CSCanada
Advances in Petroleum Exploration and Development
Vol. 10, No. 2, 2015, pp. 93-97
DOI:10.3968/8080

ISSN 1925-542X [Print]
ISSN 1925-5438 [Online]
www.cscanada.net
www.cscanada.org

Mechanical Calculation for Workover String in Highly-Deviated and Horizontal Well

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Received 18 November 2015; accepted 28 December 2015

Abstract

Force analysis and calculation of workover string in the highly-deviated and horizontal well is the basis of designing and checking string strength, selecting tools and determining operation parameters, which determines the operation safety and success of engineering accidence treatment. In this paper, by comprehensive consideration of wellbore structure, string assembly, string load and workover operation conditions, the workover string mechanical model has been built under three kinds of working states of lifting, lowering and rotating. The downhole string mechanics has been analyzed and calculated. By field verification, the string assembly, tool selection and operation parameter optimization can be achieved, which can improve the safety and success rates of workover engineering accident treatment.

Key words: Workover job; Horizontal well; String mechanics; Mechanical model; Accident treatment

Liu, H., Liu, X. Y., & You, Y. R. (2015). Mechanical calculation for workover string in highly-deviated and horizontal well. *Advances in Petroleum Exploration and Development*, *10*(2), 93-97. Available from: URL: http://www.cscanada.net/index.php/aped/article/view/8080
DOI: http://dx.doi.org/10.3968/8080

INTRODUCTION

The casing in highly-deviated and horizontal well is curved, so by the limits of the casing workover string is curved[1-2]. It makes workover string not only by the force of its own gravity, but also by the friction between the casing and workover string as well as the torque caused by friction. In the treatment process of engineering accident, some conventional processing tools, appliance and treatment methods cannot satisfy the need of accident treatment, and it even make the engineering accident more complicated[3-4].

As a result, workover string mechanical model is established according to the characteristics of highly-deviated and horizontal well, through stress analysis and calculation can guide the field construction, which has important meaning to improve the safety and success rates of workover engineering accident treatment[5-6].

1. WORKOVER STRING MECHANICAL MODEL MODEL OF HIGHLY-DEVIATED AND HORIZONTAL WELL

In the workover string force analysis of the highly-deviated and horizontal wells, the tubing string is the analysis object, the string is taken as flexible pole to analyze its stress, and the mechanical models of workover string under lifting, lowering and rotating states are established.

1.1 The Mechanical Model of Lifting State

Figure 1 is the mechanical model of string when lifting it in the uniform rate. The string is basically in a vertical state above the kickoff point A, and begin to contact with casing below the point A (approximately beginning with point A), until the point B, the string divides with the casing. Because of the gravity the string gradually becomes vertical with the casing. The string is contacted with the bottom of casing from the kickoff end point C to the casing bottom. Because the distance between the point B and C is very short, it can be considered as a point. The force on the string is as follows:

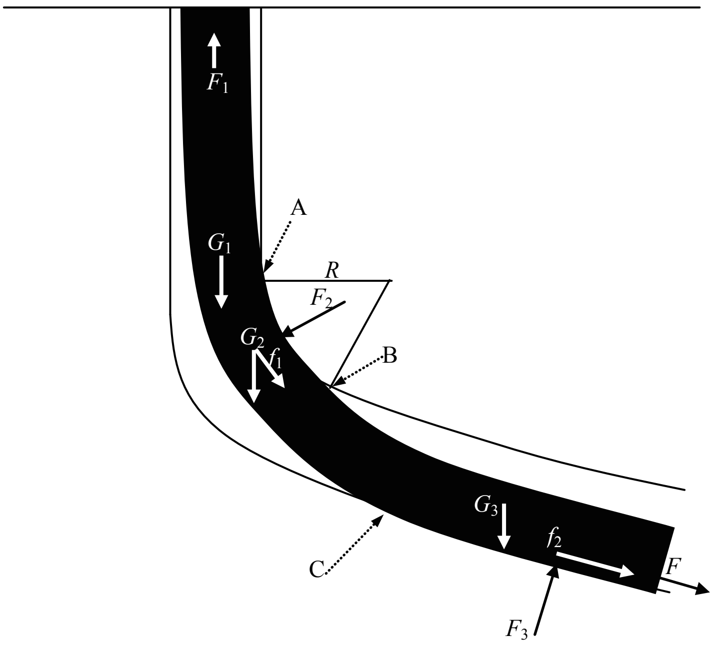

Figure 1
The Mechanical Model of String in Lifting State

(a) The pulling force of the string (hook hoisting load) F_1.

(b) The weight of the string above the deflection point G_1.

