Chapter 15
Hydraulic Steel Gates

15.1 General

15.1.1 Functions and Components

Almost every hydraulic project needs a reservoir (or pool) to control flood as well as to store water for irrigation, power generation, domestic, and/or industrial water supply. A spillway or headwork with control devices such as gates or shutters is almost invariably demanded for releasing excessive flood inflow, or diverting water into canal system (Mayer and Bowman 1969; Zuo et al. 1987; Ministry of Construction of the People's Republic of China 2006; Ministry of Water Resources of the People's Republic of China 1995; Ministry of Water Resources of the People's Republic of China, Electric Power Industry Ministry of the People's Republic of China 1995). Delivery of water also may be undertaken by hydraulic gates installed in tunnels and dam body conduits. However, control of flow in closed pipes such as penstocks conveying water for turbines is done by valves, which are different from gates in the sense that they come together with the driving equipment, whereas gates require separate driving (hoisting) equipments.

A hydraulic gate normally consists of movable member, stationary member, and mechanical equipment (Fig. 15.1).

The moveable member is also termed as "gate leaf" and used to shut the opening of the hydraulic work, to control discharge, to pass boats, and to flush silt. It consists of skin plate, frame, support and travel member, hanger, and water tightness (Fig. 15.2).

The stationary member is embedded into the pier or sidewall structure and intended to guide the gate, to carry loads imposed on gate support, to provide water tightness in areas of gate-to-structure contacts, to warm up these contacts, and to prevent concrete surface and edge from crushing.

The mechanical equipment is hoist and/or handle mechanism, for operating the gates during erection and shutdown.

S.-H. Chen, *Hydraulic Structures*, DOI 10.1007/978-3-662-47331-3_15

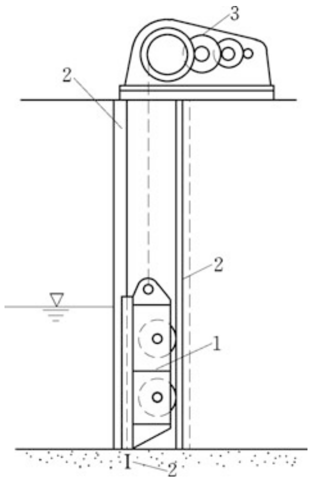

Fig. 15.1 Components of hydraulic gate. *1* moveable structure; *2* stationary members; *3* mechanical equipment

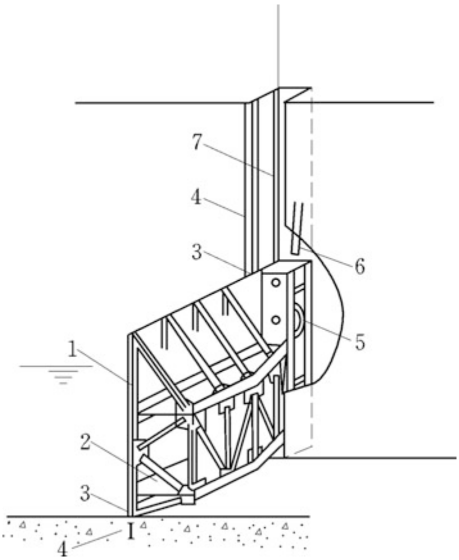

Fig. 15.2 Leaf components of plate gate. *1* skin plate; *2* framework; *3* water tightness; *4* embedded water tightness; *5* support and travel member (wheel); *6* embedded support and travel member; *7* hanger

15.1.2 Classification of Gates

Different types of hydraulic gate and hoist working on different principles and mechanism are used in spillways, sluices, and tunnels, etc. (Cai and Qu 1988; Chen and Chen 2014; Erbisti 2004; Fan 2000; Grishin 1982; Lewin 1995; Mayer and Bowman 1969).

By operational purpose, hydraulic gates fall into service (main) gate used for routine operation, bulkhead gate providing temporary damming surface to enable the dewatering of a lock chamber or gate bay between dam piers, and emergency gate to close the opening in case of accident fraught with dangerous consequences.

By material used, hydraulic gates are distinguished as steel gate, reinforced concrete gate, wooden gate, etc., of which the steel gate is the most prevalent due to its high strength of material, high impact resistance, and durability.

By the location of opening with respect to headwater, hydraulic gates are divided into crest (surface) gate intended to close overflow openings (e.g., overflow dam monolith, sluice, and shore spillway) and submerged gate to close bottom orifices, which may be installed at position in the conduit between inlet and outlet. Hydraulic gates operating under heads up to and in excess of 50 m are conventionally referred to as "high-pressure gates."

The prevalent classification of hydraulic gate is based on their structure and operation feature as shown in Fig. 15.3.

1. Stoplog gates

Stoplogs are smaller beam or girder structures that span the opening and are stacked to a desired damming height. A number of stacked stoplogs make up a stoplog gate, which is usually used in small sluices or culverts (Fig. 15.3a).

2. Vertical lift plate gates

Vertical lift plate (plain) gates have been widely employed in locks and spillways (Fig. 15.3b). They are raised and lowered vertically to open or close a lock chamber or a spillway vent. They are essentially a stiffened plate structure that transmits the water load exerting on the skin plate along horizontal girders into the sidewalls of the lock monolith or spillway piers. Vertical lift gates can be operated under moderate heads, but not be applicable under reverse head conditions.

3. Roller gates

They are mostly used at the exit of pumping station which may be further divided as flap gate (Fig. 15.3c), pivot leaf gate (Fig. 15.3d), and cover board gate (Fig. 15.3e).

4. Floating pontoon gates

They are similar to empty cases floating on water (Fig. 15.3f) and used as bulkhead gates by floating to the position and sinking down after the filling of water.

5. Radial gates

Radial (or Tainter) gate is a segment of cylinder mounted on radial arms, or struts, that rotate on trunnions anchored to the sidewalls or piers (Fig. 15.3g). Although numerous types of framing exist, yet the most common type comprises two or three frames, each of which consists of a horizontal girder that is supported at each end by a strut. Each frame lies in a radial plane with the struts joining at the trunnions. The girder supports the stiffened skin plate assembly that forms the damming surface.

