Reservoir Pressure and Mechanical Integrity of the Overburden

Fluiddruck in Porenraumspeichern und mechanische Integrität des Deckgebirges

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Abstract
A prerequisite for the economical operation of a pore storage facility is maintaining the maximum possible fluid pressure within it. However, the mechanical integrity of the directly overlying rocks must be guaranteed. For this the appropriate rock mechanics analyses must be made in advance. In carrying out the analyses the pore pressure changes and their effects, including those of modified pore pressure effectiveness on in situ effective stresses in the upper storage zone, and the deformations derived from them, must be considered. Through coupling of the modified storage zone loadings and the deformations with the rock parameters and the initial stress conditions in the overburden the induced loading changes there and the stability situation can be calculated. For the loading mechanisms it is necessary to distinguish between an undisturbed, intact and a disturbed overburden (and then between primary 2D fault planes and/or 3D zones of loosening resulting from loading). Further, the two different types of store must be considered. Aquifer storage facilities have a quite distinct loading and deformation path from that of depleted gas or oil reservoirs. In a similar way, it must be considered that there are different stress conditions far from boreholes and in their immediate vicinity. For these complex evaluations of the mechanical integrity of the overburden during changes of reservoir pressure there is a comprehensive analysis procedure available. In this the rock mechanics input parameters are determined with specialized RACOS®-Kernanalysen.

1 Introduction
Worldwide, 96% of natural-gas underground storage is in pore volume. Most such storage is in depleted hydrocarbon reservoirs. Storage in aquifers only makes up about 15% of the total [1]. The highest allowable pore pressure is decisive for the economics of a storage system. An important criterion for this maximum pore pressure is based on the necessity to guarantee that the overburden remains mechanically intact (avoiding cracking or the formation of frac, or the activation of fault zones etc.). For sealing, cap rock must have a very low in-situ gas permeability. In clay cap rock it is also necessary to consider the gas closure pressure, in order to ensure that the pore water is not displaced.

In this article the mechanical integrity issues are addressed, considering the interactions of pore pressure changes in the upper part of the storage zone with the stress conditions in the directly overlying strata. The predominant zone in the overburden is that in a primary stress condition, away from boreholes, but the secondary stress conditions immediately around the boreholes are also considered.

Storage in depleted hydrocarbon reservoirs is addressed, and also those in aquifers. Concluding, a comprehensive practical procedure is presented for evaluating the effects of different pore pressures and so defining a maximum storage pressure. This procedure includes the determination on core samples of the relevant 3D in situ rock and rock mass parameters and their interrelationships.

2 Overburden Loading Mechanisms
In assessing the interactions between the storage zone and the overburden which are related to pore pressure, and in identifying the relevant factors influencing these, a first step is developing an understanding of the mechanisms which can operate. The starting point is the effects of pore pressure changes in the storage zone (see Section 3) on the effective in situ stresses in the overburden. For this it is necessary to distinguish between undisturbed, intact overburden strata and strata with faults or fracture zones. These faults or fractures may have arisen due to primary loading and/or have resulted from secondary loadings, e. g. during the operation of the storage facility.

2.1 Undisturbed, intact overburden
In undisturbed, intact overburden strata (Fig. 1) the changes of pore pressure in the storage zone ($\Delta P_{\text{reservoir}}$) cannot (unless the gas closure pressure is exceeded) migrate into the pore space of the overburden. Therefore they...
do not cause directly an immediate change of the effective situ stress condition in the overburden. However, the modification of the effective in situ loadings in the storage zone ($\Delta \sigma_{\text{reservoir}}^\text{eff}$) results in deformations ($\epsilon_{\text{reservoir}}$).

In the contact zone, modifications of the effective stresses and deformations are transmitted to the overburden strata. These result in changes of the in situ stresses ($\Delta \sigma_{\text{reservoir}}^\text{intact}$), at least in the lowest section of overburden (see Section 5).

In considering the stability of the intact overburden under the modified in situ stresses unchanged rock strengths are considered at first.

### 2.2 Disturbed overburden

Disturbed overburden contains existing primary fault zones and/or fractures and cracks caused by loading changes resulting from storage (Fig. 2). If the increased permeability in the damaged areas is sufficient to allow the storage pressure ($\Delta P_{\text{reservoir}}$) to migrate into these discrete in situ elements ($\Delta P_{\text{caprock/fault/fractures}}$), the effective pressures immediately around them change too ($\Delta \sigma_{\text{disturbed caprock}}$). This can lead to further extension of the local instabilities.

If there are many interconnected fractures and cracks, large zones of pore pressure related load changes can occur. In disturbed overburden there occur in addition the stress changes and deformation in the reservoir, as described above. When assessing the mechanical integrity of disturbed overburden, in addition to the changed in situ stresses, it is also necessary to take account of the local (weak surfaces) or zonal strength reduction caused by the disturbance.

