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# Research and Calculation on the Optimization of Hydraulic Lifting Mechanism for New Steel Gate

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**Abstract:** The steel gate based on the principle of hydraulic lifting mechanism has been widely used in urban water ecological construction, but the retaining height of this kind of gate is mostly 1-5m at present. With the development of water conservancy engineering and the deepening of the application research of steel gate, the retaining height gradually grows to 6-8m. However, at present, there are few researches on hydraulic lifting mechanism in the case of large retaining height. In this paper, Inventor is used to firstly establish three-dimensional visual entity models of the direct push type, Booster type and Maleli type hydraulic lifting mechanism. Then, the changing rules and relations among hydraulic cylinder diameter, stroke and stability safety factor of the three hydraulic lifting mechanisms are calculated and analyzed by changing the constraint conditions in the case of large retaining height (4m, 5m, 6m, 7m, 8m) and different opening and closing angles. It is aimed at providing a scientific basis for the optimization of hydraulic lifting mechanism of steel gate under the condition of large retaining height.

## 1. Introduction

Water gate is a very common low-head hydraulic structure in hydraulic engineering, which controls the flow and water level of the river channels, ditches and reservoirs by controlling the gate opening and plays an important role in irrigation, flood control and drainage, etc [1]. At present, the common steel gate includes lifting-tilting type gate, pneumatic shield gate, steel dam gate, hydraulic lifting dam and hydraulic elevator dam [2]. Among them, the gates of hydraulic lifting mechanism type, such as hydraulic elevator dam, hydraulic lifting dam, etc., mostly adopt the direct push type lifting mechanism, and the retaining height of this kind of gate under construction is mostly 1-5m. At present, the highest gate of this type under construction is only 6m, which is built on Nanyang River in Tianzhen County [3]. With the development of water conservancy engineering and the in-depth study of steel gate, the gate structure gradually transits from single water retaining function to multi-function development. In addition to optimizing the structure and key components to meet the traditional water retaining & draining and flood control functions of water gates, the diversification of water gates must be more closely combined with the construction of local humane water conservancy landscape. The retaining height gradually increases from the conventional water retaining height of 1-5 m to the larger retaining height of 6-8m.

At present, some research achievements have been made on the gate of the common hydraulic cylinder Direct-push lifting mechanism type which is suitable for the retaining height of 1-5m. For example, Chen Yeyin[4]et al. analyzed the working principle and structural state of 4m high hydraulic lifting dam, and used the three-dimensional finite element method of elastic mechanics to calculate the stress and deformation of the faceplate and support structure under different working conditions; Wang Xueyan[5]et al. made detailed description of structural principles of hydraulic dams, and conducted optimization design analysis on the structure of hydraulic dams. Zhou Jianfang[6]et al. established the limit state equation for the reliability analysis of hydraulic steel gate structure in normal use under the limit state, and adopted JC method to conduct calibration calculation and analysis on the reliability index of the limit state of hydraulic steel gate structure in normal use; Li Li[7]et al. established and verified the solution equation for the acting stress of hinge supports on the bottom plate of hydraulic dam, and then analyzed the stress characteristics of the hinge support on the gate floor of 2.0m,3.7m and 5.0m.

However, there is almost no research on the hydraulic lifting mechanism suitable for the large retention height of 6-8m. Only Yu Haojie[8] et al. explored the working characteristics of the support structure of the folding hydraulic dam during the lifting process, and analyzed the stress variation law under different closure angles of faceplate. This paper explores the other two types of hydraulic lifting mechanisms, namely Maleli type and Booster type, which are compared with the common Direct-push type hydraulic lifting mechanism. The three-dimensional visual entity model is established for the steel gate of these three types of lifting mechanisms by using Inventor, the variation rule and relationship among the hydraulic cylinder diameter, stroke and stability safety factor of the hydraulic cylinder are calculated under the condition of large retaining height (4m, 5m, 6m, 7m, 8m) in combination with its movement principle, and the applicable conditions of different hydraulic lifting mechanisms under different large retaining height are analyzed. Therefore, the lifting mechanism will be safer and more economical based on the premise that the stress condition, lifting space, hydraulic cylinder diameter, stroke and stability meet the design requirements and applicable conditions, so as to provide theoretical basis for the application of steel gate at a large retaining height.

