10 Casing and Well Cementation

The casing program of CCSD-1 Well was different from that of conventional oil drilling and water well drilling in two aspects: not only were the standards of casing program different but also the moving casing techniques employed. In oil drilling, a casing program of 508.0 mm (20 in.) × 339.7 mm ($13^3/_8$ in.) × 244.5 mm ($9^5/_8$ in.) × 177.8 mm (7 in.) was generally employed, whereas in CCSD-1 Well a casing program of 339.7 mm ($13^3/_8$ in.) × 273.0 mm ($10^3/_4$ in.) × 193.7 mm ($7^5/_8$ in.) × 127.0 mm (5 in.) was adopted in design and in construction. In CCSD-1 Well, the program of "two boreholes combined into one" was realized, with four times of normal casing setting and cementation (not including wellhead conductor) and two times of setting moving casing, shown in Table 10.1.

10.1 Borehole Structure and Casing Program

10.1.1 Borehole Structure and Casing Program for the Pilot Hole

After penetrating through unstable surface layer of 100.36 m deep by non-core drilling with 444.5 mm roller cone bit, 339.7 mm intermediate casing was run and well was cemented. After that 244.5 mm moving casing was set and then diamond core drilling was conducted.

Core drilling reached to the designed depth of 2000 m, where the formation was broken, being unfavourable for setting casing. Under these circumstances, core drilling was continued, finally to the depth of 2046.54 m. The actual borehole structure and casing program of the pilot hole can be found in Table 10.2 and in Fig. 10.1.

10.1.2 Borehole Structure and Casing Program for the Main Hole

Because the quality of the pilot hole satisfied the requirement of "two holes combined into one", reaming was conducted on the basis of the pilot hole and the reamed pilot hole became a part of the main hole. 273.0 mm casing was run after reaming and cementation conducted, then 193.7 mm moving casing was set. 157 mm diamond core drilling was started from the hole depth of 2046.54 m. "Two holes combined into one" saved large funds and much time.

In the third opening, when core drilling reached to 3665.87 m, 244.5 mm reaming drilling was conducted as a result of complicated borehole conditions. When reaming drilling reached to the depth of 3525.18 m, because fish existed at the hole bottom, 244.5 mm sidetrack drilling-around was employed. 193.7 mm intermediate casing was set and hole cemented. Then 157 mm diamond core drilling was continued.

Core drilling in the fourth opening drilled to 5118.2 m and after drilling tool test reached to the final hole depth of 5158 m. Then 127 mm tail pipe was run, cementation was conducted and the borehole was completed.

The actual borehole structure and casing program of CCSD-1 Well can be found in Table 10.3 and in Fig. 10.2.

10.1.3 Casing Design

1. **Downhole temperature estimation**

The static temperature and circulating temperature (Table 10.4) at different hole depths could be estimated by using geothermal gradient of 2.5 °C/100 m, which was derived from the temperature curve of CCSD-PP2 hole and the predictive temperature curve of CCSD-1 well.

D. Wang et al., *The China Continental Scientific Drilling Project*,
Springer Geology, DOI 10.1007/978-3-662-46557-8_10

Table 10.1 Casing and cementation construction schedule

No.	Hole section	Construction	Description
1	0–100.36 m	Set 339.7 mm surface casing and cementation	Set 339.7 mm surface casing and cementation was smoothly operated
2	0–101 m	Set and withdraw 244.5 mm moving casing	Set 244.5 mm moving casing and at the lower position of the moving casing string were installed three rigid centralizers and at the upper part were three elastic centralizers
3	0–2028 m	Set 273.0 mm intermediate casing and cementation	Set 273.0 mm intermediate casing. Casing string: float shoe + float collar + one piece of short casing (5 m) + setting seat + one piece of short casing (3 m) + retaining joint assembly + casing string. Cementation was smoothly operated
4	0–2019 m	Set and withdraw 193.7 mm moving casing	Set 193.7 mm moving casing. Casing string: insert guide head + inserted sleeve + casing string + landing joint. On to the five pieces of casing near the retaining joint each was added with an elastic centralizer and on the sixth piece of casing above was added with a rigid centralizer. For other casings a centralizer was added for every two pieces, with rigid and elastic centralizer alternately added
5	0–3620 m	Set 193.7 mm intermediate casing and cementation	Set 193.7 mm intermediate casing. The position of stage collar was at 1928.11 m. Casing string: guide shoe + one piece of casing + float collar + six pieces of casing + float collar + casing string + stage collar + casing string. Staged cementation was smoothly operated
6	3523.55–4790.72 m	Set 127.0 mm tail pipe and cementation	Set 127.0 mm tail pipe. Casing string: float shoe + one piece of casing + float collar + one piece of casing + float collar + one piece of casing + ball seat + casing + joint + hanger + running- in tool + drill rod. Cementation was smoothly operated.

Note In No. 4, seventy two steel pieces of the elastic centralizer fell into the borehole after withdrawing moving casing

Table 10.2 The actual borehole structure and casing program of the pilot hole

Opening (spud-in)	Drill bit size		Drilled depth (m)	Casing size		Casing setting depth (m)	Remarks
	mm	in.		mm	in.		
1	Man digging		4.0	508.0	20	4.0	Conductor
2	444.5	$17^1/_2$	101.00	339.7	$13^3/_8$	100.36	Cementation
	Set 244.5 mm moving casing to the depth of 101.00 m						
3	157.0	$6^3/_{16}$	2046.54	The pilot hole was completed and two holes combined into one, reaming for the main hole			

2. **Basic data of casing**

The basic data of the casing employed for CCSD-1 well are shown in Table 10.5.

3. **Other data**

Elastic modulus of casing E: 207 GPa
Thermal expansion coefficient of casing k_t: 1.25×10^{-5} m/°C
Permissible tension safety factor (St): 1.8
Permissible collapsing safety factor (Sc): 1.125
Permissible internal pressure safety factor (Si): 1.1

4. **Calculation of effective internal pressure**

Effective internal pressure denotes the difference between the maximum internal pressure that inside casing may bear and the fluid column pressure outside casing. Generally speaking, when well control operation is conducted in case of well kick and well shut-in intermediate casing bear the maximum internal pressure. Therefore, intermediate casing should be designed based on the load of well shut-in and checked by using the condition of oil well kick.

Suppose well kick happens when drilling next layer and the whole borehole is full of brine, then in well shut-in, Wellhead pressure

$$P_s = P_p - P_{os} = (G_P - G_{os})H_s \tag{10.1}$$

Effective internal pressure

$$P_{be} = (P_s + G_{os}H) - G_w H \tag{10.2}$$

in which,

P_s wellhead pressure, MPa
P_p formation pore pressure, MPa
P_{os} brine column pressure, MPa
G_p formation pore pressure gradient, MPa/m
G_{os} brine column pressure gradient, MPa/m
H_s well depth where casing shoe is located in the layer, m

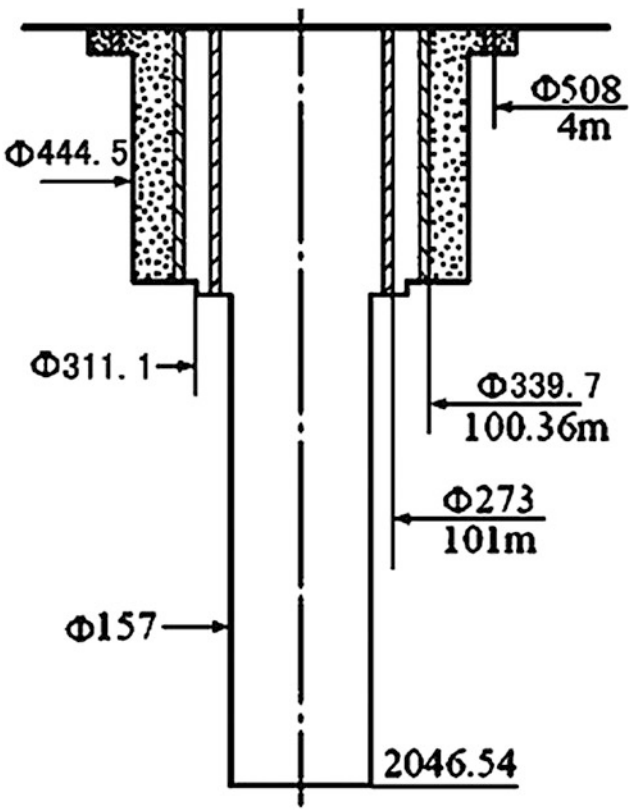


Fig. 10.1 The actual borehole structure and casing program of the pilot hole

P_{be} effective pressure at arbitrary well depth, MPa
H arbitrary well depth, m
G_w fluid column pressure gradient outside casing, MPa/m (calculated based on mud density).

5. **Calculation of effective external pressure**

Effective external pressure denotes the difference between the maximum external pressure that casing string may bear and the minimum internal pressure inside casing. The maximum external pressure that casing bears and the

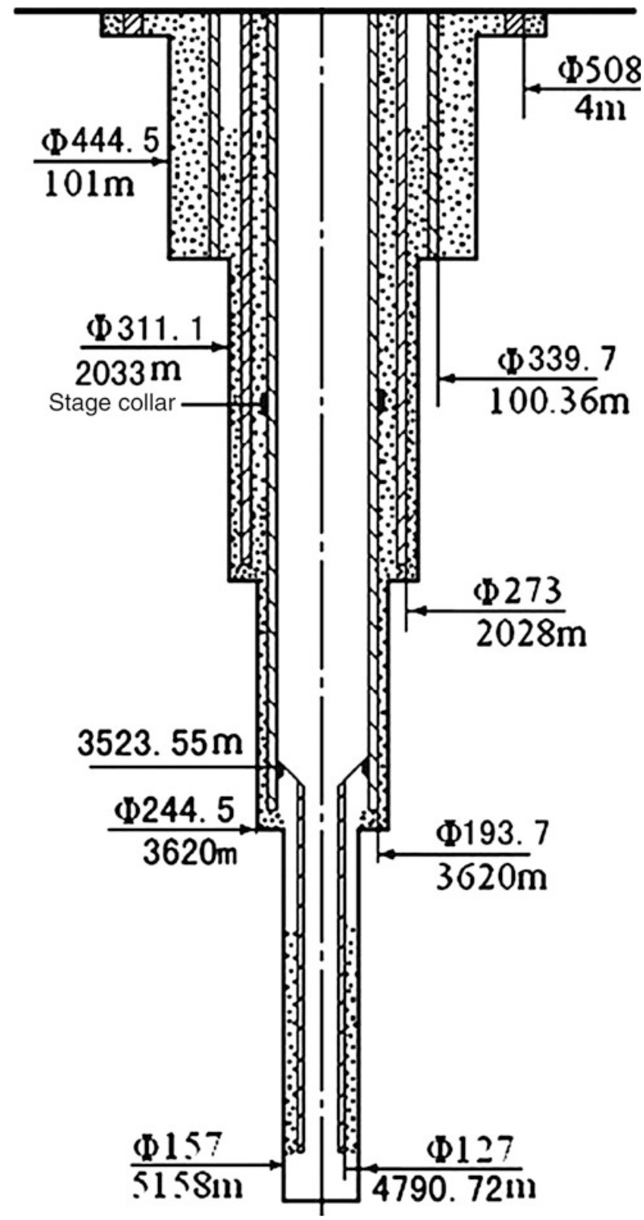


Fig. 10.2 The actual borehole structure and casing program of the main hole

Table 10.3 Borehole structure and casing program of the pilot hole of CCSD-1 Well

Opening (spud-in)	Drilling		Casing		Remarks
	Drill bit size [mm (in.)]	Drilled depth (m)	Casing (tail) size [mm (in.)]	Setting depth (m)	
First opening	444.5 ($17^1/_2$)	101.00	339.7 ($13^3/_8$)	100.36	Non-core drilling
Second opening	157 ($6^3/_{16}$)	2046.54			Core drilling
First reaming	311.1 ($12^1/_4$)	2033.00	273 ($10^3/_4$)	2028	Cementation
	193.7 mm moving casing was then run, to the depth of 2019 m				
Third opening	157 ($6^3/_{16}$)	3665.87			Core drilling
Second reaming	244.5 ($9^5/_8$)	3624.16	193.7 ($7^5/_8$)	3620	Cementation
Fourth opening	157 ($6^3/_{16}$)	5118.20			Core drilling
	157 ($6^3/_{16}$)	5158.00	127 (5)	4770.72	Drilling tool test
	127 mm tail pipe was set to the depth of 4790.72 m. The suspension position of the top of the tail pipe was at 3523.55 m. Cementation and then well completion				

Table 10.4 Downhole temperature

No.	Hole depth (m)	Static temperature (°C)	Circulating temperature (°C)
1	100	28	22
2	2000	75	60
3	3000	100	73
4	4500	138	113
5	5000	150	125

minimum internal pressure inside casing are related to casing type and formation conditions. In this design, calculation for 273 mm intermediate casing is based on 1/2 emptied while for 193.7 mm moving casing 1/3 is emptied.

$$P_{ce} = G_{wl}H - G_{ml}(H - H_{lost}) \text{ when } H > H_{lost}. \quad (10.3)$$

$$P_{ce} = G_{wl}H \text{ when } H \le H_{lost} \quad (10.4)$$

in which,

- P_{ce} effective squeeze pressure at arbitrary well depth, MPa
- H arbitrary well depth, m
- G_{wl} fluid column pressure gradient outside casing, MPa/m (calculated based on saturated brine gradient)
- H_{lost} level depth of lost fluid, m; $H_{lost} = H_{sl}\ (8 - G_o/G_{ml})$
- G_{ml} drilling fluid pressure gradient of the depth for setting casing when drilling to next layer, MPa/m
- H_{sl} setting depth of casing shoe for next layer, m
- G_o pressure gradient of formation supporting fluid column (0.0105–0.0115), MPa/m.

6. **Calculation of effective axial force**

The effective axial force of casing string is the sum of vectors of dead weight, buoyance, inertial force, impact force, frictional force, bending moment force and the additional axial force produced by the variation of in-the-hole temperature and pressure after well cementation. In the master design of CCSD-1 Well, dead weight and buoyance were the main factors to be considered. Buoyance factor method was adopted to calculate buoyance. The effective axial force *Te* at arbitrary well depth is:

$$T_e = \left[\sum_{i=1}^{n} \mathrm{T_i} + (H_x - H)Q_j\right] K_f \quad (10.5)$$

in which,

- T_e effective axial force at calculation level, kN
- H hole depth at calculation level, m
- H_x casing running depth of calculated section, m
- Q_j casing weight per meter of calculated section, kN/m
- T_i casing weight of the i section below the casing of calculated section, kN
- n number of casing section below the casing of calculated section
- K_f buoyance factor, dimensionless, $K_f = 1 - \rho_m/\rho_s$
- ρ_m drilling fluid density, g/cm^3
- ρ_s casing density, g/cm^3; ρ_s = 7.85 g/cm^3.

