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Original scientific paper

Structural Design of Pressure Pipeline Wedge-Shaped Concrete Piers

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Abstract: This paper proposed a wedge concrete fixed pier device based on self-locking to solve the problems existing in the fixed pier of water supply pipeline in utility tunnels. The system converted the horizontal thrust, originally applied to the weld seam in the pipeline, into oblique downward pressure by bending the pipeline upward. When the pipeline was bent upward at an angle equal to twice the horizontal angle of the wedge concrete fixed pier, then the fixed pier achieved the variable pressure-bearing effect in the horizontal direction through the self-locking between the concrete pier and the bottom plate of the utility tunnels. In addition, this avoided the damage to the fixed pier device, caused by the instantaneous pipeline internal pressure exceeding the maximum bearing thrust of the weld seam. The wedge fixed pier could be poured twice when the pipeline entered the utility tunnels, saving the rework cost of pouring the concrete again due to the changes of the design positioning of the water supply pipeline. As long as the area of the built-in steel fittings in the wedge concrete exceeded a certain range, the wedge concrete pier would not be crushed.

Keywords: pipeline bending; self-locking; variable pressure bearing; wedge concrete fixed pier

1 INTRODUCTION

The underground utility tunnels are structures and auxiliary facilities built under the city to accommodate two or more types of urban engineering pipelines, which is a multi-level network connection system composed of the main trunk utility tunnels, the branch utility tunnels and the cable utility tunnels. The utility tunnels include water supply, rainwater, sewage, reclaimed water, natural gas, heat, electricity, communication and other urban engineering pipelines [1-3]. China began to fully construct the utility tunnels since 2015. The *Government Work Report* in March 2016 determined "the construction of more than 2000 km of the underground utility tunnels". The construction of 4005 km of underground utility tunnels was finished in 147 cities and 28 counties across China by the end of 2020. In recent years, the utility tunnels construction still shows a rapid growth momentum, and has become one of the important contents of urban infrastructure construction in China. However, for structural design of the utility tunnels, most designers directly referred to the national standard collective drawings, and had little in-depth design on the detailed structures of the utility tunnels. In the past few decades, some researchers have focused on utility tunnels. Ministry of Housing and Urban-Rural Development of the People's Republic of China stipulated the general technical standards of the industry, refering to Technical guidelines for urban underground utility tunnels construction planning [4]. Zhou, et al. (2020) proposed a risk assessment method based on a Bayesian network (BN) and Dempster-Shafer (D-S) Evidence theory was developed to evaluate complicated sewer pipeline accidents in a utility tunnel [5]. Jiang, et al. (2020) studied the seismic response of underground utility tunnels: shaking table testing and FEM analysis [6]. Bai, et al. (2020) proposed the EPE model (Energy transfer theory-Preliminary hazard analysis-Evolution tree), to overcome the shortage of traditional hazard identifications and match the characteristics of UUTs [7]. Zhao, et al. (2022) conducted the quasi-static experimental and numerical studies to investigate the cross-sectional mechanical behavior of prefabricated multi-cabin utility tunnels for lifeline pipelines under the free-field racking deformation [8]. A detailed history of utility tunnels is summarized in the Chen, et al. (2010). Comparing with the conventional cast-in-place construction method, the prefabricated utility tunnel has many advantages, including cost reduction, better quality control, easier maintenance, less construction period, minimal noise and environmental pollution, and easier adjustment to the existing municipal pipeline system, hence minimizing the impact on urban traffic during construction [9]. In the actual design and construction, the time for the pipelines to enter the utility tunnels is uncertain, so the fixed bearing concrete pier and the built-in fitting at the bottom of the bearing may be poured again, resulting in a profound waste of resources; that is a problem in fixed bearing pier forms of water supply pipeline in the existing utility tunnels. And the maximum horizontal thrust in the pipeline may exceed the maximum bearable horizontal limit thrust instantaneously in extreme cases, resulting in damage to the pipeline weld seam and failing to meet the requirements of the structural design useful life. On the basis of summarizing the fixed pier forms of water supply pipeline in the existing utility tunnels, this paper deepened the design research of the fixed pier with "self-locking" as the basic principle [10] .

