GROUND WATER AND GEOTECHNICAL PROBLEMS

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ABSTRACT

This paper is based on the Author's lectures presented during his stay as a Visiting Professor at The City University, London, in November 1982. Starting from a general view of the main problems, it describes the driving forces in hydro-geomechanical processes, especially the forces induced by pressure changes in the underground water. The estimation of the stresses and strains in the ground (soil and rock) requires the solution of coupled systems of equations of soil and ground water flow and geotechnical strain or failure of the ground. The paper describes in detail problems of regional ground subsidence due to pumping in open-cast mine areas and problems of estimation of seepage forces in saturated or unsaturated loose rocks with anisotropic conductivities and in fissured hard rocks with conductivities characterised by a tensor. Possibilities of the solution of those problems with analog and numerical models are briefly discussed.

MAIN PROBLEMS

We have to distinguish between hydrogeomechanical processes on microscopic and on macroscopic levels.

On the microscopic level, the two phases, the solid material and the fluid flowing in the connected channel network of the porous or fissured solid material, are considered as two different systems (two single phases) coupled with each other. In the centre of interest are stability problems of the solid skeleton and problems of the transport of fine solid particles through the skeleton. The concept divides the solid material into a skeleton which transfers effective stresses σ' and into fine solid particles which do not. The most interesting processes are:

- Chemical dissolution and precipitation, if solids are not in thermodynamical equilibrium with the solid minerals (1) (important e.g. in carbonate rocks).
- Hydromechanical suffosion and clogging, i.e. the passage or blocking of solid materials which are not part of the skeleton (2) (important, e.g., for the design of filters in suffosion-endangered loose rocks).
- Internal erosion (e.g. piping and, on the ground surface, sand boiling) (3); internal erosion, in contrast to suffosion, involves all solid material in the process of transportation.
- Interface erosion, i.e. especially processes of erosion and bridging in the vicinity of filters in cohesive and non-cohesive materials (2) (important, e.g., for the design of filters in water engineering).

On the macroscopic level the hydrogeomechanical processes are considered as problems of continuum mechanics, i.e. the fixed solid material and the flowing fluid are two components of one single phase penetrating each other and each filling the whole space volume continuously like the components oxygen and nitrogen in the single phase air. The mass density of each of the components is then the bulk density. It is useful to distinguish between "local" and "global" problems.

The most important local problems of hydrogeomechanical processes on the macroscopic level are:

- Local failures where the upward gradient of the piezometric head exceeds the effective stress (e.g. formation of quicksands in opencast pits).
- Local mud flow on slope toes, i.e. the formation of mud tongues with water flowing out of slopes.
- Local slip failures on the surface of the slopes directly above an impermeable or semipermeable layer.

The most important global problems (which may, of course, also be treated as local problems) are:
- Subsidence problems due to elastic and plastic deformation (4) (e.g. land subsidence due to a change in effective stress by draw-down of ground-water).
- Slipping and collapse of geotechnical structures (e.g. failures along slip planes, perhaps along a logarithmic spiral).
- Viscous soil flow (e.g. in dump areas during a rise of ground water, especially in the vicinity of residual mines with rising water levels).

DRIVING FORCES

The driving forces in hydrogeomechanical processes which cause deformations, failures and collapses are above all the chemical forces, the hydromechanical acceleration and changes in underground water pressure.

Chemical forces are proportional to the deviation of the saturation index SI from 1.0 ($F \sim SI - 1.0$). For a mineral of the structure $A_mB_n(s)$, e.g. $CaF_2(s)$, dissociating in water as the solvent in m cations with the charge of +n (e.g. 1 Ca^{2+}) and in n anions with the charge of -m (e.g. $2F^-$), SI is (1) (5)

$$SI = \{A^{+n}(aq)\}^m \{B^{-m}(aq)\}^n / K_{eq} \tag{1}$$

{ } - symbol for the activity of the substance standing inside the brackets

K_{eq} - thermodynamical equilibrium constant

SI < 1.0 means therefore mineral dissolution and SI > 1.0 precipitatio

The hydromechanical acceleration force f follows from Newton's law in a flow channel,

$$f = \rho_{f\ell}\, dv/dt = \rho_{f\ell}(\partial v/\partial t + v\partial v/\partial \ell). \tag{2}$$

