Settlement of Venice and General Estuarine Deposits

Tassement de Venise et Alluvions Gènèrales des Estuaires

A.D.W.SPARKS Dept. of Civil Eng., University of Cape Town, Rondebosch, South Africa

SYNOPSIS

Artesian conditions, such as at Venice, can exist in other offshore or estuarine deposits. The previous existence of artesian groundwater pressures increases the settlements due to pumping. Attention is drawn to the fact that soil layers located below the deepest major well can suffer delayed compression due to pumping from the wells. Mathematical computer models based on finite differences are derived for steady-state and dynamic conditions for a general aquifer-aquitard system in which the permeabilities and thicknesses of the layers vary laterally from one position to another. The future settlement at Venice is estimated. A physical model constructed at UCT is mentioned. A solution is proposed.

INTRODUCTION

Examples of settlement due to the lowering of the water table include the following:-

a) Three large areas in the San Joaquin Valley (inland from San Francisco) have subsided due to groundwater lowering. Certain areas have settled more than 20 metres.
b) Mexico City has settled more than 7 metres because of pumping from the groundwater.
c) Portions of the Everglades in Florida have subsided by 2 metres due to land drainage.
d) Koto district of Tokyo has settled below sea level due to groundwater pumping.

Artesian conditions exist when the water level (piezometric level) in a standpipe from a lower aquifer rises above the water table level for higher soil layers.

Publications usually omit to mention the particular settlement process caused by the release of artesian pressures in lower aquifers, which occurs even though the surface water level (e.g. a lagoon level) remains constant.

Artesian conditions should be suspected if soil layers slope upward towards higher ground levels. Inclined layers of this kind occur naturally in offshore and estuarine deposits, or in soil layers deposited in valleys or in dish-shaped lakes (synclines), or where horizontal layers are subsequently tilted towards the sea or lower levels.

A building load applied to a soil surface causes compression of a small zone of soil near the surface, But lowering the water table, by pumping, causes compression along the whole soil profile below the original water level. If artesian conditions exist prior to the pumping, then the compression can be much greater. Shaded areas in Figure 1 indicate the relative settlements.

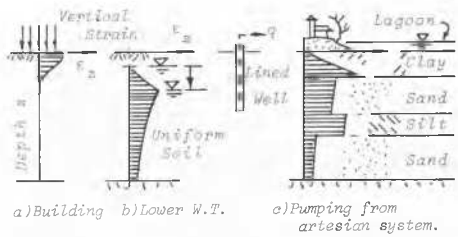


Fig.1- Settlements are equal to shaded areas.

GEOLOGY OF THE VENICE REGION

The Alpine mountainchain was formed by the North-South compression of thick sediments laid in the dish-shaped depression of the Tethys Sea. An East-West tensile system then separated Italy and Greece. The Adriatic Sea and Po basin were formed in this process. During and since the formation of the Adriatic Sea, the Po basin settled between 10 km and 20 km.

Rates of deposition in the Venice lagoon have been measured by Fontes and Bortolami who conclude that the rate of subsidence of the Po basin has been negligible during the last 3000 years. Tectonic movements should not be blamed for the high settlements during the last 30 years. This has been caused mainly by the pumping of groundwater from the mainland region of Marghera.

Compressible Quaternary soil deposits laid on the floor of the Po basin are 1000 metres thick under Venice (ref.4), and become thinner (a few metres) and coarser near the Alpine foothills.

The soil under Venice consists mainly of of sand and silt layers (Fig.6). Ricceri and Butterfield (ref.15) and Gambolati *et al* (ref. 7) provide good details.

At a depth of 825 m under Venice, the artesian head is 36,2 m which is higher than Treviso (15 m). Hence the recharge zone must be in or near the Alpine foothills.