2 FIXED PIER FORMS OF WATER SUPPLY PIPELINE IN UTILITY TUNNELS

2.1 Fixed Pier Device of Water Supply Pipeline in the Existing Utility Tunnels

According to the analysis of pipelines entering the utility tunnels in the *Technical Guidelines for the Construction and Planning of Urban Underground Utility tunnels* [4], the water supply main trunk for water transmission and distribution should be incorporated into the utility tunnels as a priority in the special water supply planning and pipeline comprehensive planning. Located usually under the motor vehicle lanes or green belts, the main trunk utility tunnels mainly accommodates the main trunk pipelines of urban engineering and provides distribution service for the branch utility tunnels, instead of directly serving the plots on both sides [11]. The main trunk or branch utility tunnels mainly have rectangular and circular sections (Fig. 1), where the water supply pipeline is set at the bottom of the utility tunnels, supported by rectangular fixed piers.

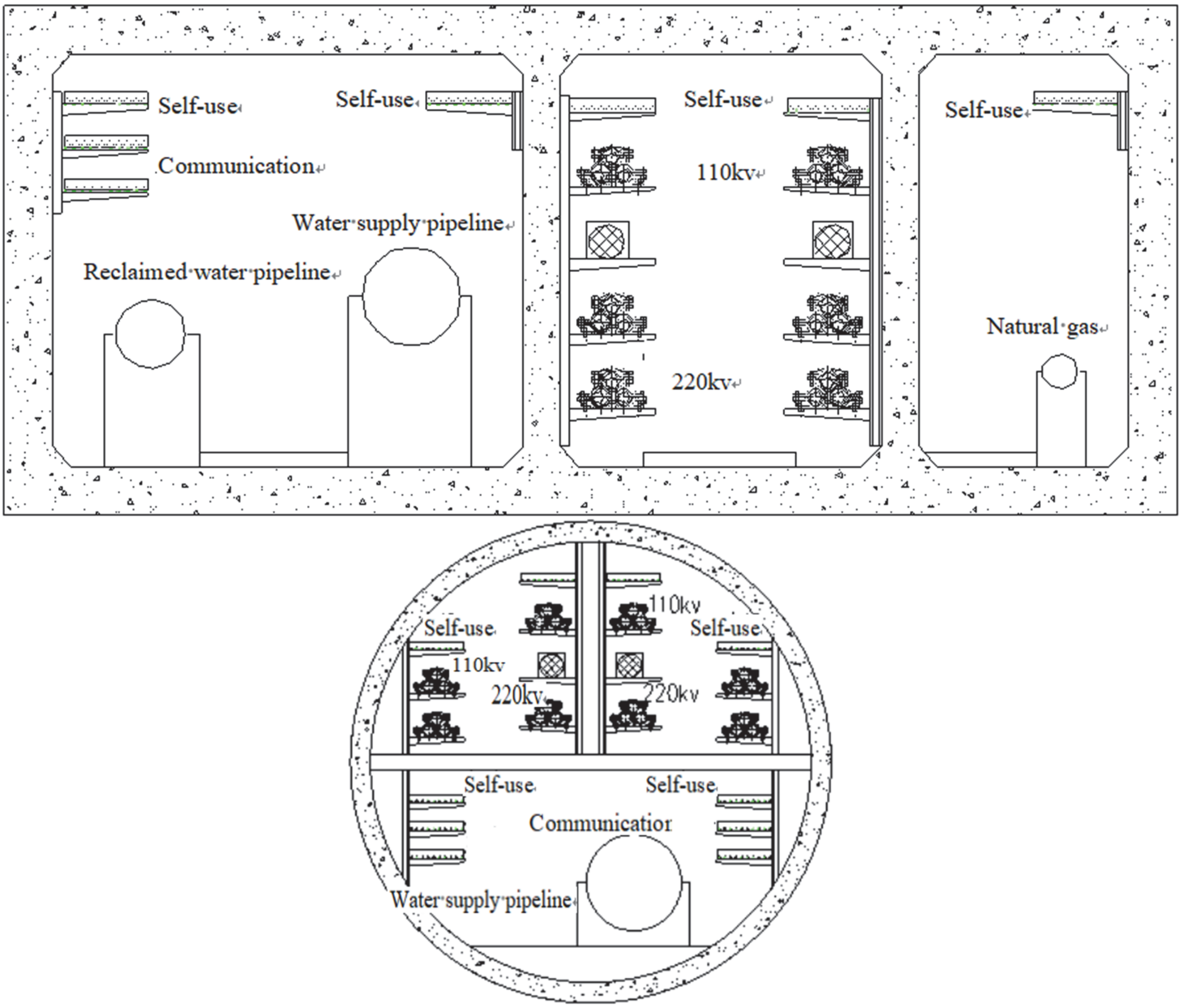

Figure 1 Section diagram of main trunk utility tunnels

There are mainly two forms of rectangular fixed pier device of water supply pipeline in the existing utility tunnels. The first is the steel pipe fixed bearing pier form in national building standard design collective drawings (17GL301). The fixed bearing pier mainly consists of two parts, the lower rectangular concrete fixed bearing pier (with built-in steel fitting in concrete) and the upper steel pipe fixed bearing (with steel pipe included in finished product) [12]. This steel pipe fixed bearing pier form has a wide application range. But the maximum horizontal thrust in the pipeline may exceed the maximum bearable horizontal limit thrust instantaneously in extreme cases, resulting in damage to the pipeline weld seam and failing to meet the requirements of the structural design useful life.

