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海底管线开沟埋设时的应力分析

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摘要 海底管线在开沟埋设过程中,在非水平长度段内,高差引起的管线局部弯曲可导致管线承受较大应力。利用材料力学的方法对海底管线的受力作了分析,得出了悬空段长度、悬空段弯矩和管线应力的解析式,并讨论了影响管线开沟应力的一些因素。为方便工程人员设计分析,给出了悬空段长度和管线应力随沟深变化的曲线。

主题词 水下管线 应力分析 管线敷设 管线设计

海底管线是海洋油田油气集输和储运系统的一个重要组成部分。为使管线在波浪和潮流等作用下保持稳定和避免可能出现的机械损伤等,一般需要予以埋设[1]。在开沟埋设过程中,管线将承受较大的应力,因为管线在不太长的局部段内,一定的高差会引起管线局部弯曲。开沟时的管子形态和应力虽然可以借助计算机分析来预测,但这对于工程设计人员来讲,是不便利的,因此笔者推导出悬空段应力的解析公式。

模型简化和公式推导

图1所示是开沟时的一种典型的管子形态。沟深为 Δ,管子在海水中的单位长度重量为 q,AB 段

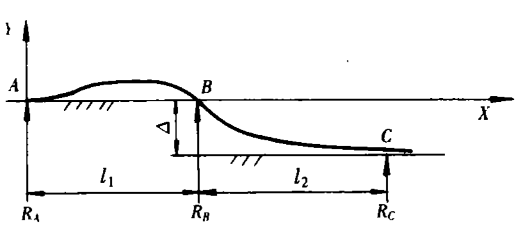

图1 开沟时的管子变形形态

为上部悬空段,设长为 l_1,BC 段为下部悬空段,设长为 l_2,假设基础是刚性的,在基础上的部分管子存在弯矩为零的边界条件,在 A、B、C 点分别作用有三个集中力 R_A、R_B 和 R_C,这三个集中力和图中的悬空长度 l_1 和 l_2 均为未知量。

对于 AB 段,弯矩方程为

$$M(x) = R_A x - qx^2/2 \tag{1}$$

弯曲微分方程为

$$EJy'' = R_A x - qx^2/2 \quad (0 \leqslant x \leqslant l_1) \tag{2}$$

式中 E——杨氏弹性模量;

J——管子横截面惯性矩。对上式逐次积分得

$$EJy' = R_A x^2/2 - qx^3/6 + C_1 \quad (0 \leqslant x \leqslant l_1) \tag{3}$$

$$EJy = R_A x^3/6 - qx^4/24 + C_1 x + C_2 \quad (0 \leqslant x \leqslant l_1) \tag{4}$$

AB 段的边界条件为

$$y''|_{x=0} = 0 \quad y'|_{x=0} = 0 \quad y|_{x=0} = 0 \quad y|_{x=l_1} = 0 \tag{5}$$

第一式自动满足,由后三式可以确定

$$C_1 = C_2 = 0 \tag{6}$$

$$R_A = ql_1/4 \tag{7}$$

由式(3)确定在 B 处的转角为

$$EJy' = R_A l_1^2/2 - ql_1^3/6 = -ql_1^3/24 \tag{8}$$

对于 BC 段,弯曲微分方程为

$$EJy'' = R_A x + R_B(x - l_1) - qx^2/2 \quad (l_1 \leqslant x \leqslant l_1 + l_2) \tag{9}$$

逐次积分得

$$EJy' = R_A x^2/2 + R_B(x - l_1)^2/2 -$$

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$$-qx^3/6 \quad (l_1 \leqslant x \leqslant l_1 + l_2) \qquad (10)$$

$$EJy = R_A x^3/6 + R_B(x - l_1)^3/6 - qx^4/24 + + C_3 x + C_4 \quad (l_1 \leqslant x \leqslant l_1 + l_2) \qquad (11)$$

在 B 点处转角连续，将式(7)代入式(10)，并和式(8)比较得

$$C_3 = 0 \qquad (12)$$

BC 段的边界条件为

$$y|_{x=l_1} = 0 \qquad (13)$$

$$y|_{x=l_1+l_2} = -\Delta \qquad (14)$$

$$y'|_{x=l_1+l_2} = 0 \qquad (15)$$

$$y''|_{x=l_1+l_2} = 0 \qquad (16)$$

由式(13)可以确定

$$C_4 = 0 \qquad (17)$$

将式(10)和(11)代入式(14)、(15)和(16)，得

$$R_A(l_1 + l_2)^3/6 + R_B l_2^3/6 - q(l_1 + l_2)^4/24 = -\Delta/(EJ) \qquad (18)$$

