

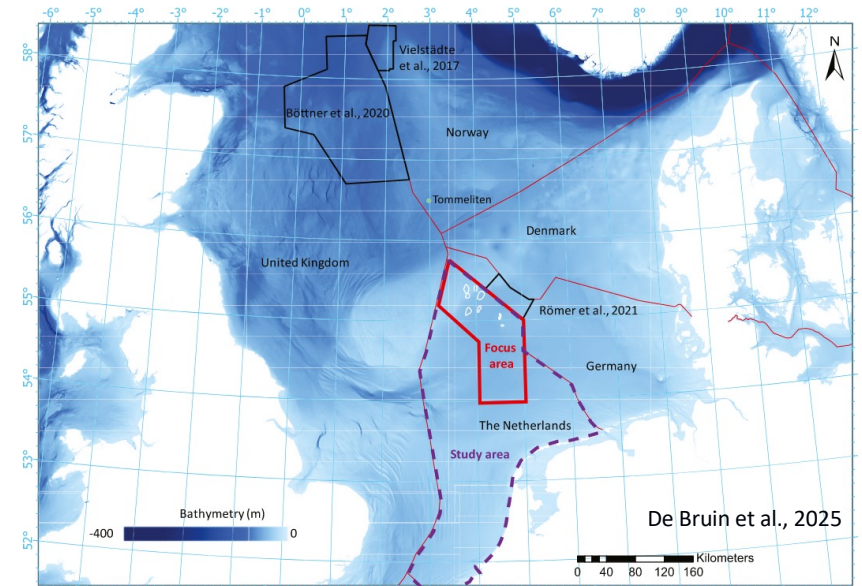
Legacy well risk-profile assessment based on lessons from methane leaks

Al Moghadam, PhD

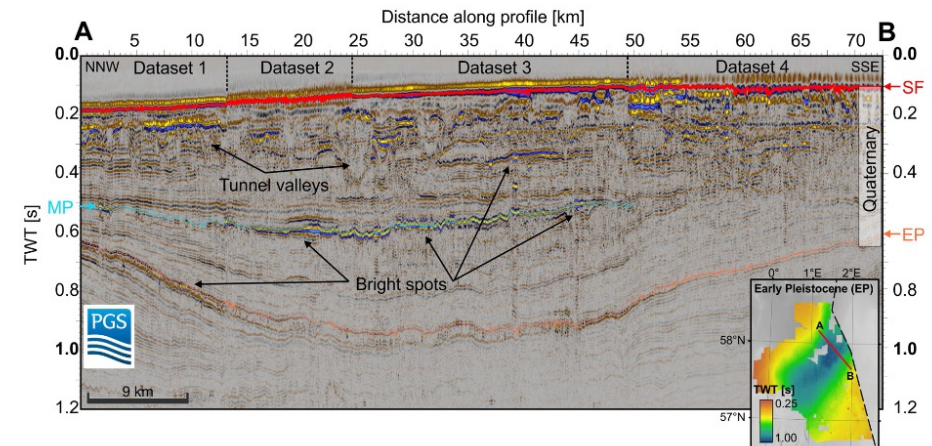


Setting the Scene

- › There is limited field experience with CO₂ leaks via legacy wells as few projects are yet mature
- › Several studies have shown gas leakage at the seabed from a number of abandoned wells in the North Sea
- › The gas is of biogenic origin from accumulations scattered around the North Sea
- › There are many wells that intersect these accumulations which makes them a potential leakage pathway
- › The mechanism for leakage in these wells is not well-understood
- › Such leakage mechanisms and pathways is to some extent applicable to legacy wells in the context of CCS operations

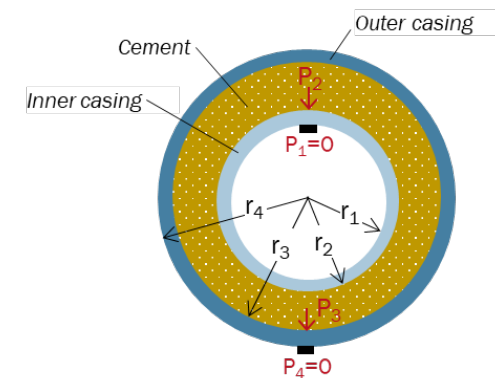
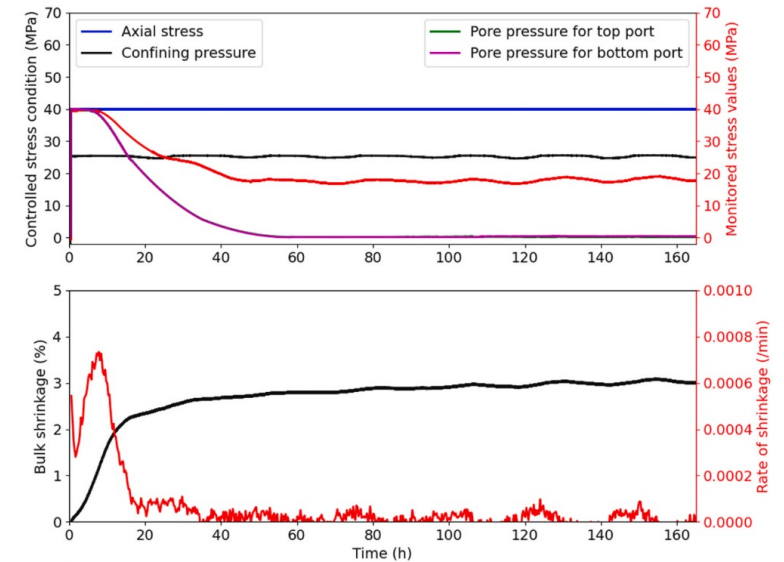


