In-situ Measurement of Rock Compressibility in a Heavy Oil Reservoir

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Proposal

Compaction drive is a potentially important recovery mechanism for weakly cemented heavy oil reservoirs. In order to assess its magnitude the knowledge of the compressibility of the reservoir sands is required. However, due to the very nature of this class of reservoirs, the reliability of laboratory measurements can be questioned as the specimens are heavily disturbed during the coring process. To circumvent this shortcoming, the option of carrying out in-situ compressibility measurements becomes attractive. The use of a dilatometer, allowing the downhole measurement of the pressure-deformation characteristics of the formation, has thus been considered.

A preliminary study was carried out involving direct numerical simulations of a dilatometer test in a sand described by a Cam-Clay model. That study showed that the mechanical parameters, in particular the elastic and plastic compressibilities as well as the consolidation pressure do affect the response, thus establishing the theoretical feasibility of such a measurement.

A series of three tests were conducted in a newly drilled well in an uncemented sandstone reservoir.

By applying an inversion technique, based on an iterative finite element algorithm, it is then possible to identify the Cam-Clay parameters of the formation sands.

Introduction

The accurate determination of depletion induced compaction is very important in weakly- to non-cemented oil reservoirs such as encountered in the heavy oil fields, as it controls the surface subsidence and, more essential, the production profile and ultimate recovery from the field.

Yet, in this class of reservoirs, the coring process generates such a mechanical damage in the recovered rock samples that

the representativity of laboratory derived rock mechanical parameters required for the computation of reservoir compaction can be questioned. Therefore, to palliate that state of facts, the feasibility of measuring *in-situ* the compressibility of the rock has been investigated.

In-situ measurement of rock compressibility with a dilatometer has been identified as a viable approach. Although widely used in geotechnical engineering to measure soil and rock *in-situ* stiffness, the deployment of a dilatometer in an oil well and the interpretation of the results in terms of rock compressibility had never been attempted so far.

Both the operational aspects of the test and the interpretation of the results are presented and discussed in this paper.

Generalities

A vast majority of heavy oil reserves are found in shallow, weakly- to non-cemented sand reservoirs. As a result, the cold production of heavy oils may be controlled to a large extent by a compaction drive mechanism which can greatly affect the total recovery. The amount of compaction will mainly depend on the mechanical properties of the reservoir rock and in particular its compressibility, both elastic and plastic. Since the plastic compressibility is many times higher than the elastic one, it is also crucial to be able to assess whether the reservoir will reach a plastic regime during its production life.

Owing to the specificity of their behavior the determination of the mechanical properties of weakly cemented sands from laboratory testing are made difficult. The main reason for this is in relation with the poor degree of representativity of the recovered samples due to the severe disturbances generated by the coring operations.

As a consequence, the feasibility of measuring the formation compressibility *in-situ* has been investigated. Two options could be envisaged.

The first one would be to equip a well with radioactive markers, shot into the formation at precisely known depth intervals. By logging, with the appropriate tool and at various depletion levels, the changes in the relative positions of those markers, it is possible to obtain a reservoir compaction profile. Although that technique is field-proven⁽¹⁾, it is not a predictive method in the sense that it does only yield *a posteriori* information on the compaction.

In the present case, it was crucial to be able to anticipate the reservoir behaviour with depletion, and therefore the option of the radioactive markers was not further considered. Instead, the use of a dilatometer, was identified as being an adequate technique to obtain the required up-front information.

However a number of issues had to be addressed, from the theoretical feasibility of a compressibility measurement with a dilatometer through to the deployment of a non-standard oilfield tool in an oil well.

The dilatometer

The dilatometer is a tool designed for measuring the radial deformation of a borehole in response to a pressure increase inside that borehole. It consists of an inflatable membrane fitted with 3 displacement sensors capable of measuring the radial displacement of the membrane and a pressure gauge reading the fluid pressure inside the tool (Fig. 1). The tool is deployed by lowering it in the borehole to be tested and the formation is submitted to various cycles of inflation-deflation during which the pressure and radial deformations are recorded.

Figure 1 : Schematics of a dilatometer

The curves generated during a test (Fig. 2) are then inverted to derive the sought formation parameters. Essentially used in geotechnical engineering, the prime use of the dilatometer is to derive the elastic modulus of the tested rock mass.

