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

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The Shiwei Bridge in Taiwan was extensively investigated in order to determine the reasons for its failure during the 1999 Chi-Chi Earthquake. Our field investigation revealed no evidence of horizontal displacement in any of the bridge's piers, although the foundations of the piers were rotated. Two possible scenarios for the failure of the girders are proposed: 1) when the foundations rotated, the distance between the piers became greater than the length of the girder, causing the girders to fall; or 2) the direction of the seismic motion was perpendicular to the axis of the bridge, causing the girders to rotate and fall.

Key Words: *Chi-Chi Earthquake, failure of structure, concrete pier, earthquake damage, pier deformation*

1. INTRODUCTION

The Chi-Chi earthquake struck the central region of Taiwan on Sept. 21, 1999. The magnitude M7.6 tremor caused severe damage to a variety of structures in the region, including bridges. The authors conducted two field surveys and investigated damage to road bridges, mainly in Taichung Prefecture.

This paper describes the damage to the Shiwei Bridge in Taichung Prefecture. The damage to the bridge structure is typical of that caused by this earthquake. The results of the survey were used to investigate the mechanism that caused the damage.

2. STRUCTURAL CONDITIONS

The Shiwei Bridge carries a prefectural road, Route 3, across a branch of the Da-Jia River (**Fig. 1**). Constructed in September 1994, the bridge is a three-span, simply supported, skew bridge. It consists of two separate 3-lane roadways running north and south. The superstructure consists of five RC girders, each with a length of 24-25 m and a width of 11.75 m. The girders are supported on elastomeric bearing pads with shear keys. The condition of the supports could not be determined by visual observation. The oval piers have a cross-section measuring 3.9 x1.5-1.8 m. The T-shaped pier is approximately 9 m in height from the ground surface to the top of the beam.

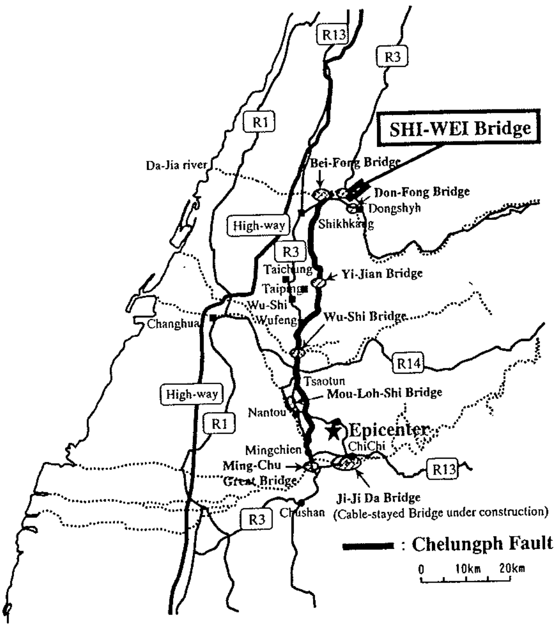

Fig.1 Geographical location of Shiwei Bridge

The elevation of the Shiwei Bridge is shown in **Fig. 2**. The bridge curves at angles ranging from 55° to 85°, as shown in **Fig. 3**.

3. DAMAGE

The damage to the Shiwei Bridge is shown in **Figs. 3** and **4.** On the Dongshyh-bound roadway, the north ends of girders D2 and D3 fell from piers P1 and P2, respectively. Similarly, on the Cholan-bound roadway, the north end of girder D3 fell from pier P2. On both roadways, girders D3 smashed into the parapets of abutments A2, the bearing pads dropped from the bridge seats, and the shear keys were damaged. This damage is shown in **Fig. 5.**

On the Dongshyh-bound roadway, pier P1 sustained no serious damage but was tilted slightly (about 0.9°) toward abutment A1. Pier P2 also did not suffer any significant damage to its column, but its foundation rotated considerably. As a result of the rotation, pier P2 tilted 10.3° toward pier P1 and 4.8° in the direction perpendicular to the bridge axis. This is shown in the photographs in **Figs. 6** and **7**.

Pier P1 on the Cholan-bound roadway suffered shear and flexural cracking in the east-west direction at a height of about 2 m from the ground. The cover concrete on the north side of the pier bottom broke loose and fell, as shown in **Fig. 8.** This pier tilted about 2.2° toward abutment A1. Pier P2 on the Cholan-bound roadway did not suffer any serious damage to its column, but its foundation rotated 7.6° toward pier P1 and 3.4° toward the east. The pier also leaned toward the north.