Böttner et al., 2020



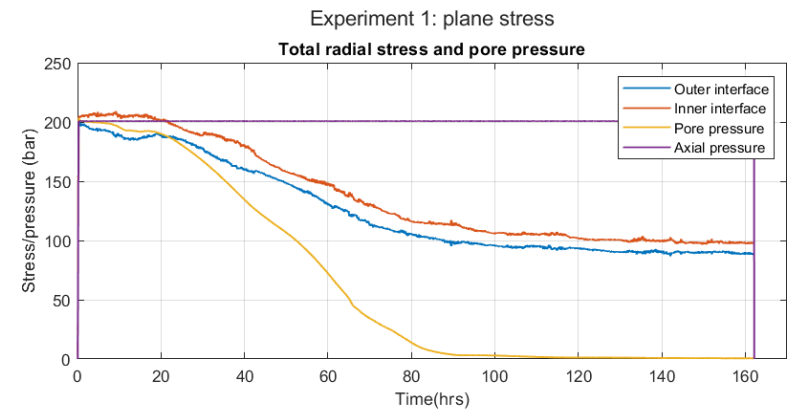
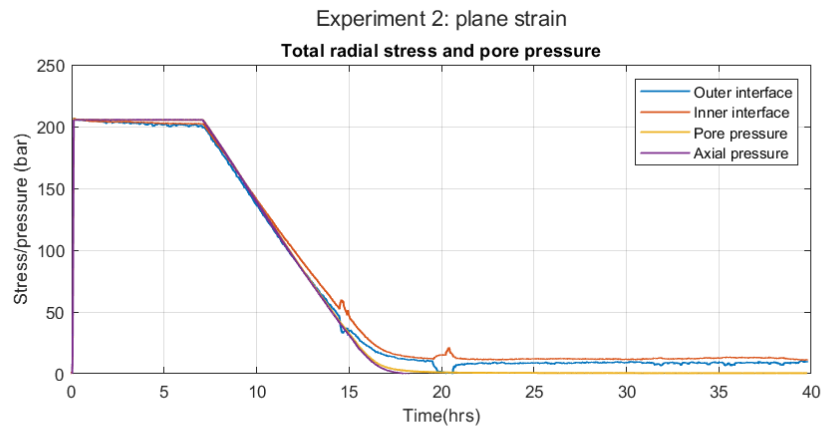
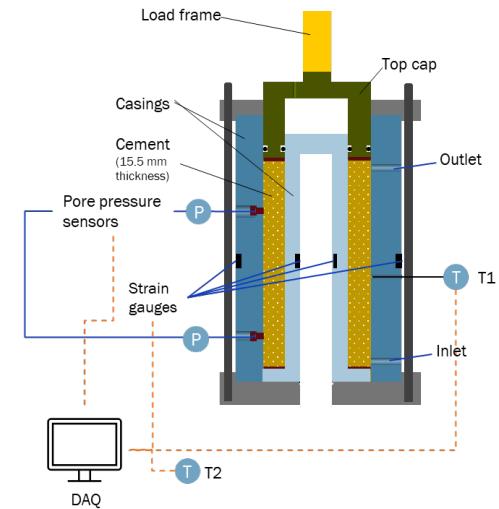
Cement's Initial Stress

- › Cement slurry placed in well annuli undergoes hydration reactions as it sets
- › These reactions cause the formation of a solid poro-elastic skeleton
- › However, they also cause an internal shrinkage
- › This leads to a pore pressure drop in the cement which results in a stress drop
- › This was first measured by Los Alamos National Lab for a cement plug
- › We have recently conducted this measurement for a cement sheath (Corina and Moghadam, 2025)
- › The stress drop in cement increases the likelihood of debonding



