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中华人民共和国石油天然气行业标准

SY/T 5435—2003
中文/English
代替 SY/T 5435—2000，SY/T 6090—94

定向井轨道设计与轨迹计算

Wellpath design & trajectory calculation for directional drilling

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前　　言

本标准代替 SY/T 5435—2000《定向井轨道设计与轨道绘图》和 SY/T 6090—94《水平井二维轨道设计方法》。

本标准对 SY/T 5435—2000 和 SY/T 6090—94 进行了整合修订，主要变化如下：

——对部分术语和定义进行了修订；

——增加了定向井三维轨道设计方法；

——轨迹计算方法规定为最小曲率法和圆柱螺线法。

本标准的附录 A、附录 B、附录 C 为规范性附录。

本标准由石油钻井工程专业标准化委员会提出并归口。

本标准起草单位：胜利石油管理局钻井工程技术公司。

本标准主要起草人：刘汝山、周跃云、刘修善、韩志勇、胡文、李小群、陈维荣、邱维清、任玉芹。

本标准所代替标准的历次版本发布情况为：

——SY/T 5435—2000；

——SY/T 6090—94。

本标准以中文和英文两种文字出版。当英文与中文两种版本有歧义时，以中文版本为准。

定向井轨道设计与轨迹计算

1 范围

本标准规定了定向井二维和三维轨道设计与轨迹计算。

本标准适用于石油天然气钻井的二维和三维定向井轨道设计与轨迹计算。

2 术语和定义

下列术语和定义适用于本标准。

2.1

轨道 wellpath

设计的井眼轴线。

2.2

轨迹 well trajectory

实钻的井眼轴线。

2.3

二维定向井 two-dimensional directional well

设计轨道在同一铅垂平面内的定向井。

2.4

三维定向井 three-dimensional directional well

设计轨道不在同一铅垂平面内的定向井。

2.5

绕障定向井 3D detouring obstacles well

绕过障碍物钻达目标点的定向井。

2.6

靶区 target area

要求轨迹在目的层中的控制范围。

2.7

水平投影长度 horizontal curvilinear length

轨迹在水平面上投影的曲线长度。

2.8

节点 key point

设计轨道上不同井段的分界点。

2.9

分点 interpolate point

相邻节点间的计算点。

2.10

三段制轨道 "J"-type wellpath

自井口至靶点，依次为直井段、增斜段、稳斜段的轨道。

2.11

双增轨道　double build-up type wellpath

具有两个增斜段且两段之间夹有一稳斜段的轨道。

2.12

五段制轨道　"S"-type wellpath

自井口至靶点，依次为直井段、增斜段、稳斜段、降斜段、稳斜段的轨道。

2.13

闭合方位角　closure azimuth

井眼轨道或轨迹上某点相对于井口的方位角。

2.14

视平移　vertical section

水平位移在设计方位线所在铅垂面上的投影。

2.15

入靶点　entry point

实钻轨迹与靶区的交点。

3　参数的符号

轨道设计与轨迹计算参数的符号及下标说明见附录A。

4　轨道设计原则及设计条件

4.1　轨道设计原则

轨道设计应遵循以下原则：

——满足勘探开发的要求；

——满足下井管柱强度的要求；

——选择形状简单、易于施工的轨道；

——设计参数的选取，应考虑到地质构造和工具特性等因素的影响。

4.2　轨道设计条件

地质设计给定的井口坐标和各靶点坐标，以及对轨道设计的要求。

5　轨道设计方法

5.1　基本换算关系

5.1.1　N_t 和 E_t 与 C_t 和 θ_t 之间的换算：

$$C_t = \sqrt{N_t^2 + E_t^2} \quad \cdots\cdots(1)$$

$$\tan\theta_t = \frac{E_t}{N_t} \quad \cdots\cdots(2)$$

$$N_t = C_t\cos\theta_t \quad \cdots\cdots(3)$$

$$E_t = C_t\sin\theta_t \quad \cdots\cdots(4)$$

5.1.2　曲率与曲率半径之间的换算：

$$R = \frac{5400}{\pi\kappa} \quad \cdots\cdots(5)$$

5.1.3　对于二维轨道设计，S＝C。

5.1.4　使用直井钻机时，造斜点以上设计成垂直井段。使用斜井钻机时，$\alpha_a \neq 0$，主要参数间的关系为：

$$D_a = L_a\cos\alpha_a \quad \cdots\cdots(6)$$

$$S_a = L_a \sin\alpha_a \tag{7}$$

5.2 设计模型

5.2.1 二维设计模型

二维轨道设计模型主要有直线模型和圆弧模型，也可以采用悬链线等变曲率模型。

5.2.1.1 直线模型

轨道在设计铅垂面内为一稳斜段，主要计算公式为：

$$\alpha_i = \alpha_{i-1} \tag{8}$$

$$\Delta D_i = \Delta L_i \cos\alpha_i \tag{9}$$

$$\Delta S_i = \Delta L_i \sin\alpha_i \tag{10}$$

5.2.1.2 圆弧模型

轨道在设计铅垂面内为一圆弧段，主要计算公式为：

$$\alpha_i = \alpha_{i-1} + 180 \times \frac{\Delta L_i}{\pi R_i} \tag{11}$$

$$\Delta D_i = R_i(\sin\alpha_i - \sin\alpha_{i-1}) \tag{12}$$

$$\Delta S_i = R_i(\cos\alpha_{i-1} - \cos\alpha_i) \tag{13}$$

5.2.2 三维设计模型

三维轨道设计模型主要有直线模型、圆柱螺线模型和圆弧模型。

5.2.2.1 直线模型

轨道为一段直线，见附录C图C.1。主要计算公式为：

$$\Delta D_i = \Delta L_i \cos\alpha_{i-1} \tag{14}$$

$$\Delta N_i = \Delta L_i \sin\alpha_{i-1} \cos\phi_{i-1} \tag{15}$$

$$\Delta E_i = \Delta L_i \sin\alpha_{i-1} \sin\phi_{i-1} \tag{16}$$

5.2.2.2 圆柱螺线模型

轨道在垂直剖面图和水平投影图上均为圆弧，即 κ_H 和 κ_V 为常数，见附录C图C.2。主要计算公式为：

$$\Delta D_i = R_{Vi}(\sin\alpha_i - \sin\alpha_{i-1}) \tag{17}$$

$$\Delta N_i = R_{Hi}(\sin\phi_i - \sin\phi_{i-1}) \tag{18}$$

$$\Delta E_i = R_{Hi}(\cos\phi_{i-1} - \cos\phi_i) \tag{19}$$

其中：

$$\alpha_i = \alpha_{i-1} + 180 \times \frac{\Delta L_i}{\pi R_{Vi}} \tag{20}$$

$$\phi_i = \phi_{i-1} + 180 \times \frac{R_{Vi}(\cos\alpha_{i-1} - \cos\alpha_i)}{\pi R_{Hi}} \tag{21}$$

在实际应用中，应考虑如下几种特殊情况：

a) 当 $\kappa_{Vi}=0$ 和 $\kappa_{Hi}=0$ 时，ΔD_i，ΔN_i 和 ΔE_i 按式（14）～式（16）计算。

b) 当 $\kappa_{Vi}=0$ 和 $\kappa_{Hi}\neq 0$ 时：

$$\Delta D_i = \Delta L_i \cos\alpha_{i-1} \tag{22}$$

$$\phi_i = \phi_{i-1} + 180 \times \frac{\Delta L_i \sin\alpha_{i-1}}{\pi R_{Hi}} \tag{23}$$

ΔN_i 和 ΔE_i 按式(18)～式(19)计算。

c) 当 $\kappa_{Vi}\neq 0$ 和 $\kappa_{Hi}=0$ 时：

$$\Delta N_i = R_{Vi}(\cos\alpha_{i-1} - \cos\alpha_i)\cos\phi_{i-1} \tag{24}$$

$$\Delta E_i = R_{Vi}(\cos\alpha_{i-1} - \cos\alpha_i)\sin\phi_{i-1} \quad \cdots\cdots(25)$$

ΔD_i 按式（17）计算。

5.2.2.3 圆弧模型

轨道为一斜面圆弧，即 κ_i 为常数，见附录C图C.3。主要计算公式为：

$$\Delta D_i = \xi_i\cos\alpha_{i-1} - \xi_i\sin\alpha_{i-1}\cos\omega_{i-1} \quad \cdots\cdots(26)$$

$$\Delta N_i = \xi_i(\cos\alpha_{i-1}\cos\phi_{i-1}\cos\omega_{i-1} - \sin\phi_{i-1}\sin\omega_{i-1}) + \xi_i\sin\alpha_{i-1}\cos\phi_{i-1} \quad \cdots\cdots(27)$$

$$\Delta E_i = \xi_i(\cos\alpha_{i-1}\sin\phi_{i-1}\cos\omega_{i-1} + \cos\phi_{i-1}\sin\omega_{i-1}) + \xi_i\sin\alpha_{i-1}\sin\phi_{i-1} \quad \cdots\cdots(28)$$