$$R_A(l_1 + l_2)^2/2 + R_B l_2^2/2 - q(l_1 + l_2)^3/6 = 0 \qquad (19)$$

$$R_A(l_1 + l_2) + R_B l_2 - q(l_1 + l_2)^2/2 = 0 \qquad (20)$$

将式(7)代入式(20)，得

$$R_B = q(l_1 + l_2)(l_1/2 + l_2)/(2l_2) \qquad (21)$$

将式(21)代入式(19)，并整理得

$$2(l_2/l_1)^2 - 2l_2/l_1 - 1 = 0 \qquad (22)$$

上式仅有一个正根

$$l_2/l_1 = (1 + \sqrt{3})/2 \approx 1.366 \qquad (23)$$

负根是没有意义的，不予考虑。将式(21)代入式(18)得

$$l_2^4 = \frac{1}{(l_1/l_2)^3 + 2l_1/l_2 - 1}\frac{24EJ\Delta}{q} \approx 51.7059\frac{EJ\Delta}{q} \qquad (24)$$

各段弯矩

AB 为 $\quad M(x) = ql_1x/4 - qx^2/2$

$$(0 \leqslant x \leqslant l_1) \qquad (25)$$

BC 为 $\quad M(x) = ql_1x/4 + 1.616ql_1(x - l_1) -$

$$-qx^2/2 \quad (l_1 \leqslant x \leqslant l_1 + l_2) \qquad (26)$$

根据式(25)和(26)，可以将管子悬空段上的弯矩用图 2 表示，从中可以看出最大弯矩作用在 B 处(见图 1)，其大小为

$$|M_B| \approx 0.1340ql_2^2 = 0.9633\sqrt{qEJ\Delta} \qquad (27)$$

很明显，最大弯矩随管子单位长度的水下重量、抗弯刚度和沟深的增大而增大。

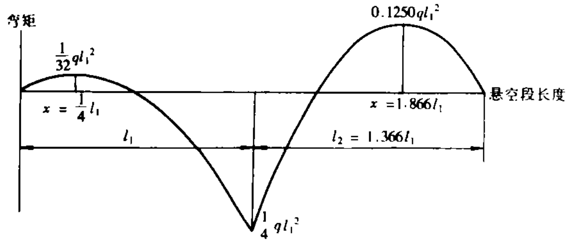

图 2 管子悬空段上的弯矩

根据材料强度，开沟埋设时的管中应力不宜超过许用应力，利用式(27)可以确定最大允许沟深为

$$\Delta_{max} = 1.078([M])^2/(qEJ) \qquad (28)$$

式中 $[M]=[\sigma]W$，$[\sigma]$和 W 分别为管材的许用应力和管截面的抗弯模量。

图 3 和图 4 分别是悬空段长度和管中最大应力随开沟深度变化的曲线。为了将悬空段长度和管中最大应力无量纲化，定义特征长度和特征应力为

$$L_C = (EJ/q)^{1/3} \qquad (29)$$

$$\sigma_C = ED/L_C \qquad (30)$$

式中 D——管子外径。

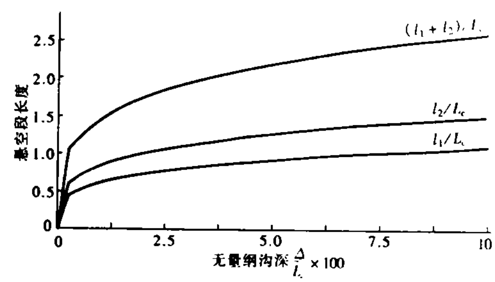

图 3 悬空长度随沟深变化的曲线

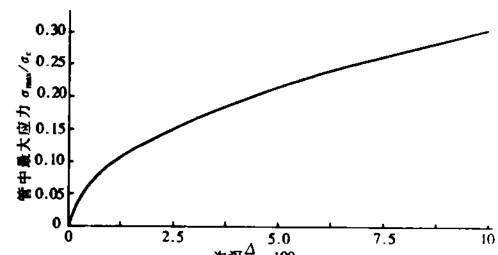

图 4 管中最大应力随沟深变化的曲线

算 例

一外管外径为 273.1mm、壁厚 9.3mm 的双层海底管道，管材的许用应力为 240MPa，开沟深度 2m，分别计算空管和管子充水时的最大应力、悬空段长度和最大允许沟深。表 1 给出了根据式(24)、(27)和(28)得到的计算结果。 (下转第 52 页)

减少和预防各种能量损失的措施

为减少和防止各种能量损失,应采取如下措施:

1. 选择合适的叶栅相对节距,通常叶栅相对节距以选 0.65~0.75 为宜。

2. 采用先扩张后收敛的叶片流道。

3. 涡轮钻具应在所设计的最佳转速下工作。

4. 在铸造涡轮时,应使其叶片的表面尽量光滑。

5. 选择合适的定、转子径向间隙(以 1mm 左右为宜)和轴向间隙(普通涡轮为 14~16mm)。

6. 尽量选择摩擦力较小的滚动轴承。

总之,涡轮钻具在无冲击工况下的能量损失中,水力损失为主要的能量损失。设计涡轮钻具时,应根据其用途尽量避免不必要的损失。

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表 1 算例计算结果

管状况	管单位长度重量(N/m)	管中最大应力(MPa)	悬空段长度 11(m)	悬空段长度 12(m)	最大允许沟深(m)
空管	416	212	43.3	31.7	2.56
管中充水	591	253	39.6	29.00	1.8

计算空管和管子充水时对应的无量纲沟深 $100\Delta/L_C$, 得 6.18 和 6.95, 查图 3 和图 4 同样可得管中最大应力和悬空段长度。

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1986 年至 1989 年, 全世界(除中国和东欧以外)使用炸药震源与可控震源的比例呈上升之势(见表 1)。

表 1 全世界使用炸药震源和可控震源所占比例 %

年份	炸药震源	可控震源	其他
1986	43.7	51.6	4.7
1987	43.8	52.9	3.3
1988	43.2	45.9	10.8
1989	51.2	46.8	2

近 20 年来, 我国共引进约 270 台可控震源, 可以装备 54 个队次; 国产可控震源共生产了 100 台以上。目前, 物探局拥有可控震源队 13 个, 各油田共拥有 14 个队, 另外地矿部还有 3~4 个队, 拥有可控震源约 130 台。

随着勘探区域的变化, 可控震源的需求量越来越大。大于 230kN 的震源为中坚力量, 而大型与小型震源的需求也在不断增长。大型可控震源主要满足深层勘探的需要。另外, 像沙漠地区, 信号衰减严重, 也需增大可控震源的出力; 小型可控震源具有轻便灵活的特点, 适合于河网地区、山地的勘探, 另外在工程勘探方面也具有一定的市场, 如地铁、建筑工地普查、煤田勘探等。

(本文编辑 江先雄)

During oil recovery by rod pump, owing to the elastic stretching and shrinking of the tubing string, the stroke loss of the subsurface pump reaches 10%. After a force analysis of the tubing string, the stretching and shrinking rate of the tubing string is calculated, and the measures for controlling the stretching and shrinking of the tubing string are presented. By adopting these measures, the stroke loss of the pump can be decreased, the pump efficiency can be improved by 3% ~ 15%, and the force condition of the subsurface pump can be improved, the overhaul peroid of the pump can be prolonged and the servic life of the rod and the tubing can be improved. Comparison of three kinds of tools for controlling the stretching and shrinking of the tubing string shows that the hydraulic tubing anchor is the best with convenient operation and low price, therefore it should be popularized.

Subject Concept Terms tubing string stretching and shrinking stroke loss control measure financial profit

Zhu Xiaoping(*Xi'an Petroleum Institute*, *Xi'an*). **Digital simulation for system reliability analysis of air balanced pumping unit.** ***CPM***, 1997, 25(8): 31 ~ 34

Through an analysis of the failure of an air balanced pumping unit system, a fault tree of the system is set up. By using the Monte Carlo method, the samples of every basic element of the system are randomly taken, and according to the logical relation of the fault tree, the influence of the failure of every basic element on the failure of the system is judged. By 20000 times of simulating calculation with an absolute error of less than 0.5%, it is concluded that the mean fault-free working time of the system is 3782.92h, and the accumulative failure probability distributing curve, reliabilty curve and failure probalility distributing curve of the system are presented. Statistic analysis of the degree of importance of the basic elements and the mode shows that the cylinder is the weakest part of the system.

Subject Concept Terms air balanced pumping unit reliability analysis digital simulation

Xing Jiguo(*Jianghan Petroleum Institute*, *Jingzhou City*, *Hubei Province*), Song Jianping, Du Lian. **Integrated test system for rock mechanical properties.** ***CPM***, 1997, 25(8): 35 ~ 36

The newly-developed integrated test system for rock mechanical properties is comprised of main stand, oil circulation control part and electric circuit control part, by which seven property indexes of a rock can be determined by using only one rock sample in a fixed sequence. The principle of the constant-voltage oil circulation and variable-voltage oil circulation and the electric circuit control are emphatically expounded. The integrated test system is small-sized, multifunctional, easy to install and operate.