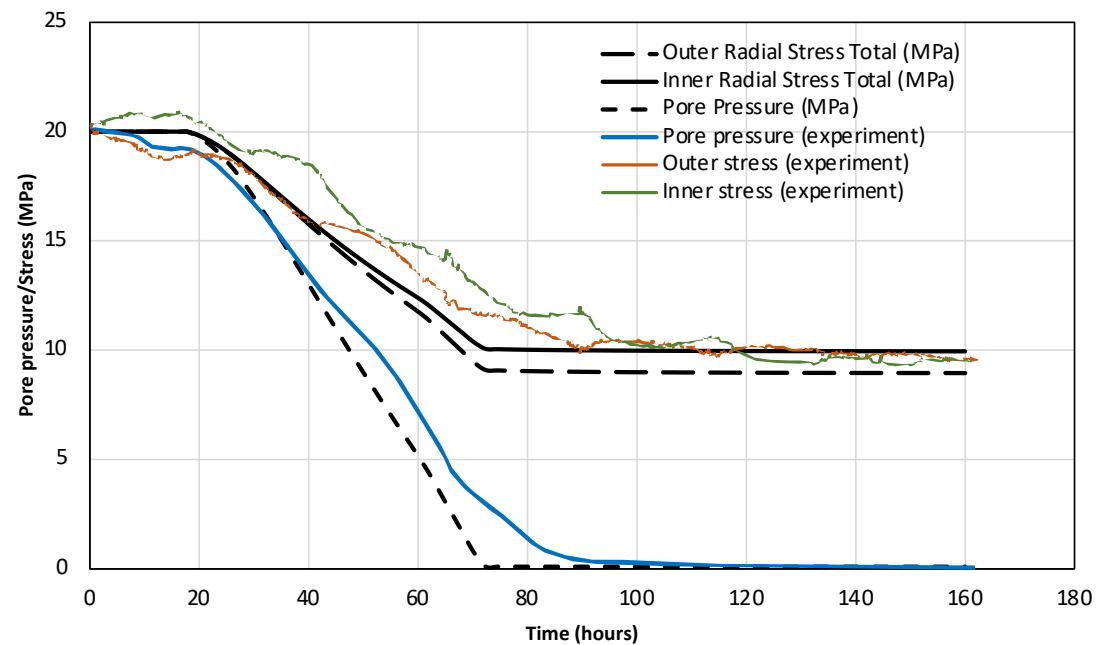
TNO's Experiments

- › We have developed a setup to measure cement pore pressure, temperature, and stress at both interfaces of cement
- › The results show a significant decline in cement stress as it cures
- › The outer interface declines more than the inner interface



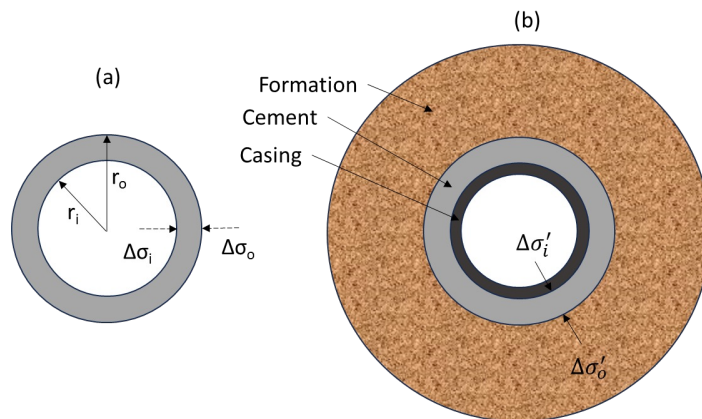
Modelling

- › Finite element modelling of the Constant pressure tests confirms the experimental observations
- › The results have been published (Moghadam and Loizzo, 2024)
- › The model also shows lower stress on the outer interface
- › This increases the confidence in our understanding of cement behavior



Analytical Method

- › We have developed an analytical method to predict the stress drop in a cement sheath during curing
- › This is verified using lab experiments (Corina and Moghadam, 2025)
- › Using analytical methods increases the efficiency of analyzing a larger dataset compared to FEA models



$$A_r^m = \frac{(1 - 2\nu^m)r_o^2r^2 + r_o^2r_i^2}{2G^m(r_o^2 - r_i^2)r}$$

$$B_r^m = \frac{-(1 - 2\nu^m)r_i^2r^2 + r_o^2r_i^2}{2G^m(r_o^2 - r_i^2)r}$$

$$\Delta\sigma_o' = \Delta P^{cem}(\alpha_o - 1)$$

$$\Delta\sigma_i' = \Delta P^{cem}(\alpha_i - 1)$$

$$(A_{r_o}^{cem} - B_{r_i}^f)\alpha_o^t + B_{r_o}^{cem}\alpha_i^t = A_{r_o}^{cem} + B_{r_o}^{cem}$$

$$A_{r_i}^{cem}\alpha_o^t + (B_{r_i}^{cem} - A_{r_o}^{cas})\alpha_i^t = A_{r_i}^{cem} + B_{r_i}^{cem}$$

Analytical Method

- › The analytical model estimates the drop in cement stress due to curing
- › The effective pressure of the slurry (slurry pressure minus formation pressure) at the depth of interest should be calculated and converted into a gradient
- › Using the plot, and considering the formation Young's Modulus, this can be converted to cement stress after curing
- › Important input parameters are formation pressure, formation mechanical properties, slurry sg, spacer/mud sg, and the length of the cement sheath