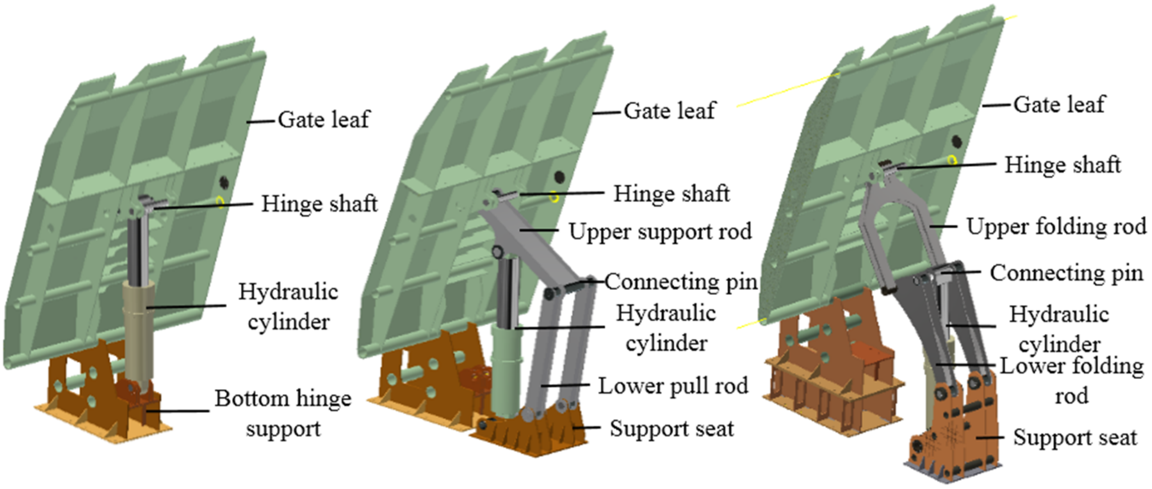
## 2. Establishment of three-dimensional model for hydraulic lifting mechanism

In this paper, Inventor is used to establish three-dimensional visual entity models for the steel gates of direct push, Maleli and Booster type hydraulic lifting mechanisms. The three types of hydraulic lifting mechanisms can realize the water retaining and draining at any gate opening and closing angle within 0-75°.

The Direct-push type hydraulic lifting mechanism consists of hydraulic cylinder, bottom hinge support, hinge shaft, etc. The hydraulic cylinder rotates and retracts to push the gate leaf directly, and the gate leaf rotates to be fixed around the bottom axis to realize the functions of "water retaining by lifting the gate and water draining by dropping the gate". The Direct-push lifting mechanism has simple structure, small angle direct pushing and supporting of hydraulic cylinder, which is not only safe and reliable, but also has certain landscape property [9];

The Maleli type lifting mechanism consists of hydraulic cylinder, upper support rod, lower pull rod, hinge shaft, connecting pin, bottom hinge support, support seat, etc. Among them, the upper support rod and the lower pull rod are hinged on the connecting pin, with the folding occurred at the connecting pin. The hydraulic cylinder retracts and rotates to push the upper folding rod to rotate and move, and the angle of the upper and lower folding rods changes to erect the gate for water retaining and drop the gate for water draining. Compared with the Direct-push type lifting mechanism, this type of lifting mechanism shortens the stroke of the hydraulic cylinder to a certain extent, and each support point is triangular structure with higher stability [10].