其中：

$$\xi_i = R_i(1 - \cos\varepsilon_i) \quad \cdots\cdots(29)$$

$$\zeta_i = R_i\sin\varepsilon_i \quad \cdots\cdots(30)$$

$$\varepsilon_i = 180 \times \frac{\Delta L_i}{\pi R_i} \quad \cdots\cdots(31)$$

5.3 约束方程

设计的轨道可以是上述模型所描述井段的组合。

5.3.1 二维设计

$$\sum \Delta D_i = D_t - D_o \quad \cdots\cdots(32)$$

$$\sum \Delta S_i = S_t - S_o \quad \cdots\cdots(33)$$

5.3.2 三维设计

$$\sum_{i=1}^{n} \Delta N_i = N_t - N_o \quad \cdots\cdots(34)$$

$$\sum_{i=1}^{n} \Delta E_i = E_t - E_o \quad \cdots\cdots(35)$$

$$\sum_{i=1}^{n} \Delta D_i = D_t - D_o \quad \cdots\cdots(36)$$

5.4 输出格式

5.4.1 轨道设计计算结果按附录B表B.1的格式打印或填写。

5.4.2 按附录B表B.1的参数绘制设计轨道的垂直投影图和水平投影图。

6 二维典型轨道设计

三段制轨道、五段制轨道和双增轨道图示见附录C图C.4、图C.5和图C.6。

6.1 关键参数的计算

$$\tan\frac{\alpha_b}{2} = \frac{D_e - \sqrt{D_e^2 + S_e^2 - R_e^2}}{R_e - S_e} \quad \cdots\cdots(37)$$

$$\Delta L_w = \sqrt{D_e^2 + S_e^2 - R_e^2} \quad \cdots\cdots(38)$$

当 $R_e = S_e$ 时：

$$\tan\frac{\alpha_b}{2} = \frac{S_e}{D_e} \quad \cdots\cdots(39)$$

$$\Delta L_w = D_e \quad \cdots\cdots(40)$$

对于三段制轨道：

$$D_e = D_t - D_a + R_1\sin\alpha_a \quad \cdots\cdots(41)$$

$$S_e = S_t - S_a - R_1\cos\alpha_a \quad \cdots\cdots(42)$$

$$R_e = R_1 \quad\cdots\cdots(43)$$

对于双增轨道：

$$D_e = D_t - D_a - \Delta D_{dt} + R_1\sin\alpha_a - R_2\sin\alpha_t \quad\cdots\cdots(44)$$

$$S_e = S_t - S_a - \Delta S_{dt} - R_1\cos\alpha_a + R_2\cos\alpha_t \quad\cdots\cdots(45)$$

$$R_e = R_1 - R_2 \quad\cdots\cdots(46)$$

对于五段制轨道，计算公式同式（44）～式（46），但 R_2 取负值。

其中，五段制轨道和双增轨道的 ΔD_{dt}，ΔS_{dt}，ΔD_{tf}和 ΔS_{tf}的计算公式为：

$$\Delta D_{dt} = \Delta L_{dt}\cos\alpha_t \quad\cdots\cdots(47)$$

$$\Delta S_{dt} = \Delta L_{dt}\sin\alpha_t \quad\cdots\cdots(48)$$

$$\Delta D_{tf} = \Delta L_{tf}\cos\alpha_t \quad\cdots\cdots(49)$$

$$\Delta S_{tf} = \Delta L_{tf}\sin\alpha_t \quad\cdots\cdots(50)$$

6.2 轨道节点数据的计算

6.2.1 第一增斜段终点

$$L_b = L_a + \frac{1}{180} \times \pi R_1(\alpha_b - \alpha_a) \quad\cdots\cdots(51)$$

$$D_b = D_a + R_1(\sin\alpha_b - \sin\alpha_a) \quad\cdots\cdots(52)$$

$$S_b = S_a + R_1(\cos\alpha_a - \cos\alpha_b) \quad\cdots\cdots(53)$$

6.2.2 第二增斜段或降斜段始点

$$L_c = L_b + \Delta L_w \quad\cdots\cdots(54)$$

$$D_c = D_b + \Delta L_w\cos\alpha_b \quad\cdots\cdots(55)$$

$$S_c = S_b + \Delta L_w\sin\alpha_b \quad\cdots\cdots(56)$$

6.2.3 第二增斜段或降斜段终点

$$L_d = L_c + \frac{1}{180} \times \pi R_2(\alpha_t - \alpha_b) \quad\cdots\cdots(57)$$

$$D_d = D_c + R_2(\sin\alpha_t - \sin\alpha_b) \quad\cdots\cdots(58)$$

$$S_d = S_c + R_2(\cos\alpha_b - \cos\alpha_t) \quad\cdots\cdots(59)$$

6.2.4 靶点

$$L_t = L_d + \Delta L_{dt} \quad\cdots\cdots(60)$$

6.2.5 轨道终点

$$L_f = L_t + \Delta L_{tf} \quad\cdots\cdots(61)$$

$$D_f = D_t + \Delta D_{tf} \quad\cdots\cdots(62)$$

$$S_f = S_t + \Delta S_{tf} \quad\cdots\cdots(63)$$

6.3 轨道分点数据的计算

6.3.1 从造斜点开始，以井深为自变量，选定步长，计算出分点数据。

6.3.2 井斜角、垂深、水平位移的计算。

a）第一增斜段：

$$\alpha_j = \alpha_a + 180 \times \frac{(L_j - L_a)}{\pi R_1} \quad\cdots\cdots(64)$$

$$D_j = D_a + R_1(\sin\alpha_j - \sin\alpha_a) \quad\cdots\cdots(65)$$

$$S_j = S_a + R_1(\cos\alpha_a - \cos\alpha_j) \quad\cdots\cdots(66)$$

b）稳斜段：

$$\alpha_j = \alpha_b \quad\cdots\cdots(67)$$

$$D_j = D_b + (L_j - L_a)\cos\alpha_b \quad \cdots\cdots(68)$$

$$S_j = S_b + (L_j - L_a)\sin\alpha_b \quad \cdots\cdots(69)$$

c）第二增斜段或降斜段：

$$\alpha_j = \alpha_b + 180 \times \frac{(L_j - L_c)}{\pi R_2} \quad \cdots\cdots(70)$$

$$D_j = D_c + R_2(\sin\alpha_j - \sin\alpha_b) \quad \cdots\cdots(71)$$

$$S_j = S_c + R_2(\cos\alpha_b - \cos\alpha_j) \quad \cdots\cdots(72)$$

d）入靶井段：

$$\alpha_j = \alpha_t \quad \cdots\cdots(73)$$

$$D_j = D_d + (L_j - L_d)\cos\alpha_t \quad \cdots\cdots(74)$$

$$S_j = S_d + (L_j - L_d)\sin\alpha_t \quad \cdots\cdots(75)$$

e）终靶以下井段：

$$\alpha_j = \alpha_t \quad \cdots\cdots(76)$$

$$D_j = D_t + (L_j - L_t)\cos\alpha_t \quad \cdots\cdots(77)$$

$$S_j = S_t + (L_j - L_t)\sin\alpha_t \quad \cdots\cdots(78)$$

6.3.3 N 坐标和 E 坐标：

$$N_j = S_j\cos\theta_0 \quad \cdots\cdots(79)$$

$$E_j = S_j\sin\theta_0 \quad \cdots\cdots(80)$$

7 三维绕障轨道设计

7.1 水平投影设计

7.1.1 换算关系

$$C_g = \sqrt{N_g^2 + E_g^2} \quad \cdots\cdots(81)$$

$$\tan\theta_g = \frac{E_g}{N_g} \quad \cdots\cdots(82)$$

7.1.2 绕障必要性判断

如附录C图C.7所示，如果将 EON 坐标系绕井口点顺时针旋转 θ_t 角度，使 N 轴通过目标点 t 而建立新的坐标系 XOY，则：

$$\begin{cases} x_g = C_g\cos(\theta_g - \theta_t) \\ y_g = C_g\sin(\theta_g - \theta_t) \end{cases} \quad \cdots\cdots(83)$$

如果 $0 < x_g < C_t$ 且 $|y_g| < R_g$，则需要进行绕障设计。

7.1.3 左右绕障判断

$$q = \mathrm{sgn}(y_g) = \begin{cases} -1, \text{左旋绕障设计} \\ +1, \text{右旋绕障设计} \end{cases} \quad \cdots\cdots(84)$$

7.1.4 初始方位角

$$\phi_0 = \theta_g - q\sin^{-1}\left(\frac{R_g}{C_g}\right) \quad \cdots\cdots(85)$$

7.1.5 方位扭转角

$$\tan\frac{\Delta\phi}{2} = \begin{cases} \dfrac{S_e}{2D_e} & \text{当 } 2R_g = S_e \\ \dfrac{D_e - \sqrt{D_e^2 + S_e^2 - 2R_gS_e}}{2R_g - S_e} & \text{当 } 2R_g \neq S_e \end{cases} \quad \cdots\cdots(86)$$

