PETROLEUM ENGINEERING

Casing Design Considerations for Horizontal Wells

Abdel-Alim Hashem* and Fouad Khalaf**

**Petroleum and Engineering Department, King Saud University, Riyadh, Saudi Arabia*
***Ministry of Petroleum & Metal Engineering Deptartment,*
Cairo University, Cairo, Egypt

(Received 25/12/1991; accepted for publication 26/10/1992)

Abstract. Horizontal Drilling is now a well established technique with growing popularity for exploiting a number of reservoirs which would otherwise be noncommercial. However, a horizontal well requires a substantial engineering work compared to conventional directional drilling. Significant advances in drilling technology have made it possible to drill horizontally in almost any situation by using very specialized tools. But some inherent weaknesses to this technique still exist, like casing design. Most of the reported horizontal wells are completed with open hole or slotted linear. This type of completion is simple and inexpensive, but may not furnish enough support to the walls of the well to allow for long well life.

This paper discusses casing design considerations for horizontal wells. It addresses the type and nature of loads applied on casing strings set in horizontal wells; examples of these loads are torque and drag, formation subsidence, effect of perforations, and bending loads. A design method for casing string under loads that prevail in horizontal wells is also included. The proposed design method shows that the horizontal section needs high collapse resistance pipe or thick-wall pipe to avoid casing failure due to non-conventional loads that prevails in horizontal wells.

Nomenclatures

A	=	cross section area of steel, sq. in.
Fn	=	net normal force acting on element, lb
Ft	=	axial tension force at lower end of element, lb
δFt	=	increase in tension over length of element, lb.
k.o.p	=	kick-off-point
L	=	total axial load, lb.
L_b	=	bending load, lb.
L_d	=	drag force, lb.
L_p	=	pulling load, lb.
L_r	=	running load, lb.

L_r	=	running load, lb.
M	=	torsion at lower end of element, ft. lb.
δM	=	increase in torsion over length of element, ft. lb.
P_c	=	collapse resistance of casting without tensile axial load, psi.
P_{cc}	=	collapse resistance of casing with tensile axial load, psi.
S_0	=	average yield strength of steel, psi.
T.V.D.	=	true vertical depth, ft.
T.S.F.	=	tension safety factor.
r	=	actual radius of pipe element, ft.
W	=	buoyed weight of pipe element, lb.
α	=	azimuth angle, degree or radians.
$\delta\alpha$	=	increase in azimuth angle over length of element, degree or radians.
θ	=	inclination angle, degree or radians.
$\delta\theta$	=	increase in inclination angle over length of element, degree or radians.
θ'	=	average inclination angle, degree or radians.
μ	=	sliding friction coefficient between casing and wellbore.

Introduction

Little publications have addressed the problems of casing design for a horizontal well. However, horizontal technology is now considered a well established technique after developing many equipment used to drill horizontal wells under variety of operational conditions. A horizontal well can be classified as a "short", "medium" and "long radius" well depending on the build-up rate or the radius of curvature it describes [1]. Wells with long radius build inclination at 2 to 6°/100 ft (30 m) with a horizontal displacement section extending up to 3000 ft (914 m). Wells with a medium radius drilling technique change from vertical to horizontal at 8 to 20°/100 ft with a horizontal length extends 1000 feet or more. Wells with a short radius systems, in comparison, change angle at 1.5 to 3° per foot (0.3 m) to have wellbore geometry from vertical to horizontal in 20 to 60 ft. Because of difficulties of cementing horizontal sections and due to the unknowns of casing design for horizontal wells, most of horizontal wells drilled worldwide are completed as open hole.

Open hole completion has some disadvantages; it restricts the production rate due to hole stability problem and the possibility of borehole failure. Studies made on this problem showed that there is a certain limit for applying a bottom hole pressure as well as a pressure draw down [2]. Moreover, open hole completion does not allow the use of pumping technique for production from horizontal well. To minimize the disadvantages of open hole completion, casing and cementing is to be recommended in horizontal well.

Casing design for horizontal well as well as for conventional wells depends on the loads applied on casing string. Casing loads in the horizontal well are not different than those developed in conventional well. However, there is a distinct difference in the magnitude of those loads. The most critical loads applied on casing in a horizontal well are bending load, torque and drag, and point and line loads resulting from formation subsidence. Moreocever, the performation intensity may reduce the crushing resistance of the casing pipe. These factors may overshadow more traditional parameters of internal yield, collapse, and tension of conventional design procedures.

