio of the hydraulic conductivity, K, of a porous medium to its unit water-storage capacity (specific storage), S_s, namely $\frac{K}{S_s}$. The specific storage, S_s, may be defined as the volume of water released from a unit volume of a saturated medium as the result of a unit decline in head. Within the regions of the aquifer system that remain saturated, S_s comprises two principal components, (1) the expansion of the pore water as head is reduced, and (2) the reduction in pore volume as the skeletal structure of the medium compresses under increasing effective stress. In a confined system, the increase in effective stress is equivalent to the decline in head if the position of the overlying water table remains unchanged (see effective stress). Under these conditions, it may be shown that

$$S_s = \gamma_w \beta_w n + \gamma_w \beta_t$$

and

$$\frac{K}{S_s} = \frac{K}{\gamma_w(\beta_w n + \beta_t)},$$

where γ_w is the unit weight of water, β_w is the compressibility of water (reciprocal of the bulk modulus of elasticity), n is the porosity, and β_t is the compressibility of the skeletal structure of the medium for stress changes in the elastic range of response.

In highly compressible fine-grained sediments subjected to stresses exceeding the preconsolidation stress, the component due to compressibility of water becomes relatively insignificant; therefore, in the terminology of soil mechanics, the diffusivity is

$$\frac{K}{\gamma_w m_v} = c_v,$$

where c_v is termed the *coefficient of consolidation*, and m_v is the coefficient of volume compressibility of the fine-grained sediment.

At any given point within a saturated porous medium, the rate at which the head changes in response to a change in head imposed at some other fixed point in the medium is a function of the hydraulic diffusivity. Thus, the hydraulic diffusivity determines the rate at which a head change of specified magnitude migrates through a porous medium.

Hydrocompaction

The process of volume decrease and density increase that occurs when moisture-deficient deposits compact as they are wetted for the first time since burial (Prokopovich, 1963; Lofgren, 1969, p. 273).

The vertical downward movement of the land surface that results from this process has been called "shallow subsidence" (Inter-Agency Committee on Land Subsidence in the San Joaquin Valley, 1958, p. 22) and "near-surface subsidence" (Lofgren, 1960; Bull, 1964).

Stress, applied, $[FL^{-2}]$, (L)

The downward stress imposed at an aquifer boundary. At any given boundary, the applied stress is the weight (per unit area) of sediments and moisture above the water table, plus the submerged weight (per unit area) of the saturated sediments overlying the boundary, plus or minus the net seepage stress (hydrodynamic drag) generated by downward or upward components, respectively, of flow within the specified saturated sediments.

Applied stress differs from effective stress in that it defines only the external stress tending to compact a deposit rather than the grain-to-grain stress at any depth within a compacting deposit. Quantitatively, the stress applied to the top of a saturated stratum differs from the effective stress at any depth within the stratum by the submerged weight (per unit area) of the intervening sediments, plus or minus the seepage stress due to vertical flow within the intervening sediments.

Manmade *changes in applied stress* are of greater practical significance than the absolute value of applied stress, inasmuch as the sediments, before disturbance, are in a state of strength equilibrium with preexisting natural stresses. Change in applied stress within an aquifer system results from either a change in load at the land surface or a change in the position(s) of the potentiometric surface(s) (confined or unconfined), or both. Change in applied stress is uniform throughout a depth interval in which head change is uniform.

The change in applied stress within a confined aquifer system, due to changes in the potentiometric surfaces, may be expressed as

$$\Delta p_a = -(\Delta h_c - \Delta h_u Y_s),$$

where p_a is the applied stress expressed in feet of water, h_c is the head (assumed uniform) in the confined aquifer system, h_u is the head in the overlying unconfined aquifer, and Y_s is the average specific yield (expressed as a decimal fraction) in the interval of water-table fluctuation. Change in stress applied to a fine-grained bed becomes effective in changing the thickness of the bed only as rapidly as the diffusivity of the medium permits decrease of excess pore pressures, and thus allows the internal grain-to-grain stress (effective stress) to change.

Stress, effective, $[FL^{-2}]$, (L)

Stress (pressure) that is borne by and transmitted through the grain-to-grain contacts of a deposit, and thus affects its porosity or void ratio and other physical properties. In one-dimensional compression, effective stress is the average grain-to-grain load per unit area in a plane normal to the applied stress. At any given depth, the effective stress is the weight (per unit area) of sediments and moisture above the water table, plus the submerged weight (per unit area) of sediments between the water table and the specified depth, plus or minus the seepage stress (hydrodynamic drag) produced by downward or upward components, respectively, of water movement through the saturated sediments above the specified depth. Thus, effective stress may be defined as the algebraic sum of the two body stresses, gravitational stress and seepage stress. Effective stress may also be defined as the difference between geostatic and neutral stress.

