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THEORETICAL BASIS FOR SLURRY COMPUTATION AND COMPOUNDING IN HIGHLY DEVIATED WELLS CEMENTING

I. J. Imorame[a], **O.A. Olafuyi**[b], **E.S. Adewole**[c]

Petroleum Engineering Department, University of Benin, Benin City, Nigeria.
Emails: [a]imorameij@hotmail.com; [b]abdulkashif@yahoo.com; [c]steveadewole@yahoo.co.uk

Abstract

Highly deviated oil and gas wellbores offer higher recovery and productivities than vertical wells. But achieving cement slurry stability and accurate volume in vertical wells is not as critical as in deviated wells chiefly because of the large overburden pressure resting on the slurry in deviated wells, among other reasons. Good slurry performance would require the use of appropriately calculated slurry volume and cement materials and additives that can optimize simultaneously the placement and mechanical properties of set cement. In most cases today, slurry volumes in deviated wells are based on rule-of-thumb and utilization of local enlargement factors. In this case, successful job is judged based on slurry returns obtained at the surface. Furthermore, slurry strength is compromised due to excessive overburden and massive casing weight acting at an angle. It is therefore necessary to search for a more appropriate slurry recipe to mitigate slurry failure due to excessive overburden pressure, casing weight and inadequate slurry volume. This paper presents a to derivation of accurate area and volume ratio equations based on well deviation to calculate appropriate slurry volumes and suggests an idealized slurry systems in deviated sections of the well based on point masses to explore an appropriate slurry recipe to achieve high slurry integrity. Results show that angle of deviation is very critical to correct cement slurry volume computation for deviated wells. There is a non-linear relationship between cross-sectional area, volume ratio and angle of deviation. As the angle tends to 900, the volume of slurry required increases compared to an equivalent volume required for an equivalent true vertical depth of a vertical well. Furthermore, particle point mass analysis shows that unequal cement particle size distribution would help to create slurry stability through reduction in interstitial water required thus sustain slurry integrity.

Keywords: slurry volume, particle redistribution, deviated well, directional drilling, drilling mud

1. Introduction

Highly deviated wells have a directional axis near or approximately 90o to the vertical. They include the extended reach, horizontal and multilateral wells. This geometrical wonder in well construction was invented so as to exposure. However, guaranteed high level of production performance of these wells hinges on long-term zonal isolation, where zonal isolation is required with cement. In addition, the integrity of a cement job can determine how long a well remains stable and productive without requiring repair. Therefore high quality cement slurry is an essential ingredient in any successful well.

Under static equilibrium, free water occurrence and sedimentation tendencies in slurries exist at varying degrees along the directional bore length. Efforts at mitigating these tendencies sometimes adversely affect slurry flow and mechanical properties such as compressive strength, porosity and permeability.

In face of the challenge, there were suggested methods (empirical and particle) in literature, for optimizing slurry designs. Goltermann et al [1] highlighted several physical approaches to optimizing slurry systems. He recognized two models, that for smaller particles and that for larger particles. Both models, based on monodispersion or characterizing system with single diameter, considered two classes of aggregates (fine and coarse) consisting of perfect spheres of a uniform diameter. These models optimize the packing of the aggregates only and assume the cement will occupy the voids between the aggregates. Empirical meth-

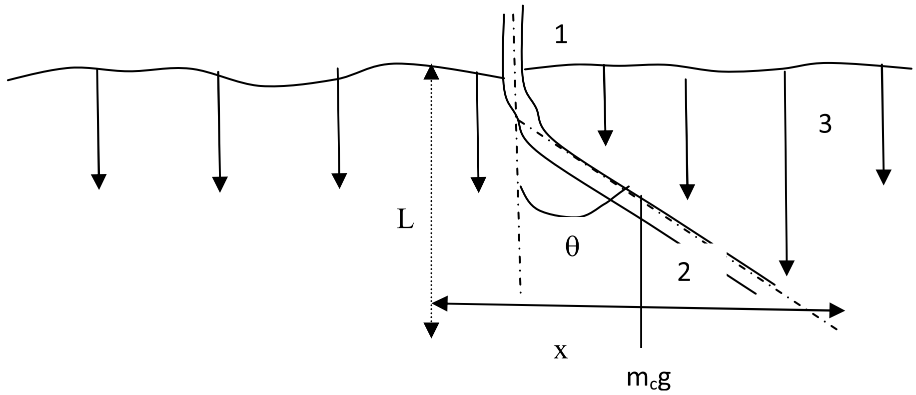

Figure 1: Free body diagram of a well with vertical and highly deviated sections showing the distribution of gravitational forces, weight of casing and overburden pressure.