The riverbank beside abutment A2 suffered significant slope failure, as seen in **Fig. 4.** According to one report, the slope failure was caused by movement along the Chelungpu fault (1).

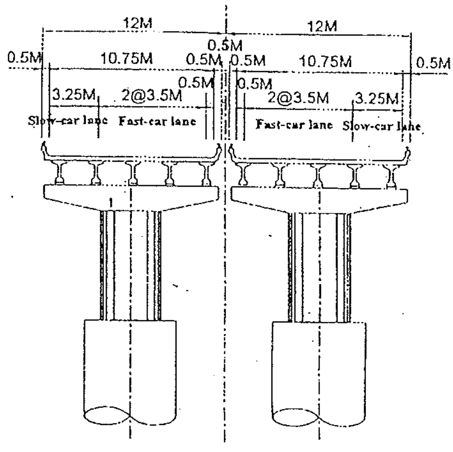

Fig.2 Elevation of SHI-WEI Bridge

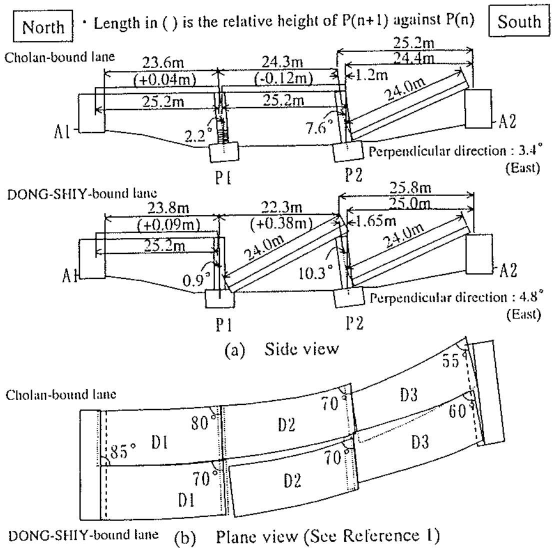

Fig.3 Damage to SHI-WEI Bridge and Measurements

4. DAMAGE MECHANISM

(1) Fallen girders D3

Figure 3 shows the distances between the substructures and the lengths of girders. These values were obtained during our field survey using

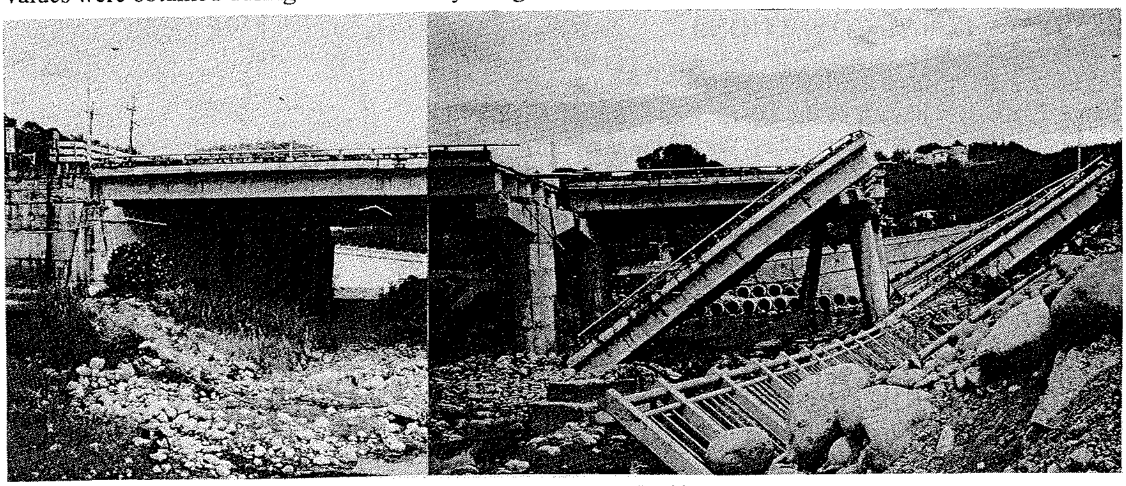

Fig.4 Damage to SHI-WEI Bridge

between piers P2 and abutments A2, which jointly an optical surveying instrument. The distances support girders D3, are 25 m for the Dongshyh-bound roadway and 24.4 m for the Cholan-bound roadway. It is obvious that girders D3 on both roadways fell because the girders (24 m) were shorter than the distances between the substructures. In contrast, girder D2 on the Dongshyh-bound roadway fell from the pier despite the fact that the 24 m girder was longer than the 22.3 m distance between piers P1 and P2.

