Study on the model to determine riverbed scour and the influence of bridge construction on riverbed deformation

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Abstract. River geomorphic features can dramatically change over time. It is undoubtedly the most dynamic geomorphic system that engineers have to manage in the design and maintenance of bridges. In the event of major floods, significant changes can take place within a short period of time. In contrast to rivers which are dynamic, bridges generally do not move except in accordance with planned structural deflections caused by anticipated static and dynamic loading. The stability and safety of bridges can be jeopardized in several ways as a result of riverbed channel changes, being the removal of bed material in the vicinity of bridge foundations (as a result of local scouring phenomenon) the most common cause of several bridge collapses worldwide. Due to the complex nature of the fluid flow, there are still many uncertainties that affect the design process of bridge piers. Therefore, different approaches have been used comprising empirical formulations, experimental studies, sophisticated numerical simulations, and, whenever possible, underwater survey activities as a manner of controlling the scouring process at bridge piers founded in alluvial/movable riverbeds. Therefore, the present study analyses the local scour phenomenon around the bridge piers of an intervened Vietnam bridge – Doanhung bridge, by using different monitoring inspection surveys over a period of time. Research results will clarify the influence of bridge piers' design and construction on movable beds, indicate future predictions to monitor and control the severity of the scouring process, and propose management measures for the safety of bridge infrastructures.

1 Introduction

The safety of bridge infrastructures depends on stable foundations (piers and abutments), which are often not visible underwater and are subject to high current velocities [1]. These currents can cause scouring near bridge foundations, which led to numerous bridge collapses worldwide with devastating consequences [2-5]. Over a 30-year period, more than 1,000 bridges collapsed in the United States, 60% of which were due to scouring at the bridge foundation [6]. In 2001, the 19th century Hintze Ribeiro bridge in Portugal collapsed, killing 59 people [9].

Research showed that most damage to bridges was caused by severe flooding or inadequate burial depth of the bridge foundation [5]. Since it is impossible to completely prevent or eliminate scour around bridge piers, the study of local scour phenomenon around bridge foundations is essential for establishing design and inspection procedures [5,7]. However, determining an accurate depth of local scoring can be challenging due to the many variables involved in the process.

The bridge pier design process is subject to many uncertainties due to the complex nature of fluid flow. To address these uncertainties, various approaches such as empirical formulations, experimental studies, sophisticated numerical simulations, and underwater investigations have been used to control scour processes in bridge piers founded in alluvial or moving riverbeds. Over the decades, several equations have been proposed to estimate equilibrium scour depth, and their predictive ability is relatively good, especially for structures with relatively simple geometry. In the work of Sturm et al. (2011) [8], two well-established equations are recommended for bridge design, namely the HEC-18 scour depth predictor [9] and the S/M equation [10]. However, bridge design often involves complex pier foundations, usually with a bottom pile on the top of a pile group, so that direct application of results derived from single piers is usually unreliable. In these cases, the computation of local scour may require adjustments, such as considering an equivalent diameter [7], to apply the methods of FDOT (Florida Department of Transportation) [11] and Yang et al. [12], both of which are applicable to both clear water and live bed scour conditions, as suggested by Bento et al. [7].

Therefore, the present study investigates the local scour phenomenon around the bridge piers of Doanhung Bridge in Vietnam by conducting various monitoring inspections over time. This study aims to clarify the effects of bridge pier design and construction on moving riverbeds, make future predictions for scour monitoring and control, and propose management measures to ensure bridge infrastructure safety by analyzing the performance of well-known empirical formulas for predicting the maximum potential scour depth near the case study of a bridge pier.