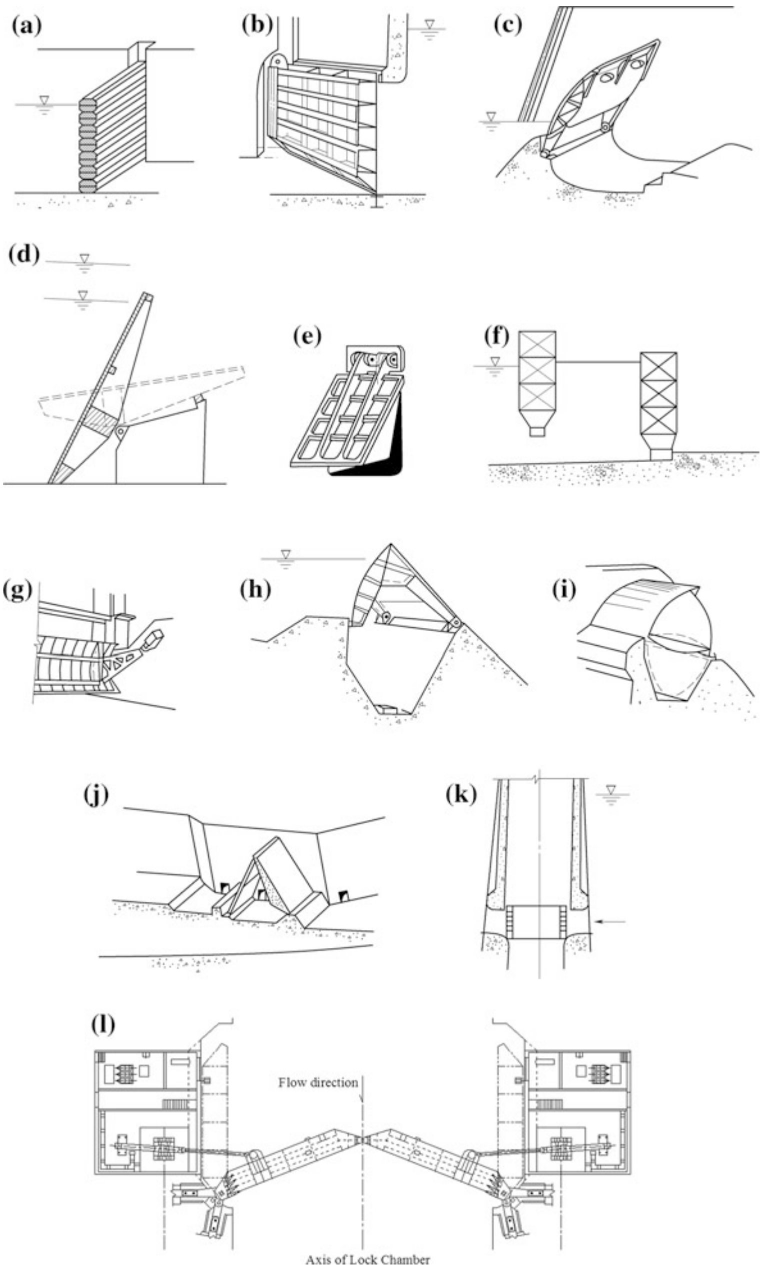

Fig. 15.3 Types of hydraulic gate. **a** Stoplog gate; **b** plate gate; **c–e** roller gate; **f** floating pontoon gate; **g** radial gate; **h** sector gate; **i** drum gate; **j** roof gate; **k** cylinder gate; **l** miter gate

6. Sector gates

They are framed similar to radial gates. Depending on the position of their axis, sector gates may be further divided as vertical axis sector gate and horizontal sector gate. The latter is actually a pair of arc gates hinged on vertical axis, which are commonly installed in navigation locks. The former usually has sealed top roof skin, and by feeling or emptying of the room inside, the gate may be moved up or down (Fig. 15.3h). Traditionally, sector gates have been used in the tidal reaches of river or canal where the dam may be subject to head reversal. Sector gates are generally limited to lifts of 3 m or less. Where the pivot trunnion is at the upstream side, it is also named as drum gates (Fig. 15.3i).

7. Roof (bear-trap) gates

They consist of two wickets turning about horizontal axes, which are also named as floating gates in China (Fig. 15.3j).

8. Ring gates

Ring gate is a cylindrical drum which moves vertically in an annular hydraulic chamber so as to control the peripheral flow of water from reservoir through a vertical shaft (Fig. 15.3k).

9. Miter gates

Miter gates are customarily used to close off the entrance and exit of a navigation lock to allow the passage of vessels between different water levels in a canal or river system. A miter gate consists of two leaves that provide a closure at one end of the lock. The miter gate derives its name from the fact that the two leaves meet at an angle pointing upstream to resemble a miter joint (Fig. 15.3l).

10. Valves

Valve is a device installed in various pipes (e.g., penstocks) that regulates, directs, or controls the flow of water by opening, closing, or partially obstructing. Valves are different from gates by their way of operation as they remain in the water both in the closed and open positions. Valves in hydraulic engineering are mostly intended to control flow in the high-pressure conduits such as penstocks conveying water to turbines for the generation of hydroelectricity.

15.1.3 Brief History of Hydraulic Gates

The manufacture of hydraulic gates is closely related with the development of irrigation and river navigation system (Erbisti 2004).

The first canal for transporting of goods is believed to appear in China, in an attempt to handle boats in the region of river rapids by building dikes with slopes on the banks of the canal. Around 987, the Chinese constructed two wood or stone piers a certain distance apart on each side of the canal, to create a pool. Vertical grooves (slots) were cut into the opposite sides of the piers, and tree trunks were fitted horizontally into or out the grooves as stoplogs. In this way, boats could enter or exit the pool and the water level could be slowly raised or brought down. Later, the tree trunks were linked, forming an integral gate that could be lifted up or lowered down like a guillotine blade.

The development of hydraulic gates in the Netherlands followed a way similar to that of China where locks were very common at the end of the fourteenth century. The gates, still of the guillotine type, were provided with lead counterweights and equipped with drains.

In 1795, the Little Falls canal lock was put into operation. Two wood swinging gates were placed at each end of the lock. Instead of closing to a flat plate, the gates closed to form an angle pointing upstream, facing the current. This may be looked at as the initiation of miter gates. The miter gates designed with cast-iron structure and steel plate shielding were firstly laid in 1828 on the Nivernais Canal in France.

With the turn of the century, inventions with respect to hydraulic gates were booming.

The oldest known application of a radial gate was in 1853, on the Seine River in Paris (France), at 8.75 m wide and 1.0 m high. Around 1870, Parker in the USA invented the radial gate in parallel, who sold his invention to Tainer. In 1886, Tainer patented the radial gate in his name.

The sector gate was invented in the USA by Cooley and used for the first time in 1907 in the Lockport Dam on the Chicago Drainage Canal.

Carstanjen in Germany invented the roller gate in 1898. Its first application was on the Sau River.

Chittenden of the US Army Corps of Engineers invented the drum gate in 1896. Its first application was at the No. 1 Dam on the Osage River (USA) in 1911.

In 1818, White constructed the first roof (bear-trap) gate in the Mauch Chunk Creek, on the Lehigh River, USA.

The ring gate was developed by the USBR for the use in morning-glory spillways. It was firstly applied in 1936 in the Owyhee Dam, with a diameter of 18 m and a height of 3.6 m and then followed by the Hungry Horse Dam in 1953, with a diameter of 19.5 m and a height of 3.6 m.

In 1883, according to Stoney's patent, wrought-iron gates at 8.9 m wide and 4.4 m high installed with rollers sliding in cast-iron grooves fixed in the piers was first constructed at Belleek, Ireland. This type of gate was widely applied in Europe, USA, Egypt, and India at the beginning of the twentieth century.

15.2 Basic Requirements for the Layout of Gates

Most existing lock gates are miter gates and vertical lift gates, with a small percentage being sector gates (Buzzell 1958). Spillway gates installed on the crest to provide a moveable damming surface and to allow for the spillway crest being located below a given water level are generally radial gates or vertical lift gates, but occasionally roller gates.

Right selection of gates and their hoists is the first step to ensure the effective control and safety of the project. A designer has to plan the gate and hoisting equipment together since separate planning of gates or hoists, sometimes will lead to unsatisfactory installation. Although the choice for the gates and hoists for spillways and outlets depends on various factors such as head, gate size, and river flow operational criteria, yet primarily the safety and convenience in operation as well as maintenance and economy, are the governing requirements in the same importance.

Gates should be installed at position where water flow is smooth. The conditions being disadvantageous for gate operation, such as the cross and swirl flow in front of gate, and the submerged flow and backflow at the back of gate, should be avoided as far as possible.

Specifically, selection of gates should take into account of following factors:

- Requirements of the project for the gate operation;
- Position of gates in the hydraulic structure, size of openings, head and tail water level, and operational head;
- Silt and floating debris;
- Type and capacity of hoists, hanger manners;
- Manufacture, transportation, installation, and maintenance; and
- Techno-economic indices.

To facilitate manufacture, transportation, and installation of gates, following requirements should be met in the design:

- Specific conditions of manufacture and installation;
- Sufficient rigid, adequate outer dimension, and self weight of the transportable unit;
- Standardized and patternized products for reducing the variety and specification of components and members;
- Less welding work for connecting structural members as far as possible; and
- Controlled assembly distortion using pins or blots for gate section joint, if possible.

Hereinafter in this chapter, an introduction is provided on the radial and plate gates, with respect to the specific purposes they may be met, the possible locations in which they may be installed, and the suitable hoists with which they are operated.

15.3 Plate Steel Gates

These are gates that move within vertical grooves (slots) incised between sidewalls or piers. The vertical lift gates for controlling flow over the crest of a hydraulic structure are ordinarily equipped with wheels. Nowadays, this type of gates is commonly used for barrages but is rarely used for dam. Instead, the radial gates (discussed later) are more and more prevalent for dam spillways.

15.3.1 Types of Plate Gates

They may be vertical lift (Fig. 15.4) and lift flap (Fig. 15.5).

