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Modeling Erosion Control in Oil Production Wells

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***Abstract*—**The sand production problem has led researchers into making various attempts to understand the phenomenon. The generally accepted concept is that the occurrence of sanding is due to the in-situ stress conditions and the induced changes in stress that results in the failure of the reservoir sandstone during hydrocarbon production from wellbores. By using a hypothetical cased (perforated) well, an approach to the problem is presented here by using Finite Element numerical modelling techniques. In addition to the examination of the erosion problem, the influence of certain key parameters is studied in order to ascertain their effect on the failure and subsequent erosion process. The major variables investigated include: drawdown, perforation depth, and the erosion criterion. Also included is the determination of the optimal mud pressure for given operational and reservoir conditions. The improved understanding between parameters enables the choice of optimal values to minimize sanding during oil production.

Keywords— Equivalent Plastic Strain, Erosion, Hydrocarbon Production.

I. Introduction

SAND production is a problem frequently encountered during the production process because approximately seventy percent of the total world's hydrocarbons reserves are found in reservoirs [1] with a high propensity of producing sand during the life span of oil production. The process of sanding occur due to in-situ stress conditions and induced changes in stress that result in the failure of the reservoir sandstone during hydrocarbon production from wellbore. It is a source of significant difficulty during hydrocarbon production. The inflow of sand into wellbores poses numerous problems. Some of which are the erosion of surface facilities such as valves and pipelines, plugging of the production liner and sand deposits in the separators [2] leading to an increase wear of equipments, devaluing of the well integrity which may culminate in wellbore failure, loss of production time, and added cost for disposal, etc.

The phenomenon of sand production can be broken into three processes. First, tensile or compressive failure within the vicinity of the perforation or open-hole and its progression further into the formation; secondly, the dislodgment of the sand particles from the failed section of the formation; and thirdly, the movement of those particles into the wellbore and then to the surface if settlement does not occur [3]. Morita and Boyd [4], divides sand production into two processes involving the concentration of stresses built up near the wellbore as a result of drilling activities, reservoir pressure depletion, and drawdown which causes mechanical degradation and possible disintegration of the rock; and the erosion or removal of the disaggregated material [5]. The mechanisms affecting sand production are presented in [6]. These are: Seepage, depletion, erosion, water-cut, and material weakening.

Sand production has been studied by using various techniques which include: Analytical methods; Numerical methods; Experimental methods; and combined Experimental and Numerical methods. Analytical methods were used by Risnes, Bratli et al [7] to study the influence of Poisson's ratio, fluid flow, permeability, rock compressibility, and rock strength. It was found that although Poisson's ratio and rock compressibility have little influence on the size of plastic zone, the pore pressure and inherent rock strength/cohesive strength have inverse effects. Using numerical methods, Nouri [6] demonstrated the effects of reservoir pressure, Modulus of elasticity, friction angle, and cohesion on the critical bottom hole pressure (CBHP). Experimental procedures were used to ascertain the influence of flow rate, confining pressure, and fluid viscosity [8]. It was observed that while increases in flow rates increases sanding rates, the confining pressure has an inverse effect. Also, for constant a constant flow rate and confining pressure, the rate of sanding increases with viscosity. Studies of the effect of flow geometry on sand production have been carried out by Unander, et al. [9] through comparing the influence between two contrasting types of flows. Han et al. [10] also observed that even in non water-sensitive formations, water production could greatly affect the sanding process through mechanisms such as pore pressure changes, capillarity, relative fluid permeability, etc. Multiphase flow behaviour is also altered through changes in the relative permeability [11].

The size, frequency, and orientation of perforations are also contributing factors in sanding phenomena. Small diameter and long perforations provide better potential for arching especially where the particle to perforation size ratio is within the favourable range [12].