Above all, the convective acceleration $v\partial v/\partial \ell$ is responsible for transport of solid particles through the channels or fissures of the skeleton. Supposing the geometrical criteria of suffosion are fulfilled (2),

$$\phi_{particle} < SF.\phi_{channel} \tag{3}$$

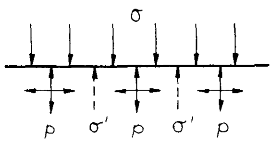
SF - slipping (or passing) factor depending on $\phi_{channel}$ (2),

the transport of a particle takes place only if $v\partial v/\partial \ell$ exceeds an estimated value depending on the shape and weight of the particle and the direction of the transport (2).

The underground water pressure is connected with the total stress σ and the effective stress σ' respectively by equation (4):

$$\sigma = \sigma' + p \tag{4}$$

σ, σ' and p are intensive variables of continuum mechanics.



If the total stress σ is constant (no changes of the load e.g. due to building of new structures or excavating of soil), the changes of the effective stress transmitted by the solid skeleton are equal to changes of underground water pressure:

$$d\sigma = 0 \quad \rightarrow \quad \boxed{d\sigma' = -\,dp} \tag{5}$$

The effective stress is connected with strain by

$$d\vec{\varepsilon} = [C']\, d\vec{\sigma}' = -\,[C']\, dp \tag{6}$$

$\vec{\varepsilon}$, $\vec{\sigma}'$ - vector of strain resp. effective stress

$[C']$ - matrix of deformability.

Land-subsidence problems are characterised by changes of p in time due to ground-water pumping:

$$dp = (\partial p/\partial t)\, dt. \tag{7}$$

Often failure problems are related to changes of p in space (steady state of underground water flow):

$$dp = \gamma d\vec{\ell}\ \mathrm{grad}(p/\gamma + z) = \gamma d\vec{\ell}\ \mathrm{grad}\ h \tag{8}$$

h - piezometric head
γ - unit weight of fluid
$d\vec{\ell}$ - infinitesimal length in direction of grad h.

The seepage force ΔS is

$$\Delta S = \gamma d\vec{\ell}\, dA \text{ grad } h = \gamma \Delta V \text{ grad } h \tag{9}$$

dA - infinitesimal area perpendicular to $d\vec{\ell}$

acting on the solid skeleton as the reaction force to the friction of the fluid flowing through the ground (2).

Many slope slips are typical failures due to changes of p in time. The shear strength τ responsible for the stability against slipping is related to the effective stress at a space point by:

$$\tau = c + \sigma_n' \tan\phi \tag{10}$$

c - factor of cohesion
ϕ - angle of friction.

Each reduction of σ' due to an increase in p (e.g. during the rise of ground water in abandoned mining areas) must reduce τ and therefore increase the danger of slip failures.

LAND SUBSIDENCE

Land subsidence often limits ground-water pumping, e.g. in Mexico City and in many areas along the coast of Japan and of the Gulf of Texas. Land-subsidence problems in the German Democratic Republic (G.D.R.) are above all connected with pumping for drainage of open-cast mines. For an output of about 300 million Mg (tons) of lignite a year, 1.5 milliard m^3 of water have to be pumped. This leads to large cones of depression, e.g. in the open-cast mining area of the Lausitz a cone of depression was formed of about 100 km length and 20 km breadth. For the estimation of the most interesting vertical land subsidence (7)