7. **Calculation result in the design**

The designed strength of casing string and the calibrated results are shown in Table 10.6, from which it can be found that the casing string strength can fully satisfy the requirement of CCSD-1 Well.

10.2 Well Head Assembly

10.2.1 Well Head Assembly for the First Opening (Spud-in)

Before the first opening (spud-in) of CCSD-1 Well, a foundation pit with the area of 12.56 m × 12.56 m × 8.70 m was dug by manpower, the position of well head coordinate was fixed, and 508.0 mm conductor was set, by rubble

Table 10.5 Basic data of casing

Type of casing	339.7 mm surface casing	273.0 mm intermediate casing	193.7 mm intermediate casing	127.0 mm tail pipe
Running interval (m)	0–100.36	0–2028	0–3620	3523.55–4790.72
Steel grade	J55	J55	P110	P110
Wall thickness (mm)	10.92	10.16	9.52	7.52
Nominal weight (kg/m)	90.86	67.77	44.24	22.34
Casing O.D. (mm)	339.7	273	193.7	127
Casing I.D. (mm)	317.9	252.7	174.6	112
Run through casing size (mm)	313.9	248.8	171.5	108.8
Casing collar O.D. (mm)	365.1	298.5	215.9	141.3
Thread type	Oval-shaped	Oval-shaped	Buttress BTC	Oval-shaped

Table 10.6 The design of casing string strength and the calibrated results

Item		339.7 mm intermediate casing	273.0 mm intermediate casing	193.7 mm intermediate casing	127.0 mm tail pipe
Casing strength	Tensile strength (kN)	4367	3180	4270	2240
	Collapsing strength (MPa)	10.6	14.4	36.8	61.1
	Internal pressure strength (MPa)	21.3	24.7	65.2	78.6
Actual safety factor/ permissible safety factor	Tensile (S_t)	55.1/1.80	3.07/1.80	2.71/1.80	25.1/1.80
	Collapsing (S_c)	17.0/1.125	1.28/1.125	1.41/1.125	1.96/1.125
	Internal pressure (S_i)	85.2/1.10	5.49/1.10	5.40/1.10	/

cemented with M20 cement slurry and on the top 200 mm reinforced concrete with 16 mm steel bar was constructed so that a well head of 3 m × 3 m × 2.2 m was formed. At the bottom of the well head was a small squared pit of 450 mm × 450 mm × 450 mm, for collecting the drilling mud in the well head.

The well head assembly for the first opening is illustrated in Fig. 10.3. The size of the conductor was 508.0 mm, with the setting depth of 4 m, acting as a casinghead for welded casing.

10.2.2 Well Head Assembly for the Second Opening (Spud-in)

After drilling to 100.36 m deep in the first opening, surface casing of 339.7 mm was set and cemented. In order to increase the upward velocity of drilling mud, 244.5 mm moving casing was run in 339.7 mm surface casing. Taking the well head of the first opening as a base, the upper conductor was cut off, a ring flange was welded, well head conductor was changed into 339.7 mm, and 244.5 mm moving casing was fixed by casing hanger (Fig. 10.4).

TF13$^3/_8$ in. × 9$^5/_8$ in −70D casing head manufactured by Jinhu Petroleum Machinery Co. Ltd. was adopted for

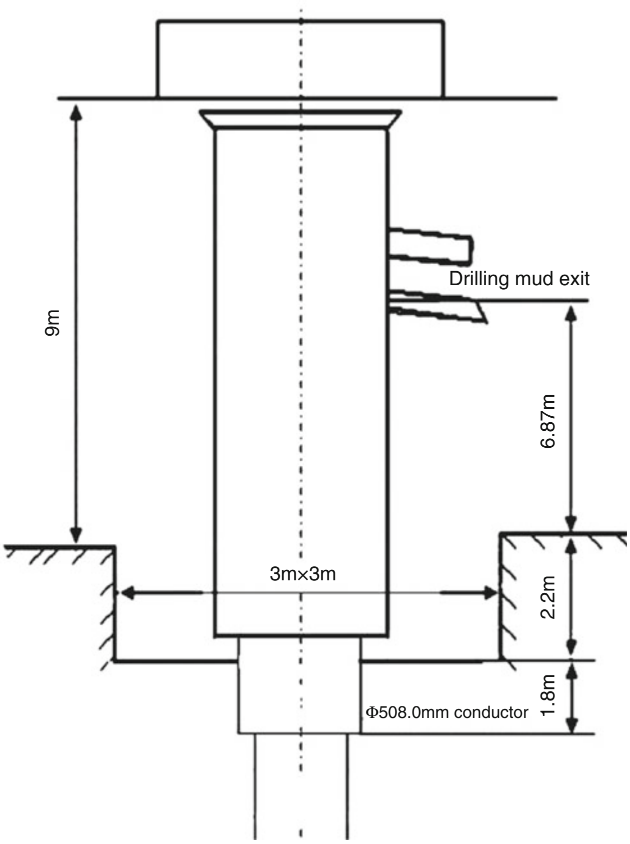


Fig. 10.3 Well head assembly for the first opening

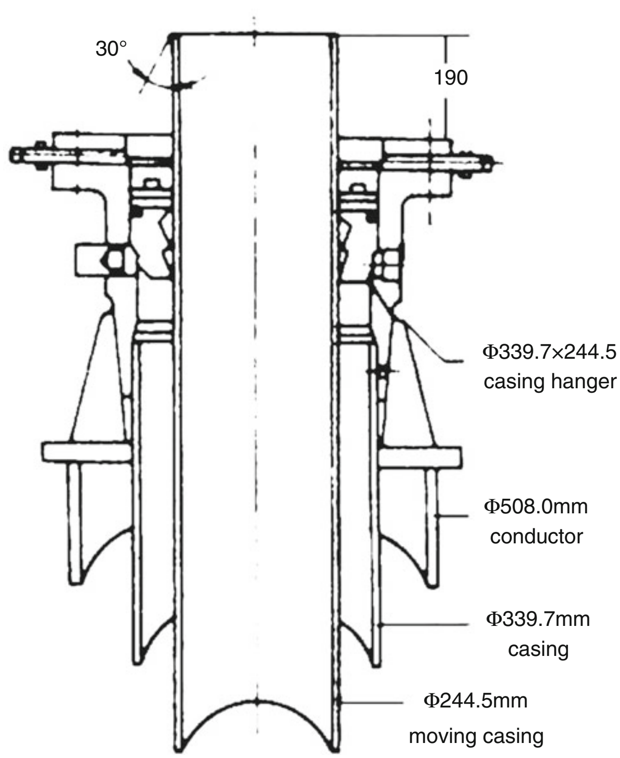


Fig. 10.4 Well head suspending system for the second opening

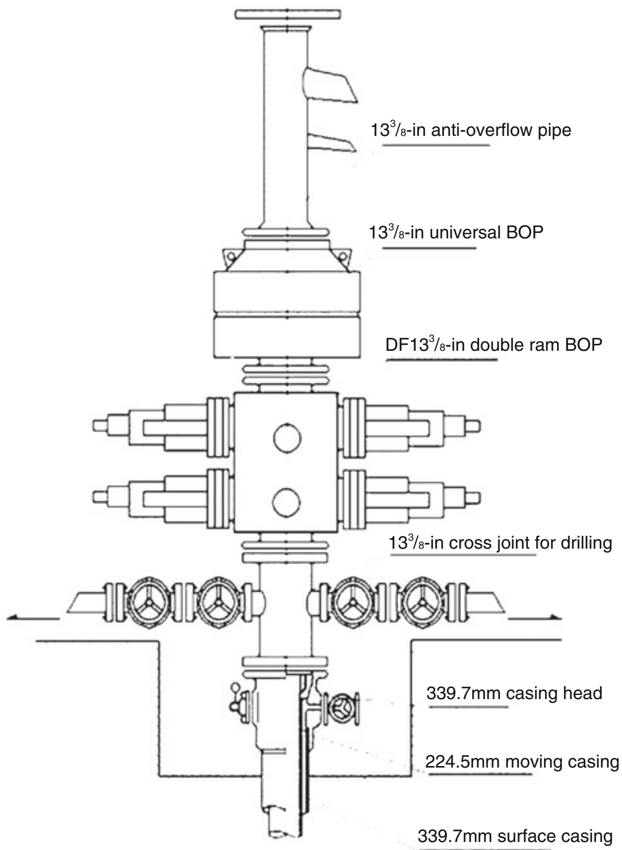


Fig. 10.5 Well head structure for the second opening

CCSD-1 Well. This well head assembly mainly consists of 339.7 mm casing head, 339.7 mm WD casing hanger, gate valve and related connection pieces. 339.7 mm casing head flange and the drift diameter of the side outlet conform to API Spec 6A standard. For 339.7 mm casing hanger, a structure of integrally opened/closed slip element was adopted. For installation, bolts are pressed by screwing in slips at the bottom of 339.7 mm casing head and the slips are excited to tightly hold casing so that a firm connection of the slips and casing is realized. The sealing between casing and casing head is realized by two BT O-rings injected with sealing oil.

Core drilling reached to 1209.61 m and a DF 13^3/$_8$ double ram blowout preventer system (Fig. 10.5) was installed at well head, with the pressure testing result shown in Table 10.7. The testing pressure at its control system and choke-line manifold was 21 MPa, standing up for 10 min, with 0 MPa pressure drop. Pressure testing was qualified.

Table 10.7 Pressure testing result of the blowout preventer

BOP type	Ram 2FZ35	Annular FH35	Throttle JG-35	Well kill YG-35
Testing result (MPa)	21	21	21	21

10.2.3 Well Head Assembly for the Third and the Fourth Opening (Spud-in)

In the second opening, 244.5 mm moving casing was withdrawn after core drilling reached to the depth of 2046.54 m, then expanding drilling was conducted to 2033 m deep, 273.0 mm intermediate casing was run and cemented. To increase the upward velocity of drilling mud, 193.7 mm moving casing was run in 273.0 mm intermediate casing and the top of the moving casing was fixed by casing hanger (Fig. 10.6).

In the third opening, 193.7 mm moving casing was withdrawn after core drilling was completed and then expanding drilling was conducted. 193.7 mm moving casing was taken as intermediate casing and run into the borehole. The well head assembly for the fourth opening was just the same as that for the third opening.

10.2.4 Well Head Assembly for Well Completion

After the completion of CCSD-1 Well, the conductor, blowout preventer and cross joint for drilling at well head were removed and gate valve was fixed on 339.7 mm casing head and casing hanger, for well shut-in and open. The drift diameter of the gate valve was 177.8 mm (7 in.), satisfying the needs of in-the-hole testing and drifting after the establishment of long-term observation station. To ensure the gate valve higher than surface, a lifting sub was installed between the gate valve and the casing head and on the gate valve were fixed tight cover and rainproof cap. Moreover, locks were fixed on the tight cover to prevent foreign objects from falling into the borehole. This specially designed well head assembly is illustrated in Fig. 10.7.

10.3 Casing Running and Well Cementing Operation

10.3.1 508.0 mm Well Head Conductor

Well head conductor was installed through a method of mechanical excavation. In foundation pit excavation, measurement, location and set-out were carried out based upon the datum mark provided by local surveying information. Location and set-out were recorded, as well as the geological conditions and the variation of underground water were recorded. Peculiar situations encountered were treated in peculiar ways. Organic impurities were strictly controlled in backfilled earthwork, which were laid in layers and correspondingly compacted, with water content strictly limited.

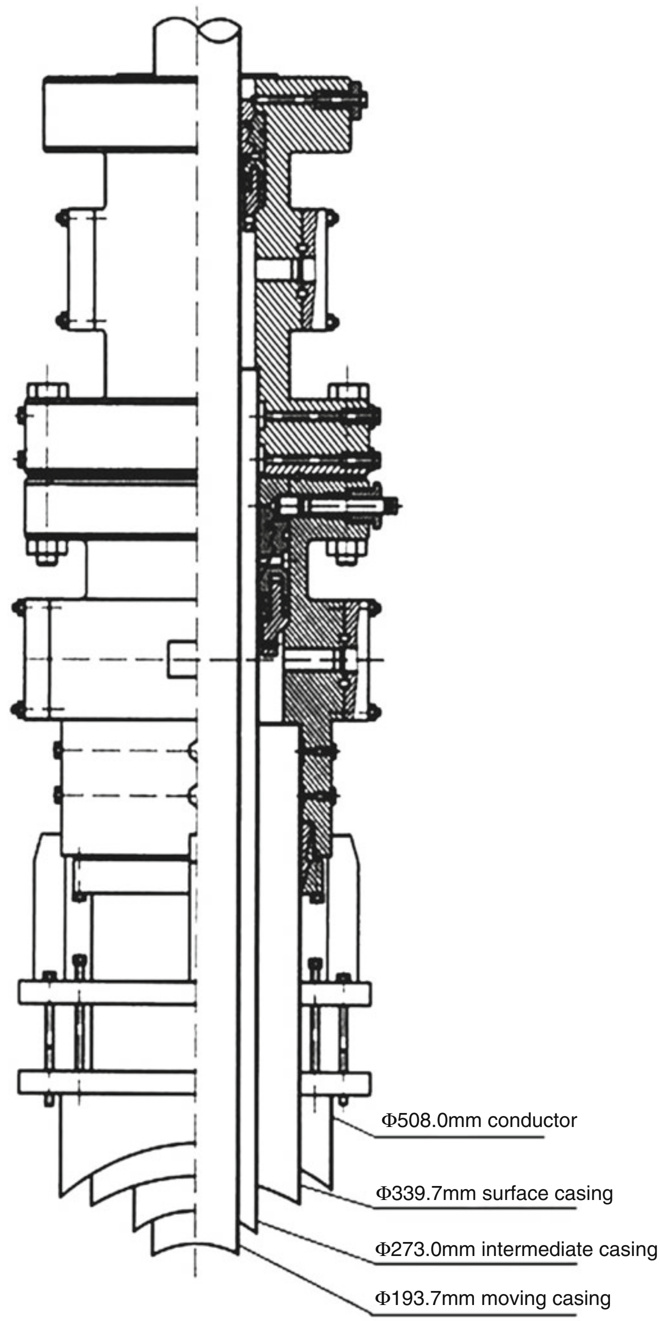


Fig. 10.6 Structure of casing head for the third opening

The geographic coordinates of the well head were X = 3809.530 km and Y = 40,377.874 km. The well head foundation was in situ concreted, with the basic materials of medium grained sand, rubble, cement, reinforcing bar and water. The mixing ratio of concrete raw materials (cement: sand:stone) was: 1:2:4 for derrick foundation, to ensure that the bearing capacity of the foundation could reach 1500 tons. The construction sequence: construction preparation, location and set-out, foundation engineering and installation. In construction a principle of "underground first and afterwards surface" was abided by. The conductor was 508.0 mm (20 in.) in outside diameter, with the buried depth of 4 m (see Fig. 10.3).

