Mechanical earth modeling and sand onset production prediction for Well X in Malay Basin

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Abstract

This study is aimed at testing Mechanical earth modeling (MEM) and Sand onset production prediction (SOP) models using well log and core data to estimate the mechanical properties of the rock, in-situ stresses and the critical conditions at which the rock failure may occur. New numerical models were developed to predict the onset of sand production for Well X. The outputs from MEM were coupled with the Mohr Coulomb failure criterion to calculate the critical wellbore pressure of the well and consequently the depth of the rock at which failure may occur. The results showed that at depth of 1061.68–1098.10 m, the calculated critical wellbore pressures were negatives, which reveal low possibility of sand production. However, at a depth of 1098.25–2230.89 m, the calculated critical wellbore pressures were positives. In this depth range, there was high possibility of rock failure. In conclusion, based on the findings, Well X may produce sand at depth deeper than 1100 m. Therefore, mitigation and preventive actions should be planned for Well X to handle and manage the possible sand production from the identified interval.

Keywords Mechanical earth modeling · Sand onset production · Critical wellbore pressure

Introduction

Sand production constitutes a major problem in oil and gas industry. According to Tabrizy and Mirzaahmadian (Tabrizy and Mirzaahmadian 2012), the sand may be produced due to the following conditions: (1) The loss of mechanical integrity of the rocks surrounding an open hole or perforation (failure), (2) separation of the solid particles from the rocks due to hydrodynamic flow (post-failure) and (3) transportation of the particles to surface by the reservoir fluids. The production of sand if not controlled with care will pose some disadvantages, such as erosion to down-hole and surface facilities, and fine migration to oil and gas wells (Fjar et al. 2008). For sand control to be implemented, normally it will need heavy investment from the operators. Thus, option to

estimate either sand control is needed before production or after some time of sand-free production has attracted great interest of the operators (Tabrizy and Mirzaahmadian 2012).

For sand control decision-making, the critical wellbore pressure and depth at which the rock failure may occurs need to be predicted. There are numerous numerical and analytical Sanding Onset Prediction (SOP) models published in the literature. Most of the published models are in need of more than one rock mechanical properties as the input parameters (Yi 2004). Thus, for the mechanical properties to be determined, MEM will be required (Fattahpour et al. 2012). By developing MEM model, the mechanical properties, such as elastic constants (Young's Modulus and Poisson's Ratio), formation strength (UCS), and in-situ stresses (S_v , SH_{max} and SH_{min}) can be estimated.

Early identification of field sanding propensity plays an essential help to select an appropriate sand management solution to assist in future development decisions. Sand issue if not managed and handled properly, it may cost the oil and gas industry billions of dollars every year. The geo-mechanical behavior of the reservoir, hence, needs to be investigated in order to minimize the risk and to maximize the reservoir productivity.

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Thus, to identify all the parameters to forecast any potential sand problems in the wells, this study covers two methods which are MEM and SOP. For MEM, it covers the estimation and determination of the rock mechanical properties and in-situ stresses. The calculated parameters from the MEM will then be applied as an input for SOP, which is to predict the critical conditions that the rock failure may occur, and sand migration is initiated. The well data, used in this study, was taken from area near the Malay Basin. Due to confidential issue, the name of the well cannot be exposed, and it will be represented as Well X. In general, the Malay Basin is located in the South China Sea offshore of West Malaysia, within the 1st order Sunda Block region of the north central region. The basin formed in partly due to tectonic collisions and strike-slip shear of the continental slabs of Southeast Asia, when the Indian Plate collided into Eurasia, and subsequent extrusion of lithospheric blocks to Indochina. The earliest rift margins of the Sunda Block were represented by the rift valleys of Palaeogene W–E, which formed the region's sinistral shear during NW–SE. Later Eocene NW–SE dextral shear of 2nd order Indochina Block rifted toward East Malaya Block opening a 3rd order Malay Basin.

Methodology

Mechanical earth modeling

MEM is a complete description of 1D state of in-situ stresses, rock mechanical properties (strength and deformation parameters, densities, etc.) and pore pressure for a continuous profile indexed to true vertical depth, TVD (Goodman and Connolly 2007). MEM is a collection of data measurements and models describing the mechanical properties of rocks and fractures, stresses, pressures and temperatures that operate on them at depth. Each MEM data point is referenced to its spatial co-ordinates and collection time. It has been acknowledged nowadays that dynamic elastic constants information with static equivalents, formation strength, and stresses prediction are critical to construct MEM. To provide a good mechanical earth model, all available data and indications of rock strength, deformity, pore pressure and in-situ stresses need to be integrated and analyzed thoroughly. Then this MEM will be calibrated as example for dynamic rock mechanical data with static test data using available core data measurements in order to arrive an internally consistent representation of the key geo-mechanical properties (Fattahpour et al. 2012). The results obtained can be applied for engineering designs and subsequent analysis, as in this study, it will be used for sand onset production prediction analysis. The following steps were taken to develop a MEM model:

1. Use of an available data to estimate relevant geo-mechanical parameters with depth.
2. Correlation of depth-corrected test data with multi-pole-array sonic logging and other high-quality digital logs to ensure correspondence with precise depths.
3. Development of a 1D model of the rock mechanical properties along the axis of the well by using correlative relationship between log data and laboratory data.
4. Building a principal stress (magnitudes and directions) and in-situ pressure profile through the studied well.

Logging data availability

The availability of logging data from Well X is checked. The data are in the Las.files format and it has been transferred and tabulated into Ms. Excel. Listed below are the available parameters extracted from the Well X logging data.

- Measured depth
- Bulk density
- Compressional sonic wave
- Gamma ray
- Neutron porosity
- Deep resistivity

Compressional and shear sonic wave

Compressional wave is the particles' motion in the direction of wave propagation; the motion is back and forth parallel to the direction of the wave in motion. It is also called 'longitudinal waves.' Shear wave is the particle motion normal to wave propagation; the motion is up and down and perpendicular to the direction of the wave in motion. It is also known as 'transverse wave. In some cases, shear sonic wave data is missing. In this situation, it needs to be estimated by using empirical equations. The compressional sonic wave is one of the essential parameters to determine the dynamic elastic constant. There are 3 well know empirical methods:

(a) Castagna equation is:

$$V_s = -0.05509V_p^2 + 1.0168V_p - 1.0305 \quad (1)$$

(b) Brocher equation is:

$$V_s = 0.7858 - 1.2344V_p + 0.7949V_p^2 - 0.1238V_p^3 + 0.006V_p^4 \quad (2)$$

(c) Carroll equation is:

$$V_s = 1.09913326 \times V_p^{0.9238115336} \quad (3)$$

Where, V_s and V_p are shear wave and compressional wave velocities with units km/s.

Dynamic elastic constant

Young's Modulus is the ratio of uniaxial compressive (tensile) stress to the resultant strain. It is the measure of the stiffness of the material. The larger is the modulus, stiffer will be the material. According to Tabrizy and Mirzaahmadian (Tabrizy and Mirzaahmadian 2012), in order to obtain the Young's Modulus (E), Shear Modulus (G) need to be determined first, as it will be one of the input parameters for the calculation of Young Modulus (E):

$$G = V_s^2 \rho_s \quad (4a)$$

where, G is shear modulus, V_s is shear wave velocity and ρ_s is the solid density. In terms of shear wave travel time Δt_s , shear modulus can be written as:

$$G = \frac{\rho_b}{\Delta t_s^2} \times a \quad (4b)$$

where, ρ_b is the bulk density and a is a constant which is 1.34×10^{10} . The shear modulus is used to determine the Young's Modulus (E) for dense sand as:

$$E = 2G(1 + \vartheta) \quad (5)$$

In this equation, ϑ is the Poisson's ratio. It is defined as a ratio of expansion in one direction of a rock or a measure of the geometric change of shape under uniaxial stress. Poisson's ratio values are ranged from 0 to 0.5. Zero (0) Poisson's ratio indicates that the material is compressed to the extent from where it would not undergo anymore expansion (cork is an example of such cases). For fluids, the value of Poisson's ratio is 0.5. Higher is the Poisson's ratio, higher would be the tendency for the material to compress or expand. The Poisson's ratio for dense sand can be expressed as:

$$\vartheta = \frac{\frac{1}{2} \left(\frac{\Delta t_s}{\Delta t_c} \right)^2 - 1}{\left(\frac{\Delta t_s}{\Delta t_c} \right)^2 - 1} \quad (6)$$

where, Δt_s and Δt_c are shear wave and compressional wave travel times, respectively.

Calibrating dynamic to static elastic constants and formation strength

The mechanical properties of rocks derived from logging data are called dynamic elastic constants. The obtained dynamic elastic constants are converted to static elastic constants for further rock strength calculations and calibrations.

Correlations to convert from dynamic to static Young's Modulus (E) have already been developed (Zhang 2011). For sandstone lithology, a constant coefficient of 0.382 is multiplied with the dynamic Young's Modulus while for shale lithology, a constant coefficient of 0.076 is multiplied with the compressional wave velocity (Zhang 2011).