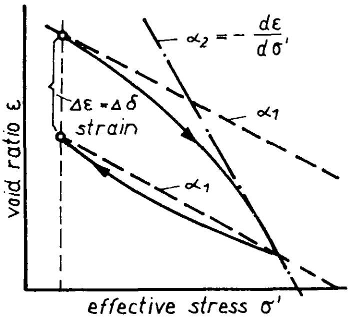
$$\delta(x, y, t) \simeq \int \frac{\alpha_v \, p^*(x, y, z, t)}{1 + \varepsilon_o} dz \tag{11}$$

α_v - vertical compressibility of the underground
ε_o - void ratio for $p^* = 0$
p^* - underground water pressure difference $p^* = p - p_o$

it is necessary to find the pressure distribution $p = p(x, y, z, t)$. For this we have to solve a partial differential equation linking the mathematical model of underground water movement with mathematical models of elastic and plastic consolidation (7) (8).

Underground water flow including source/sink terms for pumping, nat. and artif. recharge, free drainage, etc.	=	Source/sink term for the elastic part of consolidation	+	Source/sink term for the plastic part of consolidation

$$\nabla \frac{K}{\rho \cdot g} \nabla p^* \mp \sum w = (\alpha_1 + n\beta) \frac{\partial p^*}{\partial t} + \frac{1}{q''} \int_0^t p^*(\tau) \exp[\;]\, d\tau \tag{12}$$



$\alpha_1 = \frac{1}{1-n}\frac{\partial n}{\partial p}$; $\beta = \frac{1}{\rho}\frac{\partial \rho}{\partial p}$ to (12)

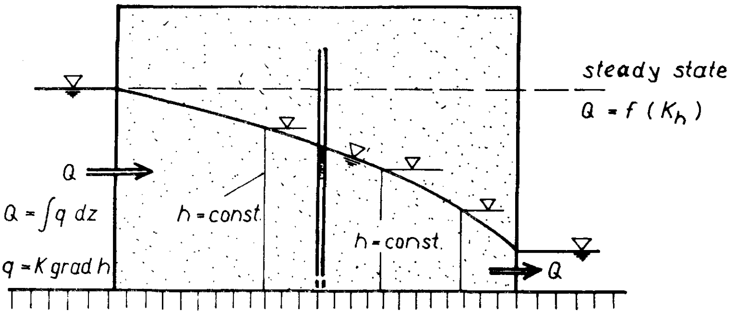
β - water compressibility
n - porosity, ρ - water density
α_1, α_2 - elastic and plastic compressibility
K - hydraulic conductivity of Darcy's Law
q" - viscosity of the soil(the whole term for the plastic part of consolidation; see,e.g, [9.p 189])
$[\ ] = [-(t-\tau)/\alpha_2 q'']$

The problems in the G.D.R. arise especially in abandoned mining areas, when the ground-water level returns to its initial value before pumping. The ground-water level in the Lausitz brown-coal field,e.g., before the start of mine drainage in many areas,was only about 1 to 1.5m below the ground surface. The plastic part of deformation during the time of miming and pumping is often in the same range. The ground-water level rises therefore,after finishing of mining activities,in the vicinity of the ground suface and changes agricultural land and forest into swamps and marshes. Pumping or other kinds of artificial drainage measures are therefore necessary in some of these agricultural or urbanised areas in the former cone of depression. But this is expensive, and,moreover, the quality of the water pumped out of the ground in the cone of depression is very bad[11]. Such water is highly acidic [11].It would be better to estimate land-subsidence before planning the restoration of the mining landscape. The best point for this planning would of course be the time before open-cast mining and drainage start [12].

SLOPE STABILITY IN LOOSE ROCKS

Ground-water flow influences slope stability by seepage forces (see eq. 9) acting on slips as driving forces and by shear forces (see eq. 10) acting on slips as resisting forces. The estimation of both requires the determination of the distribution of the piezometric head h(x, y, z) both in the saturated and in the unsaturated zones. The suction in the vadose zone (zone above the groundwater table) acts like a fictitious cohesion, but seepage forces in this zone are of the same range as in the groundwater zone.

