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Study on the Probabilities of Vessel-Bridge Collision Considering the Influence of Existing Structures

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Study on the Probabilities of Vessel-Bridge Collision Considering the Influence of Existing Structures

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Abstract. In order to take the protection provided by existing structures into account, Protection Factor was introduced to revise the method for calculating collision probability in the Guide Specification for Vessel Collision Design of River-Crossing Bridges in Three Gorges Reservoir of Chongqing City. This revised method was utilized to calculate the annual frequency of collision and collapse of Urban Rail Transit Egongyan Bridge at present, in the short term and long term, considering the influence of the relative location of nearby existing bridge with the same span layout. The results indicate that when the existing bridge is assumed to be located upstream, the annual frequency of collision and collapse both decreases significantly. The revised method presented in this paper offers a reference for probability analysis of vessel collision for bridges protected by existing structures nearby.

1. Introduction

Recently with the rise of China's national economic level, land and water transportation has been developing rapidly. According to statistics, by the end of 2017 the number of highway bridges has already exceeded 800 thousand. The number of bridges crossing the Yangtze River downstream from the City of Yibing, including those open to traffic and under construction, has reached 135. Meanwhile, the navigation capacity of inland waterways such as the Yangtze River Golden Waterway in China has been improved significantly. The density of water transport and ship tonnage has also increased substantially. Those two factors combined lead to more and more frequent occurrence of vessel-bridge-collision accidents which could result in vessel damage and bridge collapse. Given the important role of bridges in facilitating smooth transportation and regional economic linkage, a severe vessel-bridge-collision accident could cause extremely bad social impact. Therefore, it is imperative to evaluate the safety of bridges against vessel collision [1].

When assessing the safety of bridges against vessel collision, factors including the influence of existing structures nearby, navigation environment, tonnage of typical vessel and etc. should be taken into account. If there exists a parallel bridge or wharf structure near the bridge under consideration, vessels from a certain direction might be block. Thus, protection of the bridge against vessel collision might be provided to some extent. This paper studies the influence of existing parallel bridge piers on the probabilities of vessel-bridge collision based on the project of Urban Rail Transit Egongyan Bridge.

The Urban Rail Transit Egongyan Bridge which is currently under construction is the key project of Chongqing rail transit loop line [2]. It is located 45 meters upstream from the existing Egongyan Bridge （figure 1）. The same span layout is arranged among these two bridges to ensure visual unity. The Urban Rail Transit Egongyan Bridge is a self-anchored suspension bridge with a main span of 600 m in length supported by two towers[3]（figure 2）.

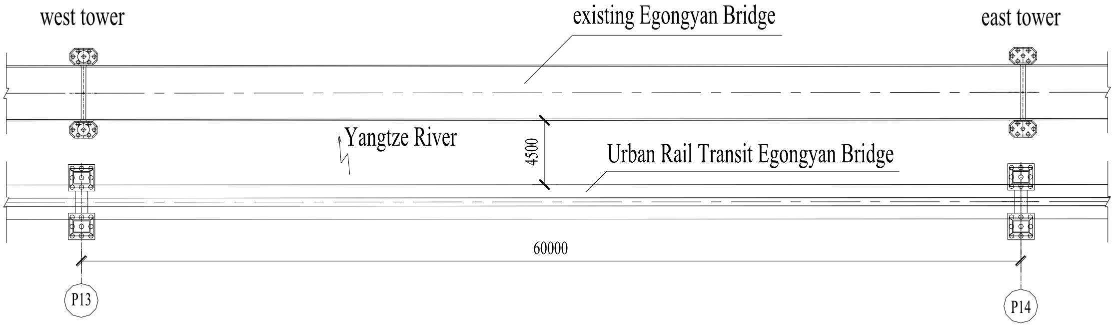

Figure 1. Plan view of Urban Rail Transit Egongyan Bridge and the existing parallel Egongyan Bridge