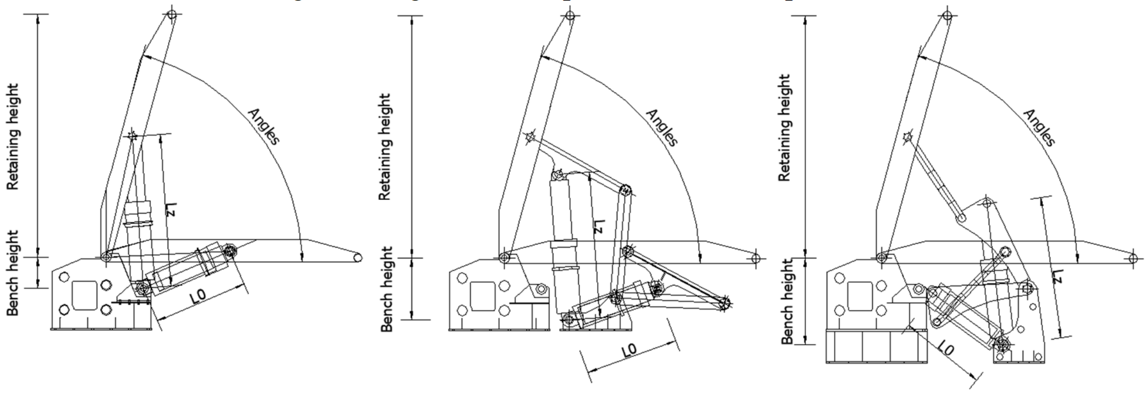
The Booster type lifting mechanism consists of hydraulic cylinder, upper folding rod, lower folding rod, connecting pin, hinge shaft, bottom hinge support, support seat, etc. Among them, the upper folding rod, the lower folding rod and the hydraulic cylinder are connected to the connecting shaft, with folding occurred at the connecting pin. The hydraulic cylinder extends and rotates to push the connecting pin, and the upper and lower folding rod rotates to generate the opening and closing stress which can fold and close up the jacking support rod, so that the gate will be erected for water retaining and the drop gate will be closed for water draining. Compared with the direct push type lifting mechanism, this type of lifting mechanism shortens the stroke of the hydraulic cylinder and saves the space after the folding rod is lowered [11]. The detailed structure of hydraulic lifting mechanism is shown in Fig. 1.



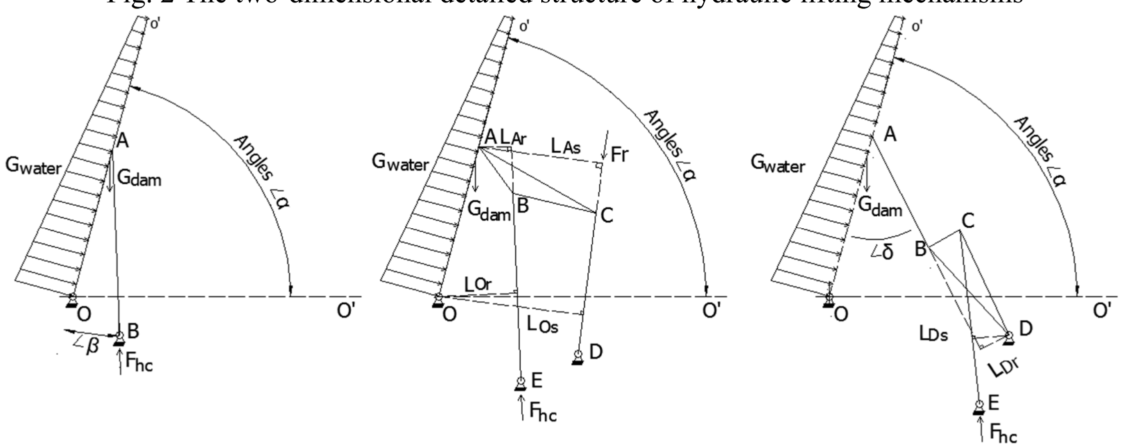

(a)Direct-push type (b)Maleli type (c)Booster type
Fig.1 The three-dimensional detailed structure of hydraulic lifting mechanisms

## 3. Selection of calculation model and parameters

The two-dimensional detailed structure and calculation of the three types of hydraulic lifting mechanisms are shown in Fig.2 and Fig.3, and the specific calculation parameters are shown in Table 1.




(a)Direct-push type (b)Maleli type (c)Booster type
Fig. 2 The two-dimensional detailed structure of hydraulic lifting mechanisms




(a)Direct-push type (b)Maleli type (c)Booster type
Fig.3 Calculation details of the three types of hydraulic lifting mechanisms