According to the well trajectory, Fig. 1, the well path can be divided into three intervals: horizontal section, build up section, and vertical section. Each section has its own load conditions and sometimes differs from the others. This paper discusses the loads that apply on casing strings in horizontal wells through the three specified intervals of the well path, clarifies the effect of these loads on the resistance of the pipe, and shows how to select casing strings for horizontal wells.

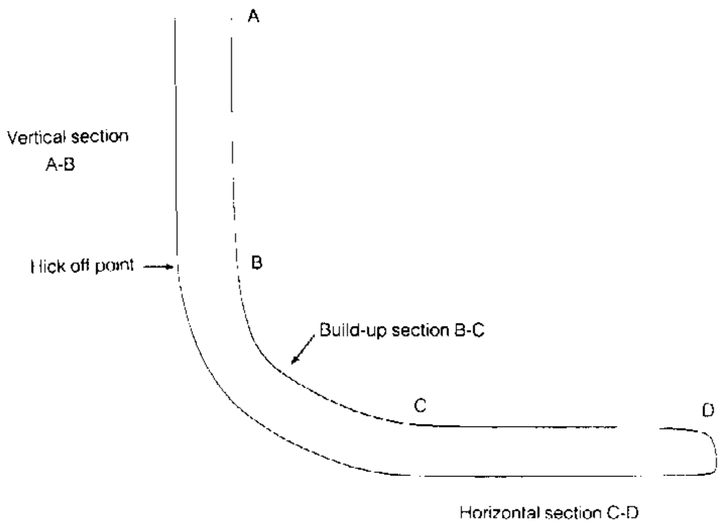

Fig. 1. Well bore sketch: Important design points.

Horizontal Section

Depending on the inclination angle, the well path in this section is horizontal or nearly horizontal. The inclination angle of a horizontal well lies between 80 and 90° depending on the dipping angle of the reservoir formation. Besides the traditional loads of the conventional procedures, this section is subjected to torque and drag forces, effect of perforation on collapse resistance, and formation subsidence. Torque and drag can be caused entirely by sliding friction forces that result from the contact of the pipe to the bore hole. Two factors affect wellbore sliding friction-the normal contact force and the coefficient of friction between casing and formation. The product of the two factors represents the magnitude of the sliding friction forces [2]. The normal contact forces between the casing string and the wall of the hole mainly depends on the effect of pipe weight and the effect of tension and compression applied on the casing. The value of sliding friction coefficient depends on the specified contacting materials and the degree of lubrication at various places in the wellbore, mainly affected by mud type.

Using the basics given in references [3,4 and 5] and illustrations shown in Fig. 2, the magnitude of the normal force that apply on a pipe can be expressed as follows:

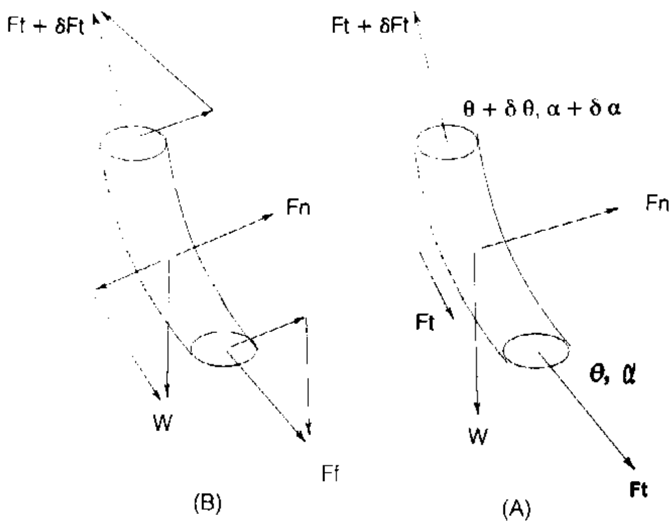

Fig. 2. Pipe element (A) and load analysis (B).

$$Fn = [\,(Ft\delta\alpha \sin\theta')^2 + (Ft\delta\theta - W\sin\theta')^2]^{1/2} \qquad ..... (1)$$

and the increment in tension at any element is

$$\delta Ft = W \cos\theta' \pm \mu\, Fn \qquad ..... (2)$$

and the torsion increment is

$$\delta M = \mu\, Fn\, r \qquad ..... (3)$$

The plus or minus sign reflects the direction of pipe motion either up or down; the plus sign is for upward motion where friction adds to the axial loads and the minus sign is for downward motion. The value of the coefficient of friction varies between 0.2 and 0.4 depending on the type of mud in hole and the formation type. Using a computer program designed by the authors, the drag forces or drag loads (L_d) are determined along the horizontal section for both closed ends and open ends casing strings of different sizes landed at different true vertical depths.