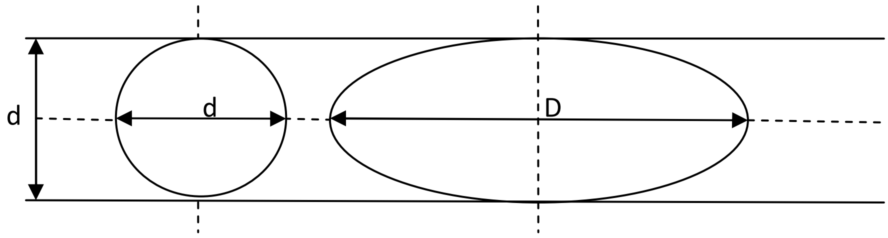

Figure 2: Plan view of annular spaces between holes.

ods, stated by Keller et al [2], Wilson and Sabins [4] vented much focus in mitigating free water and sedimentation in deviating sections only by use of additives and representative experiments. But this analysis is set to employ a particle approach in ensuring the proper integration of flow and mechanical property of set cement for use in horizontal sections of highly deviated wells. Miranda et al [8] treated influence of optimization efforts on not only porosity and rheological properties but also on chemical and mechanical resistance of the resulting slurry.

2. Derivation of Area Equation for a Deviated Wellbore

To mathematically prove that wellbore fluids encounter increasing surface areas.

In the vertical section the gravitational force act on all particles within the constant cross sectional area. In the deviating planes it acts as though distributed on all particles continuously along a non uniform cross sectional areas which vary with changes in deviation angle θ. Virtually all inherent challenges facing the construction of deviating wells are as a result of this distributed gravitational force and the massive weight of casing, m_c, and other bottomhole equipment. They induce bending moment and casing pipe eccentricity, in the event complicating two phase immiscible displacement models needed for optimizing the displacement of cement-spacer-preflush-mud system.

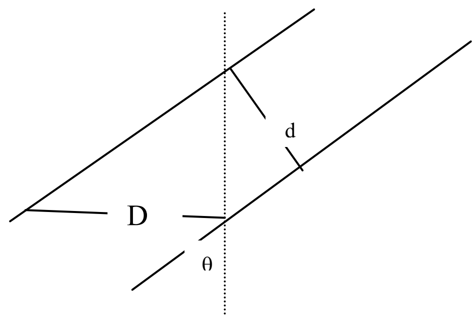

Figure 3:

With due regard to slurry systems, gravitational forces themselves challenge their stability under static conditions, in the formation of free water and sedimentation of heavy particles in the slurry system. Though it creates these challenges, it also holds the answers we need.

From Fig. 1, slurry occupies two elliptic annular spaces: (1) vertical hole-vertical well annulus, (2) deviated hole-deviated well annulus. The plan view showing these annuli is shown in Fig. 2.

The diameters are external diameter, d is the diameter of the small hole while D is the external diameter of the large hole. They are inclined to each other at angle θ as shown in Fig. 3.

Therefore, with respect to their diameters

$$d = D\cos\theta \quad (1)$$

or

$$D = d \sec \qquad (2)$$

Elliptical area

$$A = \pi \left(\frac{d}{2}\right)\left(\frac{D}{2}\right) \qquad (3)$$

From Eq. 1, therefore

$$\text{Area equation} = 0.7854 d^2 \sec\theta \qquad (4)$$

From Eq. 4, as θ tends to $0°$, we obtain area that would have been created by a vertical well given as:

$$\text{True vertical well area} = 0.7854 d^2 \sec\theta \qquad (5)$$

As θ tends to $90°$, we obtain the area of the largest deviation possible.

$$\text{Volumetric ratio} = \frac{V_{deviated}}{V_{vertical}} = \sec^2\theta \qquad (6)$$

Assume axial length to be filled by slurry owing to the deviation is x, the most nontrivial expression is

$$x = \frac{L}{\cos\theta} \qquad (7)$$

Therefore,

$$\text{volume of deviated section} = 0.7854 d^2 L \sec^2\theta \qquad (8)$$

And

$$\text{Volume of equivalent vertical section} = 0.7854 d^2 L \sec^2\theta \qquad (9)$$

Therefore, from Eq. 6,

$$\text{Volume Ratio} = \sec^2\theta \qquad (10)$$

For $d = 6$ and 9 inches, Fig 4 shows variation of area under the well against well deviation, while Fig 5 shows variation of volumetric ratio with angle of deviation.