其中：

$$D_e = C_t\cos(\theta_t - \phi_0) - C_g\cos(\theta_g - \phi_0) \quad\cdots\cdots(87)$$

$$S_e = C_t\left|\sin(\theta_t - \phi_0)\right| \quad\cdots\cdots(88)$$

7.1.6 节点的水平投影长度

$$S_P = C_g\cos(\theta_g - \phi_0) \quad\cdots\cdots(89)$$

$$S_Q = S_P + \frac{1}{180} \times \pi R_g \Delta\phi \quad\cdots\cdots(90)$$

$$S_t = S_Q + \sqrt{D_e^2 + S_e^2 - 2R_g S_e} \quad\cdots\cdots(91)$$

7.2 垂直剖面设计

垂直剖面的设计方法与二维定向井轨道设计相同。

7.3 轨道节点数据的计算

7.3.1 垂直剖面上节点参数的计算

见6.2。

7.3.2 水平投影上节点参数的计算

当 $S_P \leqslant S_a$ 时：

$$L_P = \frac{S_P}{\sin\alpha_a} \quad\cdots\cdots(92)$$

$$D_P = \frac{S_P}{\tan\alpha_a} \quad\cdots\cdots(93)$$

当 $S_a < S_P \leqslant S_b$ 时：

$$L_P = L_a + \frac{1}{180} \times \pi R_1(\alpha_P - \alpha_a) \quad\cdots\cdots(94)$$

$$D_P = D_a + R_1(\sin\alpha_P - \sin\alpha_a) \quad\cdots\cdots(95)$$

其中：

$$\cos\alpha_P = \cos\alpha_a - \frac{S_P - S_a}{R_1} \quad\cdots\cdots(96)$$

当 $S_b < S_P \leqslant S_c$ 时：

$$L_P = L_b + \frac{S_P - S_b}{\sin\alpha_b} \quad\cdots\cdots(97)$$

$$D_P = D_b + \frac{S_P - S_b}{\tan\alpha_b} \quad\cdots\cdots(98)$$

当 $S_c < S_P \leqslant S_d$ 时：

$$L_P = L_c + \frac{1}{180} \times \pi R_2(\alpha_P - \alpha_b) \quad\cdots\cdots(99)$$

$$D_P = D_c + R_2(\sin\alpha_P - \sin\alpha_b) \quad\cdots\cdots(100)$$

其中：

$$\cos\alpha_P = \cos\alpha_b - \frac{S_P - S_c}{R_2} \quad\cdots\cdots(101)$$

当 $S_P > S_d$ 时：

$$L_P = L_d + \frac{S_P - S_d}{\sin\alpha_t} \quad\cdots\cdots(102)$$

$$D_P = D_d + \frac{S_P - S_d}{\tan\alpha_t} \quad\cdots\cdots(103)$$

节点Q的参数计算方法与节点P相同，见式（92）～式（103）。

7.4 井眼曲率校核

$$\kappa = \sqrt{\kappa_V^2 + \kappa_H^2 \cdot \sin^4\alpha} \qquad (104)$$

当 κ 大于井眼曲率的限定值时，应增大绕障半径 R_g，重复上述设计过程。

7.5 轨道分点数据的计算

7.5.1 井斜角、垂深、水平投影长度的计算方法见6.3.2。

7.5.2 井斜方位角、N 坐标和 E 坐标的计算见式（105）～式（113）。

当 $S_j \leqslant S_P$ 时：

$$\phi_j = \phi_0 \qquad (105)$$

$$N_j = S_j \cos\phi_j \qquad (106)$$

$$E_j = S_j \sin\phi_j \qquad (107)$$

当 $S_P < S_j \leqslant S_Q$ 时：

$$\phi_j = \phi_P + \frac{1}{180} q \times \frac{S_j - S_P}{\pi R_g} \qquad (108)$$

$$N_j = N_P + qR_g(\sin\phi_j - \sin\phi_0) \qquad (109)$$

$$E_j = E_P + qR_g(\cos\phi_0 - \cos\phi_j) \qquad (110)$$

当 $S_j > S_Q$ 时：

$$\phi_j = \phi_0 + q\Delta\phi \qquad (111)$$

$$N_j = N_Q + (S_j - S_Q)\cos\phi_j \qquad (112)$$

$$E_j = E_Q + (S_j - S_Q)\sin\phi_j \qquad (113)$$

8 轨迹计算

8.1 规定

对轨迹计算作以下规定：

——测点自上而下编号，$i=1,2,3,\cdots$。

——测段自上而下编号，$i=1,2,3,\cdots$。第 i 个测段指第 $i-1$ 个测点与第 i 个测点之间的测段。

——井口为计算始点，直井钻机 $\alpha_0=0$，$\phi_0=\phi_1$；斜井钻机 α_0 等于钻机导斜角，ϕ_0 等于钻机导斜方位角。

——井斜方位角应进行磁偏角及子午线收敛角校正。

——当测点的井斜角为零时，该测点井斜方位角的取值与该测段另一测点的井斜方位角相等。

——当 $|\phi_i - \phi_{i-1}| < 180°$，$\Delta\phi = \phi_i - \phi_{i-1}$。当 $|\phi_i - \phi_{i-1}| > 180°$ 时，$\Delta\phi = \phi_i - \phi_{i-1} - \mathrm{sgn}(\phi_i - \phi_{i-1}) \times 360$。

当 $|\phi_i - \phi_{i-1}| = 180°$ 时，$\Delta\phi$ 的正负号按上测段方位变化趋势选取。

8.2 测段数据的计算

8.2.1 段长和平均井眼曲率

$$\Delta L_i = L_i - L_{i-1} \qquad (114)$$

$$\kappa_i = 30 \times \frac{\varepsilon_i}{\Delta L_i} \qquad (115)$$

其中：

$$\varepsilon_i = \cos^{-1}[\cos\alpha_{i-1}\cos\alpha_i + \sin\alpha_{i-1}\sin\alpha_i\cos(\phi_i - \phi_{i-1})] \qquad (116)$$

8.2.2 坐标增量

8.2.2.1 最小曲率法

$$\Delta D_i = \lambda_i(\cos\alpha_{i-1} + \cos\alpha_i) \qquad (117)$$

$$\Delta S_i = \frac{1}{360} \times \frac{\pi\lambda_i\Delta\phi_i(\sin\alpha_{i-1} + \sin\alpha_i)}{\tan(\Delta\phi_i/2)} \qquad (118)$$

$$\Delta N_i = \lambda_i(\sin\alpha_{i-1}\cos\phi_{i-1} + \sin\alpha_i\cos\phi_i) \qquad (119)$$

$$\Delta E_i = \lambda_i(\sin\alpha_{i-1}\sin\phi_{i-1} + \sin\alpha_i\sin\phi_i) \qquad (120)$$

其中：

$$\lambda_i = 180 \times \frac{\Delta L_i \tan(\varepsilon_i/2)}{\pi\varepsilon_i} \qquad (121)$$

8.2.2.2 圆柱螺线法

$$\kappa_{Vi} = 30 \times \frac{\Delta\alpha_i}{\Delta L_i} \qquad (122)$$

$$\kappa_{Hi} = \begin{cases} 30 \times \dfrac{\Delta\phi_i}{\Delta L_i \sin\alpha_i} & \text{当 } \kappa_{Vi} = 0 \\ \dfrac{1}{180} \times \dfrac{\pi\Delta\phi_i\kappa_{Vi}}{\cos\alpha_{i-1} - \cos\alpha_i} & \text{当 } \kappa_{Vi} \neq 0 \end{cases} \qquad (123)$$

$$\Delta S_i = \begin{cases} \Delta L_i \sin\alpha_{i-1} & \text{当 } \kappa_{Vi} = 0 \\ R_{Vi}(\cos\alpha_{i-1} - \cos\alpha_i) & \text{当 } \kappa_{Vi} \neq 0 \end{cases} \qquad (124)$$

ΔD_i，ΔN_i 和 ΔE_i 按式（17）～式（25）计算。

8.3 测点数据的计算

$$D_i = D_{i-1} + \Delta D_i \qquad (125)$$

$$S_i = S_{i-1} + \Delta S_i \qquad (126)$$

$$N_i = N_{i-1} + \Delta N_i \qquad (127)$$

$$E_i = E_{i-1} + \Delta E_i \qquad (128)$$

$$C_i = \sqrt{N_i^2 + E_i^2} \qquad (129)$$

$$\tan\theta_i = \frac{E_i}{N_i} \qquad (130)$$

$$V_i = C_i\cos(\theta_0 - \theta_i) \qquad (131)$$

8.4 入靶数据的计算

根据选定的轨迹计算方法，用插值法计算入靶点 e 的数据。

8.4.1 水平靶的靶心距

$$J = \sqrt{(N_t - N_e)^2 + (E_t - E_e)^2} \qquad (132)$$

8.4.2 铅垂靶的纵偏移和横偏移

$$H = D_t - D_e \qquad (133)$$

$$W = (N_t - N_e)\sin\phi_t - (E_t - E_e)\cos\phi_t \qquad (134)$$

8.5 输出格式

轨迹计算数据表按附录 B 表 B.2 和表 B.3 的格式打印或填写。

8.6 绘图

8.6.1 二维定向井轨迹可据附录 B 表 B.2 数据绘出垂直投影图和水平投影图，见附录 C 中图 C.8。垂直投影图的两个坐标是 D 和 V。

8.6.2 三维定向井轨迹可据附录 B 表 B.2 数据绘出垂直剖面图、水平投影图和三维轨迹图。垂直剖面图的两个坐标是 D 和 S。

附 录 A
(规范性附录)
参数的符号

表 A.1 和表 A.2 中给出了轨道设计与轨迹计算参数的符号及下标说明。

表 A.1 参数的符号

序号	符号	名称	单位
1	L	井深	m
2	α	井斜角	(°)
3	ϕ	井斜方位角	(°)
4	N	N 坐标	m
5	E	E 坐标	m
6	D	垂深	m
7	S	水平投影长度	m
8	C	水平位移（闭合距）	m
9	θ	闭合方位角	(°)
10	V	视平移	m
11	ΔL	井深增量	m
12	$\Delta\alpha$	井斜角增量	(°)
13	$\Delta\phi$	井斜方位角增量	(°)
14	ΔN	N 坐标增量	m
15	ΔE	E 坐标增量	m
16	ΔD	垂深增量	m
17	ΔS	水平投影长度增量	m
18	ΔL_w	稳斜段长	m
19	κ	井眼曲率	(°)/30m
20	κ_V	垂直剖面图上的曲率	(°)/30m
21	κ_H	水平投影图上的曲率	(°)/30m
22	R	曲率半径	m
23	R_V	垂直剖面图上的曲率半径	m
24	R_H	水平投影图上的曲率半径	m
25	R_1	第一圆弧段的曲率半径	m
26	R_2	第二圆弧段的曲率半径	m
27	R_g	绕障半径	m
28	ω	装置角	(°)
29	ε	弯曲角	(°)

