Peculiar aspects in man-induced landsubsidence

Aspects singuliers des affaissements provoqués par l'homme

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SYNOPSIS: The withdrawal of fluids from underground reservoirs provokes an impact on the overground environment. Depending on the situation the landsurface may subside rapidly or slowly, locally or regionally, jeopardizing coastal defence structures and drainage systems. A new culprit with similar consequences is sealevel rise due to man-induced climat changes the importance of which, however, is still a subject of vivid discussion. Countermeasures are required in early stage but accurate prediction of subsidence is complicated due to special effects: retarded response, nonlinear and post-production behaviour, which will be discussed in the present contribution.

1 INTRODUCTION

In populated coastal areas and river deltas the demand for agricultural, industrial, and housing land is met by reclamation of wetlands into polders: lowlands with precise drainage controll, protected by dykes and waterdefence structures. Reclaimed land naturally shrinks, but man's activities may invoke a more serious threat. The gradual increase of fluid recovery for industrial and domestic need made land subsidence manifest as a serious environmental problem (Holzer 1984).

The consequences of anthropogenic climat changes due to combustion of fossil fuel includes a significant effect on the mean sea level related to melting land ice, a problem of global scale. At present many places all over the world are to be safeguarded against high water and flooding (Fig. 1). Sea level rise represents a serious threat to coastal defence structures, particularly in landsubsiding areas.

The sudden awareness to slowly sink with hearth and home under sealevel may give a shock evolving in a principal political issue. The UNEP decided to investigate the importance of this hazard to society by the evaluation of case studies. Parties interested in participating in this program are invited.

Fig. 1 Coastal areas critical to sealevel rise

2 LAND SUBSIDENCE

To assess the prediction of landsubsidence two main problems arise. First, the geological system is complex and its characterization by acquired data is generally insufficient.

The lack of adequate data can only be resolved by comprehensive measurements which should include surface deflections, production and reservoir behaviour.

Second, existing simulation models show either a weak phenomenological relevance or a nonpractical level of sophistication.

A large variety of models is available and their applicability is outlined in a series of conferences, recommended are symposia held in Tokyo 1969, Anaheim 1977, and Venice 1984.

A general observation shows that it is difficult to properly simulate a reservoir response.

If pressure decline is monotonic and moderate, linear(ized) deformation behaviour can be adopted. However, in the case of pressure recovery the unloading stiffness has to be accounted for. The decrease in porosity, eventually by crushing, may cause drastic changes in the reservoir transmissivity. Reservoirs existing of loose sandy deposits may show significant compaction.

A reservoir environment of clayey deposits is affected by the pressure decline. Induced shrinkage may contribute to landsubsidence. The shrinkage process of clay is devided into an elastic and a plastic stage; the transition between both is marked by the so-called preconsolidation pressure, which varies with the rate of stress variations. Plastic deformations are most important for landsubsidence.

The use of a sophisticated model suited for nonlinear deformation of a complex geological formation over a long period of time requiring a great amount of data is very costly.

From a practical point of view it is most realistic to adopt an approach as simple as possible covering relevant phenomena as best as possible. Of course, not all requirements can be met, and some concessions are to be accepted.

The next sections clearify that some special effects can be taken into account without additional complication.

3 PERMEABILITY EFFECT

3.1 Pressure induced porosity changes

Empirical experiments have shown that the permeability of a porous medium can be expressed by (Chillingarian 1975):

$$K = k\rho g/\mu; \qquad (1)$$

with: $k = cTD^2n$; $n = n^a e^b$; $e = n/(1-n)$

in which K is the hydraulic permeability including fluid material properties ρ and μ (dynamic viscosity). The intrinsic permeability k reflects the porous medium properties by a constant c depending on the type of soil, by the tortuosity T, by a characteristic grain size D and by a relation with the volumetric porosity n. The value of the empirical constants is in the range 1<a<1.5 and 1<b<2.
When the porous skeleton deforms the corresponding volume changes will cause a variation of the permeability:

$$k/k_1 = (e/e_1)^{\kappa} \quad \text{with} \quad \kappa = a(1-n)+b \qquad (2)$$

