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Studies of *in situ* Pore Pressure Fluctuations at Various Scales

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Résumé — Études des fluctuations *in situ* de la pression de pore à différentes échelles — Les fluctuations de la pression de pore dans les formations géologiques saturées en fluides, d'origine naturelle ou anthropogéniques, peuvent être observées à différentes échelles. Les fluctuations naturelles, par exemple celles d'origine sismique, barométrique ou marémotrice, ainsi que les effets provoqués par l'exploitation de réservoirs de fluides souterrains par l'homme, ou encore les chargements initiaux et cycliques de lacs servant de réservoirs, peuvent avoir des longueurs d'ondes allant du mètre au kilomètre.

Le contrôle *in situ* des processus, pour lesquels la déformation de la roche ainsi que les variations de pression sont significatives, améliore notre connaissance sur la réaction mécanique et sur le rôle de la pression de pore dans les roches poreuses et les couches sédimentaires. Les capteurs de pression pour un enregistrement continu des variations du niveau de fluide dans les puits (reflétant les changements de pression en profondeur) ou les inclinomètres de puits, sensibles à la déformation du sol causée par des gradients de variations de pression de pore, constituent des moyens relativement simples permettant de suivre les dynamiques de telles interactions roches-fluides. Les données obtenues sont généralement interprétées de deux manières différentes : par l'utilisation de solutions analytiques — avec des conditions poroélastiques homogènes ou des modèles de fracture unique en milieu élastique homogène — et par la simulation numérique qui permet de prendre en compte, dans le modèle, certaines hétérogénéités.

Les cas de gisements présentés dans cet article incluent des mesures inclinométriques proches des puits de pompage (échelle allant de 1 à 100 m), des contrôles du niveau de fluide dans les puits profonds (échelle du puits) et des études sur les variations de la pression de pore d'origine sismique (échelle allant de 1 à 100 km). Les paramètres caractéristiques des roches qui peuvent être soumis à des contraintes sont le coefficient de Skempton, la diffusivité hydraulique et le type de la rhéologie effective. Dans le cas des mesures d'inclinométrie, l'anisotropie d'écoulement du fluide peut également être détectée.

Mots-clés : fluides dans les roches, pression de pore, poroélasticité, hydrologie.

Abstract* — *Studies of* in situ *Pore Pressure Fluctuations at Various Scales — *Pore pressure fluctuations in fluid saturated geological formations, either of natural or anthropogenic origin, can be observed at different scales. Natural fluctuations, e.g., due to tidal, barometric or seismogenic forcing, or man-made effects as through use of underground fluid reservoirs, or initial filling and cyclic loading of lake reservoirs may have wavelengths from meters to kilometers.*

In situ *monitoring of processes, in which both rock deformation and pore pressure changes are significant, improves our knowledge on the mechanical behaviour and the role of pore pressure in porous rocks and sedimentary layers. Pressure transducers for continuous recording of fluid level variations in wells, reflecting pore pressure changes at depth, or borehole tiltmeters that are sensitive to* *ground deformation caused by gradients of pore pressure fluctuations are relatively simple means to trace the dynamics of such rock-fluid interactions. The obtained data series are usually interpreted in two ways: by application of analytical solutions—adopting homogeneous poroelastic conditions or single fracture models in a uniform, elastic medium—and by simulation through numerical calculations allowing for some heterogeneity in the model volume.*

Field cases presented in this article include tilt measurements in the vicinity of pumped wells (1 to 100 m scale), fluid level monitoring in wells (borehole scale), and studies of pore pressure effects induced by seismic events (1 to 100 km scale). Specific rock parameters that can be constrained are the Skempton ratio, the hydraulic diffusivity, and the type of the effective rheology. In cases of tiltmeter studies, anisotropy of pore fluid flow can also be detected.

Keywords: fluids in rocks, pore pressure, poroelasticity, hydrology.

INTRODUCTION

Hydrological aspects of rock formations like pore pressure, porosity, permeability, and the nature of fluids hosted in the pore space are of major economic interest, e.g., for the use of ground water or hydrocarbons. Fluids also play a dominant role during the evolution of rocks, in subsidence cases, and in seismotectonics. Therefore, rock-fluid interactions have become research objects of many geoscientists.

Various types of rock-fluid interactions are to be investigated, all of them as a function of temperature, chemical composition, and pressure. Here, we focus on pore pressure effects on time scales from minutes to years, in systems where other aspects of fluid transport and other controlling parameters are negligible. Still, because of the complexity of natural rocks, many pore pressure phenomena are poorly understood. Better knowledge of factors affecting pore pressure distributions in space and time may help to improve the management of fluid reservoirs, assess the extent of ground water contamination from waste disposals, estimate impacts of intense agricultural use, predict land slides and subsidence, as well as to understand earthquake mechanics, to list only some examples.