表 A.1（续）

序　　号	符　　号	名　　称	单　　位
30	q	符号变量	
31	J	水平靶的靶心距	m
32	H	铅垂靶的纵偏移	m
33	W	铅垂靶的横偏移	m
34	R_e	中间变量	m
35	D_e	中间变量	m
36	S_e	中间变量	m
37	λ	中间变量	m
38	x	过渡坐标	m
39	y	过渡坐标	m
40	ξ	过渡坐标	m
41	η	过渡坐标	m
42	ζ	过渡坐标	m

表 A.2　下标说明

序　　号	符　　号	名　　称
1	O	坐标原点
2	a	造斜点
3	b	第一圆弧段终点
4	c	第二圆弧段始点
5	d	第二圆弧段终点
6	t	靶点
7	f	轨道终点
8	g	障碍物中心点
9	P	三维绕障设计的扭方位始点
10	Q	三维绕障设计的扭方位终点
11	i	变量
12	j	变量
13	e	入靶点

附 录 B
（规范性附录）
轨道设计及轨迹计算输出格式

表 B.1 给出了×××井轨道设计数据表格式。

表 B.2 给出了×××井轨迹计算数据表格式。

表 B.3 给出了×××井中靶数据表格式。

表 B.1 ××× 井轨道设计数据表

井底设计垂深： m	井底水平位移： m	井底闭合方位角： (°)

靶点数据						
靶点名称	垂 深 m	*N* 坐标 m	*E* 坐标 m	靶区半径 m	纵偏移 m	横偏移 m

轨道节点数据										
井深 m	井斜角 (°)	井斜方位角 (°)	垂深 m	*N* 坐标 m	*E* 坐标 m	水平位移 m	井眼曲率 (°)/30m	井斜变化率 (°)/30m	方位变化率 (°)/30m	靶点名称

轨道分点数据											
井深 m	井斜角 (°)	井斜方位角 (°)	垂深 m	*N* 坐标 m	*E* 坐标 m	水平位移 m	视位移 m	闭合方位角 (°)	井眼曲率 (°)/30m	井斜变化率 (°)/30m	方位变化率 (°)/30m

表 B.2 ×××井轨迹计算数据表

计算方法：

序　号	测深 m	井斜角 (°)	井　斜 方位角 (°)	垂深 m	*N* 坐标 m	*E* 坐标 m	水平位移 m	视平移 m	闭　合 方位角 (°)	井眼曲率 (°)/30m
1										
2										
3										
…										

表 B.3 ×××井中靶数据表

靶点名称	斜深 m	垂深 m	*N* 坐标 m	*E* 坐标 m	水平位移 m	闭合方位角 (°)	靶心距 m	纵偏移 m	横偏移 m
A									
B									
C									
…									

附 录 C
（规范性附录）
轨道形状图和轨迹图

轨道形状图和轨迹图见图 C.1～图 C.8。

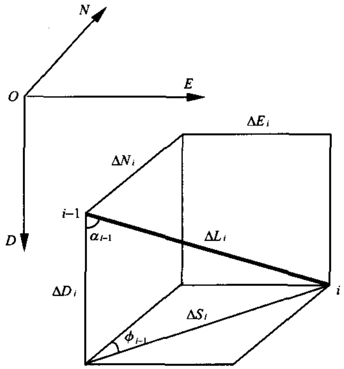


图 C.1 直线模型

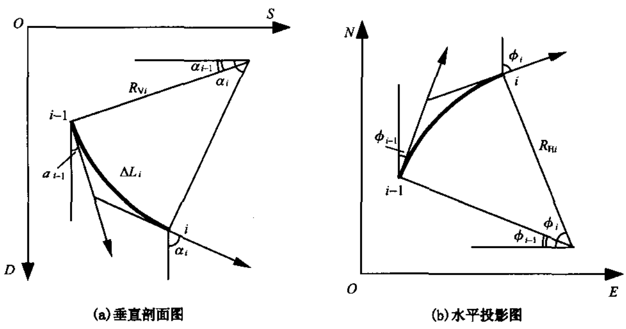


图 C.2 圆柱螺线模型

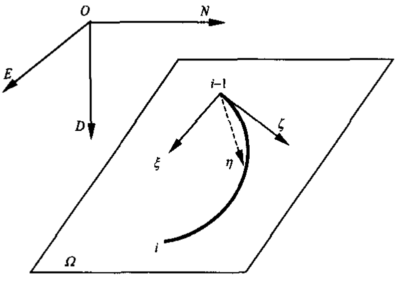


图 C.3　圆弧模型

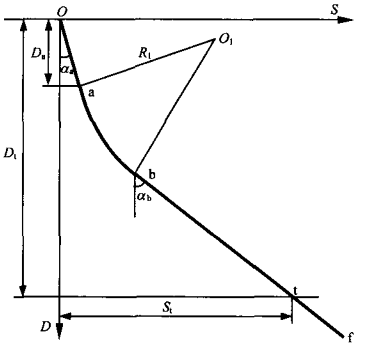


图 C.4　三段制轨道

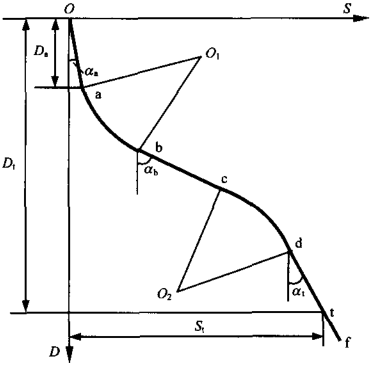


图 C.5　五段制轨道

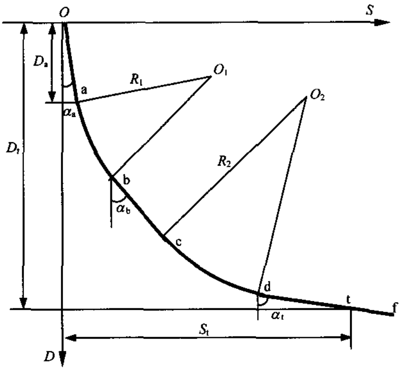


图 C.6 双增轨道

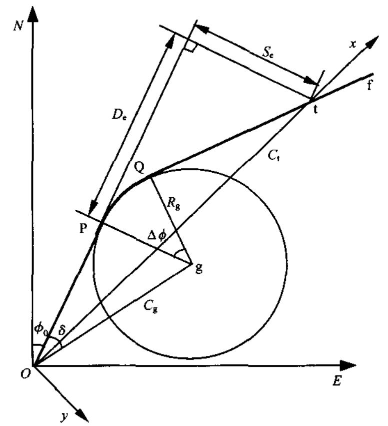
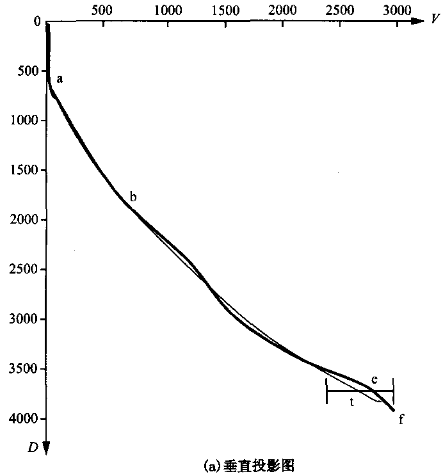
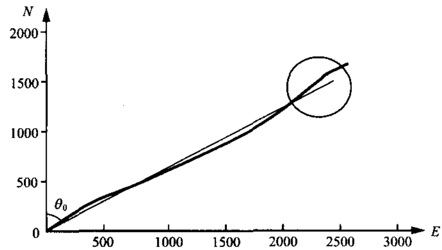


图 C.7 三维绕障轨道的水平投影



(a)垂直投影图



(b)水平投影图

图 C.8　轨迹图

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SY

The People's Republic of China
Standard of Petroleum and Natural Gas Industry

SY/T 5435—2003
Replace SY/T 5435—2000, SY/T 6090—94

Wellpath design & trajectory calculation for directional drilling

Issued Date: 03 – 18 – 2003 Implementation Date: 08 – 01 – 2003

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Contents

Tables

Foreword

This standard replaces SY/T 5435—2000 *Methods of directional wellpath design & trajectory graphing* and SY/T 6090—94 *Methods of 2-dimension horizontal wellpath design*.