1. Vertical lift gate

The vertical lift gate, with wheels (rollers) at each end, moves vertically in slots and consists of a skin plate and horizontal girders that transmit the horizontal water thrust into the piers. Like the radial gate, it must be hoisted at both ends, and the entire weight is suspended from the hoisting chains or cables (cables are generally desirable). Piers must be extended to a considerable height above water in order to provide guide slots for the gate in a fully raised position. Vertical lift gates have been designed for spans in excess of 25 m. Historically, gantry cranes traveling on the barrage/spillway deck or working platform have been the standard equipment for operating vertical lift gates. However, fixed hoists may be justified as advantageous over gantry cranes, especially if the operating speed is important or remote control is desired. Dogging devices are sometimes provided on the gate to hold it at

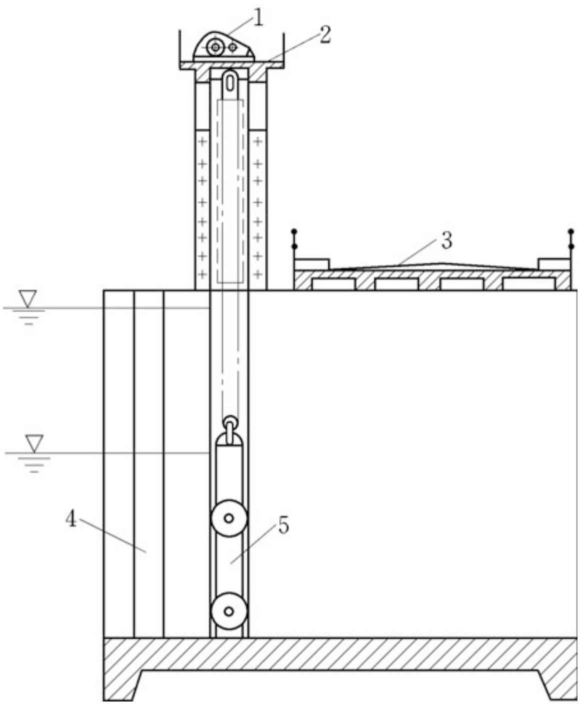

Fig. 15.4 Vertical lift gate. *1* hoist; *2* operating bridge; *3* access bridge; *4* bulkhead gate slot; *5* vertical lift gate

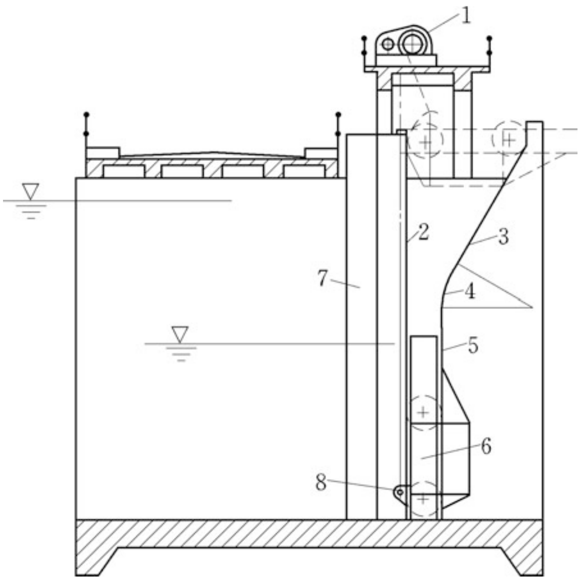

Fig. 15.5 Lift flap gate. *1* hoist; *2* guide track; *3* inclined track; *4* circular track; *5* straight track; *6* plate gate; *7* bulkhead gate slot; *8* hanger

the proper elevation. In some cases, it may be advantageous to mount the dogs in the gate and provide a dogging ladder in the gate slot.

Some of the main advantages of vertical lift gates over radial gates are ease of fabrication, considerably shorter of erection time, and in most cases, shorter supporting piers. The load from the gate to the supporting piers or sidewalls is in one direction, which simplifies the design of supports. Some of the main disadvantages of using vertical lift gates are heavier lifting effort which requires greater hoist capacity, more labor intensive operation, greater time required for gate operation if only one gantry crane is provided, gate slots can lead to cavitation and debris collection, and fatigue under constant cyclic loading since the main load resisting frame relies on a tension flange.

Vertical lift gates would be preferred to radial gates when the elevation of the maximum controlled pool is far above the sill that excessively long piers would be demanded for radial gates, flood discharges, or drift conditions are such that any obstruction to the flow below the spillway bridge is impermissible.

2. Lift flap gate

With the lift flap gate, the track of wheel support is divided into three parts: vertical, circular, and inclined. The hanger is mounted at the upstream bottom of the leaf near the lower main girder. The gate is flapped gradually as its lifting until horizontal position. Lift flap gate may lower down the height of operating bridge or platform to obtain higher seismic resistance. Some of the main disadvantages of lift flap gate are the hanger on upstream side resulting in its corrosion; the horizontal position of lifted gate is inconvenient for repairing; and during the operation when it is in the position of inclination, the gate is vulnerable to the flow and wave actions which give rise to strong swing and vibration.

15.3.2 Layout and Structure of the Leaf of Plate Gate

Leaf is the main body of a gate consisting of skin plate, stiffeners (tiers), horizontal girders, and end girders (Fig. 15.6).

Vertical lift gates may be framed of plate girders or horizontal trusses, and economy index normally indicates which frame system will be preferred. Support and travel members are intended to permit the traveling of gate and transfer pressure through slot and guide members to the embedded facilities. To limit the lateral displacement, misalignment, and vibration of gate, uses are made of side and reverse subsidiary supports and guide means (wheel, struts). Seals overlap the gaps between the movable gate structure and slot and guide members. Hangers connect the gate to the hoist.

The size of plate gate is dependent on the vent size of waterway. Although the crest gate permits overtopping of wave, yet its upper edge should be at least 0.3 m higher above the maximum level (inclusive of wind-wave pileup) maintained by the gate.

High vertical lift gates may be fabricated of two or more segments in order to facilitate storage, to reduce hoist capacity, or to facilitate passing of ice and debris, and they are termed as "two-tier gates" which can be operated separately, but when fully closed, they act as monolithic gates (Fig. 15.7). However, this does increase operating difficulties because the top leaf has to be removed and placed in another gate slot.

1. Layout of framework

The gate framework structure may be distinguished as simple crossbar, crossbar and vertical stiffener grid, and complex crossbar and stiffener grid (Fig. 15.8).

The framework structure selected will depend on the span, hydrostatic head, and lift requirements. Horizontal girders (crossbars) are the principal structural members

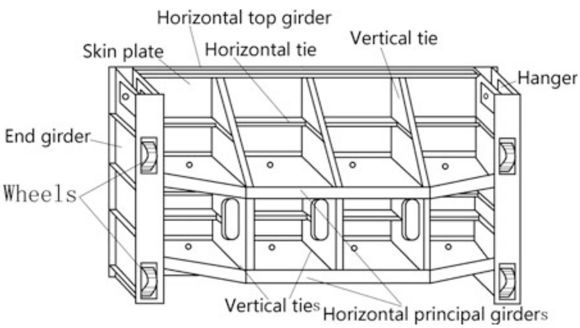

Fig. 15.6 Structural layout of an unitary vertical lift gate

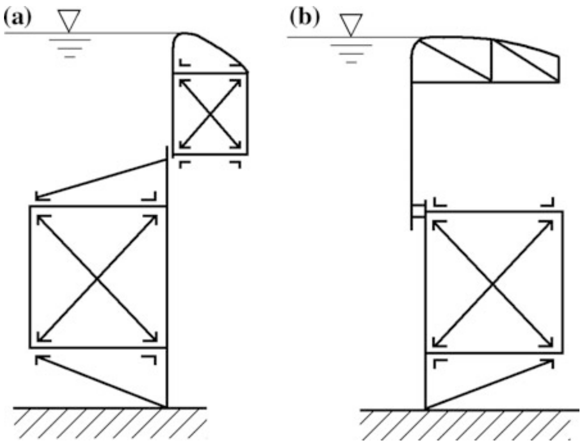

Fig. 15.7 Two-tier gates

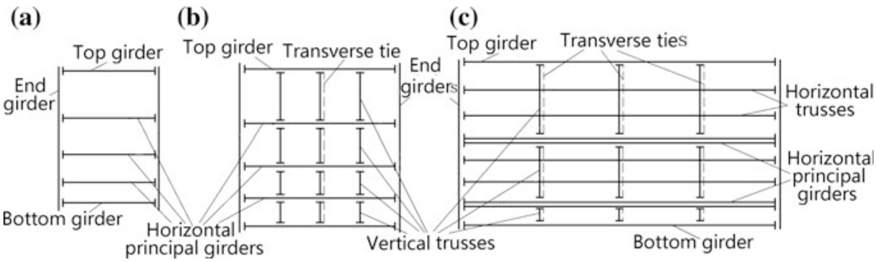

Fig. 15.8 Typical layout of frameworks for plate gates. **a** Simple crossbar; **b** crossbar and vertical stiffener grid; **c** complex crossbar and stiffener grid

