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A New Buckling Model Successfully Validated with Full-Scale Buckling Tests

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Abstract

Buckling of tubulars inside wellbores has been the subject of many researches and articles in the past. An increasing number of observations in the field suggest that existing buckling theories have to be challenged, as they fail to predict the buckling phenomenon, such as lockup. Indeed, existing buckling theories assume generally that the wellbore is idealistically perfect without any dog legs. Recent advancements in drillstring mechanics modelling have demonstrated that dog legs, friction and rotation greatly affect the buckling phenomenon. For the first time, this paper compares results of full-scale buckling tests with a new buckling model that takes into account the actual tortuosity of the wellbore.

Full-scale buckling tests have been performed in a 2000 m depth well in testing two (2) different drill string configurations. Various weights on bit have been applied for buckling drill pipe in the wellbore, and then a high accuracy continuous gyroscope has been run into the drill pipe to estimate its deformed geometry. This paper shows for each drill string and weight on bit experimental and theoretical results in terms of weight transfer (lockup prediction) and buckling state (sinusoidal or helical). Although existing models failed to predict observed buckling behaviour, the new buckling model has given excellent predictions for each full-scale buckling test performed, not only in terms of deformed buckling shape, but also in terms of weight transfer.

This paper shows for the first time to the drilling industry that a new buckling model has been derived and successfully validated in the field. This model has proved its ability to realistically predict the onset and severity of buckling in any kind of 3D trajectory.

Buckling theories

Buckling occurs when the compressive load in a tubular exceeds a critical value, beyond which the tubular is no longer stable and deforms into a sinusoidal or helical shape. The sinusoidal buckling (first mode of buckling) corresponds to a tube that snaps into a sinusoidal shape. This first mode of buckling is sometimes called lateral buckling, snaking or two-dimensional buckling. The helical buckling (second mode of buckling) corresponds to a tube that snaps into a helical shape (spiral shape).

The first work dedicated to the buckling behavior of pipes in oil well operation was initiated by Lubinski[1,2]. Since then, many theoretical works and/or experimental studies have been developed to better understand the buckling phenomenon. First theories were developed for perfect vertical wellbores without friction by Lubinski[1]. Then, the buckling behavior of drill pipes in inclined wellbores was first proposed by Dawson & Paslay[3], based on earlier work by Paslay & Bogy[4]. The authors came to the following known critical buckling load for sinusoidal mode:

$$F_{sin} = 2\sqrt{\frac{EI\,\omega\, sin(Inc)}{r}} \qquad (1)$$

where EI is pipe stiffness, ω is the buoyed linear weight of the pipe, Inc is the wellbore inclination and r is the radial clearance between the pipe and the wellbore. The critical force given by Eq. (1) is considered by the authors as the onset of buckling in an inclined hole, and is widely used in the drilling industry.

Although there seems to be a general consensus for the onset of buckling (sinusoidal mode) in a perfect wellbore geometry, there is some controversy regarding the solution for the critical helical buckling load[5,6]. Indeed, the equation for critical helical buckling in a straight deviated wellbore is given by:

$$F_{hel} = \lambda \sqrt{\frac{EI\omega \sin(Inc)}{r}} \qquad (2)$$

where λ varies from 2.83 to 5.65 depending on the authors[5,6] and different assumptions taken into account. In conducting laboratory experiments and numerical analysis in a perfect horizontal well without rotation, Menand et al[7] and Thikonov et al[8] found similar results about the relationship between λ number and the deformed shape of the drill pipes: λ close to 2.83 enables to predict the onset of the first helix, and λ close to 5.65 enables to predict the full helical drillstring deformation in a perfect wellbore geometry (without rotation).

While many equations had been derived for perfect vertical, inclined, horizontal or curved wellbores, no theory was developed for actual well geometry, that is in a naturally tortuous wellbore. Based on a new numerical method and an experimental facility, Menand *et al*[7] have demonstrated the strong effect of tortuosity on the critical buckling load, showing for example that a helix could be formed at a load lower than the critical helical buckling load predicted by all equations found in the literature. Moreover, most literature equations are based on simplifying assumptions: the pipe is continuous, without rotation, and the friction between the buckled drill pipes and the constraining wellbore is often ignored. It is worth noting that an analytical equation taking into account simultaneously all the effects seen above, such as natural tortuosity (dog legs), tool-joint, tapered strings, rotation, torque and friction, cannot be derived. To handle this highly complicated problem, one has to use numerical modeling. Although this drill string modeling is generally solved by using finite element analysis (FEA), the new model presented in this paper, is based on a unique semi-analytical approach that allows to greatly reduce computational time, and remains as accurate and robust as FEA.

