Quantitative study of the factors affecting the behavior of reinforced concrete bridge piers against floods

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ABSTRACT

Evaluating the vulnerability of bridges to flooding is essential for risk-informed planning of their maintenance. This paper aims to develop a systematic model for investigating the behavior of bridges at the time of flooding, in which structural, geotechnical, and hydraulic parameters are considered. A three-dimensional finite element model of reinforced concrete bridge piers was developed, in which the material nonlinearity and the interactions between the pier and the surrounding soil and the flood water were taken into account. The parameters used in the model were validated based on experimental data from a single pile and a reinforced concrete column under axial and lateral loading. The validated modeling approach was then used to simulate an existing bridge pier, for which the structural, geotechnical, and hydraulic parameters were varied to evaluate the sensitivity of the load-deformation behavior to each parameter. The results showed that the presented modeling approach is capable of providing reliable predictions of the performance of bridge piers at the time of flooding, which makes it suitable for practical vulnerability assessment of bridges. Moreover, it was observed that the behavior of the bridge piers against floods was more sensitive to geotechnical and hydraulic parameters than structural parameters, to the level that by changing the soil type from medium sand to loose sand, the lateral displacement of the structure is changed by 1.87 times. Moreover, increasing the longitudinal slope of the river from 0.004 to 0.005 and decreasing the river bed roughness coefficient from 0.025 to 0.021, increased the lateral displacement of the structure by 2.57 and 6.55 times its initial value, respectively.

KEYWORDS

Bridge, Reinforced concrete, Flood, Scour, Finite element method.

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1. Introduction

Scouring, as a natural phenomenon during floods, leads to the removal of soil around the foundations of bridges, which poses a great risk to the stability of bridges. In recent years, the behavior of bridge piers exposed to scouring has been studied in several studies [1]; However, the purpose of this study is to provide a systematic model to investigate the basic behavior of bridge piers against flood risk and then use the model to study the sensitivity of the overall pier performance to structural, geotechnical and hydraulic parameters.

2. Methodology

A three-dimensional finite element model of a bridge pier including the piles and the pile cap was developed, as shown in "Figure 1". The model incorporated nonlinear material properties for steel and concrete and Winkler springs with nonlinear properties to simulate soil. The model was successfully validated using experimental results from laterally loaded piles and reinforced concrete columns [2, 3].

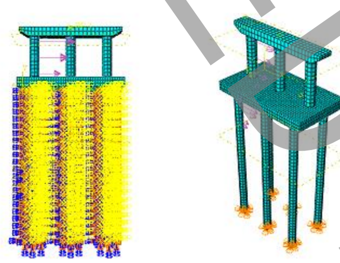

Figure 1. Nonlinear three-dimensional bridge pier model

The Manning equation and the equations presented in FHWA guideline were used to estimate the flow rate and local scour depth, respectively [4, 5]. The load due to the flow on the bridge piers was calculated in accordance with AASHTO LRFD regulations [6]. The flow distribution on the piers was assumed to be triangular, so that the water surface had a maximum pressure of $2P_{ave}$ and the pressure varied linearly from the maximum at water surface to zero at the river bed [1]. The gravity load on the bridge pier was taken as 700 tons, and a water free board of 2 m was assumed. A summary of the important assumptions used for the modeling are given in "Tables 1 through 4".

Table 1. Average structural and hydraulic properties

Property	Assumption
Compressive strength of concrete	24 MPa
Yield strength of steel	400 MPa
River flow width	68 m
Longitudinal slope of the riverbed	0.004
Manning roughness coefficient of the riverbed	0.025

Table 2. Average geotechnical properties

Soil Depth (m)	0-5	5-10	10-15	15-20
SPT	15	17	19	21

Table 3. Structural dimensions

Member	L (mm)	Long. rebar	Trans. rebar
Column	5830	14Ø32	Ø14@90
Pilecap	7400x 13200	Ø20@200	Ø20@175
Pile	20000	16Ø18	Ø12@150

Table 4. Average flow properties

Flow Depth (m)	Flow Discharge (m^3/s)	Flow Velocity (m/s)	Scour Depth (m)
6.23	3243	7.66	7.71

3. Results and Discussion

Once the model was developed using the average properties, the parameters of interest were varied and changes in behavior were evaluated, as follows.