The empirical constant κ is characteristic for a particular soil and weakly dependent on the porosity; k_1 is measured at void ratio e_1.
The volumetric porosity n is related to the volume strain ε for a porous medium with relatively rigid particles according to:

$$d\varepsilon = dn/(1-n) \qquad (3)$$

Elaboration yields the following approximate expression for the relative permeability change:

$$dk/k = (\kappa/n_0)d\varepsilon \quad \text{with} \quad \kappa = a(1-n_0)+b \qquad (4)$$

in which n_0 is an average value within the range of variation considered.
For horizontal reservoirs one-dimensional deformation can be assumed. The volume strain ε is then expressed by:

$$d\varepsilon = -\alpha d\sigma' = -\alpha(d\sigma-dp) \qquad (5)$$

in which α is the compressibility coefficient of the porous medium, σ' the effective vertical pressure, σ the vertical total (overburden) pressure and p the excess pore pressure (with reference to the initial pressure p_1). For a constant overburden pressure $d\varepsilon=\alpha dp$ holds and the permeability becomes:

$$k = k_1\exp[(\kappa\alpha/n_0)p] \qquad (6)$$

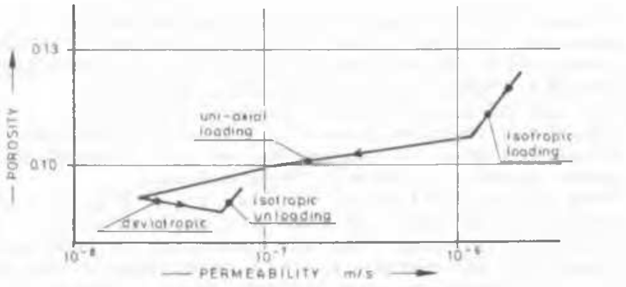

Fig. 2 Permeability effect in a triaxial test

The parameter $\kappa\alpha/n_0$ is characteristic for permeability variation due to excess pore pressures. The value of κ/n_0 is of the order 10, but in the case of internal erosion by crushing at the intergranular contacts (nonlinear skeleton compressibility) the effect can be much higher. This is shown in Figure 2 reflecting results of permeability changes in a soft rock sample in a triaxial test (Luger 1984).

3.2 Soluble gas effect

Most fluids are compressible. This behaviour is usually expressed in terms of a compressibility coefficient which relates relative density changes under pressure variations, according to:

$$\beta = d\rho/\rho dp \qquad (7)$$

If the fluid contains gas bubbles or gas pockets which are eventually locked in the pore geometry, the interaction between the liquid and gas needs to be considered. Physical processes involved are gas solution, surface tension, vapour pressure and gas compression. For an equilibrium gas solution the compressibility of the mixture can be expressed by (Barends 1980):

$$\beta' = d\rho'/\rho' dp = \beta + f(p,w,\omega,\theta,r) \qquad (8)$$

in which ρ' is the density of the mixture, ω the gas solubility coefficient, θ the surface tension, r a characteristic bubble radius, and w is the vapour pressure. Close inspection of the function f shows a peculiar discontinuous behaviour which strongly depends on initial saturation and solubility.
A range of pressures where the composite compressibility is relatively high and pressure dependent, and a range of (higher) pressures where the compressibility is equal to the liquid compressibility; all gas has been dissolved (Figure 3). This behaviour has been observed in experiments by Schuurman (1966).
The pressure drop exerted to a reservoir during depletion may bring the actual pressure into the