Table 1 Parameters of the three types of hydraulic lifting （unit：mm）

| | Retaining height | Bench height | 75° | 0° | stroke | Hydraulic cylinder lever diameter | Hydraulic cylinder inside diameter | Hydraulic cylinder outside diameter | Piston |
|---|---|---|---|---|---|---|---|---|---|
| | h | / | Lz | L0 | L | d | $D_2$ | $D_1$ | b |
| Direct-push type | 4m | 900 | 2886 | 1520 | 1366 | 220 | 250 | 299 | 100 |
| | 5m | 1100 | 3695 | 1902 | 1793 | 280 | 320 | 377 | 110 |
| | 6m | 1300 | 4388 | 2209 | 2179 | 320 | 380 | 460 | 130 |
| | 7m | 1500 | 4976 | 2529 | 2447 | 380 | 420 | 510 | 150 |
| | 8m | 1700 | 5762 | 2931 | 2831 | 420 | 460 | 560 | 180 |
| Maleli type | 4m | 900 | 2272 | 1227 | 1045 | 270 | 300 | 377 | 110 |
| | 5m | 1100 | 3119 | 1628 | 1491 | 350 | 400 | 500 | 150 |
| | 6m | 1300 | 3759 | 2045 | 1714 | 360 | 420 | 526 | 150 |
| | 7m | 1500 | 4164 | 2137 | 2027 | 420 | 500 | 620 | 180 |
| | 8m | 1500 | 4655 | 2404 | 2251 | 500 | 560 | 700 | 200 |
| Booster type | 4m | 1400 | 2265 | 1194 | 1071 | 300 | 380 | 480 | 130 |
| | 5m | 1500 | 2518 | 1337 | 1181 | 380 | 420 | 510 | 180 |
| | 6m | 1500 | 2736 | 1473 | 1263 | 460 | 530 | 660 | 200 |
| | 7m | 1600 | 3010 | 1565 | 1445 | 560 | 620 | 750 | 200 |
| | 8m | 1600 | 3480 | 1788 | 1692 | 650 | 750 | 850 | 220 |

## 4. Calculation formula

*4.1 Calculation of hydraulic cylinder diameter*

Simulate the engineering conditions, and when the gate is lodging, the dam surface is horizontal, that is, the opening and closing angle is 0 °; when the gate is erected, the dam surface has a certain tilt angle, that is, the opening and closing angle is 75°; when the working condition is that the superhigh overflow in front of the gate is 30cm and there is no water behind the gate, different opening and closing angles (0°, 15°, 30°, 45°, 60°, 75°) are selected to analyze the stress of the gate.

Calculation shall be made according to the dynamic water pressure when the opening and closing angle is 0°, 15° and 30°; calculation shall be made according to the hydrostatic pressure when the opening and closing angle is larger than 40°, 60° and 75°:

$$G_{dynamic} = 0.583\gamma ghbH \tag{1}$$

$$G_{hydrostatic} = \frac{\gamma g}{2}(h_1 + h_2)bH \tag{2}$$

$$e_{dynamic} = 0.5H \tag{3}$$

$$e_{hydrostatic} = \frac{H(2h_1+h_2)}{3(h_1+h_2)}; \tag{4}$$

For the Direct-push structure, the dam surface OO’ and the hydraulic cylinder AB are regarded as a balance stress system to establish the static equilibrium equation with the bending moment 0 at the point O, so that the stress acting on the hydraulic cylinder is derived as below:

$$F_{hc} = \frac{\mu(G_{water}\cdot e+0.5G_{dam}\cdot cos\alpha\cdot H)}{sin\,\beta\cdot OA} \tag{5}$$

For the Maleli structure, from the perspective of stress, firstly the upper support rod AC, the lower pull rod CD and the hydraulic cylinder BE are taken as a balance stress system, and there are only thrust stress of hydraulic cylinder and pull stress of lower pull rod in this system; the static equilibrium equation with the bending moment of 0 at point A is established to obtain the relationship between the thrust stress of hydraulic cylinder and pull stress of lower pull rod; then, the gate OO', the upper support

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rod AC, the lower pull rod CD and the hydraulic cylinder BE are taken as one balance stress system; in this system, the water pressure of gate, dead weight of gate, thrust stress of hydraulic cylinder and pull stress of lower pull rod are considered to establish the static equilibrium equation with bending moment of 0 at the point O, so that the stress formula of the hydraulic cylinder can be deduced as below:

$$F_{hc} = \frac{\mu \cdot L_{Ar} \cdot (G_{water} \cdot e + 0.5 G_{dam} \cdot cos\alpha \cdot H)}{(L_{Ar} L_{Os} - L_{Or} L_{As})} \tag{6}$$

For the Booster type lifting mechanism, the gate leaf OO' and upper folding bar are taken as a balance stress system from the point of view of stress. In this stress system, the water pressure of gate and dead weight of gate are considered to establish the static equilibrium equation with the bending moment of 0 at the point O, so as to obtain all thrust stress of the upper folding rod; then, the upper folding rod AB, lower folding rod BD and hydraulic cylinder CE are regarded as a balanced stress system on the whole; in this system, the stress acting on the upper folding rod, hydraulic cylinder and lower folding rod is considered to establish the static equilibrium equation with the bending moment of 0 at the point D, so that the stress formula of hydraulic cylinder can be deduced as below:

$$F_{hc} = \frac{\mu \cdot L_{Dr} (G_{water} \cdot e + 0.5 G_{dam} \cdot cos\alpha \cdot H)}{L_{Ds} \cdot sin\, \delta \cdot OA} \tag{7}$$

