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COMPUTING ACCURATELY THE INDUCED LAND SUBSIDENCE AFFECTING THE MAIN SINKING CITIES LOCATED AT MAJOR RIVER MOUTHS

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ABSTRACT

Because of their geographical situation, coastal or delta plains situated at the major river mouths are highly populated and, of course, it leads to a very important fresh-water demand. Many of the cities located there, experienced severe land subsidence induced by the groundwater withdrawal. Indeed the low consolidated recent sediments compact in response to additional stresses from load of overlying material and to the decrease of water pore pressures by intensive pumping. The land subsidence, largely due to man-induced factors has become an alarming aspect of the giant cities in the present day coastal plains.

The literature abounds with engineering studies on land subsidence but usually limited to a general overview of the case added to a computational analysis based on empirical, analytical or numerical models assuming many restricting hypothesis like homogeneity, and isotropy. Most often no calibration on historical data is presented, and constant parameters of flow and consolidation are assumed.

A rigorous and complete methodology is developed to handle with accuracy this kind of subsidence problems in order to propose a new groundwater management, solving or stopping the subsidence process.

In a first step, a profound study has to be completed aiming at the determination of the three-dimensional spatial distribution of the distinguished deposits, each bearing their particular geotechnical and hydrogeological properties. This implies that the geological, geotechnical and hydrogeological research should complement each other continuously. Only such an approach yields the badly needed accurate quantitative information about the variables involved in land subsidence. These parameters form the basic data for the design of mathematical models.

In the second step of the study, the computer codes designed for modelling the coupled problem of groundwater flow and land subsidence , have to include the fact that the flow and the geotechnical parameters are variable and highly interdependent in time during the consolidation process leading to non linearities and coupling in the numerical procedure.

It is only in these conditions, added to an adequate calibration, that a numerical model simulating the land subsidence process could be taken in consideration to proceed with prediction computations.

An example is given of the application of this methodology, applied to the case study of the land subsidence in the central zone of Shanghai.

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INTRODUCTION

Rivers entering the sea, form a delta or an estuary. Together with its surrounding lowlands the lower reach of the river and its mouth form coastal dynamic features with complex depositional systems, composed of sediments of greatly differing characteristics and environments. It is recognized as the vast lowlying flat landscape, usually named delta plain or coastal plain (Baeteman, 1989). The sediment load of the rivers consists predominantly of silt, clay and fine sand (Einsele, 1992). The sediment discharged by the river sinks where space is available, in active depositional basins all characterized to a certain extent by subsidence (Rieke and Chilingarian, 1974).

Near the mouths, coastal configurations and sediments bodies have, at least, one particular feature in common : they are deposited near or below sea level. Hence, the sediments possess a high water saturation or moisture content; they are unconsolidated and compactable or compressible. They compact in response to pressures from load of overlying material, or from structural deformation or in response to fluid withdrawal. The nearly instantaneous result of the compaction is land subsidence, the lowering of the land surface. However, land subsidence in coastal lowland areas is largely aggravated by man-induced factors. Groundwater withdrawal from aquifers in the subsurface of coastal plain results in land subsidence. Venice (Italy) is only a case with historical background; more serious are the metropolises with millions of people concentrated at or even below mean sea level, e.g. Tianjin (China) with a maximum subsidence of about 2.50 m, Shanghai (China) with 2.7 m, Bangkok (Thailand) with 1.6 m, Taipei (Taiwan) with 1.9 m, the Southwest of Taiwan with 2.43 m, the lowlands of The Netherlands with 1.5 to 2.0 m, London (U.K.) with 0.35 m, the Po delta (Italy) with 3.2 m, Ravenna (Italy) with 1.2 m, Tokyo (Japan) with 4.59 m, New Orleans (U S.A.) with 0.8 m, Houston-Galveston area (U.S.A.) with 2.75 m ...

A particular depositional environment produces a sediment body that bears well-defined hydrogeological and geotechnical properties. Then, models of the rheology of Quaternary loose sediments can be chosen and the conditions of normal or over-consolidation of the sediments discussed. The hydrogeological and geotechnical parameters have to be determined adequately in heterogeneous formations, according to the accurate 3D geological description. A particular attention is given on the variation of the hydrogeological and geotechnical parameters during the consolidation process, and how to take into account this particular behaviour in the accurate computations that can be made in the cases where sufficient data are available.