Buckling Model Description

This paragraph briefly presents the numerical model developed by Mines ParisTech university and dedicated to drillstring mechanics, from the drilling bit to the rig surface. More details, such as main hypotheses and resolution steps, can be found in previous papers[7,9,10]. The numerical model is now implemented in commercial software. The model can simulate any drilling tool equipment : for directional analysis such as point-the-bit or push-the-bit rotary steerable systems, steerable mud motor, adjustable gage stabilizers, for torque/drag and buckling analysis, all the tubulars going from conventional drillstring to coiled-tubing, or for sag analysis concerning wellbore placement uncertainty evaluation. Each detail of the element is taken into account such as tool-joint of the drillpipe. As the drillstring is meshed in very small beam elements, the model enables to focus on any critical drillstring component, such as measurement while drilling (MWD) tools or any electronic measurement subs. The model takes into account any external forces applied on each element of the drillstring, such as hydraulic forces, temperature effect in case of high-pressure/high-temperature (HP/HT) wells, and can handle any new materials such as aluminum, titanium or composite drill pipes (Young modulus and linear weight variations). This is the first numerical model than can simultaneously perform torque, drag and buckling analysis, taking into account in the friction analysis the increased contact force generated by the buckling.

Thanks to this numerical breakthrough, the software can fully simulate the mechanical behaviour of a very long drillstring in a 3D well trajectory within a few minutes (instead of hours with FEA), making real-time monitoring while drilling possible.

Since no assumption is made as to the points of contact between the drillstring and the borehole, the model more realistically predicts the side forces along the drillstring. This 3D stiff-string model takes into account tubular stiffness, friction, rotation, temperature, hole size and clearance effects, and can handle the micro and macro tortuosity of actual well paths.

Figure 1 shows an example of buckled drill pipes in a perfect horizontal wellbore and highlights the 3D contacts between the wellbore and the drill string.

Full Scale Description

Statoil performed some full scale tests to evaluate drill string buckling models that exist in the industry today[11]. The objective was to put different drill strings in compression (to make them buckle) and then measure the deformed drill string with a continuous gyroscope. The test well chosen is about 2020 m deep with a vertical, build-up and tangent profile, as shown in Figure 2. A down hole weight measurement sub was placed at different part along the drill string to control the down-hole weight put on the bit. Hook load were recorded at surface with a special weight sub. The deformation of the drill pipes was measured using a commercially available continuous wire line gyroscope tool, with a one (1) m (3.3 ft) survey spacing used during the tests. In this paper, one presents the results obtained with two (2) drill strings which characteristics are described in Table 1. These drill strings consist of a bit, followed by some 5 inch drill pipes, 6 ½ and 8 inch drill collars and at last 5-inch drill pipes again.

The well is cased with 10 ¾ inch from well head to 229 m (751 ft) and 9 5/8 inch from there to total depth at 2020 m. The gyroscope tool enables measurement of inclination and azimuth along the drill string. In this analysis, the interesting information lies in the deviation of the buckled drill string from the unbuckled reference measurement. The inclination measurements directly represent deviations from the well path direction in the vertical plane, and the azimuth directions are measured relative to the horizontal plane. Various weights on bit (from 22 to 70 tons) have been applied to impose voluntarily drill pipe buckling in the wellbore. It is worth noting that these full scale tests have been performed without rotation, and weight was slacked off gradually up to the wanted weight on bit. More details about the test program and other results can be found in a previous paper[11].

The friction factor 0.28 used in the simulations has been chosen according to the slack off weight (54.5 tons) and pick-up weight (100 tons) recorded with the drill string DS#2. The block weight is 9 tons and the mud density is 1.02 sg. Table 2 shows weights applied on the bit and parts of gyroscope measurements (start and end depth measurements) for the 2 drill strings simulated.

