

Working String Axial Force in L-Shaped Oil Well

L S Wang*, B K Gao and L Gao

Department of Petroleum Engineering, China University of Petroleum-Beijing,
Beijing, 102249, China

Email: pewangls@163.com.

Abstract. The bottom section of a L-shaped well warps upward, so it is a different type against normal horizontal well and should be designed carefully. With regard to the peculiar geometry of borehole, in this paper, the working string axial force is calculated and the feasibility of string running in and out the hole is discussed. String buckling and bottom sticking are considered. This papers suggested that the tip-tilted section makes string tripping in more difficult, while makes tripping out easier; during tripping out, the ratio between the increase of hook load and sticking force is a certain value; string buckling begins at the kick of point firstly and at the target secondly during tripping in; the friction caused by buckling in the L-shaped well is more obvious than in normal horizontal well; the smaller the string size is, the shorter the largest extending length will be.

1. Introduction

For the exploration of unconventional reservoirs, some special well types have been developed, such as directional wells, horizontal wells, large extended wells and etc. In China, horizontal well is usually the well which deviation angle is not less than 86° and extended to certain length in the reservoir [1]. Currently, although the deviation angle of most horizontal wells is 90° , the deviation angle of certain well is greater than 90° , which is defined as L-shaped well in this paper.

Tubular string, such as drill stem, tubing and casing, plays an important role in the process of well drilling and completion. Working string confronts various difficulties because borehole is narrow and down-hole condition is complicated. In the area of tubular string mechanics, many scholars have made a large number of researches: In 1950, Lubinski researched the buckling behavior of strings in the vertical borehole and calculated the critical load of buckling ignoring the gravity[2]; In 1984, Johan Sick analyzed the mechanics of strings in the whole wellbore and calculated the axial force by the method of iteration from bottom to the wellhead[3]. Sheppard revised Johan Sick's method by taking drilling fluid viscosity and string inner and outer pressure differential into consideration[4]; Without ignoring the effect of gravity, Yu-che Chen, in 1990, calculated the critical load of buckling in horizontal well[5]; Gao Deli and Gao Baokui calculated the critical load of helical buckling in deviated well section and contact force between pipe and wellbore after buckling[6]; Han Zhiyong studied the method to calculate the real axial force in vertical, horizontal, and deviated wellbore[7]. In 2008, S.Menand established mechanic model of minor-sized string and studied the influence on critical load when string rotated [8].

In horizontal well, focuses of string mechanics investigation are mainly on strength check, friction calculating, tripping feasibility and extending limits. L-shaped well faces more mechanic difficulties compared with conventional horizontal wells since its bottom section warps upward against the



horizontal plane. In the process of tripping in, working strings is easier to get buckling because of the increase of friction and compression; while in the process of tripping out, it's easier to extract the strings. The transfer coefficient of hook load and bottom hole sticking load is different between L-shaped well and normal horizontal well when sticking occur. However, the previous researches didn't focus on L-shaped well. Therefore, it's necessary to calculate the friction and axial force of the working strings in L-shaped well, and analyze their tripping capacity in order to direct the practical construction.

2. Analyses of String Mechanics

2.1. Description of wellbore and assumptions

A typical L-shaped well trajectory is shown in Figure 1 a), where AB is vertical section, BC is curved section and CD is tip-tilted deviated section.

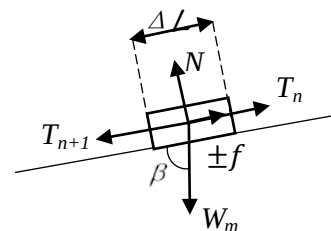
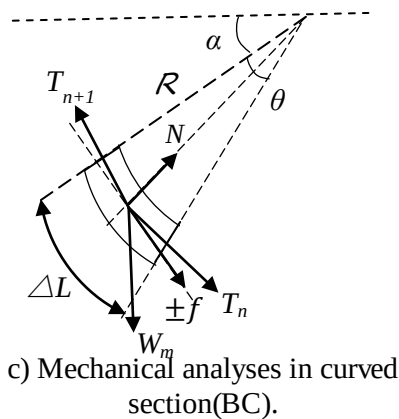
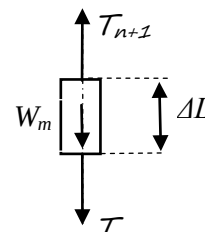
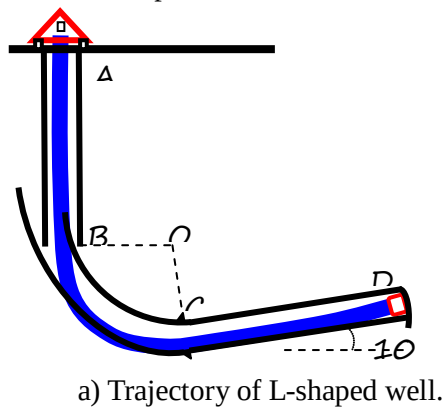