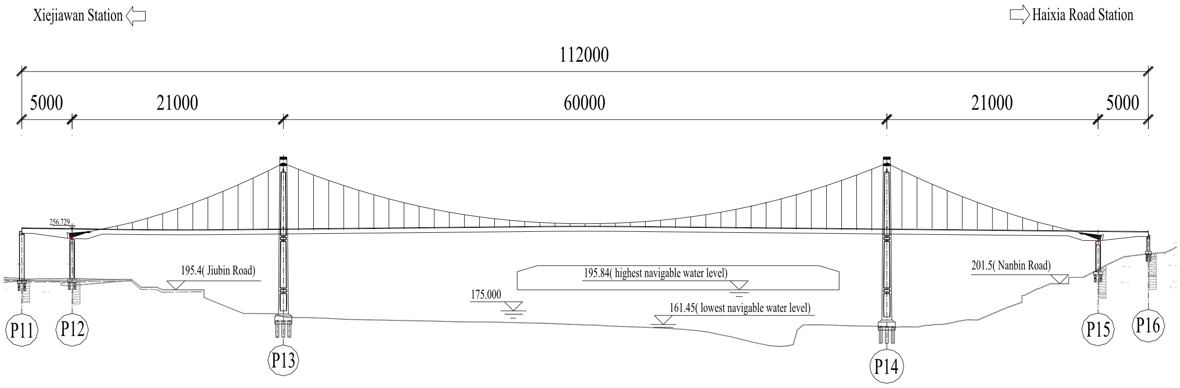

Figure 2. Span arrangement of Urban Rail Transit Egongyan Bridge

These towers are portal-framed structures consisting of two columns with a reinforced concrete box cross-section. Made of flat steel box, the main girder is 4.5m deep along this centerline. Each tower foundation comprises a dumbbell-type pile cap and a group of 9 bored piles, each 3.0m in diameter.

The design highest and lowest navigable water levels are 195.84m and 161.45m (1985 National Height Datum), respectively. The Urban Rail Transit Egongyan Bridge crosses the Yangtze River at the Sanjiaoqi Waterway which is Grade Ⅰ waterway. Located within the fluctuating backwater region of the Three Gorges Reservoir, the water level and flow pattern vary significantly throughout the year [1].

2. Method for analysing the probability of vessel-bridge collision

The probability of vessel-bridge collision for Urban Rail Transit Egongyan Bridge has already been analyzed [4] utilizing the method of Guide Specification for Vessel Collision Design of River-Crossing Bridges in Three Gorges Reservoir of Chongqing City [5]. Factors including flow velocity, typical water levels, the density of water transport, velocity of vessel, dimensions of navigation clearance, vessel transit path, ultimate bridge element strength and etc. were taken into account. The annual frequency of collapse was also calculated and compared to the acceptance criteria for critical bridges.

However, the influence of existing parallel Egongyan Bridge on the probability of vessel collision for Urban Rail Transit Egongyan Bridge has not been considered. As shown in figure 1, located 45m downstream from the new bridge, the existing Egongyan Bridge provides protection by blocking vessels from hitting bridge piers in certain directions. This article introduces the concept of Protection Factors (PF) proposed by the Guide Specifications and Commentary for Vessel Collision Design of Highway Bridges[6] to account for the effectiveness of protection provided by existing structures nearby on a bridge pier. PF can be calculated as follows:

$$PF = 1 - (\% \text{ Protecion provided}/100) \tag{1}$$

As shown in figure 3, from the diameter of the existing structure, D, and the width of vessel, B, the effective diameter of the existing structure, D_E, can be calculated. Based on D_E and the distance between the existing structure and the pier, L, the protection angle, θ, can be computed. D_E and θ should be computed as:

$$D_E = D + 0.75B \tag{2}$$

$$\theta = \sin^{-1}\left(\frac{D_E}{2L}\right) \tag{3}$$

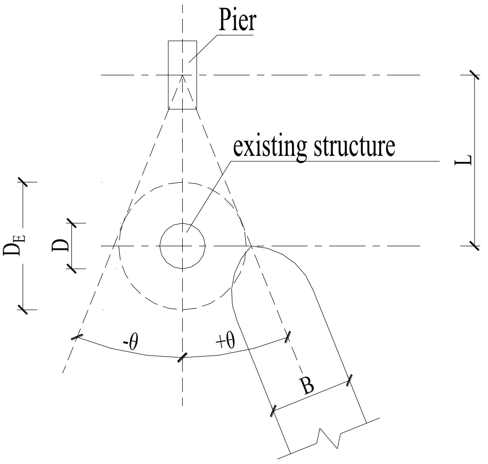

Figure 3. Plan view of protection.

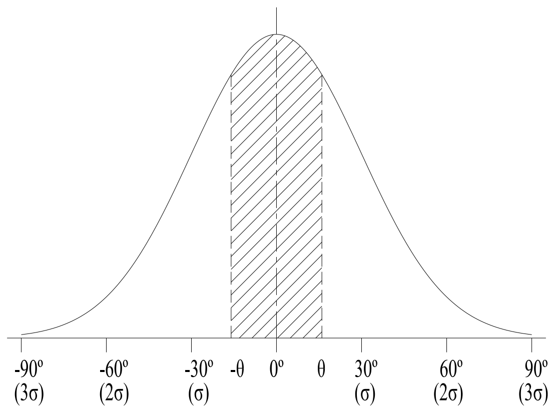

Figure 4. Model of the protection factor (PF).

The normal distribution with 0° as the median and 30° as the standard deviation is utilized to simulate the vessel collision trajectories around bridge pier, as shown in figure 4. The area of the density function between $-\theta$ and $+\theta$ is the protection provided. Thus, 1 minus the protection provided is PF.

With the model presented in figure 3 and figure 4 and the equations above, the value of PF_j corresponding to vessels of different tonnages can be used as a reduction factor of the annual frequency of collision. Thus, PF_j is utilized to revise the collision probability method proposed by Guide Specification for Vessel Collision Design of River-Crossing Bridges in Three Gorges Reservoir of Chongqing City [5] as follows:

$$P_{wi} = \sum_{j=1}^{n} PF_j N_j \int_{\mu_x - 3\sigma_x}^{\mu_x + 3\sigma_x} f(x) \int_0^D \lambda(s)[1 - F(s)] \int_{\theta_1}^{\theta_2} f(\theta) \mathrm{d}\theta \mathrm{d}y \mathrm{d}x \tag{4}$$

Where, P_{wi}: annual collision frequency for a certain water depth;

N_j: annual number of vessels classified by tonnage;

$f(x)$: density function of the distribution of passing vessel transit paths;

$\lambda(x)$: probability of vessel aberrancy;

$F(x)$: probability that vessel stops before hitting a pier;

$f(\theta)$: density function of the distribution of aberrancy angle;

$W_1(s)$: probability of a transit path of a vessel hitting a pier;

$W_2(s)$: probability that an accident is not prevented;

μ_x: the mean of the distribution of the vessel transit path;

σ_x: the standard deviation of the distribution of the vessel transit path.

Since the existing Egongyan Bridge is located downstream from the new bridge under construction, only the annual collision frequency corresponding to vessel traffic moving upstream should be reduced by PF_j. In order to further analyze the influence of the location of the existing structure relative to bridge piers, the collision frequency assuming the existing bridge piers located upstream from the new bridge was also calculated as a comparison

Parameters including water depths, flow speed, velocity of vessel, annual number of vessels passing under the bridge, bridge element strength and etc. remain the same as that in the previous analyze [4].