In an aquifer system, a given change in applied stress results in an immediate equivalent change in effective stress within the aquifers (coarse-grained beds). The increase in stress applied to an interbedded aquitard, however, becomes an increased effective stress within the aquitard only as rapidly as excess pore pressures can decrease. Because of the low diffusivity of the aquitards, months or years may be required to reach equilibrium—that is, for the change in applied stress to become fully effective.

Stress, geostatic, $[FL^{-2}]$, (L)

The total load per unit area of sediments and water above some plane of reference.

Stress, gravitational, $[FL^{-2}]$, (L)

The downward stress within a body of sediments produced by the weight per unit area of sediments and moisture above the water table plus the submerged (buoyed up) weight per unit area of sediments below the water table. Gravitational stress differs from *geostatic (total) stress* in that, below the water table, it includes only the submerged weight of the deposits, whereas the geostatic stress includes the full weight of the saturated deposits (solids plus contained water).

Stress, neutral $[FL^{-2}]$, (L)

Fluid pressure exerted equally in all directions at a point in a saturated deposit by the head of water. The neutral stress (pressure) is equal to the pressure head multiplied by the unit weight of water, or

$$u_w = \gamma_w \cdot h_p,$$

where u_w is the neutral pressure, γ_w is the unit weight of water, and h_p is the pressure head (Terzaghi and Peck, 1948, p. 52). Neutral pressure is transmitted to the base of the deposit through the pore water, and does not have a measurable influence on the void ratio or on any other mechanical property of the deposits.

The total load per unit area (geostatic stress), p, normal to any horizontal plane of reference in a saturated deposit, comprises two components, a neutral stress, u_w, and an effective stress, p'. Therefore, $p = p' + u_w$.

Stress, preconsolidation, $[FL^{-2}]$, (L)

The maximum antecedent effective stress to which a deposit has been subjected, and which it can withstand without undergoing additional permanent deformation. Stress changes in the range less than the preconsolidation stress produce elastic deformations of small magnitude. In fine-grained materials, stress increases beyond the preconsolidation stress produce much larger deformations that are principally inelastic (nonrecoverable).

Stress, seepage, $[FL^{-2}]$, (L)

When water flows through a porous medium, force is transferred from the water to the medium by viscous friction. The force transferred to the medium is equal to the loss of hydraulic head. This force, called the seepage force, is exerted in the direction of flow.

The vertical seepage force, F, at the base of a stratum across which a hydraulic head differential exists can be expressed as:

$$F = (h_t - h_b)\gamma_w \cdot A,$$

where h_t and h_b are the heads at the top and bottom respectively, of the stratum, γ_w is the unit weight of water, and A is the cross-sectional area normal to the direction of seepage.

Under conditions of steady vertical flow, the seepage force is distributed through the body of the medium in the same way as a gravitational force. The average vertical seepage force per unit volume, $\underline{J}$, analogous to average unit weight, is

$$\underline{J} = \frac{F}{A \cdot m} = \frac{(h_t - h_b)\gamma_w}{m},$$

where m is the thickness of the stratum.

The seepage force per unit area, referred to in this report as the seepage stress, J, is

$$J = \underline{J} \cdot m = (h_t - h_b)\gamma_w.$$

This vertical seepage stress is algebraically additive with the gravitational stress at the base of the stratum in question, and the sum is transmitted downward through the granular structure of the aquifer system. If the seepage stress, or pressure, is expressed as an equivalent head of water, then γ_w is not required and the expression is simply

$$J = h_t - h_b.$$

Subsidence

Sinking or settlement of the land surface, due to any of several processes. As commonly used, the term relates to the vertical downward movement of natural surfaces although small-scale horizontal components may be present. The term does not include landslides, which have large-scale horizontal displacements, or settlement of artificial fills.

Subsidence/head-decline ratio

The ratio between land subsidence and the hydraulic head decline in the coarse-grained beds of the compacting aquifer system.

Unit compaction/head-decline ratio, $[L^{-1}]$

The ratio between the compaction per unit thickness of the compacting deposits and the head decline in the coarse-grained beds of the compacting aquifer system; equals specific unit compaction if the observed head decline is a direct measure of increase in applied stress.

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