The second is the reference of corporate collective drawings (Q/XPT001.1-2017), such as the arrangement of steel pier at the vertical upward elbow of ductile iron pipe in the collective drawings. The fixed pier mainly consists of two parts, the lower built-in fitting at the bottom of the bearing (built in the bottom plate of the utility tunnels) and the upper steel pier support structure system, which is composed of steel pier, rubber pad, ductile iron pipe and flat steel pipe clamp [13]. Utility tunnel ductile iron pipe steel piers are suitable for the design of flexible interface pipelines in utility tunnel, with nominal pipe diameter of DN200~1000, and are suitable for non-seismic fortification areas and areas with seismic fortification intensity less than or equal to 8 degrees.

2.2 Problems in Fixed Bearing Pier Forms of Water Supply Pipeline in the Existing Utility Tunnels

The above two fixed pier forms mainly have two problems:

(1) Both the fixed bearing concrete pier (including built-in steel fitting) and the built-in fitting at the bottom of the bearing in the corporate reference drawings need to be poured at the same time as the bottom plate of the utility tunnels. However, the time for the pipelines to enter the utility tunnels is uncertain, and the pipeline positions may be adjusted in the actual design and construction. In the later stage, either the fixed bearing concrete pier or the built-in steel fitting of the bottom plate in the utility tunnels may be poured again, resulting in a profound waste of resources;

(2) The civil engineering design of the utility tunnels adopts the limit state design method based on probability theory, and the useful life of its structural design is 100

years [4]. Let F be the maximum bearable horizontal limit thrust of both the steel pipe fixed bearing weld seam on the upper part of the fixed pier and the steel pier structure weld seam in the corporate drawings, which must be greater than or equal to the horizontal thrust P generated by the pipeline water supply. However, P, the maximum horizontal thrust in the pipeline, may exceed F instantaneously in extreme cases, resulting in damage to the pipeline weld seam and failing to meet the requirements of the structural design useful life.