Figure 2 Typical dilatometer test output

Feasibility study

Since, in this particular situation, the information sought deals with the plastic range of rock deformation, which goes beyond the usual field of application of the dilatometer, to validate the approach a theoretical feasibility study was undertaken.

This has been achieved by means of numerical simulations. In that exercise, a dilatometer test was modeled numerically, using a Finite Element (FE) code, and the impact of the rock properties on the response (in terms of pressure vs. lateral displacement) was investigated.

Model geometry and boundary conditions

The model was set up to simulate the behavior of a dilatometer (1m long, 8 1/2" diameter) in a vertical borehole of the same diameter as the tool. In view of the various symmetries of the problem (vertical axis and horizontal plane through the middle of the dilatometer), only the top half of a vertical section has been considered. The boundary conditions, as shown on the diagram (Fig. 3), assumed constant vertical and horizontal stresses and no vertical displacement across the bottom boundary (plane of symmetry for the problem).

To simulate the whole operational process, the loading phase was split in two stages:

- i) First, an unloading of the horizontal stress, simulating the drilling phase, was applied along the entirety of the borehole wall (left vertical boundary of the model). This unloading corresponds to the difference between the virgin horizontal *in-situ* stress and the mud pressure applied during the drilling phase.
- ii) Secondly, the dilatometer test itself was simulated by an increasing load (stress) applied on the borehole wall over the half-length of the dilatometer (vertical symmetry). Perfectly drained conditions were assumed during that second stage.

Fig. 3 : Model geometry and boundary conditions for feasibility study

The various simulations carried out show that the results of a dilatometer test are significantly affected by the compressibility properties of the rock being tested. In the present case, within the framework of a Cam-clay formulation, both the consolidation pressure (P'_{c0} – see Fig. 4) and the plastic compressibility (λ) have a definite influence on the simulated radial displacements of the dilatometer membrane as a function of the applied pressure. In addition, when looking at the results of the simulations in the stress space – not presented here-, it can be seen that the plastification of the material induces a strong increase in the mean stress which is associated with a strongly contractant behavior.

These two observations are a clear sign that the use of a dilatometer to evaluate the compressibility of the rock is feasible and thus validate the approach taken. This statement however does not imply, at this stage, that the sought information (plastic compressibility and consolidation pressure, for example) can readily be obtained by mathematical inversion of the results.

Fig. 4 Impact of consolidation pressure on dilatometer response

Inversion procedure

Having established the theoretical feasibility of the measurement with a dilatometer, the issue of parameter identification from a dilatometer test was addressed.

Existing work on *in-situ* compressibility measurements using a dilatometer, mainly focussed on soft, low permeability sediments⁽²⁾ could be adapted to typical high permeability,

weakly cemented heavy oil reservoir formations. The numerical method developed there to inverse dilatometer tests consists in minimising the difference between the outcome of a simulation and the actual test data. To achieve this, an iterative direct (or forward) modelling scheme is used in combination with a parameter optimisation routine. The flow chart describing the process is shown in Fig. 5.

Fig. 5 : Flow chart of the inversion procedure

In addition to the above, a preliminary analysis is usually done to fine tune the initial set of parameters used. This warrants that the inversion scheme converges towards a physically acceptable solution. This is achieved by a rough sensitivity analysis until a set of data is obtained that gives a resulting simulation 'close enough' to the experimental data.

The approach described above having been primarily developed to analyse dilatometer tests in low permeability (typically argillaceous), shallow sediments, it remained to be seen whether it was applicable to heavy oil reservoirs. For this, the inversion of a synthetic case representing a highly permeable formation saturated with a viscous fluid, was set up with a particular attention paid to the number and the nature of the parameters that could be simultaneously identified from a single dilatometer curve.

The exercise was carried out by generating the results of a synthetic test from a base set of input parameters chosen so as to represent a dilatometer test in a typical heavy oil well. Then, a perturbation introduced on selected parameters would generate a new set of input data, which was used as initial data set for the inversion scheme. It then could be checked whether the 'true' parameter values could be found again, thus the validity of the inversion. At the same time the sensitivity of non-perturbed parameters on the obtained value was also evaluated.