10.3.2 339.7 mm Surface Casing

Non-core drilling reached to 100.36 m with hole diameter of 444.5 mm ($17^1/_2$ in.) on July 9th, 2001. 339.7 mm ($13^3/_8$ in.) surface casing was run and cemented.

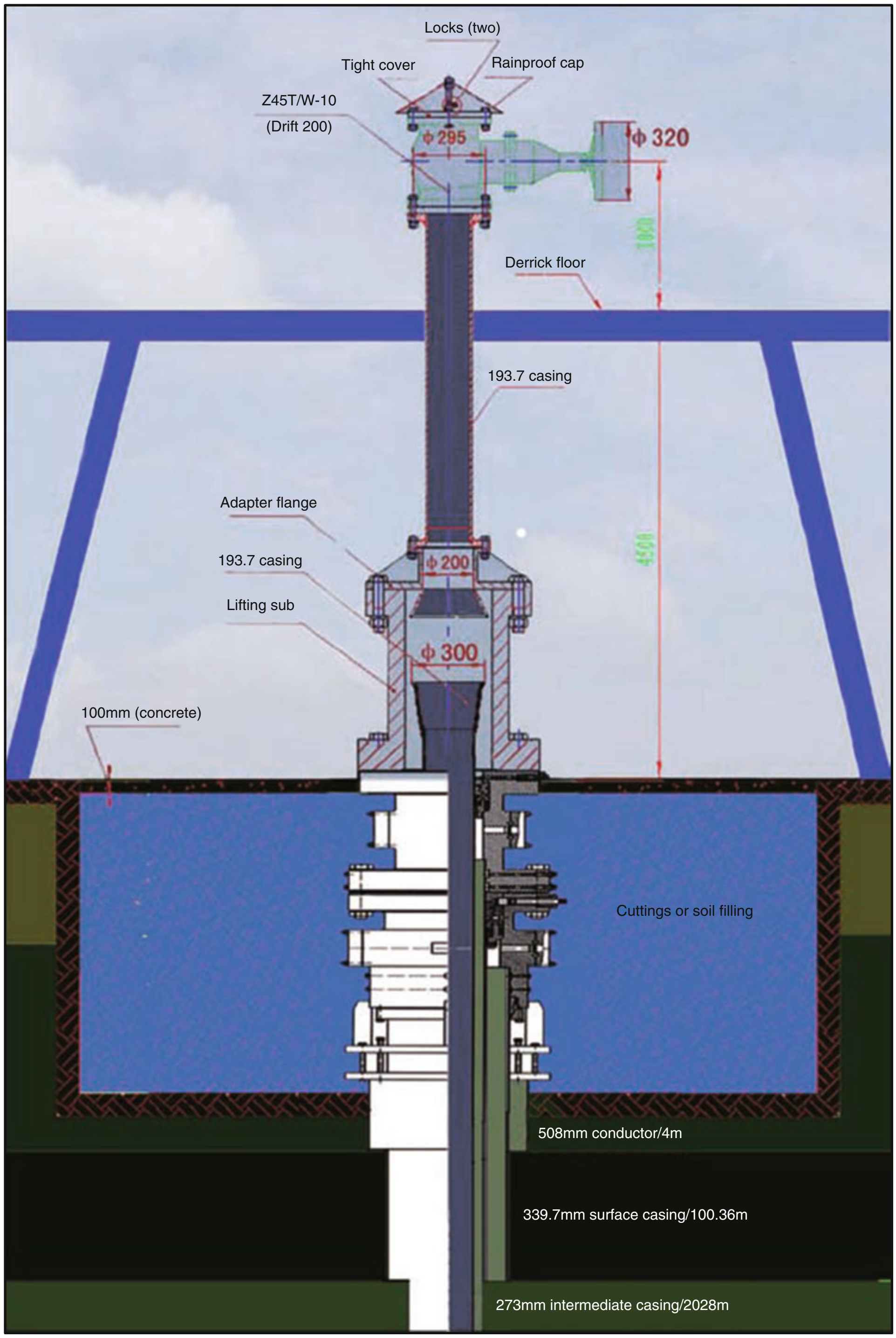


Fig. 10.7 Well head assembly for well completion

The formula of the cement slurry for well cementation was Jiahua G grade cement + 4.0 % G203 (early strength agent) + 0.6 % G301 (dispersant) + 2.0 % G201 (curing accelerator), with water-cement ratio of 0.44 and cement density of 1.86 g/cm^3.

After running 339.7 mm surface casing, cementation operation was started. Drilling mud was circulated for 3 h, injection pipeline was connected, 8 m^3 spacer fluid was injected and 22 m^3 cement slurry was injected. After injecting cement slurry, displacing slurry of 8.1 m^3 was injected under a displacement pressure of 11 MPa. The mud displacement operation was normal, cement slurry returned to well head and cementation was smoothly completed.

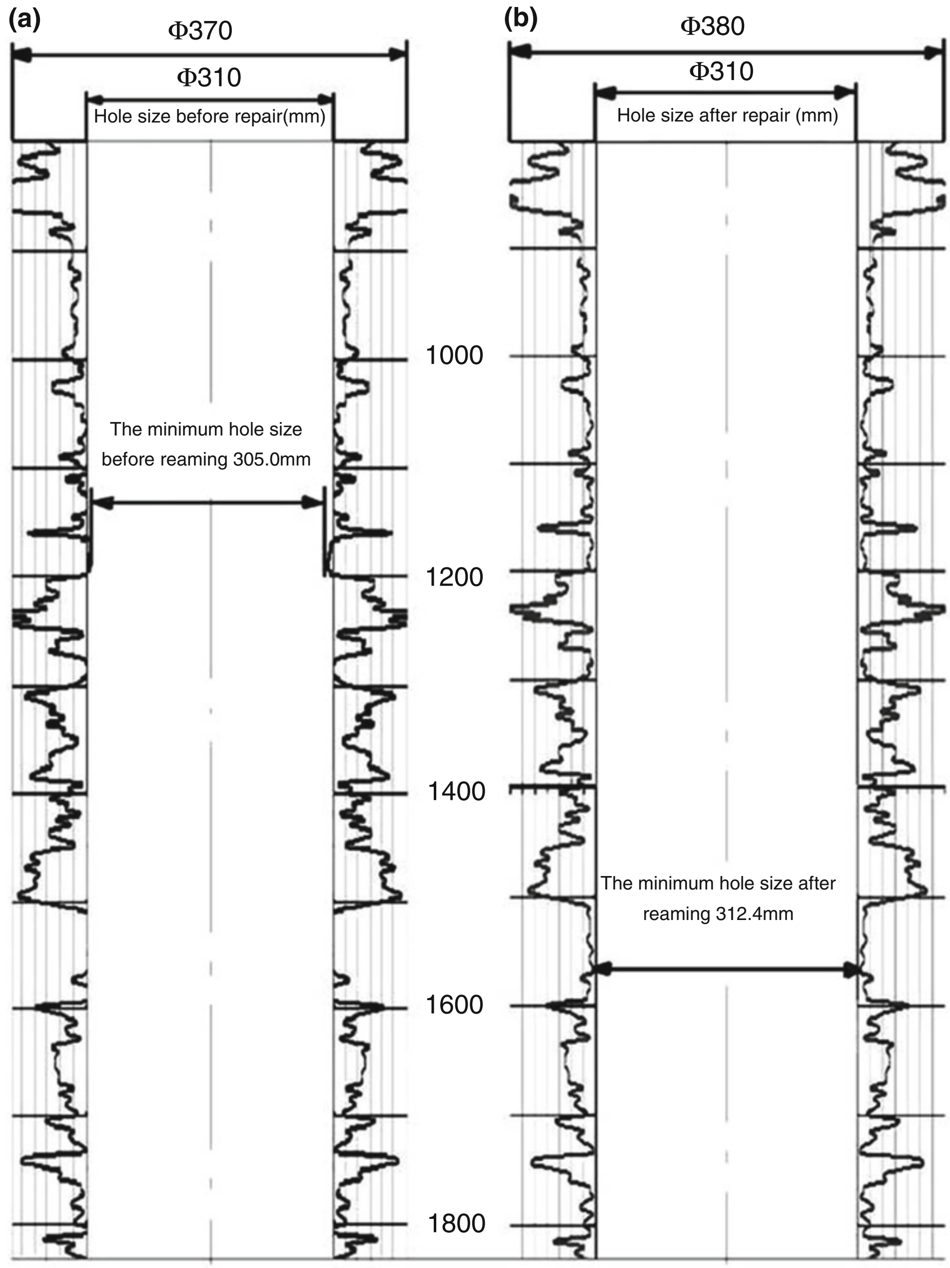


Fig. 10.8 The curves of caliper logging before and after 311.1 mm borehole repairing

10.3.3 273.0 mm Intermediate Casing

After 311.1 mm reaming drilling to 2028 m deep, a pocket of 5 m was drilled by using 215.9 mm cone bit. Through drifting, well flushing and circulating slurry displacement, cementation operation with 273.0 mm ($10^3/_4$ in.) intermediate casing was started on September 9th, 2002. Casing running and cementation in this interval was typically an operation in small clearance in hard rock, with the following characteristics:

(1) It was difficult to run casing in small clearance

It was an exploratory construction technique for reaming drilling by using cone guide bit in ultra high pressure metamorphic crystalline rock formations with drillability from 8 to 11 grade. Generally, cone bit is suitable for drilling rock formations with drillability lower than 6 grade, whereas its gauge protection capacity is obviously inadequate in drilling ultra high pressure metamorphic crystalline rock formations with drillability from 8 to 11 grade. As a result, the actual diameter of the drilled hole is smaller than nominal size. The curves of caliper logging for CCSD-1 Well reamed by 311.1 mm cone bit are shown in Fig. 10.8a, from which it can be found that lots of hole intervals from 1000 to 1360 m and from 1512 to 1855 m had the diameters smaller than 310.0 mm, with the minimum of 305.0 mm. As the outside diameter of the collar of 273.0 mm intermediate casing was 298.5 mm, when casing was in the middle, the clearance between borehole wall and casing was 6.3 mm, with the minimum clearance of only 3.3 mm. Furthermore, borehole had dogleg to a certain extent, and this would inevitably bring about unfavourable influence on running casing and cementation.

(2) Cementing slurry leaked easily

The clearance between the collar (298.5 mm) of 273.0 mm intermediate casing and 311.1 mm hole wall and between the collar (215.9 mm) of 193.7 mm intermediate casing and 244.5 mm hole wall were both very small, thus the upward resistance of cement slurry was very large, the equivalent density of cement slurry might be larger than that of formation leakage and that of formation fracturing pressure, resulting in cement slurry leakage.

1. **Borehole preparation**

Borehole repairing, redressing and trial casing running before setting casing were the technical measures that must be adopted for running casing and cementation in small clearance and in hard rock. 311.1 mm diamond repairing tool not only had the ability of wiping, but also the ability of reaming, being favourable for wiping borehole wall and reaming borehole size. The reaming shell was composed of drill bit steel body brazed with diamond impregnated strips, which were mixed with polycrystalline diamond, natural diamond and carbonado diamond, so that the gauging property of each material could be fully utilized, for instance, abrasive resistance of polycrystalline diamond, high strength of natural diamond and high hardness of carbonado, and in this way the cutting capacity and the service life of the reaming shell were improved and satisfactory borehole repairing result obtained.

Borehole repairing tool assembly: 311.1 mm tri-cone bit + 311.5 mm diamond repairing tool (Fig. 7.11a) + 203.2 mm drill collar (one piece) + 309 mm stabilizer + 203.2 mm drill collar (one piece) + 305 mm stabilizer + 203.2 mm drill collar (four pieces) + 177.8 mm drill collar (four pieces) + 127.0 mm drill rod.

Borehole repairing tool assembly simulated the rigidity of 273 mm intermediate casing (including collar). Tri-cone bit, diamond repairing tool, the upper 309 mm stabilizer and 305 mm stabilizer all had a certain cutting capability, thus in the process of borehole repairing and redressing the flex point and its neighboring hole sections could be enlarged, dogleg degree was decreased, the resistance for running down 273 mm intermediate casing was reduced and then smooth running to the position for 273 mm intermediate casing could be ensured. The curves of caliper logging after borehole repairing can be found in Fig. 10.8b. After borehole repairing the minimum hole size was 312.4 mm, the clearance between casing collar and borehole wall was increased to 6.95 mm and therefore the resistance for running casing and the pressure for cement slurry displacement were both effectively decreased.

2. **Trial run casing**

It was decided to trial run casing in order to guarantee a successful casing setting on its first run.

The trial casing running tool assembly included guiding shoe + 273.0 mm casing (two pieces) + 177.8 mm drill collar (nine pieces) + 178 mm jar while drilling + 127 mm drill rod. As a result, trial run casing was successful, however, resistance was encountered in the hole section from 1891 to 1975 m with the maximum resistance of no more than 3 t (according to stipulation in trial running the resistance was no more than 6 t). This indicated that the condition for running casing was satisfied.

3. **Casing**

After cementing 273.0 mm intermediate casing, 193.7 mm ($7^5/_8$ in.) moving casing was to be run. The lower end of this moving casing was set on the retaining sub at the bottom of 273.0 mm outer casing. For this reason in the program of 273.0 mm intermediate casing cementation the cementing program for 193.7 mm moving casing should be considered at the same time. The process of setting 193.7 mm moving casing in 273.0 mm intermediate casing can be found in Fig. 10.9.

(1) Structure of casing string

The steel grade of 273.0 mm intermediate casing was J55, wall thickness was 10.16 mm, outside diameter was 273.0 mm and inside diameter 252.7 mm. Casing structure: float shoe + floating collar + short casing (one piece, 5 m) + setting seat + short casing (one piece, 3 m) + (moving casing) retaining sub assembly + casing string. The structure of the lower part of casing string is shown in Fig. 10.10.

(2) Casing accessories

i. Retaining sub assemblyRetaining sub assembly consisted of retaining collar, bearing seat, insert sleeve and insert guide head. The retaining collar was connected with the casing string and the bearing seat was fixed on the retaining collar, for bearing partial weight of 193.7 mm moving casing. At the upper part of the bearing seat was machined with teeth, to prevent 193.7 mm moving casing from rotating. The insert sleeve was connected in 193.7 mm moving casing string and inserted into the bearing seat. The insert sleeve was machined with teeth, which had the opposite direction to the teeth on the bearing seat, and the teeth meshing could prevent 193.7 mm lower casing from rotating and thread loosing. The structure of retaining sub assembly can be found in Sect. 10.4 of this chapter.