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II. Model Description

In the work presented here, FEM (Finite Element Method) numerical modelling was carried out to provide a parametric study on the sand production problem using the code, ABAQUS 6.8-1. Cased wells consisting of two components; the main wellbore and a series of perforation tunnels created perpendicularly and equi-distanced vertically and azimuthally were modelled in three dimensions. The model domain constructed comprise of a quarter section of the entire domain due to symmetry, including only one perforation which is adequate for such geometry since the perforations are assume to be spaced at right angles from each other. Typical perforation dimensions, especially the depth may reach an upper range of above 2m, and its actual depth is influenced by several factors including [13]: initial speed of the discharged explosives, effective surface area, casing strength, cement strength, and type of formation.. The failure behaviour of the rock (sandstone) material was described using a linear Drucker-Prager model with hardening, and the casing regarded as linearly elastic. Contrary to models adopted by some other researchers, the onset of sanding is defined by a distinct criterion delineated from the more general failure criterion that describes the rock behaviour.

Although some erosion prediction models attempt to synchronize the initial shear or compressive failure of the rock material with initiation of sanding, this assumption has been established as overly conservative. Two criteria are hence adopted in this model. A material failure criterion effectively described by the Drucker-Prager model, and a sanding criterion given in an eroded solid mass generation equation formulated by Papamichos and Stavropoulou [14], presented thus:

$$\frac{\dot{m}}{\rho_s} = \lambda(1-\varphi)c\sqrt{q_i q_i} \qquad (1)$$

Where, $\dot{m}$ is the rate of solid mass eroded, ρ_s is the solids density, λ denotes the sand production coefficient, φ is the porosity, c is concentration of fluidized solids transported, and q_i is the fluid flux. The left-hand term of the equation, $\frac{\dot{m}}{\rho_s}$ is denoted as the erosion velocity, V_e, and the term $\sqrt{q_i q_i}$ given as the pore fluid velocity. As shown by experiments, initiation of sanding occurs when a critical external stress value is exceeded; which is incorporated in equation 2 making the sand production coefficient, $\boldsymbol{\lambda}$ dependent on the plastic shear strain, $\boldsymbol{\gamma}^p$. [14, 15]. This implies that erosion can only take place in the rock material when its maximum strength is surpassed and the failure regime is in the plastic softening stage.

The Model analysis was completed in five steps, described as follows: The Geostatic step; within which the initial geostatic stress field was defined and equilibrium established in order to represent a steady-state equilibrium form of an undisturbed rock material subjected to geostatic loading. The drilling step; where the wellbore and perforation tunnel were removed by a contact deactivation procedure. The first Steady-State Soil Analysis; where new boundary conditions were set to apply pore pressure on the perforation tunnel face. The second Steady-State Soil Analysis; where drawdown was instigated by reducing both the pore pressure at the perforation face (changing the boundary condition), and the applied pressure (mud pressure) on the same face. The Soil Consolidation Analysis; where erosion was simulated at a constant drawdown pressure using 'Adaptive Meshing'.

TABLE I
GEOMETRIC DIMENSIONS

Description	Dimension
Domain diameter	10m
Wellbore diameter	0.15m
Perforation tunnel diameter	0.043m
Perforation tunnel length	0.51m

III. Results And Discussion

Based on the modelling results, examination of the influence of certain key parameters was conducted to ascertain their effect on the failure and subsequent erosion of the material. These include: drawdown, depth of wellbore (perforation depth), and erosion criterion. Also included is the determination of the optimal mud pressure for a given operational and reservoir condition.

A. Effect of Wellbore Dept

Sand production: The region considered with respect to the depth of wellbore is subject to the location of the perforation tunnel, and is given by the magnitude of the vertically downward pressure. The results show obviously that sand production increases with depth. The graphical plots are shown below:

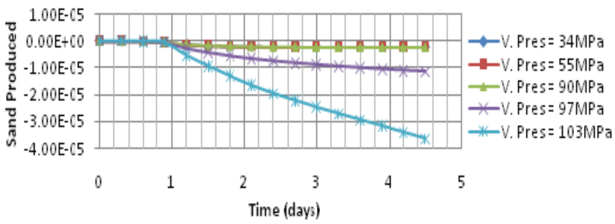

Fig. 1 Sand production with increasing vertical pressure

Pore Fluid Velocity: High fluid velocities are noticed at the wellbore/perforation region which tend to decrease at increasing depth as revealed in figure 2 The reason for the sudden increment in interstitial velocities around the wellbore is amongst other factors attributed to the pore pressure distribution and changes in drawdown conditions, which will be discussed further later in this section.