In view of the problems of the fixed pier in the existing water supply pipeline, this paper did an in-depth design research and proposed a wedge concrete fixed pier based on the principle of self-locking.

3 PRINCIPLE OF SELF-LOCKING

When an object and the contact surface are rough, once there is a trend of relative motion, it will be affected by the static friction ($0 \le f \le f_{\max}$), and also supported by the contact surface [10, 14]. Since the support and the friction always appear in pairs, their combined force is usually called "whole reaction force". If a force F is applied to an object in a direction that is at an angle α to the normal, the force can be divided into horizontal component $F_x = F\sin\alpha$ and vertical component $F_y = F\cos\alpha$ and $F_x = F_y \tan\alpha$ as shown in Fig. 2.

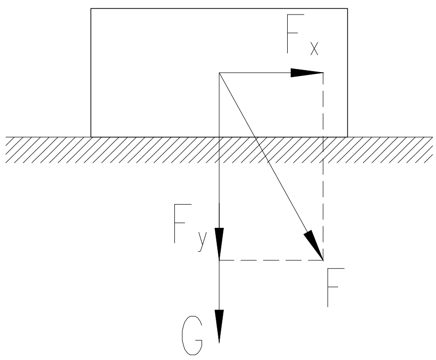

Figure 2 Diagram of the oblique downward force *F*

The pressure on the contact surface is $F_N = F_y + G$, where, G is the gravity of the object. When the static friction reaches the maximum value $\left(f_{\max} = \mu F_N\right)$, then α, the angle between F and the normal of the contact surface, is called the friction angle, which is also the maximum value of the angle between the whole reaction force and the normal, with the action line of the whole reaction force within the friction angle. At this time,

$$\tan\alpha = f_{\max} / F_N = \mu \tag{1}$$

$$\text{thus } f_{\max} = \mu F_N = F_N \tan\alpha > F_y \tan\alpha = F_x \tag{2}$$

Due to $F_N > F_y$, this formula shows that no matter how large F is, its component F_x is always less than the maximum static friction $f_{\max}$ That is, it cannot make the object slide relatively, which is the "self-locking" on the horizontal plane. When the angle between F and the normal is $\alpha' < \alpha$, then

$$F_x' = F\sin\alpha' < F\sin\alpha = F_x < f_{\max} \tag{3}$$

which means the self-locking still exists. According to the above self-locking, as long as the angle between the force F and the normal is less than or equal to the friction angle α, no matter how large F is, the component force in the horizontal direction F_x is always less than the friction between the object and the contact surface. That is, the relative sliding between the object and the contact surface does not occur.

4 STRUCTURAL DESIGN OF LOCKING WEDGE CONCRETE FIXED PIER

Based on the self-locking, design of the wedge concrete fixed pier structure system was composed of two parts, the lower wedge concrete pier and the upper steel pipe fixed bearing support device (with steel pipe included in the finished product), as shown in Fig. 3.

