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Progressive collapse of a drilled-shaft bridge foundation under vessel impact

Y.E. Lu [a], L.M. Zhang [b,*]

[a] State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, China
[b] Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong

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ABSTRACT

On 15 June 2007, a pier of the 1675 m-long Jiujiang Bridge near Guangzhou, China was impacted by a vessel. The pier being impacted and two adjacent piers collapsed in a sequence and approximately 200 m of the bridge deck fell into the river. Each of the three piers was supported on a 1.7 m diameter, 2 × 2 drilled shaft group. The mechanisms of the progressive failure of the bridge foundation under vessel impact are investigated through nonlinear finite element analysis. The simulation model includes all three drilled shaft groups as an integrated system connected by a bridge deck. A possible system progressive failure mode is proposed based on the analysis. The bending moment, displacement and soil reaction along the drilled shafts are computed. The pier foundation being impacted collapsed first. The failure of this pier was initiated at the connections between the pile cap and the drilled shafts and between the pile cap and the pier columns. The collapse of the adjacent pier foundations occurred one by one in a sequence, which was not directly caused by the vessel impact load but by the centrifugal forces from the rotation of the adjacent bridge deck when it fell about one end.

1. Introduction

Bridge piers adjacent to navigation channels are usually at risk of accidental collisions by errant ships. Sometimes ships deviate from the navigation channel and collide on off-navigation channel piers, which can lead to catastrophic consequences since the off-navigation channel piers are often designed with a relatively small lateral bearing capacity. On 15 June, 2007, a pier of Jiujiang Bridge near Guangzhou, China was impacted by a sand-laden vessel carrying a cargo of sand amid thick fog. As a result, the pier subjected to vessel impact, two adjacent piers and a 200-m section of bridge deck collapsed. This is a typical case of progressive collapse of bridge structure.

Different structural systems exhibit different degrees of sensitivity to progressive failure, which is often neglected in conventional design analysis. Traditional design usually pays more attention to the safety of individual structural elements than to the safety of the entire structural system. For example, the design of bridges pays much attention to the bearing capacity of each individual member but the effects of element failure on the safety of the whole structure are less understood. As a result, failure of one member of a bridge system may cause the progressive collapse of several members or even the whole system. This raises a system safety or reliability problem.

Several studies have been conducted to study the behavior of bridge piers subjected to vessel impacts (e.g. Consolazio et al., 2005, 2006; Chu and Zhang, 2011) or rock impacts (Lu and Zhang, 2012). They mainly focused on the impact loads and the behavior and capacity of a single bridge pier under impacts rather than on the safety of the entire bridge structure. However, a number of progressive collapse events that happened after local failure similar to the collapse of Jiujiang Bridge have been reported previously. On December 15, 1967, Silver Bridge over the Ohio River was damaged due to a defect in a single link, eyebar 330. It caused the 220-m center span, two 116-m side spans, and the tower to collapse (Biezma and Schanack, 2007). Sunshine Skyway Bridge in Florida was collided by a cargo ship in 1980, causing the collapse of one pier and three spans 396-m in length (Knott, 1998). An I-40 highway bridge over the Arkansas River in Oklahoma was struck by a barge in 2002, leading to the damage of two piers and four spans about 150-m long (Yuan, 2005). In these cases, the piers and bridge decks near the impacted pier also collapsed progressively and led to catastrophic consequences.

Ghali and Tadros (1997) investigated progressive collapse mechanisms of Confederation Bridge crossing Northumberland Strait by analytical and experimental studies. It was demonstrated that more than one hinge should be designed to prevent progressive collapse of the bridge. Starossek (1999, 2006) also reported a progressive collapse study of Confederation Bridge and proposed a compartmentalization approach against progressive collapse.

The purpose of this paper is to investigate the system failure mechanisms of bridge foundations under vessel impact. A possible

* Corresponding author. Tel.: +852 2358 8720; fax: +852 2358 1534.
E-mail addresses: yelu@whrsm.ac.cn (Y.E. Lu), cezhangl@ust.hk (L.M. Zhang).

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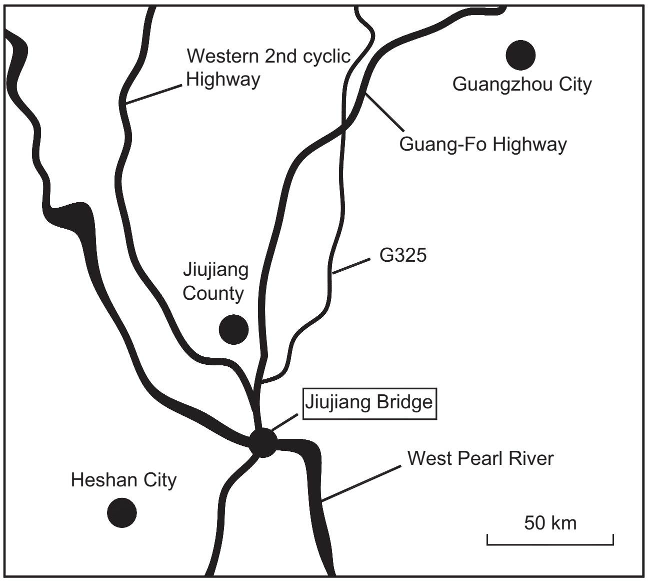

Fig. 1. Location of Jiujiang Bridge.

progressive failure process of Jiujiang Bridge during a vessel impact is studied through numerical and theoretical analyses.