3. Protection factor

As shown in figure 5, the distance between the tower columns of the existing bridge and the new bridge, L, is 30m. For the design vessel of collision of 19.2m in width (B), the protection angel θ equals 28°. The θ corresponding to vessels of other tonnages can be calculated similarly. Then with the normal distribution for the vessel collision trajectories around bridge pier, PF_j corresponding to vessels of different tonnages can be computed, as shown in table 1.

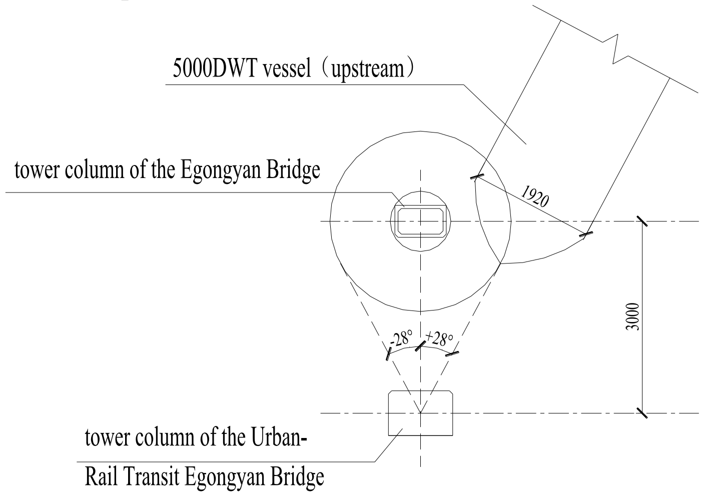

Figure 5. Protection angle provided by the existing Egongyan Bridge.

Table 1. Protection angle θ.

Vessels classified by tonnage	θ (°)	*PF*
>50t	14	0.6528
50T～200T	16	0.5824
200T～600T	19	0.5286
600T～1600T	23	0.4532
1600T～3000T	26	0.3954
3000T～5000T	28	0.3422
5000T～8000T	32	0.2892

As shown in table 1, as the size and tonnage of vessel increases, θ goes up while PF decreases.

4. Results of risk analysis

Utilizing the revised collision probability method proposed above, the risk of vessel collision for the Urban Rail Transit Egongyan Bridge corresponding to the vessel traffic density at present, in the short term and long term, forecasted based on statistics of water transportation in Chongqing [7], was analyzed. Both the actual and assumed relative positions of these two bridges were considered. The results are listed in table 2. The results without the consideration of PF is also listed as comparison.

As shown in table 2, with the influence of existing bridge downstream taken into account, the annual collision frequency in the long term for the new bridge would decrease from 1.18 to 0.958. The annual frequency of collapse would reach 4.09×10^{-4}, slightly lower than that without PF. Located downstream from the new bridges, the existing tower column of Egongyan Bridge can only block vessels moving upstream from a certain direction. However, the lower velocity of vessels moving upstream results in smaller collision impact force compared to the vessel moving downstream. For the given bridge element strength, smaller collision impact force leads to lower probability of collapse. Thus, protection provided downstream from the bridge pier under consideration has an insignificant influence on the annual collapse frequency.

Table 2. Comparison of results.

Time	Without PF[4]		With PF			
			Existing bridge downstream (actual position)		Existing bridge upstream (assumed position)	
	Annual collision frequency	Annual frequency of collapse	Annual collision frequency	Annual frequency of collapse	Annual collision frequency	Annual frequency of collapse
present	3.97×10^{-1}	4.58×10^{-5}	3.28×10^{-1}	4.55×10^{-5}	2.35×10^{-1}	1.44×10^{-5}
short term	6.52×10^{-1}	1.28×10^{-4}	5.35×10^{-1}	1.27×10^{-4}	3.81×10^{-1}	4.08×10^{-5}
long term	1.18	4.12×10^{-4}	9.58×10^{-1}	4.09×10^{-4}	6.73×10^{-1}	1.30×10^{-4}

However, when the existing bridge is assumed to be located upstream from the new bridge, both the annual collision and collapse frequency decreases significantly. The long-term annual collision frequency would go down to 0.673, a decrease of 41%. The long term annual frequency of collapse would come down to 1.3×10^{-4}, a decrease of 68%. Located upstream from the new bridges, the existing tower column could provide partial protection against collision from vessels moving downstream, instead. The relatively higher velocity of vessels moving downstream results in impact force of larger magnitude compared to the vessel moving upstream. For the given bridge element strength, larger collision impact force leads to higher probability of collapse. Thus, protection provided upstream from the bridge pier under consideration plays a much more effective role in mitigating vessel-bridge collision risk.