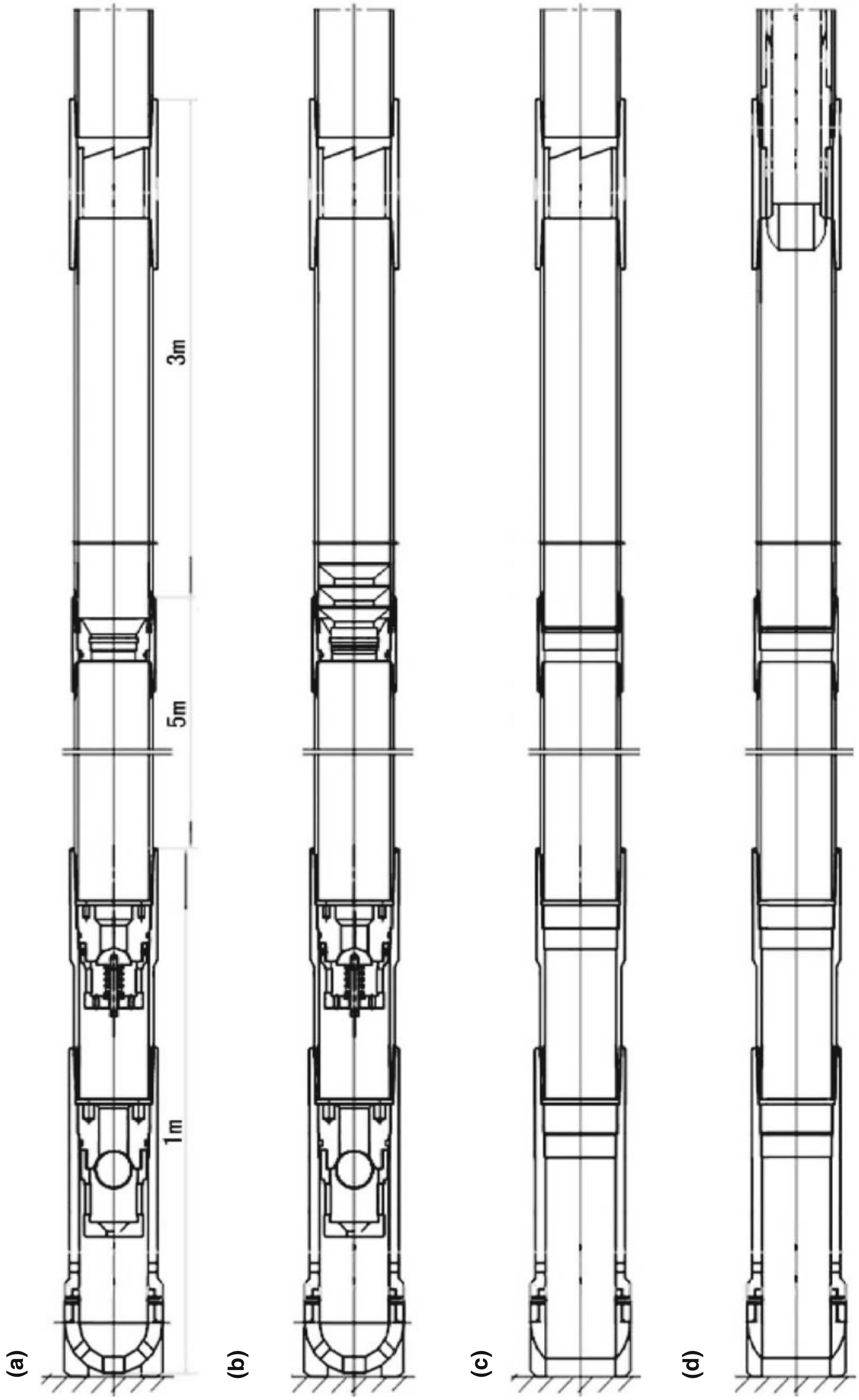


Fig. 10.9 Construction process of setting 193.7 mm moving casing in 273.0 mm intermediate casing. **a** Structure of the lower part of 273.0 mm casing. **b** Cementation setting of 273.0 mm casing. **c** After drilling off 273.0 mm casing accessaries. **d** After running down 193.4 mm moving casing

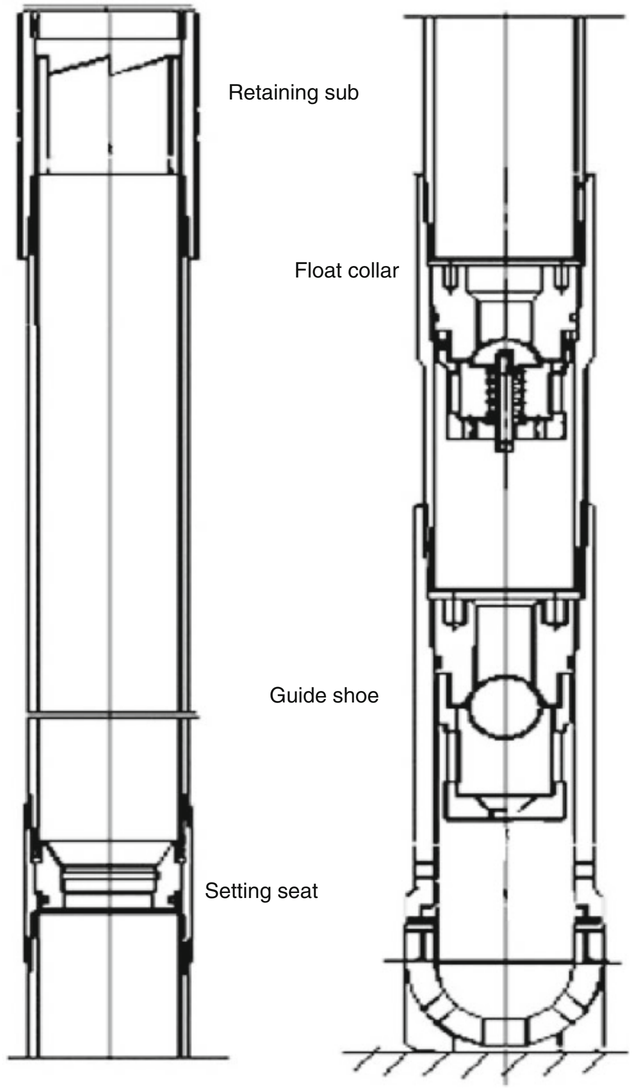


Fig. 10.10 The structure of the lower part of 273.0 mm casing

ii. Rubber plug and setting seat
Rubber plug (Fig. 10.11) was made into a structure of flexible cup, which could smoothly pass through the retaining sub. At the top of the rubber plug, spring hoop and sealing ring were designed to avoid retrace. Setting with the setting seat, spring hoop entered into the groove, to avoid rubber plug retrace. Through sealing ring to avoid back press, safety was further improved. For the core parts of the rubber plug and the setting seat (Fig. 10.12), materials with good drillability such as cast aluminium was used, for easy drill-out.

iii. Floating collar
Valve tructure was adopted and cast aluminium was used for the core parts (Fig. 10.13).

iv. Float shoe
A structure of nylon floating ball was used and cast aluminium was used for the core parts, for easy drill-out (Fig. 10.14).

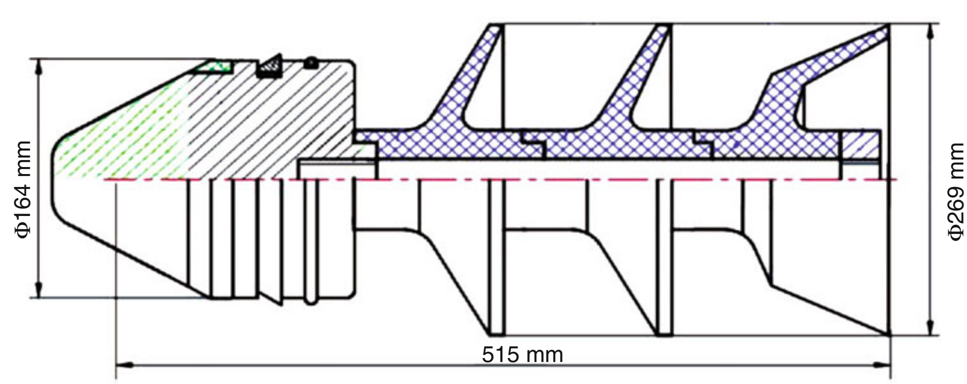
The floating collar and the float shoe adopted different structures, to ensure a success of anti-back press.

(3) Casing running operation

To guarantee concentricity between 273.0 mm casing and borehole wall to obtain good cement consolidation quality, elastic centralizer was to be fixed onto the casing body of 273.0 mm casing in the original design. However, the designed outside diameter of the centralizer for 273.0 mm casing was 370 mm, whereas the borehole size was 311.1 mm, downhole accident might happen if the centralizer was run down. So, an elastic centralizer was set at 1938.44, 1947.71, 1957.04 and 2000.53 m of the casing string respectively. A technical measure of enhancing lubrication property for drilling fluid was adopted, for a smooth run-down of the casing. Special-purpose drilling fluid of 50 m^3 was prepared, with the formula of 3 % LBM + 2 % liquid lubricant + 0.5 % solid friction reducer. The solid friction reducer was a high strength 60 mesh plastic ball evenly dispersed in drilling fluid, playing the roles of supporting and rolling between casing and borehole wall, in this way drilling fluid would have extremely good lubrication property and the frictional resistance between casing and borehole wall would be effectively reduced.

The lower parts of casing string was assembled and casing was run down based upon casing cementation procedure, with run-down velocity controlled and cement

Fig. 10.11 Rubber plug for 273.0 mm casing cementation



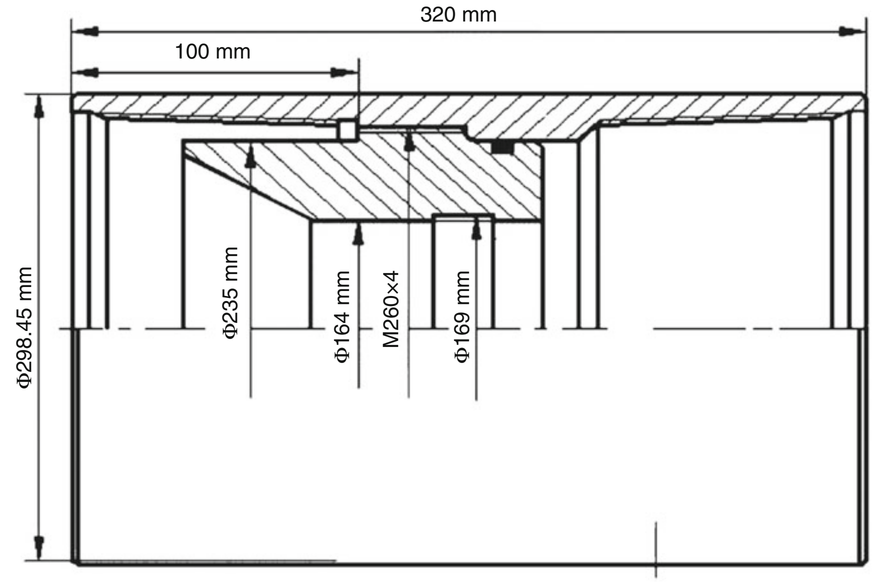


Fig. 10.12 Setting seat for 273.0 mm casing cementation

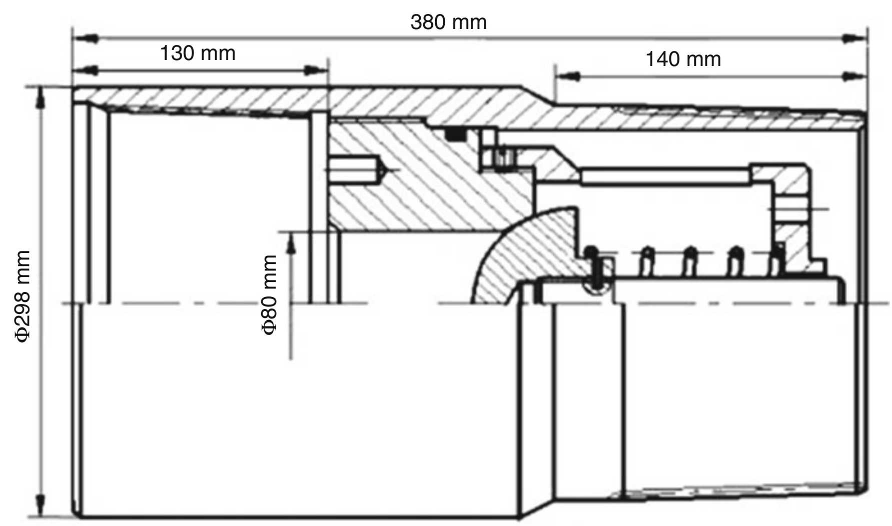


Fig. 10.13 Floating collar for 273.0 mm casing

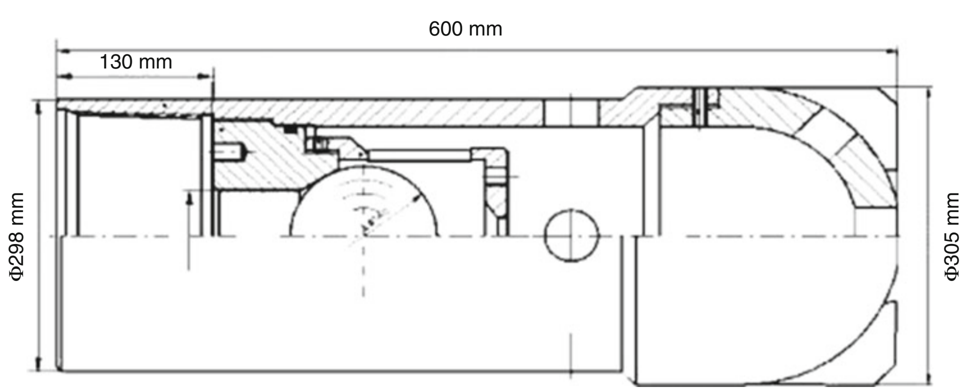


Fig. 10.14 Float shoe for 273.0 mm casing

Table 10.8 Calculation of annular volume for 273.0 mm intermediate casing

Well depth (m)	Hole section length (m)	Hole diameter (cm)	Annular volume (L/m)	Volume (L)
0–100	100	31.4	18.68	1868
100–2028	1928	35	37.6	72,493

grouting was conducted once for every 20 pieces of casing. Started at 8:00 on September 9th, 2002 and ended at 18:53 on September 10th, the operation of running 273 mm casing was successfully completed, taking 36 h and 53 min.

4. **Well cementation**

(1) Design and calculation

i. Basic data

Drill bit size × well depth: 311.1 mm × 2028 m; casing size × running depth: 273 mm × 2028 m; returned height of cement: ground surface

ii. Calculation of cement quantity

Length of cementation: 2028 m; total volume: 74,361 L (Table 10.8); average annular volume: 36.7 L/m; average hole size of the opened borehole: 350 mm; borehole diameter enlargement ratio: 12.5 %.