(c) The weight of the string with the friction tape of casing AB is G_2 and the friction force between the string and casing f_1.

(d) The weight of the string below the point C is G_3 and the friction force between the string and the casing is f_2.

(e) The anchorage force of the string with the friction tape of casing AB as well as below is F_2 and F_3.

(f) The pulling force F to the bottom of the string by the fish, for 0 when the fish is not retrieved.

The relationships of the forces are as follows:

$$F_1 = G_1 + G_2 \cdot \cos\frac{\alpha}{2} + f_1 + G_3 \cdot \cos\alpha + f_2 + F, \quad (1)$$

$$f_1 = F_2 \cdot \mu, f_2 = F_3 \cdot \mu, F_3 = G_3 \cdot \text{sina}\alpha. \quad (2)$$

When fish is not retrieved,

$$F_2 = \frac{(G_2 \cdot \cos\frac{\alpha}{2} + G_3 \cdot \cos\alpha + G_3 \cdot \sin\alpha \cdot \mu)\sqrt{2(1-\cos\alpha)} - G_2 \cdot \sin\frac{\alpha}{2}}{1-\sqrt{2(1-\cos\alpha)} \cdot \mu}. \quad (3)$$

When fish is retrieved and jam is released,

$$F_2 = (F_1 - G_1)\sqrt{2(1-\cos\alpha)} - G_2 \cdot \sin\frac{\alpha}{2}. \quad (4)$$

At this time,

$$F = F_1 - G_1 - G_2 \cdot \cos\frac{\alpha}{2} - F_2 \cdot \mu - G_3 \cdot \cos\alpha - G_3 \cdot \text{sina}\alpha \cdot \mu. \quad (5)$$

Where,

$G_1 = w \cdot L_1$, $G_2 = w \cdot L_2$, $G_3 = w \cdot L_3$.

α—The maximum degree of slope, °;

w—The unit weight of the string in the wellbore, N/m;

L_1—The length of the vertical string, m;

L_2—The length of the kickoff string, m;

L_3—The length of the slanted string, m;

μ—The friction coefficient between the string and casing.

1.2 The Mechanical Model of Lowering State

Figure 2 is the force state of string in lowering state. At the uniform lowering state, the bending of the string is almost the same with the lifting state except the point B moved up. The force on the string is as follows:

(a) The pulling force of the string (hook hoisting load) F_1.

(b) The weight of the string above the deflection point G_1.

(c) The weight of the string with the friction tape of casing AB is G_2 and the friction force between the string and casing f_1.

(d) The weight of the string below the point C is G_3 and the friction force between the string and the casing is f_2.

(e) The anchorage force of the string with the friction tape of casing AB as well as below is F_2 and F_3.

The relationships of the forces are as follows:

$$F_1 = G_1 + G_2 \cdot \cos\frac{\alpha}{2} - f_1 + G_3 \cdot \cos\alpha - f_2, \quad (6)$$

$$f_1 = F_2 \cdot \mu, \quad f_2 = F_3 \cdot \mu, \quad F_3 = G_3 \cdot \text{sina}\alpha, \quad (7)$$

$$F_2 = \frac{(G_2 \cdot \cos\frac{\alpha}{2} + G_3 \cdot \cos\alpha - G_3 \cdot \sin\alpha \cdot \mu)\sqrt{2(1-\cos\alpha)} - G_2 \cdot \sin\frac{\alpha}{2}}{1-\sqrt{2(1-\cos\alpha)} \cdot \mu}, \quad (8)$$

$$G_1=w\cdot L_1,\ \ G_2=w\cdot L_2,\ \ G_3=w\cdot L_3,\ \ G_4=w\cdot L_4,\ \ L_2=\frac{\alpha_B}{\alpha}L_0. \quad (9)$$

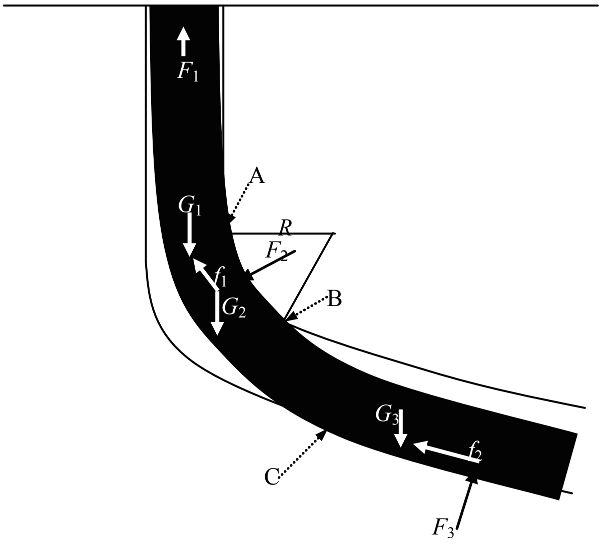

Figure 2
The Mechanical Model of String in Lowering State

1.3 The Mechanical Model of Rotating State

Figure 3 is the force and moment of the string in circulate state. Because of the circulation, the axial friction force of the string is 0. The friction force mainly causes the counter torque T_1 and T_2 opposite to the moment of the wellhead.