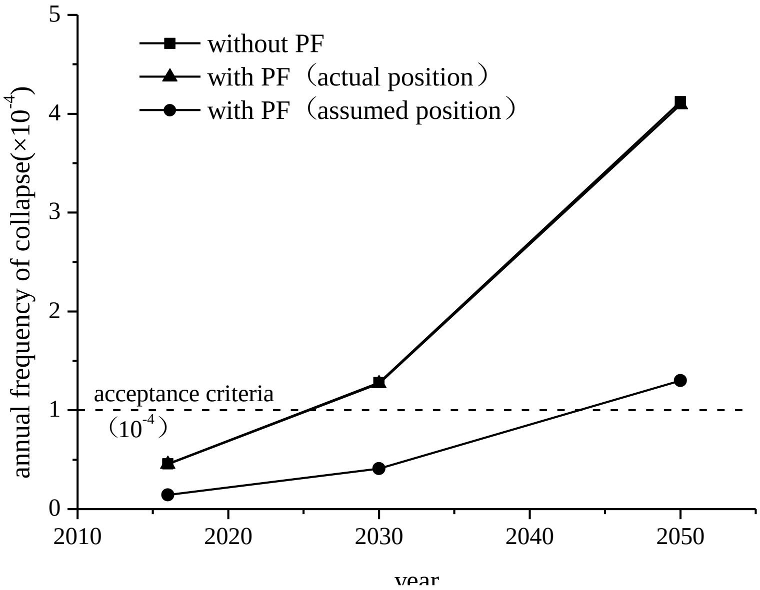

Figure 6. Variation of annual frequency of collapse with time.

The variation of annual frequency of collapse with time is shown in figure 6. According to relevant guides [5][6], the acceptable annual frequency of collapse shall be 10^{-4} for critical bridges. As shown in figure 6, the annual frequency of collapse would increase with time, as the number of vessels passing by rises. When PF is not taken into account, the annual frequency of collapse would reach 10^{-4} in 2026. When PF is utilized to account for the protection provided by the existing tower columns downstream, the annual frequency of collapse for the new bridge decreases slightly. When the existing tower columns is assumed to be located upstream, revised by PF the annual frequency of collapse for the new bridge goes down significantly. Moreover, the year when the acceptance criteria would be reached is delayed to roughly 2044.

5. Conclusions

According to the results presented above, it's necessary to take the influence of existing structures such as a parallel bridge, a wharf facility and etc. into consideration when assessing the vessel-bridge collision risk or validating the effectiveness of protection facilities. Otherwise, the annual frequency of collision and collapse can be significantly overestimated. The revised method with the concept of Protection Factor proposed here offers a reference for probability analysis of vessel collision for bridges protected by existing structures nearby. The following conclusions can be reached.

1. Utilizing the revised collision probability method proposed above, the annual collision frequency for the Urban Rail Transit Egongyan Bridge decreases by roughly 18% compared to that computed without PF. And the annual frequency of collapse goes down by only less than 1%.
2. When the existing tower columns is assumed to be located upstream, the annual collision frequency of collision and collapse for the new bridge decreases by about 41% and 68%, respectively.
3. When the existing structure is located upstream from the bridge under consideration, the protection against vessel collision is much more effective.
4. The protection angle increases with larger tonnage and size of vessel, while the value of PF decreases.

Acknowledgments

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