It was designed that the volume of leading cement slurry was 35708 L; the volume of tail cement slurry was 37605 L. Cardinal number of leading cement was 33 t and with 15 % addition, thus the total quantity of leading cement was 38 t. Cardinal number of tail cement was 50 t and with 15 % addition, thus the total quantity of tail cement was 58 t. The total quantity of cement was 96 tons.

iii. Design of cement slurry

In the light of well cementation in small clearance, cementation with dual density cement slurry (conventional density and low density) was utilized, to solve the technical difficulties of large pressure drop in cement injection and in displacement of cement slurry, as well as the problem of leakage.

Leading slurry: BHST = 75 °C, BHCT = 60 °C, pressure = 35 MPa. Formula: Jiahua G grade cement + 2 % G404 (fluid loss reducer) + 1 % G106 (retardant) + 0.6 % G301 (dispersant) + 5 % G203 (early strength agent) + 0.6 % G603 (defoamer) + 15 % G605 (lightening agent) + 1 % G202 (expanding agent). Water-cement ratio: 0.58, density: 1.55 g/cm^3, bleeding ≤3.5 ml, filter loss ≤150 ml/60 °C × 7 MPa × 30 min, thickening time >200 min/60 °C × 35 MPa × 50 min, initial consistency ≤25BC, compressive strength ≥5 MPa/24 h × 25 °C × 0.1 MPa, ≥10 MPa/24 h × 75 °C × 21 MPa, rheological property n > 0.7, K < 0.3 Pa·s^n.

Tail slurry: BHST = 75 °C, BHCT = 60 °C, pressure = 35 MPa. Formula: Jiahua G grade cement + 0.6 % G301 (dispersant) + 1.5 % G404 (fluid loss reducer) + 1.0 % G106 (retardant) + 0.6 % G603 (defoamer). Water-cement ratio: 0.44, density: 1.90 g/cm^3, bleeding ≤3.5 ml, filter loss <150 ml/60 °C × 7 MPa × 30 min, thickening time >200 min/60 °C × 35 MPa × 35 min, initial consistency ≤25BC, compressive strength ≥14 MPa/24 h × 75 °C × 21 MPa, rheological property n > 0.7, K < 0.3 Pa·s^n.

Table 10.9 Calculation of displacing slurry volume

Well depth (m)	Hole section length (m)	Wall thickness (mm)	Annular volume (L/m)	Accumulation (L)
0–2028	2028	11.43	49.17	99,717

iv. Design of spacer fluid and rubber plug pressing fluid

Spacer fluid: SNC15 % + H_2O, 6m^3 + 2m^3, or make-up water 6–8m^3 (defined according to the test result).

Rubber plug pressing fluid: deep well type, 2 m^3.

v. Calculation of displacing slurry (see Table 10.9)

vi. Calculation of pressure

Hydrostatic fluid column pressure of annular cement slurry:

Cement slurry: Ps1 = 0.01 × 1000 × 1.55 = 15.5 MPa

Cement slurry: Ps2 = 0.01 × 1028 × 1.90 = 19.5 MPa

Hydrostatic fluid column pressure of annular spacer fluid: Psp = 0.01 × 0 × 1 = 0 MPa

Annular total fluid column pressure: Pan = 15.5 + 19.5 + 0 + 0 = 35 MPa

Fluid column pressure in casing: Pim = 0.01 × 2028 × 1.20 = 24 MPa

Hydrostatic column pressure difference: P = Pan − Pim = 35 − 24 = 11 MPa

Calculation of formation equivalent density: 35 × 100/2028 = 1.73 g/cm^3.

(2) Cementation operation

Cement head (Fig. 10.15) and cementing pipeline were installed at 19:40 of September 10th, 2002 and drilling mud was circulated at 6:40 of September 11th, for 1 h and 20 min. Cement slurry injection pipeline were connected, 6 m^3 spacer fluid was injected, 37 m^3 low density (1.56 g/cm^3) cement slurry was injected, and 38 m^3 high density (1.89 g/cm^3) cement slurry was injected. Rubber plug was set, 2.4 m^3 rubber plug pressing fluid was injected. Displacing slurry was injected by large pump, 33 m^3 weighted mud (with density of 1.52 g/cm^3) was firstly displaced and then 66 m^3 mud (with density of 1.08 g/cm^3) was displaced, under the slurry displacement pressure of 13 MPa, setting pressure of 14.5 MPa, and with cement slurry returned to the well head for 3 min. Pressure releasing was normal and no mud returned to well head. Started from 19:40 of September 10th and ended at 11:00 of September 11th, the cementation operation was successfully conducted according to design, with 13 h and 40 min lasted.

Fig. 10.15 Cement head for 273.0 mm intermediate casing cementation

10.3.4 193.7 mm Intermediate Casing

In the main hole of CCSD-1 Well, when core drilling reached to the depth of 3665.87 m, the lower reaming shell in the core drilling tool was broken, and fishing failed for many times. After technical argumentation it was decided that the upper 193.7 mm moving casing was to be withdrawn for 244.5 mm reaming drilling. Reaming drilling was conducted to 3525.18 m deep, because of many fishes in the hole and hole enlargement, it was decided that sidetrack drilling around (to avoid the underground obstacles) was to be carried out. After successful sidetrack drilling around, non-core drilling reached to 3623.91 m, 193.7 mm ($7^5/_8$ in.) intermediate casing was set and cemented. In order to come up to the requirement of design (cement slurry returns to well head), two-stage dual density cement slurry cementation was adopted, with the casing stage collar (Fig. 10.16) and technical service provided from Top-Co Industries Ltd.

1. **Casing**

(1) Casing string structure

The running depth of 193.7 mm intermediate casing was 3620 m, wall thickness of the casing was 9.52 mm, and the position of stage collar was at 1901.5 m (designed at 1928 m). The structure of the casing string (Fig. 10.17) was:

Fig. 10.16 193.7 mm stage collar

193.7 mm guide shoe + 193.7 mm casing (one piece) + 193.7 mm float collar + 193.7 mm casing (six pieces) + 193.7 mm float collar + casing string + 193.7 mm stage collar + casing string.

(2) Operation of running casing

At 3:00 on April 29th, 2004 the operation of running 193.7 mm casing was started (Fig. 10.18). Based upon 193.7 mm casing program and requirement of casing running, casing was run and cement was grouted once for every five pieces of casing. From the 202nd casing (well depth below 2015.92 m), an elastic centralizer was added between every two pieces of casing. Until 4:00 of May 1st, casing was smoothly run down to 3620 m deep, with 49 h lasted.

2. **Well cementation**

(1) Design and calculation

i. Conditions for calculation (see Table 10.10)

ii. Calculation of cement quantity

The first stage cementing: leading slurry 2028–2600 m, quantity of cement needed (2600−2028) × 29.5/(105 × 20) = 8.0 t, addition for technological consideration 2 t, total 10 t; Tail slurry 3620−2600 m, quantity of cement needed (3620−2600) × 29.5/(38 × 20) = 39.6 t, addition for technological consideration 5.4 t, total 45 t. Accumulative cement quantity needed was 55 t.

The second stage cementing: 0–1928 m, in the upper casing: 1928 × 20.7/(38 × 20) = 52.5 t, addition for technological consideration 5.5 t, total 58 t.

iii. Design of cement slurry

The first stage cementing: BHST = 2.5 °C/100 × 3620 + 15 °C = 106 °C, BHCT = BHST × 0.7 % = 74.2 °C.

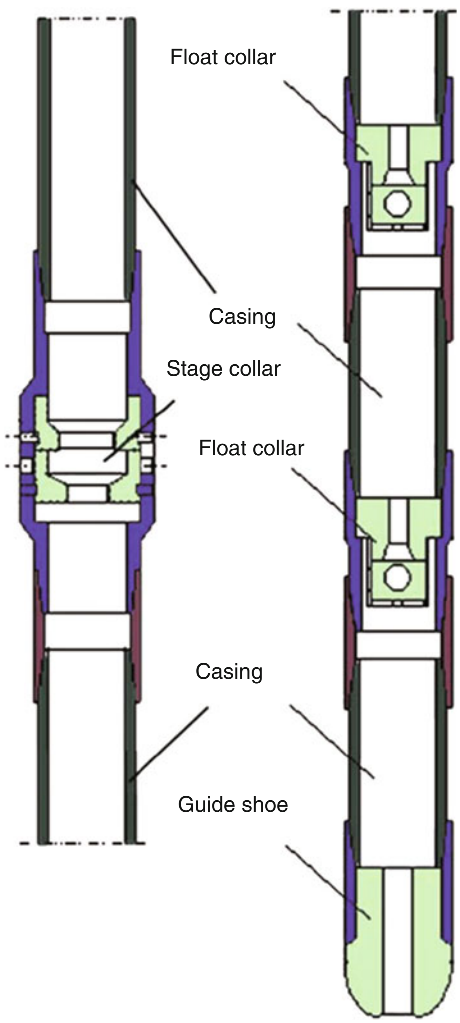


Fig. 10.17 Lower structure of the casing string for 193.7 mm two-stage cementation

Fig. 10.18 Running 193.7 mm casing

Leading slurry: 2028–2600 m, Formula: Jiahua G grade cement + 2.5 % G404 (fluid loss reducer) + 1.0 % G105 (retardant) + 1.0 % G301 (dispersant) + 0.3 % G603 (defoamer) + 3.0 % G202 (expanding agent) + 35 % G606 (high temperature thermal stabilizer) + 10.0 % G605 (lightening agent) + 20.0 % G607 (high temperature strengthening agent). Water-cement ratio: 1.15, density: 1.35 g/cm^3, bleeding ≤3.5 ml, filter loss ≤200 ml/77 °C × 7 MPa × 30 min, thickening time >300 min/77 °C × 40 MPa, initial consistency ≤25BC, compressive strength ≥5 MPa/24 h × 25 °C × 0.1 MPa, ≥ 14 MPa/24 h × 74.2 °C × 21 MPa, rheological property n > 0.7 %, K < 0.3 Pa·s^n.

Tail slurry: 3620–2600 m, Formula: Jiahua G grade cement + 2.0 % G404 (fluid loss reducer) + 1.0 % G105 (retardant) + 0.6 % G301 (dispersant) + 0.3 % G603 (defoamer) + 1.0 % G202 (expanding agent). Water-cement ratio: 0.44, density: 1.90 g/cm^3, bleeding ≤3.5 ml, filter loss ≤100 ml/74.2 °C × 7 MPa × 30 min, thickening time >200 min/74.2 °C × 48 MPa, initial consistency ≤15BC, compressive strength ≥14 MPa/24 h × 106 °C × 21 MPa, rheological property n > 0.7 %, K < 0.3 Pa·s^n.

The second stage cementing: 0–1928 m, BHST = 69 °C, BHCT = 49 °C, pressure = 36.6 MPa. Formula: Jiahua G grade cement + 2.0 % G404 (fluid loss reducer) + 0.6 % G301 (dispersant) + 0.3 % G603

Table 10.10 Calculation conditions for 193.7 mm casing cementation

Item	Parameter	Item	Parameter
Drill bit diameter (mm)	244.5	Density of cement slurry (g/cm^3)	1.35/1.90
Casing O.D. (mm)	193.7	Sack prepared grout (L)	105/38
Position of stage collar (m)	1928	Annular volume of opened hole (L/m)	29.5
Returned height, the first stage (m)	2028	Annular volume between 273.0 and 193.7 mm casing (L/m)	20.7
Returned height, the second stage (m)	Surface	Average hole diameter (cm)	27.4
Position of choke ring (m)	3550	Hole diameter enlargement ratio (%)	12

Table 10.11 Calculation of displacing fluid volume

Stage	Well depth (m)	Hole section length (m)	Casing wall thickness (mm)	Volume of casing (L/m)	Accumulation (L)
The first stage	0–3550	3550	9.52	23.95	85,022.5
The second stage	0–1928	1928	9.52	23.95	46,175.6

(defoamer) + 1.0 % G202 (expanding agent). Water-cement ratio: 0.44, density: 1.90 g/cm^3, bleeding ≤3.5 ml, filter loss ≤100 ml/49 °C × 7 MPa × 30 min, thickening time >150 min/49 °C × 40 MPa, initial consistency ≤25BC, compressive strength ≥14 MPa/24 h × 69 °C × 21 MPa, rheological property n > 0.7 %, K < 0.3 Pa·s^n.

iv. Design of spacer fluid and rubber plug pressing fluid
Spacer fluid: the first stage was SNC15 % + H_2O, 6 m^3 + 2 m^3; the second stage was make-up water 4 m^3.
Rubber plug pressing fluid: clear water type (same for the first and the second stages), 2 m^3 for each stage.

v. Calculation of displacing fluid (see Table 10.11)

vi. Calculation of pressure
The first stage:
Hydrostatic fluid column pressure of annular cement slurry:
Cement slurry: Ps = 0.01 × (3620 − 2600) × 1.90 + 0.01 × (2600 − 2028) × 1.35 = 27.1 MPa
Hydrostatic fluid column pressure of spacer fluid: Psp = 0.01 × 245 × 1.0 = 2.45 MPa
Annular drilling fluid column pressure: Pm = 0.01 × 1928 × 1.18 = 19.2 MPa
Annular total fluid column pressure: Pan = 27.1 + 2.45 + 19.2 = 48.75 MPa
Fluid column pressure in casing: Pim = 0.01 × 3620 × 1.18 = 42.7 MPa
Hydrostatic column pressure difference: P1 = Pan − Pim = 48.75 − 42.7 = 6.05 MPa
Circulating pump pressure: Pz = 0.0018 × 3620 = 6.5 MPa
Maximum operating pressure: P = P1 + Pz = 12.55 MPa
Calculation of formation equivalent density: 49.15 × 100/3620 = 1.36 g/cm^3
The second stage:
Hydrostatic fluid column pressure of annular cement slurry:
Cement slurry: Ps1 = 0.01 × 1928 × 1.90 = 36.6 MPa
Annular total fluid column pressure: Pan = 36.6 MPa
Fluid column pressure in casing: Pim = 0.01 × 1928 × 1.18 = 22.75 MPa
Hydrostatic column pressure difference: P1 = Pan − Pim = 36.6 − 22.75 = 13.85 MPa
Circulating pump pressure: Pz = 0.0018 × 1928 = 3.5 MPa
Maximum operating pressure: P = P1 + Pz = 17.35 MPa (displacing fluid should be weighted to decrease 3 MPa pressure)

Fig. 10.19 Operation of 193.7 mm casing cementation

Formation equivalent density: 1.90 g/cm^3.