The compressive strength of concrete and yield stress of steel were varied separately according to normal distribution with coefficient of variation of 0.19 and lognormal distribution with coefficient of variation of 0.08, respectively [7, 8]. Typical results are presented in "Figures 2 and 3", which shows slight changes in the behavior due to variations in concrete properties but very small changes due to variations in steel properties.

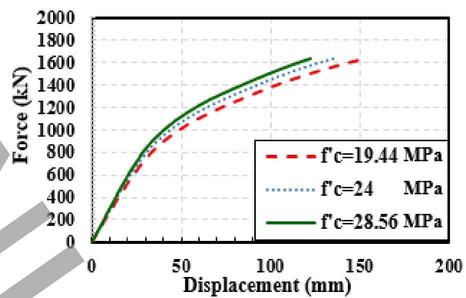

Figure 2. Load-displacement curve for different values of compressive strength of concrete

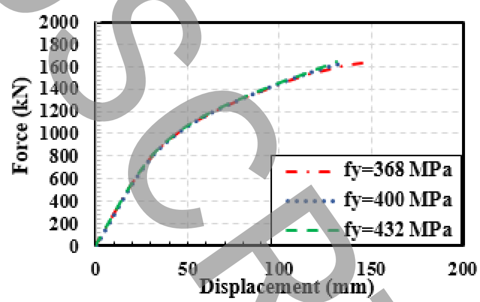

Figure 3. Load-displacement curve for different values of steel yield stress

To investigate the effect of geotechnical parameter, the structure was evaluated in three geotechnical conditions of loose, medium, and dense sand. [9]. The results in the "Figure 4" show the significance of geotechnical conditions assumed in the model. For the loose sand, the maximum pier displacement reached 1.87 times that of the medium sand.

Normal distribution with coefficient of variation of 0.15 was used for the Manning roughness coefficient of the riverbed whereas lognormal distribution with coefficient of variation of 0.25, was used for the riverbed slope [10, 11]. The flow rate was assumed to be a constant value and other hydraulic parameters were calculated. The results are presented in "Figure 5 and 6", which show that by increasing the longitudinal slope from 0.004 to 0.005 and decreasing the roughness coefficient from 0.025 to 0.021, the lateral displacement of the structure will change to 2.57 and 6.55 times its initial value, respectively.

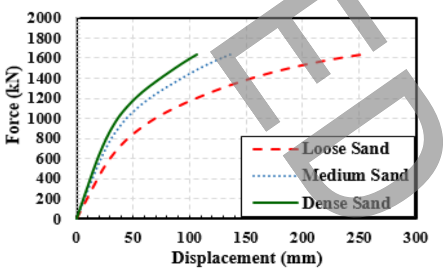

Figure 4. Load-displacement curve for different soil conditions

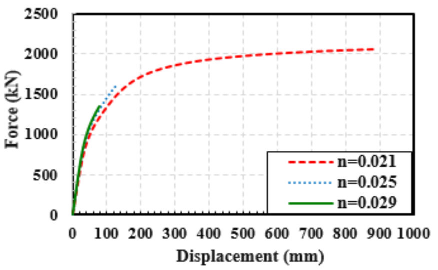

Figure 5. Load-displacement curve for different values of Manning roughness coefficient

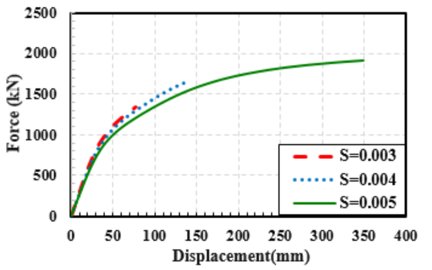

Figure 6. Load-displacement curve for different values of longitudinal slope of the riverbed

4. Conclusion

In this study, a quantitative investigation of the factors affecting the behavior of bridge piers exposed to flood scour was presented. The results showed that the behavior of the bridge piers at the time of flooding is more sensitive to geotechnical and hydraulic parameters than to structural parameters. Changing the soil type from medium sand to loose sand would increase the lateral displacement of the structure by 1.87 times. Moreover, increasing the longitudinal slope of the riverbed from 0.004 to 0.005 and decreasing the roughness coefficient from 0.025 to 0.021 were observed to increase the lateral displacement of the structure by 2.57 and 6.55 times its initial value, respectively.

The observations made in this study show that proper determination of geotechnical and hydraulic conditions is of critical importance when assessing the bridge vulnerability to flooding. The developed is also shown to be capable of reliably simulating the pier behavior under flood conditions in more comprehensive studies.

5. References

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