The stress diameter of the hydraulic rod of the hydraulic cylinder is calculated by the formula:

$$D = \sqrt{\frac{4F_{hc}}{\pi P}} \tag{8}$$

Where, $G_{water}$ is the water pressure on dam surface; $G_{dam}$ is the dam weight; $\mu$ is the safety factor, taking 1.2; $b$ is the length of dam surface supported by single hydraulic cylinder, taking 3m; $H$ is the length of dam surface; $h$ is the retaining height, taking 4m, 5m, 6m, 7m and 8m; $\gamma$ is the volume weight of water, taking 10$KN/m^3$; $g$ is the acceleration of gravity, taking 10$N/kg$; $h_1$ is the superhigh overflow, taking 30cm; $h_2$ is the vertical distance between dam surface bottom and water surface; $\alpha$ is the opening and closing angle; $\beta$ is the included angle between the hydraulic cylinder and the dam surface; $e$ is the distance between the center of water pressure and the bottom; $OA$ is the distance from the bottom shaft of the dam surface to the intersection between the lifting mechanism and the dam surface; $P$ is the working pressure, taking 16Mpa.

### *4.2 The stability and safety calculation of hydraulic cylinder*

Euler formula is used for calculation according to reference [12]

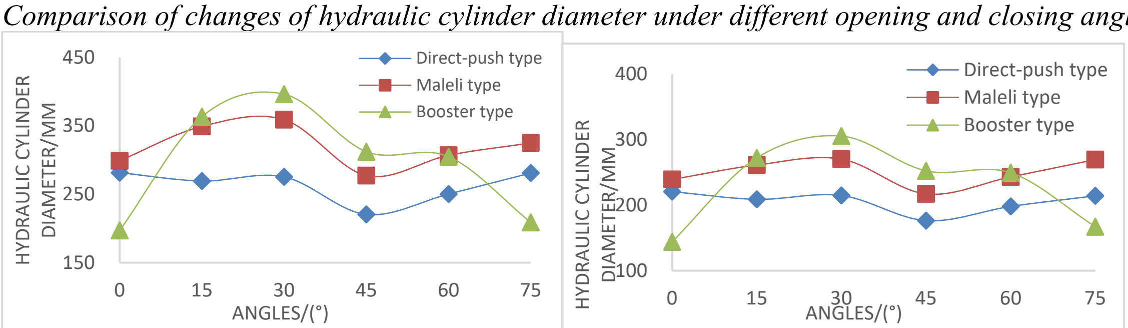
$$F_{cr} = \frac{\pi^2 E I_d}{(\mu_0 \mu L_z)^2} \tag{9}$$

$$k = \frac{F_{cr}}{F} \tag{10}$$

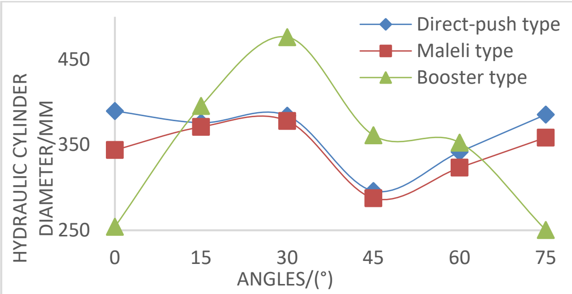
Where, $k$ - stability safety factor of hydraulic cylinder; $F_{cr}$ - critical pressure of hydraulic cylinder; $F$ - axial pressure of hydraulic cylinder; $E$ - longitudinal elastic modulus of piston rod material, taking 2.06×10^5Mpa; $I_d$ - sectional moment of inertia of piston rod, mm$^4$; $\mu_0$ - length reduction coefficient; $\mu$ - length coefficient, end hinge $\mu$ =1; $Lz$-fulcrum distance of piston rod in full stroke extension state, mm.