Full-scale Buckling Tests Results

Figures 3 and 4 show the survey (inclination & azimuth) as measured by the gyroscope versus survey as calculated by the buckling model (survey converted from the pipe deformations), for the run three (3) of the drill string DS#1 (WOB=46 tons). In these two (2) figures, the black curve represents the wellbore survey. The wavy shape of the inclination and azimuth curves observed in these figures means that the drill string buckles, either in sinusoidal mode, in helical mode, or neither mode. As already stated, the buckling shape is sometimes strongly linked to the dog leg shape of the wellbore, and it is difficult to determine the buckling mode. Figure 5 shows the 3D view of the deformed drill string DS#3 simulated for the runs 1, 2 and 3. One notices that without compression (WOB=0 ton), the drill string lays on the low side of the borehole, and for the two (2) other compressions, the drill string strongly buckles. Notice that the deformation on this 3D view has been amplified by a factor 400 to better see the buckling phenomenon.

One observes in figures 3 and 4 that the buckling model is able to correctly reproduce the measurements made by the gyroscope. It is interesting to notice in figure 4 between 1150 m (3773 ft) and 1400 m (4593 ft), that the drill string does not buckle. Indeed, this part corresponds to the position of drill collars that have a strong buckling resistance. It is important to note that the friction factor has only been fitted for the slack-off (without compression) and pick-up test. Without changing this friction factor value for the buckling tests, and in taking into account the actual weight on sub recorded down hole (± 3 tons), the buckling model demonstrates that it can correctly reproduced the buckling phenomenon as observed in the field.

Figure 6 shows the theoretical inclination obtained from the buckling model for three (3) different WOB. One notes that the sinusoidal variation observed on the curve increases with an increasing WOB. Figure 7 shows the weight measured at surface versus the weight on bit during the slack off of the drill string DS#2. One notices that up to a WOB of 30 tons, the surface weight follows a normal trend meaning that the slack off weight is efficiently transferred down hole (normal weight transfer line on the plot). With a higher WOB, the surface weight decreases more rapidly up to the full lock-up, indicating that no more WOB can be applied. Let's notice that the buckling model properly reproduces this tendency.

Literature equations (1) and (2) are unable to reproduce the buckling phenomenon as observed in these field tests. Indeed, as the well bore has some numerous dog legs, these equations cannot be applied. Moreover, some other equations[12] taking into account the local curvature effects give non consistent results.

Conclusion

Although existing models failed to predict observed buckling behaviour, the new buckling model has given excellent predictions for each full-scale buckling test performed, not only in terms of deformed buckling shape, but also in terms of weight transfer. This paper has shown for the first time to the drilling industry that a new buckling model has been derived and successfully validated in the field. This model has proved its ability to realistically predict the onset and severity of buckling in any kind of 3D trajectory.

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Nomenclature

E - Young's Modulus, Pa
Fsin - Sinusoidal critical compressive force, N
Fhel - Helical critical compressive force, N
I - Moment of inertia of drill pipes, m^4
Inc - Inclination, deg.
ω - Buoyed linear weight of drill pipe, N/m
r - Radial clearance, m

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Table 1: Drill string main characteristics

Element	Drill string #1 (DS#1)	Element	Drill String #2 (DS#2)
Bit	1 m	Bit	1 m
Sub measurement	10 m	5 inch DP	480 m
5 inch DP	600 m	Sub measurement	10 m
6 ½ and 8 inch DC	250 m	5 inch DP	630 m
5 inch DP	1150 m	6 ½ and 8 inch DC	330 m
		5 inch DP	560 m

Table 2: Test program overview for the 2 drill strings

Test	Gyroscope measurements		WOB (ton)	Weight on Sub (ton)	Instrumented Sub position (m)
	Start depth (m)	End depth (m)			
DS#1 run 1	1421	1990	0	0	1997-2009
DS#1 run 2	1422	1990	22	18,3	1997-2009
DS#1 run 3	768	1990	46	31,9	1997-2009
DS#2 run 1	745	1475	0	0	1516-1528
DS#2 run 2	745	1475	20	15,8	1516-1528
DS#2 run 3	745	1474	41	27,8	1516-1528
DS#2 run 4	745	1474	60	37,8	1516-1528
DS#2 run 5	745	1473	70	39,6	1516-1528