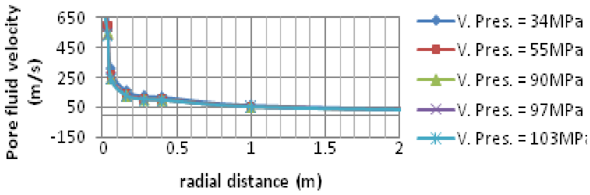

Fig. 2 Pore fluid velocity variation at varying vertical pressures

B. Effect of Drawdown

Sand production: Figure 3 shows the cumulative sand production with time at various drawdown conditions. Sand production increases with drawdown, and a drastic increase in eroded sand noticed when a constant drawdown of 10.3Mpa is applied.

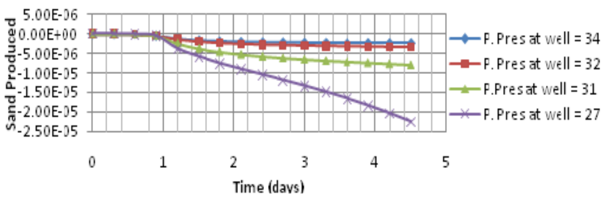

Fig. 3 Sand production with increasing constant drawdown

Plastic Strain: Changes in drawdown also indicate an increase in the plastic strain with rising drawdown. This is particularly pronounced within the vicinity of the perforation tunnel, extending outward to a region of almost 1.5m before tapering off to zero. The equivalent plastic strain $\bar{\varepsilon}^p$ is a scalar variable that is used to indicate inelastic deformation and yield. A value of plastic strain, $\bar{\varepsilon}^p$ greater than zero indicates material yield, and its magnitude shows the extent of plastic deformation. Figures 4a - 4b show an obvious increase in $\bar{\varepsilon}^p$ as drawdown is increased form 3.72Mpa to 10.34Mpa.

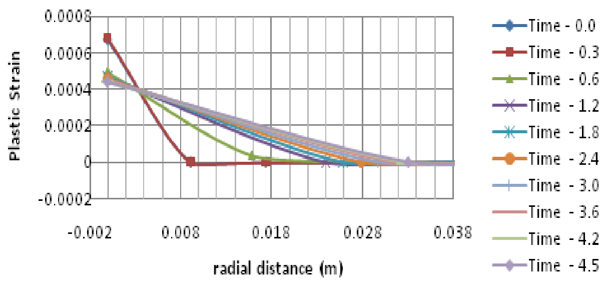

Fig. 4a Variation in plastic strain with time (DD=3.72MPa)

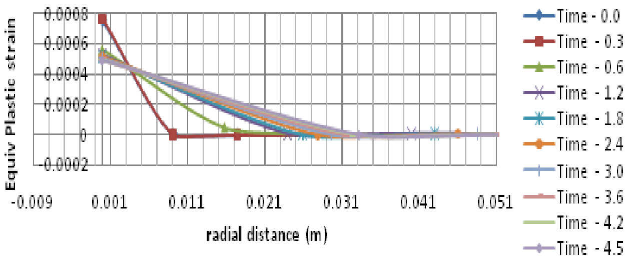

Fig. 4b Variation in plastic strain with time (DD = 6.89MPa)

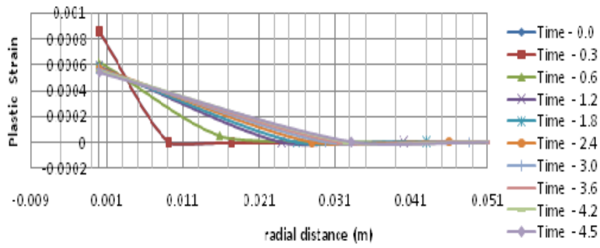

Fig. 4c Variation in plastic strain with time (DD=10.3MPa)

The sanding process is self-driven. The eroded area which is initiated at the vicinity of the wellbore and perforation tunnel enlarges due to the erosion process. This weakens the material causing a redistribution of stress to more intact areas situated further away from the wellbore, thereby increasing its susceptibility to erosion. The extent of erosion therefore reduces as it progresses away from the wellbore vicinity; the maximum magnitude being at the perforation and wellbore.