A crucial point when considering pore pressure as a geomechanical parameter is: What dominates flow properties and the rheological behaviour of the medium? Some simplifications have to be made to maintain control over the relevant physical processes. As we restrict to cases of saturated formation and the shallow subsurface where thermal aspects are of minor importance, poroelasticity appears to be adequate to describe typical features of many field observations.

The examples given here represent a small selection of such problems, typical for investigations of basic research. They comprise deformation studies in the vicinity of pumped wells and of water consuming trees, interpretation of fluid level fluctuations in open boreholes induced by earth tides and by changes in barometric pressure, and relations between pore pressure and seismicity. Possible links to more applied subjects are, however, obvious: Tilt measurements at shallow depths can be used to monitor the subsidence history over productive zones and indicate, whether a reservoir compacts uniformly or with substantial lateral variations. Analyses of tidal fluctuations of fluid level signals in abandoned reservoir boreholes constrain relevant petrohydraulic parameters under *in situ* reservoir conditions. And the study of mechanisms behind seismicity triggered by the cyclic filling of lake reservoirs gives insights that are useful for assessing site effects which may also be encountered with the production or stimulation of underground reservoirs.

It is not intended to present a complete overview on similar works that have been published in this field. Rather, references are mostly given to studies of the recently established "*in situ* Pore Pressure Physics Group" of the Applied Geophysics Section at the *Geological Institute,* Bonn, with early investigations on such problems dating back to the eighties.

1 RHEOLOGICAL CONCEPTS

Assuming saturated conditions for chemically inert porous media, the theory of poroelasticity as introduced by Terzaghi (1923) and Biot (1941), and reformulated by Rice and Cleary (1976), appears to be adequate to describe the stress-strain behaviour and pore pressure response when forces are applied. Different from a typical hydrological approach, in which rock deformation is solely expressed through the storage coefficient, deformation of the rock matrix is inevitably related to a change in pore pressure and vice versa. The pressure of the pore fluid is a function of the confining pressure acting on the rock matrix, pore pressure gradients result in directional strain and in pore fluid flow, and the strength of the rock is linked to the effective pressure, which is assumed to be confining pressure minus pore pressure.

In poroelasticity, the medium is considered to be macroscopically homogeneous, that is the structure and the size of a pore are not taken into account. Accordingly, deformational behaviour depends on a few, effective rock parameters, i.e., bulk compressibilities c, c_u, and Poisson ratios ν, ν_u for drained and undrained conditions, respectively, the rock's shear modulus G, that is independent of the conditions of fluid flow, and the Skempton ratio B, denoting the change in pore pressure per unit change in confining pressure for undrained conditions (Kümpel, 1991a; Wang, 1993). For isotropic media, only four of these parameters are independent from each other. The ease of pore fluid flow is expressed by the hydraulic diffusivity D (in m^2/s), which is proportional to intrinsic permeability k (in m^2) by:

$$D = \frac{2}{9} \frac{(1-\nu)(1+\nu_u)^2}{(1-\nu_u)(\nu_u-\nu)} B^2 G \frac{k}{\eta} \qquad (1)$$

where η denotes dynamic fluid viscosity.

Since inertial terms in the presented examples are not significant, the mechanical parameters hold for quasi-static deformation. They may grossly differ from those for dynamic deformation which apply, e.g., for the propagation of seismic waves (Ohkubo and Terasaki, 1977; Schön, 1983). When temperature changes in addition to those of pore pressure can not be neglected, the theory may easily be extended for application to thermo-poroelastic problems (McTigue, 1986). As noted before, in classical hydrology the deformational behaviour of the rock is expressed by a single parameter, the storage coefficient S. Under homogeneous full-space conditions, it can be shown to be related to the other parameters by:

$$S = \frac{9}{2} \frac{(\nu_u-\nu)\rho_f\, g}{(1+\nu)(1+\nu_u) B^2 G} \qquad (2)$$

with ρ_f denoting fluid density and g gravitational acceleration (Kümpel, 1991a). However, if S is used as the only mechanical rock parameter, strain in a three-dimensional sense is disregarded.

For some situations, namely when the formation's pore structure is dominated by the presence of large, open fractures, the concept of a macroscopically homogeneous medium may not be appropriate. In such cases, single fracture models appear to yield better results for simulations of fluid level fluctuations in boreholes (see e.g. Bower, 1983; Hanson, 1983). These authors presume that the geometry of a fracture has the main influence on the fluid level signal; the fracture itself is taken to be embedded in compact, elastic rock. Analytical solutions, like in the case of poroelasticity, do only exist for very elementary problems. Accordingly, application of numerical techniques like finite difference or finite element methods is necessary to simulate the impacts of the free surface, of alterations in formation parameters, or of nonelementary forcing functions. A quite different approach has been suggested by Lahaie and Grasso (1998). They used a cellular automaton to explain scaling features of rock-fluid interactions in volcano mechanics, which might be extended to phenomena ranging from the granular rock to the lithosphere scale. Recognizing that the earth's crust seems to bear an inherent variability on many scales (Pilkington and Todoeschuk, 1993; Dolan *et al.,* 1998; Leonardi and Kümpel, 1996, 1998, 1999), models should be regarded as equivalent scenarios, at most.