SY/T 5435—2000 and SY/T 6090—94 have been revised, the main changes are listed below:

——Parts of terms and definitions have been revised;

——Wellpath design for 3D directional drilling has been added;

——Minimum curvature method and curvature radius method are specified as the trajectory calculation methods.

Annex A, B and C of this standard are normative.

This standard was proposed by and is under the jurisdiction of China Petroleum Standardization Committee for Drilling Engineering.

This standard was drafted by Drilling Engineering & Technology Corporation, Shengli Petroleum Administration Bureau.

This standard was mainly drafted by Liu Rushan, Zhou Yueyun, Liu Xiushan, Han Zhiyong, Hu Wen, Li Xiaoqun, Chen Weirong, Qiu Weiqing and Ren Yuqin.

This standard will replace the following previous editions:

——SY/T 5435—2000;

——SY/T 6090—94.

This part is published in both Chinese and English. In the event of any discrepancy between the texts, the Chinese version shall prevail.

Wellpath Design & Trajectory Calculation for Directional Drilling

1 Scope

This standard specifies rules for wellpath design and actual trajectory calculation of two-dimensional (2D) and/or three-dimensional (3D) directional well.

This standard is applicable to wellpath design and actural trajectory calculation of two-dimension-al (2D) and /or three-dimensional (3D) directional wells for oil and gas drilling.

2 Terms and definitions

For the purposes of this standard, the following terms and definitions apply.

2.1

Wellpath

The planned borehole axis.

2.2

Well trajectory

The actual borehole axis.

2.3

Two-dimensional directional well

Any directional well whose planned wellpath is limited on a certain vertical plane.

2.4

Three-dimensional directional well

Any directional well whose planned wellpath is not limited on a certain vertical plane.

2.5

3D detouring obstacles well

Any directional well whose planned wellpath bypasses specified obstacles and reaches a predetermined objective bellow the earth surface.

2.6

Target area

Defined as an predetermined control area in the target formation to be penetrated by the wellbore trajectory.

2.7

Horizontal curvilinear length

Defined as the accumulative course length of the wellpath projected onto the horizontal plane.

2.8

Key point

Any point on the planned wellpath that divides different borehole sections.

2.9

Interpolate point

Any point between two adjacent key points on the planned wellpath used for data calculation.

2.10

"J" -type wellpath

A directional hole whose planned wellpath has a vertical section, a build-up section and a hold-on (or simply hold, or tangent) section from the wellhead to target sequentially.

2.11

Double build-up type wellpath

A directional hole whose planned wellpath has a vertical section, a build-up section, a hold-on (or simply hold, or tangent) section and another build-up section from the wellhead to target sequentially.

2.12

"S" -type wellpath

A directional hole whose planned wellpath has a vertical section, a build-up section, a hold-on (or simply hold, or tangent) section, a drop-off section and another hold-on section from the wellhead to target sequentially.

2.13

Closure azimuth

Defined as the direction at a point on the planned wellpath or actual wellbore trajectory relative to the wellhead.

2.14

Vertical section

Defined as the scalar value of the horizontal displacement projected onto the planned azimuth plane (made from the vertical and azimuthal lines) .

2.15

Entry point

Defined as the point at which the actual wellbore trajectory intersects the target area.

3 The general symbols for parameters

Annex A shows the general symbols and their associated subscripts used for wellpath design and trajectory calculations.

4 Principles and conditions for wellpath design

4.1 Wellpath design principles

The following principles shall be followed when plan /design a wellpath:

——Satisfy requirements for oil and gas exploratory and development;

——Satisfy requirements for drill string strength;

——Select wellpath that is in simple shape and easy for drilling;

——Other factors, such as geological structure, tool performances and specifications shall be considered when selecting the design parameter.

4.2 Wellpath design conditions

Coordinates for the wellhead and each target, determined by geological design, and associated wellpath design requirements.

5 Wellpath design method

5.1 Basic equations

5.1.1 Relationship between N_t, E_t and C_t, θ_t:

$$C_t = \sqrt{N_t^2 + E_t^2} \tag{1}$$

$$\tan\theta_t = \frac{E_t}{N_t} \tag{2}$$

$$N_t = C_t\cos\theta_t \tag{3}$$

$$E_t = C_t\sin\theta_t \tag{4}$$

5.1.2 Calculation of Curvature Radius:

$$R = \frac{5400}{\pi\kappa} \tag{5}$$

5.1.3 For 2D wellpath design, $S = C$.

5.1.4 For conventional rigs, the borehole over the kick-off point shall be designed as vertical section. For slant rigs ($\alpha_a \neq 0$), relationships between the main parameters are as follows:

$$D_a = L_a\cos\alpha_a \tag{6}$$

$$S_a = L_a\sin\alpha_a \tag{7}$$

5.2 Design model

Straight-line and circular-arc models are the basic models for 2D wellpath design. However, other curve models such as catenary model, may also be applied.

Slant straight-line model, cylindrical helicoid model and spatial-circular-arc model are the basic models for 3D wellpath design.

5.2.1 2D Wellpath design model

5.2.1.1 Straight-line model

The wellpath on the planned vertical plane is a hold-up section. Equations for the key parameters are as follows:

$$\alpha_i = \alpha_{i-1} \tag{8}$$

$$\Delta D_i = \Delta L_i\cos\alpha_i \tag{9}$$

$$\Delta S_i = \Delta L_i\sin\alpha_i \tag{10}$$

5.2.1.2 Circular-arc model

Wellpath on the planned vertical plane is a section of circular-arc. Equations for the key parameters are as follows:

$$\alpha_i = \alpha_{i-1} + 180 \times \frac{\Delta L_i}{\pi R_i} \tag{11}$$

$$\Delta D_i = R_i(\sin\alpha_i - \sin\alpha_{i-1}) \tag{12}$$

$$\Delta S_i = R_i(\cos\alpha_{i-1} - \cos\alpha_i) \tag{13}$$

5.2.2 Design model for 3D wellpath

5.2.2.1 Straight-line model

Wellpath is a section of spatial straight-line (see Figure C.1 of Annex C) . Equations for key parameters are as follows:

$$\Delta D_i = \Delta L_i\cos\alpha_{i-1} \tag{14}$$

$$\Delta N_i = \Delta L_i\sin\alpha_{i-1}\cos\phi_{i-1} \tag{15}$$

$$\Delta E_i = \Delta L_i\sin\alpha_{i-1}\sin\phi_{i-1} \tag{16}$$

5.2.2.2 Cylindrical helicoid model

Both vertical and horizontal projections of the wellpath are circular-arc, parameter κ_H and κ_V are constant (see Figure C.2 of Annex C) . Equations for key parameters are as follows:

$$\Delta D_i = R_{Vi}(\sin\alpha_i - \sin\alpha_{i-1}) \quad (17)$$

$$\Delta N_i = R_{Hi}(\sin\phi_i - \sin\phi_{i-1}) \quad (18)$$

$$\Delta E_i = R_{Hi}(\cos\phi_{i-1} - \cos\phi_i) \quad (19)$$

where

$$\alpha_i = \alpha_{i-1} + 180 \times \frac{\Delta L_i}{\pi R_{Vi}} \quad (20)$$

$$\phi_i = \phi_{i-1} + 180 \times \frac{R_{Vi}(\cos\alpha_{i-1} - \cos\alpha_i)}{\pi R_{Hi}} \quad (21)$$

Some of the following exceptional situations shall be considered in practice:

a) In case of $\kappa_{Vi} = 0$ and $\kappa_{Hi} = 0$, for calculation of ΔD_i, ΔN_i and ΔE_i, equations (14) ~ (16) shall be followed.

b) In case of $\kappa_{Vi} = 0$ and $\kappa_{Hi} \neq 0$,

$$\Delta D_i = \Delta L_i \cos\alpha_{i-1} \quad (22)$$

$$\phi_i = \phi_{i-1} + 180 \times \frac{\Delta L_i \sin\alpha_{i-1}}{\pi R_{Hi}} \quad (23)$$

Equations (18) ~ (19) shall be used for calculation of ΔN_i and ΔE_i.

c) In case of $\kappa_{Vi} \neq 0$ and $\kappa_{Hi} = 0$.

$$\Delta N_i = R_{Vi}(\cos\alpha_{i-1} - \cos\alpha_i)\cos\phi_{i-1} \quad (24)$$

$$\Delta E_i = R_{Vi}(\cos\alpha_{i-1} - \cos\alpha_i)\sin\phi_{i-1} \quad (25)$$

Equation (17) shall be used for calculation of ΔD_i.

5.2.2.3 Spatial-circular-arc model

Wellpath is a section of circular-arc on a slant plane and κ_i, curvature of the spatial arc, is constant (see Figure C.3 of Annex C) .