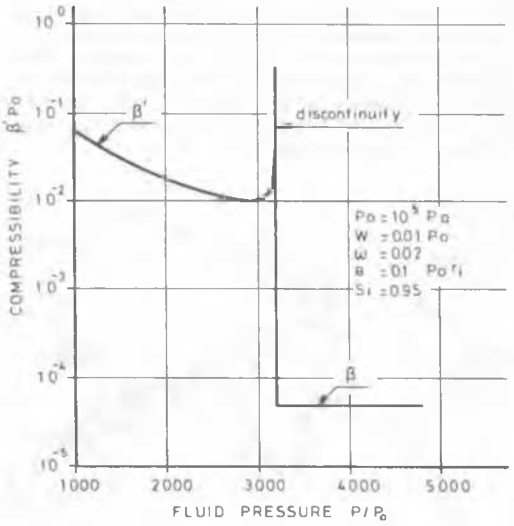

Fig. 3 Gas-liquid compressibility

lower range allowing dissolved gas to evolve into bubbles and pockets. At the same time the compressibility changes drastically. The subsequent large fluid expansion may favour depletion. In oil recovery this effect is well known (solution gas drive).
The appearance of gas bubbles and gas pockets will influence the permeability significantly. Bubble behaviour involves a bulk volume change $d\varepsilon = n\beta' dp$ and similar to equation (6) the permeability change due to bubbles becomes:

$$k \approx k_1 \exp[(\kappa\beta')p] \qquad (9)$$

3.3 Permeability effect in the flow process

The compaction of a reservoir with a mixture gas/liquid due to fluid production is described, in the most simple case, by a linearly elastic consolidation process. Mass conservation of the fluid is expressed by:

$$-\nabla \cdot \rho' q = \rho'(\dot{\varepsilon} + n\beta'\dot{p}) \qquad (10)$$

in which q is the specific discharge, which is related to the fluid pressure p by Darcy's law:

$$q = -(k/\mu)\nabla p \qquad \text{with} \qquad \mu = \nu\rho \qquad (11)$$

Here, μ and ν are the dynamic and kinematic viscosity, respectively. Note that for the viscous reaction in the fluid the gas bubbles are not essential. Elaboration of equation (10) employing (4), (5), (6), (8) and (9) yields for a horizontal reservoir:

$$\nabla^2 p + m(\nabla p)^2 = \dot{p}/c \qquad (12)$$

$$\text{with:} \qquad m = \beta' + (\alpha + n_0\beta')\kappa/n_0$$
$$c = k/(\mu(\alpha + n_0\beta'))$$

The permeability and density effect appears as a second order term.
A simple transformation renders equation (12) into a linear one (Barends, 1980):

$$\nabla^2 \chi = \dot{\chi}/c \qquad \text{with} \qquad \chi = \exp[mp] - 1 \qquad (13)$$

The actual mass flux becomes:

$$\rho' q = -\rho'(k/\mu)\nabla p =$$
$$= -\rho_1' \exp[\beta' p]\; k_1 \exp[\kappa(\alpha/n_0 + \beta')p]\; \nabla p/\mu$$
$$= -k_1 \rho_1' \exp[mp]\; \nabla p/\mu$$
$$= -k_1 \rho_1' (\chi + 1)\; \nabla p/\mu$$
$$= -k_1 \rho_1'/m\mu\; \nabla \chi \qquad (14)$$

A linear function of χ. Hence, the permeability effect can be easily taken into account, whereas boundary conditions in terms of p or q are directly related to χ and the initial state. For practical purposes the transient behaviour can be assessed by adopting for c (consolidation coefficient) an average constant value: $c = k_0/(\mu(\alpha + n_0\beta))$. If not, iterative calculations are required.

3.4 The significance of the permeability effect

3.4.1 A well with a constant discharge

The importance of the permeability effect can be shown by considering the steady state solution of a well in a confined horizontal reservoir with height H. If a constant discharge Q is imposed at $r = r_0$, the corresponding boundary condition in terms of χ becomes:

$$\nabla \chi = -m\mu Q/2\pi r_0 k_1 H \qquad \text{at} \qquad r_0 \qquad (15)$$

The solution becomes with $\chi = p - p_1 = 0$ at $r = R$:

$$\chi = -(m\mu Q/2\pi k_1)\ln[r/R] \qquad (16)$$

The actual pressure p can be obtained by inverse transformation $p = (1/m)\ln[1+\chi]$ leading to:

$$p = (1/m)\ln[1 - (m\mu Q/2\pi k_1 H)\ln[r/R]] \qquad (17)$$

Evaluation of this solution shows that it is consistent with the linear solution when m tends to zero. The steady state pressure variation with respect to r depends on the boundary condition; it is different for infiltration (Q>0) and withdrawal (Q<0), as shown in Figure 4a. For infiltration the generated pressure is less in absolute sense than for withdrawal at equal intensity.