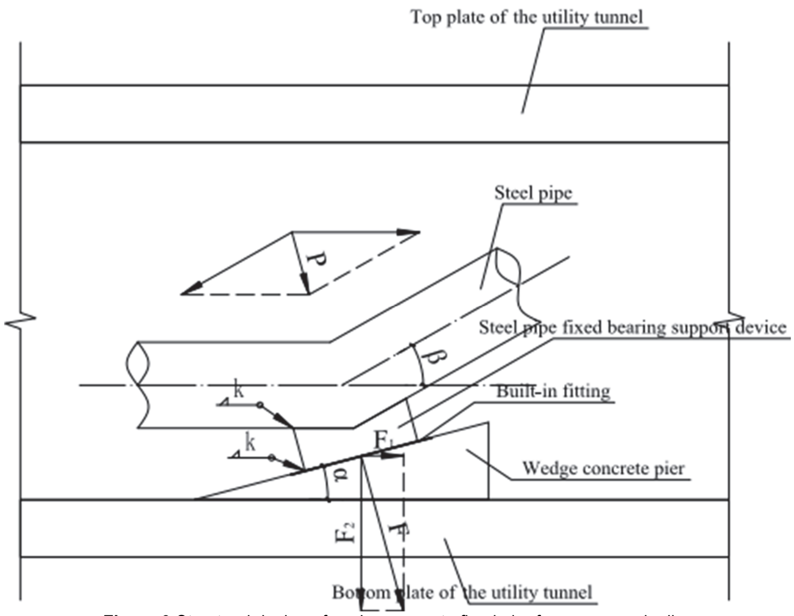

Figure 3 Structural design of wedge concrete fixed pier for pressure pipeline

The basic principle of the wedge fixed pier was explained as follows:

(1) Let the horizontal angle of the wedge concrete pier be equal to α (friction angle) and F be the pressure perpendicular to the concrete slope. When F's horizontal component $F_1 = F\sin\alpha = F_2 \tan\alpha$ and F's vertical component $F_2 = F\cos\alpha$ (Fig. 3), then the combined vertical pressure of the pipeline fixed pier on the bottom plate of the utility tunnels was $F_N = F_2 + mG$, where G is the gravity of the wedge concrete fixed pier system, m is the gravity adjustment coefficient according to the pressure change in the pipeline. According to the self-locki. $n = f_{\max} / F_N = \mu$, where μ is the friction coefficient between the wedge concrete pier and the bottom plate of the utility tunnels, then the maximum static friction bween the wedge concrete fixed pier and the bottom plate was

$$f_{\max} = \mu F_N = F_N \tan\alpha \geq F_2 \tan\alpha = F_1 \tag{4}$$

(See the formula derivation process in the above self-locking principle, due to $F_N > F_2$). At this time, no matter how large the pressure F was, its horizontal component F_1 was always less than the maximum static friction $f_{\max}$. In addition, when the horizontal angle of the wedge concrete pier was less than α, the self-locking still existed. That is, when the horizontal angle of the wedge concrete pier was less than or equal to α. (the friction angle), no matter how large F. was, its horizontal component F_1 was always less than the maximum static friction $f_{\max}$, then the wedge concrete pier and the bottom plate of the utility tunnels did not slide relatively on the horizontal plane.

(2) Let β be the angle at which the pipeline was bent upward, and $P_1 = P_2$ be the pressure from two directions in the pipeline (Fig. 4), then the resultant force of the pressure of the water supply in the pipeline on the fixed pier system was $P = 2 \times \frac{\pi dn^2}{4} F_{wd \cdot k} \times \cos\frac{\beta}{2}$, where P. is the resultant force of the downward thrust of the vertical upward elbow, dn is the pipeline diameter, $F_{wd \cdot k}$ is the standard value of the pipeline internal water pressure during the pipeline operation, and β is the angle of the pipeline elbow [4]. If the direction of P was perpendicular to the wedge concrete slope, that is, P and F had the same magnitude and direction, then $\beta = 2\alpha$ was required, where α is the horizontal angle of wedge concrete pier, which was less than or equal to the friction angle. The specific derivation process is shown as follows (Fig. 4).

Let P_1 be the line segment OA and P_2 be the line segment OB, due to $P_1 = P_2$, then the direction of the resultant force P of P_1 and P_2 was perpendicular to AB. That is, $OM \perp AB$ (the diamond diagonals were perpendicular and bisected to each other and each group of opposite angles was bisected).

If P and F had the same direction, then P was perpendicular to CD, the wedge concrete pier slop. That is, $OM \perp CD$. Thus, $CD // AB$.

Let $A'B'$ be the straight line passing through the point M and parallel to AB, then $OM \perp A'B'$ and $\angle 1 = \angle 2$ (the diamond diagonals were perpendicular and bisected to each other and each group of opposite angles was bisected).