Equations for key parameters are as follows:

$$\Delta D_i = \xi_i \cos\alpha_{i-1} - \xi_i \sin\alpha_{i-1}\cos\omega_{i-1} \quad (26)$$

$$\Delta N_i = \xi_i(\cos\alpha_{i-1}\cos\phi_{i-1}\cos\omega_{i-1} - \sin\phi_{i-1}\sin\omega_{i-1}) + \xi_i \sin\alpha_{i-1}\cos\phi_{i-1} \quad (27)$$

$$\Delta E_i = \xi_i(\cos\alpha_{i-1}\sin\phi_{i-1}\cos\omega_{i-1} + \cos\phi_{i-1}\sin\omega_{i-1}) + \xi_i \sin\alpha_{i-1}\sin\phi_{i-1} \quad (28)$$

where

$$\xi_i = R_i(1 - \cos\varepsilon_i) \quad (29)$$

$$\zeta_i = R_i \sin\varepsilon_i \quad (30)$$

$$\varepsilon_i = 180 \times \frac{\Delta L_i}{\pi R_i} \quad (31)$$

5.3 Constraint equations

The actual planned wellpath may be a combination of different wellpath sections, based on any of the above-mentioned models.

5.3.1 2D wellpath design

$$\sum \Delta D_i = D_t - D_o \quad (32)$$

$$\sum \Delta S_i = S_t - S_o \quad (33)$$

5.3.2 3D wellpath design

$$\sum_{i=1}^{n} \Delta N_i = N_t - N_o \quad (34)$$

$$\sum_{i=1}^{n} \Delta E_i = E_t - E_o \quad (35)$$

$$\sum_{i=1}^{n} \Delta D_i = D_t - D_o \quad (36)$$

5.4 Output format

5.4.1 Calculation results of wellpath design shall be printed or tabulated based on the format specified in Table B.1 of Annex B.

5.4.2 Graphing of planned wellpath vertical profile and horizontal projection shall be plotted using data in Table B.1 of Annex B.

6 Typical design for 2D wellpath

For illustrations of "J" -type Wellpath, Double Build-up type Wellpath and "S" -type Wellpath, see Figure C.4, Figure C.5 and Figure C.6 of Annex C.

6.1 Calculation for key parameters

$$\tan\frac{\alpha_b}{2} = \frac{D_e - \sqrt{D_e^2 + S_e^2 - R_e^2}}{R_e - S_e} \quad (37)$$

$$\Delta L_w = \sqrt{D_e^2 + S_e^2 - R_e^2} \quad (38)$$

In case of $R_e = S_e$:

$$\tan\frac{\alpha_b}{2} = \frac{S_e}{D_e} \quad (39)$$

$$\Delta L_w = D_e \quad (40)$$

For "J" -type Wellpath:

$$D_e = D_t - D_a + R_1 \sin\alpha_a \quad (41)$$

$$S_e = S_t - S_a - R_1 \cos\alpha_a \quad (42)$$

$$R_e = R_1 \quad (43)$$

For Double Build-up type Wellpath:

$$D_e = D_t - D_a - \Delta D_{dt} + R_1 \sin\alpha_a - R_2 \sin\alpha_t \quad (44)$$

$$S_e = S_t - S_a - \Delta S_{dt} - R_1\cos\alpha_a + R_2\cos\alpha_t \quad (45)$$

$$R_e = R_1 - R_2 \quad (46)$$

For "S" -type Wellpath, equations (44) ~ (46) can be used, however R_2 is negative.

For "S" -type Wellpath and Double Build-up type Wellpath, ΔD_{dt}, ΔS_{dt}, ΔD_{tf} and ΔS_{tf} shall be calculated as follows:

$$\Delta D_{dt} = \Delta L_{dt}\cos\alpha_t \quad (47)$$

$$\Delta S_{dt} = \Delta L_{dt}\sin\alpha_t \quad (48)$$

$$\Delta D_{tf} = \Delta L_{tf}\cos\alpha_t \quad (49)$$

$$\Delta S_{tf} = \Delta L_{tf}\sin\alpha_t \quad (50)$$

6.2 Calculation of key points

6.2.1 Endpoint of the first build-up section

$$L_b = L_a + \frac{1}{180} \times \pi R_1(\alpha_b - \alpha_a) \quad (51)$$

$$D_b = D_a + R_1(\sin\alpha_b - \sin\alpha_a) \quad (52)$$

$$S_b = S_a + R_1(\cos\alpha_a - \cos\alpha_b) \quad (53)$$

6.2.2 Startpoint of the second build-up section or drop-off section

$$L_c = L_b + \Delta L_w \quad (54)$$

$$D_c = D_b + \Delta L_w\cos\alpha_b \quad (55)$$

$$S_c = S_b + \Delta L_w\sin\alpha_b \quad (56)$$

6.2.3 Endpoint of the second build-up section or drop-off section

$$L_d = L_c + \frac{1}{180} \times \pi R_2(\alpha_t - \alpha_b) \quad (57)$$

$$D_d = D_c + R_2(\sin\alpha_t - \sin\alpha_b) \quad (58)$$

$$S_d = S_c + R_2(\cos\alpha_b - \cos\alpha_t) \quad (59)$$

6.2.4 Target

$$L_t = L_d + \Delta L_{dt} \quad (60)$$

6.2.5 Finish point of wellpath

$$L_f = L_t + \Delta L_{tf} \quad (61)$$

$$D_f = D_t + \Delta D_{tf} \quad (62)$$

$$S_f = S_t + \Delta S_{tf} \quad (63)$$

6.3 Calculation of interpolate points

6.3.1 When calculating interpolate point data, one should use MD as an independent variable, with a predetermined step length started from the KOP.

6.3.2 Inclination, TVD, and horizontal displacement of a interpolate point should be calculated as follows:

a) For the first build-up section:

$$\alpha_j = \alpha_a + 180 \times \frac{(L_j - L_a)}{\pi R_1} \quad (64)$$

$$D_j = D_a + R_1(\sin\alpha_j - \sin\alpha_a) \quad (65)$$

$$S_j = S_a + R_1(\cos\alpha_a - \cos\alpha_j) \quad (66)$$

b) For the hold-on section:

$$\alpha_j = \alpha_b \quad (67)$$

$$D_j = D_b + (L_j - L_a)\cos\alpha_b \quad (68)$$

$$S_j = S_b + (L_j - L_a)\sin\alpha_b \quad (69)$$

c) For the second build-up section or drop-off section:

$$\alpha_j = \alpha_b + 180 \times \frac{(L_j - L_c)}{\pi R_2} \quad (70)$$

$$D_j = D_c + R_2(\sin\alpha_j - \sin\alpha_b) \quad (71)$$

$$S_j = S_c + R_2(\cos\alpha_b - \cos\alpha_j) \quad (72)$$

d) For the borehole section in the target area:

$$\alpha_j = \alpha_t \quad (73)$$

$$D_j = D_d + (L_j - L_d)\cos\alpha_t \quad (74)$$

$$S_j = S_d + (L_j - L_d)\sin\alpha_t \quad (75)$$

e) For the borehole section below the final target:

$$\alpha_j = \alpha_t \quad (76)$$

$$D_j = D_t + (L_j - L_t)\cos\alpha_t \quad (77)$$

$$S_j = S_t + (L_j - L_t)\sin\alpha_t \quad (78)$$

6.3.3 Calculation of E/W and N/S Coordinates:

$$N_j = S_j\cos\theta_0 \quad (79)$$

$$E_j = S_j\sin\theta_0 \quad (80)$$

7 3D detouring obstacles wellpath design

7.1 Horizontal projection

7.1.1 Calculation for C_g and θ_g

$$C_g = \sqrt{N_g^2 + E_g^2} \quad (81)$$

$$\tan\theta_g = \frac{E_g}{N_g} \quad (82)$$

7.1.2 Judgment for 3D detouring obstacles design necessity

A new XOY coordinates can be created by rotating EON coordinates clockwise around the wellhead by the amount of θ_t and pointing axis N to target t (See Figure C.7 of Annex C) .

$$\begin{cases} x_g = C_g\cos(\theta_g - \theta_t) \\ y_g = C_g\sin(\theta_g - \theta_t) \end{cases} \quad (83)$$

3D Detouring obstacles design would be necessary if $0<x_g<V_t$ and $|y_g|<R_g$.

7.1.3 Criteria for clockwise or counterclockwise 3D detouring obstacles design

$$q = \mathrm{sgn}(y_g) = \begin{cases} -1, \text{Counterclockwise detouring design} \\ +1, \text{Clockwise detouring design} \end{cases} \quad (84)$$

where, sgn is the sign function.

7.1.4 Calculation of initial azimuth

$$\phi_0 = \theta_g - q\sin^{-1}\left(\frac{R_g}{C_g}\right) \quad (85)$$

7.1.5 Calculation of azimuthal change

$$\tan\frac{\Delta\phi}{2} = \begin{cases} \dfrac{S_e}{2D_e} & (2R_g = S_e) \\ \dfrac{D_e - \sqrt{D_e^2 + S_e^2 - 2R_gS_e}}{2R_g - S_e} & (2R_g \neq S_e) \end{cases} \quad (86)$$

where

$$D_e = C_t\cos(\theta_t - \phi_0) - C_g\cos(\theta_g - \phi_0) \quad (87)$$

$$S_e = C_t|\sin(\theta_t - \phi_0)| \quad (88)$$

7.1.6 Key point curvilinear length of horizontal projection

$$S_P = C_g\cos(\theta_g - \phi_0) \quad (89)$$

$$S_Q = S_P + \frac{1}{180} \times \pi R_g\Delta\phi \quad (90)$$

$$S_t = S_Q + \sqrt{D_e^2 + S_e^2 - 2R_gS_e} \quad (91)$$

7.2 Vertical profile design

Design of vertical profile for 3D wellpath is the same as that for 2D wellpath.