QUATERNARY GEOLOGY AT THE MAJOR RIVER MOUTHS

One of the major forcing processes in the building up of the coastal accumulation is the change in sea level. Rivers incise the lower reaches of their courses and discharge large amount of sediments increasingly further out onto the shelf. Deltas emerge and fluvial channels are cut, dissecting and eroding parts of the delta plain. Every river responds differently to sea-level changes and experiences its very own evolution according to many various factors. The availability of sediment is another overwhelming factor. If sea level is rising sufficiently rapidly with respect to the rate of river sediment input, river mouths become estuaries. Estuaries trap not only fluvial sediments, but also sediment from the littoral system. Additionnally, the coastal or littoral hydrodynamic processes (waves, tides and coastal currents) can produce important modifications at river mouths. Coastal processes are the major factor in redistributing sediments (from the river, and eroded from subaqueous part of the delta) and hence creating the various coastal sedimentory depositional environments (Baeteman, 1989).

In normally consolidated sediments, the fabric strength or compaction state is in equilibrium with the overburden pressure at all depths below the sediment-water interface. However, if a new increment of sediment is added on top, a new equilibrium has to be established between the increased vertical stress and the compaction state, some pore water must be expelled. In a fairly permeable sediment, this pore water expulsion takes place more or less simultaneously with the growth of the sedimentary column, so the sediment maintains its state of normal consolidation. Normal consolidation can be maintained in fine-grained sediments if the sedimentation rate is low and the pore water has sufficiently time to escape. If, by contrast, the sedimentation rate is high and the growing sedimentary column has a low permeability and becomes less permeable with depth, the pore water to be released by prograding compaction cannot escape readily to the sediment-water interface. Hence, compaction is delayed, and the sediment is in a state of underconsolidation (Einsele, 1992). Compaction affects all sediments, but are most pronounced in fine-grained sediments, such as silts and clays. The factors that influence compaction in sands are mostly shapes and sorting of particles and depth of burial. During compaction, sand particles respond by shifting into more-dense packing arrangements, hence porosity decreases. Angular and poorly sorted sands are more compressible than rounded and well-sorted sands. Peat is the most compressible of all natural sediments because of its very high porosity and its weak skeletal framework of vegetable fiber. Not only will it compress beneath an applied load, but under certain conditions it will also compress under its own weight, a process which is called autocompaction. Peat shows a rapid reduction in permeability with change of volume, than e.g. in clay.

SEDIMENT CHARACTERISTICS AND SRATIGRAPHIC SEQUENCE

Concerning the geotechnical properties conditioning compaction, a fundamental distinction related to the genesis of the deposit is to be made. The sediments that originate as subaerial features are much more consolidated than those formed as submerged features or subaqueous. In the fluvial system, distinction is to be made between on the one hand the flood plain and levee deposits which originate subaerially, and on the other hand the channel and patterns of deltaic surfaces which initiated as submerged features (Russell,1967) and which as a result are very compressible. Because of their deposition above the groundwater table, floodplain deposits are overconsolidated and, in the sedimentary sequence, they form stiff compact layers.

In view of the many factors interacting and contributing to the final depositional record, it is self-evident that the resultant vertically stacked succession of the deposits is characterized by frequent lateral and vertical facies changes. It is clear that investigations aiming at the research of the characteristics of the deposits conditioning compaction, must emphasis on the three-dimensional facies geometry. Every particular facies bears its particular geotechnical and hydrological properties, although conditions may change later on. However, establishing the geometry of the various facies in the depositional body of a coastal plain requires an enormous amount of data. And it is self-evident, the more data available, the more accurate the delineation of the geometry will be.

In order to obtain a 3D picture of the complex mosaic being the subsurface of the depositional body, every core is to be interpreted. The various units distinguished from the boreholes (loggings) are to be correlated; filling the blanks between the data points remains the ever critical decision ! Correlating boreholes involves the understanding of the interplay of all relevant factors and processes that built the depositional body. Detailed cross-sections also implies that all available data must be used. Doing so, the general record of events can be identified, and eventually the development of the coastal plain in space and time can be delineated.