Unconfined compressive strength (UCS) is an index measure of formation strength. It denotes maximum compressive stress, which a material can sustain when unconfined. The condition of rock fails in compression occurs when the magnitude of compressive stress is greater than compressive strength. Numerous relations have been proposed that relate rock strength to parameters measurable with geophysical logs like elastic constants and other parameters such as bulk density, compressional slowness (us/ft.), shear slowness (us/ft.), and compressional velocity. Based on Tabrizy and Mirzaahmadian (Tabrizy and Mirzaahmadian 2012), for sedimentary rocks the correlation applied for UCS calculation is as follow:

$$UCS = 0.008EV_c + 0.0045E(1 - V_c) \quad (7)$$

where, V_c is the compressive wave velocity and E is the Young's Modulus.

Sand onset production prediction (SOP)

The rock mechanical properties and dynamic elastic constants derived in MEM were imported as the input to predict the onset of sand production. Several assumptions were made in conducting the prediction, for example, the sandstone formation was assumed linear poro-elastic, homogeneous reservoir and the fluid-flow induced forces, which result from production, were not considered. The steps to forecast the depth of sand production are listed below:

1. Import of rock mechanics parameters from the MEM (formation strength and in-situ stresses).
2. Application of rock failure criterion in sand strength analysis.
3. Calculation of critical wellbore pressure along the depth for Well X.
4. Determination of onset of sand production by observing the value of critical wellbore pressure. Negative value means that the rock failure is not probable to happen, whereas positive values indicate that the sand production problem may occur within the interval.

Stress analysis and critical wellbore pressure

With all the calculated elastic properties, pore pressure and overburden pressure in MEM, the stresses within the

formation and around the wellbore can be estimated. The element of the formation is considered rectangular. Equations for triaxial stresses acting on the formation are as follows:

$$\sigma_x = mP_o + \alpha P_p(1 - m) \quad (8)$$

$$\sigma_y = mP_o + \alpha P_p(1 - m) \quad (9)$$

where,

$$m = \frac{\vartheta}{1 - \vartheta} \quad (10)$$

$$\sigma_z = P_o \quad (11)$$

In these equations, σ_x , σ_y , σ_z are three components of stress, P_o is overburden pressure, P_p is pore pressure, α is a constant, ϑ Poisson's ratio.

Critical wellbore pressure is the maximum wellbore pressure in which the production of hydrocarbon can be continued without sand production. For critical wellbore pressure, the shear strength (τ_i) of intact rock is required which calculated as:

$$\tau_i = \frac{0.025UCS}{10^6 C_B} \quad (12)$$

Using this equation, the critical wellbore pressure can be determined as:

$$P_c = \frac{1.5\sigma_x - 0.5\sigma_y - 0.5\alpha P_p \left(\frac{1-2\mu}{1-\mu} \right) - 1.732\tau_i}{1 - 0.5\alpha \left(\frac{1-2\mu}{1-\mu} \right)} \quad (13)$$

From Eq. (13), the critical wellbore pressure along the depth for Well X was determined.

Results and discussion

Estimation of shear sonic wave using compressional sonic wave

Due to the unavailability of sonic shear wave from the data, the above discussed methods were applied to obtain the shear sonic wave data, as summarized in Table 1. The Brocher equation was utilized in this study in consonance with Maleki et al. (Maleki et al. 2014). This equation is valid for compressional sonic wave (V_p) between 1.5 and 8.5 km/s in the presented work, the compressional sonic wave (V_p) of Well X remained between 2.15 and 5.87 km/s.

Table 1 Shear sonic wave estimation

Depth (m)	Compressional wave (us/ft)	Shear wave (us/ft)		
		Castagna	Brocher	Carroll
1061.6764	62.8349	− 0.9858706	113.156505	64.4765340
1061.8288	62.8349	− 0.9858706	113.156505	64.4765340
1061.9812	62.8349	− 0.9858706	113.156505	64.4765340
↓	↓	↓	↓	↓
1650.8548	106.126	− 0.9795049	239.478729	104.635840
1651.0072	102.974	− 0.9797861	226.369675	101.761589
1651.1596	99.1612	− 0.9801503	211.356655	98.2757761
1651.312	95.399	− 0.9805385	197.437067	94.8261986
1651.4644	95.4646	− 0.9805315	197.672239	94.8864352
↓	↓	↓	↓	↓
2230.5844	79.8183	− 0.9825405	149.007412	80.4242704
2230.7368	79.8183	− 0.9825405	149.007412	80.4242704
2230.8892	79.8183	− 0.9825405	149.007412	80.4242704

Formation strength identification

Calculated Young's Modulus, Poisson's Ratio and Unconfined Compressive Strength (UCS) obtained using analytical equations are presented in Fig. 1. The red square dots are the measured data from the core measurement. It is observed that the measured Young's Modulus, Poisson's Ratio and UCS from core measurement match properly with the empirical equation applied for each parameter. Thus, there is no need to apply calibration factor in this case.