GENERAL MODELS FOR AQUIFER-AQUITARD SYSTEMS

Steady-state flow

Under steady-state conditions, water enters the aquifers in the recharge zones and flows laterally along the aquifers. The water eventually seeps out via aquitards into higher aquifers until the water reaches the lowest surface-water reservoir (e.g. the sea). For steady-state flow it is not necessary to consider the compressibility of the aquifers or the aquitards. No pressure changes occur at a particular point in the soil during the steady-state flow, and hence no portions of the soil deform to act as local sources or as extra local receptacles for groundwater.

The steady-state solution will be the same for incompressible soil layers and for compressible layers of similar soils. The steady-state solution depends entirely on the boundary conditions (water levels or flow rates) and on the permeabilities and geometries of the layers.

Figure 2 displays the flow through an aquifer-aquitard system. The vertical dimensions have been overemphasised. The solid lines illustrate the approximate shapes of the equipotential lines. The main flow through the aquifers is in the lateral direction parallel to the bedding of the aquifers, whereas the main flow in aquitards is normal to the bedding of these aquitards.

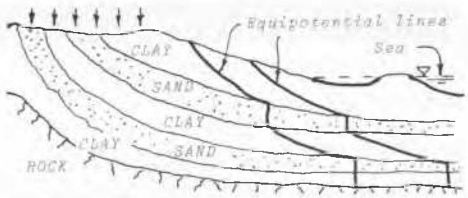


Fig.2- An artesian aquifer/aquitard system.

Importance of steady-state solutions

Assume that the previous steady-state boundary conditions (piezometric levels or flow rates) are changed, for example by steady pumping from wells. The seepage regime will eventually change from its previous steady-state system to a new equilibrium steady-state flow pattern. If this change occurs so that the changes in the effective pressures $\bar{p}$ are monotonic, then the maximum possible final settlement of the compressible soil layers can be obtained from the initial and final steady-state seepage solutions.

Comparison of the initial and final steady-state solutions will yield the local changes in the pore pressures u. Hence from the known values of the total pressures p, it is possible to estimate the initial values and the increments in the effective stresses $\bar{p}$. These values are used in conjunction with the e-$\bar{p}$ characteristics for each layer to estimate the compression of each layer.

Saturated fine-grained aquifers located above the level of water in a well, can be subjected to high negative suction pressures prior to air entry into such aquifers. The final value of $\bar{p}$ in such aquifers could be lower than an intermediate value. The value of $\bar{p}$ will not have changed monotonically. However, if the compressibility of the aquifer is low, this intermediate precompression effect can be neglected.

Aquifers located below lagoons will not usually be subjected to air entry. But aquifers above the water level of a lined well sunk from an island may have high negative water pressures, especially below the highest aquitard which prevents air entry into the aquifers.

Compressibility of soil layers

The compressibility of soil layers and pore fluids imparts a storage capacity to soil elements. During dynamic decreases in pore pressure, this compressibility causes extra sources for the groundwater. This extra groundwater must seep through to other regions in the soil mass. The compressibility, or even the ability of the soil to expand slightly, tends to delay the transfer of effects of changes in the water pressure u from one region of the soil to another.

The final maximum possible settlement can be calculated by ignoring the compressible storage of the soil and fluids. However, this compressible storage must be considered if one wishes to determine rates of settlement or the rates of change of piezometer levels.

Checking an aquifer-aquitard model

A proposed dynamic model for an aquifer-aquitard system should be checked against natural conditions by comparing available measured rates of settlement, and rates of change of piezometric levels, and rates of flow or seepage with those for the model. The inherent parameters of the system are:

a) Geometry (position, confines) of the layers
b) Permeabilities (can vary even in a layer)
c) Compressibility of the layers (e versus $\bar{p}$)
d) Compressibility of the fluids.

The boundary conditions (piezometric levels or imposed flow rates) are not listed.

If one ignores the compressible storage effect, it might be possible to obtain good agreement between a model and nature for initial time periods, but this could be due to using inaccurate permeabilities to compensate for ignoring the compressible storage contribution. This means that the final steady-state solution would be incorrect. Hence the total final settlement predicted by the model could be incorrect even though good agreement exists for the initial time periods.