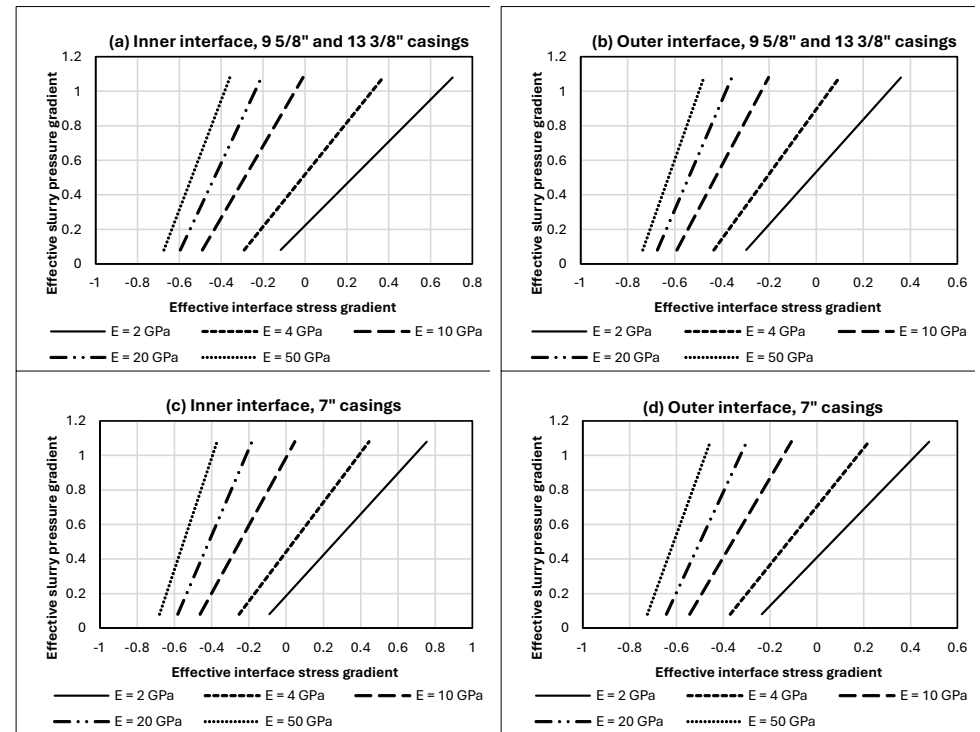
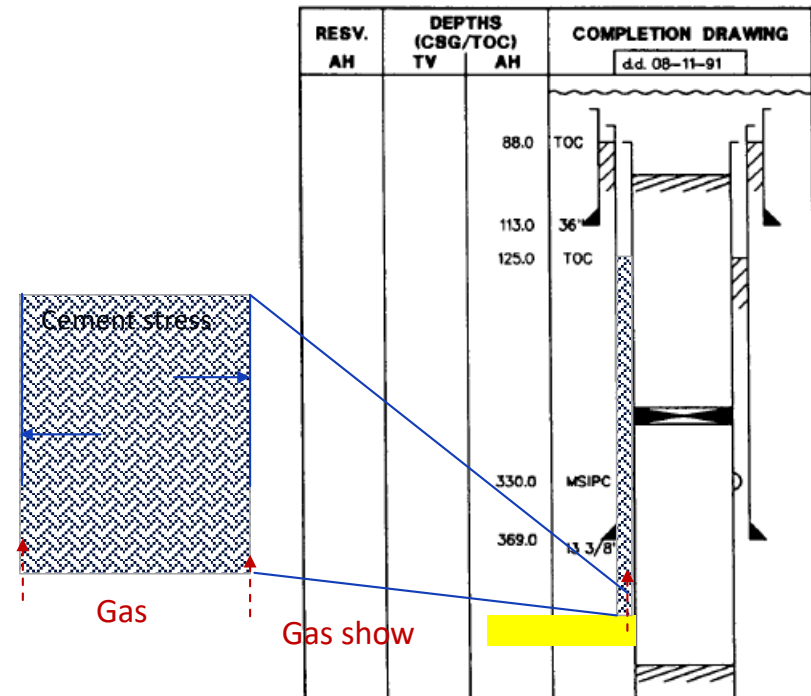


Figure 1: Summary of the cement interface stress results at various initial slurry pressures and formation Young's Moduli (E). The results for 9 5/8" and 13 3/8" are similar and therefore presented in the same subfigures. (a) and (b) subfigures show the inner and outer interface stresses after curing, respectively, for the 9 5/8" and 13 3/8" casing sizes. (c) and (d) subfigures show the inner and outer interface stresses, respectively, for the 7" casing size.

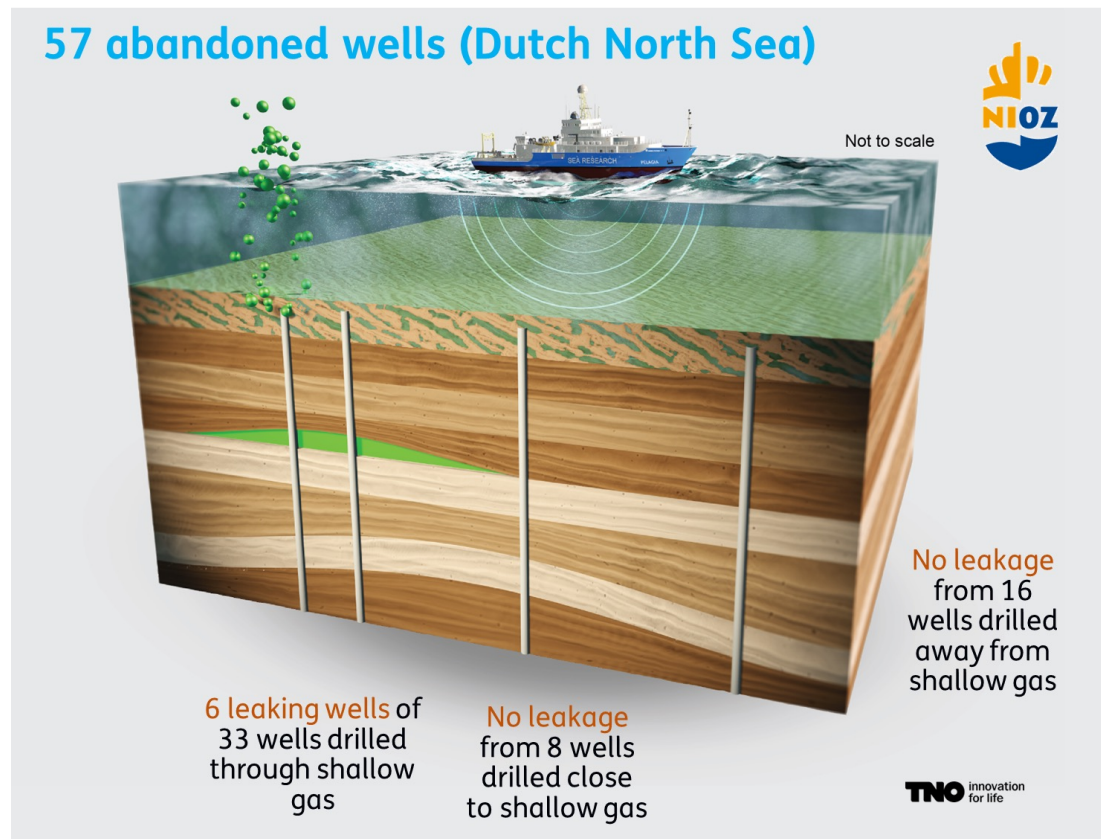
Hypothesis

- › We can estimate the initial effective slurry pressure gradient in a cement sheath using typical well data available
- › The analysis should be conducted at a depth just above the shallow gas zones
- › Using the analytical model we can then estimate the cement's interface stress
- › **We hypothesize that wells with a lower cement interface stress are more prone to debonding and leakage if shallow gas is present**