From the various attempts, it could be demonstrated that the simultaneous inversion for up to two parameters (e.g. consolidation pressure and plastic compressibility) could be achieved with satisfactory accuracy from one single dilatometer curve.

Optimization of the operational procedure

An important corollary of the above work is that it allows optimizing the operational procedure to be followed so as to maximize the probability of obtaining a set of experimental results that can be conclusively inverted.

The general dilatometer test sequence is a continuous pressurization of the tool with a series of two or three

unloading-reloading cycles at various pressure levels in the test. The sole objective of these cycles is to allow the determination of the elastic parameters of the formation tested. Previous work⁽³⁾ had shown that the response of the dilatometer is strongly affected by the drainage conditions during the test, and that, unless the pore pressure could be measured, the inversion of the results could only be achieved for situations close enough to either perfectly drained or else undrained conditions. Thus, for the present case, optimizing the sequence amounted to determining the optimum pressurization rate to be applied during the dilatometer test so as to ensure that the tests are done under conditions close enough to perfectly drained.

For a given pressurization rate, the pore pressure response during a test will be governed, among other parameters, by the permeability of the formation and the viscosity of the pore fluid. In the present case, using the formation permeability value and the *in-situ* oil viscosity yielded a 10^{-7} ms^{-1} intrinsic permeability. To account for some degree of variability around those values, it was assumed that the actual intrinsic permeability value would be in the 10^{-7} and 10^{-6} ms^{-1} range.

From the results it appears that, under the assumed prevailing conditions, a loading rate of 1 bar/min, corresponds, for all practical purposes.

At the other end of the scale, and for the same permeability conditions, an undrained test would require a loading rate of 100 000 kPa/min (1000 bar/min!). This rate being unrealistic in practice, the option of performing an undrained test was not further considered.

The operational program

The operational program consisted of three phases:

- i) the drilling of the well down to the top of a potential test interval
- ii) the coring of the test interval, so as to ensure maximum borehole wall quality, and
- iii) the performing of the test itself.

Drilling program

The proposed drilling program included a two-stage operation. First, an S-shape pilot hole would be drilled so as to reach the expected top sands vertically but with a limited offset (less than 50 ft) to the top of the hole. The objective of that pilot was to identify the potential sand intervals to be tested; the data acquisition program would include basic MWD (Gamma ray & resistivity) to identify the sand intervals and a wireline caliper. The reason for running that additional log was to evaluate the quality of the hole, considering that it had been observed in several instances that some zones can show a natural tendency to caving. Of course such zones, if present, should be avoided in the coring process. Following the logging acquisition, the pilot hole would then be plugged and abandoned.

The actual test well would be a vertical sidetrack of the pilot hole, drilled out of the casing shoe down to the top of the first sand to be tested.

Coring program

Subsequently, a 20ft section of sand would be cored, rather than drilled, to maximize the chances that the resulting borehole is of perfect quality. The diameter of the hole in the

test interval has to allow sufficient clearance between the tool and the borehole wall so that it is possible to run the tool, but that clearance has to be minimized so as to maximize the 'useful' range of the displacement sensors. The basis for design was a nominal 4" hole (101.6 mm), which would leave a 5.8 mm clearance with a 90 mm diameter dilatometer. Nevertheless, it was decided to design a 3"7/8 OD coring tool (98.425 mm) in anticipation of some degree of wash-out. With no tool available with that diameter, the entire coring assembly had to be designed and fabricated.

Dilatometer testing program

Once the test hole cored and logged with a caliper, the dilatometer would be rigged up and lowered in place on drillpipe. The testing itself would consist in pressurizing the dilatometer at the required rate of 1 bar/min until either the maximum pressure available or the maximum allowable tool deformation has been reached. A number of unloading-reloading cycles would be performed at various pressure stages during the test to evaluate the elastic properties of the tested interval.

The operations

The drilling and logging of the pilot hole allowed to identify potential test intervals (Fig. 6). The test well was drilled down to the top of the identified interval which was cored with the specially designed coring tool. The coring operation went smoothly and, despite the inability to recover any core material, the hole was perfectly smooth (Fig. 7).