The calculations are carried out for three casing sizes (5″, 18#; 7″, 26#; and 9-5/8″, 47#) set in a horizontal well with different horizontal sections ranging from zero to 4000′. The true vertical depth of the horizontal well is assumed to be 6000 feet. The pipe is considered as open ended pipe and the coefficient of friction is taken as 0.4. The results are plotted in Fig. 3. This figures shows the load applied at point (C) of Fig. 1, required to push the casing through the horizontal section. This load increases by increasing lateral section, casing size and true vertical depth.

The calculations are devoted to 5 inch casing pipe having a normal weight of 18 lb/ft. The results are plotted in Figs. 4 and 5, which give the running load (L_r) applied at point (C) required to push the casing through the horizontal section for both open and closed ended casing. This load increases by increasing the horizontal displacement for open ended casing. For closed ended casing, the load depends on the horizontal distance, the true vertical depth, and mud weight and equals the sum of the buoyancy and the drag forces. The drag force is the same for both closed and open ended casing while the buoyancy force for closed ended casing is function of the outside area of the casing. For exampe, the drag force in a 3000 ft horizontal displacement at 6000 ft true vertical depth is about 18576 pound. Taking into consideration the effect of buoyancy, the running load for a closed ended casing applied at point (C) is 51150. This load can actually cause casing damage while running-in and it is recommended to be considered in casing design. This drag acts as a compression load in case of casing running-in and as a tension load while pulling-up the string, while the buoyancy acts as a compression in both running-in and pulling-up.

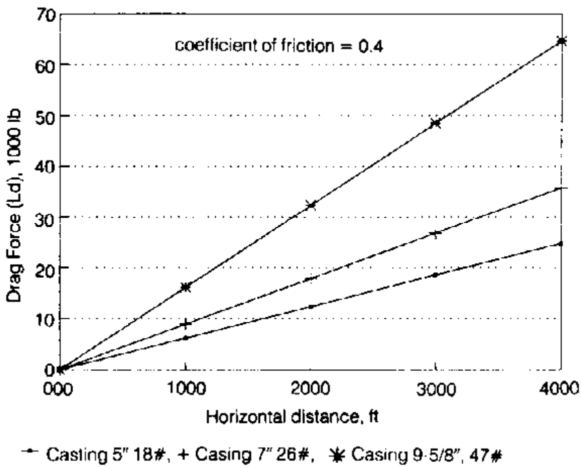

Fig. 3. Drag force on casing due to horizontal section.

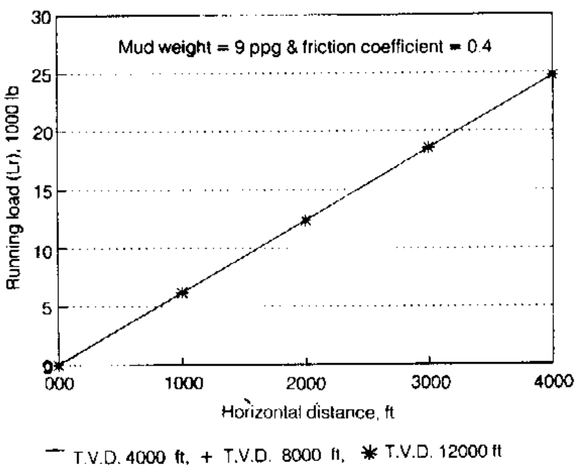

Fig. 4. Running load applied at point (C) on open-end horizontal casing string (casing 5", 18#).