Girders D3 on both roadways probably fell due the significant displacement of piers P2 toward the north. This displacement was triggered by ground deformation and the ensuing rotation of the foundations. This assumption is substantiated by the fact that, when the distance between pier P2 and abutment A2 before the earthquake (24 m) is added to the horizontal displacement at the top of pier P2 (1.64 m for the Dongshyh-bound roadway, and 1.2 m for the Cholan-bound roadway), the resulting length is nearly equal to the distances between pier P2 and abutment A2 after the earthquake (25.8 m for Dongshyh-bound roadway and 25.2 m for the Cholan-bound roadway).

The same assumption applies to the case of piers P1 and P2. The distance between piers P1 and P2 before the earthquake was 24 m for Dongshyh-bound roadway and 25.2 m for Cholan-bound roadway. If the displacement at the top of the pier, caused by rotation of the pier, is deducted from these distances, the resulting lengths roughly equals the distance measured after the earthquake (22.3 m for Dongshyh-bound roadway and 24.3 m for the Cholan-bound roadway).

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

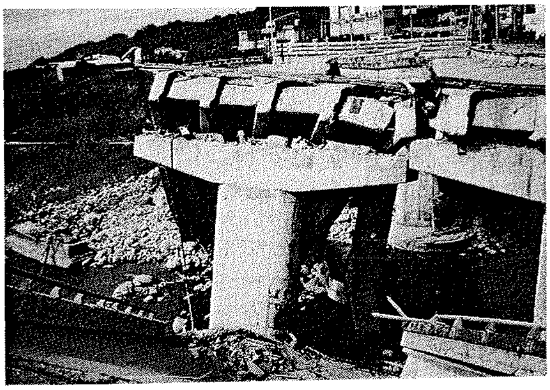

Fig.7 Tilting of Pier P2 toward the perpendicular direction on the DONG-SHYH-bound lane

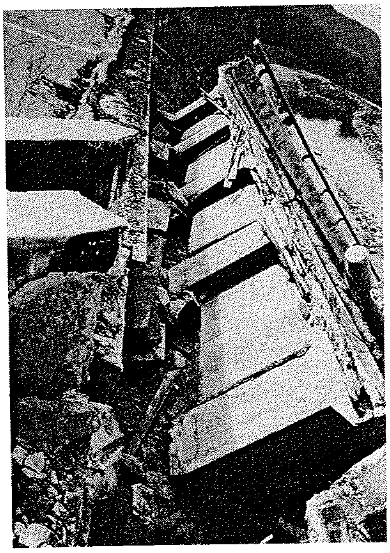

Fig.5 Damage to a shoe near abutment A2

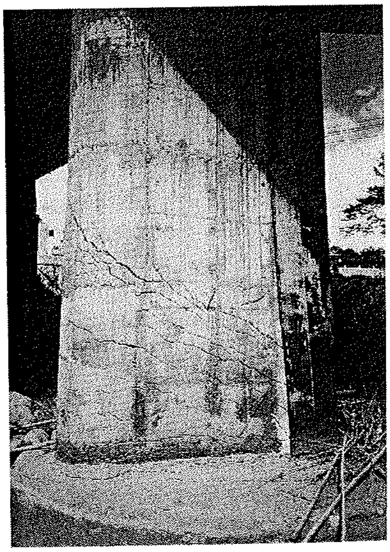

Fig.8 Damage to Pier P1 on the Cholan-bound lane

(2)Fallen girder D2 on the Dongshyh-bound roadway

(a)Assumption 1: Fall due to seismic motion in the direction of the bridge axis

Girder D2 on the Dongshyh-bound roadway fell from the pier despite the fact that the length of the girder was greater than the distance between piers P1 and P2. This was probably because the seismic motion generated inertia force in girder D2 and this force acted in the direction of abutment A2 before girder D3 fell. Subsequently, because of the short length of its seating, girder D2 was pushed toward abutment A2. The fallen girder is shown in **Fig. 10**. Evidence of such a large inertia force includes such observed damage as spalling of the concrete and flexural and shear cracking at the bottom of pier P1 on the Cholan-bound roadway, and the damage to abutments A1 and A2 caused by the girders smashing into the parapets. Girder D2 on the Cholan-bound roadway did not fall, probably because 1) the seismic energy was absorbed by the colliding girders, 2) the damage to the pier P1, and 3) the rise of the road surface at abutment A1 caused by the girder being pushed about 0.4 m toward the north. This resulted in a seismic response that was smaller than that of the Dongshyh-bound roadway. The other girder D2, which did not fall, is seen in the background of **Fig. 9**.