2. Site description

Jiujiang Bridge is part of National Highway G325, which crosses West Pearl River and connects Jiujiang and Jiangmen City in Guangdong Province, China, as shown in Fig. 1. It is 1675 m long and has 43 spans (Fig. 2). The bridge has been on service since June 12, 1988. The major part of the bridge consists of two navigation channel spans, each 160 m long and 21 off-channel spans including 19 spans 50 m in length and 2 spans 40 m in length. In addition, there are 20 approach spans, each 16 m long. The bridge deck is 15.5 m wide with a 14 m wide carriageway and two 0.75 m wide pedestrian lanes on both sides.

2.1. Piers and superstructure

Piers no. 23, 24 and 25 had the same type of structure. Each consisted of four drilled shafts, two columns, one pile cap, and one pier cap, as shown in Fig. 3. In the figure, S1, S2, S3, S4, C1 and C2

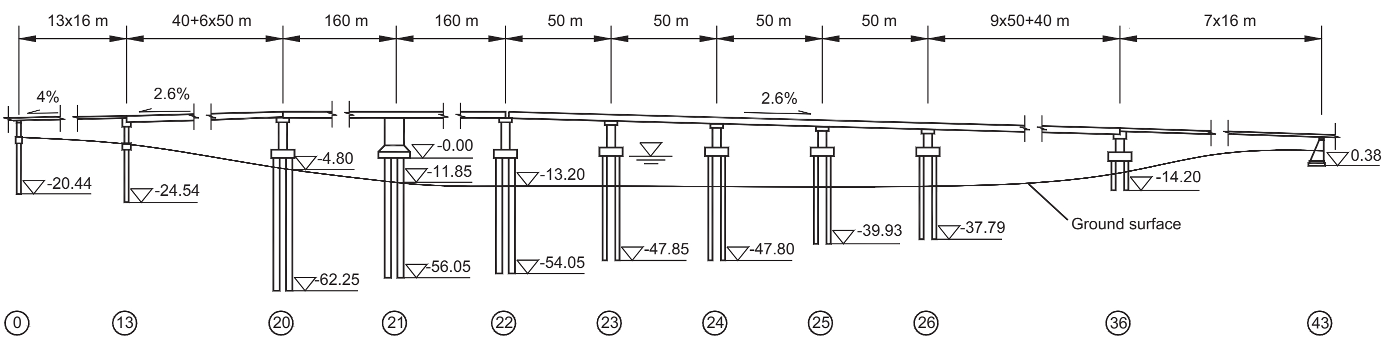

Fig. 2. Front view of Jiujiang Bridge (elevations in meter).

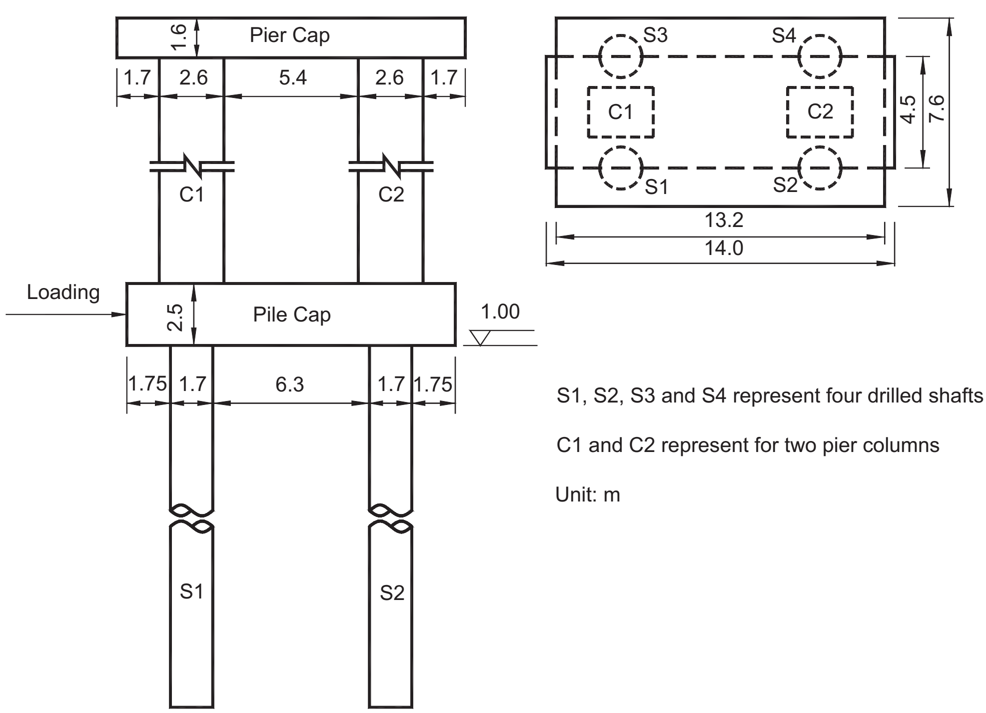

Fig. 3. Simplified vertical and plan view of the damaged bridge piers.