2 Riverbed Scour Evaluation

Local scour phenomenon can cause severe damage to the bridge foundation, resulting in bridge failure and loss of life and property. Therefore, a comprehensive scour analysis is critical to ensure the safety and longevity of the bridge infrastructure. In this sense, prudent design requires the estimation of a potential maximum scour depth, i.e., the deepest scour depth that can be reached at a given design flood. For decades, several equations have been proposed for estimating the maximum local scour depth, and their predictive ability is particularly useful for structures with relatively simple geometry. In this study, FDOT [11]'s and Yang et al. [12]'s equations were selected for predicting the scour depth near the two middle piers of the Doanhung Bridge in Vietnam due to their complex geometry, as suggested in Bento et al. [7].

The results will help to make future predictions for scour monitoring and evaluate the performance of the above empirical equations for the specific case study by comparing their results with the collected field data for three different times, specifically: (i) the 2005-2014 period, (ii) the 2014-2020 period, and (iii) the 2020-present period.

3 Doanhung bridge case study

3.1 Hydrographic region characterization

Doan Hung belongs to the northern midlands' region of Vietnam (**Fig. 1**). It is influenced by a hot and humid tropical monsoon climate with two distinct seasons. The rainy season is very rainy and intense, accounting for about 90% of the annual rainfall (**Fig. 2**)**.** It is sunny and sometimes there are local tornadoes and hail. The average total annual rainfall is about 1644 mm.

Fig. 1. A Map of the Doan Hung district and location of the Doan Hung bridge.

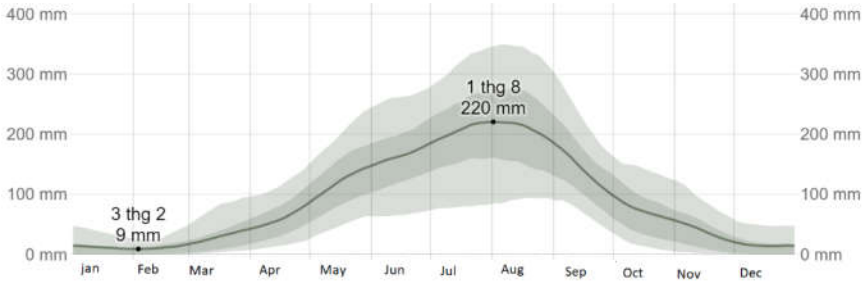

Fig. 2. Rainfall chart of Doanhung District.

Doanhung district has two major rivers: Chay river and Lo river. These two rivers have fast-flowing water, the combined rainy season causes large floods in the region. The Doanhung bridge is located near the confluence of the two rivers, so the hydrological conditions are very complicated.

3.2 Bridge characteristics

The Doanhung bridge (**Fig. 1**) is located in Doanhung District, Phutho Province, Vietnam. The bridge crosses the Chay River at km 111+300 of National Highway 2 and serves traffic on the route from Hanoi to Hagiang.

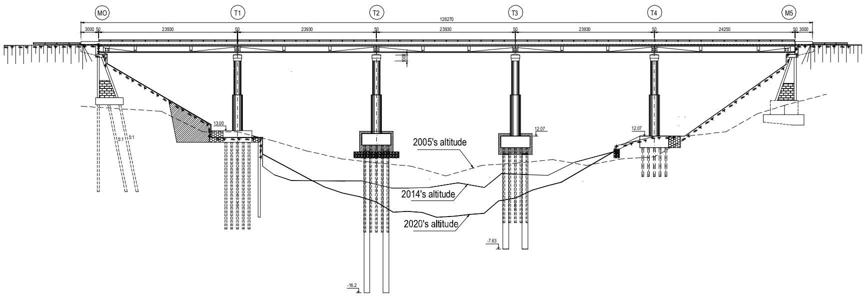

Fig. 3. General of the bridge and elevation of the natural riverbed over the years.

The bridge consists of 5 simple girders with a length of 24 m long, a total length of Ltc = 145.07 m and a bridge width B = 9.0 m. The bridge was built in 1984 with an allowable load of H13-X60. The foundation of the bridge is a rectangular pile foundation with 28 piles of size 30 x 30cm. The bridge has been strengthened and repaired several times. In 2004, the bridge was repaired and reinforced with girder span structure to increase the operating load to H30-XB80 (**Fig. 4**).