2 FIELD CASES

The type of studies outlined below may be summarized as in Figure 1. Petrohydraulic parameters together with the appropriate rheology govern the behaviour of the probed, saturated formation. Natural or man-induced forcing may be applied and quantitatively investigated on various scales. Well level recordings or tilt deformation signals bear useful information that can be analysed to improve the insight in the underlying physical process and to learn about effective *in situ* parameters.

2.1 One to Hundred Meter Scale: Pump Induced Ground Deformation

In poroelasticity, any change in pore pressure results in rock matrix deformation and vice versa. Merely by chance, this effect has been nicely observed in a ground water saturated, sandy terrain in Northern Germany and is documented in a high resolution recording of a borehole tilt sensor, obtained at some 120 m distance from a farmer's well that was regularly pumped (Kümpel, 1982). The phenomenon was later verified by controlled *in situ* experiments with further wells (Fig. 2). The tilt signals could be shown to constrain the values of three petrohydraulic rock parameters: the hydraulic diffusivity D (Eq. (1)), a modified Skempton ratio:

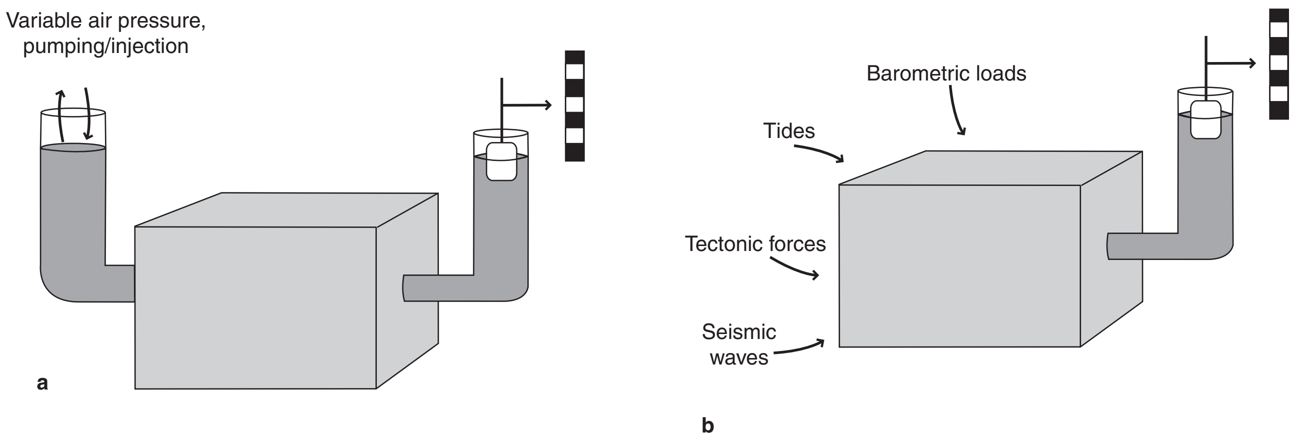
$$B' = \frac{B}{3} \frac{(1+\nu_u)}{(1-\nu_u)} \qquad (3)$$

and—by combining Equations (1) and (3)—a parameter:

$$\Gamma = \frac{(1-\nu_u)(1-\nu)}{\nu_u-\nu} \frac{k}{\eta} G \qquad (4)$$

(Kümpel, 1989). Similar observations at various other sites have revealed that pump induced tilt signals can rather easily be observed in unconsolidated sediments (Fig. 3; Kümpel *et al.,* 1996), with some greater efforts even in crystalline rocks (Kümpel, 1989, 1997a).

Borehole tiltmeters, in fact, appear to be well suited to sense rock deformation due to pore pressure gradients. The minimum resolution required is roughly in the order of µrad. For this quality, they are available at reasonable costs and can be installed in boreholes of only a few meters depth. Also, tiltmeters indicate if the induced pore fluid flow is isotropic or follows a preferential direction. In the latter case, the azimuth of the maximum tilt amplitude would generally deviate from the line connecting the positions of the pumped well and the tiltmeter. Similar studies with multicomponent