3.4.2 A well with a constant head

In a similar way the solution for a constant well pressure p_0 can be found:

$$p = \left(\frac{1}{m}\right)\ln\left[1 + \left(e^{mp_0} - 1\right)\frac{\ln[r/R]}{\ln[r_0/R]}\right] \qquad (18)$$

Also, here, the steady state for infiltration differs from withdrawal, shown in Figure 4b. Now the generated pressures for infiltration is larger than for withdrawal, in absolute sense. The penetration of pressures is more significant for infiltration. Although the pressure gradient for infiltration is less, the infiltration discharge is larger than for withdrawal at equal pressure drop because of the permeability effect. Elaboration of the ratio between infiltration and withdrawal discharge at equal absolute excess well pressure p_0 yields:

$$|Q(\text{inf})/Q(\text{pump})| = \exp[m|p_0|] > 1 \qquad (19)$$

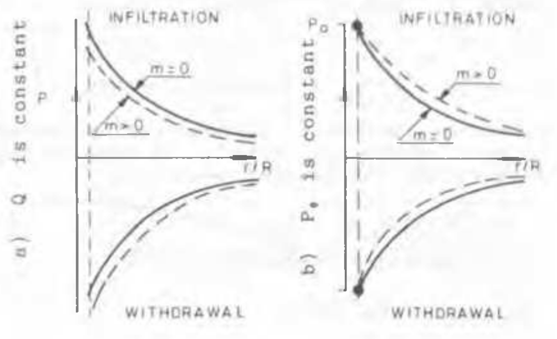

Fig. 4 Steady-state permeability effect

which shows that infiltration is easier than extraction of fluids from a porous reservoir. This is, however, valid if the fluid compressibility β' is constant, which holds for higher pressure range, and if the skeleton compressibility α is constant, which is not the case if plastic deformations are induced (range beyond the preconsolidation pressure). For monotonic pressure changes it is sometimes possible to use linearized parameter values and the previous theory can be applied.

4 GRANULAR COMPRESSIBILITY EFFECT

4.1 Effect on the permeability

The compaction of reservoirs of sediment deposits exhibits in general a nonlinear behaviour characterized by the preconsolidation pressure which matches the maximum effective stress the reservoir ever being exposed to. If effective stresses remain under this point the deformation behaviour is reversible (α is a constant). If effective stresses reach beyond deformation behaviour becomes nonlinear according to:

$$\alpha = \eta/\sigma' = \eta/(\sigma-(p+p_1)) = \eta/(\sigma_1'-p) \qquad (20)$$

where η is the compressibility coefficient, a constant in the order of 0.1 depending on the type of soil and its constitution, subscript 1 refers to initial absolute pressures, and p is the actual excess pore pressure.
Elaboration of equation (4) for a horizontal reservoir yields:

$$dk/k = (\kappa/n_0)(\eta/(\sigma_1'-p) + n_0\beta')\ dp \qquad (21)$$

which can be rewritten into:

$$k/k_1 = (1-p/\alpha_1')^{-m'} + \exp[\kappa\beta' p] \quad \text{with} \quad m'=\kappa\eta/n_0$$

which is only slightly different from equation (6) if $p/\alpha_1'<1$.

4.2 Effect on the flow process

Along the same line followed in the preceding sections the flow behaviour in horizontal reservoirs is worked out. Elaboration of equation (10) assuming $\beta'=0$ yields:

$$(k/\eta\mu)\{(\sigma_1'-p)\nabla^2 p + \kappa\eta/n_0(\nabla p)^2\} = \dot{p} \qquad (22)$$

or:

$$(k/\eta\mu)\{\sigma_1'\nabla^2 p - \tfrac{1}{2}\nabla^2 p^2 + (1+\kappa\eta/n_0)(\nabla p)^2\} = \dot{p}$$

Linearization towards p introducing an average excess pore pressure p_0 within the range of pore pressure variations exposed leads to:

$$\nabla^2 p + m_0(\nabla p)^2 = (\dot{p})/c_0 \qquad (24)$$

with
$$m_0 \approx \alpha_0(1/\eta+\kappa/n_0)$$
$$c_0 \approx \alpha_0(k/\mu)$$
$$\alpha_0 \approx \eta/(\sigma_1' - p_0/2)$$