(a) The pulling force of the string (hook hoisting load) F_1.

(b) The weight of the string above the deflection point G_1.

(c) The weight of the string with the friction tape of casing AB is G_2 and the friction force between the string and casing f_1 as well as the moment T_1 caused by f_1.

(d) The weight of the string below the point C is G_3 and the friction force between the string and the casing is f_2 as well as the moment T_2 caused by f_2.

(e) The anchorage force of the string with the friction tape of casing AB as well as below is F_2 and F_3.

(f) The pulling force F to the bottom of the string by the fish.

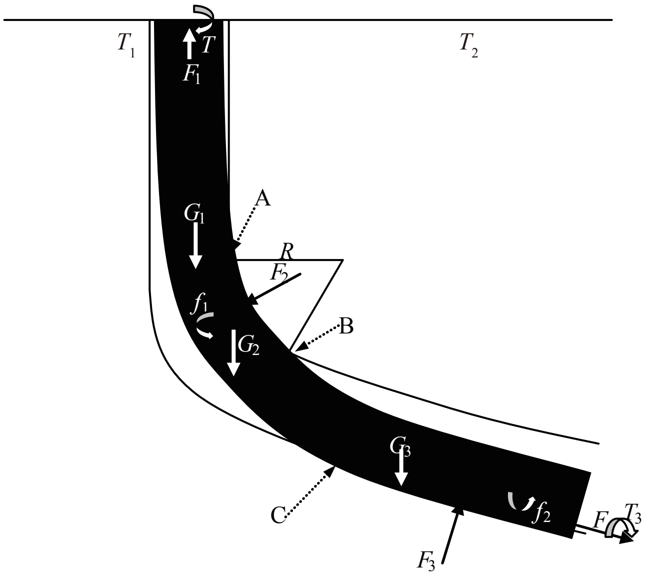

Figure 3
The Mechanical Model of String in Rotating State

The relationships of the forces are as follows:

$$F_1 = G_1 + G_2\cdot\cos\frac{\alpha}{2} + G_3\cdot\cos\alpha + F, \quad (10)$$

$$f_1 = F_2\cdot\mu,\ \ f_2 = F_3\cdot\mu,\ \ F_3 = G_3\cdot\text{sina}\alpha, \quad (11)$$

$$F_2 = (F_1 - G_1)\sqrt{2(1-\cos\alpha)} - G_2\cdot\sin\frac{\alpha}{2}, \quad (12)$$

$$F = F_1 - G_1 - G_2\cdot\cos\frac{\alpha}{2} - G_3\cdot\cos\alpha, \quad (13)$$

$$G_1 = w\cdot L_1,\ \ G_2 = w\cdot L_2,\ \ G_3 = w\cdot L_3, \quad (14)$$

$$T_1 = f_1\cdot\frac{d}{2},\ \ T_2 = f_2\cdot\frac{d}{2},\ \ T = T_1 + T_2 + T_3. \quad (15)$$

T—Torque provided by the power equipment on well head, (N·m);

T_1—Torque caused by f_1, (N·m);

T_2—Torque caused by, (N·m);

T_3—torque that wellhead torque transfer to the fish after overcoming friction torque, (N·m);

d—outer diameter of string where friction takes place, (m).

2. THE CALCULATION OF THE FORCE AND MOMENT IN WELL NANFANGB-1 STRING

Well nanfangb-1 is a new fractured well constructed by some job team. The string falls to well in the process of sand washing after fracture, fish top is 73 mm pipe couplings, depth is 2,682.31 m, the length of fish is 710 m. Now the force of the well in the salvage construction and the torque of the string in rotating state are analyzed and calculated. The results are as follows.

2.1 The Condition of the Well

The string salvaged in well is the string assembly of 89 mm and 73 mm (outer thickening) of N80, the length is 1,182 m and 1,500 m. Known that the weight of 89 mm tubing in well is 117.6 N/m, and 73 mm outer thickening tubing is 83.5 N/m (density of well liquid is 1.0 g/cm^3), and the fish in well is of 73 mm tubing of J55, the weight is 81.5 N/m.