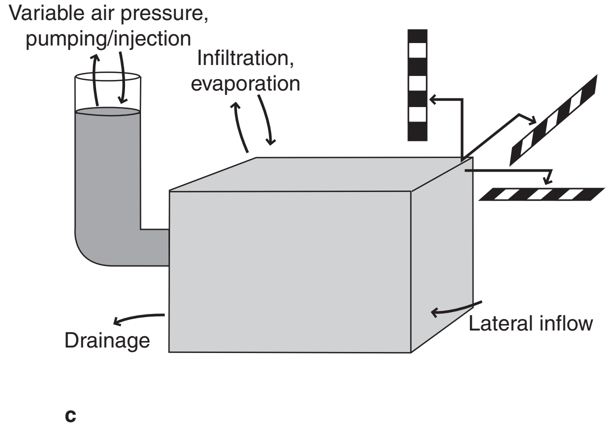


Figure 1

Scheme of testing and monitoring mechanical rock-fluid interactions in a saturated rock formation, represented by the rectangular solid. a: induced pore pressure change seen by pore pressure response; b: rock matrix deformation seen as pore pressure change; c: induced pore pressure change seen as rock matrix deformation.

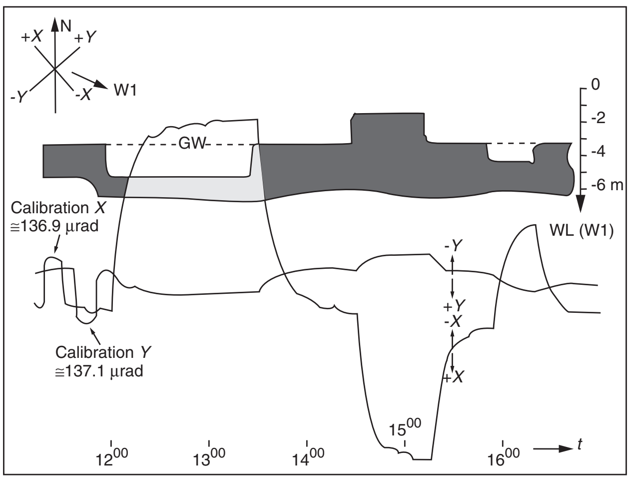


Figure 2

Tilt amplitudes at 30 m depth over about 6 h (lower curves), induced by ground water pumping (2 cycles) and injection (1 cycle) in a well (W1) that is at 50 m horizontal distance and 10 m deep; sandy aquifer. Orientations of perpendicular tilt sensors *X* and *Y* and direction to well are plotted at upper left. Tilt amplitudes are scaled by calibration signals at beginning of tests. WL denotes well level depth below top of casing; yield was about 3 m^3/h during the first pump cycle and 1.5 m^3/h during the second. GW = depth of undisturbed ground water level; *t* = hours, local time.