It can be observed from Fig. 1 that at depth between 1060 and 1100 m, Young's Modulus is high, which indicates the rock formation within this depth range is stiff. As it goes deeper along the depth, Young's Modulus decreases and fluctuates at some points. The calculated Young's Modulus from the logging data is a dynamic modulus; it needs to be calibrated to obtain the static modulus to match with the available core measurement data. The Poisson's ratio at depth of 1060 m to 1100 m was observed at low value, which is in the range of 0.28–0.30. Greater the value of Poisson's ratio, higher will be the tendency for the material to compress or expand when force is applied. Low Poisson's ratio indicates the material is stiffer.

Unconfined compressive strength (UCS) for Well X in the depth of 1060 m to 1100 m was observed high, which indicates that the formation strength was greater in this depth range. Condition of rock fails in compression occurs when the magnitude of compressive stress is greater than the compressive strength. When it goes deeper, the strength decreases, which means high possibility for the rock formation strength to fail.

Fig. 1 Elastic constants and rock strength along the depth of Well X

Fig. 2 Critical wellbore pressure along depth of well

Critical wellbore pressure determination

The calculated critical wellbore pressure versus depth is plotted in Fig. 2. According to Tabrizy and Mirzaahmadian

(Tabrizy and Mirzaahmadian 2012), it can be analyzed that if the critical wellbore pressures fall at negative region; the rock failure is not probable to happen, whereas if the critical wellbore pressure is positive, it indicates the possibility of sand production may occur within the interval.

It is observed that at depth of 1061.68–1098.10 m, critical wellbore pressures are negative, which reveal low possibility of sand production while at depth of 1098.25 m of 2230.89 m, the critical wellbore pressure is positive showing the sand onset condition has been met (Maleki et al. 2014; Chang et al. 2006).

Conclusions

From this study, it is observed that these newly developed models; Mechanical earth model and Sand onset production prediction could be used as tools to identify sanding problems in wells. It is identified that rock failure and sand production could be predicted from evaluation of petrophysical data and various analytical techniques published in the literature. The calculated critical wellbore pressure for Well X in the depth range of 1061.68–1098.10 m exhibited negative values which means the rock failure is not probable to happen for this range. However, for the depth range of 1098.25–2230.89 m, the values start to fall in positive region indicating high possibility for the rock to fail. It is concluded that the Well X may produce sand at depth deeper than 1098.25 m. With this information, the mitigation action can be considered and planned to prepare with any suitable sand control method from the identified depth.

To reduce uncertainty in the results, it is recommended to run the shear velocity log during the wire-line logging even though extra cost might be needed, but the data provided is valuable for better estimation of dynamic elastic constants. Future work suggestion for continuation of this study is to predict the volumetric sand production using the same or modified models.

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References

- Chang C, Zoback MD, Khaksar A (2006) Empirical relations between rock strength and physical properties in sedimentary rocks. *J Pet Sci Eng* 51(3):223–237
- Fattahpour V, Pirayehgar A, Dusseault M, Mehrgini B (2012) “Building a mechanical earth model: a reservoir in southwest Iran”. 46th US Rock Mechanics/Geomechanics Symposium, USA
- Fjar E, Holt RM, Horsrud P (2008) *Petroleum related rock mechanics*. Elsevier Sci. Technol, United Kingdom
- Goodman HE, Connolly P (2007) Reconciling subsurface uncertainty with the appropriate well design using the mechanical Earth model (MEM) approach. *Lead Edge* 26(5):585–588
- Maleki S, Moradzadeh A, Riabi RG, Gholami R, Sadeghzadeh F (2014) Prediction of shear wave velocity using empirical correlations and artificial intelligence methods. *NRIAG J Astron Geophys* 3(1):70–81
- Tabrizi VA, Mirzaahmadian Y (2012) Investigation of sand production onset: a new approach based on petrophysical logs. *SPE International Symposium and Exhibition on Formation Damage Control*, Lafayette
- Yi X (2004) Numerical and analytical modeling of sanding onset prediction. Texas A & M University, College Station
- Zhang J (2011) Pore pressure prediction from well logs: Methods, modifications, and new approaches. *Earth-Sci Rev* 108(1):50–63

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