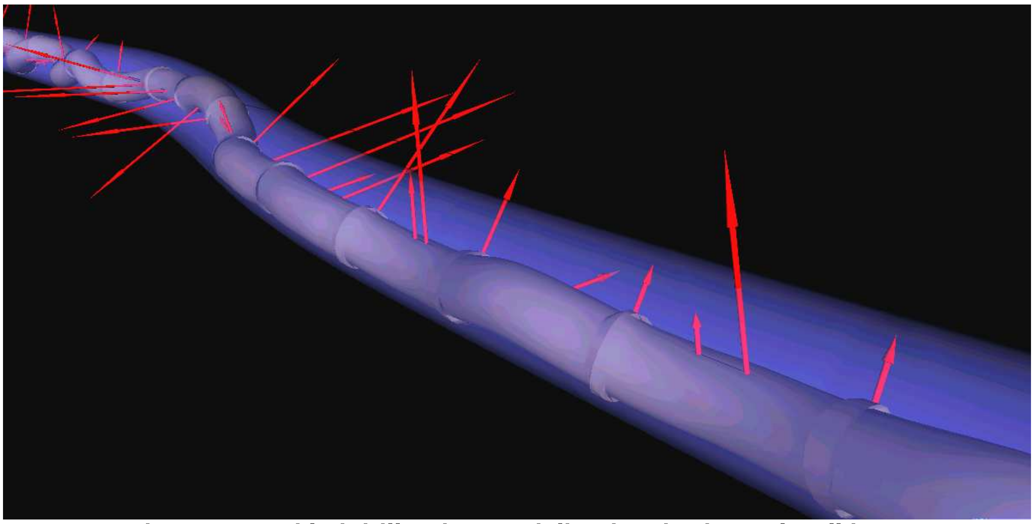

Figure 1: Buckled drill string modeling in a horizontal well bore

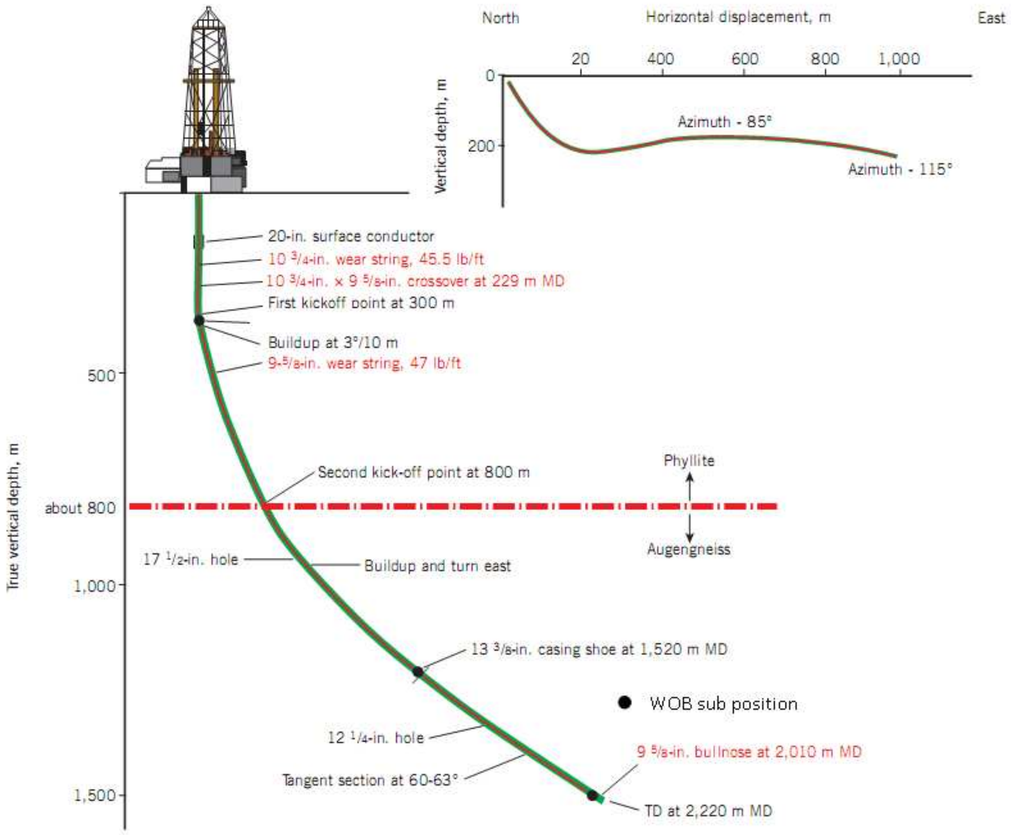

Figure 2: Trajectory of the well for full scale buckling tests

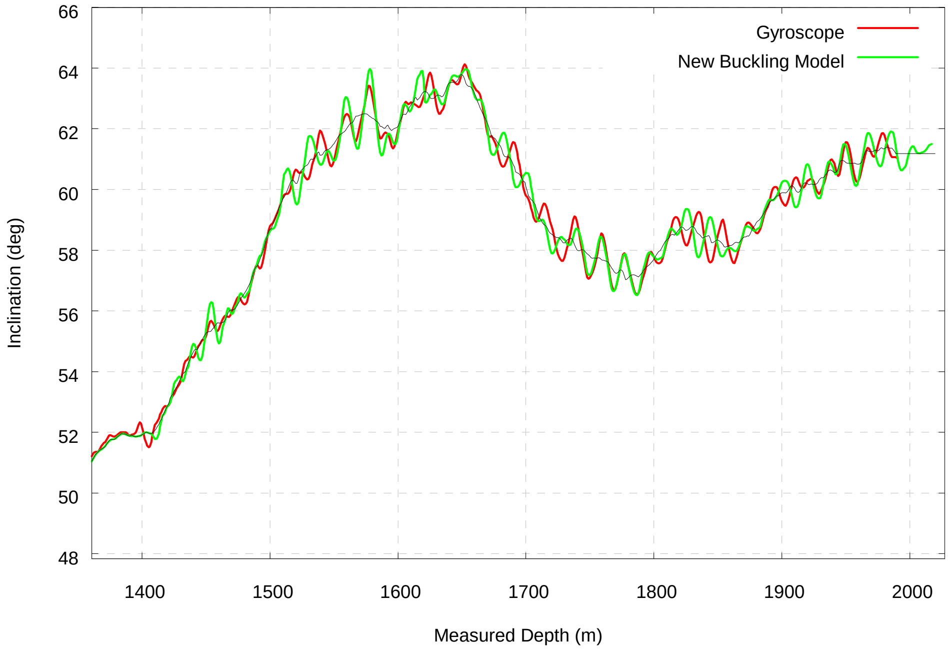