## 5. Result Analysis

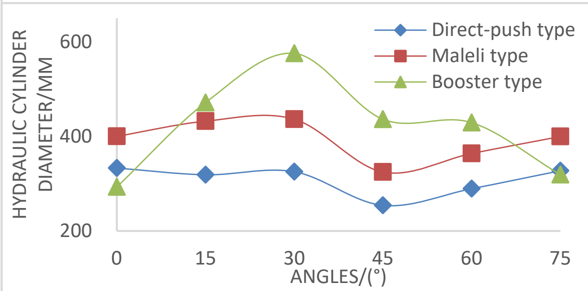
### *5.1 Comparison of changes of hydraulic cylinder diameter under different opening and closing angles*



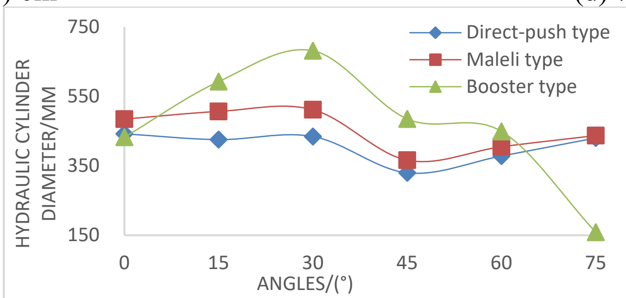

(a) 4m (b) 5m




(c) 6m




(d) 7m




(e) 8m

FIG.4 Variation curve of hydraulic cylinder diameter under different opening and closing angles

In order to analyze the stress of the hydraulic cylinder of three types of hydraulic lifting mechanisms under different opening and closing angles, several opening and closing angles (0°, 15°, 30°, 45°, 60° and 75°) are selected for calculation and analysis respectively. In the process of the gate opening and closing, the stress of the hydraulic cylinder is different with the change of the opening and closing angles under different stress conditions, and then the inverted hydraulic cylinder diameter reflects the stress of the hydraulic cylinder under this opening and closing angle.

As shown in Fig.4, the change process curve of the cylinder diameter value of the hydraulic cylinder with the opening and closing process of the gate is analyzed under different retaining heights (4m, 5m, 6m, 7m, 8m). It can be seen that the cylinder diameter of three types of hydraulic lifting mechanisms varies greatly with the change of opening and closing angle during the gate opening process.

When the Direct-push hydraulic lifting mechanism starts the pushing (namely, the opening and closing angle is 0°), the hydraulic cylinder suffers the largest stress. With the lifting of the gate, the stress of the hydraulic cylinder decreases gradually to an extent that the opening and closing angle for gate lifting is around 45°, and then the stress of hydraulic cylinder is gradually increased until the gate is fully lifted (namely, the opening and closing angle is 75°). When the gate is fully lifted, the stress on hydraulic cylinder is close to the stress condition when the pull is started. It can be seen that when the Direct-push type hydraulic lifting mechanism is pushed, the hydraulic cylinder suffers the maximum stress; when the opening and closing angle is 75°, its stress is also similar with that when the pull is started, but it is comparatively larger.

For the Maleli type lifting mechanism, the stress of hydraulic cylinder increases gradually in the range of 0-45° with the increase of the opening and closing angle, and also shows a growth trend in the range of 45-75°. It can be seen that the Maleli type lifting mechanism does not need a very large pull stress when the pull is started; the hydraulic cylinder suffers the largest stress when the opening and closing angle is 45°; when the gate is fully lifted (namely, the opening and closing angle is 75°), the stress is slightly smaller than 45°, but it is still relatively large.

For the Booster type lifting mechanism, the stress on the hydraulic cylinder is very small when the pull is started. With the increase of the opening and closing angle, the stress is gradually increased and reaches the maximum value when the opening and closing angle is about 45 °; then, the stress of the hydraulic cylinder gradually decreases, and it reaches the minimum value when the gate is fully lifted.

From this, it can be seen that the stress on the hydraulic cylinder is small when the structure is pulled and fully lifted.

*5.2 Comparison of diameter and stroke of hydraulic cylinder under different retaining heights*

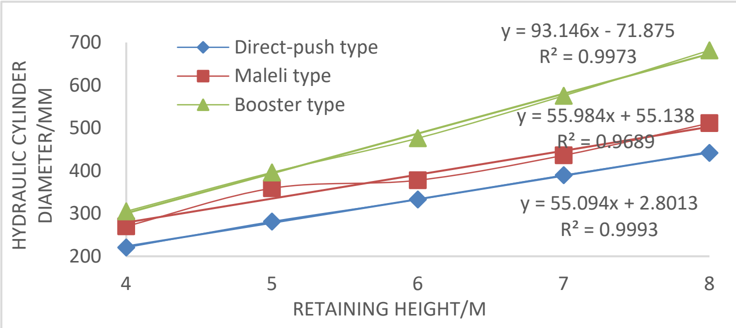



FIG.5 Variation curve of hydraulic cylinder diameter under different retaining height