The dilatometer was made-up and the whole system (tool + pressure system + data acquisition) successfully tested at surface by inserting the tool in a steel pipe of adequate diameter (a drill pipe rack in this instance) and applying a slight pressure to check the proper functioning of the equipment. The dilatometer was then rigged up and connected to the drill pipe. The tool was run in at moderate speed to allow two to three straps per stand of drill pipe. The experimental set-up did not allow a continuous monitoring of the electric communication with the tool, but checks were done at regular intervals during the running-in.

The running speed was lowered to a minimum (estimated at 3-4 ft/min) to enter the test hole. Entry into the small diameter hole was confirmed by a very little slack-off of the hook load, thus confirming the correct depth correlation.

The actual test went smoothly as per the program. The raw test data are shown in Fig. 8.

Fig. 6 : MWD data in the pilot hole for dilatometer interval selection

Fig. 7 : Caliper data across the cored interval

Fig. 8 : Dilatometer test results

The results show that the readings given by the three sensors are slightly different, which could be attributed to a marginal formation anisotropy. Also, it can be noticed during the first unloading-reloading cycle, performed at a similar pressure rate as the test i.e. 1 bar/min, that the recorded deformation continues even with a decreasing tool pressure. This feature indicates some degree of time dependent behavior of the reservoir. Subsequent cycles were done at a faster pressurization rate and do not show that feature.

Analysis of the results

The raw data as shown in Fig. 8 were pre-processed to allow the inversion to be carried out. First, in the absence of a strong anisotropy in the data, the average of the three readings was used. In a second step, the 'useful' part of the curve (Fig. 9) was determined (i.e. discarding of the initial part of the curve until the contact between the tool and borehole wall is firmly established). And of course, in the inversion process the portions of the signal associated with the unloading-reloading cycle are not considered.

Fig. 9 : 'Useful' part of the dilatometer results

Then, the analysis of the unloading-reloading cycles allowed to deduce the value of the elastic parameters. The determination of the elastic parameters is done using the relation between the shear modulus G and the slope of the (linearized) unloading-reloading cycles:

$$G = \frac{E}{2(1-\nu)} = \frac{\Delta P}{2 \Delta u / R_0} \dots\dots\dots (A.1)$$

Where u is the radial displacement, and R_0 the initial wellbore diameter

Using each of the unloading cycles (including the final one) the following values of G are derived. The corresponding values of the Young modulus, assuming a 0.3 Poisson ratio, are calculated (Tab. 1). A Young modulus value ranging from 640-720 MPa was found, except for the initial part of the curve, from which a value of 220 MPa was deduced. Although the results were fairly consistent from one cycle to the other, the values found were unexpectedly low, considering the depth of the tested interval.

	Initial slope	1 st cycle	2 nd cycle	3 rd cycle	Final unloading
Shear modulus (MPa)	84	247	247	271	229
Young Modulus (MPa)	219	642	642	705	595

Tab. 1 : Young modulus values calculated from the test data

A series of forward simulations of test #1 have been run with the objective of defining an acceptable range of variation for the parameters related to the compressibility of the sand.

In those runs, the following values have been assumed:

- Slope of the critical state line $M = 1,16$ (determined from laboratory testing);
- Plastic compressibility $\lambda = 0,1$
- Elastic compressibility $\kappa = 0,01$
- Poisson ratio $\nu = 0,3$
- initial void ratio = 0,43

In addition, the test conditions were supposed perfectly drained.

Having set those values, a simulation was run with the derived Young modulus value, including that of the initial slope. However, because these values seemed rather low, an arbitrary value of 1000 MPa was also considered. From the results (Fig. 10) it appears that none of the values give a satisfactory match, but the initial part of the curve is better described with the lower value of 250 MPa. Although this value does not agree with the interpretation of the unloading-reloading cycles, it will nevertheless be used in the subsequent simulations.

Fig. 10 : Impact of Young modulus on direct test simulations

Then, the impact of the slope M of the critical state line was assessed without more success (Fig. 11).

Fig. 11 : Impact of the value of M on direct test simulations

Finally the combined influence of the consolidation pressure and compressibilities (characterized by β , the difference between the plastic and elastic compressibilities) was considered. It appeared that only the hypothesis of a strong over-consolidation allowed matching the experimental data (Fig. 12).