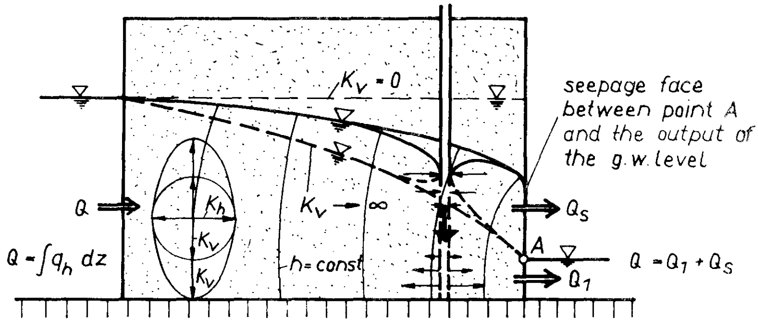
Most calculations of groundwater drainage, especially in multi-aquifer systems, are based on Dupuit's assumptions. This holds for all models using the transmissivity T as parameter or the Girinskij potential ϕ as dependent variable. The solution of these models yields therefore only the so called "Dupuit surface" and h(x,y) beneath this surface. In the vertical plane such a surface may have, e.g., the form sketched below.



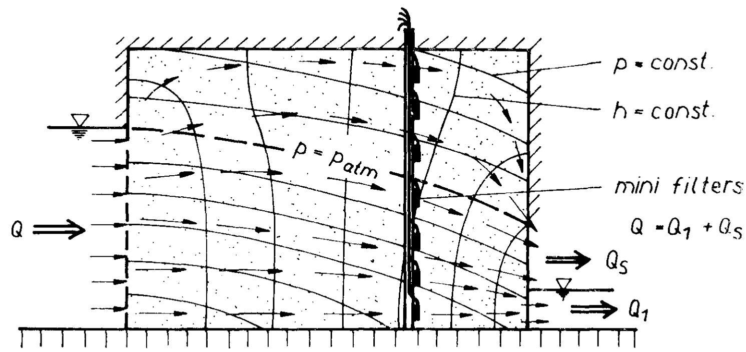
It is typical for these calculations that they yield correct values for the discharge Q, which may be verified by actual measurement. Both the Dupuit surface and the discharge are dependent only on K_h. The anistropy of the conductivity (e.g. the value of K_v) is without influence on the location of Dupuit's surface and the value of Q. Pumping-test data and grain-size distribution represent at first K_h and are insensitive on K_v (h stands for horizontal and v for vertical). A stand pipe with a short filter at the bottom of the aquifer shows a water level in good agreement with Dupuit's surface.

All these reasons speak of course for using such a model. But for the estimation of slope stability there is, beside the lack of the approximate distribution of h below the Dupuit surface, the uncertainty of estimation of values of seepage forces above this surface. Attempts are therefore often made to calculate the elevation of the groundwater table instead of the Dupuit surface. After a scale distortion depending on the factor K_h/K_v [2][8], the estimation of the groundwater surface (independent of the ratio K_h/K_v) by means of electrically conductive paper [2] [8] or numerical models (based on the Dupuit surface along stream lines [2, p 239]) for areas in the vicinity of the slope is possible at comparatively small expense.

The groundwater level coincides with the Dupuit surface for $K_v \to \infty$ and is horizontal for $K_v = 0$. The value of Q is independent of this. The problem of using such a concept is related to the estimation of K_v and the measurements of the groundwater level under field conditions. The best way of estimating K_v seems to be to take undisturbed vertical soil samples during the drilling of observation bore holes. The measurement of the free groundwater table is practically only possible with a chain of single transducers or mini-filters. Mini-filters work both in groundwater and the vadose-water zone, i.e. they have proved satisfactory devices for measuring both pressure and suction in groundwater. The installation of numerous boreholes with porous walls, over a great part of the aquifer, on the other hand, must be avoided. They serve as elements transporting water in the vertical direction and so disturbing the distributions of pressure and flow [2, p 77].