of gate, to transfer the water pressure from the skin plate and vertical stiffeners (if any) to the end girders or end arms of the gate. Vertical stiffeners (also called as vertical tiers or vertical beams) are the structural members spanning vertically across horizontal girders to support the skin plate.

(a) Simple crossbar

The skin plate is supported on the crossbars (also called as horizontal girders), to which the hydrostatic pressure of water is transferred directly. This type is generally applied to small span gates.

(b) Crossbar and vertical stiffener grid

To reduce the thickness of skin plate, vertical stiffeners may be installed. This type is generally applied to medium span gates.

(c) Complex crossbar and stiffener grid

For a larger span plate gate, water exerts pressure on the skin plate which transfers it to the structural stand consisting of horizontal beams (strings) and vertical beams (stiffeners) before transfers it further to the crossbars.

2. Connection of framework with skin plate

There are three types of framework connecting with skin plate: inbuilt structural stand, lower stand, and extended (outside) stand (Fig. 15.9).

(a) Inbuilt stand

Horizontal and vertical beams and crossbars are included in its arrangement and linked directly with skin plate. The major advantage of this type lies in its higher stiffness of the framework; therefore, the amount of steel consumption may be reduced. The major disadvantage of this type is the inconvenience in manufacture —the horizontal beams are cut first and then connected to the vertical beams, the same occurs at the connection of vertical beams with the crossbars. This may be partially improved by using diaphragm plates as vertical beams, and the holes may be made through these diaphragms to let the horizontal beams pass through the holes directly, in this way they may be continuous. This is widely exercised for the connection of framework with skin plate.

(b) Lower stand

The crossbars and horizontal beams are connected directly with the skin plate, while the vertical beams are located to the downstream face of horizontal beams. In this way, the horizontal beams are kept continuous.

(c) Extended (outside) stand

The horizontal and vertical beams are located between the skin plate and crossbars. This design is simpler, but the sharing proportion of skin plate in the operation of

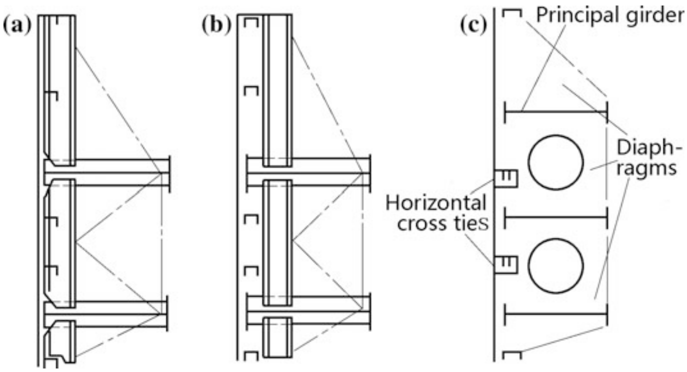

Fig. 15.9 Connection of framework with skin plate. **a** Inbuilt stand; **b** lower stand; **c** extended stand

the entire gate structure is rather small, let alone the augment in the gate thickness. This type is seldom practiced nowadays.

3. Layout of crossbars

The number of crossbars is depending on the size of gate. Where the span L of gate is smaller than the height (i.e., $L \leq H$), the number of crossbars is more than two, which is named as multi-crossbar gate. On the contrary, with a large ratio of span to height (e.g., $L \geq 1.5H$), two-crossbar gate is commonly employed. Most often, crest gates possess two crossbars rather than three crossbars. Crossbars are equal-loaded by positioning them at an equal distance from the resultant of water thrust exerting on the skin plate.

4. Layout of end girders

End girders (also called as support beams) can be single-walled or double-walled (Fig. 15.10).

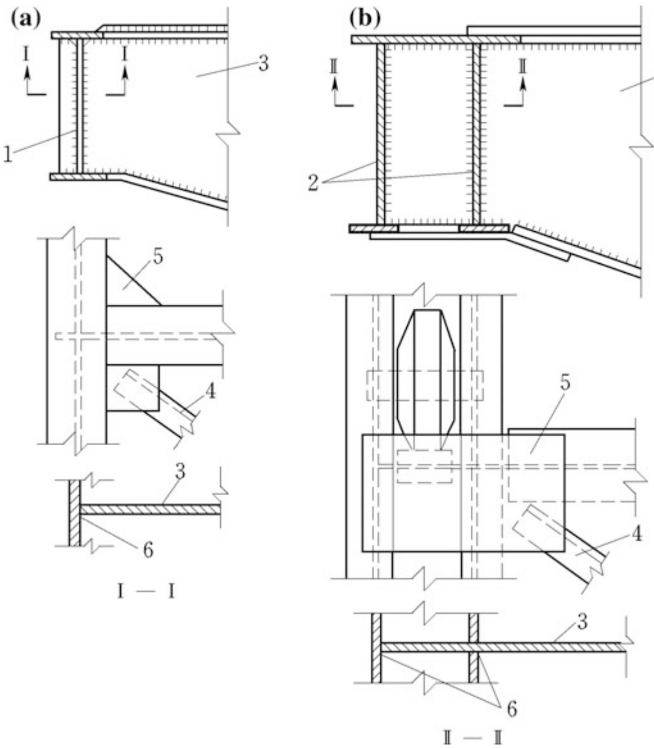

Fig. 15.10 Types of support beams. **a** Single-walled support beam; **b** double-walled support beam. *1* single-walled support beam; *2* double-walled support beam; *3* crossbar web; *4* cross-tie of truss for hanger; *5* strengthened plate of node; *6* k-type welding line

Single-walled support beam is simple and convenient to be connected to crossbars, but it has low stiffness against torsion. It is suitable for the gate with slide support, or for the fixed wheel support of small size. In the latter case, an additional support plate should be installed at the inner side of the web of support beam.

Double-walled support beam has high stiffness against torsion and is convenient for the installation of support wheels and hanger, but it is complex in structure and high in steel consumption. It is suitable for the large gate with fixed wheel support.

5. End supports

End supports are intended to transfer the loads to gate guides. The basic types of supports are slides and wheels, and the latter may be further divided as fixed, tractor (caterpillar), and Stoney. Structural steel guide members, such as guide rollers, should be provided to restrict the lateral and/or transverse movements of gate, either in the upstream or lateral direction (Fig. 15.11).

(a) Slide supports

Slide gate, as the name implies, is the gate in which the gate leaf slides on the sealing surfaces provided on the frame. In most cases, the sealing surfaces are also the load-bearing surfaces. Slide gates may be with or without top seal depending on whether they are used in a close conduit or as on a free flow crest. A typical installation of slide gate consists of a gate leaf and embedded parts (Fig. 15.12), and the latter serves the following purposes:

- Transmit water load on the gate leaf to the supporting concrete (sidewalls or piers);
- Guide the gate leaf during operation; and
- Provide sealing surface.