The transformation: $\chi_0=\exp(m_0 p)-1$ renders equation (24) linear:

$$\nabla^2\chi_0 = \dot{\chi}_0/c_0 \qquad (25)$$

The resulting expression for the flux needs special attention. Similar to expression (14) it is expected that the conservation of mass, which is the origin of equation (25), will provide an approximate linear expression for the flux in terms of χ_0 and initial conditions.
Inverse transformation leads to:

$$p = (1/m_0)\ln(\chi_0+1) \quad \text{and} \quad \nabla p \approx \nabla\chi_0/(m_0(\chi_0+1))$$

In this respect the flux according to equation (11) becomes:

$$q = -(k/\mu)\nabla p \approx -(k/\mu)\nabla\chi_0/(m_0(\chi_0+1))$$

which is only linear in χ_0 if $k/(\chi_0+1)=k_1$ is a constant. This implies a constraint to the permeability variation. Elaboration yields:

$$k/k_1 = \exp(m_0 p)$$
$$\approx \exp[p\alpha_0(1/\eta+\kappa/n_0)]$$

or: $$dk/k \approx (1/\eta + \kappa/n_0)d\varepsilon$$

Comparison with equation (4) shows an additional term $1/\eta$ related to the nonlinearity in α. Finally the expression for the discharge q becomes:

$$q \approx -(k_1/(\mu m_0))\ \nabla\chi_0 \qquad (27)$$

which is linear in χ_0 and as such satisfies the conservation of mass expressed in the flow equation (25). It is, therefore, possible to include nonlinearity in granular compressibility in the form of an extra term in the permeability effect. The solution of boundary value problems involving prescribed fluxes is straight forward. Conclusions about this effect are in line with those mentioned in previous sections, except that in this case the linearization applied limits the general validity of the approach.

5 EFFECT OF THE ENVIRONMENT

Landsubsidence observed during reservoir depletion is partly attributed to consolidation of adjacent compressible slowly draining layers (aquitards). If the extracted fluid is replaced by fluid intruding at the boundaries (water drive) effects beyond the reservoir may be expected. The amount of water leaking from semi-pervious layers is related to the pressure drop in the reservoir but also to the duration of the pressure decline. The relatively low permeability provokes drainage to proceed slowly. Consequently, the reaction in the aquitard is retarded and its effect may become apparent at later stage. If a reservoir is abandoned this retarded effect may continue for some time.
The incorporation of leaking layers in the reservoir performance is usually accounted for in an uncoupled fashion assuming that the retarded effect is unimportant in the reservoir flow process, and resulting reservoir pressures unset consolidation in the aquitards

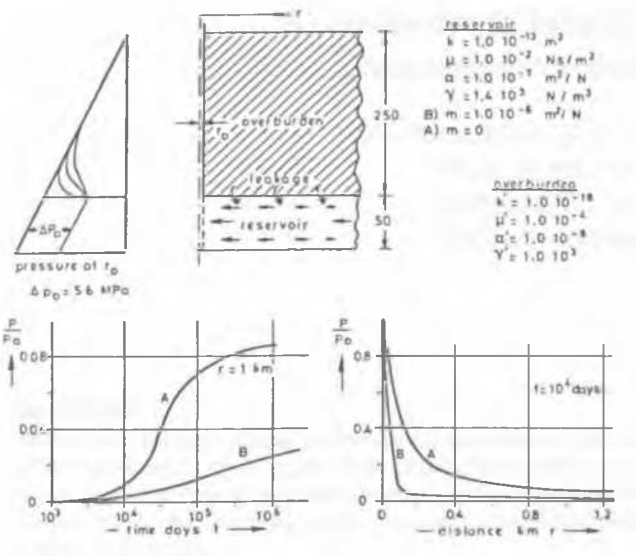

Fig. 5 Application to a time-dependent problem

separately. This approach, however, may influence the results of a simulation significantly. A coupled approach using the technique of the transient leakage factor is possible without introducing extra complications (Barends 1984). In Figure 5 the response of a leaky reservoir subjected to withdrawal by a constant well is shown including the nonlinear effects described in the preceding sections. The resulting reservoir pressure includes the actual consolidation process of adjacent layers and as such it represents a better value to determine the actual effects in these layers. This method is applied to the evaluation of landsubsidence at lake Maracaibo, Venezuela.