Pore Fluid Velocity: Drawdown was instigated by changing the pore pressure boundary conditions at the perforation region. This causes pore pressure gradients which are larger within close range of the wellbore. The larger pressure gradients results in considerable increases in the pore fluid velocity at the wellbore region. Figure 5 shows that apart from an obvious rise at the near borehole region, pore fluid velocity also increases generally with drawdown. It distinctly shows that higher velocities of the pore fluid occur at the immediate surroundings of the perforation tunnel, which is further emphasized in figures 6a and 6b. It was also noticed that for a constant drawdown of 3.72Mpa the pore fluid velocity was about 1m/s, increasing to 5.6m/s when the drawdown was increased to 10.34Mpa.

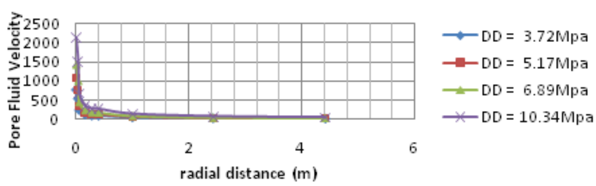

Fig. 5 Pore fluid vel. variation at different drawdown conditions

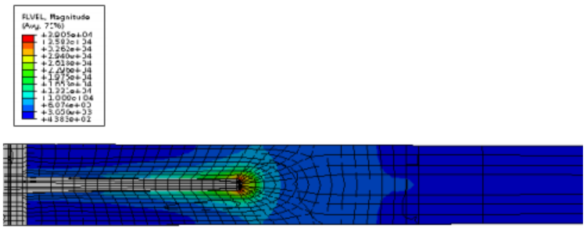

Fig. 6a Plot displaying higher pore fluid velocities at perf. tunnel dd =3.72MPa

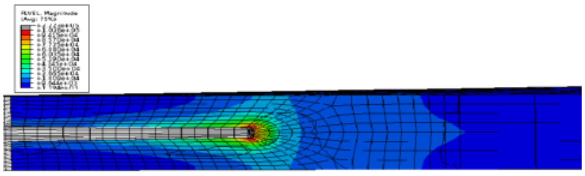

Fig. 6b Plot displaying higher pore fluid velocities at perf. tunnel, dd= 10.34MPa

The minimum distance from the perforation tip after which there is zero equivalent plastic strain for a constant drawdown of 3.72Mpa shows an apparent flattening at the top; indication that after 1.2 days plastic strains do not spread much further. In figure 7 a comparison is made at various drawdown conditions. The results are quite intriguing, displaying a progressively increase in the outer radial regions that are plastic strained, with decreasing constant drawdown, which indicates an increase of the plastic zone with decreasing drawdown. Interestingly, this is somewhat inconsistent with literatures which state that the stress/strains conditions around wells causes the development of plastic regions at the near wellbore vicinity and plastic regions at a further radius away from the wellbore; the extent of the plastic radius being a function of the prevailing stress/ strain conditions, amongst other factors. A similar pattern was observed when the vertical pressure was varied, as shown in figure 7b.

