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UNLOADING-RELOADING UNIAXIAL COMPRESSIBILITY OF DEEP RESERVOIRS BY MARKER MEASUREMENTS

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Abstract

The radioactive marker technique appears to be a promising tool for the in situ measurement of the uniaxial vertical compressibility c_M of deep gas/oil reservoirs. A constitutive model for $c_{M,\text{unload}}$ in the Northern Adriatic sedimentary basin in unloading-reloading (II cycle) conditions is derived. This relies on marker measurements obtained from an instrumented borehole located in depleted gas reservoirs that had experienced a pore pressure recovery over the period 1997-1999. Record analysis indicates that $c_{M,\text{unload}}$ is on the order of $5\text{-}6{\cdot}10^{-5}$ MPa^{-1} over the effective stress interval $35 \leq \sigma_z \leq 65$ MPa, i.e. for a burial depth between 3200 and 5800 m in undisturbed conditions. The ratio of virgin loading $c_{M,\text{load}}$ to $c_{M,\text{unload}}$ varies between 1.5 and 3 with an average value equal to 2.2. The $c_{M,\text{unload}}$ constitutive law derived for rock expansions is implemented into a coupled finite element consolidation model in an attempt to reproduce, also quantitatively, the vertical deformation recorded i the marker borehoole after field abandonment.

1. Introduction

The radioactive marker technique (RMT) for in situ compaction measurements in deep producing gas/oil reservoirs was originally developed 30 years ago (De Loos, 1973) and since then continuously improved from a technological standpoint (Mobach and Gussinklo, 1994). At present RMT appears to be a very attractive approach for a most realistic estimate of the actual uniaxial vertical compressibility c_M of producing gas/oil reservoirs, which is of paramount importance for a reliable prediction of the anthropogenic land subsidence caused by the field development and the subsequent surface rebound that generally takes place after the field abandonment.

The marker technique is based on repeated measurements of the vertical distance between weakly radioactive isotopes located into bullet-shaped steel containers (called markers) and shot about 10.5 m apart within the producing formation through the wall of a vertical, generally unproductive, well prior to the casing operations. An invar rod carrying two pairs of gamma-ray detectors with a spacing approximately equal to that of a pair of adjacent bullets is slowly raised at a constant speed from the borehole bottom and records the count rate peaks when the detectors are facing the markers. The recording procedure is typically repeated three to five times to offset as much as possible the instrument or the operational errors. Finally the measurements are processed to obtain an average estimate of the shortening Δh_i of the i-th monitored interval. If Δp_i is the average pore pressure drawdown experienced by the formation where the i-th marker pair is located, the in situ uniaxial rock compressibility can be estimated as:

$$c_{M,i} = \frac{\Delta h_i}{h_i \Delta p_i} \tag{1}$$

with h_i the initial marker spacing approximately equal to 10.5 m.

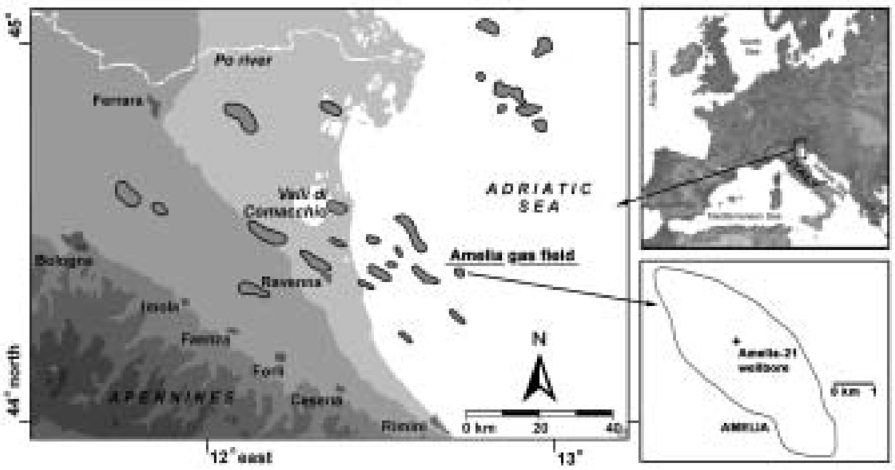

Fig. 1: Map of the Northern Adriatic and nearby coastland. The Amelia-21 wellbore is shown.