(a) Base data (Table 1)

Table 1
The Base Data of Well Nanfangb-1

Item	Number	Item	Number	Item	Number
Casing external diameter	139.7 mm	Casing thickness	9.17 mm	Casing depth	3,410.0 m
Drilled depth	3,416.0 m	Cement return height	Wellhead	Cement quality	Qualified
Artificial botoum hole	3,394.4 m	Fish top depth	2,682.31 m	Distance between tubing and bushing	4.72 m
Kickoff point	1,417.2 m	Biggest inclined point	2,201.2 m	Maximum Angle	37.49°

(b) The base data about the string assembly of 89 mm and 73 mm (outer thickening) of N80 (Table 2)

Table 2
the Base Data of Tubing Used to Salvage

Tubing	External diameter/ (mm)	Thickness/ (mm)	Inner diameter/ (mm)	Grade	Weight/ (N/m)	Volume/ (L/m)	Tensile strength/ (kN)	Coupling OD / (mm)	Buckled torque /(N·m)		
									Min.	Best	Max.
89	88.9	6.5	76.0	N80	134	1.67	708	107	2,150	2,850	3,600
73up	73.02	5.5	62.0	N80	95	1.17	645	93	2,400	3,200	4,000
73	73.02	5.5	62.0	J55	93	1.17	323	89	1,100	1,450	1,800

2.2 Known Conditions

$A = 37.5^\circ$, $L_1 = 1{,}417.2$ m, $L_2 = 784$ m, $L_3 = 481.1$ m, $\mu = 0.15$, $w_{89} = 117.6$ N/m, $w_{73up} = 83.5$ N/m, $w_{73} = 81.5$ N/m, $d = 73$ mm $= 0.073$ m, $\mu = 0.4$.

According to the above conditions the following can be worked out.

$G_1 = 158.6$ kN, $G_2 = 65.5$ kN, $G_3 = 40.2$ kN, $\sin\alpha = 0.61$, $\cos\alpha = 0.79$, $\cos\frac{\alpha}{2} = 0.95$, $\sin\frac{\alpha}{2} = 0.32$.

2.3 At the Lifting State

(a) Before fish is retrieved $F = 0$, and

$$F_2 = \frac{(G_2 \cdot \cos\frac{\alpha}{2} + G_3 \cdot \cos\alpha + G_3 \cdot \sin\alpha \cdot \mu)\sqrt{2(1-\cos\alpha)} - G_2 \cdot \sin\frac{\alpha}{2}}{1-\sqrt{2(1-\cos\alpha)} \cdot \mu} = 62.8\ (\mathrm{kN}),$$

$f_1 = F_2 \cdot \mu = 25.1$ (kN),

$F_1 = G_1 + G_2 \cdot \cos\frac{\alpha}{2} + f_1 + G_3 \cdot \cos\alpha + f_2 = 287.5$ (kN).

(b) When fish is retrieved and jam is released 600 kN,

$F_2 = (F_1 - G_1)\sqrt{2(1-\cos\alpha)} - G_2 \cdot \sin\frac{\alpha}{2} = 266.0$ (kN),

$F = F_1 - G_1 - G_2 \cdot \cos\frac{\alpha}{2} - F_2 \cdot \mu - G_3 \cdot \cos\alpha - G_3 \cdot \cos\alpha \cdot \mu = 231.2$ (kN).

2.4 At the Lowering State

$$F_2 = \frac{(G_2 \cdot \cos\frac{\alpha}{2} + G_3 \cdot \cos\alpha - G_3 \cdot \sin\alpha \cdot \mu)\sqrt{2(1-\cos\alpha)} - G_2 \cdot \sin\frac{\alpha}{2}}{1-\sqrt{2(1-\cos\alpha)} \cdot \mu} = 45.6\ (\mathrm{kN}),$$

$F_1 = G_1 + G_2 \cdot \cos\frac{\alpha}{2} - f_1 + G_3 \cdot \cos\alpha - f_2 = 224.5$ (kN).

2.5 At Natural Rotation in Uniform Rate

(a) Naturally rotating the string before salvaging fish, at this time,

$F = F_1 - G_1 - G_2 \cdot \cos\frac{\alpha}{2} - G_3 \cdot \cos\alpha = 0$, so $F_1 = 252.6$ (kN),

$F_2 = (F_1 - G_1)\sqrt{2(1-\cos\alpha)} - G_2 \cdot \sin\frac{\alpha}{2} = 40.1$ (kN),

$T_1 = f_1 \cdot \frac{d}{2} = F_2 \cdot \mu \cdot \frac{d}{2} = 586.0$ (N·m),

$T_2 = f_2 \cdot \frac{d}{2} = G_3 \cdot \sin\alpha \cdot \mu \cdot \frac{d}{2} = 281.0$ (N·m),

$T_1 + T_2 = 586.0 + 281.0 = 867$ (N·m).