Slide gates use face-to-face contact for end support. A machined surface that is mounted to the front face of gate bears directly against a machined guide surface in the gate slot. The two bearing surfaces also serve as the gate seal. Materials for the

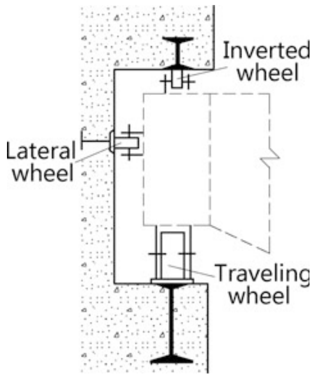

Fig. 15.11 Guide rollers on the sides of a gate

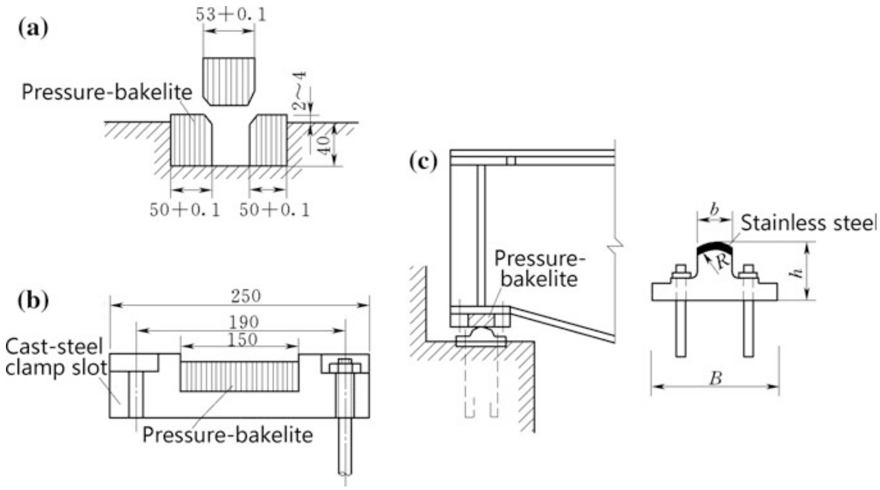

Fig. 15.12 Structure of pressure-bakelite slides (unit: mm)

gate seal surface may be aluminum, bronze, stainless steel, or pressure-bakelite. The last one is the most prevalent attributable to its high mechanism performance, low friction, and good processability. Under definite lateral confined stress, the bearing capacity of pressure-bakelit slides may reach up to 160 MPa and the friction coefficient between the pressure-bakelit slide and the smooth steel track may be as low as 0.09–0.13. The top of steel track is generally in a shape of circular. To control the slide friction, 3–5 mm thick stainless steel is coasted on the track top and is polished at least up to 6–7 degree of finish (Fig. 15.12).

This type of gate may be employed for the intake/outlet of tunnels under high heads, where a head cover (bonnet) is used to seal off the guide slot from the gate operator for submerged flow installations.

(b) Wheel support

With this type of end support, the wheels revolve on fixed axes, which are customarily supported by the web of end girders attached to the gate framework. The wheels also may be mounted by pairs in trucks that carry the wheel loads through center pins to end girders. When the gate is operated without static head, this type of end support will be most economical.

In some cases such as where the gate moves on the tracks provided on the face of dam, skin plate is customarily installed on the downstream side, or skin plates are provided on both downstream side and upstream side if the downstream water is above sill. Under the latter circumstances, the gate may be fully or partially buoyant. This buoyancy should be taken into account in determining the net balance of vertical forces and addition of ballast, to ensure the closure without difficulty. The bottom of gate should be so shaped that satisfactory performance and

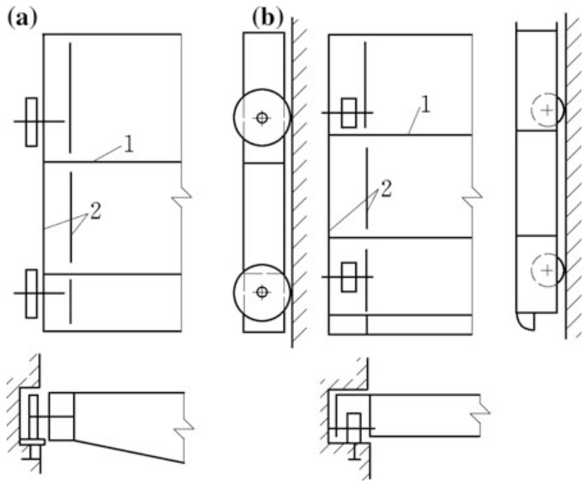

Fig. 15.13 Typical layout of wheels. **a** Cantilevered axis wheel; **b** simply pin-supported wheel. *1* crossbar; *2* side girder

freedom from harmful vibrations are attained under all conditions of operation in addition to minimum down-pull.

The wheel support permits the use of a smaller hoist capacity for gate operating, which is preferable to large size and high-head gates, particularly where the gate should be shut down by its self weight.

The unitary gate is the simplest type of wheel gates with four wheels on cantilevered pins or pins fixed between the walls of end girders (Fig. 15.13). Wheels on cantilevered pins need shallower gate slots and are convenient in installation and repair, but the outside web of the side girder in torsion and the cantilevered pins in bending entail them only be applicable for the gates of small size and under low head.

Pins fixed between the walls of side girder are mainly employed for the gates of large size and under high head.

The larger head and size of opening, the greater diameter and/or number of wheels will be, and it in turn deepens and widens the slots. Since the rigid support of a great number of wheels fails to ensure a uniform distribution of load on these wheels, use is often made of two-wheeled carriages. Hinges are provided between the carriages and end girders.

For small gates, cast iron is a commonly used wheel material. However, where the wheel pressure is in excessive of 200 kN, carbon steel or alloy steel should be alternatives.

6. Seals

Seal is a device for preventing the leakage of water around the periphery of hydraulic gate—a bottom seal is provided at its bottom, whereas side seals are fixed to its vertical ends, and a top seal (if any) is one that is installed at its top. As the pressure downstream of the gate drops, the seal, under the actions of head pressure, moves toward the seal plate.

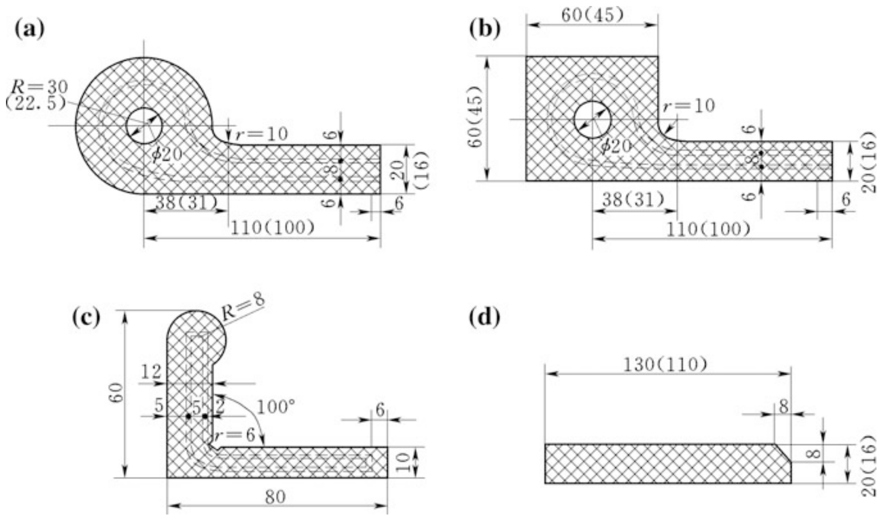

Fig. 15.14 Rubber seals (unit: mm). **a** J-type (or P-type) seal with circular bulb; **b** J-type (or P-type) seal with square bulb; **c** L-type (or angle-shaped type) seal; **d** rectangular seal

Rubber is almost universally employed for seals owing to its ability to form a watertight contact against any reasonably smooth surface. Seal types, sizes, and available molds are listed in their catalogs of major rubber seal manufacturers. J-type (or P-type, music note type) seal of circular bulb is mainly applied to seal the gate top and sides (Fig. 15.14a), while J-type seal of square bulb (Fig. 15.14b) is mainly employed for the sealing of gate top and sides of submerged radial gate. For crest radial gates, L-type (or angle-shaped type) (Fig. 15.14c) is commonly adopted as the side seal. Rectangular seal (Fig. 15.14d) is merely used for bottom seals.