PROCESS OF LAND SUBSIDENCE DUE TO WATER WITHDRAWAL

Young unconsolidated or semi-consolidated elastic sediments of high porosity, laid down in alluvial or shallow marine environments form, most often, a succession of layers which can be characterized (from an hydrogeological point of view) as semiconfined or confined aquifer systems (Poland, 1984) consisting in aquifers of silty sand and sand of high permeability (hydraulic conductivity) and low compressibility, interbedded with clayey aquitards of low vertical permeability and high compressibility. The geostatic pressure or total stress (σ) that any point undergoes in the soil is usually considered as the result of two components: the fluid pore pressure (p) and the effective stress (σ'), according to the Terzaghi(1943) principle. This principle is sufficiently accurate for the computations of the total settlements; as a matter of fact, the soil compressibility is a factor 20 to

1000 larger than the grain compressibility, so that it would be particularly uneasy and useless to choose another principle based for example on Biot (1956) theory. One can express very simply the new stresses created by the lowering of the piezometric head in a confined aquifer. For an initial pore pressure considered in a complete equilibrium state, the pressure is decreased in the aquifer and partially decreased in the underlying and/or overlying aquitards. During this stage, the total stress can be easily assumed constant (the layers are maintained saturated due to the recharge from the top or due to the very slow propagation of the pressure decrease through the aquitards). Consequently, the slow propagation of the pore pressure variation in the semi-permeable layers induces automatically an equivalent increase in effective stress in these compressible layers... and a drained consolidation process is started. The second stage is distinguished in the long term, when the pore pressure decrease has reached the top of the confining layer and then, as for unconfined situations, provokes a decrease of the thickness of the saturated soils. The total stress can no more be considered as a constant except if there is an important infiltration or recharge. The transient behaviour of the phenomena is very important because the main consolidation (called usually primary consolidation) is activated by the decrease of pore pressure as long as the hydrostatic equilibrium is not restored.

The geomechanical behaviours of the soils can be idealized in term of rheological models. The skeleton deformation under increasing effective stress is supposed to follow elastic, plastic or viscoelastic laws or any combination of them. Clayey soils and loose sediments have a geomechanical behaviour qualified more often as non linear elasticity with progressive plasticity and viscosity. This particular behaviour leads, in practice, to choose rather models based on experimental laws than on combinations of theoretical models. Elasto-visco-plastic laws in 1D or 3D can be established from experimental results. Different loading steps, more or less elaborated, can be applied to the samples in order to parameterize an experimental law. Often these constitutive laws allow a more easy introduction of non linear and interaction effects of the parameters.

VARIATION OF THE PERMEABILITY AND OF THE STORAGE COEFFICIENT

Geotechnical scientists have long been aware that during consolidation of highly compressible clays, changes in porosity due to a rearrangement of the soil skeleton may lead to decreases in both the permeability and the compressibility of the porous medium. Lambe and Whitman (1969) have presented data indicating that permeability can change by orders of magnitude and compressibility can decrease significantly as void ratio decreases. Neither of these variation relationships is linear.

It is well known that neglecting the fluid compressibility, the specific storage coefficient of a confined aquifer (S_S) can be written in function of the volumetric compressibility coefficient (α) of the porous medium:

$$S_s = \rho.g.\alpha$$

where $\rho.g$ is the density of the water (fluid). The compressibility is not a constant; it depends of σ' and of the effective preconsolidation stress (σ'_{prec}). From results of oedometer tests, this last relation can be linearized (fig.1a) using two constants A (swelling constant) and B (compression constant), so that the specific storage can be expressed in function of $1/\sigma'$ values (fig.1b):

$$\alpha(\sigma') = 1/(A.\sigma')$$
$$\alpha(\sigma') = 1/(C.\sigma')$$

For silty and clayey formations, the permeability coefficient is more often measured in consolidation tests (oedometer and triaxial tests). The permeability is obtained at different stages of effective stress, leading to a relation with the void ratio (e) : $K = f(e)$

Many relations linking the permeability coefficient K to the total porosity or to the void ratio have been proposed by petroleum engineers, in order to interpret the porosity logs in terms of