Simple two-dimensional models

Simplified two dimensional models are useful to check a concept (See Fig.3) but they do not usually provide accurate quantitative data for a real problem.

A two-dimensional model can be used to replace a radial "cake slice" which represents portion of a three-dimensional system with symmetry about a central axis.

Errors due to ignoring layers below wells

Certain analysts have assumed that the pumping from a well only affects the pore pressures in the aquifers located above the bottom of the well. The simplified two-dimensional system in Figure 3 shows that this approach can be incorrect in some cases.

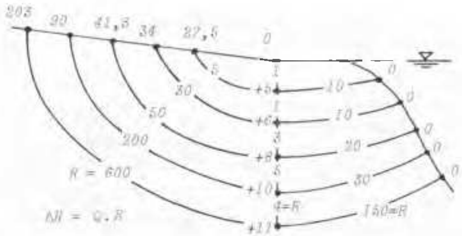


Fig.3(a)- Before pumping.

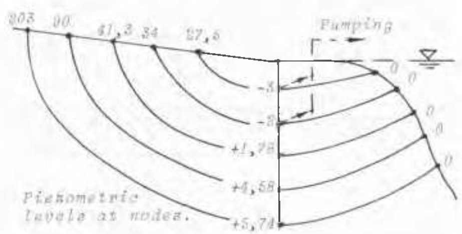


Fig.3(b)- After pumping from upper two aquifers.

Arbitrary resistance values R have been allocated to the seepage limbs of the model. The head difference across each limb is $\Delta H=Q.R$ where Q=volume rate of flow. The value at each node is the piezometric level with respect to the downstream lake level. Figure 3(a) shows the values before pumping. In Figure 3(b) it is assumed that a well located at another site penetrates the upper two aquifers, and lowers the heads for these two aquifers by 8 metres. It will be noticed that the heads in the lower aquifers are also lowered by amounts which cannot be neglected (approx. 5 metres).

Three-dimensional networks

Radial-cylindrical networks are not suited to conditions which lack symmetry about one axis. The following are suitable for general problems:-

1) a)A square nodal grid on the central surface of each aquifer, for the lateral flow within the aquifer. The grid follows the slope of the aquifer, but will be called a "horizontal" grid. Subdivision of portion of the grid is possible.

   b) Selected nodes on the above mesh are connected by "vertical" links through the aquitards.

2) a)A hexagonal (i.e. triangular) grid can also be used to analyse lateral flow in the aquifers, instead of the square grid. Each triangle can be subdivided into four equilateral triangles.

   The triangular grid has the following advantages:-

   i)Finite difference approximations for the triangular mesh contain error terms which are smaller than those for a square grid of similar spacing.

   ii)It can easily fit irregular lateral boundaries.

   iii)Radial effects can be studied around a node at a well.

   b)"Vertical" linear links of nodes are provided through the aquitards between selected nodes in the aquifers.

3) Grids of irregular shape. Formulae for these can be obtained by studying the derivation of formulae for hexagonal grids.

4) A simplified network can be constructed like a three-dimensional plumbing system between selected inlet and outlet nodes. Limbs of the plumbing system contain linear resistances to flow. Errors might be made when deciding on the form of this type of model.

The author prefers the hexagonal system (2) for the aquifers, and considers the nodes which are within the aquifers as column nodes. Along the height of a column node, the piezometric level is constant at any instant. The upper and lower tips of the column nodes touch the aquitards, and form the boundary nodes for the "vertical" linear nodal links through the aquitards.

If the aquifer is very thick, or if its permeability is only slightly greater than the permeability of the aquitards, then the column node should be subdivided into a number of separate nodes (e.g. in a region where the flow is mainly vertical).

Convergence, stability, and solution techniques

During a solution process, piezometric levels are calculated for each of the nodes. Finite element methods can be applied to certain problems, or electrical analogs can be used for simplified systems. However the author will assume that use is being made of equations derived from finite difference approximations.

1) Steady-state conditions

The solution of steady-state conditions does not involve instability or nonconvergence. If a large core storage is not available for solving simultaneous equations, use can be made of relaxation methods or iterative averaging techniques.