(b) Assumption 2: Fall due to seismic motion in the direction perpendicular to the bridge

As shown in **Fig. 3**, Shiwei Bridge is a skew bridge that curves at angles ranging from 55° to 85°. Trace evidence suggested that the bridge had been exposed to seismic motion in the direction perpendicular to the bridge, as well as along the bridge axis. This can be seen in from **Fig. 5**. This led us to investigate pier P2 on the Dongshyh-bound roadway to see if it underwent rotation due to seismic motion in the perpendicular direction, causing girder D2 to fall.

Since girder D2 was supported by pier P1 and the northern portion of the girder fell, it is presumed that rotation occurred around the rotational axis, which is located at Point A at the end of the girder on the obtuse angle side above pier P2. **Figure 11** shows a schematic description of a configuration of the girder that can undergo geometric rotation.

If the end point A of the girder on its obtuse angle side is considered as the center of rotation, rotation can occur when DC≦DH is held on the opposite side. **Figure 11-C** shows this case. Namely, the point C moves to the inside of the side DC and the girder begins to rotate.

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

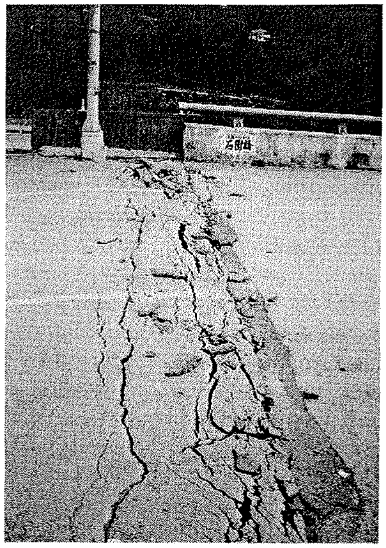

Fig. 9 Damage around abutment A1 on the Cholan-bound lane

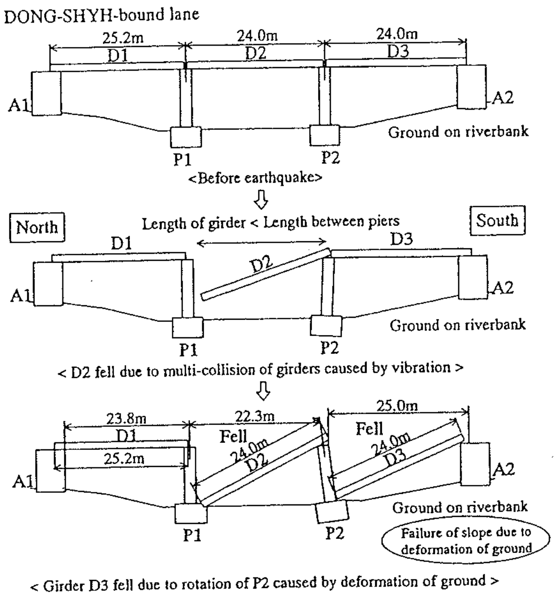

Fig.10 Possible mechanism for fallen girders on the DONG-SHYE-bound lane

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

where,

DC=b / sin θ and DH = L・cos θ

L : girder length

b : width of the superstructure

θ : oblique angle

The equation for determining the occurrence of rotation when the space between girders is taken into consideration is given as equation (3).

$$\left(1+\frac{\Delta_1+\Delta_2}{L}\right) L \geq \frac{1}{\sin\theta}\sqrt{b^2+\left(L-\frac{b}{\tan\theta}\right)^2} \quad (3)$$

where,
L : girder length
b : width of the superstructure
θ : oblique angle
$\triangle_1$, $\triangle_2$: length of spacing on both ends of girder D2

Figure 12 shows the relationship between the configuration ratio (b/L) and the oblique angle (θ) of a skew bridge that can undergo rotation. Here, 'b' is the width of the superstructure, and 'L' is the girder length. The area enclosed by slashes satisfies Equation (2) and is the range of the girder that can undergo rotation(2). The ● symbol in **Figure 12** indicates the relationship between the configuration ratio (b/L = 0.47) and the oblique angle (=70°) of girder D2 on the Dongshyh-bound roadway. As its position is located outside the area where the girder can fall, girder D2 could not rotate geometrically, if the positions of the girder and the piers remained unmoved during the earthquake.