7.3 Calculation of key points

7.3.1 Calculation of key point on vertical profile

See 6.2.

7.3.2 Calculation of key point on horizontal projection

In case of $S_P \leqslant S_a$:

$$L_P = \frac{S_P}{\sin\alpha_a} \quad (92)$$

$$D_P = \frac{S_P}{\tan\alpha_a} \quad (93)$$

In case of $S_a < S_P \leqslant S_b$:

$$L_P = L_a + \frac{1}{180} \times \pi R_1(\alpha_P - \alpha_a) \quad (94)$$

$$D_P = D_a + R_1(\sin\alpha_P - \sin\alpha_a) \quad (95)$$

where

$$\cos\alpha_P = \cos\alpha_a - \frac{S_P - S_a}{R_1} \quad (96)$$

In case of $S_b < S_P \leqslant S_c$:

$$L_P = L_b + \frac{S_P - S_b}{\sin\alpha_b} \quad (97)$$

$$D_P = D_b + \frac{S_P - S_b}{\tan\alpha_b} \quad (98)$$

In case of $S_c < S_P \leqslant S_d$:

$$L_P = L_c + \frac{1}{180} \times \pi R_2(\alpha_P - \alpha_b) \quad (99)$$

$$D_P = D_c + R_2(\sin\alpha_P - \sin\alpha_b) \quad (100)$$

where

$$\cos\alpha_P = \cos\alpha_b - \frac{S_P - S_c}{R_2} \quad (101)$$

In case of $S_P > S_d$:

$$L_P = L_d + \frac{S_P - S_d}{\sin\alpha_t} \quad (102)$$

$$D_P = D_d + \frac{S_P - S_d}{\tan\alpha_t} \quad (103)$$

Calculation of key point Q is the same as that of the key point P, see equations (92) ~ (103) .

7.4 Calibration for borehole curvature

$$\kappa = \sqrt{\kappa_V^2 + \kappa_H^2 \cdot \sin^4\alpha} \quad (104)$$

If κ is greater than the predetermined borehole curvature value, R_g, 3D detouring curvature radius, shall be increased and the 3D Detouring obstacles wellpath design repeated.

7.5 Calculation of interpolate points

7.5.1 For calculation of inclination, TVD and horizontal curvilinear length, see 6.3.2.

7.5.2 Calculation of azimuth, N/S coordinates and E/W coordinates, see equations (105) ~ (113) .

In case of $S_j \leqslant S_P$:

$$\phi_j = \phi_0 \quad (105)$$

$$N_j = S_j\cos\phi_j \quad (106)$$

$$E_j = S_j\sin\phi_j \quad (107)$$

In case of $S_P < S_j \leqslant S_Q$:

$$\phi_j = \phi_P + \frac{1}{180} \times \frac{q(S_j - S_P)}{\pi R_g} \quad (108)$$

$$N_j = N_P + qR_g(\sin\phi_j - \sin\phi_0) \quad (109)$$

$$E_j = E_P + qR_g(\cos\phi_0 - \cos\phi_j) \quad (110)$$

In case of $S_j > S_Q$:

$$\phi_j = \phi_0 + q\Delta\phi \quad (111)$$

$$N_j = N_Q + (S_j - S_Q)\cos\phi_j \quad (112)$$

$$E_j = E_Q + (S_j - S_Q)\sin\phi_j \quad (113)$$

8 Trajectory calculation

8.1 Provisions

Trajectory data shall be calculated in accordance with the following provisions:

——Survey stations shall be numbered from top to bottom, $i = 1, 2, 3, \cdots$.

——Survey station intervals shall be numbered from top to bottom, $i = 1, 2, 3, \cdots$; the i^{th} interval is the interval between the $(i-1)^{th}$ station to the i^{th} station.

——The calculation shall be started from the wellhead; for conventional rigs, $\alpha_0 = 0$, $\phi_0 = \phi_1$; for slant rigs, α_0 is equal to the inclination angle of the rig and ϕ_0 is equal to the azimuth of the rig.

——The azimuth utilized in the trajectory calculation shall be calibrated with magnetic declination and meridian convergence.

——In case of well inclination at a survey station is zero, the well azimuth at the point shall be the same as that at another point in the same survey station interval.

——In case of $|\phi_i - \phi_{i-1}| < 180°$, $\Delta\phi = \phi_i - \phi_{i-1}$. In case of $|\phi_i - \phi_{i-1}| > 180°$, $\Delta\phi = \phi_i - \phi_{i-1} - \mathrm{sgn}(\phi_i - \phi_{i-1}) \times 360$. In case of $|\phi_i - \phi_{i-1}| = 180°$, the sign of $\Delta\phi$ shall be determined according to the azimuth change trends of its up station interval.

8.2 Calculation for survey station interval

8.2.1 Length of survey station interval and average borehole curvature

$$\Delta L_i = L_i - L_{i-1} \quad (114)$$

$$\kappa_i = 30 \times \frac{\varepsilon_i}{\Delta L_i} \quad (115)$$

where

$$\varepsilon_i = \cos^{-1}[\cos\alpha_{i-1}\cos\alpha_i + \sin\alpha_{i-1}\sin\alpha_i\cos(\phi_i - \phi_{i-1})] \quad (116)$$

8.2.2 Calculation of coordinates increment

8.2.2.1 Minimum curvature method

$$\Delta D_i = \lambda_i(\cos\alpha_{i-1} + \cos\alpha_i) \quad (117)$$

$$\Delta S_i = \frac{1}{360} \times \frac{\pi\lambda_i\Delta\phi_i(\sin\alpha_{i-1} + \sin\alpha_i)}{\tan(\Delta\phi_i/2)} \quad (118)$$

$$\Delta N_i = \lambda_i(\sin\alpha_{i-1}\cos\phi_{i-1} + \sin\alpha_i\cos\phi_i) \quad (119)$$

$$\Delta E_i = \lambda_i(\sin\alpha_{i-1}\sin\phi_{i-1} + \sin\alpha_i\sin\phi_i) \quad (120)$$

where

$$\lambda_i = 180 \times \frac{\Delta L_i \tan(\varepsilon_i/2)}{\pi\varepsilon_i} \quad (121)$$

8.2.2.2 Radius of curvature method

$$\kappa_{Vi} = 30 \times \frac{\Delta\alpha_i}{\Delta L_i} \quad (122)$$

$$\kappa_{Hi} = \begin{cases} 30 \times \dfrac{\Delta\phi_i}{\Delta L_i\sin\alpha_i} & (\kappa_{Vi} = 0) \\ \dfrac{1}{180} \times \dfrac{\pi\Delta\phi_i\kappa_{Vi}}{\cos\alpha_{i-1} - \cos\alpha_i} & (\kappa_{Vi} \neq 0) \end{cases} \quad (123)$$

$$\Delta S_i = \begin{cases} \Delta L_i\sin\alpha_{i-1} & (\kappa_{Vi} = 0) \\ R_{Vi}(\cos\alpha_{i-1} - \cos\alpha_i) & (\kappa_{Vi} \neq 0) \end{cases} \quad (124)$$

ΔD_i, ΔN_i and ΔE_i should be calculated using equations (17) ~ (25) .

8.3 Calculation for survey stations

$$D_i = D_{i-1} + \Delta D_i \quad (125)$$

$$S_i = S_{i-1} + \Delta S_i \quad (126)$$

$$N_i = N_{i-1} + \Delta N_i \quad (127)$$

$$E_i = E_{i-1} + \Delta E_i \quad (128)$$

$$C_i = \sqrt{N_i^2 + E_i^2} \quad (129)$$

$$\tan\theta_i = \frac{E_i}{N_i} \quad (130)$$

$$V_i = C_i\cos(\theta_0 - \theta_i) \quad (131)$$

8.4 Calculation for target entry points

The target entry point e shall be calculated using interpolation method and in accordance with applied trajectory model.

8.4.1 Off-target distance of a horizontal target

$$J = \sqrt{(N_t - N_e)^2 + (E_t - E_e)^2} \quad (132)$$

8.4.2 Longitudinal and latitudinal offsets of a vertical target

$$H = D_t - D_e \quad (133)$$

$$W = (N_t - N_e)\sin\phi_t - (E_t - E_e)\cos\phi_t \quad (134)$$

8.5 Output format

Trajectory calculation should be tabulated and printed according to the format specified in Table B.2 and Table B.3 of Annex B.

8.6 Graphing

8.6.1 Vertical profile and horizontal projection graphing for a 2D directional well may be plotted using data shown in Table B.2 of Annex B. D and V are the coordinates in the vertical projection (see Figure C.8 of Annex C) .

8.6.2 Vertical profile, horizontal projection and 3D trajectory graphing for a 3D directional well may be plotted using data shown in Table B.2 of Annex B. D and S are the coordinates in the vertical profile.

Annex A
(normative)
The general symbols nomenclature

Tables A.1 and Table A.2 show the general symbols and their associated subscripts used for well-path design and trajectory calculations.