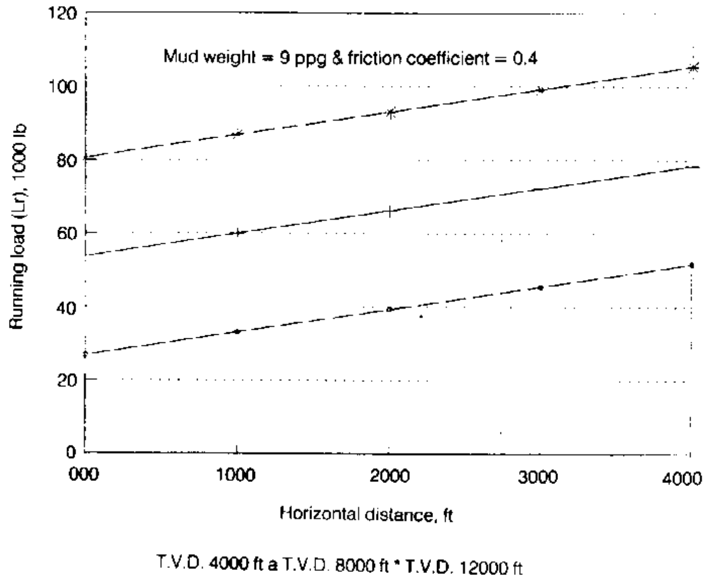

Fig. 5. Running load applied at point (C) on closed horizontal casing string (casing 5", 18#).

The second major factor in the load considerations is the formation subsidence which results in a nonuniform load on the casing string equivalent to the overburden load [6], specially in case of poor cement job. A previous work [6], proved that the collapse resistance of casing pipe under that type of load will be reduced to about 25% of its original collapse resistance. According to those results, the casing string may suffer major collapse problem after running-in if this load is discarded from the design procedures. To avoid such failure a proposed collapse safety factor, named formation subsidence safety factor with a value of 2.0 is used with the overburden pressure to select the specified casing.

The third factor is the effect of perforations on the casing resistance which depends on the intensity of the perforations per longitudinal foot. Experiments made by King [7] showed that a perforation intensity higher than 4 perforations per foot reduces the crushing resistance of the pipe by 10 to 60 percent of its original resistance. The crushing resistance has normally a direct relationship to the collapse resistance and its reduction may cause collapse failure of pipe. Depending n the intensity of perforations, a perforation factor is assumed to correct the collapse resistance of horizontal sections. Figure 7 shows this load as a function of the build-up rate. It shows that the load increases in nonlinear manner till a rate of about 25°/100 ft. For rates from 25° and 45°/100 ft, the load stays constant and then above 45°/100 ft it starts to decrease again. This phenomenon is mainly due to decrease of the measured depth through the build-up section by increasing the build-up rate and is due to the decrease of the component of load that affected the drag force.

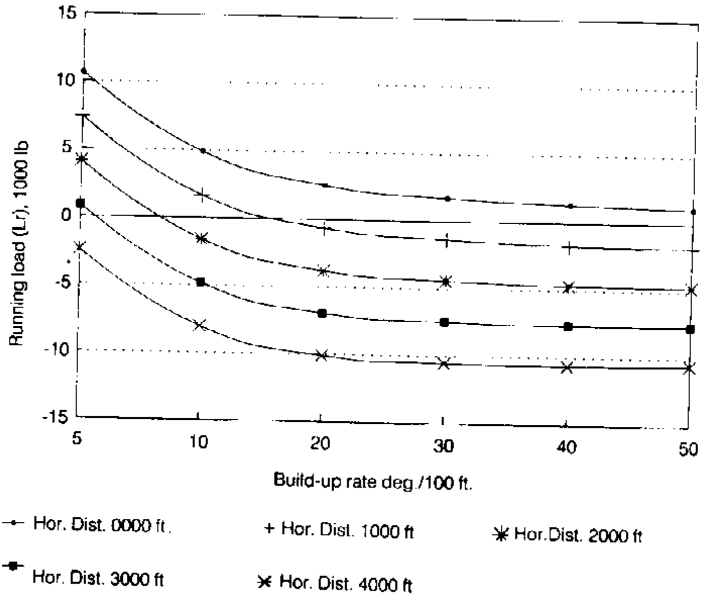

Fig. 7. Running load at k.o.p., point (B) function of build-up rate (casing 5", 18#).

In case of pulling-up the string, the drag force will result in a tension load at point (B). For the same previous example, the running load (Lr) at point (B) during running the 5 inch casing, 18 lb/ft, in a horizontal section of 3000 ft and at a rate of 20°/100 ft is 6950 pounds, compression load, while the pulling-up load (L_p) at the same point is 41250 pounds, tension load, Fig. 8. This means that during reciprocation the point (B) will be subjected to a load changed between −6950 pound and +41250 pound.