RMT is being used worldwide, e.g. the North Sea (Menghini, 1989), the Netherlands (Mobach and Gussinklo, 1994), the Gulf of Mexico (De Kock et al., 1998) and the Northen Adriatic Sea (Baù et al., 1999 and 2002), where several gas reservoirs are currently being developed.
RMT was essentially devised to measure compaction. However, in the Northern Adriatic fields expansions have also been recorded due to the natural pore pressure recovery exhibited by monitored intervals previously depleted and later abandoned. Since the Northern Adriatic is a normally pressurized and normally consolidated basin, field compaction during gas production takes place on the virgin loading curve (I cycle) while expansion occurs on the unloading-reloading profile (II cycle). The present communication is concerned with the measurement of expansions, hence the evaluation of unloading-reloading c_M by eq. (1) where Δh_i is the increase of the marker spacing occurred during the interval over which the Δp_i increase was observed.

2. Unloading-reloading compressibility by RMT

Fig. 1 shows the map of the Northern Adriatic Sea and nearby coastal area where several gas fields are located. The Amelia field along with the Amelia-21 wellbore is indicated. The wellbore was equipped with the marker instrumentation more than 10 years ago and over the period December 1997-December 1999 expansions were recorded in 9 marker pairs (Tab. 1) by CMI (Compaction Monitoring Instrument) tool operated by Western Atlas. Tab. 1 gives the upper and lower marker depth for each pair, the monitored expansion Δh_i, the corresponding pore pressure recovery Δp_i and the unloading uniaxial compressibility $c_{M,i}$ computed by eq. (1). The latter is also shown in the log-log plot of Fig. 2 vs the effective intergranular stress σ_z. The stress $\sigma_{z,i}$ corresponding to each $c_{M,i}$ value is calculated as:

$$\sigma_{z,i} = \hat{\sigma}_z \left(\frac{z_{i,0} + z_{i+1,0}}{2} \right) - p_{i,0} - \frac{\Delta p_i}{2} \qquad (2)$$

where:

- $\hat{\sigma}_z(z_i)$ = total vertical stress = $z_i \cdot \mathrm{obg}(z_i)$ [MPa]
- z_i = depth of top of marker pair i [m]
- z_{i+1} = depth of bottom of marker pair i [m]
- obg(z_i) = overburden gradient function = $0.012218174 \cdot z_i^{0.0766}$ [MPa/m]
- Δp_i = overall pore pressure variation from undisturbed conditions [MPa]

Spacing	Depth [m]		$\Delta h_{i,97\text{-}99}$	$\Delta p_{i,97\text{-}99}$	$c_{M,i}$
i	upper marker	lower marker	[mm]	[MPa]	[MPa^{-1}]
1	2869	2880	+7.1	+12.0	5.63_10^{-5}
2	3230	3240	+5.0	+7.6	6.27_10^{-5}
3	3240	3251	+2.2	+8.3	2.52_10^{-5}
4	3251	3261	+3.9	+4.9	7.58_10^{-5}
5	3348	3359	+2.8	+4.8	5.56_10^{-5}
6	3359	3369	+2.6	+2.0	1.24_10^{-4}
7	3667	3678	+0.8	+1.6	4.76_10^{-5}
8	3678	3688	+0.4	+1.2	3.17_10^{-5}
9	3688	3699	+0.4	+0.6	6.35_10^{-5}

Tab. 1: Marker expansions over the period December 1997-December 1999 measured in the Amelia-21 wellbore.