Figure 3: Inclination versus measured depth - Comparison between the measurements and the new buckling model – Drill string DS#1 – run 3

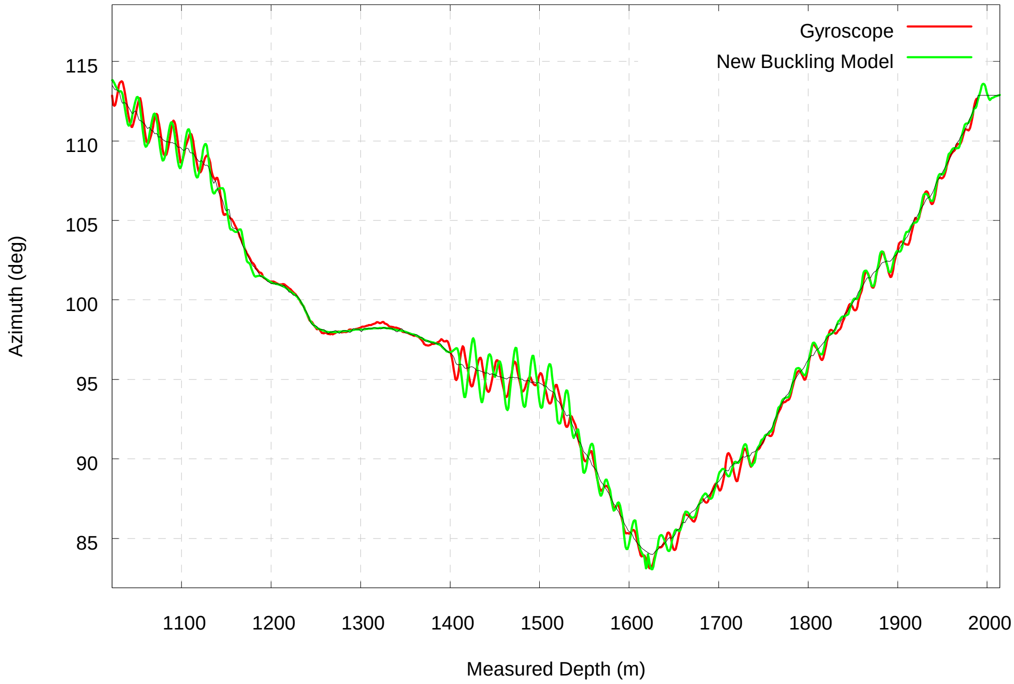

Figure 4: Azimuth versus measured depth - Comparison between the measurements and the new buckling model – Drill string DS#1 – run 3

