Reconciling static and dynamic elastic properties of Opalinus Clay at multiple scales

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Introduction

Previous data records have indicated that static Young's moduli of Opalinus Clay constrained in undrained laboratory tests typically need to be scaled by a factor of two to four to match dynamic values (i.e. calculated from sonic and ultrasonic wave velocities and material density). Such apparent discrepancy is unsatisfactory for site appraisal, i.e. when building a mechanical model from exploration data, as the latter are typically dominated by dynamic measurements (sonic logs and seismics). Opalinus Clay core was sourced at the Mont Terri rock laboratory for core tests investigating the frequency dependency of dynamic elastic properties and the strain-dependency of static elastic properties. The laboratory tests were complemented by static and dynamic in situ measurements in the boreholes used to source the cores for laboratory tests. This study reconciles the static and dynamic elastic properties of the Opalinus Clay at multiple scales.

Methods and results

Static and dynamic measurements of Opalinus Clay core were conducted under controlled stress conditions in the laboratory at SINTEF AS. Cores were subjected to two different effective[1] stress levels (4 and 10 MPa, respectively). Dynamic measurements were performed at ultrasonic frequency (500 Hz) and low (seismic) frequencies (1-150 Hz). In contrast to the ultrasonic measurements for which the dynamic stiffness is inverted from velocity and density data, the measurements in the low-frequency domain on core samples are measured directly. This requires highly specialized equipment and is not done routinely. The calculated Young's moduli from dynamic velocities indicate a relatively small dependency on frequency in the low frequency domain but a marked increase of approximately 150% from the seismic to the ultrasonic frequency (Fig.1) attributed to dispersion.

High resolution interval velocity measurements (IVM sonic logging) were also conducted in the 131 mm diameter borehole, with a centre frequency of approximately 50 kHz. Stress modelling of the borehole trajectory indicates that the effective stress behind the borehole wall is similar to the lower effective stress level (4 MPa) used in the laboratory tests. When inverted the sonic logging yields a higher Young's modulus (E-moduli) than the core data at seismic frequency, and lower E-moduli than the core data at ultrasonic frequency, just as could be expected from the lab measurements. Static measurements were also conducted on cores by mechanical unloading-reloading of variable amplitude. The equivalent frequency of the mechanical (static) test can be estimated from the strain rate and yield values of approximately 0.5 Hz in the reported experiments. The static test results are in broad agreement with the dynamic measurements at similar equivalent frequencies, especially when the amplitude (or stress-strain increment) is reduced to infinity («zero strain» amplitude) (Fig.1). Since the borehole was drilled perpendicular to bedding, sonic logging provides in situ estimate of (dynamic) moduli *perpendicular* to bedding. In contrast, in the (static) dilatometer test the loading and unloading is in the direction *parallel* to bedding. Total mean in situ stress can be well approximated around the wellbore to 2-4 MPa.

[1] Terzaghi effective stress, i.e. total stress minus pore fluid pressure

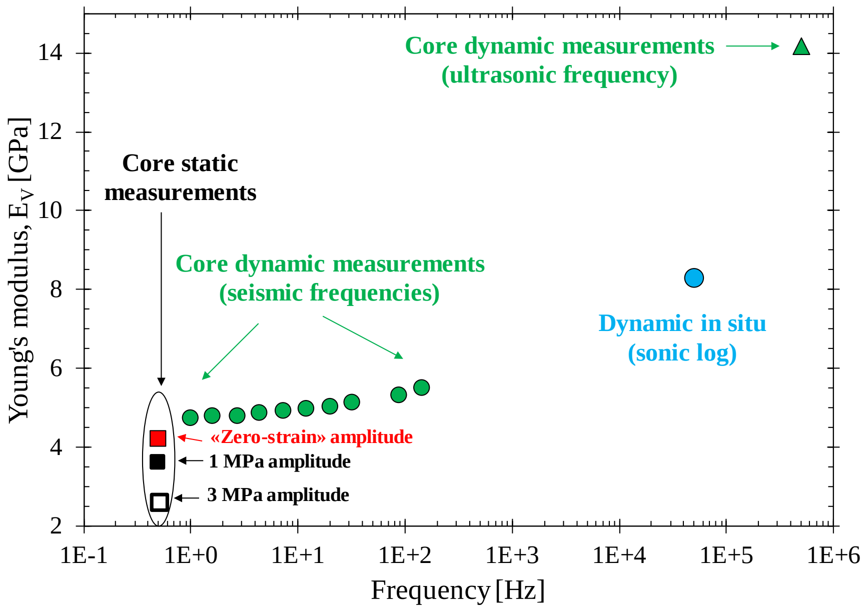

Fig. 1: Compilation of Young's moduli in the direction vertical to the bedding. Cores were 50 mm long and 25 mm in diameter and tests shown here constrained at 4 MPa effective stress.

But pore fluid pressure is difficult to evaluate since the borehole was drilled dry (air-flushed) and close to the borehole could also be negative (suction), hence effective stress could be much greater. The results of the dilatometer test at the selected depth is therefore compared with the core data performed at two different stress levels (Figure 2). As in Figure 1, the black symbols indicate unload-reload cycles at low stress amplitudes (0.5 MPa), whereas the red symbols refer to the «zero strain» amplitude values. The plot highlights (i) broadly similar trend of both static and dynamic values with stress for the core data, and (ii) good general agreement of the values obtained in situ and core tests if effective stress is considered. Considering the dynamic measurements (seismic frequencies) and the zero-strain results from the static tests, the discrepancy is less than 10%.

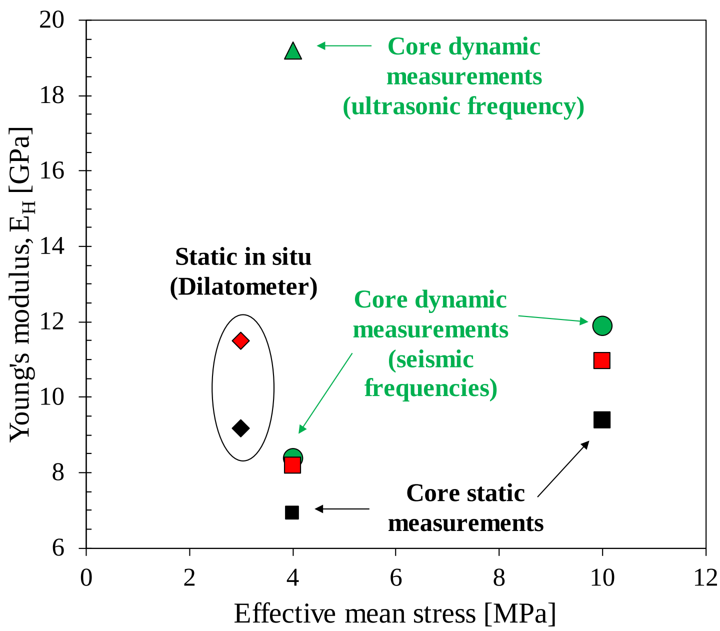

Fig. 2: Young's moduli in the direction horizontal to bedding. Note scale on y-axis. The red symbols refer to the « zero strain » amplitude values of the static measurements.

In conclusion, there is consistency between static and dynamic moduli when frequency dependency in the dynamic measurements («dispersion») and strain dependency in the static measurements is taken into account.