Figure 1. Trajectory of conceptual L-shaped well and Mechanic analyses

In this paper the following assumptions are used: the influence of pipe couplings and steps of are ignored; the friction coefficients in casing section and bare section are constant respectively; axial tension is positive while compression is negative; and no pipe buckling occurs in curved borehole section.

2.2. String mechanic analyses in vertical section

Taking a micro-section from string in the vertical section, then the mechanic analyses without buckling is shown in Figure 1 b).

In Figure 1 b), T_{n+1} is axial load in upper section, kN; T_n is axial load in lower section, kN; W_m is unit weight of string in drilling fluid, kN/m; $W_m = W_a \times (1 - \rho_m / \rho_s)$; W_a is unit weight of string in air, kN/m; ρ_m is fluid density, g/cm³; ρ_s is steel density, g/cm³; ΔL is the length of micro-section, m.

According to the mechanic equivalent

$$T_{n+1} = T_n + W_m \times L \quad (1)$$

Buckling is likely to happen when the string axial force is compressive and greater than the critical force. String buckling, which will increase the contact force and friction, should be considered for calculating axial force distribution.

The critical force of helical buckling in the vertical section is [5]:

$$F_{hel} = 5.5 \sqrt{EI W_m^2} \quad (2)$$

Where F_{hel} is the critical force in vertical section, kN; EI is bending rigidity, kPa·m⁴.

The contact force between string and borehole wall caused by buckling is

$$N = r F^2 / (4EI) + W_m \sin \beta \quad (3)$$

Where N is the contact force, kN/m; r is the clearance between string and bore wall, m; F is the axial force, kN; β is deviation angle, rad.

The friction caused by buckling is

$$f = \mu \times N \quad (4)$$

Where f is the friction caused by buckling, kN; μ is the friction coefficient.

2.3. String mechanical analyses in curved section

In curved section, string may partly contact with upper wall and the rest contact with the lower wall. Without loss of generality, this paper takes a micro-section n, with angle θ , which contacts with the lower wall, to analyze the mechanical condition, as shown in Figure 1 c) [9].

In Figure 1 c), α is the angle between upper section and horizontal level, rad; θ is the angle of micro-section, rad; R is radius of the curve section, m; N is unit contact force between micro-section and bore wall, kN/m.

From normal force equilibrium, we have

$$W_m \times R \times \theta \times \sin(\alpha + \frac{\theta}{2}) = N \times R \times \theta + (T_{n+1} + T_n) \times \sin(\frac{\theta}{2}) \quad (5)$$

The contact force N can be derived from equation (5)

$$N = W_m \times \sin(\alpha) - \frac{T(\alpha)}{R} \quad (6)$$

When $N \geq 0$, string contacts with the lower wall; when $N < 0$, string contacts with upper wall.

From tangential force equilibrium, we have

$$T_{n+1} \times \cos(\frac{\theta}{2}) = T_n \times \cos(\frac{\theta}{2}) + W_m \times R \times \theta \times \cos(\alpha + \frac{\theta}{2}) \pm |f| \quad (7)$$

In the last term of equation (7), positive sign means tripping out, while negative sign means tripping in.

2.4. String mechanical analyses in deviated section

Take a micro string section from tip-tilted deviated section, as shown in Figure 1 d), β is the deviation angle.

From normal force equilibrium, we have

$$N = W_m \times L \times \sin \beta \quad (8)$$

From axial force equilibrium, we have

$$T_{n+1} + W_m \times L \times \cos \beta = T_n \pm f \quad (9)$$

So the axial force, T_{n+1} , can be derived from equation (8) and (9)

$$T_{n+1} = W_m \times L \times (\pm \mu \times \sin \beta - \cos \beta) + T_n \quad (10)$$

In the second term of equation (10), positive sign means tripping out, while negative sign means tripping in.