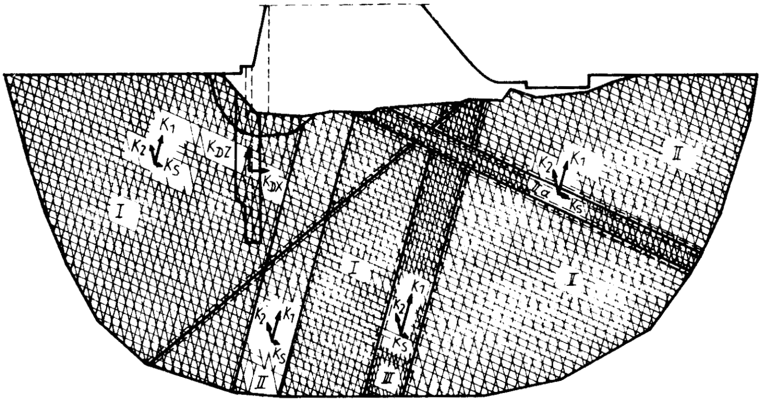
Of course even the model concept of a groundwater table instead of the Dupuit surface is not fully sufficient. A little better seems to be instead to use the interface between the saturated and unsaturated zone ($\Delta H = p_{air\ entrance}/\gamma$ above) or even the interface of fictitious saturation ($\Delta H_f = (1/K_{sat}) \int K_{uns}\, dz$ above the water table). But only the simultaneous modelling of underground water movement in the whole groundwater and vadose-water zone with anisotropic parameters of the hydraulic conductivity seems to be a meaningful solution for the estimation of seepage forces and effective stresses to calculate slope stability and to estimate the degree of approximation of other model concepts.



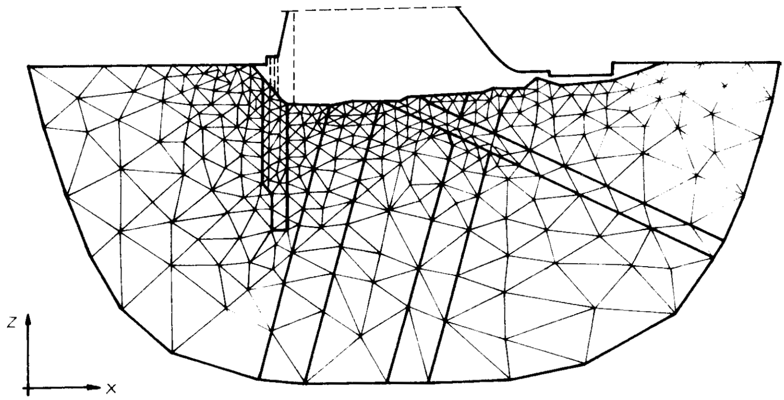
For using such a model concept it is necessary to estimate the dependence of K_v and K_h on the degree of saturation of the soil with water [14]. The measurement of p or h is again possible by means of a vertical chain of mini-filters. As the computer code we are using the program VEREGO [13].

SEEPAGE FORCES IN FISSURED ROCKS

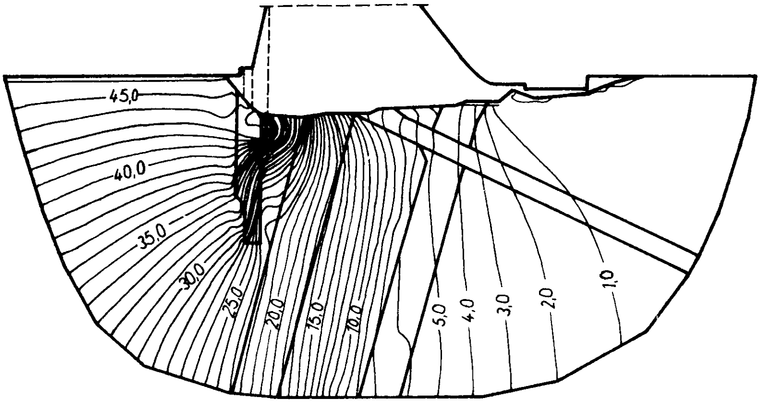
For fissured hard rocks it is typical to have a hydraulic conductivity of tensorial character. Several faults act as special zones with high conductivity. The opposite holds for grout curtains.



