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MECHANISM OF DAMAGE TO SHIWEI BRIDGE CAUSED BY 1999 CHI-CHI EARTHQUAKE

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An Extensive field investigation was conducted on the Shiwei Bridge in Taiwan damaged by the 1999 Chi-Chi Earthquake and its failure mechanism was inferred. No piers of the bridge showed a displacement in the horizontal direction, but their foundations were found to have been rotated. It is probable that the girders fell off the piers becausethelengthbetweenthepiersbecameenlarged due to the rotation of theirfoundations or the girders exhibitedrotational behavior due to seismicmotion in thedirectionperpendicular to thebridge axis.

Key Words: *Chi-Chi Earthquake, failure ofstructure, concretepier,earthquakedamage, deformation ofpier*

1. INTRODUCTION

The M7.6 earthquake that occurred in Chi-chi in the central region of Taiwan on Sept. 21, 1999 caused tremendous damage to various structures in wide areas including Taichung and Nantou Prefectures. The authors conducted a field survey after the earthquake mainly in TaichungPrefecture to investigate damage incurred on road bridges. Extensive measurements werealsoperformed.

Reported in this paper is the damage to the Shiwei Bridge situated in the north-east area of Taichung which exemplifies typical damage to bridge structures in the earthquake-affected region. The detailed damage pattern and the possible damage mechanism of the Shiwei Bridge presumed from our measurement results are described.

2. STRUCTURAL CONDITIONS

The Shiwei Bridge is located on the prefectural road Route 3 which crosses a branch of the Da-Jia river (Fig. 1). The bridge, completed in September 1994, is a three-span simple skew bridge with separated north- and south- bound roadways accommodating three lanes each. The superstructure consists of RC-made five girders with a length of 24-25 m and a width of 11.75 m each. The girders are supported by rubber bearings. The bearing conditions were not known from our visual observation. The piers are oval-shaped RC piers with a cross section of 3.9 × 1.5-1.8 m. The height from the pier bottom aboveground to the upper side of the beam is approximately 9 m. The cross sectional view of the Shiwei Bridge is shown in Figure 2. The bridge is a skew bridge with oblique angles from 55 to 85°, as shown in Figure3.

3. DAMAGE

The damage suffered by the Shiwei Bridge is shown in Figures 3 and 4. On the Dongshyh-bound lanes, the north ends of the girders D2 and D3 fell from the piers P1 and P2, respectively.

Similarly, on the Cholan-bound lanes, the north end of the girder D3 fell off the pier P2. On both lanes, the girders clashed to the parapets at the abutments A2, the rubber bearings dropped from each bridge seat, and shear keys damaged, as seen from Figure 5.

No serious damage was observed on the pier P1 on the Dongshyh-bound lanes, though it is slightly (about 0.9°) tilted toward the abutment A1. The pier P2 also showed no serious damage to the column itself, but its foundation underwent a significant rotation, as shown in Figures 6 and 7. It tilted 10.3° toward the P1 side and 4.8° toward the direction perpendicular to the bridge axis.

With regard to the pier P1 on the Cholan-bound lanes, shear and flexural cracking occurred in the east-west direction at a height about 2 m from the bottom and concrete fell at the bottom of the pier on the north side, as shown in Figure 8. It also tilted about 2.2° toward the abutment A1 side. The pier P2 on the Cholan-bound lanes suffered no serious damage to its column, but again its foundation rotated significantly with a degree of 7.6° toward the P1 side and 3.4° toward the east side. The pier leaned toward the north as a whole.

A significant slope failure was observed on the river bank of the abutment A2 side, as seen from Figure 4. One report says that the slope failure may have been caused by the movement of the Chelungpu fault.[1)]

4. DAMAGE MECHANISM PRESUMED

4.1 Mechanism for drop of D3girders

Figure 3 shows both the length between substructures and the length of girders,allobtained