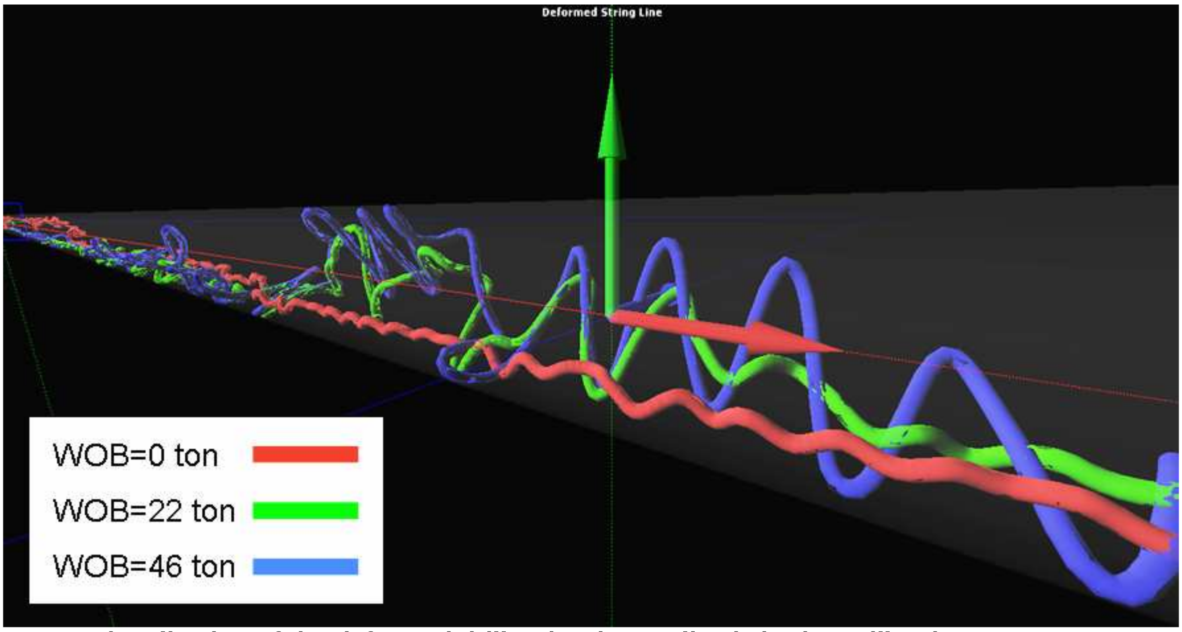

Figure 5: 3D visualization of the deformed drill string (normalized view) – Drill string DS#1 runs 1,2 and 3 – Deformation amplification factor = 400.