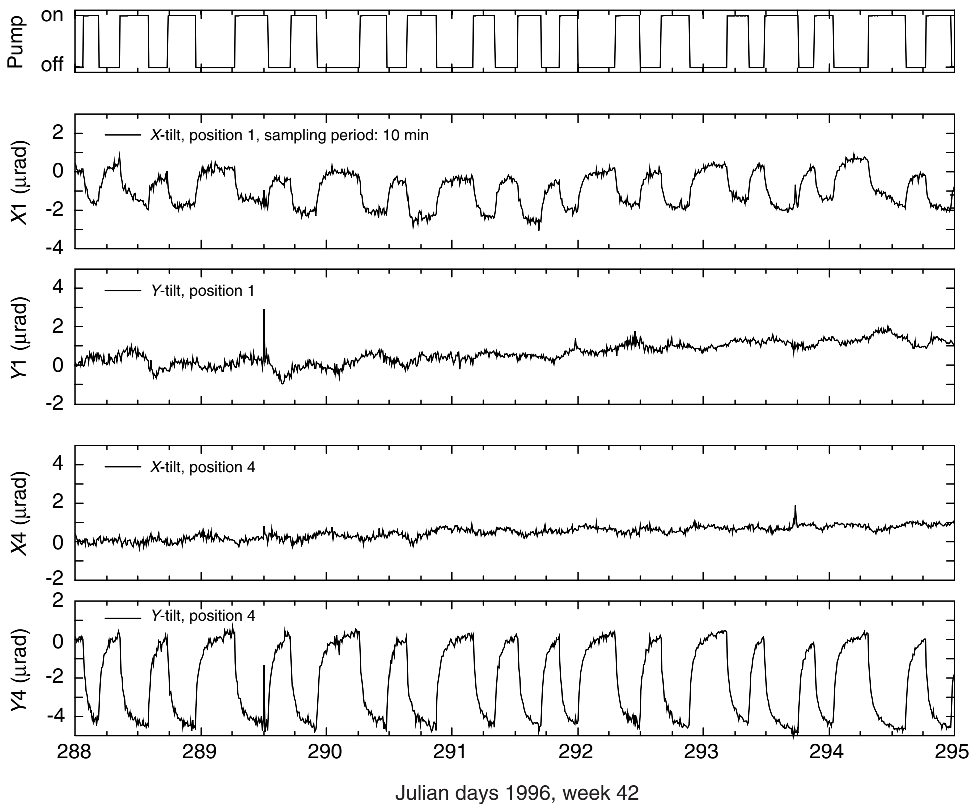


Figure 3

Tilt signals at 4 m depth at two positions of test site Nagycenk, Hungary, induced by ground water pumping from depth intervals 56 to 61 m and 66 to 74 m, unconsolidated sediments; yield is about 35 m^3/h. Tilt sensors *X*1, *Y*1 are at 8 m distance from the well, sensors *X*4, *Y*4 at 64 m distance; sensors *X*1 and *Y*4 are roughly orientated towards the well (Kümpel *et al.,* 1996).

borehole strainmeters, have not yet been made, but seem to be on the verge (Fujimori *et al.,* 1999).

Another example for this kind of rock-fluid interaction was found when a tilt recording from a site close to a deciduous tree had been analysed (Rebscher, 1996). On sunny days in spring and summer, regular diurnal tilt variations occurred, consistent with local ground deformation induced by natural fluctuations in the water consumption of the tree (Fig. 4). Additional systematic studies have recently been initiated at a test site in Western Germany to further explore this phenomenon (Lehmann *et al.,* 1998).

Resuming the findings from a series of poroelastic response tests conducted with different types of tiltmeters in various geological environments over the last 15 years, the state of the art of this technique can be quoted as follows.

- Well resolvable deformation signals can be induced by pumping or injecting fluids out of or into the fluid saturated subsurface.
- The signals can usually be monitored without much difficulty by tiltmeters installed in shallow boreholes, at distances from meters to about 100 m.
- Poroelastic pump- or injection tests yield good control over the forcing function (i.e., the time history of the induced pore pressure anomaly), making the petrohydraulic formation properties the only unknowns in such experiments. Repeated testing allows enhancement of the signal-to-noise ratio by stacking.
- Effective *in situ* parameters D, B', and Γ of the formation affected by the test can be constrained.
- Monitoring with a biaxial tiltmeter allows recognition of anisotropic expansion of the induced pore pressure anomaly and hence of potentially anisotropic fluid flow.
- Tiltmeters respond with no delay to a pore pressure anomaly since the rock matrix deformation propagates instantaneously, i.e., with seismic velocity. Well level changes in adjacent wells, on the other hand, may be delayed, initially even inverted (Verruijt, 1969; Maruyama, 1994), depending on the conditions of hydraulic diffusivity.
- Effects of alterations in formation parameters (influence of the free surface, limited thickness of aquifers, degree of anisotropy, presence of major fractures) need to be modelled numerically to fully exploit the information of the tilt signals.

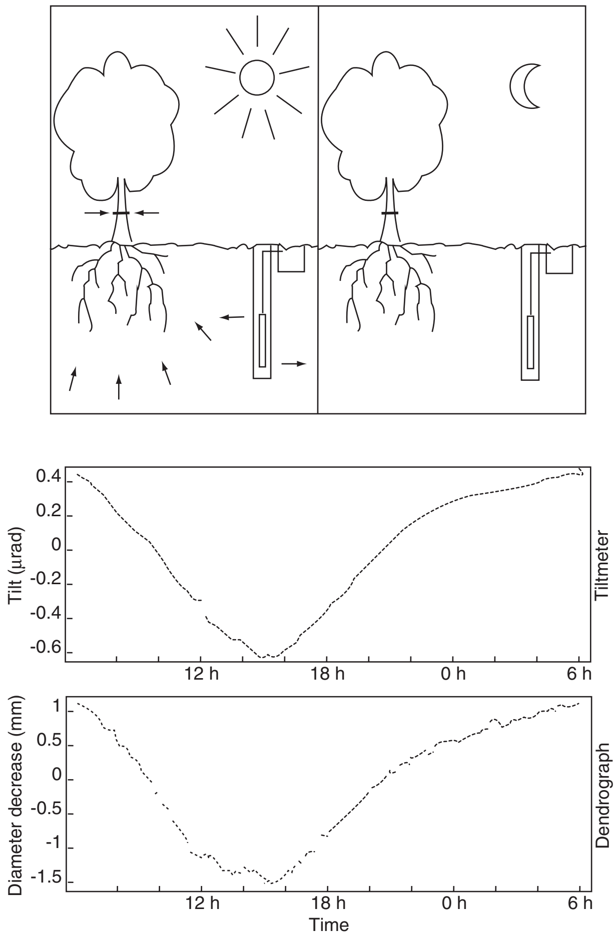


Figure 4

Scheme of ground deformation cycle induced by trees consuming soil water during day time, as verified by a borehole tiltmeter and a device to control the diameter of the tree's stem (top). Recordings show signals stacked over 16 days (bottom) (Rebscher, 1996).