(2) Cementation operation

The operation sequence of cementation (Fig. 10.19): pressure testing → injecting spacer fluid → cement injection, first stage → pressing rubber plug → slurry displacement → setting → blowdown to check backflow → putting in gravity plug → opening circulation hole → well flushing (small displacement circulation at first, then circulating displacement was increased when pump pressure became normal, to flush out surplus cement slurry) → curing → injecting spacer fluid → cement injection, second stage → pressing rubber plug → slurry displacement → setting → pressurizing to close shut-off sleeve → pressure relief to check the closing condition → construction completed.

At 4:00 of May 1st, 2004, casing running was completed, at 4:30 drilling mud was circulated, at 9:30 6 m^3 SNC 15 % and 2 m^3 H_2O were injected, 17 m^3 low density (1.35 g/cm^3) cement slurry was injected, and 34 m^3 high density (1.90 g/cm^3) cement slurry was injected. Rubber plug was set, 2.0 m^3 rubber plug pressing fluid was injected. 84.60 m^3 displacing slurry (theoretical calculation 84.4 m^3) was injected by large pump, and then stopped because of no setting. 0.5 m^3 returned with pressure relief and this showed that the back-pressure valve was in a good condition. Cement head (Fig. 10.20) was released and gravity plug was put in and it would reach stage collar in 33 min according to calculation. At 12:00 pressure was built up to 4 MPa in cement truck and the circulation hole of the stage collar was opened for circulation. Approximate 2 m^3 of cement slurry returned. At 18:00 circulation was stopped and the second

Fig. 10.20 Cement head for 193.7 mm casing cementation

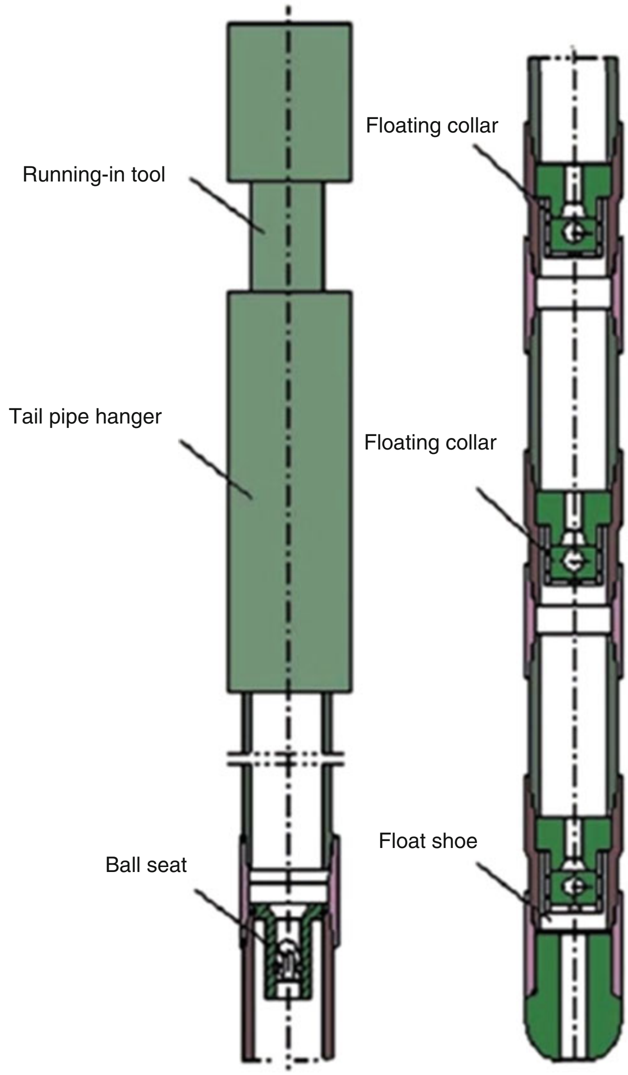


Fig. 10.21 Structure of the lower part of 127.0 mm tail pipe string

stage cementation was started. 4 m^3 of make-up water was injected, and 42 m^3 cement slurry (1.90 g/cm^3) was injected. Rubber plug was set, 2.0 m^3 rubber plug pressing fluid was injected. 44.1 m^3 displacing slurry was injected by large pump and the setting pressure increased from 11 to 15 MPa. In order to close the circulation hole, pressure was built up to 18 MPa with the cement truck, pressure was stabilized for 5 min for observation and then pressure was relieved. 0.4 m^3 water returned, drilling mud did not flow backwards, circulation hole was closed, cement slurry returned to surface for 2 min and then the construction was completed.

From 11:00 to 20:00 of May 1st, the operation of two-stage cementation was smoothly completed according to the requirements of the design, with 9 h lasted.

10.3.5 127.0 mm Tail Pipe

On March 8th, 2005, drilling reached to the final hole depth of 5158 m. And on March 9th the job of running 127.0 mm (5 in.) tail pipe and cementation was started. The tail pipe hanger, tail pipe running-in tool, construction and technical service were provided by Shenzhen Baiqin Petroleum machinery and Technical Development Co.

1. **Casing**

(1) Structure of casing string

Casing running depth was from 3540 to 4800 m, with wall thickness of 7.52 mm. Structure of casing string (Fig. 10.21) was: float shoe + casing (one piece) + floating collar + casing (one piece) + floating collar + casing (one piece) + ball seat + casing + joint + hanger + running-in tool + drill rod.

(2) Running casing

At 10:00 of March 9th, 2005, operation of running casing was started. Tail pipe was run according to the structure of tail pipe string and the requirements of operation; cement was grouted for each piece of casing and cement was fully grouted for every ten pieces of casing. An elastic centralizer was fixed at the depth of 3534, 3563.7, 3603.3, 4769.79 and 4780.06 m respectively. 127.0 mm × 193.7 mm tail pipe hanger (Fig. 10.22), tail pipe running-in tool (Fig. 10.23) and 89 mm drill rod were run into the borehole, and the suspending weight of tail pipe string was 34 t (including the

Fig. 10.22 127 mm tail pipe hanger

Fig. 10.23 Running-in tool assembly for 127 mm tail pipe

suspending weight of crane). Tail pipe was run to the position, with a length of 1271 m; and the total length of running-in tool was 3530 m, with 3.45 m kelly-up left, for connecting pipeline. 2 MPa was the maximum pressure for circulating mud, uplifting 110 t and running down 94 t (crane and swivel 14 t), dropping a ball and pumping for 15 min till the ball to the position. Building the pressure to 12.5 MPa and stabilizing the pressure for 3 min, running down the drilling tool, suspending weight decreased, and it was indicated that setting was successful. Pressing to 64 t so as to guarantee setting was reliable. The float shoe of the casing string was set to 4790.72 m and the top of the hanger to 3523.55 m. Turning clockwise for 25 rounds and back off, uplifting 1.4 m to verify drop-off, suspending weight increased to 78 t and stopped, drop-off was successful. Pressure of 24 MPa was built to reject ball seat, and circulation was established. The operation of running casing was completed at 23:45 of March 10th, with 37 h and 45 min lasted.

2. **Well cementation**

Cementing operation was started after successful setting, suspension of the tail pipe and drop-off, and establishment of circulation.

(1) Design and calculation

i. Conditions for calculation (see Table 10.12)

ii. Calculation of cement quantity

Cement quantity for opened hole section: (4800 − 4200) × 12.57 = 7542 L; cement quantity in casing: (4800 − 4760) × 9.85 = 394 L; total cement quantity was 7936 L, 7936/50 = 159 sacks, i.e. 8 t.

iii. Design of cement slurry

Cement slurry: 4200–4800 m, BHST = 135 °C, BHCT = 122 °C, pressure = 54 MPa. Formula: Jiahua D grade cement + 30 % SiO_2 + 0.5 % WS + 1.2 % G106 (retardant), density: 1.85 g/cm^3, heating time: 45 min, bleeding ≤3.5 ml, filter loss <50 ml/7 MPa × 30 min, thickening time >250 min/122 °C × 54 MPa, initial consistency <25BC, compressive strength >14 MPa/24 h × 135 °C × 21 MPa, rheological property n > 0.7 %, K < 0.3 Pa·s^n.

iv. Design of spacer fluid and rubber plug pressing fluid

Spacer fluid: SNC15 % + H_2O, 6 m^3 + 2 m^3 or make-up water 6–8 m^3

Rubber plug pressing fluid: make-up water, 2 m^3

v. Calculation of displacing fluid (see Table 10.13)

vi. Calculation of pressure

Hydrostatic fluid column pressure of annular cement slurry: Cement slurry: Ps = 0.01 × 600 × 1.85 = 11.1 MPa

Hydrostatic fluid column pressure of spacer fluid: Psp = 0.01 × 636 × 1.0 = 6.36 MPa

Table 10.12 Calculation conditions

Item	Parameter	Item	Parameter
Drill bit diameter (mm)	157	Density of cement slurry (g/cm^3)	1.85
Casing O.D. (mm)	127	Sack prepared grout (L)	50
Returned height of cement slurry (m)	4200	Water-cement ratio	0.58
Casing running depth (m)	4800	Annular volume of opened hole (L/m)	12.57
Cementing interval (m)	600	Volume in casing (L/m)	9.84
Position of choke ring (m)	4760	Annular volume between 193.7 and 127 mm casing/(L/m)	11.28

Table 10.13 Calculation of displacing fluid volume

Well depth (m)	Section length (m)	Wall thickness (mm)	Volume per meter (L/m)	Total volume (L)
0–3540	3540	9.35 (89 mm drill rod)	3.87	13,700
3540–4760	1220	7.52	9.84	12,004.8
Total	4760			25,704.8

Annular drilling fluid column pressure: Pm = 0.01 × 3564 × 1.08 = 38.49 MPa
Annular total fluid column pressure: Pan = 11.1 + 6.36 + 38.49 = 55.95 MPa
Hydrostatic fluid column pressure of rubber plug pressing fluid: Psp = 0.01 × 203 × 1.0 = 2.03 MPa
Drilling fluid column pressure in casing: Pm = 0.01 × 4597 × 1.08 = 49.65 MPa
Total fluid column pressure in casing: Pim = 2.03 + 49.65 = 51.68 MPa
Hydrostatic column pressure difference: P1 = Pan− Pim = 55.95−51.68 = 4.27 MPa
Circulating pressure: Pz = 0.0018 × 4800 + 3 = 11.64 MPa
Maximum operating pressure: P = P1 + Pz = 4.27 + 11.64 = 15.91 MPa
Calculation of formation equivalent density: 55.95 × 100/4800 = 1.17 g/cm^3

(2) Cementation operation

The operation sequence of cementation: pressure testing → injecting spacer fluid → cement slurry injection → pressing rubber plug (to flush the cement slurry injection pipeline at the same time) → slurry displacement → setting → pressure relief to check the setting condition.

Cementation (Fig. 10.24) was started at 10:10 of March 11th, 2005. 8 m^3 spacer fluid was injected, 10 m^3 cement slurry was injected (2 m^3 more than design), and then rubber plug was set and slurry displaced. Setting pressure increased from 11 to 15 MPa, and pressure released without water backflow. Cementation operation was completed at 15:10.

Fig. 10.24 Cement head for 127 mm tail pipe cementation

10.4 Moving Casing Techniques

Mostly used in continental scientific drilling engineering, moving casing denotes the casing run into the borehole for a certain purpose in drilling construction and can be completely retrieved from the borehole after the completion of the drilling construction. Because the complex formations would be encountered, borehole would be deep, complicated drilling technologies were to be utilized, more casing program was to be used and core drilling was required, thus in design a method of advanced open hole drilling was adopted. Generally, small sized core drilling was conducted and then reaming. In drilling construction, after the large sized casing was set in the upper section of the borehole and core drilling was conducted in the lower section, the inside diameter of the casing in the upper section of the borehole would be much larger than the diameter of core drill bit (Fig. 10.25) and under these circumstances it would be

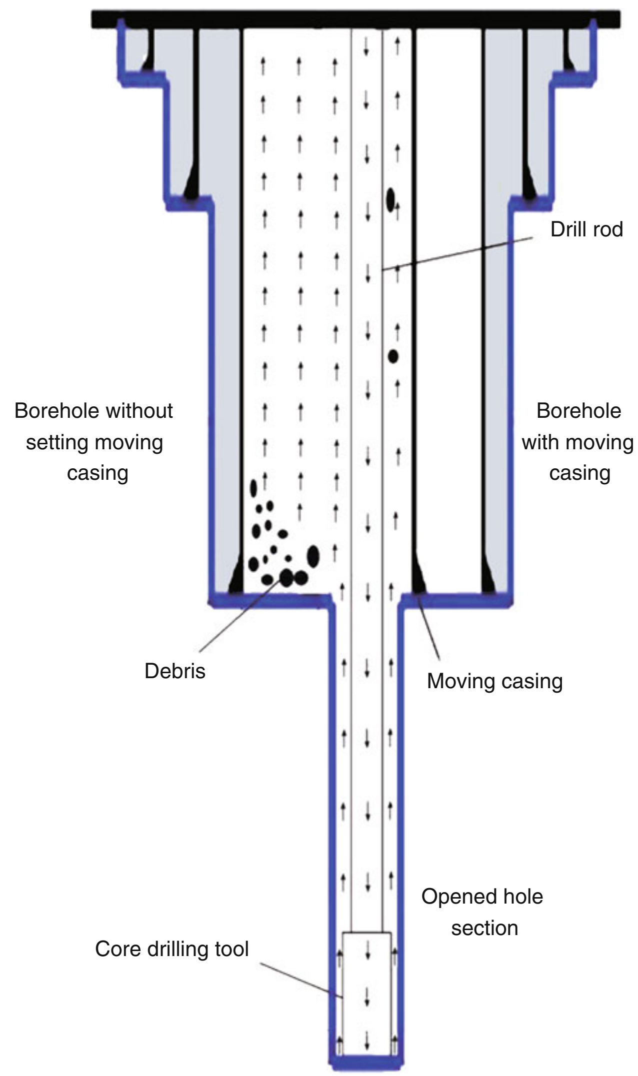


Fig. 10.25 Sketch of moving casing techniques

necessary to run moving casing, to reduce the difference between the inside diameter of the casing and the diameter of the lower opened hole section, so as to ensure a smooth return of the cuttings (Fig. 10.25).

Moving casing techniques mainly have following advantages:

i. to reduce casing program and construction cost;
ii. to avoid an excessive oscillation of drill string, being favourable to stable rotation;
iii. to avoid vortex deposition of cuttings, which may cause drill bit burying (bit freezing);
iv. borehole structure can be flexibly adjusted, being favourable for implementation of drilling technology.

10.4.1 Overall Programme

In drilling construction design of CCSD-1 Well, moving casing was to be run twice, with basic data shown in Table 10.14, in which the deepest moving casing designed was 2000 m. The overall programme design of moving casing construction was mainly based upon 193.7 mm ($7^5/_8$ in.) moving casing running to 2000 m.