Due to $\angle 1 = \angle 3$, thus, $\angle 2 = \angle 3 = \beta / 2$.

The two sides of $\angle 3$. were parallel to that of $\angle\alpha$, thus, $\angle\alpha = \angle 3$ and $\angle\alpha = \beta / 2$, that is $\beta = 2\alpha$.

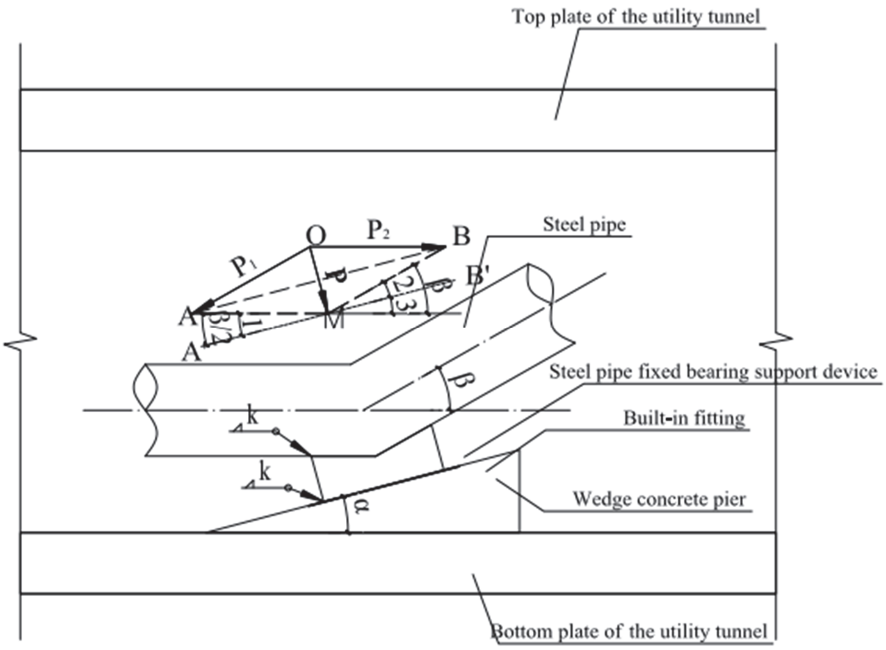

Figure 4 Relationship between α (the horizontal angle of wedge concrete pier of pressure pipeline) and β (the upward bending angle of steel pipe)

According to the above principle, if β, the upward pipeline bending angle, was equal to 2α (with α as the horizontal angle of wedge concrete pier, which was less than or equal to the friction angle), then the direction of the resultant force P of the water supply pressure P_1 and P_2 in the pipeline was perpendicular to the slope. The resultant force P was transmitted to the wedge concrete pier through the steel pipe fixed support system, and then to the bottom plate of the utility tunnels. P, the pressure borne by the wedge concrete fixed pier system (with P and F having the same magnitude and direction, which was obtained from the above derivation process) was divided into F_1 and F_2, the horizontal and vertical force, respectively (Fig. 3). When the horizontal angle of wedge concrete pier was less than or equal to the friction angle α, the self-locking occurred in the wedge concrete pier and the bottom plate of the utility tunnels in the horizontal direction. At this time, no matter how large the pressure in the pipeline P was, its horizontal component was always less than the maximum value of static friction $f_{\max}$, which did not cause any horizontal sliding damage to the fixed pier system, thus realizing the variable pressure-bearing effect of the fixed pier in the horizontal direction. However, if the pressure born by the wedge concrete fixed pier was

$$P > F_{\max}\left(F_{\max} = f_{cc} \times A\right) \tag{5}$$

where, $F_{\max}$ is the concrete failure load , f_{cc} is the axial compressive strength design value of plain concrete and A is the pressure-bearing area [15-18], then the concrete was crushed.