Field Evidence

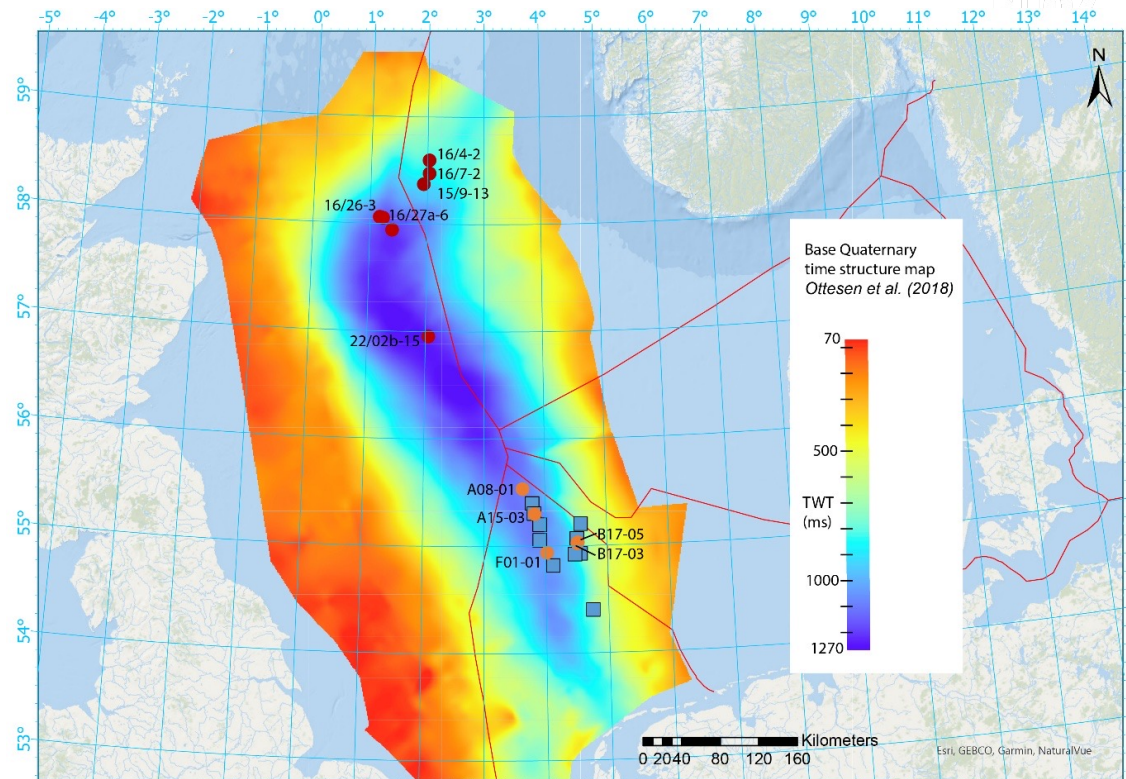
- TNO AGE/NIOZ have conducted a measurement campaign on several wells in the North Sea that penetrate shallow gas (De Bruin et al., 2025)
- Some of these wells show methane plumes at the seabed
- We reviewed some of these wells and extracted relevant information from public sources
- In addition, we investigated several wells from the Norway and UK sectors that were recently investigated (Vielstädte et al., 2015, 2017; Böttner et al., 2020)
- It is important to look at wells that are leaking and non-leaking in the same region to test our hypothesis
- The goal is to understand whether we can predict the state of the cement sheath and potential leaks using modelling



Theme name

Study Area

- Map of all the wells considered in this study in the Netherlands (de Bruin et al., 2025), the UK (Böttner et al., 2020) and Norway (Vielstädt et al., 2015), plotted on the base Quaternary map (Ottesen et al., 2018)
- All wells are found in the same North Sea Basin
- Blue squares are non-leaking wells in the Netherlands, and the circles indicate leaking wells



Input Data

- › In total, we evaluated 20 wells
- › 14 wells from the Dutch sector, 3 from Norway, and 4 from the UK
- › Generally casing sizes intersecting the shallow gas are 7", 9 5/8", or 13 3/8"
- › Cement slurry SG ranges between 1.5 and 1.9 (various blends of class G with bentonite and Pozzolan plus proprietary blends)
- › The length of the cement sheath varies considerably
- › The depth of analysis is selected to be above the highest shallow gas zone