The second major load in the build-up section is the bending load (L_b). The load can be calculated by the following equation:

$$L_b = 63\,80\ W\ D \qquad \text{..... (4)}$$

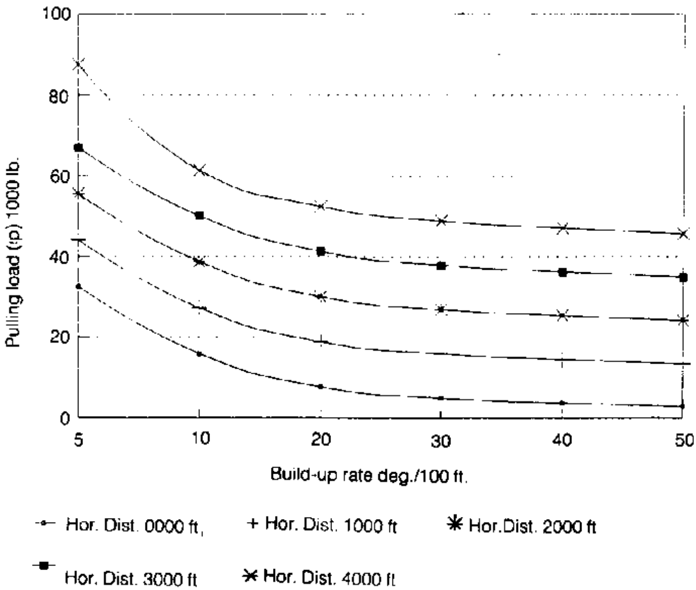

Fig. 8. Pulling-up load applied on open end closed casing string at k.o.p. (casing 5", 18#).

This load increases linearly with the build-up rate (see Fig. 9) and results in a compression load on the convex side of the pipe and in tension load on the concave one. For the previous example, this load is ± 113400 pound. By adding this value to the running or pulling load at point B, the casing string will be subjected to a compression load of 120350 pound and a tension load of 154650 pound which may cause joint failure in casing string.

Vertical Section

In the vertical section of the well, the load is maximum at point (A), see Fig. 1. This load is the sum of the weight of casing string from surface to the kick-off-point and the load at point B. For the previous example, the kick-off-point lies at 5715 true vertical depth. This section results in a load of 88470 pound and the tension load at point B is 41250 pound. This means that at point (A) the casing will be subjected to 129720 pound during pulling-up compared to 154650 pounds for point B. It is clear therfore, that the maximum compound load in the string lies at the point B due to both drag and bending during pulling-up the string. Meanwhile, the horizontal sec-

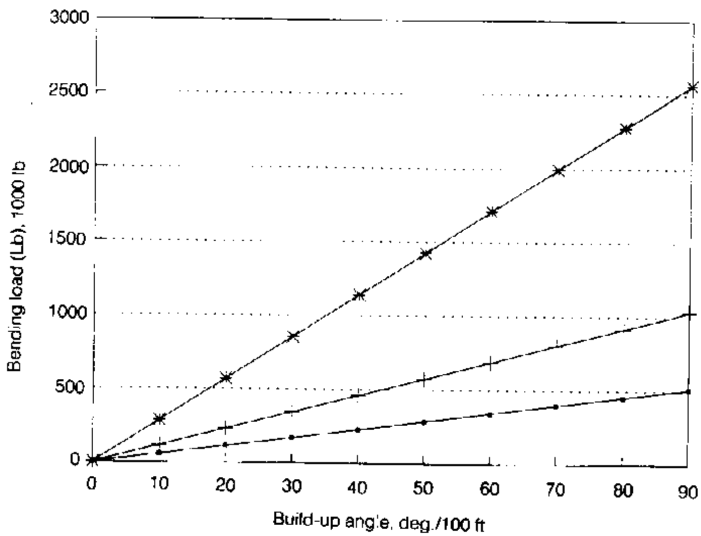

Fig. 9. Bending load on casing due to rates of build-up.

tion will be subjected to nonuniform load that reduces the collapse strength to about 25% of its original resistasnce. The following procedure shows how to select a casing string for such a horizontal well based on the previous analysis.

Design Procedures

The proposed design method is based on biaxial collapse resistance of casing pipe, Fig. 10, which incorporates the conventional loads, and the loads due to horizontal configuration, discussed previously. This biaxial curve is available in text books or can be constructed according to the following biaxial stress formula (5).

$$P_{cc} = \frac{LP_c}{2AS_o} \left\{ [4(AS_o/L)^2 - 3]^{1/2} - 1 \right\} \quad \ldots\ldots (5)$$

The design begins from the total depth of the well, point (D) to the surface, point (A). Assuming a 5 inch casing to be set in a 6000 feet true vertical depth well with 3000 feet horizontal displacement and buil-up angle of 20°/100 ft, this method is illustrated through the following example.