5 DATA VALIDATION

According to research, under certain working conditions, the concrete friction coefficient is mostly between 0.55 and 0.75 in dry state, and mostly between 0.50 and 0.70 in wet state. The statistical results of the measured data showed that the lowest limit friction coefficient is 0.50 and the highest limit friction coefficient is 0.75 in the dry and wet state, respectively, that is $0.5 \le \mu \le 0.75$. Due to $\tan\alpha = \mu$, the wedge concrete friction angle was $26° < \alpha < 37°$, then the upward bending angle of the pipeline was $52° < \beta = 2\alpha < 74°$ [19].

The resultant force of the pressure of water supply in the pipeline on the fixed pier system was

$$P = 2 \times \frac{\pi d n^2}{4} F_{wd \cdot k} \times \cos\frac{\beta}{2} \tag{6}$$

The diameter of water supply pipeline, commonly used in the utility tunnels, is usually less than or equal to 1 m, and the internal water pressure standard value in the pipeline during the steel pipeline operation is usually less than 0.9 MPa [18], then $P < 2 \times \frac{3.14 \times 1^2}{4} \times 0.9 \times 10^6 \times 0.8988 = 1270$ (KN) ($52° < \beta = 2\alpha < 74°$). If the concrete grade of the wedge concrete pier was C35, then the concrete failure load $F_{\max} = f_{cc} \times A = 0.85 \times 16.7 \times A = 14.195 \times A$ [18]. If the concrete was not crushed, then $P < F_{\max} = f_{cc} \times A = 14.195 \times A$ should be met. Therefore, the contact area between the steel pipe support system and the wedge concrete pier $A > P / f_{cc} = 1270 \times 1000 \div 14.195 = 89468.12$ mm^2 ≈ $0.09\,\text{m}^2$. That is, the area of the built-in fitting of the upper steel pipe fixed bearing support device in the wedge concrete was greater than or equal to 0.09 m^2 (Fig. 3).

Data verification showed that the structural design of the wedge concrete fixed pier was feasible. In the application of utility tunnels engineering, combined with specific working conditions, the friction angle $\alpha = \tan^{-1}\mu$ could be determined by determining μ, which is the friction coefficient between wedge concrete and the bottom plate of utility tunnels, thus determining the upward bending angle of the pipeline $\beta = 2\alpha$. After determining the pipeline diameter according to the maximum water volume and flow requirements of the water supply pipeline, combined with the internal water pressure standard value in the pipeline, this paper calculated and determined the area of the built-in fitting in the wedge concrete pier was $A > P / f_{cc}$.

6 CONCLUSIONS

In conclusion, the wedge concrete fixed pier system converted the horizontal thrust, originally applied to the weld seam, into oblique downward pressure through the upward pipeline bending. When the relationship between α (with α less than or equal to the friction angle), which is the horizontal angle of the wedge concrete fixed pier, and β, which is the angle of upward pipeline bending, was $\beta = 2\alpha$, then the wedge fixed pier device, through the self-locking of the concrete pier and the bottom plate of the utility tunnels. The grade range of concrete fixed piers commonly used in utility tunnel is C30-C40. So when the level of the wedge-shaped concrete fixed pier is C30, the area of the built-in fitting of the upper steel pipe fixed bearing support device in the wedge concrete was greater than or equal to 1.04 m^2, and when the level of the wedge-shaped concrete fixed pier is C35, the area was greater than or equal to 0.09 m^2, and when the level of the wedge-shaped concrete fixed pier is C40, the area was greater than or equal to 0.08 m^2, the wedge concrete pier would not be crushed. The wedge concrete fixed piers can be widely used in steel pipe support in utility tunnel. It solved the problem of the fixed pier being damaged due to the instantaneous pipeline internal pressure exceeding the maximum limit pressure limit. In addition, the wedge fixed pier could be poured twice when the pipeline entered the utility tunnels, saving the rework cost of re-pouring concrete due to the design positioning changes of the water supply pipeline entering the tunnels.

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