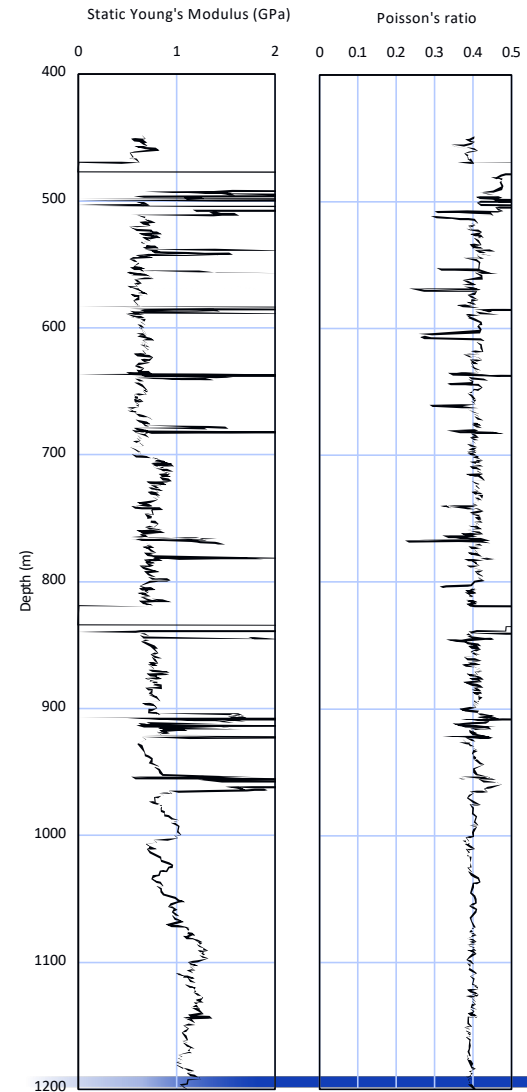
Collected data for each well from public databases:

Well	Jurisdiction	Plume at seabed?	Casing size (in.)	Hole Diameter (in.)	Cement Type (lead cement)	Lead Slurry Density (SG)	TOC (m)	Cementing Technique
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Spacer Density (SG)	Spacer Volume (m ³)	Spacer Type	Mud Density (SG)	Mud Type	CBL/VDL	Depth of shallow gas (m)	Pressure Gradient at Gas Show	Pressure Gradient Method
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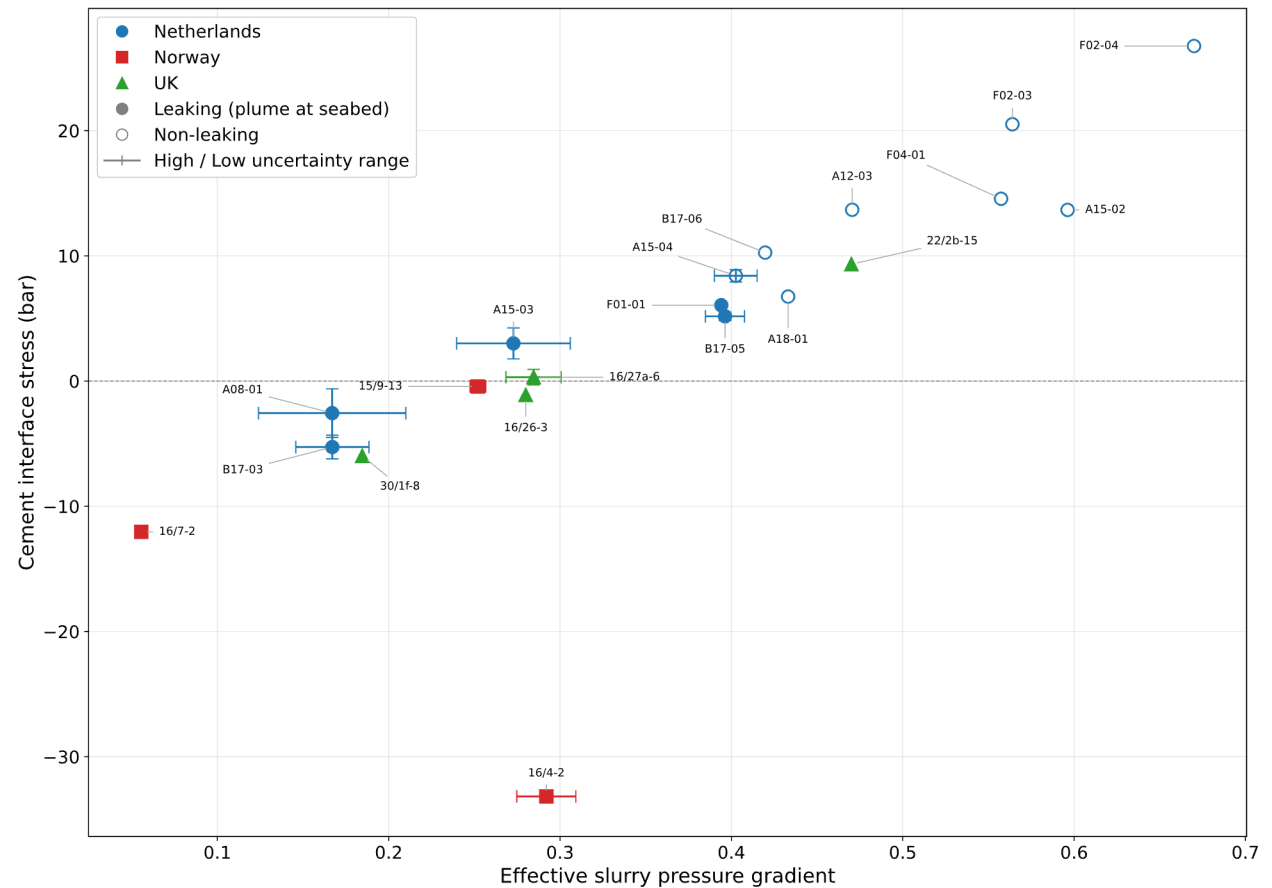
Input Data