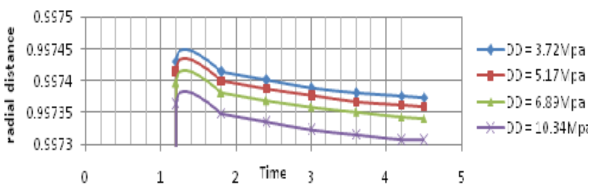

Fig.7a Minimum distance of zero strain values at different drawdowns

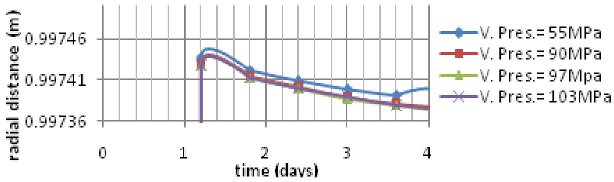

Fig. 7b Min. dist. of zero strains at different vertical pressures

C. Erosion Criteria

As stated earlier, the equivalent plastic strain parameter is adopted as the criterion guiding the onset of erosion, whereby ablation of the material will occur if and only if the equivalent plastic strain, $\bar{\varepsilon}^p$ value exceeds a cut-off value above zero. Above this, the material is assumed to have yielded and the actual sanding process signified by the detachment of rock particles can only take place if $\bar{\varepsilon}^p$ reaches or exceeds a predetermined value referred hereafter as the 'erosion or sanding criterion' or 'cut-off equivalent plastic strain'. For the preliminary study, values for $\bar{\varepsilon}^p$ were chosen arbitrary so as to enable a more pronounced evidence of erosion. Varying the criterion values indicated an inverse relationship with lower values resulting in greater sand production. Thus, in figure 8 significant changes occurs when the cut-off is reduced to 0.01. The importance of determining an accurate and more realistic criterion value is not underplayed here, however that will be subject to future work as it invariably entails laboratory experimentation.

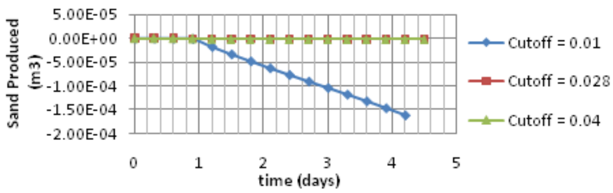

Fig. 8 Sanding at varying criteria

Influence of Pressure Applied to Wellbore/Perforation face: The efficacy of the pressure applied to the wellbore/perforation face on the erosion process was tested by conducted numerous simulation runs with varied pressures, all other conditions remaining the same. The applied pressures are considered representative of the well operation Mud Pressure normally applied to maintain the integrity of the wellbore during drilling and production phases. The values used were arbitrary selected and the outcome as represented in figure 9 displays a drastic reduction in the quantity of sand eroded with increasing mud pressure. Nevertheless, a closer observation indicates a relatively less significant effect after the mud pressure is increased above 37.2Mpa. Above this value the amount of pressure applied seems to have very little effect, leading to the conclusion that the optimal mud pressure under the prevailing well operation condition is about 37.2Mpa. Beyond this value negligible reductions are observed.

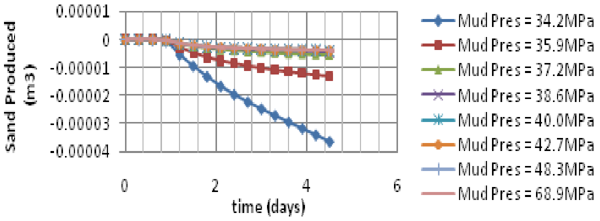

Fig. 9 Effect of mud pressure on sanding

IV. Conclusion

An extension of parametric studies was conducted in this paper by examining the influence of certain reservoir formation and production parameters on the failure and subsequent erosion of the formation material using the FEM modelling technique. The major factors considered include: drawdown, wellbore/perforation depth, and erosion criterion; in addition to determining the optimal mud pressure. Variations in wellbore depth indicated an increase in sand production with wellbore/perforation depth, and a corresponding decrease in value of high fluid flow velocities typically observed at the wellbore/perforation zone. Changes in constant drawdown conditions showed an increase in sand production with drawdown, especially at the drawdown pressure of 10.34MPa. An increase in plastic strains was also noticed with increasing drawdown.

Measurement of the minimum distances from the perforation base after which there were no plastic strains showed that after the initiation, the rate of increase of the plastic zone reduced significantly. Also noticed was a progressively increase of the plastic region with decreasing constant drawdown. The same effect was observed when the wellbore/perforation depth was reduced. The magnitude of pressure applied on the wellbore/perforation face, which represents the applied mud pressure showed a significant reduction in the severity of sand production with an optimal value occurring when the mud pressure was increased to 37.2MPa. Above this value negligible changes were observed.

The results obtained so far show trends which are in line with the observed sanding phenomenon, some of which have been confirmed with findings of past studies. However, since hypothetical values were used, the future work will entail the adoption of actual parameter values in order to adequately represent field conditions quantitatively.

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