If the axial compressive force is greater than the critical force, the friction caused by buckling should be taken into consideration.

The critical force of helical buckling in deviated section is^[5]

$$F_{hel} = 2 \sqrt{\frac{2EIW_m \sin \beta}{r}} \quad (11)$$

Where F_{hel} is the critical force in deviated section, kN.

The equations of contact force and friction are same as equation (2) and (3).

3. Case Study

Take a conceptual L-shaped well for example, as shown in Figure 1 a). Main parameters of wellbore and working string are listed in Table 1.

Table 1. Main parameters of wellbore and working string

Parameter	Value
Length of vertical section AB (m)	2000
Radius of curvature of curved section BC (m)	150
Length of section CD (m)	2000
Inclination angle of section CD (°)	100
Hole diameter of section CD (mm)	152.4
Friction coefficient in section CD	0.25
Casing diameter of section AC (mm)	177.8
Wall thickness of casing section AC (mm)	8.05
Friction coefficient in section AC	0.15
Density of working fluid (g/cm ³)	1.05
External diameter of tubing (mm)	114.3
Internal diameter of tubing (mm)	88.9
Unit weight of tubing (kg/m)	32.14
Density of tubing material (g/cm ³)	7.85

3.1. Axial force sensitivity to deviation

The string axial force distributions while tripping in and tripping out are drawn in Figure 2 a) and Figure 2 b) respectively. In order to investigate the influence of inclination of deviated section, Figure 2 gives the axial force curves corresponding to deviation angle of 80°, 90°, 100° and 105°.

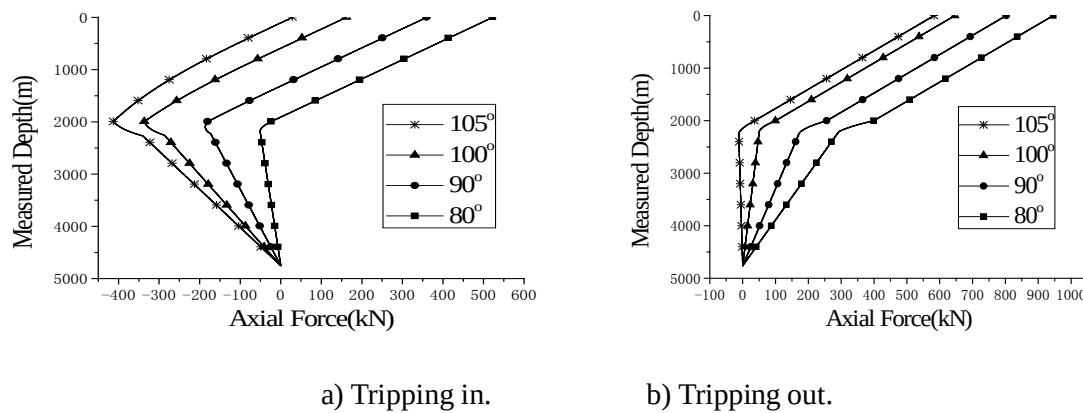


Figure 2. Axial force under different inclination

Figure 2 a) illustrates that, in the process of tripping in, the hook load decreases with the increase of inclination. Hook load approaches zero when inclination increases to about 105°, and it's hard to tripping in in this condition. This means that the tip-tilted section diminishes the capacity of tripping in.

Figure 2 b) shows that, in the process of tripping out, hook load decreases when inclination increases, which means it's easier to tripping out.

3.2. Axial force sensitivity to sticking force

Axial force will be changed if string is stuck at bottom during tripping in or out. The axial forces correspond to different sticking force is shown in Figure 3.