In the overall programme design of moving casing, following problems should be considered:

i. The length of moving casing will change along with the variation of the temperature of drilling fluid in borehole, and resulting in a dynamic expansion and contraction, and a stress variation during the BTC period of construction.
ii. The fixing of moving casing, besides the fixing of top and bottom ends, the stability of the whole casing should be taken into consideration.
iii. When rotating in high velocity in moving casing, drill string will produce dynamic frictional force in circumferential direction to the inside wall of moving casing, which may cause back-off for some casing joints.
iv. In design, withdrawal of moving casing after usage should be taken into consideration.

The overall programme of moving casing: a method of fixing casing at both ends was adopted, i.e. some of the casing weight load was to be hanged at the top end while some of the casing weight load was to be set at the bottom end. This programme could prevent the moving casing from back-off and improve the stability of the whole casing. A casing hanger for oil drilling was adopted to hang the top end of the moving casing (Fig. 10.6) while a specially designed casing shoe was utilized to support the bottom end. The casing shoe of the moving casing was set on a specially designed fillet (sub) at the bottom of outer casing (Fig. 10.26).

The method of fixing casing at both ends required that appropriate load should be added on the both ends, mainly based on the length of moving casing and possible variation range of temperature. As the top hanging load and the bottom supporting load varied along with the temperature variation of moving casing, the expansion and contraction of the moving casing resulted from temperature variation could be adjusted by utilizing the variation of the force bearing state of the whole moving casing in the borehole (the change of top hanging and bottom supporting weights). This programme could satisfy the requirement of running long moving casing of 2000 m under hole bottom temperature no higher than 150 °C (Wenjian et al. 2003).

10.4.2 Design of Fixing Moving Casing

In the design of fixing moving casing, the length of casing hanged at top and set at bottom could be calculated according to the possible temperature variation and the weight of the moving casing, so as to guarantee that the entire state of the moving casing (moving casing bore a certain load at top and bottom) would not change when temperature varied, that is, the variation of the force borne at top and bottom of the moving casing was used to compensate for the length change of moving casing resulted from temperature variation.

In running moving casing, the designed depth was 2000 m whereas the maximum possible well depth might reach 5000 m after completion of the well. Based upon Table 10.4, it could be calculated that the maximum temperature variation during the working period of 2000 m moving casing would not exceed 30 °C.

Table 10.14 Basic data of moving casing

Type	Running in hole interval (m)	Steel grade	Nominal weight (kg/m)	O.D. (mm)	Wall thickness (mm)	I.D. (mm)	Run through size (mm)	Collar O. D. (mm)	Thread type
244.5 mm moving casing	0–101	N80	64.79	244.5	11.05	222.4	218.4	269.9	Oval-shaped
193.7 mm moving casing	0–2019	P110	44.24	193.7	9.52	174.6	171.5	215.9	Buttress BTC

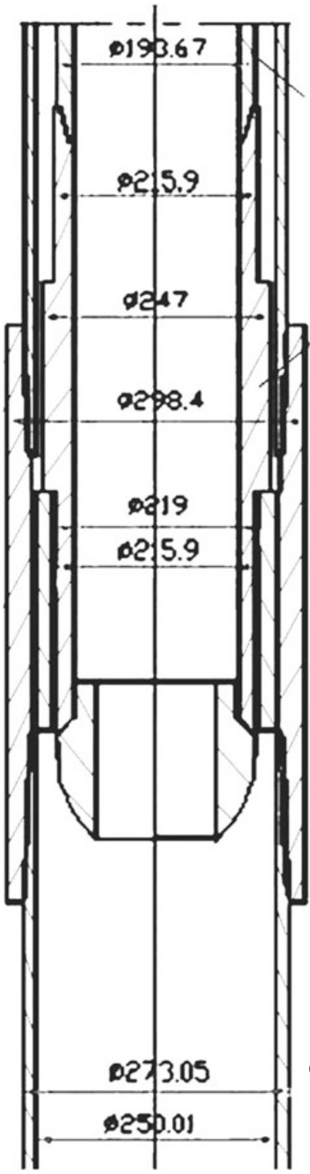


Fig. 10.26 Bottom end setting of 193.7 mm moving casing

Supposing wall thickness is 9.52 mm, length of the moving casing is 2000 m, and density of drilling fluid is 1.2 g/cm^3, then 193.7 mm moving casing should be designed as follows:

Casing with the length L is pulled or pressed by its dead weight when under the vertical state, its deformation dimension should be:

$$\Delta L = (QgL^2)/(2AE) = KL^2 \quad (10.6)$$

in which,

Q unit weight of moving casing, 44.24 kg/m
g gravitational acceleration, 9.8 m/s^2
A cross sectional area of moving casing, 0.00551 m^2
E elastic modulus of moving casing, 207 GPa
K calculation coefficient, in air K = 0.1901 × 10^{-6}; in drill mud K = 0.1610 × 10^{-6}

When moving casing has been run into borehole, supposing the casing length that hanged at top is L_1 and the casing length that set at bottom is L_2, then

$$L_1 + KL_1^2 + L_2 - KL_2^2 = 2000 \quad (10.7)$$

Supposing that 80 % of the total length of moving casing is hanged at well head and 20 % of the total length of moving casing is set at the bottom, the neutral point (where the axial force is zero) is at the position of 1600 m. Moving casing of 1600 m is hanged at well head and 400 m set at the bottom, and

$$L_1 + KL_1^2 = 1600 \quad (10.8)$$

$$L_2 - KL_2^2 = 400 \quad (10.9)$$

Based upon Formulas (10.8) and (10.9), it can be obtained that

$$L_1 = 1599.585 \text{ m}$$
$$L_2 = 400.026 \text{ m}$$

The natural total length of the moving casing to be run is 1999.611 m. The weight of the moving casing to be hanged by the hanger at well head is 60,208 kg while the weight of the moving casing to be set at the bottom is 15,052 kg.

When the average temperature of the moving casing increases to the maximum, i.e. the average temperature of the whole moving casing increases by Δt = 30 °C, suppose the casing length hanged at top is L_{11} while the casing length set at bottom is L_{21}, then

$$L_{11} + KL_{11}^2 + L_{21} - KL_{21}^2 + \Delta t \times k_t \times (L_{11} + L_{21}) = 2000 \quad (10.10)$$

$$L_{11} + L_{21} = L_1 + L_2 \quad (10.11)$$

in which, kt denotes the thermal expansion coefficient of moving casing, 1.25 × 10^{-5} m/°C

From Formulas (10.10) and (10.11), it can be obtained that

$$L_{11} = 442.254 \text{ m}$$
$$L_{21} = 1557.357 \text{ m}$$

The position of the neutral point can thus be further derived

$$L_0 = L_{11} + KL_{11}^2 + \Delta t \times k_t \times L_{11} = 442.451 \text{ m}$$

That is, the weight hanged at the top is 16,642 kg and the weight set at the bottom is 58,603 kg, about 70 % of the weight is supported at the bottom.

Because the temperature variation of the whole moving casing is uneven, being a linear variation from top to bottom, with large temperature change at top and little change at bottom, hence the above calculation results should be revised. However, the temperature variation has slight influence on the neutral point, which moves downwards after the revision.

When mud loses, casing temperature decreases. Based upon an extreme condition, i.e. drilling mud completely loses at a low speed and casing is under a low temperature state, supposing the casing length hanged at top is L_{12} and the casing length set at bottom is L_{22}, then

$$L_{12} + KL_{12}^2 + L_{22} - KL_{22}^2 = 2000 \quad (10.12)$$

$$L_{12} + L_{22} = L_1 + L_2 \quad (10.13)$$

Then,

$$L_{12} = 1510.94 \text{ m}$$

$$L_{22} = 488.671 \text{ m}$$

When drilling mud loses quickly and casing is under a high temperature state, it can be obtained that

$$L_{12} = 525.491 \text{ m}$$
$$L_{22} = 1474.12 \text{ m}$$

It can be found from the calculation results that mud loss has a limited influence on the neutral point (zero stress) of moving casing. The influence of mud loss on the position of the neutral point is that the neutral point tends to the central point.

From above calculation results it could be known that the fixing programme of moving casing that 80 % hanged at top and 20 % set at bottom was feasible. In running the moving casing, 80 % was to be hanged at top and 20 % set at bottom. When mud temperature in borehole changed, casing temperature changed accordingly. When temperature reached the maximum, approximate 30 % moving casing was to be hanged at top and about 70 % set at bottom (retaining 10 % innage so as to increase the safety factor of the casing to forestall temperature change). During the entire period of scientific drilling, the fixing state of moving casing only varied quantitatively, without any qualitative variation. Therefore, the programme of fixing 2000 m moving casing was that in running casing 80 % of the casing was to be hanged by hanger at top while 20 % of the lower casing was set on the retaining sub of the outer casing.

10.4.3 Moving Casing Strength Check

The maximum load of 2000 m casing hanged at top was 88,480 kg while the maximum load of 1557.36 m casing set at bottom was 68,898 kg. The method of buoyancy factor was adopted to calculate buoyancy. The effective external collapsing force was calculated based on 50 % casing emptied; external fluid column pressure was calculated based on full borehole saturated salt water (with density of 1.15 g/cm^3) and internal pressure was calculated based on oil well kick. The checked results can be found in Table 10.15.

10.4.4 Design of Casing Shoe and Retaining Sub

1. **Casing shoe**

20–70 % of moving casing was set on the retaining sub of the outer casing and supported by casing shoe of the moving casing. Casing shoe consisted of inserted sleeve and inserting guide head. In order to guarantee a stable and reliable support by casing shoe and ensure that the normal tripping for follow-up drilling was not to be affected, casing shoe of moving casing must be designed according to in-the-hole condition when moving casing was run and the drilling tool condition for follow-up drilling.

Moving casing diameter was 193.7 mm, wall thickness 9.52 mm and length 2000 m. The weight of casing set on casing shoe was (calculated when weight was the maximum) (weight of casing centralizer can be ignored): 2000 × 70 % × (44.24 − 1.2 × 5.508) = 52,682 kg.

And compressive stress of casing was 52,682 × 9.8/5508 = 93.7 N/mm^2.

As the yield strength of P110 steel is 760 N/mm^2, so casing can satisfy the requirement for yield strength. The material similar to P110 can be selected for casing shoe, with wall thickness the same as that of casing. Based upon the bit size for drill-off after outer casing cementation, drift

Table 10.15 Checked results for strength of 193.7 mm moving casing

Item		193.7 mm moving casing
Casing strength	Tensile strength (kN)	4180
	Collapsing strength (MPa)	36.8
	Internal pressure strength (MPa)	65.2
Actual safety factor/permissible safety factor	Tensile S_t	4.7/1.8
	External collapsing S_c	1.4/1.125
	Internal pressure S_i	5.4/1.10
	Compressive S_y	7.3/1.8

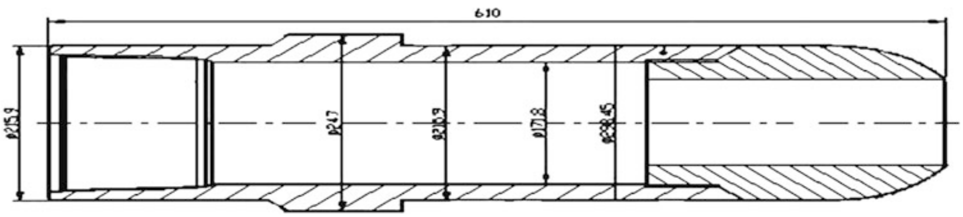


Fig. 10.27 Casing shoe structure for 193.7 mm moving casing

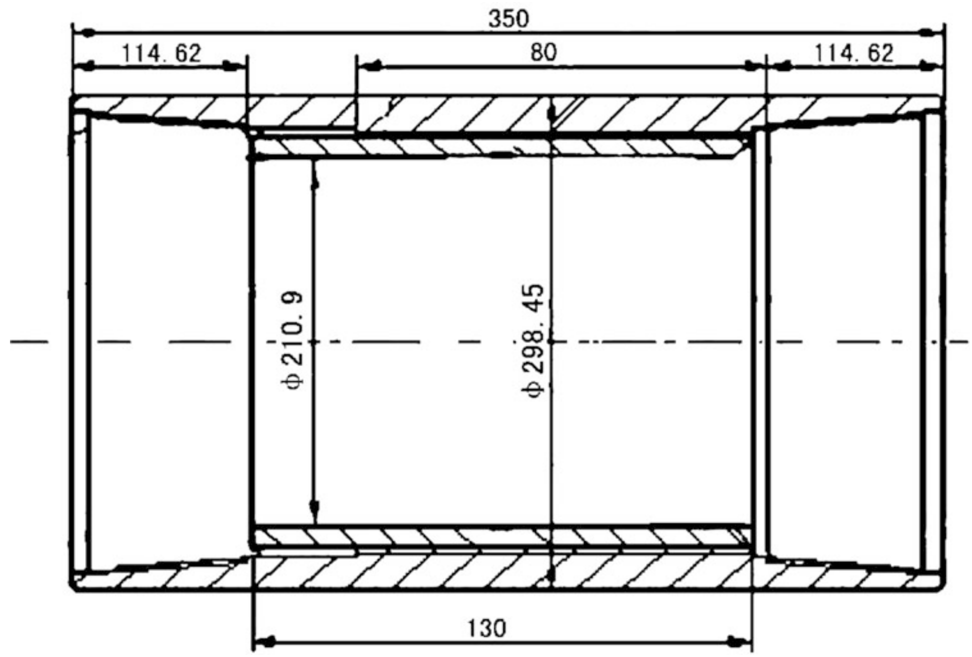


Fig. 10.28 Structure of retaining sub

diameter requirement for follow-up drilling and other technical requirements, casing shoe for moving casing can be designed, with the structure shown in Fig. 10.27.

2. **Retaining sub**

Retaining sub consists of retaining coupling and bearing seat, fixed on the upper section of the setting seat of outer casing. According to the matching requirements for moving casing shoe, strength requirement and the structure of outer casing, the structure of retaining sub can be designed (Fig. 10.28).