However, as stated earlier, it is known that seismic forces acted not only in the direction perpendicular to the bridge but also in the direction of the bridge axis. If $\triangle$ (=$\triangle_1$ +$\triangle_2$) , the total of the space at both ends of girder D2, is assumed to have increased, due to seismic forces, by about 0.35 m ($\triangle$/L = 1.5 %) from the original space before the earthquake, the area in which the girder can fall is the area enclosed by the heavy dotted line ($\triangle$/L = 1.5 %) in **Fig. 11** from the condition equation (2). The ● indicates the relationship between the configuration and the oblique angle of girder D2, subsequently lies within the area in which the girder can fall, which means the girder can rotate geometrically.

Pier P1 on the Dongshyh-bound roadway showed very little residual displacement, but the pier P2 on the same roadway inclined 4.8° in the direction perpendicular to the bridge axis, which results in a 0.75 m displacement toward the east when measured at the top of the pier. It is therefore assumed that this displacement also worked to allow rotation of the girder, in addition to permitting displacement in the direction of the bridge axis.

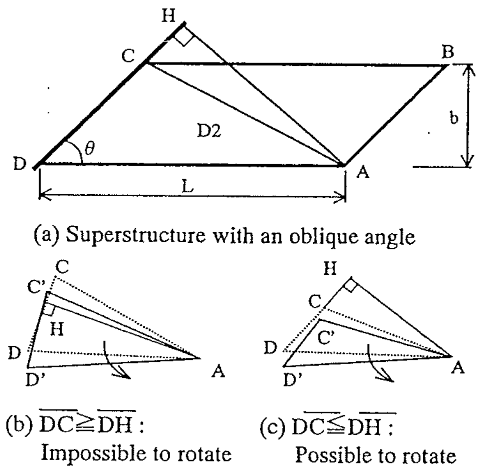

Fig.11 Determination of rotation possibility

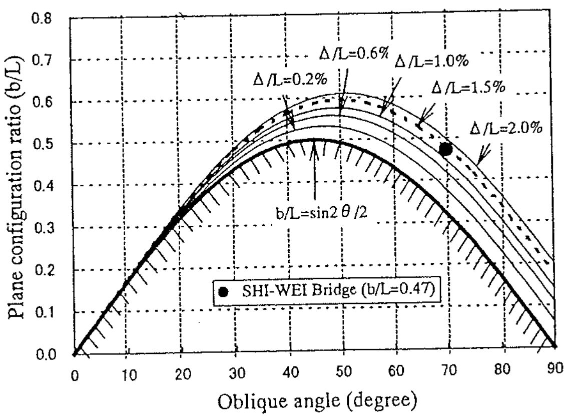

Fig.12 Relationship between an oblique angle(θ) and a plan configuration ratio(b/L)

As a follow-up study, the authors intend to conduct a time-based response analysis that takes the girders into account, as well as conduct forced displacement analysis in both directions. These analyses will confirm that girder D2 on the Dongshyh-bound roadway fell from pier P1 due to seismic motion in the direction perpendicular to the bridge axis.

5. CONCLUSIONS

(1) Girders D3 on both the Dongshyh- and Cholan-bound roadways fell primarily because piers P2 were displaced significantly toward the north due to rotation of their foundations as a result of ground deformation.
(2) The fall of girder D2 on the Dongshyh-bound roadway is presumed to have preceded the fall of girder D3 due to the large inertia force that acted in the direction of girders D2 and D3.

(3) The seismic motion acting in the direction perpendicular to the bridge axis forced girder D2 to rotate. Assuming that the space at both ends of the girder D2 on the Dongshyh-bound roadway increased by a total of 0.35 m as a result of seismic motion in the direction of the bridge axis, girder D2 would exceed its seating length over pier P1, causing the girder to fall.
(4) Considering the mechanism that caused the girders to fall, it can be concluded that if the superstructure had been a continuous girder, it would not have fallen.

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