- › Elastic properties of formations are needed to use the analytical model
- › We used the sonic and density log data from the A15-03 well to evaluate the dynamic Young's Modulus and Poisson's ratio
- › We used a correlation by Horsrud (2001) that is based on soft shales in the North Sea to convert the values to static
- › Overall, the formations in the North Sea Group are soft
- › We use a Young's Modulus of 0.7 GPa and Poisson's ratio of 0.4 for the entire study, assuming that it is representative for all the wells



Results

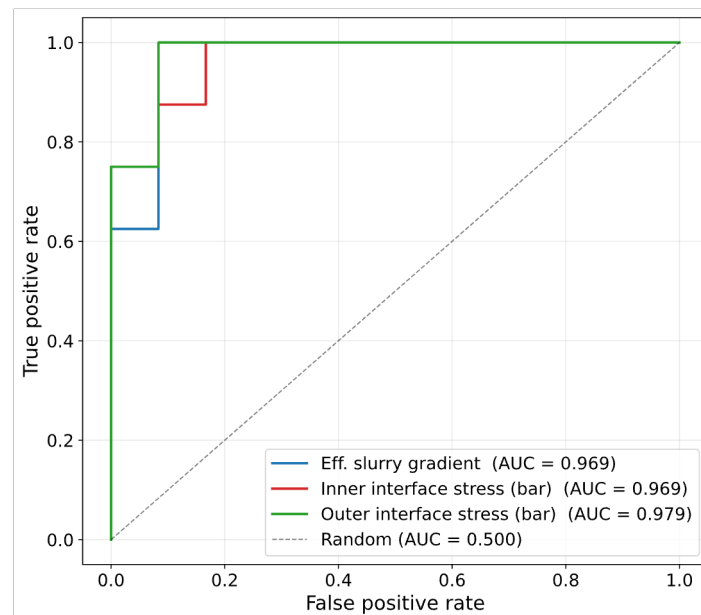
- This figure presents the plot of cement interface stress versus the initial effective slurry pressure gradient
- The non-leaking wells are generally in the top right corner
- This indicates that as expected, wells with higher cement stress may have a lower chance of leaking
- The impact of well operations such as pressure tests, production tests, and abandonment operations was not considered



Statistical evaluation

- We carried out a quantitative evaluation of the predictive ability of the computed cement stress indicators
- Mann-Whitney U tests (p-value < 0.0001)
- Receiver Operating Characteristic (ROC) analysis (AUC = 0.979)
- A leave-one-out cross-validation (LOOCV) procedure (11 of the 12 leaking wells correctly identified)
- The results show that the indicators are statistically significant
- The outer interface stress parameter has the best performance

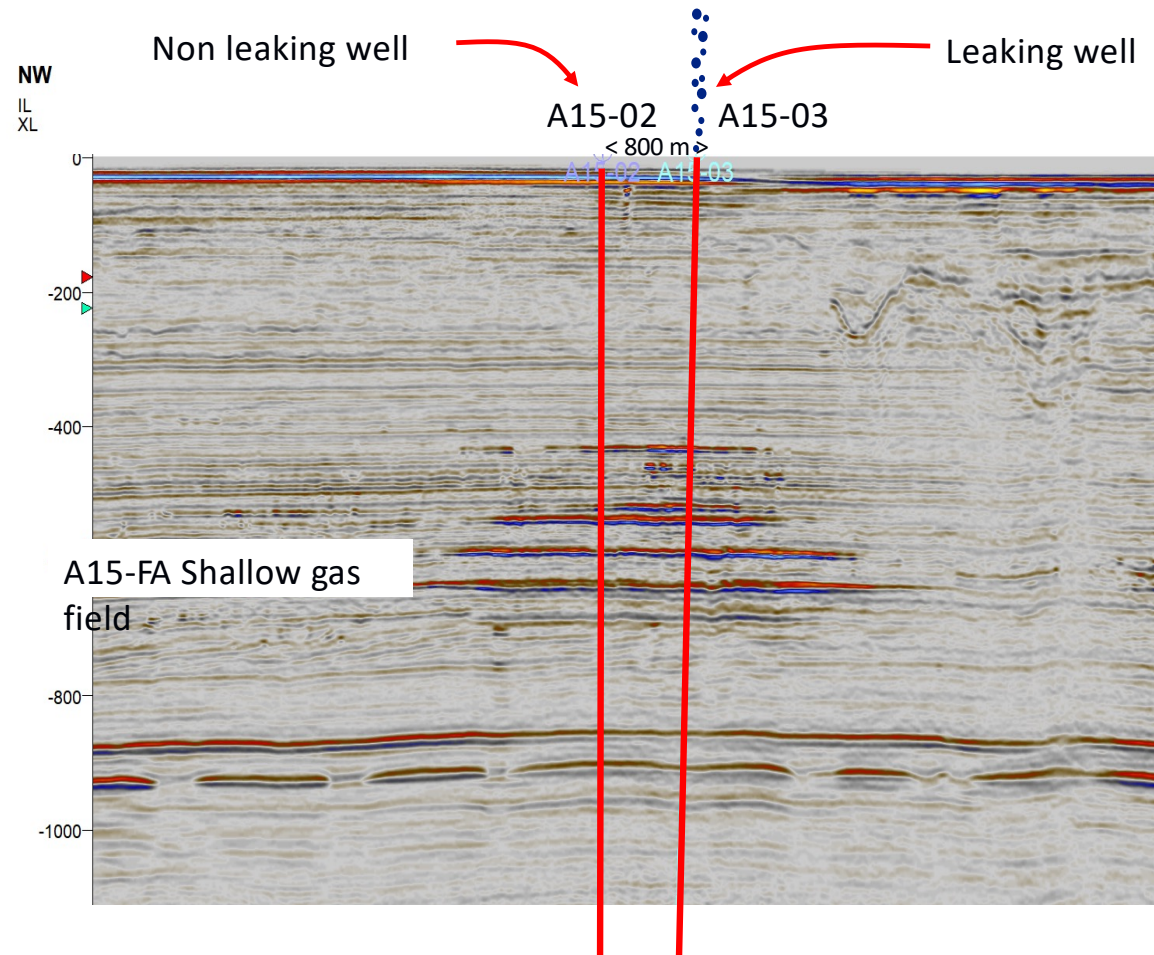
Predictor	Leaking mean \pm sd	Non-leaking mean \pm sd	p-value
Eff. slurry gradient	0.3 \pm 0.1	0.5 \pm 0.1	< 0.0001
Inner interface stress (bar)	10.8 \pm 13.3	32.6 \pm 12.8	< 0.0001
Outer interface stress (bar)	-3.1 \pm 10.7	14.3 \pm 6.2	< 0.0001