– Effects from water consumption of trees, too, lead to poroelastic deformation that can be monitored by borehole tiltmeters.

2.2 Borehole Scale: Strain Induced Well Level Fluctuations

Classical well testing starts by changing the fluid level in a well (i.e., by extracting or adding a certain amount of fluid), observing the recovery of the well level over time, and ends by matching this curve to a type-curve which reveals values of certain hydrologic formation parameters (usually transmissivity and storage coefficient; e.g., Brown *et al.,* 1972). When this technique is applied, little is known about how rock matrix deformation is involved. This is understandable because both, the forcing action (leading to the change in the fluid level) and the system's observed reaction (level recovery) belong to the same side of the rock-fluid interaction, the pore pressure signal. To achieve better control over the other side of the coin, the deformation signal, either the forcing or the observation should be of this type, and both should be well known.

Fluid level fluctuations in open boreholes happen permanently, particularly due to earth tidal rock deformation and varying barometric loads. These are, however, only visible if the formation, to which the well is open, is confined or semi-confined, i.e. if the effective vertical hydraulic diffusivity to the earth's surface is much smaller than the radial diffusivity from the formation to the well.

Various publications cover the extraction of petro-hydraulic parameters from such level recordings (e.g., Bower, 1983; Van der Kamp and Gale, 1983; Rojstaczer and Agnew, 1989; Evans *et al.,* 1991; Roeloffs, 1996; Kümpel, 1997b). When the barometric signal is analysed, the barometric efficiency:

$$A_e = 1 - \frac{g\rho_f\,\Delta h}{\Delta\sigma_{zz}} = 1 - \frac{(1+H)(1+\nu_u)B}{3\left[1-(1-H)\nu_u\right]} \qquad (5)$$

can be obtained, reflecting basically a combination of the bulk, undrained vertical compressibility of the aquifer formation and its ability to absorb a pore pressure change applied via the fluid column of the borehole. The term $g\rho_f\,\Delta h$ is the observed pressure change of the well water column (height change Δh) due to the additional surface load $\Delta\sigma_{zz}$, which is subtracted from 1, the direct influence of the barometric pressure change on the fluid column. The parameter H can be understood as the ratio of the areal to vertical strain for a finite, though potentially big lateral extension of the atmospheric loading, and takes values between 0 and 1 (Rojstaczer and Agnew, 1989). $H = 0$ is the traditional assumption in hydrology (vertical strains only) and $H = 1$ holds for the half-space solution of finite, extended loads.

Taking the tidal signal allows to assess the tidal efficiency:

$$T_e = g\rho_f\,\Delta h\,\frac{c_u}{\varepsilon_A} = \frac{1-2\,\nu_u}{1-\nu_u}\;B \qquad (6)$$

which characterizes the response of the aquifer to the global tidal strain and its modulations in the surroundings of the aquifer. Herein, ε_A denotes the effective areal strain induced by tides (stress free surface) and Δh the associated change in well level height. Accordingly, T_e/c_u indicates, how sensitive a well level responds to tidal forces. When phase shifts between the forcing functions and the level fluctuations are resolved, the horizontal hydraulic diffusivity of the aquifer can be estimated as well.

A recording of several months is usually required to clearly identify the barometric or tidal signals. However, uncertainty about the spatial extension of a barometric load change hampers the derivation of more precise effective petrohydraulic parameters from A_e. Similarly, limited knowledge of the regional strain tide leaves parameters deduced from T_e uncertain by a factor of two (Beaumont and Berger, 1975). Still, the interpretation of natural, deformation induced well level fluctuations presents an easy and cheap way to obtain some idea about the values of *in situ* parameters of mechanical rock-fluid interactions.

Figure 5 is an example from a rather deep "well", the pilot hole of the continental deep drilling project KTB in Bavaria, Germany (Schulze *et al.,* 1998, 1999). The hole has a total depth of 4000 m and is uncased for the lowermost 150 m.