Subject Concept Terms rock mechanics rock property test system structure

Che Dengxian(*Downhole Technology Research Institute*, *Shengli Petroleum Administration*, *Dongying City*, *Shandong Province*), Liu Huaguo, Yang Yusheng, et al. **Model YZG – Ⅰ tubing transmission hydraulic setting tool.** ***CPM***, 1997, 25(8): 37 ~ 38

In the light of the difficulty in the packing of the oil formation in viscous oil wells, deviated wells and high pressure wells, Model YZG – Ⅰ tubing transmission hydraulic setting tool is designed. The tool is suitable for using in both straight wells and deviated wells, for setting of both ø110 and ø150 drillable bridge plugs. The design feature, working principle and basic parameters of the tool are expounded. Test shows that Model YZG – Ⅰ tubing transmission hydraulic setting tool can meet the need of setting of drillable bridge plug with a resistance to pressure of 100MPa and a releasing force of 300kN.

Subject Concept Terms hydraulic setting tool structural design technical index application

Shuai Jian(*University of Petroleum*, *Beijing*). **Stress analysis of marine pipeline in trench digging and laying.** ***CPM***, 1997, 25(8): 39 ~ 40, 52

In the course of trench digging and laying of the marine pipeline, in the non-horizontal section, the local bending resulted from the height differential may caused the pipeline to bear fairly large stress. The force on the marine pipeline is analyzed by the method of mechanics of materials, and the analytical expressions for the length and bending moment of the suspended section and the stress on the pipeline are worked out, and the factors influencing the stress on the pipeline in trench digging are discussed. For the convenience of the design and analysis by the technicians, the curves of the variation of the length of the suspended section and the stress on the pipeline with the depth of the trench are given.

Subject Concept Terms marine pipeline stress analysis pipeline laying pipeline design

Qu Zhan(*Xi'an Petroleum Institute*, *Xi'an*). **Influence of downhole temperature on inherent frequency of drillstring lateral vibration.** ***CPM***, 1997, 25(8): 41 ~ 42

On the basis of the general expression of the inherent frequency of the drillstring lateral vibration, the influence of the downhole temperature on the inherent frequency of the drillstring lateral vibration is investigated, and the result shows that, the inherent frequency of the drillstring lateral vibration decreases gradually with the rise of the downhole temperature. A specific equation for computing the inherent frequency of the drillstring lateral vibration in consideration of temperature influence is given out, and an example of computation is presented.

Subject Concept Terms drillstring lateral vibration downhole temperature inherent frequency calculation

Liu Hongbin(*Equipment Research Institute*, *Bureau of Geophysical Prospecting*, *CNPC*, *Zhuozhou City*, *Hebei Province*), Chen Ruheng. **Development of seismic source for geophysical exploration.** ***CPM***, 1997, 25(8): 43 ~ 45, 52

The excition sources of the seismic signal include explosive seismic source and non-explosive seismic source in the geophysical prospecting. The former has been used since 1920s, while the later, from the previous weight drop to today's vibroseis, has become a perfect mechanical and electronic equipment, which is suitable for the seismic exploration under complex working conditions and for different geological structures. The development of the non-explosive seismic source is introduced, and the typical structure, principle and some new techniques for the vibroseis are also expounded.

Subject Concept Terms seismic exploration vibroseis structural analysis developing trend

Li Kejian(*Well Logging Group Co.*, *Shengli Petroleum Administration*, *Dongying City*, *Shandong Province*). **Causes of damage of perforating guns and precautions.** ***CPM***, 1997, 25(8): 46 ~ 48

Besides the influence of the well fluid corrosion and the downhole temperature and pressure, the main causes of the damage of the gun body of a perforator lies in the high pressure and tremendous impact wave produced in launching the perforating charge. In the light of this situation, corresponding measures are presented, including: 1. improving the quility of the gun body; 2. strengthening the operation management; 3. carrying on technical modification and innovation; 4. conducting further investigation in the causes of the damage of the gun body.

Subject Concept Terms perforating gun fracture precaution

Li Zengliang(*University of Petroleum*, *Dongying City*, *Shandong Province*), Yan Tingjun, Gu Yuhong, et al. **Energy loss of turbine of turbodrills.** ***CPM***, 1997, 25(8): 49 ~ 52

An analysis of the test efficiency curve of ø240 turbodrill shows that the energy loss of the turbine lies mainly in the hydraulic loss, which includes the loss of blade contour, impact loss and end wall loss. To decrease and eliminate all kinds of energy loss, the relative pitch of the bladings, the radial and axial clearances between the stator and the rotor must be rationally selected. And the turbine must work under the best working condition, and the surface of the blades should be as smooth as possible.

Subject Concept Terms turbodrill turbine energy loss precaution