Fig. 12 : Impact of the value of the consolidation pressure on direct test simulations

Having identified a set of parameters that gives a satisfactory simulation of the operational results, the following step should have been, in principle, the application of the inversion algorithm. However, at a significant level of over-consolidation, as identified in the preliminary study, it appears that the compressibility no longer impacts the response of the dilatometer. This can be clearly seen on Fig. 12. Therefore, after fine-tuning of the determination of the adequate consolidation pressure, it was not deemed useful to launch the full inversion scheme.

Discussion

On the dilatometer results

The results obtained here indicate a strong over-consolidation of the tested interval. This result can be interpreted in several ways. A light cementation, providing some degree of cohesion in the sand, could be causing a behavior such as recorded.

Another hypothesis for such an over-consolidation could be that a significant erosion, geological or glacial, has taken place, in which case it would imply that, at some stage in its history, the reservoir has been buried at a greater depth than the current one.

In the framework of a Cam-Clay formulation, a rapid estimation of the thickness of the eroded column can even be made under simple assumptions, which are probably somewhat restrictive, but nevertheless adequate to obtain an order of magnitude. These assumptions are:

- 1 No major tectonic event occurred during the whole erosion process, i.e. the total horizontal to vertical stress ratio has remained constant in time,
- 2 The pore pressure gradient has remained hydrostatic,
- 3 The current estimate of the overburden stress gradient at the current reservoir level can be extended down to the

maximum historical burial depth of the reservoir determined from this calculation.

Only a geological study focussed on a possible erosion would confirm and quantify the above conclusions.

However, matching indications of over-consolidation of these formations was found in the analysis of logs in several wells in the same field in the form of a systematic trend in the sonic data across the shale intervals. That trend, indicating higher velocities than the normal trend can be interpreted as an indication of over-compaction, i.e. over consolidation.

Implications for the reservoir

If such a reservoir is produced by depletion, the formation undergoes compaction as the pore pressure decreases. Since the formation is over-consolidated, that compaction will take place in the elastic domain –meaning a small rate of deformation- until a state of stress is reached that corresponds to the current consolidation pressure. Beyond that point, plastic compaction –i.e. a larger rate of deformation- occurs, leading to an increased compaction drive mechanism.

Assuming that the reservoir compaction takes place in the vertical direction only –i.e. oedometric deformation-, it is possible to determine the state of stress, and also the associated pore pressure, at which the transition between elastic and plastic deformation will take place.

In practical terms, this indicates that compaction drive, if any, will only become significant past that threshold depletion. Depending on the current state of stress and the Over consolidation Ratio, this threshold may only be reached very late in the field life, thus meaning that the compaction drive, hence the associated additional recovery, might be negligible.

The above remark will be particularly pertinent for strongly over-consolidated reservoir rocks. With this remark in mind, the impossibility to determine, with the dilatometer, the plastic compressibility, and therefore the importance of the additional recovery from compaction drive, becomes a side issue.

On the inversion scheme

In the above study, two major assumptions have been made : i) the formation properties are homogeneous over the domain investigated by the dilatometer and ii) the behavior of the formation is not time dependent (i.e. any creep phenomenon has been disregarded). It may be that none of those two assumptions are strictly valid.

Homogeneity of the mechanical properties over the investigated domain

Considering the first hypothesis, it amounts to implicitly deny the presence of a filter cake of significant thickness and compressibility and assume that, despite the minute operational clearance available, the positioning of the tool can be achieved without significant mechanical damage being caused to the borehole wall. In the present case, in view of the low *in-situ* mobility of the pore fluid, it can be assumed that no massive filtration has taken place during the drilling phase and, consequently, that no thick filter cake has been deposited. In addition, given the low tool clearance (less than 3 mm), it is unlikely that any filter cake left after the tool is in place, will be significant enough to affect the test results.

As to the presence of a near wellbore mechanical damage, the minimal clearance available when maneuvering to set the dilatometer in place, can be of consequence. Assuming as a

fact that a mechanically 'disturbed' zone is generated, the question is then to integrate it into the inversion process which poses the problem of identifying the physical parameters both for the damaged and the intact formation. The resolution of the induced complication would require further work.