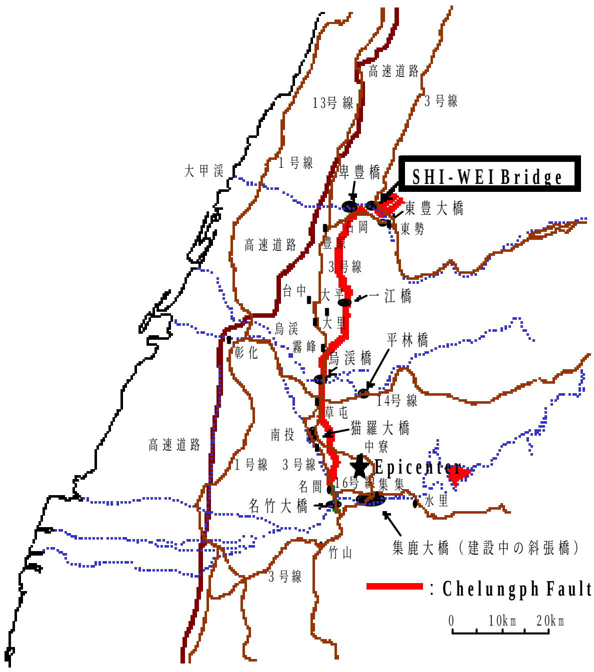

Fig.1 Geographical locationofShi-Weibridge

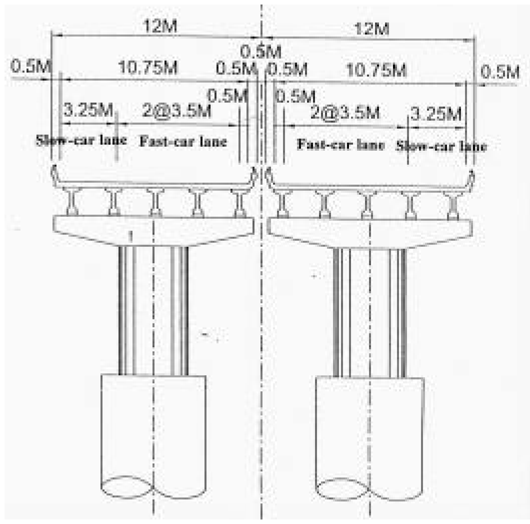

Fig.2 ElevationofShi-Weibridge

Fig.4 Damage toShi-Wei bridge

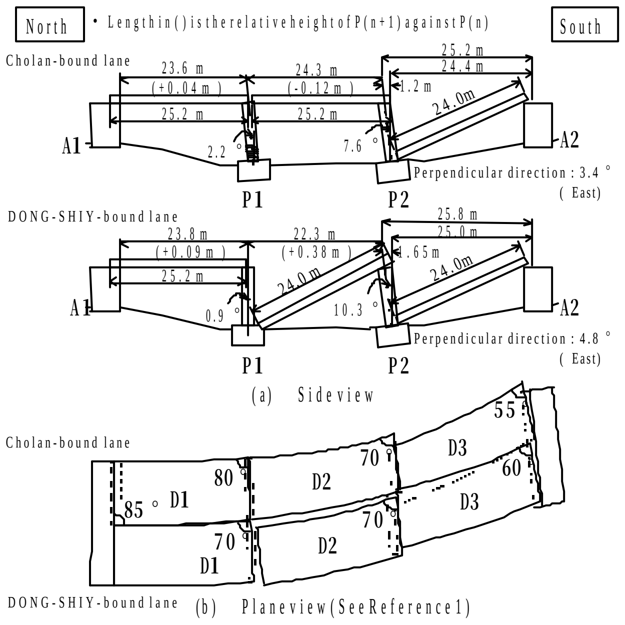

Fig.3 Damage to Shi-Wei bridge and measurements

by our measurements. According to the measurement results, the length between P2 and A2 which jointly supported the girder D3, was 25 m for the Dongshyh-bound lanes and 24.4 m for the Cholan-bound lanes. It is obvious that the girders fell because the girder length on both lanes, 24 m each, was shorter than the length between the substructures supporting it. In contrast, the girder D2 on the Dongshyh-bound lanes dropped despite the fact that the length of the girder, 24 m, was longer than the length between piers P1 and P2 which was 22.3m.

The falling of the girders D3 on both bound lanes is presumed to have been caused primarily by the significant displacement of the piers P2 toward the north triggered by the rotation of their foundations as a result of the ground deformation occurred. The occurrence of the ground deformation is verified by the slope failure observed on the river bank. The above assumption is substantiated by the fact that when the length between P2 and A2 before the earthquake, namely 24 m, is added to each horizontal displacement at the top of P2 piers, which is 1.64 m (rotation angle: 10.3°) for the Dongshyh-bound lanes and 1.2 m(rotation angle: 7.6°) for the Cholan-bound lanes, the derived length on each lane nearly equals to the length between P2 and A2 obtained by our measurements after the earthquake, which is 25.8m for

Fig. 5 Damage to a shoe near abutment A2

Fig.6 Tilting of Pier P2 towards the bridge axis direction on the Dong-Shyh bound lane

Fig. 7 Tilting of Pier P2 towards the perpendicular direction on the Dong-Shyh bound rane

Dongshyh-bound lanes and 25.2 m for the Cholan-bound lanes.