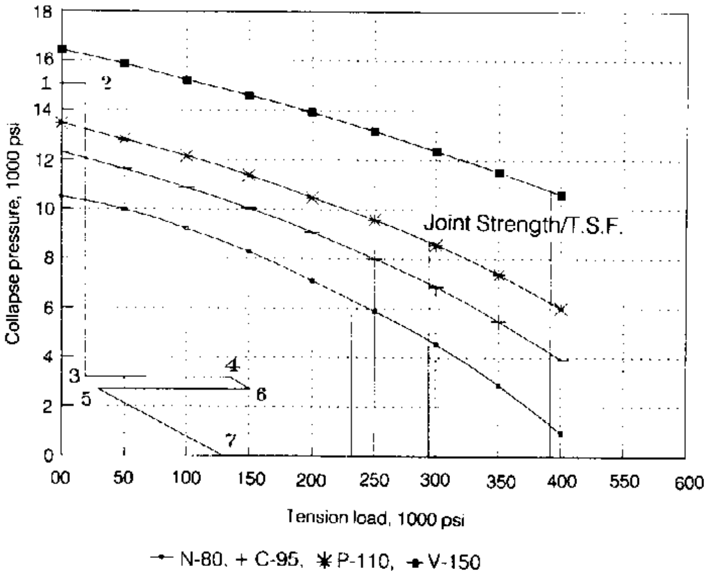

Fig. 10. Graphical design method of 5", 18# of a horizontal well.

1. Calculate the overburden pressure at the bottom of the well, point (D). Using overburden pressure gradient of 1.0 psi/ft, this value will be 6000 psi.

2. Correct this value to meet the nonuniform load and the effect of perforation by multiplying this value by nonuniform and perforation correction factor. The correct value is 15000 psi, using correction factors 2 and 1.25, respectively for nonuniform load and perforations.

3. Plot the corrected value on the biaxial relationship curve Fig. 10, point (1).

4. Calculate the normal collapse pressure at point (C) using the normal collapse pressure formula which is the value of the hydrostatic pressure at that point (C). This value will be 3180 psi.

5. Calculate the pulling-up load at point (C) using the computer program (18570 lb) and plot it on the same figure using the corrected value of overburden pressure and the normal collapse pressure, points (2) and (3).

6. Calculate the load and the normal hydrostatic pressure (3185 psi) and the pulling-up load at point (B) using the computer program, 131970 lb, and determine the position of point (4).

7. Calculate the bending load through the build-up section using equation (4), 113400 lb, and add its value to the line from 3 to 4 to become 5 to 6.

8. Calculate the load at point (A) which is equal to the casing weight at the end of the vertical section and the pulling-up at point (B), 129720 lb, and plot point (7).

9. Follow the line 1-2-3-5-6-4-7 and choose the grade that possess a resistance curve covering each section.

In this example, the grade V-150 is recommended for the horizontal section and N-80 for both build-up and vertical sections. This method neglects the torque applied on casing during rotation of string, the compression design of the tool joints, and the biaxial compression effect. These factors will be discussed in later publications.

Conclusions

From the previous analysis and discussions, the following conclusions can be recommended:

1. The drag force, formation subsidence, effect of perforations, and bending loads as well as the conventional loads are the major loads applied on casing strings set in horizontal wells. These loads can cause major casing failure if they are not considered in the design. The drag force depends on the type of mud and the drilled formation. This load is compressive in case of running in the string and tensile in case of pulling up.

2. Formation subsidence produces nonuniform overburden load acting as a point line load on the pipe and reduces the collapse resistance drastically. This reduction can reach to about 25 percent of its original resistance.

3. Perforation technique results in a reduction of 10 to 60 percent of the crushing resistance as well as the collapse resistance of the pipe depending on the intensity of the perforations.

4. The proposed design method calculates the loads applied on the horizontal sting, proposed two new factors to correct the loads for horizontal loading conditions, namely formation subsidence factor of 2.0 and perforation effect factor of 1.11, and allows the selection of the proper specified pipe to be run in a horizontal well.