The subscript 0 in eq. (2) denoted the initial value of the corresponding variable, i.e. the value in undisturbed conditions. The $c_{M,i}$ data of Fig. 2 have been regressed by a straight-line in a double log-log plot to provide (Baù et al., 2002):

$$c_{M,\mathrm{unload}} = 2.9087 \cdot 10^{-4} \sigma_z^{-0.4315} \tag{3}$$

with the 68% and 95% confidence intervals defined by the factors before $\sigma_z^{-0.4315}$ equal to $1.7471 \cdot 10^{-4}$ and $4.8426 \cdot 10^{-4}$ (68%), and $1.0494 \cdot 10^{-4}$ and $8.0623 \cdot 10^{-4}$ (95%), respectively. In eq. (3) σ_z is in [MPa] and $c_{M,\mathrm{unload}}$ in [MPa^{-1}]. The validity range of eq. (3) is $35 \le \sigma_z \le 65$ MPa, i.e. $3200 \le z \le 5800$ m in undisturbed conditions. The regressed $c_{M,\mathrm{unload}}$ is shown in Fig. 2 along with the confidence intervals.

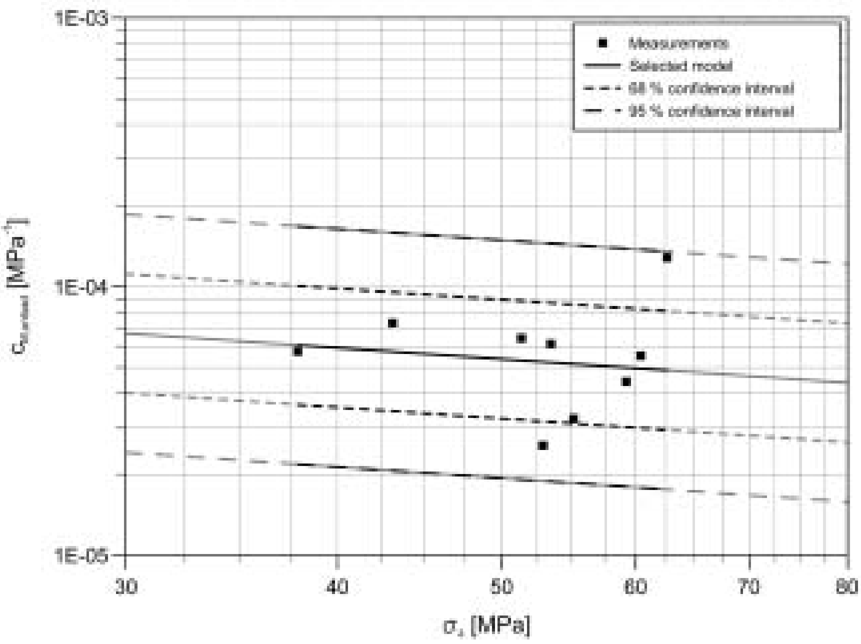

Fig. 2: Constitutive $c_{M,\mathrm{unload}}$ model and associated confidence interval as derived from linearly regressing the pointwise marker data on a double log-log plot.