A15-03 versus A15-02

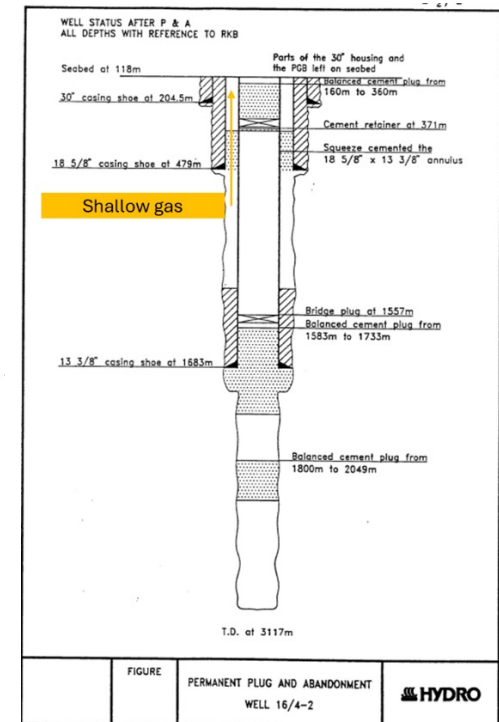
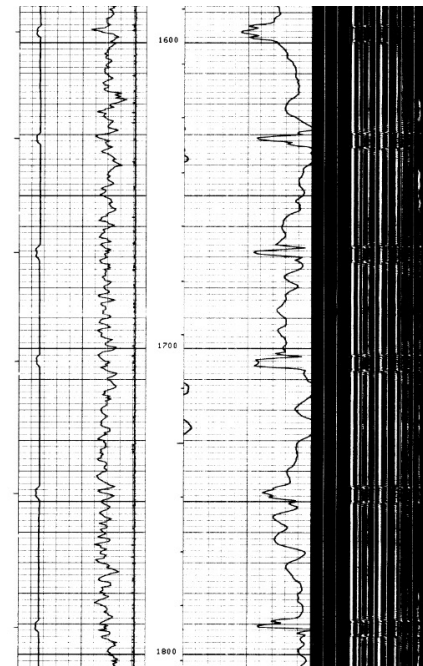
- Wells A15-03 and A15-02 are only 800 m apart
- They both intersect the same shallow gas zone
- However, only A15-03 well shows leakage at the seabed
- Well A15-02 has annular cement with a specific gravity of 1.86 above the shallow gas, with a TOC at 100 m, using a two-stage cementing technique
- However, A15-03 was cemented with a 1.5 SG slurry, with TOC at 230 m
- The initial cement stress available for the A15-03 well cement is significantly lower

	NO plume	YES plume
Two-stage cement	5 (83 %)	1 (17 %)
Single-stage cement	3 (21 %)	11 (79 %)



General observations

- › The wells in the Norwegian sector have a considerably lower slurry sg and shorter cement column above shallow gas making them more prone to leaks
- › A well in Norway was not cemented against the shallow gas zone
- › Another well indicates gas bubbles around the wellhead that does not seem to have been remediated (failed squeeze attempt)
- › Another well has reported major cementing issues (ran out of cement) that lead to a poor cement sheath confirmed by CBL/VDL
- › Generally, we find that well leakage can be largely attributed to poor well design against the shallow gas zones



Problems were encountered while cementing the 18^{5/8}" casing and a proper seal could not be obtained. Gas bubbles were seen seeping around the wellhead. A high viscosity plug consisting of 6 ppb Hicell was pumped, and a 20ppg barite plug squeezed against it in an attempt to control the gas. Nevertheless the gas seepage occurred intermittently throughout the well.

Limitations

- › This work only considers 20 wells in the North Sea that intersect shallow gas.
- › It is not clear whether this assessment can be applied to deeper gas sources. Leaking gas from deeper sections may enter permeable intermediate formations. Thus, leaks may not be identifiable at the surface or seabed.
- › The assessment in this work only considers the stress change in cement due to hydration shrinkage, ignoring the operational parameters.

Lessons learned

- › There is a statistically significant relationship between cement stress and presence of a leakage pathway
- › Generally, we see a better performance for higher effective slurry pressure (this is typically limited by formation fracture pressure)
- › Lower formation stiffness, higher cement density, and a longer cement sheath improve the cement bond quality
- › Two-stage cementing allows for longer and heavier annular cement which reducing leakage risk
- › This methodology can potentially be applied to legacy wells to identify higher risk boreholes
- › In addition, it can be used to enhance the design of new wells to avoid leakage issues in the future



› **THANK YOU FOR
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