### Pore Pressure Induced Alteration of In Situ Stresses

The main in situ loadings are the total rock stress (produced by the overburden rock mass plus tectonic influences) and the pore pressure, modified by the pore pressure effectiveness, which acts against this. The effective stress, the sum of both in situ loading components, is the relevant one for deformation, strength and stability.

Pore pressure changes produce changes in the effective in situ stresses corresponding to the relation between effective and total loading components. Depending on the in situ constraint conditions this can also result in variation of the total stress. There are two possible limits (free all-round deformation or complete lateral constraint) for the in situ constraint conditions [2]. In the case of a freely deformable reservoir rock mass the total stresses remain unchanged. This boundary condition results in the maximum pore pressure related change in the effective stresses and therefore in the greatest deformations and effects on mechanical integrity. It is therefore regarded as the worst case when defining the maximum reservoir pressure.

The change in the in situ stress condition resulting from the pore pressure change during injection or depletion also depends on the pore pressure effectiveness. The values of pore pressure effectiveness decline (as does porosity) with increasing effective stress, and most markedly in low stress conditions (Fig. 3). For this reason the effective stress changes resulting from a given pore pressure change are generally smaller under conditions of higher loading. This effect is particularly strong in rocks containing micro-cracks/fractures and/or in clay/marl/siltstones [3].

### Deformations Resulting from Stress Changes

Significant rock mechanics parameters for the evaluation of the load-dependent behaviour of pore volume storage are the total deformation of the storage rock (including the vertical displacement) and of the pore volume (including changes of porosity and permeability).

It should be distinguished between elastic strain parameters (used for the effective stress calculations) and the total deformation, used for the description of reservoir compaction/dilatation (Fig. 4).

During successive loading and unloading cycles (injection and depletion in storage facility operation) in the absence of fractures the successive amounts of deformation decrease as a result of irreversible strains. Also the stress-strain curves are generally not identical for loading and unloading (hyster-
5 Stress Changes in the Cap Rock

When considering the changes of loading which occur in the cap rock as a result of pore pressure changes in the storage zone it is necessary to distinguish between the predominant zone with primary stresses (away from boreholes), which may be intact or disturbed rock, and the much smaller zones with secondary stress conditions immediately around boreholes.

5.1 Primary stress changes in undisturbed, intact overburden

As there are no flow pathways, pore pressure variations in the storage zone cannot migrate directly into an undisturbed, intact cap rock. However, modifications in the effective stresses in the storage zone, resulting from pore pressure changes, can be transmitted through deformation of the rock mass into the overlying rocks. If the connection between the storage zone and the cap rock is strong enough, the deformations in the storage zone, resulting from the effective stress changes, are applied to the overlying stratum. This will result in additional stresses in that stratum. When evaluating the effects of this phenomenon it must be considered that the stresses resulting from equal deformations will depend on the elastic parameters, which are likely to differ. Stress differences between the storage zone and the cap rock will result in shear stresses which can damage the connection between them and thereby limit the extent to which the deformations are transferred. The maximum possible stress variations are therefore determined by the shear strength of the rock region connecting the storage zone and the overburden. Besides this, the maximum change in the effective stresses in intact overburden is the change produced in the storage zone by the pore pressure change.

5.2 Primary stress changes in disturbed overburden

In disturbed overburden further loadings can arise in addition to those described above. It is necessary to distinguish between two mechanisms, which are essentially determined by the in situ rock mass structure. When interconnected cracks have developed in the overburden, and these are hydraulically connected to the storage zone, then pore pressure changes in the storage zone also have an effect in the overburden. If the pore pressure effectiveness (resulting from the damage) in one direction or in 3D is higher than in the storage zone, then larger changes of effective stress may be produced in the overburden than in the storage zone itself. These are independent from and additional to the stress changes resulting from transfer of deformations. It should be noted that another effect of the development of the interconnected cracking in the overburden is a reduction of the rock strength. The other case of a disturbed overburden is a pre-existing fault, or cracks resulting from loading. If these have a direct hydraulic connection to the storage zone then pore pressure increases act directly on the boundaries of these planes of weakness. This leads to a reduction of the normal stress and thus to an increased risk. It should be noted that such 2D planes of weakness generally have a lower strength than the surrounding rock.

5.3 Stress situation around boreholes

In the vicinity of boreholes the primary in situ stresses become modified into secondary conditions [3]. These secondary loadings are described by the stresses parallel and perpendicular to the borehole, and possibly by shear stresses parallel to the borehole axis. In the immediate vicinity of the borehole these loadings act as a normal stress component parallel to the borehole axis, a radial stress perpendicular to the borehole wall and a tangential stress parallel to it. It must be emphasized that these loadings depend on the orientation of the borehole relative to the primary effective in situ stresses. They also depend on the amount of deformation which can occur at the borehole wall, and this is influenced by the type of completion.