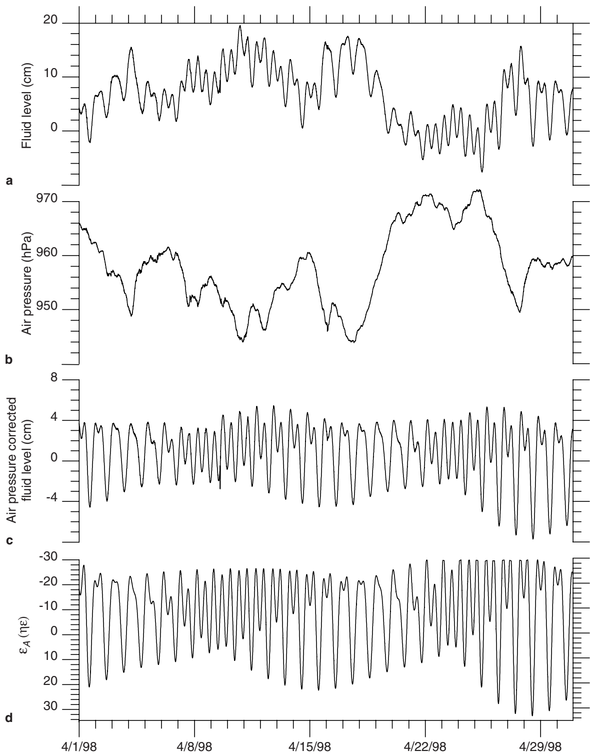


Figure 5

Fluid level changes observed in 4 km deep KTB pilot hole (a) and air pressure data on-site (b) of April 1998 are clearly anticorrelated. After correction of the air pressure effect, residual fluid level fluctuations (c) can easily be recognized as correlated to areal strain tides ε_A (d) (Schulze *et al.,* 1998; strain tides after Wenzel, 1996).

The data shown yields $A_e = 0.64$ and, assuming $\nu_u = 0.26$, $H = 1$, a Skempton ratio $B = 0.43$ and $T_e = 0.28$ (Schulze *et al.,* 1999). This is a remarkably high B value for crystalline rock at 4 km depth. It indicates that a high proportion of any variation in rock matrix strain is transferred into pore pressure change, much like in saturated, unconsolidated sediments, and hence confirms the results of other investigators that pore fluids play a prominent role in the mechanical behaviour of these rocks (Huenges *et al.,* 1997; Zoback and Harjes, 1997).

In summary, tidal and barometric fluctuations in well level recordings may be used to assess one or several of the following parameters under *in situ* conditions:

– the degree of hydraulic confinement of a probed rock formation;
– the ratio of undrained pore pressure change per unit change of confining pressure (Skempton ratio B);
– the bulk hydraulic diffusivity D of the formation, including influences of matrix deformation;
– other poroelastic rock parameters, in particular the undrained compressibility C_u and the shear modulus G, when some of these quantities are constrained by different studies.

Porosity and the specific storage coefficient S are poorly constrained by this technique.

2.3 One to Hundred Kilometer Scale: Seismotectonically Induced Well Level Anomalies and Reservoir Induced Seismicity

The former examples dealed with deformation processes that are basically linearly elastic, i.e. behave identically for extension and compression, except for a change of signs, and are fully reversible. Such type of behaviour can only be expected in rather homogeneous media, whereas it will not hold for seismogenic phenomena in the source regions. Moreover, local heterogeneities on the regional scale become more influential. Numerous observations of pre-, co-, and postseismic hydrologic anomalies, mostly unusual well level changes, testify that seismotectonic redistribution of the stress regime in the crust can somehow lead to local strain enhancement and, consequently, to pore pressure variations (Wakita, 1975, 1981; Roeloffs, 1988a; Kissin and Grinevsky, 1990; Kümpel, 1991b, 1991c, 1992, 1994). In general, strain enhancement is believed to occur at mechanically weak zones, e.g. fractured faults, that are favourably oriented with respect to the altering stress field. In individual cases, however, the understanding is vague because the geometrical distributions of weak zones and contrasts in stiffness parameters in the heterogeneous crust are simply unknown. And, since the majority of the observations are made by chance (e.g., no representative areal coverage with observation wells; lack of reports on wells showing no anomaly), the use of seismogenically induced well level changes in deciphering crustal features may be questioned.

To cite some promising efforts, Wakita (1975) has described a systematic distribution of the signs of coseismic well level anomalies that occurred during the 1974 Izu-Hanto-Oki earthquake in Japan. Similar observations were recently made by Grecksch *et al.* (1997, 1999) for the M_L= 5.9 Roermond earthquake of 1992 in Mid-Europe (Fig. 6). A more complex situation was reported by Igarashi