Fig. 4. Bridge foundations: from 1984-2013 (left); b. from 2014-2019 (middle); and c. 2020-current (right).

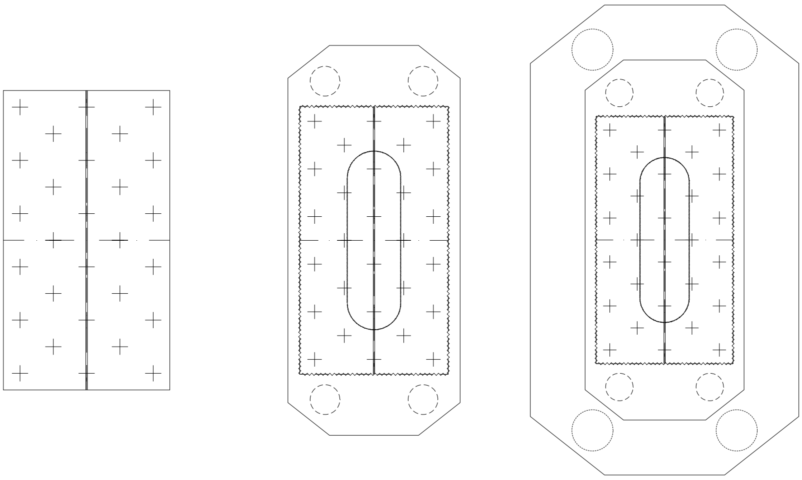

Fig. 5. Top view of foundation in T3: from 1984-2013 (left); b. from 2014-2019 (middle); and c. 2020-present (right).

In 2013, 4 additional bored piles with a diameter of D = 1.2 m were reinforced at the position of piers T2 and T3, increasing the size and thickness of piers T2 and T3. Due to the complex hydrodynamic conditions, the bridge in the middle of the riverbed has been severely undermined over the years. In 2020, four bored piles with a diameter of D = 1.5 m continued to be reinforced at the position of piers T2 and T3, enlarging the piers and increasing their thickness (**Fig. 4** and **Fig. 5**).

3.3 Results and discussion

The computed flow velocities varied between 2.96 ms-1 and 3.45 ms-1, even under subcritical regime conditions. Riverbed surveys, performed in the vicinity of the bridge under study, allowed the establishment of the median grain size (D50) of 2.65 mm. More particularities are given in the UCT report [13]. This information was also required for the evaluation of the total scour depth at pier T3.

In accordance with the Report in 2021 of University of Transport Communications Limited Company (UCT), the hydraulic conditions at the bridge section under study are given in Table 1 where *Q* is the flow discharge, *V* is the flow depth and *H* is the flow depth.

Table 1. Hydraulic conditions at Doanghung bridge.

Year	*Q* (m3/s)	*V* (m/s)	*H* (m)	D_{50} (mm)	Pile groups (D is the pile diameter)
2005	-	-	5.31	2.65	28 rectangular piles 35*35 cm
2014	2400.00	2.96	7.41		Add more 4 round piles D=1.2 m
2020	4467.23	3.45	12.45		Add more 4 round piles D = 1.5 m

Table 2 and **Fig. 6** presents the local scour estimates at pier T3, obtained through the two well-established equations, namely Yang et al. [12] and FDOT [11]. To evaluate the former's model performance, the two well-developed empirical formulas were compared against the field surveys performed at the different time periods.

Table 2. The results of scour depth calculation and monitoring at pier T3.