2) Dynamic conditions

Finite difference relationships may be used to set up equations which can be arranged for solution by the following methods:-

a) Explicit method (Forward time differences)

In this method, the new piezometric level $h_{i,t+\Delta t}$ at a certain node i is expressed in terms of the piezometric levels which existed at the previous instant t at the node i and its surrounding nodes. e.g

$h_{i,t+\Delta t} = f(h_t$ values in region of i)

A single equation of this type exists for each node, hence a single calculation can be made for each node. However, small time intervals must be used because the solution method becomes unstable for large time intervals.

b) Implicit method (Backward time differences)

For each time level it is possible to set up a system of simultaneous equations. Each equation constitutes a link of the new piezometric levels at several adjacent nodes. The known piezometric level at the central node of the group (for the previous time t) also appears in each equation.

At each time level, the solution of the simultaneous equations provides the set of piezometric levels for this new time level. A computer with a large core storage is required. The solution method is stable.

c) Central time difference methods

Undesirable instability can occur if use is made of central differences involving $h_{i,t-\Delta t}$ and $h_{i,t+\Delta t}$.

d) Combinations of implicit and explicit methods

Simple differential equations for consolidation due to one-dimensional flow can be solved by Crank-Nicolson methods. In the case of three-dimensional aquifer systems it is necessary to use more complicated expressions.

When applied to three-dimensional aquifer systems, the divergence expression (incorporating second order differentials with respect to distance) is taken as the average of the divergence at times t and t+Δt. A forward time difference expression is used for the first order time differential.

Simultaneous equations must be solved at each time level, as in the implicit method. This method is stable, and is more accurate than the above methods.

NON-UNIFORM LEAKY AQUIFERS (STEADY-STATE)

A practical model should take into account the lateral variations in thickness and permeability within the aquifers and the confining aquitards.

Assumptions and notation used (See Fig.4):-

"Lateral" flow occurs in aquifers.
"Vertical" flow occurs in aquitards.
The nodes 0,1,2,3 ...6 are column nodes.
The upper and lower surfaces of the hexagonal "prism" are midway between nodes 7 and 0, and 8 and 0 respectively.
z = lateral nodal distance on triangular grid.
D_{n0} = average aquifer thickness between node 0 and node n.
k_{n0} = average coefficient of permeability between node 0 and node n.
h_n = piezometric level at node n, e.g. relative to sea level.

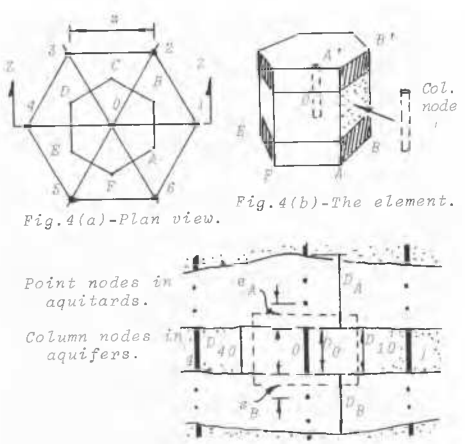


Fig.4(a)-Plan view.
Fig.4(b)-The element.
Fig.4(c)- Section Z-Z.
Fig.4.

The nett flow rate into the element in Fig.4c is

$$\frac{\Sigma Q}{t} = \frac{1}{\sqrt{3}}\left[\sum_{n=1}^{n=6}[(kD)_{n0}\cdot h_n] - h_0\cdot\sum_{n=1}^{n=6}(kD)_{n0}\right] + z^2\cdot\frac{k_A}{s_A}\frac{\sqrt{3}}{2}(h_7-h_0) + z^2\cdot\frac{k_B}{s_B}\frac{\sqrt{3}}{2}(h_8-h_0) \quad ....(1)$$

For steady state conditions this expression is zero, hence h_0 can be expressed in terms of the h values at adjacent nodes.