(b) When salvaging tubing and picking up 300 kN to back off,

$F_2 = (F_1 - G_1)\sqrt{2(1-\cos\alpha)} - G_2 \cdot \sin\frac{\alpha}{2} = 71.0$ (kN),

$T_1 = f_1 \cdot \frac{d}{2} = F_2 \cdot \mu \cdot \frac{d}{2} = 1{,}036.6$ (N·m),

$T_2 = f_2 \cdot \frac{d}{2} = G_3 \cdot \sin\alpha \cdot \mu \cdot \frac{d}{2} = 281.0$ (N·m),

$T_1 + T_2 = 1{,}036.6 + 281.0 = 1{,}317.6$ (N·m).

(c) If back off from the bottom of fish (fall fish is buried by sand),

$F = G \cdot \cos\alpha = w_{73} \cdot L \cdot \cos\alpha = 45{,}706$ (N) $= 45.7$ (kN),

$$F_2 = \frac{(G_2 \cdot \cos\frac{\alpha}{2} + G_3 \cdot \cos\alpha + F)\sqrt{2(1-\cos\alpha)} - G_2 \cdot \sin\frac{\alpha}{2}}{1-\sqrt{2(1-\cos\alpha)} \cdot \mu} = 94.4\ (\mathrm{kN}),$$

$T_1 = f_1 \cdot \frac{d}{2} = F_2 \cdot \mu \cdot \frac{d}{2} = 1{,}378.2$ (N·m),

$T_2 = f_2 \cdot \frac{d}{2} = G_3 \cdot \sin\alpha \cdot \mu \cdot \frac{d}{2} = 281$ (N·m),

$T_2' = f_2 \cdot \frac{d}{2} = (G_3 \cdot \sin\alpha \cdot \mu + G \cdot \sin\alpha \cdot \mu) \cdot \frac{d}{2} = 685.6$ (N·m),

$T_1 + T_2 = 1{,}378.2 + 281.0 = 1{,}659.2$ (N·m),

$T_1 + T_2' = 1{,}378.2 + 685.6 = 2{,}063.8$ (N·m),

T_2'—The sum of counter torque generated by the string lower friction part and fish.

3. THE RESULTS AND THE FIELD TESTS

(a) The load of uniformly lifting the string is 287.5 kN, while the load of lowering it is 224.5 kN, so the difference of the two loads is 63 kN; the solution force got by fish top is 231.2 kN when jam is released to 600 kN, the load loss is 81.3 kN and it accounts for a quarter of the rise load.

(b) The torque that can make string rotate uniformly is calculated to be 1,104.5 N·m, with the carry load increasing, the friction torque of string also increases, that has effects on string's back-off and leads to a wrong position.

(c) In the actual construction, the load of string is verified. The load of lifting the string uniformly is 290 kN, while the load of lowering the string uniformly is 220 kN, and the difference is 70 kN. Oil pipe wrench torque table shows 940 N·m when turning a string uniformly. It is found that the loads in lifting and lowering process are basically identical with calculated results. The error of rotating torque is larger a little (74 N·m), through the analysis the influence of tubing string couplings diameter leads to a bit larger error but still in the acceptable range. The results above illustrate that calculation formula can meet the needs for all kinds of force and torque analysis.

(d) In the construction using drill pipe, due to the large diameter of drill pipe couplings and large area of cross-sectional, the friction between the casing and drill pipe will further increase, that can have large effects on treatment success rate of all kinds of the conventional technology in the construction of highly-deviated and horizontal wells.

CONCLUSION

(a) Force analysis and calculation of workover string in the highly-deviated and horizontal well is the basis of designing and checking string strength, selecting tools and determining operation parameters, which determines the operation safety and success of engineering accidence treatment.

(b) Force analysis of workover string in the highly-deviated and horizontal well must consider the factors of well structure, string combination, string load as well as the operation condition. The calculation of string load and the friction in every operation condition must consider the buckle deformation of the string and the constrain of the well structure and the fish.

(c) Through the calculation methods and simplified formula of workover string load, deformation and stress in highly-deviated and horizontal wells, the mechanics calculation about the downhole strings is made and the results id verified. Through the safety factor, the string assembly, tool selection and operation parameter optimization can be achieved, which can improve the safety and success rates of workover engineering accident treatment.

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