According to the stress state of hydraulic cylinder, when the three types of hydraulic lifting mechanisms work at different opening and closing angles (0 °, 15°, 30°, 45°, 60° and 75°), the largest diameters of cylinder shall be selected as the cylinder diameter used for actual projects, and the hydraulic cylinder diameters are compared and analyzed at different retaining heights. The cylinder diameter of the three types of lifting mechanisms increases with the increase of the retaining height, and there is a linear relationship. The cylinder diameter of the direct push type lifting mechanism increases the slowest with the increase of the retaining height, and the cylinder diameter of the Booster type lifting mechanism increases the fastest with the increase of the retaining height. It shows that the diameter of the direct push type cylinder is smaller under the same larger retaining height, and with the increase of the retaining height, the cylinder diameter growth rate is slow, and there are certain advantages.

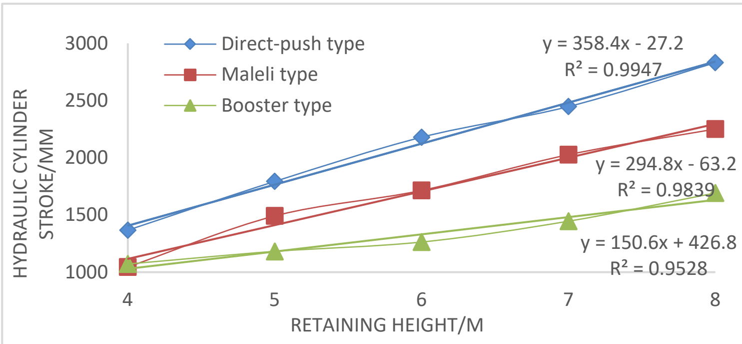



FIG.6 Variation curve of hydraulic cylinder stroke under different retaining height

The parameters reflecting the safety of hydraulic cylinder include not only the diameter of the hydraulic cylinder, but also the stroke of the hydraulic cylinder. Fig. 6 is a comparative analysis of the stroke of the hydraulic cylinder under different retaining heights. The stroke of the hydraulic cylinder of the three types of lifting mechanisms increases with the increase of the retaining height, and there is a certain linear relationship. The stroke of the hydraulic cylinder with the Direct-push lifting mechanism increases the fastest with the increase of the retaining height, and the diameter of the hydraulic cylinder with the booster lifting mechanism increases the slowest with the increase of the retaining height. It indicates that the stroke of the Booster type lifting mechanism is smaller under the same larger retaining height, and the stroke growth is slower with the increase of the retaining height, which has certain advantages.

*5.3 Comparison of the stability and safety of hydraulic cylinder under different retaining heights*

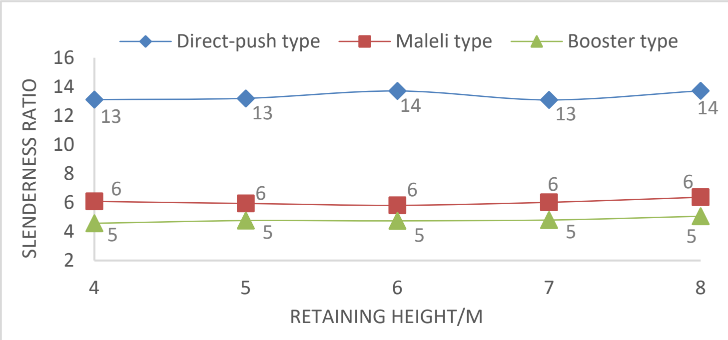



FIG.7 Variation curve of hydraulic cylinder slenderness ratio under different retaining height

During the lifting and lowering process of the gate, the hydraulic cylinder suffers the axial pressure as a whole, and the ratio between the fulcrum distance $L_z$ of piston rod in full stroke extension state and the diameter $d$ of the hydraulic rod is called the slenderness ratio [13]. When the slenderness ratio is greater than 10, there may be risks, and safety and stability calculation is required [13]. It can be seen from Fig.7 that the slenderness ratio of the direct push type lifting mechanism is in the range of 13-14, which has exceeded 10, and the safety and stability is poor, so it is necessary to check and calculate the safety and stability, while the slenderness ratio of the Booster type and Maleli type is in the range of 5-6, which indicates that the safety and stability is higher.