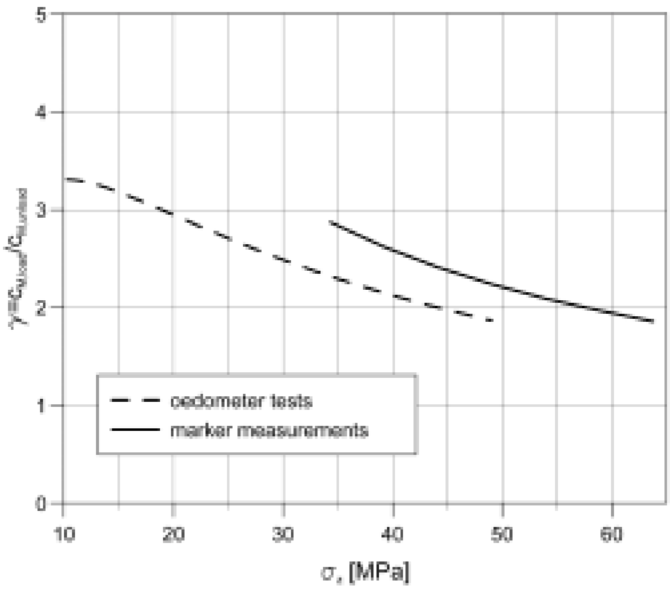

Fig. 3: Ratio between $c_{M,\text{load}}$ and $c_{M,\text{unload}}$ as obtained from using eqs. (3) and (4) (solid profile) compared to the ratio obtained using the c_M values from oedometer tests performed on Northern Adriatic gas field core samples.

The uniaxial compressibility $c_{M,\text{load}}$ in virgin loading conditions for the same Amelia-21 marker spacings was assessed using the marker response from 1992 to 1996-1997 when the sediments experienced a σ_z increase and hence a compaction. By the use of a larger number of measurements the average expected $c_{M,\text{load}}$ turns out to be (Baù et al., 2002):

$$c_{M,\text{load}} = 1.0044 \cdot 10^{-2} \sigma_z^{-1.1347} \tag{4}$$

over the σ_z interval $10 \le \sigma_z \le 80$ MPa, i.e. approximately for $900 \le z \le 7000$ m.
Eqs. (3) and (4) may be compared to assess the hardening factor of the Northern Adriatic basin in unloading-reloading conditions, i.e. the ratio $\gamma = c_{M,\text{load}} / c_{M,\text{unload}}$. This is shown by the solid profile of Fig. 3. Fig. 3 also provides γ as obtained from using compressibilities based on oedometer tests (dashed profile). These has been performed on Northern Adriatic core samples taken from other existing boreholes. Although lab $c_{M,\text{load}}$ are generally larger than in situ $c_{M,\text{load}}$ (Cassiani and Zoccatelli, 2000) it is interesting to notice that γ is about the same irrespective of the nature of the c_M measurements. This is a good evidence of the validity of the solid profile of Fig. 3 over the basin scale, i.e. the unloading-reloading (II cycle) c_M is few times (between 2 and 4) smaller than the virgin loading (I cycle) c_M.

3. Numerical simulations of marker expansions

Eqs. (3) and (4) have been implemented into a three-dimensional coupled finite element consolidation model of the porous medium surrounding the Amelia-21 wellbore (Ferronato et al., 2003). The purpose of the finite element analysis was to validate the constitutive laws (3) and (4) by reproducing the observed field deformations at the marker scale (10.5 m). For the selection of representative litho-stratigraphies and medium parameters (basically the hydraulic conductivity and porosity) see Gambolati et al. (2000). Fig. 4 compares the observed 1997-1999 marker expansions (Tab. 1) and the expansions predicted by the numerical model. Experimental and simulated values match quite well providing evidence of the reliability of the constitutive (II cycle) c_M law (3).