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From Figs. 4 and 5, we notice a non-linear relationship of cross sectional area and volumetric ratio with θ. As angle tends to 90o, the cross section area in contact with fluids tends towards infinity. More cement slurry is required for a deviated well compared to an equivalent vertical section of the same true vertical depth and the amount increases with the angle of deviation. This means that more water is required for mixing the cement to form slurry. Therefore, there are higher free water tendencies in equivalent deviating sections. In the event where a conventional slurry is pumped in a 90o‘ horizontal drain hole, free water, on occurrence, would tend to contact a large area and since gravitational force distributes itself across the entire length, at that angle it interacts with more particles in suspension, and without the proper yield point they will settle to the bottom. It is thus deemed a critical case.

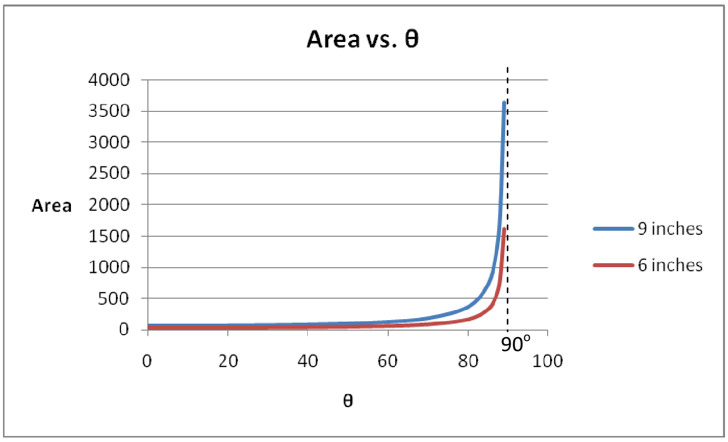

Figure 4: Variation in cross sectional area with deviation.

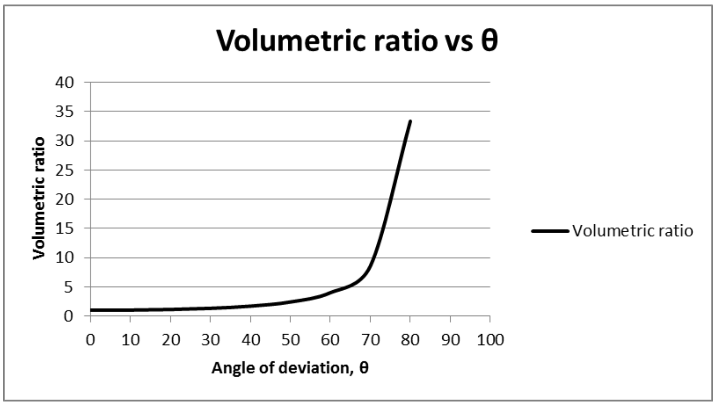

Figure 5: Volumetric ratio variation with angle of deviation.

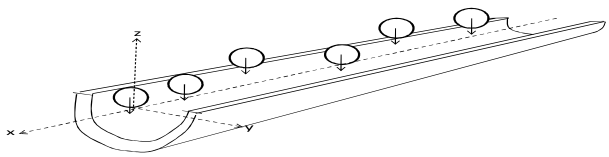

Figure 6: Horizontal drain hole with uniform spheres suspended in interstitial water (conventional).

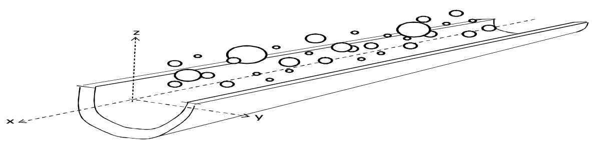

Figure 7: Redistributed particle size in horizontal drain hole.