Period	Monitoring scour depth (m)	Yang et al. [12]'s method		FDOT [11]'s method	
		Local scour depth (m)	Difference (m)	Local scour depth (m)	Difference (m)
2005-2014	2.03	1.59	0.44	2.02	0.01
2014-2020	3.888	4.21	0.32	4.68	0.79

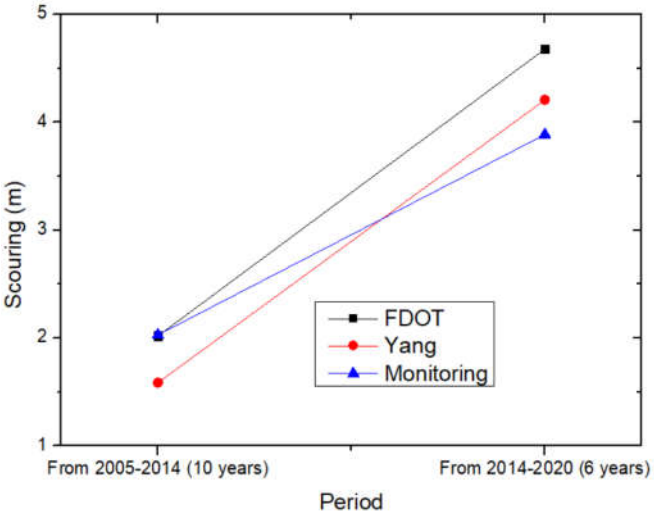

Fig. 6. Results of calculation and monitoring of scour at pier T3 in two periods 2005-2014 and 2014-2020.

In the first scenario, where a single pile type (rectangular pile 35cm*35cm) is used for the foundation of the T3 pier, the difference between monitoring and calculation by FDOT [11]'s method proves to be more effective than Yang et al. [12]'s method. The difference between FDOT [11]'s method and monitoring are only 0.01 m, while the difference between Yang et al. [12]'s method and monitoring is 0.44 m. However, when the scenario occurs that bored piles are added to strengthen the pier, Yang et al. [12]'s method estimates more accurately.

From the calculations using two different methods and the monitoring results, Yang et al. [12]'s method is more effective when mixed piles are used. During the period from 2020 to the present, 4 bored piles with a diameter of 1.5 m were installed on the T3 pier of Doan Hung Bridge. Using Yang et al. [12]'s method to estimate the future scour depth of the bridge at T3 pier can provide the results are shown in **Fig. 7**.

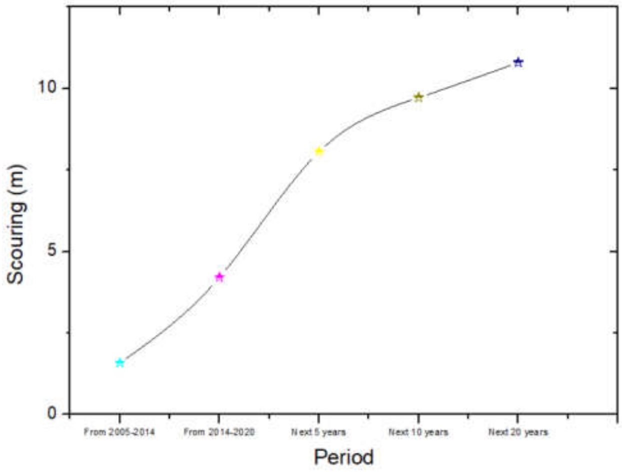

Fig. 7. Forecast of erosion at bridge pier T3 bridge in the future.

4 Conclusions

The scour that occurs around a bridge pier is a complex phenomenon that can be difficult to measure. However, to ensure the safety of bridge piers, it is essential to be able to accurately predict the scour depth. In this study, we evaluated the performance of two well-known empirical equations, namely the Yang et al. [12]'s and FDOT [11]'s equations, in predicting the maximum scour depth at the two central piers of the Doanhung Bridge founded on the moving riverbed. The study included three different scenarios: (i) the 2005-2014 period, (ii) the 2014-2020 period, and the most recent, (iii) the 2020-present period. The results show that the Yang et al. [12]'s formula outperforms the FDOT [11]'s estimates when these estimates are compared to the corresponding field studies. It should be noted that the performance of these empirical equations can only be evaluated individually because the bridge foundations considered have undergone changes. However, the Yang formula provided better results for the bridge case study.

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