In a simpler method the point nodes are removed from the aquitards. Nodes 7 and 8 are now aquifer column nodes and $s_A=D_A$, $s_B=D_B$.

NON-UNIFORM COMPRESSIBLE LEAKY AQUIFERS

Column nodes in hexagonal lateral grids will be assumed to exist in aquifers. These are separated by links of point nodes within the aquitards. In a particular vertical link within an aquitard, several single nodes are separated by equal intervals. See Fig.4(b).

a) At an internal node in an aquitard

The following equation for one-dimensional consolidation applies:-

$$c_v.\frac{\delta^2 h}{\delta z^2} = \frac{\delta h}{\delta t}$$

i) Use can be made of the *forward difference (explicit)* method. i.e.

$$h_{0,t+\Delta t} = h_{0,t} + \left(\frac{c_v.\Delta t}{s^2}\right)(h_{a,t}+h_{b,t}-2h_{0,t}) \quad ....(2)$$

Δt must be chosen so that $(c_v.\Delta t/s^2) \leq 1/2$ Subscripts a and b are for nodes respectively above and below the node 0.

ii) The *implicit* method (*backward differences*) entails solving simultaneous equations of the form

$$\left(1+\frac{2\Delta t}{s^2}\right)h_{0,t+\Delta t}+\frac{\Delta t}{s^2}(h_{a,t+\Delta t}+h_{b,t+\Delta t})=h_{0,t} \quad ....(3)$$

b) At a column node in an aquifer

The element in Figure 4(b) shows the three soil portions which contribute to the compressible volume storage surrounding an aquifer column node. The nett volume rate of flow into the element is

$$\frac{\delta(V_v)}{\delta t} = \gamma_w.\frac{\delta h}{\delta t}.\frac{\sqrt{3}}{4}.z^2\left[s_A\frac{a_{va}}{1+e_a}+2D_0\frac{a_{v0}}{1+e_0}+s_B\frac{a_{vb}}{1+e_b}\right] \quad ....(4)$$

where subscripts 0,a,b refer to aquifer at node 0, the upper aquitard near 0, and the lower aquitard near 0 respectively. The above expression can also be used if the total pressure p varies with time, providing h is varied accordingly.

In the *implicit* method, a backward difference approximation is used for $\frac{\delta h}{\delta t}$ in (4), prior to equating the expression (1) evaluated at time t+Δt, and the expression (4).

This yields an equation of the following form for each aquifer column node:

$$h_{0,t+\Delta t}\left[1+\frac{4\Delta t\sum_1^6 (kD)_{n0}}{z^2.M_o}+\frac{2\Delta t k_A}{s_A.M_o}+\frac{2\Delta t.k_B}{s_B.M_o}\right] - \frac{4\Delta t}{3M_o z^2}\left[(kD)_{10}.h_{1,t+\Delta t}+...+(kD)_{60}.h_{6,t+\Delta t}\right] - \frac{2\Delta t}{M_o}\left[\frac{k_A}{s_A}h_{7,t+\Delta t}+\frac{k_B}{s_B}h_{8,t+\Delta t}\right] = h_{0,t} \quad ....(5)$$

where

$$M_o = \gamma_w\left[s_A\frac{a_{va}}{1+e_a}+2D_o\frac{a_{v0}}{1+e_0}+s_B\frac{a_{vb}}{1+e_b}\right]$$

A GRID NETWORK FOR THE VENICE REGION

Figure 5 illustrates a suitable coarse network for the aquifers in the region of Venice. This network may be subdivided to provide finer detail.