The same applies to the length between P1 and P2. The length between P1 and P2 before the earthquake was 24 m for Dongshyh-bound lanes and 25.2 m for Cholan-bound lanes. If the rotational displacement length is each deducted from the above lengths, the derived length on each lane roughly equals to the lengths measured by us after the earthquake, which is 22.3 m for Dongshyh-bound lanes and 24.3 m for the Cholan-bound lanes.

Fig. 8 Damage to Pier P1 on the Cholan-bound lane

4.2 Mechanism for drop of D2 girder on Dongshyh-bound lanes

(1) *Assumption 1: drop due to shaking in the bridge axis direction*

The drop of the girder D2 on the Dongshyh-bound lanes despite a longer girder length compared with the length between P1 and P2 was probably because inertia force due to seismic motion acted toward the A2 side before the falling of the girder D3 and following that the girder D2 dropped because of the lack of the seating length, as shown in Figure 10. The occurrence of the inertia force is substantiated by the damages observed, such as falling of concrete and flexural and shear cracking at the bottom of the pier P1 on the Cholan-bound lanes, and by a scar of clash seen at the parapets of abutments A1 and A2. The reason why the girder D2 on the Cholan-bound lanes did not fall off the pier was possibly because the arising seismic energy was absorbed by the damageoccurred on P1 and a rise of road surface occurred at the abutment A1 due to the 40-cm sink of the girder toward the A1 side, as seen in Figure 9, resulting in a smaller seismic response compared with that on the Dongshyh-bound lanes.

Fig. 9 Damage around abutment A1 on the Cholan-bound lane

(2) *Assumption 2: drop due to shaking in the direction perpendicular to bridge axis*

As indicated in Figure 3, the Shiwei Bridge is a skew bridge with oblique angles varying from 55° to 85°. As there was a trace that the bridge was also subjected to seismic motion in the east-west direction (direction perpendicular to the bridge axis), as seen from Figure 5, verification was conducted as to the possibility that the girder D2 on the Dongshyh bound lanes had received seismic motion in the perpendicular direction, undergone rotation and resulted in the falling of the piergeometrically.

As to the girder D2 on the Dongshyh bound lanes, it was inferred that the rotation occurred on the north side of the girder having an oblique angle of 70°, taking Point A at the end of the girder on the obtuse angle side near P2 as its rotation axis, because D2 fell off from the P1 side. Figure 11 is a schematic description of a plan configuration which can undergo rotation geometrically. Figure 12 shows the relationship between the plan configuration ratio (b/L) and the oblique angle (θ) of a skew bridge which can rotate. The area surrounded by slash which satisfies Equation (1) is the range that can rotate.[2] The ● mark in Figure 12 indicates the relationship of plan configuration ratio (b/L = 0.47) and oblique angle (=70°) of the girder D2 on the Dongshyh bound lanes. It is seen that the girder D2 is not able to rotate geometrically because the girder is located out of the rotatable area, provided that the positions of the girder and the piers are the same with those before the earthquake.

However, as stated earlier, it is known that the seismic force also acted in the bridge axis direction. If the total of $\triangle$ ($=\triangle_1 + \triangle_2$) of joint gaps at both ends of D2 is assumed to have widened by about 35 cm ($\triangle/L$ = 1.5 %) due to seismic forces compared with the gap width before the earthquake, the rotatable area will become the area indicated by a dotted line ($\triangle/L$ = 1.5 %) in Figure 11 from the condition equation (2).[2] In this case, the ● mark showing the girder D2 comes within the rotatable area and hence it can be said rotatable geometrically.

The pier P1 on the Dongshyh bound lanes showed virtually no residual displacement, but P2 on the same lanes was inclined 4.8° to the direction perpendicular to the bridge axis and 75 cm toward the east direction by the displacement at the top of the pier. It is therefore presumed that the pier was subjected to forces acting in both directions, but it tilted toward the direction easy to rotate.