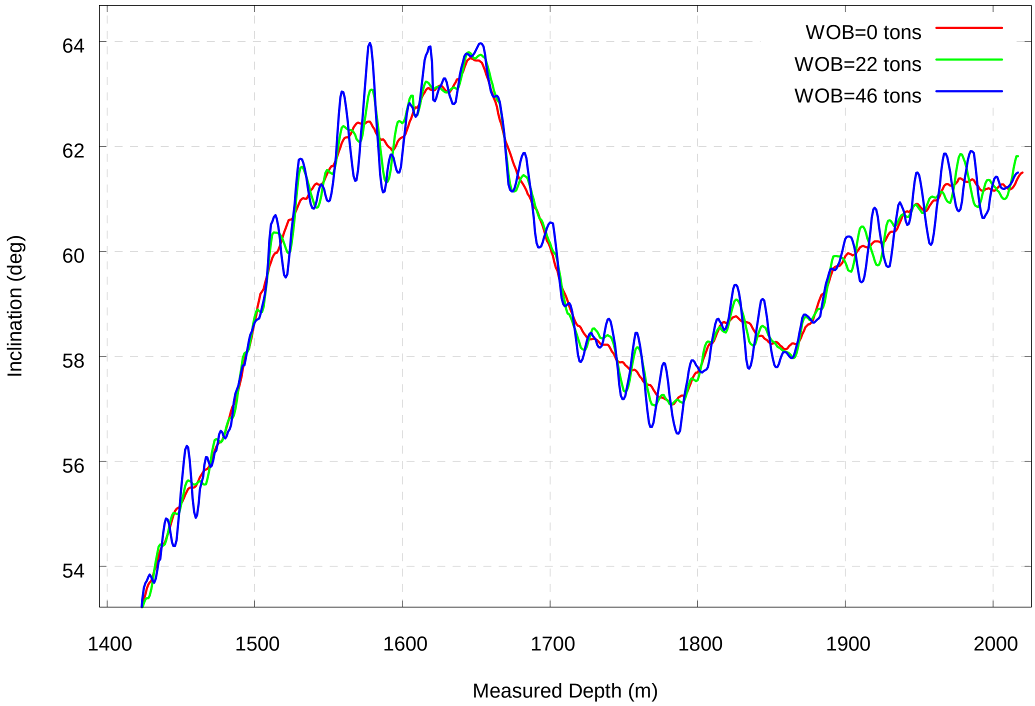

Figure 6: Inclination predicted by the buckling model - Comparison between 3 WOB – Drill string DS#1 – runs 1, 2 and 3

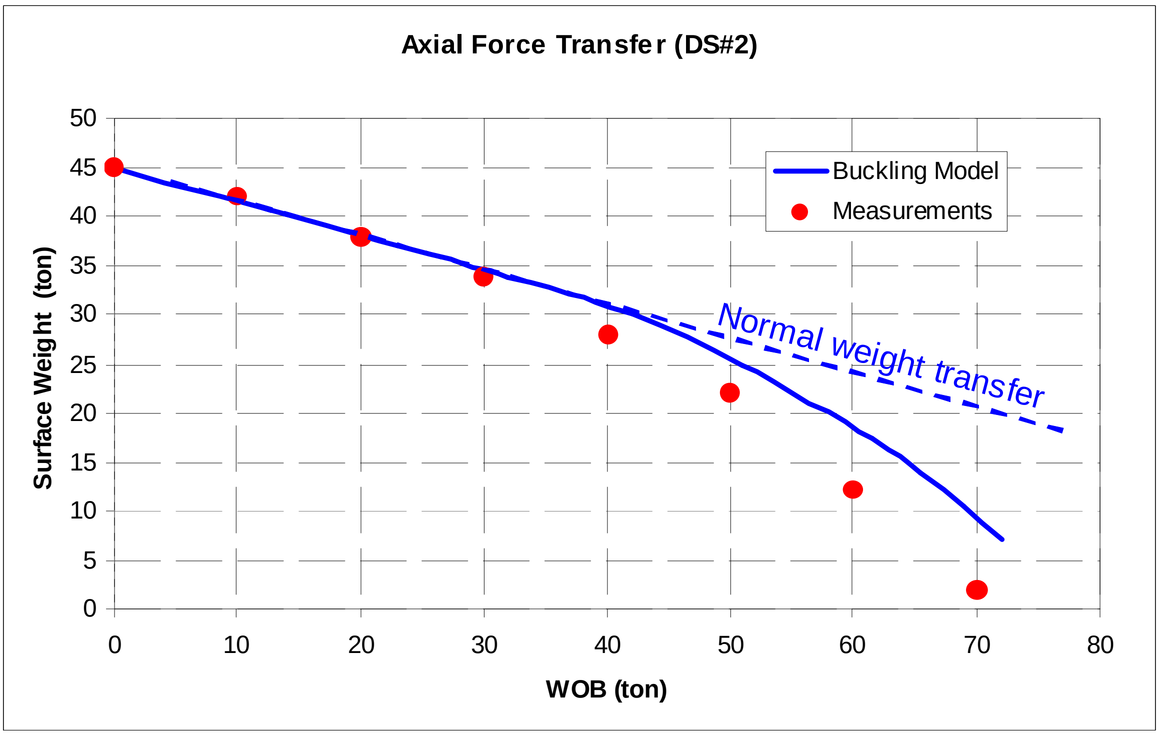

Figure 7: Axial force transfer evolution – Comparison between the measurements and the buckling model – Drill string DS#2