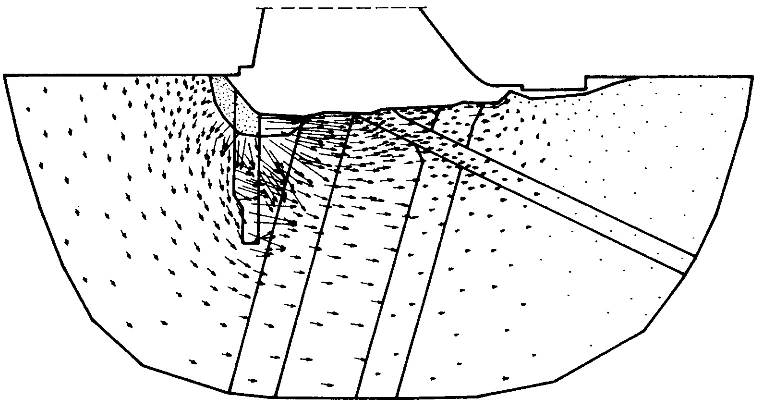
The best way for solution of such an underground flow problem is a numerical model with finite elements fitting the individual areas of different permeabilities.



The results of the computer (we use for this the computer program POFEM [15]) are then the distribution of piezometric head h(x,z) drawn by a plotter

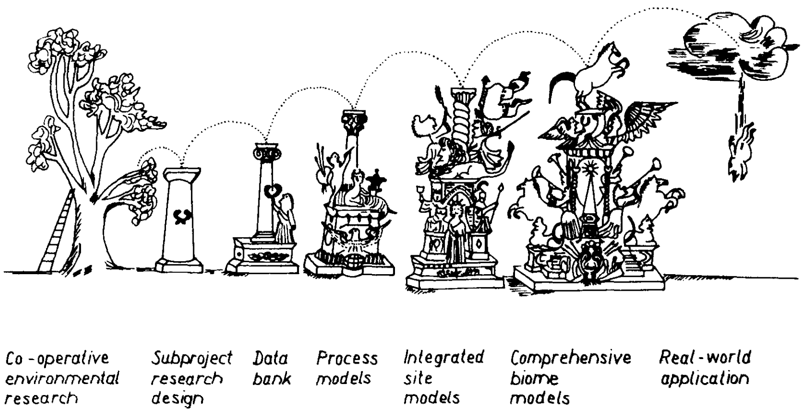


and the gradients of piezometric head grad h = f(x,z) also drawn by a plotter.



The most important problem is that the width of the fissures, and therefore the permeability, is a function of effective stress. We solve this problem by an iteration procedure. The high groundwater pressures upstream of this grout curtain and the force moment due to the horizontal pressure force of the water body in the reservoir on the concrete dam cause the permeability in this area to reach very high values. It is also possible that the upper part of the grout curtain becomes fissured and loses its effect, as is shown in the last two pictures.

In cases where the underground water movement is disturbed by local (e.g. drainage) elements, the use of three-dimensional modules is necessary. We use in such cases the computer program RAUM-1 (15). But the most sophisticated model does not always yield the best results in practice. Today's problem is that the possibilities of process simulation often exceed the possibilities of fitting such a model with the necessary data. But because the results of simulations can only be as good as the weakest part, it will also in future be very important to know the easier methods of solution like analytical solutions and modelling with not too complicated electrical analog devices (e.g. electric paper models). The last picture shows how REMMERT saw this problem (16) :



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