For low- and moderate-head installations, the most frequently exercised side and top seals is the J-type with a 45 mm bulb and a 15 mm stem. The J-type seal of circular bulb or square bulb mounted on either the upstream or downstream side is most suitable for vertical lift gates, which is commonly employed as top and side seals of lower head gates (Fig. 15.14).

J-type seals are available with both hollow and solid bulbs. Hollow bulb seals provide a greater contact area with seal plates, thus aiding water tightness in low-head gates.

To allow greater flexibility for the seal and permit it to deflect toward the seal plate, the seal stem should be attached to the gate on the outer edge by the clamp bars. Seal mounting details should be carefully considered to prevent damage to the rubber under all conditions of operation.

All top seals should be fluorocarbon-clad to help prevent the bulb from rolling during the operation of gate. The bottom seal is normally a wedged rubber that relies on the weight of gate to provide the seal compression for sealing.

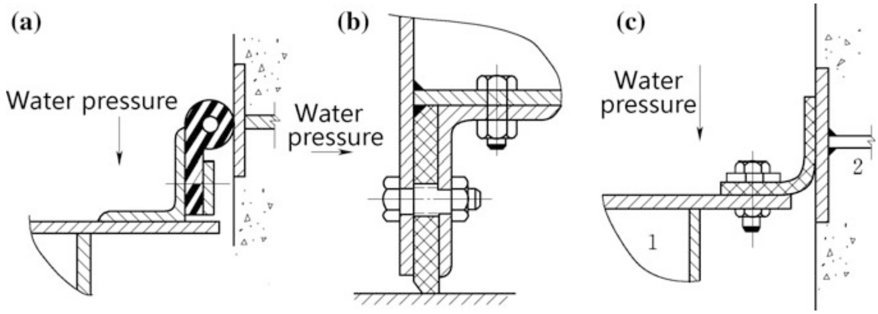

Fig. 15.15 Typical side seal layouts for crest gates. *1* gate leaf; *2* cushion of seal

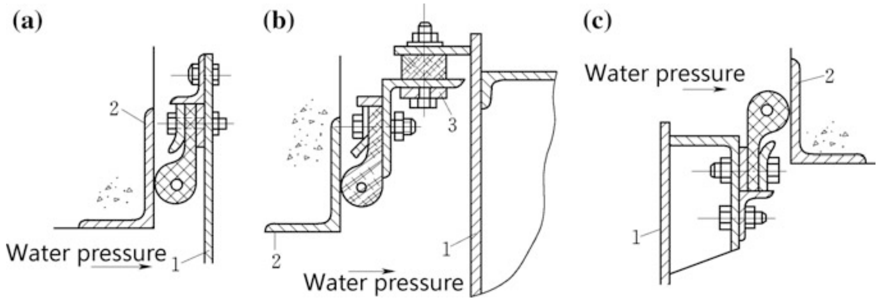

Fig. 15.16 Typical side seal layouts for submerged gates. *1* gate leaf; *2* seal cushion; *3* circular cushion

Figure 15.15 shows typical side seal layouts for crest gates, and Fig. 15.16 shows typical seal layouts for submerged gates.

15.3.3 Raising and Lowering Efforts and Hoists

1. Computation of hoisting force

Hydraulic down-pull or uplift is the net force exerting on a gate in vertically downward or upward direction under hydrodynamic condition (Sagar 1977a, b, c; Sagar and Tullis 1979).

(a) Lowering effort F_W

$$F_W = n_T(T_{zc} + T_{zs}) - n_G G + P_t \tag{15.1}$$

where n_T = revision coefficient with regard to the friction due to the reverse and side supports, and the inaccuracy in the calculation of frictional forces

($n_T = 1.2$); n_G = factor of under load against possible departure from the design weight of the gate (n_G = 0.9–1.0); T_{zc} = friction resistance of supports, kN; T_{zs} = friction resistance of seals, kN; G = gate weight of movable portion, kN; and P_t = uplift from bottom seal and bottom edge, the latter is related to the bottom shape of the gate, kN.

The negative result of F_W means the gate may be lowered down to shut the opening by its self weight. Where the calculated result is positive, pressure should be applied to help the closure of gate, i.e., the gate lowering needs assisting by down-pull which may be cared for by the use of a down-pull gear, a clamp beam, or a ballast to increase the weight of gate.

(b) Hoisting effort F_Q

$$F_Q = n_T(T_{zc} + T_{zs}) + P_X + n'_G G + G_j + W_s \tag{15.2}$$

where n'_G = factor of over-load against possible departure from the design weight of the gate (n'_G = 1.0–1.1); W_s = water column pressure on the top of the gate, kN; P_X = downward suction force due to ingress, which may be neglected for crest gate or submerged gate of open flow under good flow pattern and vented sufficiently, kN; and G_j = weight of ballast, kN.

2. Hoists

Hoists are the mechanical installations used for operating the gates, which are distinguished as mechanical hoists and hydraulic hoists.

Mechanical hoists fall into screw-operated type, rope-drum type (winch, chain-pulley block, monorail crane, gantry crane, etc.), and hydraulic cylinder type.

Screw-operated hoists are simple and reliable and able to provide both lowering effort and hoisting effort, but their capacities are smaller compared to the other types therefore applicable ordinarily for small gates.

Rope-drum hoists may be employed to spillway crests, outlets, and navigation locks. They are more preferable for gates that have deep submergence, where hydraulic cylinders above the deck is not allowed for, or when hoisting loads are too large and economics makes hydraulic cylinders impractical.

A hydraulic cylinder hoist system generally possesses two cylinders located at each side of the gate framework. The hoist cylinder normally consists of pump, reservoir, control, and piping. More recent applications use telescoping cylinders to accommodate deep submergence gates.

Where there is a fairly large number of gates and there are no requirements for simultaneous operation, instead of fixed hoists, movable hoists such as gantry cranes may be advisable.

15.4 Radial Gates

These are hinged gates, with the leaf (or skin) in the form of a circular arc whose center of curvature is at the hinge or trunnion. Radial gates have unique advantages over other gate types as follows:

- The radial shape provides efficient transfer of hydrostatic loads through the trunnion;
- A lower hoist capacity is demanded;
- They have a relatively fast operating speed; and
- Gate slots are not required, and favorable hydraulic conditions of discharge flowing are provided, by which problems associated with slot cavitation, and buildup of floating debris and ice, are avoided or alleviated.

The disadvantages brought about by the installation of radial gates are given as follows:

- To accommodate trunnions, the pier and foundation will likely be longer in the downstream direction than would be necessary for vertical gates;
- The hoisting arrangement may require taller piers, especially where the wire rope hoist system is employed. However, radial gates with hydraulic cylinder hoists generally demand lower piers than with wire rope hoists;
- Due to greater height of larger piers, seismic resistance will be lower;
- End frame members may encroach on water passage. This is more critical with inclined end frames; and
- Long strut arms are often demanded where flood levels are high, to allow for a clearance of the opened gate from the water surface.

15.4.1 Leaf Structure and Layout of Radial Gate

A radial gate has an upstream skin plate bent to an arc with its convex surface on the upstream side. The center of the arc is at the trunnion pins around which the gate rotates. The skin plate is supported by properly spaced stiffeners either horizontal or vertical or both. If horizontal stiffeners are adopted, they are supported by properly spaced vertical diaphragms which are connected together by horizontal girders (crossbars) transferring the load to the two vertical end diaphragms (end girders). The end diaphragms are supported by radial arms. If vertical stiffeners are adopted, they are supported by properly spaced horizontal girders (crossbars) which are supported by radial arms. The arms transmit the water load to the trunnions. Suitable seals are provided along the curved edges of the gate and along the bottom. If it is employed as a regulating gate in the tunnel or conduit, a horizontal seal fixed to the headroom structure seals the top edge of the gate in its closed position. Guide rollers are also necessitated to limit the swing of the gate during hoisting or lowering operation.