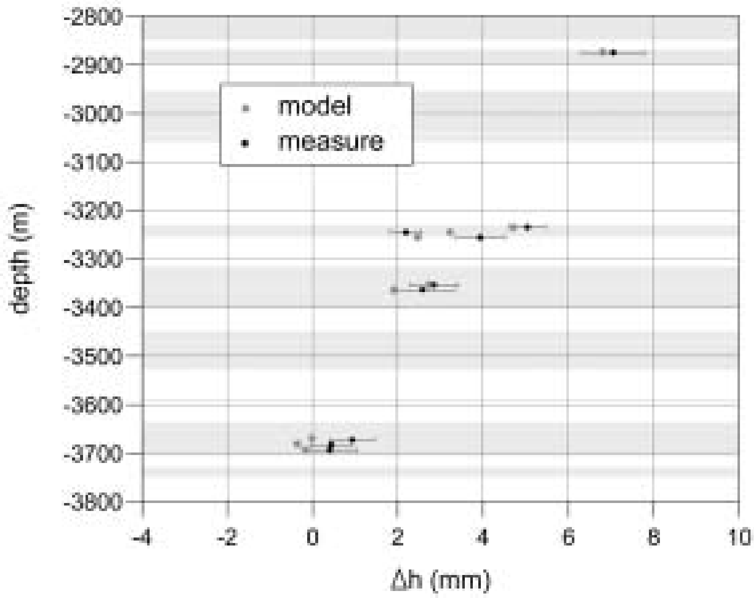

Fig. 4: Comparison between marker expansion measurements and expansions predicted with the aid of a three-dimensional coupled finite element consolidation model. The grey shaded areas indicate the producing gas reservoirs.

4. Conclusions

After the field abandonment a natural pore pressure recovery is usually experienced by the depleted reservoirs with a vertical expansion of the stressed sediments. If the radioactive marker technique (RMT) has been implemented into ad hoc boreholes the measured expansions may allow for the evaluation of the in situ reservoir c_M under unloading-reloading (II cycle) conditions. The expansions observed in Amelia-21 wellbore in the Northern Adriatic basin over the period 1997-1999 and measured by RMT have been used to derive the II cycle c_M of the Northern Adriatic gas fields. This has turned out to be a few times (between 2 and 4) smaller than the virgin loading c_M. The observed expansions have been reproduced by a three-dimensional coupled finite element consolidation model that has used the II cycle c_M based on the RMT measurements.

Acknowledgements

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References

Baù, D., Gambolati, G. and Teatini, P. (1999). Statistical analysis of in-situ compaction measurements for anthropogenic land subsidence prediction in the Northern Adriatic basin. *Proceedings of the 5th Conference of the International Association of Mathematical Geology*, vol. 2, A.N.S.J. Lippard and R. Sinding-Larsen eds., Norway, 299-304. Tapir Publ.

Baù, D., Ferronato, M., Gambolati, G. and Teatini, P. (2002). Basin-scale compressibility of the Northern Adriatic by the radioactive marker technique. *Géotechnique*, 52, 605-616.

Cassiani, G. and Zoccatelli, C. (2000). Towards a reconciliation between laboratory and in-situ measurements of soil and rock compressibility. *Proceedings of 6th International Symposium on Land Subsidence*, vol. 2, (L. Carbognin et al. eds.), Italy, 3-15. La Garangola Publ.

De Kock, A.J., Johnson, J., Hagiwara, T., Zea, H.A. and Santa, F. (1998). Gulf of Mexico subsidence monitoring project with a new formation-compaction monitoring tool. *SPE Drilling & Completion*, December, 223-230.

De Loos, J.M. (1973). In-situ compaction measurements in Groningen observation wells. *Verhandenlingen Kon. Ned. Geol. Mijnbouwk. Gen.*, 28, 79-104.

Ferronato M., Gambolati, G., Teatini, P. and Baù, D. (2003). Radioactive marker measurements in heterogeneous reservoirs: a numerical study. *International Journal of Geomechanics*, in press.

Gambolati, G., Teatini, P., Baù, D. and Ferronato, M. (2000). Importance of poroelastic coupling in dynamically active aquifers of the Po river basin, Italy. *Water Resources Research*, 36, 2443-2459.

Menghini, M.L. (1989). Compaction monitoring in the Ekofisk area chalk fields. *Journal of Petroleum Technology*, 41, 735-739.

Mobach, E. and Gussinklo, H.J. (1994). In-situ reservoir compaction monitoring in the Groningen field. *Proceedings of EUROCK 94, Rock Mechanics for Petroleum Engineering*, The Netherlands, 535-547. A.A. Balkema Publ.