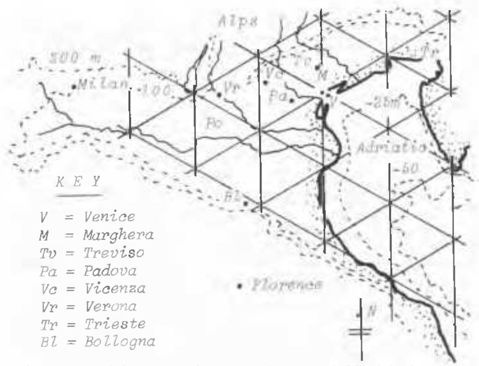
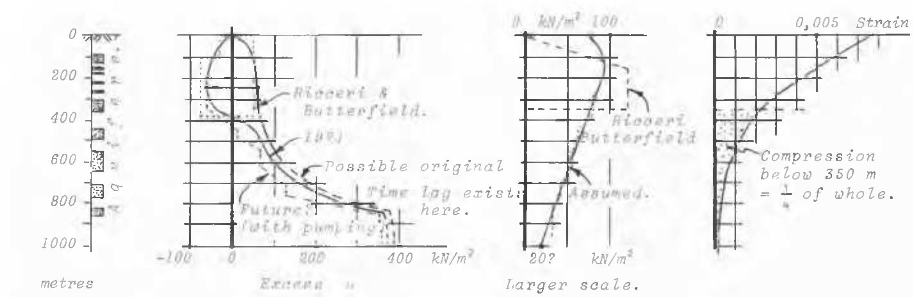


Fig.5 - This net is further subdivided.



a) Profile b) Artesian pressures. c) Δu decrease. d) ε_z in aquitards.

Fig.6 - Diagrams for settlement calculations.

A SETTLEMENT CALCULATION

Figure 6(b) shows assumed original and future artesian pressures(if pumping were to be continued at Venice).The upper portion shows good agreement with values given by Ricceri and Butterfield.

Values of C_c equal to 0,25 for silt and e_o=1,0 at $\bar{p}$=100 kN/m^2 yield a vertical strain distribution in the silt aquitards as in Fig.6(d). See Conclusion 9.

MODEL CONSTRUCTED AT UCT

Figure 7 shows a demonstration model constructed by the author at the University of Cape Town(April 1973).Large settlements were visible due to "pumping at Marghera."

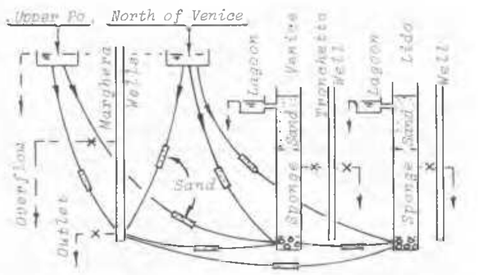


Fig.7- Model;sand resistances,plastic sponge.

CONCLUSIONS

1)The model derived in this paper overcomes the symmetrical limitations used in the radial model by Gambolati *et al*.(ref.7).
2)The settlement of layers below wells may not always be ignored(ref.15 ignores this).
3)The delay of settlement of layers below wells depends on compressible storage, intervening aquitards,and nature of recharge sources(e.g.limited rain,or distant rivers).
4)Initial agreement between computed and measured settlement rates and drawdown rates does not imply that the theoretical model is correct,especially if the model only considers the upper layers.
5)Further Soil Mechanics details are required to check the computational models for Venice.
6)The shape of the Po-Adriatic basin has a lateral confining effect on water flowing seawards in aquifers,thus causing higher natural artesian pressures under Venice than would occur in aquifer deposits on a convex coast(e.g.at a fan delta of a river).
7)In a lecture to the Dante Alighieri Society (April 1973) the author suggested that sea water could be fed into three aquifers under Venice to re-establish artesian pressures, apart from the stopping of well pumping. Aesthetically suitable water towers can be distributed around the periphery of the major islands. Each tower could house three tanks. The highest tank would feed the lowest depth. An experiment of this kind could be tried in the first instance near St.Mark's church.
8)If well pumping is halted,an injection grout-curtain on the seaward side of the Lido islands is an alternative to (7)
9)For aquifer:aquitard ratio of 7:3,the full future settlements (from 1850) could be as high as 0,6 metre using C_c=0,25 or approximately 27 cm using C_c=0,1. From 1900 to 1972 the settlement was about 22 cm(ref.15). The cessation of pumping can prevent further settlement(8 cm?)e.g.of layers below the wells.

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