6 POST-PRODUCTION EFFECT

Beside the retarded effect due to consolidation of adjacent slowly-draining layers another effect may occur at later stage. This effect is related to soluble gas (Figure 6). In the original state the reservoir pressure is relatively high and gas is dissolved in the liquid. During depletion the pressure drop causes gas to escape and form free pockets, allowing the pore fluid to expand at almost constant reservoir pressure. This process continues during depletion. When the production is stopped, the low reservoir pressure will recover slowly by leaking fluids from the surroundings. At the same time free gas will dissolve again. This causes the pressure to raise very slowly until all gas has been dissolved. During this process the free gas volume will be occupied by fluids from the surroundings. Therefore, the effects related to consolidation in adjacent layers will continue after abandonment of a reservoir. An estimate of this post-production effect with respect to landsubsidence can be made by considering the total gas volume which may dissolve. This effect is important with regard to liability after the exploitation of a reservoir.

7 MAN-INDUCED SEA LEVEL RISE

In the last 100 million year sea level has changed more than 100 meter. Last interglacial period was about 2°C warmer and the sealevel 7m higher. At the end of the last ice period (9 millenia ago) sealevel was about 40m lower. Two millenia ago sealevel was about 1m lower than at present. Tydal motion shows a more pronounced variation. The recent increase in CO_2 and some other gases influences the radiation balance in the atmosphere resulting in a global temperature rise and consequently in a climate change. In fact the oceans may absorbe this surplus of volatile gases, but it will take several centuries. A temperature change will effect flora and fauna to an extent not yet known, it will cause melting of landice and thermal expansion of seawater, both resulting in sealevel rise. It is expected that this rise is significant and the rate of change is much larger than actual tectonic and other autogenic processes: a rise in the order of 2m in the next century (Barth, 1984).
Most areas of known subsidence are along coasts where the land sinking becomes obvious as the water level creeps steadily higher up the shore. Flooding of populated and industrialized areas is a major problem resulting from subsidence of coastal areas in Tokio, Shanghai, Bankok, Venice, Long Beach, New Orleans. Investments to protection works, extensive systems of dikes, flood walls, locks, pumping stations and other remedial measures reach billions of dollars. This subsidence is mostly caused by man's activity: drainage, landreclamation and fluid withdrawal. Countermeasures on regional scale are sufficient, sometimes requiring a special law (groundwater protection). Problems can be solved by a nation.
The new hazard of sealevel rise which represents a new attack on coastal defence structures and coastal drainage systems, is, however, a global problem. Only by cooperation of all nations mankind may limit the effects of atmospheric pollution and protect the investments already made.

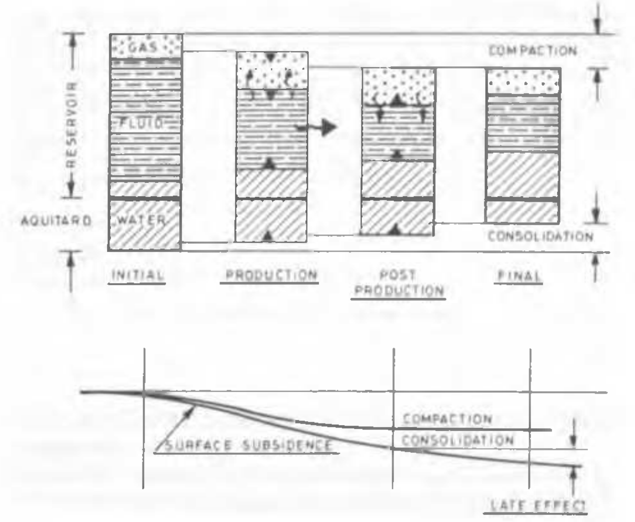

Fig. 6 Post-production effect to landsubsidence

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