1. Layout of framework

The layout of crossbars gives rise to two basic types of framework for radial gates, which is mainly dependent on the ratio of width to height of the gate.

For wide gates with large ratio of width to height, horizontal girder framework is commonly employed. Structurally, the skin plate acts compositely with the ribs to form the skin plate assembly, which is, in turn, supported by the horizontal crossbars (girders) that span the gate width. The horizontal girders are supported by the end frames, which consist of radial struts or strut arms and bracing members that converge at the trunnions which are anchored to the piers. Structural bracing members (e.g., horizontal girder lateral bracing, downstream vertical truss, end frame bracing, and trunnion tie) are incorporated to resist specific loads and/or to brace compression members.

Where the horizontal girder framework is employed, three types of arms arrangements may be adopted: permitted by the support condition, the type shown in Fig. 15.17a is desirable; if the support is on the sidewalls, the type in Fig. 15.17b may be applied; and the type in Fig. 15.17c is applicable if the vent clearance is not sufficient.

Types in Fig. 15.17a, b are advantageous to reduce the bending moment at the middle portion of girders, which in turn reduce the amount of steel consumption. However, the type in Fig. 15.17a requires definite structure condition, and the type of Fig. 15.17b complicated the structure of trunnion. The type in Fig. 15.17c is advantages in simple structure and in convenient installation and manufacturing, but has higher steel consumption.

For tall gates with small ratio of width to height, vertical girders have to be used to simplify the end frame configuration. Curved vertical girders (crossbars) are employed to support several horizontal girders. Each vertical girder is supported by the corresponding end frame that may include two or more struts (Fig. 15.18).

2. Location of trunnion

Although it is sometimes practical to allow for submergence in the events of flood, especially on navigation dams, yet it is normally desirable to locate the trunnion above the maximum water surface, to prevent it from contacting with floating ice and debris, and to avoid the submergence of the operating parts. Trunnion is generally located on the position of (1/2–3/4)H, (2/3–1)H, and 1.1H, above sill

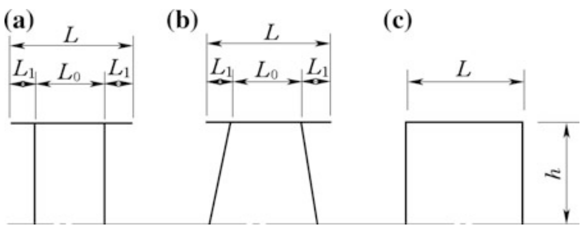

Fig. 15.17 Horizontal girders framework—arrangement of arms (plan)

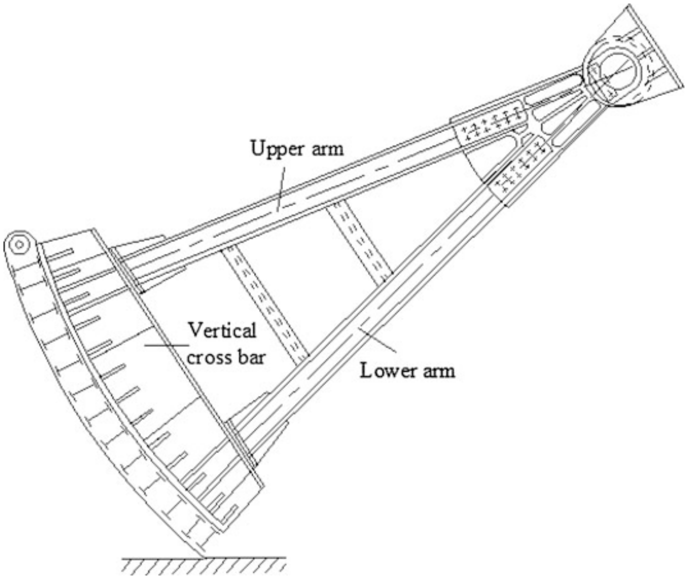

Fig. 15.18 Vertical girder framework—arrangement of arms (elevations)

(H = height of gate), for the crest gates of spillway, the crest gates of barrage, and the submerged deep gates, respectively.

If other considerations do not control, it will be desirable to so locate the trunnion as the maximum reaction is approximately horizontal. This will allow for simplified design and construction, where the trunnion post-tensioned anchorage may be placed in horizontal layers.

3. Seals

The standard side seals provide increased sealing force in proportion to the increased head, and seals usually tend to leak under low heads rather than high heads. Therefore, the J-type or L-type side seal arrangement is demanded for crest radial gates (Fig. 15.19). The seals may have a hollow bulb to increase flexibility under low-head applications. The seals are available with the rubbing surface coated with fluorocarbon (Teflon) to reduce friction. The seal attachment plate must have slotted bolt holes to allow for field adjustment of the seals. Bottom seal is laid by direct contact between the skin plate edge and the sill plate. The lip of the radial gate should form a sharp edge, and the downstream side of the lip should be perpendicular to the sill. It is not recommended to use rubber seals on the gate bottom unless normal leakage cannot be tolerated. If the leakage is critical, a narrow rubber bar seal attached rigidly to the back side of the gate lip should be installed.

For submerged radial gate, top seals should be installed on the upstream of skin plate (Fig. 15.20). Since the side seals of submerged gate cannot be located on the upstream, therefore the J-type of square head rubber may be employed as side seals to obtain their good connection with the top seal (Fig. 15.19c).

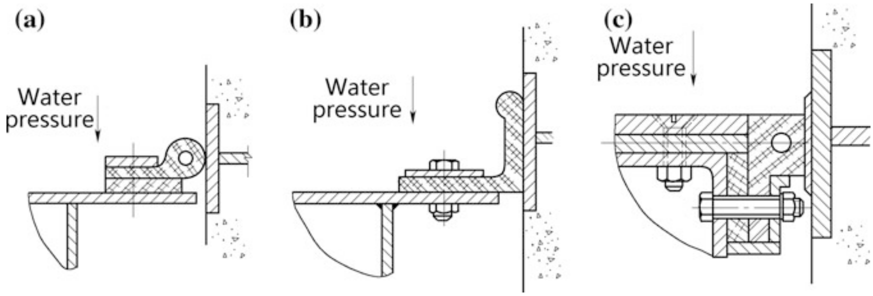

Fig. 15.19 Side seals of crest radial gate

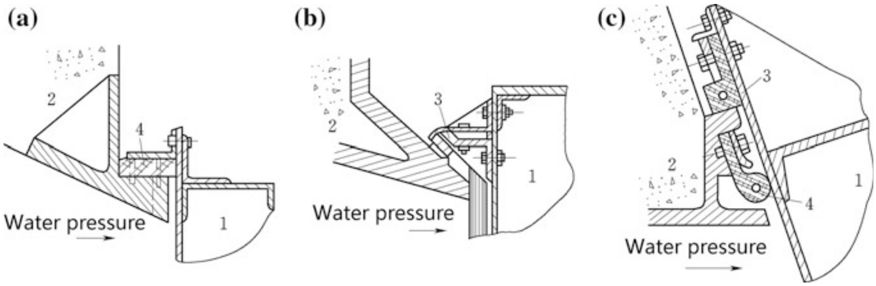

Fig. 15.20 Side seals of submerged radial gate. *1* gate leaf; *2* parapet wall; *3* seals for gate leaf; *4* seals for parapet

15.4.2 Raising and Lowering Efforts and Hoists

1. Computation of hoisting force

(a) Lowering effort F_W

$$F_W = \frac{1}{R_1}[1.2(T_{zd}r_0 + T_{zs}r_1) + P_t r_3 - 0.9Gr_2] \tag{15.3}$$

where T_{zd} = rotation resistance of trunnion hinges, kN; r_0 = radius of T_{zd}, m; T_{zs} = friction resistance of seals, kN; r_1 = radius of T_{zs} with respect to the rotation center of the gate, m; G_2 = gate weight of movable portion, kN; r_2 = radius of G_2 with respect to the rotation center of the gate, m; P_t = percolation force on lower seal, kN; r_3 = radius of P_t with respect to the rotation center of the gate, m; and R_1 = radius of lowering effort F_w with respect to the rotation center of the gate, m.