3. Physical Analysis of Redistributed Slurry Sizes Theory

Fig. 6 shows the conventional slurry distribution over the annular space of a casing landed in a deviated well. Grain size distribution of the slurry is uniform. Free water and sedimentation tendencies exist. Hence it is expected that every little inter-granular space would be occupied with equal hydrostatic pressure throughout the system. The slurry water component would therefore segregate easily at static conditions. This segregation reduces the bond between cement slurry grains, thus leading to premature formation of slurry of low strength. High yield value is required to keep individual particles in suspension due to higher gravitational force, resulting in unfavorable rheology.

4. Slurry Compounding Based on Physical Analysis

This conceptual solution idealizes a slurry system as perfect spheres suspended in a medium of interstitial water in a horizontal bore. It aims at disbanding the ties between density and rheology through particle size redistribution. From Newtons law of universal gravitation, the force of attraction between two bodies is proportional to the product of their masses and inversely proportional to their distance apart as follows:

$$F = \frac{GMm}{r^2} \tag{11}$$

We suggested a redistributed slurry system as shown in Fig. 7, where large slurry particles are interspersed with smaller particle although with the particles having the same density. In it therefore (1) compressive strength is not compromised, (2) particles experience lower gravitational force thus lower yield point is required to keep particles in suspension, thus keeping the rheology intact, (3) higher surface area exposed to interstitial water for hydration, and (4) exact hydrostatic gradient is existent.

In the conventional slurry system shown in Fig.6, particles are uniform in mass and size and they are monodispersed. Let the mass of a uniform sphere be taken as m_L. The gravitational force that we intend to balance per particle, with a certain yield point is:

$$F = \frac{GMm_L}{r^2} \tag{12}$$

Now from Fig. 7, the particles are now redistributed in size but still maintaining the same total fluid density; we calculate again the gravitational force we intend to balance per particle to preclude segregation as:

$$F = \frac{GMm_S}{r^2} \tag{13}$$

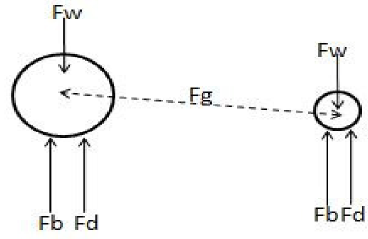

Figure 8: Slurry under static condition.

Figure 9: New proposed slurry under flow condition.

Therefore, given the same M, r, and G, the gravitational force in Eq. 13 is greater than that of Eq. 12. Furthermore, the overall gravitational force is reduced particulately in the interspersed system on the smaller particles of mass compared to the system of the uniform size sphere of mass m_L.

Under static conditions as shown in Fig, 8, the gravitational forces causing settling are lower than the conventional system due to the presence of smaller particles. The few larger particles, by exercising local gravitational fields around smaller particles will contribute slightly to stability since buoyancy and drag force and particle weight balance under static condition. This gives rise to higher packing factors that reduce the amount of needed interstitial water.

Under flow conditions as shown in Fig. 9, the smaller particles will tend to act as lubricating ball bearings and the overall yield value is smaller than the conventional system of equally sized uniform spheres.

Slurry particle redistribution can be achieved by using additives with slightly larger particle size than neat slurry formula, provided slurry pumps ability is not compromised. Sand in one of the most cheaply available additive that readily serve this purpose. Sand is used to increase slurry density and requires no additional water to be added to the slurry. It has little effect on the pumpability of cement slurry, but causes the cement surface to be relatively hard (Bourgogue et al, 1991). Because of the tendency to form hard cement, sand often is used to form a plug in an open hole as a base for setting a whipstock tool used to change the direction of the hole. Furthermore, because of the very low compressibility, no amount of overburden pressure would change the bond formed by sand.

5. Conclusion

A hypothetical guide for computing slurry volumes and compounding cement slurry based on angle of deviation and the simple physics of gravitation has been presented for a deviated wellbores. The physical consideration is capable of optimizing both placement and mechanical properties of set cement simultaneously. Although further improvements is required to determine the maximum particle size for redistribution, advances in particle engineering, slurry pump ability and cost are on the way of these theory. However, this theoretical study shows that:

1. Slurry volumes are more accurate when based strictly on the angle of deviation.
2. Unequal cement particle size distribution helps to create slurry stability through reduction in interstitial water required thus sustain slurry integrity.
3. Additives should be selected carefully to achieve the desired slurry rheology.
4. Unequal cement particle size distribution would also help to reduce loss circulation usually caused by migration of slurry fines into the adjacent formation.

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