The strength of bearing seat of retaining sub was checked as follows:

(1) Maximum shear strength

Shear area:

$$S = \pi dh = \pi \times 247 \times 800 = 62{,}077\,\text{mm}^2$$

in which,

d diameter of bearing seat, mm
h height of bearing seat, mm

The material selected was 45# steel, in normalized condition

Yield strength σ_s = 353 MPa
Safety factor η = 2.5
Then permissible stress $[\sigma]$ = 353/2.5 = 141 MPa
Permissible shearing stress $[\tau] = 0.5\,[\sigma]$ = 70.5 MPa

Thread could be calculated on the basis of approximate value, for safety:

$$Q = 0.5[\tau]\,S = 0.5 \times 70.5 \times 62{,}077 = 2{,}188{,}214\ \text{N} = 2188\ \text{kN}$$

(2) Compressive damage

$$\text{Compressive area } S = \pi(D^2 - d^2)/4 = \pi(247^2 - 219^2)/4 = 10{,}247\ \text{mm}^2$$

$$[\sigma_{jy}] = [\sigma] = 141\ \text{MPa}$$

$$Q_{jy} = [\sigma_{jy}]\,S = 141 \times 10{,}247 = 1{,}444{,}827\ \text{N} = 1445\ \text{kN}$$

(3) Maximum potential bearing load

193.7 mm casing wall thickness δ = 9.52 mm
Casing unit weight q = 44.24 kg/m
2000 m casing weighs 88.5 t
70 % of the weight set on the retaining sub, 61.9 t

Even though all the weight of 193.7 mm moving casing was set on the retaining sub, its safety factor can still satisfy the requirement of strength.

10.4.5 Design of Thread Back-off Proof for Moving Casing

The whole state of moving casing is stable when hanged at top and set at bottom. To prevent moving casing from slipping off the casing head, anti-slipping block can be welded on the top for connection while to prevent moving casing from rotating at the bottom anti-slipping teeth can be machined at the connected part between the retaining sub and moving casing shoe (Fig. 10.29).

Fig. 10.29 Inserted sleeve and inserting guide head for 193.7 mm moving casing

In follow-up drilling, due to the frictional force between rotating drill rod (drilling tool) and moving casing, thread loosening of some casing and large torsional deformation of long casing, thread back-off or even thread off may happen for some joints of the moving casing, and normal drilling will be affected. For this reason, measures should be adopted for the connection of the whole moving casing string, to prevent casing from thread back-off.

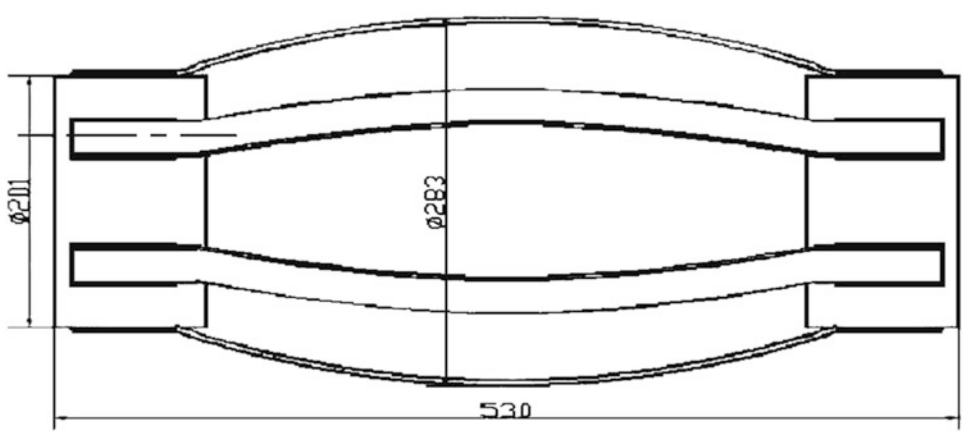
As the type of moving casing was determined and the casing string was rather long, mechanical and technological methods for preventing thread back-off can only obtain a limited result, with unsatisfied reliability. Based upon the experiences and measures adopted for preventing casing thread back-off in oil drilling, sticking was the only feasible method, which was realistic, well-developed and easy for use.

However, after using this method the stuck casing thread must be heated when break-out in casing removal and this heating operation was rather troublesome and would affect the reuse of the casing. Therefore, it was decided that only some casing joints where back-off easily happened should be stuck, this could not only prevent casing from back-off, but also improve the service life of casing and the operability of construction. Sticking glue for oil casing purpose was adopted to ensure casing safety and to avoid casing accident.

10.4.6 Design of Centralizer

Without consolidated support by cement sheath, it was a crux to keep moving casing fixed and stable in the follow-up operations. Besides the fixing at the top and the bottom, appropriate fixing in the middle was necessary, to guarantee that moving casing would not shake in the outer casing, and the best way was to install centralizer onto moving casing to improve the rigidity and stability of the moving casing string. Because moving casing would bear frequent impact and vibration from drilling tool during drilling operations, high quality centralizer, especially with good solidity would be required. For moving casing, integrally welded elastic centralizer (Fig. 10.30) should be utilized. Meanwhile, to reduce the oscillating amplitude of moving casing and decrease the force borne on the elastic centralizer, rigid centralizer (Fig. 10.31) should be added on the moving casing string.

Fig. 10.30 Structure of elastic centralizer



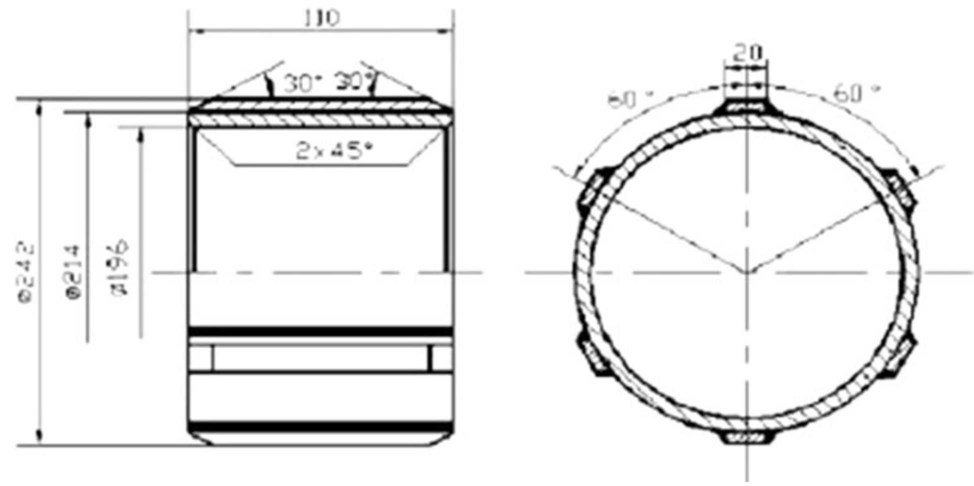


Fig. 10.31 Structure of rigid centralizer

As the upper casing string was in tension, the installation interval of the elastic centralizer could be calculated by reference to the Standards of Petroleum and Natural Gas Industry SY/T5334-1996. Because of the large vibration from the upper drill rod against casing, some rigid centralizers should be installed so as to ensure the moving casing at well head stable. Because the lower casing string was under the pressure, the installation interval of the rigid centralizer could be designed and calculated in accordance with the semiwave length of casing. To reduce the vibration of the rigid centralizer on the moving casing to the outer casing, some elastic centralizers should be installed.

The structure of rigid centralizer was adopted by reference to the rigid centralizer used in oil and natural gas drilling (Fig. 10.31) while for the structure of elastic centralizer an integrally welded elastic centralizer (Fig. 10.30) for oil and natural gas drilling was utilized.

As the lower casing string was under the pressure, rigid centralizers should be installed, if not the casing would be unstable. For the installation interval of the rigid centralizer, the bending radius of the lower moving casing, i.e. the installation interval could be calculated by using the method of energy. The maximum installation interval of rigid centralizer that could keep the compressed casing string stable could be calculated with the following equation:

$$qL^3 - 2P_bL^2 + \gamma EI = 0 \qquad (10.14)$$

where,

Pb axial pressure at the bottom of casing string, N
q axial distributing force on casing string, N/m
E elastic modulus 207 GPa
I inertia moment of casing string cross-sectional area, m^4
γ constraining coefficient, γ = 74.63.

A meaningful solution could be obtained:

$$L = x_1 + a_1 \qquad (10.15)$$

in which,

$x_1 = 2a_1\cos(\theta_1 + 3\pi/4)$
$\theta_1 = \arccos\ (-s/2t)$
$s = -2t + \gamma EI/q$
$t = a_1^3$
$a_1 = 2P_b/(3q)$

In drilling mud, q = (44.24 − 1.2 × 5.508) × 9.8 = 368.774 N/m

$$I = \pi \times (D^4 - d^4)/64 = 2.3368 \times 10^{-5}\ m^4$$

In application, the axial pressure at the lowest bottom of casing string P_{b1} should be calculated first and then the installation interval of the first centralizer L_1 calculated, afterwards the installation interval of other centralizers successively calculated. The axial pressure at any lower end of casing string $P_{bi} = P_{bi} - L_{i-1} \times q$, i = 1, 2, 3… when the axial pressure at the lower end of casing was less than critical load $P_{bi} = qL_i$, calculation should be stopped.

Based upon the calculation of moving casing fixing design, under the highest temperature the maximum length of the lower casing string that under pressure was approximate 1557 m. Based on the length of the lower casing string that under pressure was 1500 m and through a trial calculation the sequence of installation interval of rigid centralizers on casing could be obtained as: 18.12; 18.23; 18.34; 18.46; 18.58; 18.71; 18.83; 18.96; 19.1; 19.23; 19.38; 19.52; 19.67; 19.83; 19.99; 20.15; 20.33; 20.5; 20.69; 20.88; 21.08; 21.28; 21.49; 21.72; 21.95; 22.19; 22.44; 22.71; 22.99; 23.28; 23.59; 23.91; 24.26; 24.62; 25.01; 25.42; 25.86; 26.34; 26.85; 27.4; 28; 28.66; 29.39; 30.19; 31.09; 32.11;

33.28; 34.63; 36.24; 38.2; 40.66; 43.92; 48.57; 56.18; and 73.68. Totally 55 rigid centralizers should be installed.

The principle of installing centralizer should be determined based upon theoretical design and calculation, and according to the actual condition of casing.

10.4.7 Operating Technology of Moving Casing

The operating technology of moving casing includes two parts: operation procedure of running moving casing and pulling moving casing.

1. **Operation procedure of running moving casing**

(1) Preparation

i. To measure and number the casings which are to be run one by one, and to clean the thread.
ii. To check carefully casing accessories (centralizer and casing shoe) and anyone damaged is forbidden for use.
iii. To check the hoisting system and to confirm that the weight indicator is sensitive and error-free.
iv. To clean the derrick floor and to fix the teeth of casing tongs.

(2) Running casing

i. To connect casing shoe with moving casing, and to coat high temperature resistant back-off proof glue or to fasten with rivets.
ii. An elastic centralizer is added for every piece of the five pieces of casing above casing shoe, on the casing body (fixed with collar clamp), being beneficial to the centralization of casing and then retaining sub is inserted.
iii. To run casing in order and add elastic centralizer (fixing by collar clamp) and rigid centralizer according to the requirement. Back-up tong is used to prevent the casing string from rotating in the borehole, producing unnecessary damage to the centralizers.
iv. After the last piece of casing connected, to run down slowly and when it approaches to the position of retaining sub the variation of weight indicator must be carefully noticed. Once bit pressure indicated, the depth and the kelly above rotary at the moment should be immediately recorded, and compared with the theoretical values.
v. To run down continuously, to release the designed casing seating weight and to set at well head and thus the running of moving casing is completed.

2. **Operation procedure of pulling moving casing**

Following points should attract attention in case of pulling casing in drilling process:

i. To slowly pull casing string while watch the weight indicator, and carefully analyze and find out the reason in case of abnormality happens.
ii. In break out, back-up tong is utilized to prevent the lower casing string from rotating. When disassembling centralizer and collar clamp, well head should be well protected so as to prevent small parts from falling into the borehole.
iii. It is recommended that the rivets near the connecting area of the accessories should be drilled off by using electric drill before breaking out casing. Check accessory (retaining sub) and analyze down hole condition.
iv. It is recommended that all the centralizers and collar clamps should be changed when moving casing is run down again.
v. Running procedure is just the same as above.

10.4.8 Application of Moving Casing Techniques

As advanced open hole drilling method was adopted for CCSD-1 Well drilling, the "hole size" of the upper cased hole section was much larger than that of cored open hole. Moreover, during core drilling, because the pump discharge was rather small and the upward velocity of drilling mud in the upper cased hole section was too slow, the problem of cuttings sedimentation easily happened. For this reason, moving casing must be set within the casing of the upper hole section, to decrease the annular clearance and to increase the flowing velocity of drilling fluid. When it was necessary to set another layer of casing, moving casing was to be removed, hole was to be enlarged and then casing was to be set and cemented.

In CCSD-1 Well, moving casing was used twice:

i. 244.5 mm ($9^5/_8$ in.) moving casing, setting depth 0–101 m
ii. 193.7 mm ($7^5/_8$ in.) moving casing, setting depth 0–2019 m

1. **Application situation**

As the setting depth was only 101 m, the operation of running 244.5 mm moving casing was rather simple. As the rock at 101 m deep was intact and hard and thus the casing was directly set on the rock at hole bottom. Three rigid centralizers and three elastic centralizers were added on the moving casing string. On July 15th, 2001, 244.5 mm moving casing was run and on May 1st, 2002 the moving casing was withdrawn, both the operations were smooth.

As the setting depth of 193.7 mm moving casing was 2019 m, both the design and running operation were complicated. Abovementioned design and running technology of moving casing were adopted. On September 10th, 2002, 193.7 mm moving casing was run and on October 22nd, 2003 the moving casing was withdrawn.

For 193.7 mm moving casing, steel grade was P110 and the wall thickness was 9.52 mm, with the moving casing string

Fig. 10.32 Elastic centralizer for 193.7 mm moving casing

Fig. 10.33 Rigid centralizer for 193.7 mm moving casing

Fig. 10.34 Running 193.7 mm moving casing

Fig. 10.35 Pulling 193.7 mm moving casing

Fig. 10.36 Elastic centralizer with elastic steel strips broken off

structure of inserting guiding head (guide shoe) + inserted sleeve + 193.7 mm moving casing + landing joint.

On the basis of theoretical design and calculation and according to the actual condition of the moving casing, the principle of installing centralizer was defined: elastic centralizer (Fig. 10.32) was installed onto 193.7 mm moving casing body and limited with collar clamp. A rigid centralizer (Fig. 10.33) was added for every piece of the five pieces of casing near the retaining sub, and on the sixth piece of casing above this an elastic centralizer was installed while for the other casing an elastic centralizer and a rigid centralizer were alternately installed for every two pieces of moving casing (Fig. 10.34).

2. **The problem existed**

In general, withdrawing 193.7 mm moving casing was smooth (Fig. 10.35). However, because of no tempering treatment after the welding between elastic steel strips and centralizing ring, 90 pieces of elastic steel strip were broken at both ends due to the vibration of drill rod and the impact of tripping, for some elastic centralizers the elastic steel strips were completely broken off, and some only with one or two pieces left (Fig. 10.36). 18 pieces of steel strip were carried out with centralizing ring, rigid centralizer and specially made guiding shoe during pulling the moving casing and 72 pieces fell into the borehole, bringing about a lot of troubles for follow-up reaming drilling.