Where the calculated effort F_W is positive, gate lowering operation needs assisting.

(b) Hoisting effort F_Q

To raise a radial gate turning about its axis, it is necessary to apply a moment to overcome the moments of self weight and friction attributable to seals and support hinges. This condition can be expressed as

$$F_Q = \frac{1}{R_2}[1.2(T_{zd}r_0 + T_{zs}r_1) + P_t r_3 + 1.1Gr_2 + P_X r_4] \quad (15.4)$$

where P_X = downward suction force due to ingress, kN; r_4 = radius of P_X force with respect to the rotation center of the gate, m; and R_2 = radius of hoist effort F_Q with respect to the rotation center of the gate, m.

2. Hoists

Close coordination with mechanical engineer is necessitated to optimize the hoisting system. Rope-drum type (winch, chain-pulley block, monorail crane, gantry crane, etc.) may only be employed for the gate whose lowering operation does not need assisting, otherwise screw-operated type or hydraulic cylinder hoists are demanded. Many new gate designs utilize hydraulic cylinder hoist system, which generally possesses two cylinders located at each side of the gate. Each cylinder pivots on a trunnion mounted on the adjacent pier, and the piston rod is attached to the gate. The force magnitude and orientation of the cylinder will change continually throughout the range of motion. In determining the optimum cylinder position, the location of the cylinder trunnion and piston rod connection to the gate are closely related. Generally, the piston rod connection position is selected first, and then, the cylinder trunnion position is determined to minimize effects of lifting forces. For preliminary design, it is often assumed that the cylinder will be at a 45° inclination angle when the gate is closed, although optimization studies may indicate a slight adjustment. Generally, the most suitable location for the piston rod connection is on the gate end frame at or near the intersection of a bracing member and strut. It is preferable to have the piston rod connection above tail water elevations, but partial submergence may be acceptable for navigation structures.

15.5 Deep Gates

15.5.1 General

Deep gates are commonly installed at the intake or exit of tunnel, the orifice in concrete dam, and the lock culvert. Covering a similar sectional area, they are exposed to heavier loads and operated in flows of high velocities.

1. Classification of deep gates

There are different classifications depending on the criteria based.

According to the head exerted, deep gates may be classified into low (below 25 m), medium (25–50 m), high (50–80 m), and particular high-pressure (above 80 m) gates.

According to the installation position, deep gates may be distinguished as intake gate, middle position gate, and exit gate, of spillways.

According to the flow pattern after the gates, deep gates fall into those of pressure flow behind and of free flow behind.

According to the structure, deep gates may be in the form of plate and radial.

2. Hydraulic features of deep gates

With the orifice partially opened, the velocities below and downstream the gate may reach 40 m^3/s or even higher. Any alteration in the flow boundary induced by gate or walls of the conduit (e.g., gate slots) will bring about an abrupt change of pressure and the formation of eddies. These would give rise to pressure pulsation and oscillation exerted on the gate, and result in localized pressure drop immediately downstream, which may induce cavitation damage to the gate slots, gate leaf, embedded facilities, rod of hoist, etc., if the pressure drop is strong enough. Therefore, requirements for high-pressure gates on the manufacture workmanship and accuracy of assembly in situ are more rigorous than that for crest gates. This is especially significant for projects that operate at high heads with small gate openings, which should be carefully studied in the design of the slot position and shape, the concrete lining surrounding the gate chamber, and the gate itself as well.

15.5.2 Deep Plate Gates

Since it requires larger hoisting capacity, deep plate gate is conventionally employed as medium—to small gate in medium to lower head projects— and often plays the role of bulkhead gate which only operated in still water.

Similar to crest gates, deep plate gates ordinarily adopt a horizontal framing system, for higher structurally efficient and easer to accommodate roller guides.

Deep plate gates may be framed with plate girders as has been described in crest and navigation lock gates. The main difference in framing is that the former requires a inclined bottom or flat bottom with lip extension on the downstream side, to reduce down-pull forces while operating with water flowing (Fig. 15.21).

Hoisting effort greatly depends on the position of the sealing contour. If the sealing contour is arranged in the upstream plane, the vertical force components of atmospheric pressure exerting on the gate are in fact balanced. Whereas if the sealing contour is arranged in the downstream plane which is the common case, the gate is exposed, from top, to a downward force of the water thrust created in the shaft, and from bottom, to a vertical force of a water load whose direction depends on the extent of gate opening. Cautions should be exercised that a check should be made with the seal manufacturer before using a seal for a particular application. To allow for the seal to move toward the seal plate, the stem should be compressed only on the

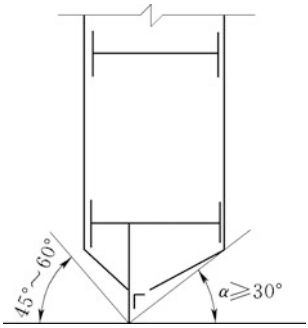

Fig. 15.21 Bottom edge of a deep plate gate

outer edge by the clamp bars. Observations of rubber seals indicate that the rubber could become extruded into the space between the clamp bar and the seal plate. To prevent this, brass-clad, or more recently fluorocarbon-clad with lower coefficient of friction (0.1) and greater flexibility and resiliency, may be employed. The lower coefficient of friction reduces the capacity of hoisting equipment. The bottom rubber seal is normally wedge-shaped that relies on the weight of the gate to provide the seal compression.

The majority of deep plate gates use slide support, which is advantageous in the reduction of cavitation and vibration. The wheeled versus slide gates need a smaller hoisting effort and are widely exercised in emergency-guard gates. The disadvantage of this type lies in the difficulty associated with protecting the wheel bosses and roller bearings against trash and liming. Where the principle hydrostatic load is considerably high, it is hardly possible to arrange wheels in numbers required by strength consideration. In this case, wheels are replaced by rollers joined by either a frame (roller supports) or a crawler belt (caterpillar supports). Control of gates with roller and caterpillar types of support demands smaller hoist efforts than with other types of support.

15.5.3 Deep Radial Gates

Radial gates are normally used as service (main) gates of large open size under high head. Their major advantage over plate gates lies in that they need considerably smaller hoisting capacities. In addition to a good flow boundary attributable to its arc gate skin, this type of gates does not necessarily need slots (grooves) and possesses support members protected against the direct actions of water and siltation. High structural stiffness reduces the vibration intensity of gate under the action of pulsating loads. The disadvantage of radial gate is a complicated design of supports whose cost is higher.

The curvature radius of deep radial gate skin is larger than that of crest one, whose proportion to the gate height may be the upper bound stipulated in the design codes, for reducing hoisting capacities and adapting the flow pattern. The framework and arms of a radial deep gate is in the form of a conventional two-cantilever portal, as shown in Fig. 15.17a. Where the pressure is high, more than two arms on each side may be installed, and they are welded and box-shaped in cross-section by bracings and ties between arms. Frameworks of either horizontal girders or vertical girders may be adopted depending on the shape of the conduit, and the latter is preferable for square or tall and narrow conduits.

Effective closing orifice of deep gate may be accomplished by reverse radial gate hinged on the upstream side. Such a gate, if incorporated at the end of a conduit, has its arms and hinges located outside, a feature which improves gate operational conditions. This type is widely applied in the ship lock culverts. By placing the trunnions upstream and with the convex surface of the skin plate facing downstream and by sealing against the downstream end of the valve well, air may be prevented from entering the culvert at the gate recess.

Sealing of high-pressure gates should be well guaranteed that:

- No leakage will manifest when the conduit is shut down;
- No contacts of sealing—slot member at the time of raising, with a view to reduce frictional force and, consequently, hoisting and lowering efforts;
- Protection of sealing elements against the actions of flow at the partial opening of gate.

Due to high pressure, the friction force attributable to rotation resistance of trunnion hinges and seals is considerably large. The gate is ordinarily cannot be lowered down only by its self weight, and an additional lowering force shall be exerted. Hydraulic cylinder hoists therefore are commonly equipped for the operation of deep radial gates. Mechanical hoists of screw-operated type, where the hoisting capacity is permitted small, also may be applied.

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