Within the borehole there is generally also an internal pressure to be considered. If the borehole wall is permeable this can cause changes of the pore pressure and thus of the effective stresses in the zone near the borehole.

The secondary effective stresses (as for the primary components) depend on the pore pressures and the 3D pore pressure effectiveness. High loadings around the borehole, and in particular of the borehole wall, can result in loosening and cracking, with resulting increases in pore pressure effectiveness. These result once again in modified (in comparison with undisturbed conditions) effective loading conditions.

6 Stability Calculation

The procedure for making stability calculations is the same for rock elements in the primary loading zone and around boreholes. In all cases, the position of the relevant 3D effective in situ stress state of the affected element is determined in relation to that of the relevant rock failure criterion. The ratio

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\[ \frac{R_{\text{failure}}}{R_{\text{stress}}} \]
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Fig. 6 Definition of the Safety-Factor

\[ S = \frac{R_{\text{failure}}}{R_{\text{stress}}} \]

Safety-Factor

\[ \tau \partial \]

Failure envelope

\[ \sigma \partial h \]

Current stress state

\[ R_{\text{failure}} \]

\[ R_{\text{stress}} \]

\[ \text{Fig. 6 Definition of the Safety-Factor} \]
of the distance to the criterion (from its axis) to the distance to the current stress state is defined as the Safety-Factor (see Figure 6).

A Safety-Factor ≤ 1 shows that the maximum available strength will be reached or exceeded in the rock element and this could mean, for example, that macroscopic failure occurs in that region. Special evaluations of the stress conditions and of their 3D orientations are used to assess the expected failure type (breakout, peeling, frac etc. at the borehole wall), intensity and extent. The influence of defined weak planes can also be assessed.

For every calculation of stability the appropriate strength parameters are required for the affected rock. These may be for macroscopic failure (peak strength) of the affected rock, or the post-failure load-carrying capacity (residual strength) for the evaluation of weak zones. It is desirable that these parameters are based in each case on strength data determined for the specific 3D effective in situ loadings.

Because of its mathematically simple and physically very clear generalization of the transition from stable to critical loading conditions, the classical Mohr-Coulomb rock failure criterion is often used. This criterion is suited to evaluating shear failure of 2D zones of weakness. The decisive disadvantage of the use of the Mohr-Coulomb criterion for realistic 3D stress conditions is its consideration of only two (the maximum and the minimum) of the three principal stress components. The resulting strength predictions are only valid when the loading configurations assumed for the criterion correspond to the in situ stress condition. This is generally not the case, and therefore stability analyses using the Mohr-Coulomb criterion (generally derived from data from compression tests $\sigma_{\text{max}} > \sigma_{\text{intermediate}} > \sigma_{\text{min}}$) can be unreliable [6]. The Tauber failure criterion [7] enables a realistic description to be made of the 3D strength with diverse triaxial loadings. It is a specific (stress invariant) 3D failure surface based on the collation of 3D strengths measured under different triaxial stress conditions.

### 7.1 Stress change in the reservoir during depletion/injection

When a hydrocarbon reservoir is depleted, the pore pressure is reduced. The resulting increase in effective stress causes a reduction in the pore pressure effectiveness. This reduced value is that which applies when gas is injected for storage. In contrast, during injection into an aquifer store the pore pressure increases from the initial condition. The resulting decrease in effective stress causes an increase in pore pressure effectiveness. Therefore in identical storage zones (with non-linear load-dependent pore pressure effectiveness) and for the same pore pressure change, the effective stress changes will be lower in a depleted reservoir than in an aquifer (Fig 7).

### 7.2 Pore pressure induced deformation in aquifer and reservoir stores

During production from a reservoir (depletion), with increasing effective stress (decreasing pore pressure), the stratum thickness and the pore volume (amongst other things) become smaller. In subsequent injection (increase of the pore pressure to the initial condition) the initial thickness and pore volume will not be recovered; the reservoir capacity remains reduced. Through injection into an aquifer store, with decreasing effective stress (increasing pore pressure), the stratum thickness and the pore volume (amongst other things) increase. During subsequent depletion, with reduction of pore pressure to the initial condition, the initial thickness and volume will not be recovered; the capacity of the aquifer store remains increased.

For otherwise identical conditions (initial stress and strain, rock, and value of the change in effective stress produced) the dilation of an aquifer during first injection can be expected to be greater than the compaction during first production from a reservoir (Fig. 8). This expected difference results from the greater deformation components found at low loading levels in rocks with non-linear stress/strain behaviour.

### 7.3 Stability of the cap rock in the top of an aquifer and a depleted reservoir

Die effects of an initial change of pore pressure were considered for an aquifer and a reservoir with the assumption that the effective stress changes in the storage zone were transferred directly into the overburden.