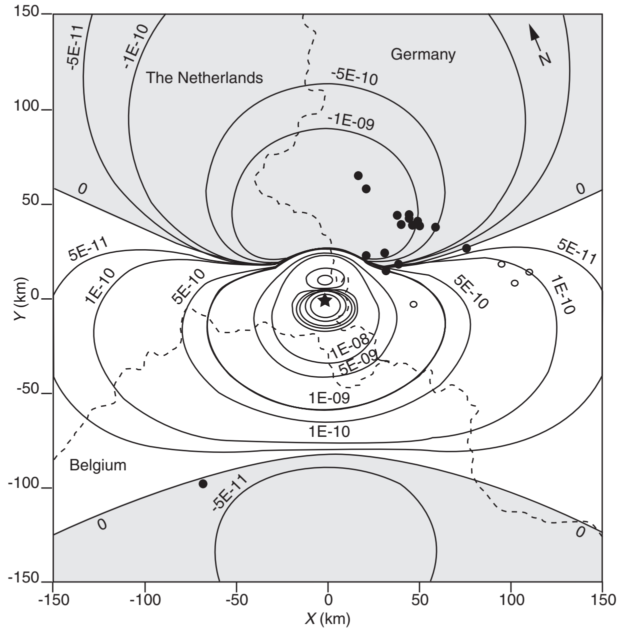


Figure 6

Coseismic static volume strain close to the earth's surface from fault plane solution of $M_L = 5.9$ Roermond earthquake of April 1992, computed for a homogeneous elastic half-space using the scheme of Okada (1992). Circles represent well locations where a step-like coseismic well level rise (filled circles) or a well level drop (open circles) were observed (Grecksch *et al.,* 1997, 1999). Positive volume strain corresponds to dilatation. Asterisk marks hypocenter of earthquake.

and Wakita (1991) who recorded coseismic well level changes with opposite signs in two adjacent wells for far field earthquakes of similar fault plane solution, azimuth, distance, and magnitude.

Perhaps more instructive results about the role of rock-fluid interactions in earthquake mechanics can be expected from investigations of induced (including triggered) seismicity. Exploitation of underground fluid reservoirs has been demonstrated to occasionally lead to a remarkably widespread seismicity (e.g. Grasso, 1992). The same is true when fluids are injected under pressure in boreholes (Healy et al., 1968; Zoback and Harjes, 1997). Apparently, rocks in the earth's crust are close to failure in many regions.

Particularly informative is the study of seismicity that is obviously associated to reservoir lakes. Data about initial filling and cyclic variations in the lake level provide reasonable control over the loading history at the lake bottom and resulting pore pressure diffusion processes, as probably the most influential input quantities (Bell and Nur, 1978; Roeloffs, 1988b; Simpson and Narasimhan, 1990).

A so far unique attempt to systematically approach the rock-fluid interactions in such an environment has recently been set-up in the area of the Koyna Dam reservoir in Maharashtra, India. This reservoir has triggered the strongest earthquake associated to a lake filling ever (M_L = 6.3, 1967, killing 200 people) and still, after thirty-five years, presents a highly significant seismicity (Gupta, 1992). Beginning in 1996, twenty-one wells have been drilled 90 m to 250 m deep into the basaltic Deccan trap formations in and close to the seismically active region, and are being equipped with autonomous well level recorders of submillimeter resolution (Chadha *et al.,* 1997; Kümpel *et al.,* 1998). Over the next several years, the project is expected to render more detailed information on:

– the mechanism of this extraordinary case of reservoir induced seismicity;
– the occasional or regular occurrence, or complete absence of hydrological precursory anomalies here;
– and specific aspects on the role of fluids in the tectonically brittle crust.

It seems that the presence of free fluids in the crust has been underestimated for long time. They cause permanent crustal instability, local rock failures, friction along faults, and facilitate efficient transport of soluble materials through migration. Seismogenically induced well level anomalies and reservoir induced seismicity provide valuable information towards a better understanding of all these phenomena on the 1 to 100 km scale. Still, the state of the art is rather a list of open questions that remain to be solved by more systematic studies; for instance:

– Can the occasionally reported zoning of the signs of seismogenically induced pore pressure changes be confirmed, in general?
– What causes local perturbations of the regional pattern of coseismic pore pressure changes?
– Are hydrological anomalies that precede earthquakes rare exceptions, and do they bear useful information to predict the size, the region, and the time of larger, pending earthquakes?
– What is the role of fluids and pore pressure in earthquake mechanics?
– To what depths do they influence the redistribution of tectonic stress in the crust?

CONCLUSIONS

Various possibilities exist to test the relevance of pore pressure as a geophysical and geomechanical parameter under *in situ* conditions, on different scales. Here we have stressed on the study of:

– tilt deformation in the vicinity of pumped wells and even trees;
– natural, strain induced well level fluctuations;
– seismogenically induced well level anomalies;
– and reservoir induced/triggered seismicity.

Land slides present another class of phenomena where pore pressure is one of the influential variables (Rebscher, 1996; Wosnitza, 1997), the stability of dam structures and micro deformations at shallow depths are further disciplines (Kümpel, 1993; Lehmann *et al.,* 1998).

The overall objective of such investigations is to improve the insights in the physics of rock-fluid interactions, and in the dominating petrohydraulic parameters. Few is known about both at present, except on the laboratory scale. Proper use of knowledge of the dynamics of these processes and the involved quantities has obvious practical aspects; for instance towards a more complete exploitation of subsurface fluid reservoirs, or a safe disposal of critical waste materials at depth. It is trivial to state that representative *in situ* data are crucial for simulations of rock-fluid mechanics at realistic conditions.

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