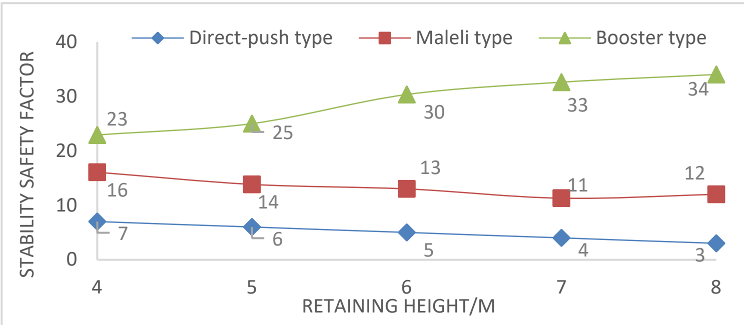



FIG.8 Variation curve of hydraulic cylinder stability safety factor under different retaining height

The ratio of axial pressure F and critical stress of hydraulic cylinder is the stability safety factor of hydraulic cylinder, and the coefficient shall not be less than 3.5 [13]. It can be seen from Fig.8 that the stability safety factors of the three hydraulic lifting mechanisms are all greater than 3.5, among which the booster lifting mechanism has the largest factor ranging from 23 to 34, while the stability safety factor of Maleli type lifting mechanism and Direct-push type lifting mechanism is within 11-16 and 3-7, respectively. However, this factor also changes greatly with the increase of retaining height. The stability safety factor of booster lifting mechanism increases with the increase of retaining height. The stability safety factor of Maleli lifting mechanism decreases slightly with the increase of retaining height, but it is still far greater than 3.5, showing a high safety. The stability safety factor of Direct-push lifting mechanism decreases greatly with the increase of retaining height; when the retaining height is 8 m, the factor has dropped to 3 which is less than 3.5, indicating that the Direct-push type hydraulic lifting mechanism can't be applied to the steel gate with the retaining height greater than 8m. It can be seen that the safety of booster lifting mechanism and Maleli lifting mechanism is high, while the Direct-push lifting mechanism is lower in safety and even unsafe.

## 6 Conclusion

(1) The hydraulic lifting mechanisms of direct push type, Maleli type and Booster type can realize the lifting and lowering of the gate, and hydraulic cylinder driving is adopted to generate power.

(2) In the process of gate lifting and lowering of the three types of hydraulic lifting mechanisms, the hydraulic cylinder bears different stress with the change of opening and closing angle. When the Direct-push lifting mechanism starts the push operation (namely, the opening and closing angle is 0°), the hydraulic cylinder bears the maximum stress, and then such stress decreases gradually. After opening and closing angle reaches 45°, the stress starts to increase again. When the gate is erected (namely, the opening and closing angle is 75°), the hydraulic cylinder bears a larger stress. When the opening and closing angle of the Maleli lifting mechanism is 45°, the hydraulic cylinder suffers the maximum stress, and the stress on the hydraulic cylinder has little change in the whole lifting process. When the booster lifting mechanism starts the push, the hydraulic cylinder bears very little stress. With the increase of the opening and closing angle, the stress on hydraulic cylinder increases gradually. When the opening and closing angle is 45°, it reaches the maximum, and then continues to decrease. When the gate is erected, the hydraulic cylinder suffers an extremely small stress.

(3) In view of the larger retaining height, it can be seen that the cylinder diameter of the direct push type hydraulic lifting mechanism is small, but the stroke is long; the cylinder diameter and stroke of the Maleli hydraulic lifting mechanism are in the middle; and the cylinder diameter of the booster hydraulic lifting mechanism is larger and the stroke is short.

(4) By analyzing the slenderness ratio of hydraulic cylinder and checking the stability safety factor, it can be concluded that the application of these three lifting mechanisms is feasible if the retaining height is less than 6m. However, for the retaining height above 6m, the Direct-push hydraulic lifting mechanism has a poor stability and safety, while the Booster type and Maleli type hydraulic lifting mechanisms have a good stability and safety.

(5) This paper only involves the analysis of the diameter, stroke and stability safety factor of hydraulic cylinder in three types of hydraulic lifting mechanisms. On this basis, finite element analysis such as ANSYS should be carried out for the three types of hydraulic lifting mechanisms to ensure the comprehensiveness of theoretical calculation.

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