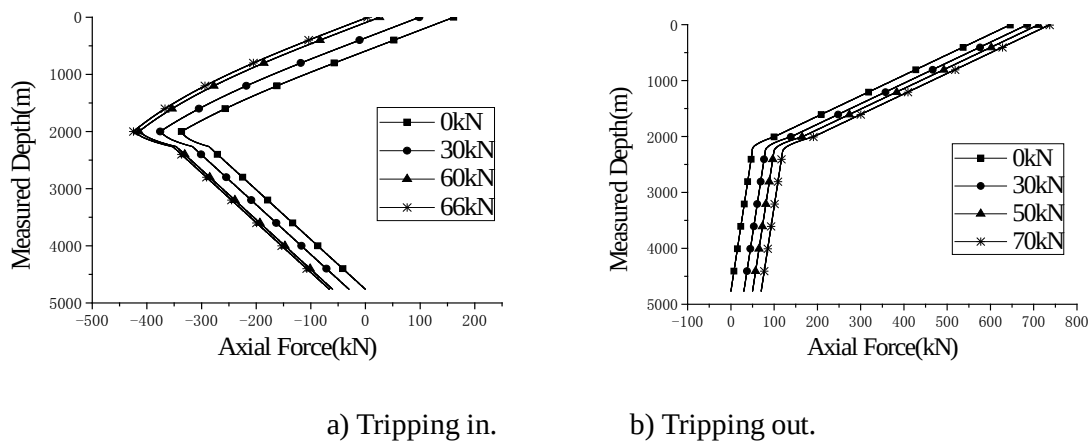


Figure 3. Axial force under different sticking force

In Figure 3 a), hook load is diminishing with the increase of sticking force. Additionally, compression is pretty large during tripping in. Thus the larger sticking force is, the severer buckling will be. It should be noticed that ratio of hook load and sticking force is not a constant value because of buckling.

From Figure 3 b), it is obvious that, in the process of tripping out, hook load increases with the increase of sticking force, and the ratio between hook load change and sticking force is constant. The reason why the ratio is constant is that buckling doesn't happen.

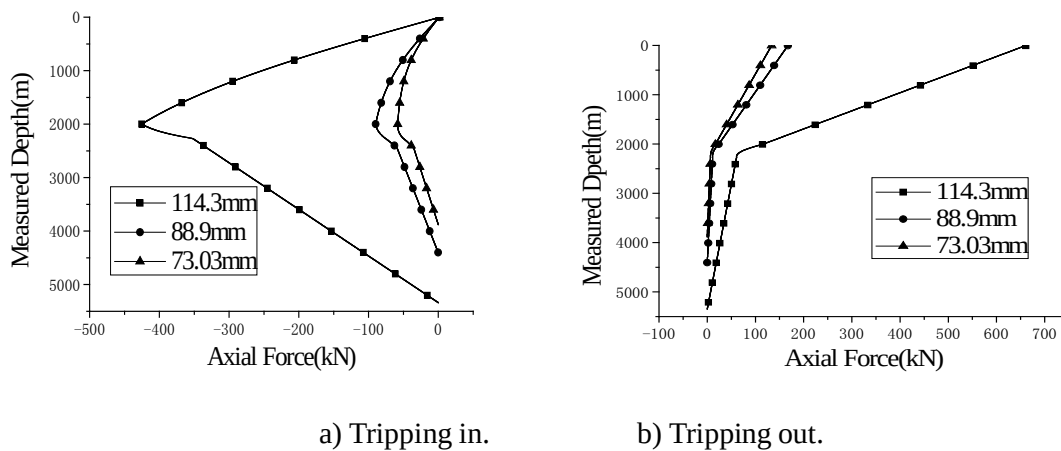
3.3. Axial force sensitive to string size

Now, change the string dimension, as listed in Table 2.

Table 2. String parameters

External diameter (mm)	Internal diameter (mm)	Unit weight in air (Nm^{-1})
114.3	88.9	315.293
88.9	80.98	82.89
73.03	65.11	67.42

According to the consequence of axial force calculating, the largest extending length of 114.3mm string is 5340m. However, if drilling operators use 88.9mm string or 73.03mm string, the largest extending length will diminish because the severe buckling happens in vertical and deviated section. The consequence of calculating shows that 88.9mm string's largest extending length is 4410m, and 73.03mm string is 3883m. The axial force distributions of tripping in and out of different string size are shown in Figure 4.

**Figure 4.** Axial force with different string sizes

4. Conclusions and Suggestions

According to the analysis above, certain conclusions can be drawn:

- (1) The design of L-shaped well should take string tripping feasibility into consideration. String is harder to tripping in in L-shaped well compared with conventional horizontal well, but easier to tripping out.
- (2) If string is stuck in L well during the process of tripping out, the ratio between changes of hook load and sticking force is constant. But the ratio is not constant during tripping in because of severe buckling.
- (3) The string size used in L-shaped well also should be chosen carefully, since the smaller the diameter is, the shorter the largest extending length will be.
- (4) In L-shaped well, tripping out doesn't lead to buckling. However, during tripping in, buckling is more likely to happen compared to conventional horizontal well both at vertical and deviated section.

Acknowledgments

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