Time dependant behavior of the formation

The time dependant behavior of the formations tested has been evidenced during the initial unloading-reloading cycles of the test and had to be performed at pressure rates higher than the rest of the test to shadow the time dependant behavior of the formation. This phenomenon is not taken into account in the inversion procedure. To remedy this, it would be necessary to incorporate into the inversion algorithm the possibility to model a visco-plastic behavior, whereas only elasto-plasticity is currently considered. There are no direct means of evaluating the impact of such a time dependant behavior on the data recorded during the tests. However, disregarding the presence of a time dependant component in the signal would lead to an underestimation of the consolidation pressure, which, in any case, would push the occurrence of plastic compaction even later in the life of the field. Nevertheless, the issue of time dependent behavior ought to be incorporated in the inversion scheme.

Conclusions

A pilot operation to measure *in-situ* the compressibility of a reservoir rock using a dilatometer has been performed in an oil field. To our knowledge, it is the first time this type of measurement has been attempted.

Operational aspects

To achieve the success of the operation, the skill and commitment of all the parties involved in the planning, design and execution of this non-conventional operation have to be emphasized as a major component of this accomplishment. The highlights of the operations were:

An original drilling program:

An 'S'-shape pilot hole was drilled and logged to identify potential test intervals. The actual test hole could be drilled as a side-track to the pilot hole. The drilling was stopped at the roof of each test interval, which was cored to ensure maximum borehole quality.

An audacious coring operation:

Despite severe operating conditions, given the nature of the formation, the non-standard tool size and the constraint for a high quality borehole, the coring operation resulted in a test hole of extremely high quality.

Tool maneuvering in difficult conditions:

The running of the dilatometer in and out of the test hole required extreme care from the drilling crew given the exceptionally small clearance available which, given the low strength of the formation, made any swab and surge effect potentially dangerous for the integrity of the test hole.

Deployment a civil engineering tool in an oilfield situation:

Because of the dissimilarities between the operational situations in geotechnical and oilfield engineering, a number of technical issues have had to be solved to achieve the test objectives. More important, the drilling crew and dilatometer

personnel showed much reciprocal curiosity and provided a great deal of mutual support, which resulted in a seamless operation.

Analytical aspects

The key conclusion of the analysis of the results of the dilatometer data is that the tested sands exhibit some degree of over-consolidation. The major consequence of that over-consolidation could be that plastic compaction of the reservoir may only occur after a significant amount of depletion.

It must be noted that the actual value of the plastic compressibility could not be determined. The reason for that is that, at the interpreted degree of over-consolidation, the results of the dilatometer are insensitive to the compressibility of the formation.

The conclusion about the occurrence of an over-consolidation is corroborated by the findings of another on-going, independent study on the compaction of the filed shales. However, that later study does not allow yet to confirm the degree of over-consolidation obtained here.

A number of recommendations can be formulated in the light of our current experience with the interpretation of dilatometer tests for *in-situ* measurement of formation compressibility in low strength reservoir rocks:

- The time dependant behavior of the formation sands should be taken into account in the inversion methodology. Note that this may impact the operational procedure.
- The model used to invert the dilatometer test data assumes homogeneous mechanical properties over the domain of investigation of the dilatometer, thus disregards the possible impact of a thick, compressible filter cake as well as that of a locally damaged formation (e.g. during the drilling or dilatometer operations).

Finally, the operation presented here has been performed in a 'logistically simple' situation (onshore, shallow well). Would such an endeavor be envisaged in more 'demanding' environments involving weakly cemented reservoir rocks (typically deep off-shore), a significant engineering effort in the dilatometer equipment ought to be considered.

Acknowledgement

The authors would like to acknowledge permission to publish the paper from Total and SINCOR management. The help and enthusiasm of the many people involved in this project has been a key element in the successful achievement of this operation.

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SI Metric Conversion Factors

ft	x 3.048*	E-01 = m
in.	x 2.54*	E+00 = cm
psi	x 6.894	E-03 = MPa

*Conversion factor is exact.

Nomenclature

E	Young Modulus (MPa)
G	Shear Modulus (MPa)
M	Slope of the critical state line
OCR	Over-Consolidation Ratio
P'_{c0}	Effective consolidation Pressure (MPa)
R_0	Initial wellbore radius (m)
u	Borehole wall displacement (m)
κ	Elastic Compressibility (-)
ν	Poisson ratio (-)
λ	Plastic compressibility (-)