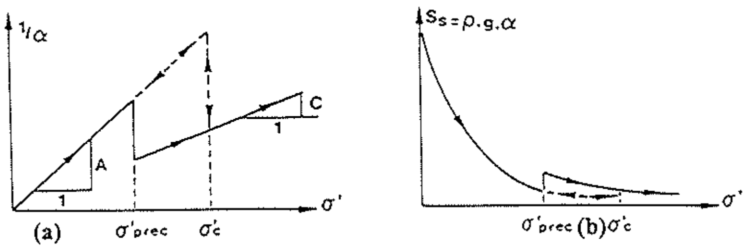

figure 1. Inverse of the compressibility (a) and specific storage coefficient (b) in function of the effective stress

permeability of the reservoirs. These relations are not applicable in consolidation and subsidence computations. They are relative to hardened rocks preferentially than to soil or loose sediments. In the case of estuarine recent sediments, we are looking for experimentally proved relations, linking the permeability K to the void ratio or the porosity in saturated porous media characterized generally by high clay and peat contents, high compressibilities and low permeabilities. The difficulties encountered when establishing this kind of relation are mainly due to the numerous parameters interacting on the permeability value of loose sediments : the lithology,the grains size, the shapes, orientations and specific surface of the grains, the pores spatial distribution. The micro-structural evolution of clays during the consolidation, orientating the plates more orthogonally to the direction of the applied effective stress, develops a structural anisotropy. This evolution increases the tortuosity of the flow channels as the flow is parallel to the vertical effective stress. This statement does not rule out the decrease in K by a decrease of the total void ratio.

It could be convenient to linearize the variation in a (log K, e) diagram (fig.2), using two experimentally determined constants C_{K1} and C_{K2}.

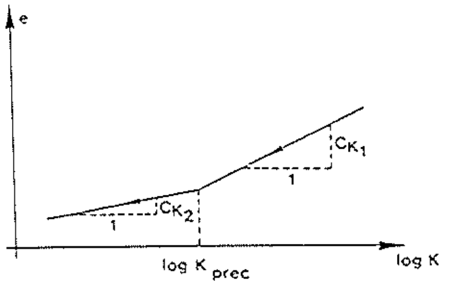

Figure 2. (log K, e) diagram very similar to the classical (log σ', e) diagram of the oedometer test.

COMPUTING THE LAND SUBSIDENCE OF SHANGHAI

The reader interested about this case history, have to see the following references: Baeteman(1989) for the Quaternary analysis, Dassargues et al.(1991) about the preparation of the hydrogeological and geotechnical data, and Dassargues & Li (1991) for a summary of the computational aspects. Moreover the Bulletin of the International Association of Engineering Geology (IAEG) will publish in the next months a group of 5 papers describing entirely the whole study.

Rudolph & Frind (1991), have shown that for a pore pressure variation imposed at the bottom of a clayey column, it takes more time to reach permanent flow conditions with varying parameters than with constant parameters. These conclusions are always verified if the K and S_S values are identical at the beginning of both computations. The differences in the calculated pore pressure spatial distributions induce automatically (by the Terzaghi principle) the main differences in the calculated subsidences. Moreover, even with pore pressures taken rigorously identical, it has been demonstrated (Dassargues, 1991) that the subsidences computed by the simulation with constant parameters will be systematically overestimated when compared with those calculated with varying parameters (if the initial parameters are taken identical).

In the case study of Shanghai, the final results (fig.3), show how inaccurate can be a model neglecting the variation of the parameters in the flow-compaction computations. Using the Finite Element Method (FEM), the computations are based on a detailed 3D flow model of the whole area, coupled to 32 non linear 1D flow-compaction models located where accurate measured data were available. Careful calibrations of both hydrogeological and geotechnical parameters have been made, and at last, future subsidences have been computed until year 2000, for pumping = 1.3 x recharge in the aquifers.

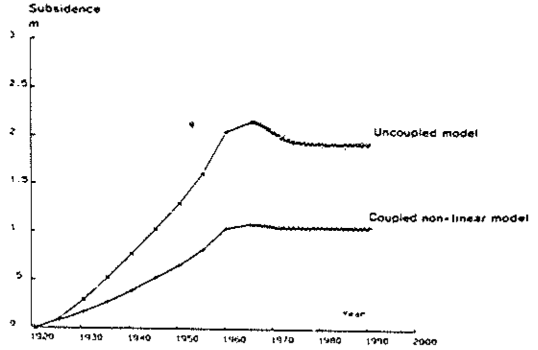

Figure 3. Total computed subsidence since 1920 for one column of the case study of Shanghai; the computation neglecting the variation of K and S_S during the consolidation process leads to an overestimation of the subsidence of nearly 100% at this place (from Dassargues, 1991).

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