The authors are intending to conduct a follow-up study, including time-based response analysis which considers the clashing of girders as well as forced displacement analysis in both directions, to investigate the cause of the drop of the girder D2 from the pier P1 on the Dongshyh bound lanes.

$$L \geq 2b / \sin 2\theta \qquad (1)$$

$$\left(1 + \frac{\Delta_1 + \Delta_2}{L}\right) L \geq \frac{1}{\sin\theta}\sqrt{b^2 + \left(L - \frac{b}{\tan\theta}\right)^2} \qquad (2)$$

where,
L: girder length
b : width of the superstructure
θ : oblique angle
$\triangle_1$, $\triangle_2$: joint gaps between girders

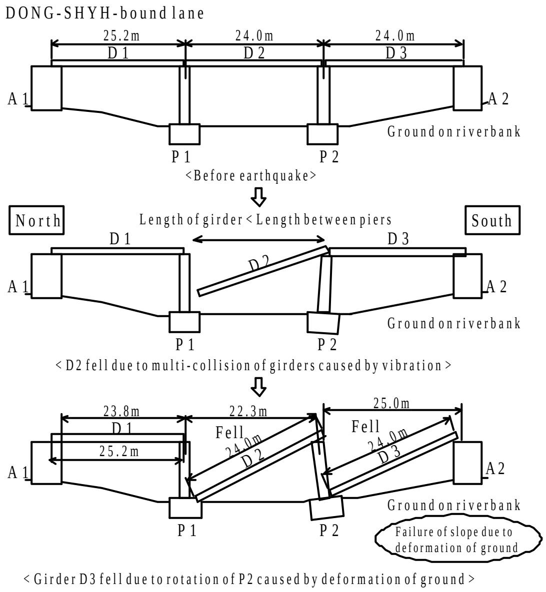

Fig.10 Possible mechanism for fallen girders on the Dong-Shye-bound lane

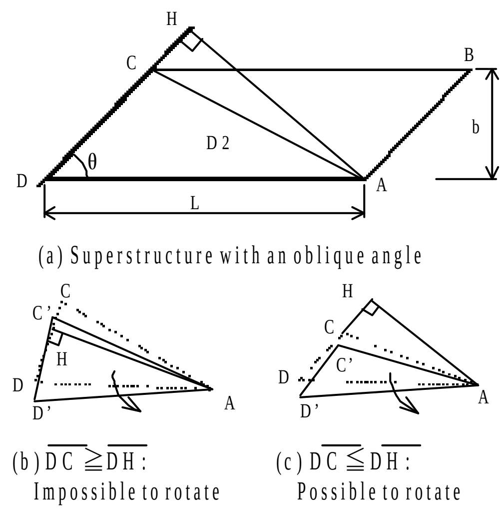

Fig.11 Determination of rotation possibility

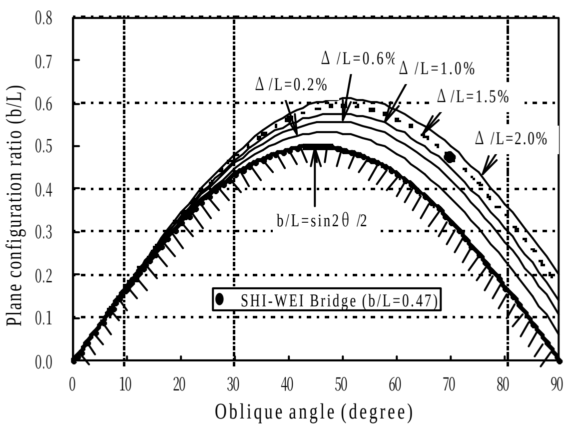

Fig.12 Relationship between an oblique(q) and a plan configuration ratio(b/L)

5. CONCLUSIONS

(1) The girders D3 on both Dongshyh- and Cholan-bound lanes fell primarily because top of the piers P2 underwent a significant displacement toward the north due to the rotation of their foundations which occurred as a result of ground deformation. The occurrence of the ground deformation was verified by the slope failure observed on the river bank.

(2) The girder D2 on the Dongshyh bound lanes is presumed to have dropped before the drop of the girder D3.

(3) When the total joint gaps at both ends of the girder D2 on the Dongshyh bound lanes is assumed to have widened by 35 cm compared with the width before the earthquake as a result of the earthquake motion in the bridge axis direction, it is probable that D2 fell after it was rotated by the earthquake motion in the direction perpendicular to the bridge axis and then exceeded the seating length over the pier P1.

(4) It is considered that if the superstructure had been constructed of a continuous girder, the drop of the girders would have been prevented.

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