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[Image of a diagram showing stress change in the reservoir during depletion/injection.]

**Example of Differences between Depleted Reservoirs and Aquifers**

When discussing pore volume stores it is sometimes necessary to distinguish between depleted reservoirs and aquifers. One difference between these two types of storage is the loading path caused by pore pressure change. This results in differing rock loadings. In order to enable the mechanisms...
With the available in situ data both load cases had safety-factors > 3 for the primary stress zone in intact cap rock. In this case, loosening and development of increased pore pressure effectiveness can be excluded. Even when there are existing faults these remain stable, unless the pore pressure changes. But if in an injected aquifer case the pore pressure in a weak zone becomes equalized with that in the storage zone then failure can occur on the weak plane.

In analyses of the conditions in the vicinity of a vertical borehole with a permeable wall, the reduced in situ effective stresses (following pore pressure increase) resulted in the greatest stability in the aquifer case. This was found to be true both for intact rock and for faults (striking in the direction of the maximum horizontal stress) without any additional pore pressure within them (Fig. 9). In cases of pressurized aquifer storage with pore pressure increase in the weak zone a marked reduction of the Safety-Factor is found, indicating instability.

**Practical Application**

To determine the effects of pore pressure changes in the storage zone (reservoir or aquifer) on the mechanical integrity of the overburden it is necessary to know the relevant in situ loadings and strengths. The mechanical integrity is one of the criteria used in fixing the maximum allowable pore pressure. These in situ parameters are quantified using the comprehensive RACOS® 3D analysis package on core samples. Amongst other things, the in situ stresses, elastic rock parameters, rock and pore space deformability and rock strength are quantified [2]. The relevant analyses are based on the determination of direction-related propagation characteristics of elastic waves in loaded rock samples. In this case these are prepared from relatively homogenous sections of core from the upper storage zone and from the cap rock. Using special analyses of the effects of loading-dependent changes in the rock structure the effective in situ stresses at the time of coring are determined directly from the measurements. In addition, a classical stress–strain test is made on an oriented plug from the same section of core. On the basis of the results of both investigations loading-dependent 3D parameters such as pore pressure effectiveness and total deformations are determined. Geographic reorientation of these parameters is carried out using results from RACOS® as well as other independent measurements. With these results the significant initial conditions in the storage zone and the overburden have been defined.

Using the derived parameter relationships the stress changes in the storage zone can be determined for defined changes of pore pressure. The resulting changes in the stress state in the overburden are calculated based on the effects described above (see Section 5). The programme BOREHOLE [8] (a numerical computation based on special 3D stress-strain analyses of a section of rock of finite thickness perpendicular to the borehole axis) can be used to calculate the 3D stress conditions around boreholes.

The stability analyses of the cap rock require strength parameters for micro and macroscopic failure (peak strength) of the affected rock. For the evaluation of weak zones the residual load-carrying capacity (residual strength) must also be included in the considerations. To obtain these data rock mechanics strength tests are carried out with simplified loading configurations (generally on cylindrical samples) and then generalized for use in specific loading cases.

From the consideration of the available strength in comparison with the relevant loading conditions in the overburden (see Section 5) the mechanical integrity of the overburden can be evaluated for different pore pressures in the storage zone.

**Conclusions**

A significant value for the storage of fluids in pore volume facilities is the maximum pore pressure at which the mechanical integrity of the overlying sealing stratum will not be damaged. To determine this it is necessary to start by considering the effects of pore pressure variation, including on the pore pressure effectiveness, on the in situ effective stresses in the storage zone.

Then the storage zone deformations must be determined. From these can be derived the changes in the in situ loading in the overburden connected with the storage zone. The evaluation of the mechanical integrity of this layer under modified storage zone conditions requires consideration of the modified loadings and of the available rock strengths. These specific conditions will be different for intact and for disturbed rocks. It must also be distinguished between depleted reservoirs and aquifer storage facilities. One difference between these two types of storage is the loading path caused by pore pressure change. This results in differing rock loadings. Assuming, for comparison, the same rock section, with identical initial conditions, calculations show that in the case of the aquifer greatest absolute values of the effective stress changes and deformations will occur than those in a depleted reservoir. Nevertheless, because of the low loadings, the resulting changes in the mechanical integrity of the cap rock are only significant when the storage pore pressure acts within a weak plane within it.

A comprehensive analysis procedure has been developed for the evaluation of storage zone pressure changes and the effect on the mechanical integrity of the overburden. This is based on RACOS® core analyses to determine all the required load-dependent 3D input parameters. Numerical analyses are used to evaluate the mechanical stability of the overburden, both for the predominant zone of primary stresses (away from boreholes) and for the secondary stress conditions immediately around them.

**References**