References

[1] Karlsson, H.; Cobbley, R. and Jaques, G.E. "New Developments in Short-, Medium-, and Long-Radius Lateral Drilling." SPE/IADC 18706, presented at *1989 SPE/IADC Drilling Conference* held in New Orleans, Louisiana, February 28 - March 3, 1989.

[2] El-Sayed, A.H. "Maximum Allowable Production Rates From Open Hole Horizontal Wells." SPE 21383, *SPE Middle East Oil Conference* held in Manama, Bahrain, (Nov. 1991), 16-19.

[3] Johancsik, C.A.; Friesen, D.B. and Dawson, R. "Torque and Drag in Directional Wells – Prediction and Measurement." *JPT*, (June 1984), 987-993.

[4] Dawson, R. "Drill Pipe Buckling in Inclined Holes." SPE paper No. 11167, presented at the *57th Annual Fall Technical Conference and Exhibition* held in New Orleans, La, (Sept. 1982), 26-29.

[5] Greenip, John. "How to Design Casing Strings for Horizontal Wells." *Petroleum Engineer International J.* (December 1989), 34-38.

[6] El-Sayed, A.H. and Khalaf, F. "Resistance of Cemented Concentric Casing Strings Under Nonuniform Loads." SPE paper No. 17927 presented at *SPE Middle East Oil Conference* held in Manama, Bahrain, March 9-11, 1989. SPE Drilling Engineering, (March 1992), 59-64.

[7] King, G.E. "Casing Crush Resistance Loss Due to High-Density Perforating: Casing Tests." SPE 20634, presented at the *65th Annual Technical Conference and Exhibition* of the Society of Petroleum Engineers held in New Orleans, (Sept. 1990), 23-26.

[8] Mueller, M.D.; Quintana, J.M. and Bunyak, M.J. "Extended-Reach Drilling From Platform Irene." *SPE Drilling Engineering*, (June 1991), 138-144.

[9] Hackney, R.M. "A New Approach to Casting Design for Salt Formation." SPE/IADC 13431, Presented at 1985 *Drilling Conference* held in New Orleans, (March 1985), 6-8.

اعتبارات تصميم القيسون للآبار الأفقية

عبدالعليم هاشم السيد و فؤاد خلف

كلية الهندسة، قسم هندسة النفط، جامعة الملك سعود، ص.ب ٨٠٠، الرياض ١١٤٢١،
المملكة العربية السعودية وقسم المناجم والبترول والفلزات، جامعة القاهرة، جهورية مصر العربية

(استُلم في ٢٥/١٢/١٩٩١م؛ قُبل للنشر في ٢٦/١٠/١٩٩٢م)

ملخص البحث. يُعَدّ الحفر الأفقي الآن تقنية راسخة ذات شعبية متزايدة لاستغلال العديد من المكامن البترولية والتي كانت تعتبر غير اقتصادية بدل تلك التقينة، علمًا بأن البئر الأفقي يتطلب عمل هندسي جوهري بالمقارنة بالحفر المائل التقليدي. ولقد أُدْخِلت تحسينات مهمة في تقنية الحفر جعلت من الممكن الحفر أفقيًا في أي موقع وذلك باستخدام معدات متخصصة جدًّا لهذا الغرض، ولكن مازال هناك نقاط ضعف ملازمة لهذه التقنية منها على سبيل المثال تصميم القيسون. فمعظم الآبار الأفقية المعلن عنها أُكْمِلَتْ بنظام الحفرة المفتوحة أو الأنابيب المثقبة، ويعتبر هذا النظام بسيط ورخيص ولكنه لا يعطي تدعيم كافٍ لحوائط البئر كما لا يسمح بعمر طويل للإنتاج.

يناقش هذا البحث اعتبارات تصميم القيسون للآبار الأفقية فهو يعنون أنواع وطبيعة الأحمال المؤثرة على أعمدة القيسون المثبتة في الآبار الأفقية على سبيل المثال، أحمال العزم والجر، وخمود الطبقات، وتأثير التخريم وأحمال الثني، كما يحتوي على طريقة لتصميم القيسون تحت الأحمال السائدة في الآبار الأفقية، وتبين طريقة التصميم المقترحة أن القطاع الأفقي من البئر يحتاج إلى أنابيب ذوات قوى تحمل عالية للضغط الخارجي أو أنابيب سميكة حتى لا ينهار القيسون نتيجة الأحمال غير التقليدية السائدة في الآبار الأفقية.