Table A.1: Description of the general symbols used in this standard

No.	Symbol	Description	Unit
1	L	Measured depth	m
2	α	Inclination	(°)
3	ϕ	Azimuth	(°)
4	N	N/S coordinates	m
5	E	E/W coordinates	m
6	D	True vertical depth	m
7	S	Horizontal curvilinear length	m
8	C	Horizontal displacement (closure distance)	m
9	θ	Closure azimuth	(°)
10	V	Vertical section	m
11	ΔL	Increment of measure depth	m
12	$\Delta\alpha$	Inclination increment	(°)
13	$\Delta\phi$	Azimuth increment	(°)
14	ΔN	N/S coordinates increment	m
15	ΔE	E/W coordinates increment	m
16	ΔD	TVD increment	m
17	ΔS	Increment of horizontal curvilinear length	m
18	ΔL_w	Length of a hold-on section	m
19	κ	Borehole curvature	(°) /30m
20	κ_V	Curvature of a vertical profile	(°) /30m
21	κ_H	Curvature of a horizontal projection	(°) /30m
22	R	Curvature radius	m
23	R_V	Curvature radius of a vertical profile	m
24	R_H	Curvature radius of a horizontal projection	m
25	R_1	Curvature radius of the first circular-arc	m
26	R_2	Curvature radius of the second circular-arc	m
27	R_g	3D detouring curvature radius	m

Table A.1 (continued)

No.	Symbol	Description	Unit
28	ω	Tool face angle on a spatial-circular-arc	(°)
29	ε	Bending angle on a spatial-circular-arc	(°)
30	q	The sign of a variable	
31	J	Off-target distance of horizontal target	m
32	H	Longitudinal off-set of vertical target	m
33	W	Latitudinal off-set of vertical target	m
34	R_e	Intermediate variable used for calculation	m
35	D_e	Intermediate variable used for calculation	m
36	S_e	Intermediate variable used for calculation	m
37	λ	Intermediate variable used for calculation	m
38	x	Intermediate coordinates	m
39	y	Intermediate coordinates	m
40	ξ	Intermediate coordinates	m
41	η	Intermediate coordinates	m
42	ζ	Intermediate coordinates	m

Table A.2: Description of the subscripts used for the general symbols

No.	Symbol	Description
1	O	Origin of coordinates
2	a	Kick-off point
3	b	Endpoint of the first circular-arc section
4	c	Startpoint of the second circular-arc section
5	d	Endpoint of the second circular-arc section
6	t	Target
7	f	Final point of wellpath
8	g	Central point of obstacles
9	P	Startpoint of direction change in detouring obstacles 3D plan
10	Q	Endpoint of direction change in detouring obstacles 3D plan
11	i	Variable
12	j	Variable
13	e	Entry point

Annex B
(normative)
Output format of wellpath design and trajectory calculation

The table format shown in Table B.1 shall be used to output wellpath design data for Well ×××.

The table format shown in Table B.2 shall be used to output trajectory Calculation data for Well ×××.

The table format shown in Table B.3 shall be used to output target entry data for Well ×××.

Table B.1: Wellpath design for well ×××

Planned TVD: m	Closure distance: m	Closure azimuth: deg

Target data

Target	TVD m	N/S m	E/W m	Target radius m	Longitudinal off-target m	Latitudinal off-target m

Key points data

MD m	Inc deg	Az deg	TVD m	N/S m	E/W m	CLsD m	DLeg deg/30m	Build deg/30m	Turn deg/30m	Target

Interpolate points data

MD m	Inc deg	Az deg	TVD m	N/S m	E/W m	CLsD m	V.Sec m	CLsA deg	DLeg deg/30m	Build deg/30m	Turn deg/30m

Table B.2: Trajectory calculation for well ×××

Calculation model:

No	MD m	Inc deg	Az deg	TVD m	*N/S* m	*E/W* m	CLsD m	V.Sec m	CLsA deg	DLeg deg/30m
1										
2										
3										
…										

Table B.3: Target entry calculation for well ×××

Target	MD m	TVD m	*N/S* m	*E/W* m	CLsD m	CLsA deg	Off-target m	Longitudinal off-target m	Latitudinal off-target m
A									
B									
C									
…									

Annex C
(normative)
Illustration graphs of planned wellpath and actual trajectory

For illustration graph of planned wellpath and actual trajectory, see Figure C.1~C.8.

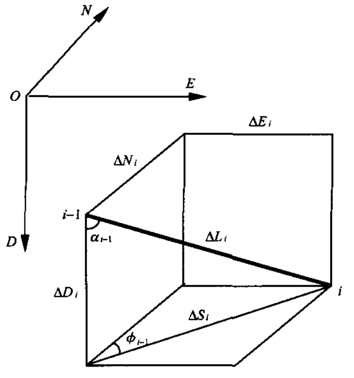


Figure C.1: Straight-line model

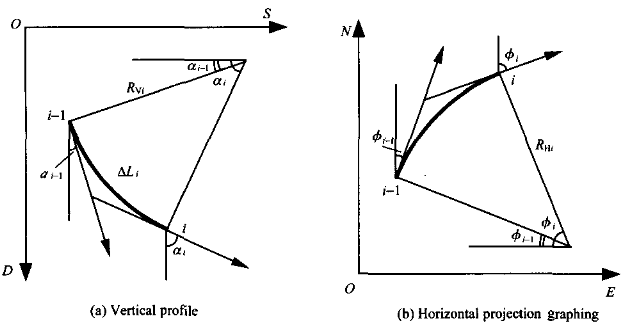


Figure C.2: Cylindrical helicoid model

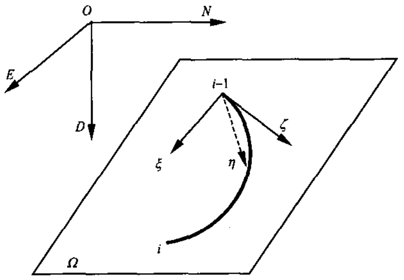


Figure C.3: Circular-arc model

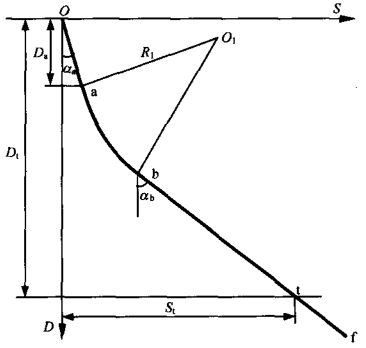


Figure C.4: "J" -type wellpath

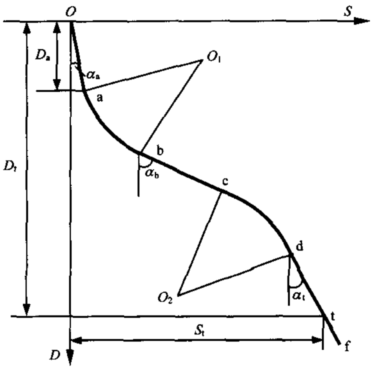


Figure C.5: "S" -type wellpath

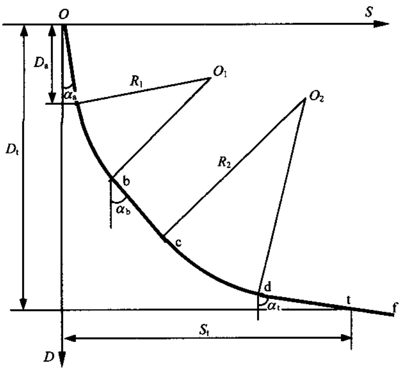


Figure C.6: Double build-up type wellpath

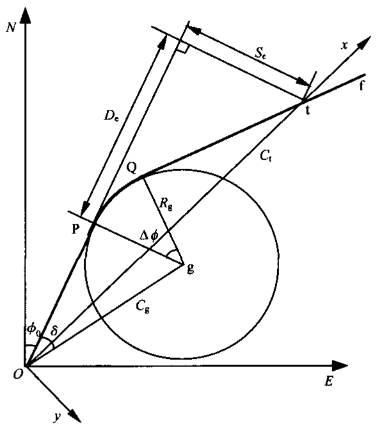
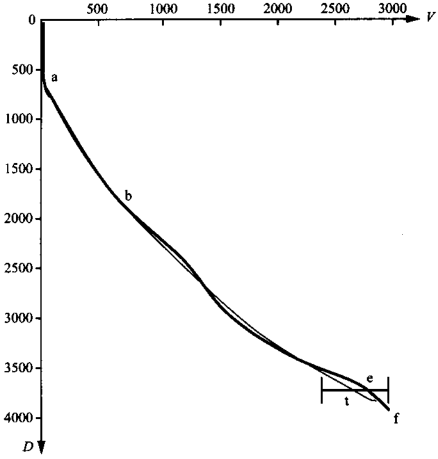
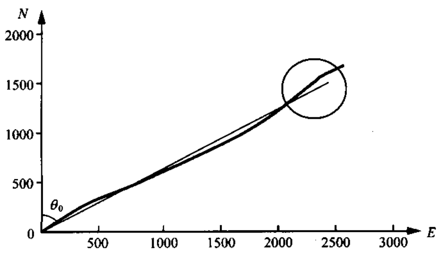


Figure C.7: Horizontal projection graphing for 3D detouring obstacles wellpath



(a) Vertical profile



(b) Horizontal projection graphing

Figure C.8: Trajectory graphing