A RETROFITTING DESIGN OF YEN-FON BRIDGE IN CENTRAL TAIWAN AFTER CHI-CHI EARTHQUAKE

Retrofit/Bridge Structure

Terng-Fen Song
Director and Senior Vice President
Moh and Associates, Inc.

Huat-Yoo Chua
Manager of Structural Engineering Dept.
Moh and Associates, Inc.

Jao-Shyong Yeh
Deputy Director General , Highway Bureau
Ministry of Transportation and Communications

Majoring in Structural Engineering and Mechanics, Mr. Song was awarded Master of Engineering from the Asian Institute of Technology in 1970. In his current position, he is responsible for business development and supervision on design and construction projects of structural engineering, geotechnical engineering for his company. More than 100 qualified engineering staffs are working under his direction on some of the most important infrastructure projects in Taiwan. These projects include design and construction of Chung-Tou, Chung-Chang and Nanliao-Chutung expressways as well as design and construction of the second freeway at Nantou section in central Taiwan.

Mr. H.Y. Chua joined MAA in 1981. He was assigned projects in the planning, design, construction supervision and contract administration in the field of high-rise buildings and bridge engineering. He was also responsible in many structural appraisal and retrofitting projects since 1987. From 1992, besides involved in the design of the cross-river tunnel in the Taipei Railway Underground project, he was also in charge of detail design work for 60km long viaduct structure in the High Speed Rail Project. Mr. Chua received his M.Eng. degree from the Asian Institution of Technology, Bangkok in 1980. He is a Chartered Engineer, U.K.

Mr. Yeh graduated from the Department and Graduate School of Civil Engineering, National Cheng Kung University. He got the award of ten excellent engineers from the Chinese Institute of Engineers and the medal of prominent planning and design from the Chinese Institute of Civil and Hydraulic Engineering. Mr. Yeh engaged in the field of civil engineering for thirty years, he made a lots of contributions in this field. In recent years, Mr. Yeh was responsible for the emergency repair work of highways after the Herb typhoon which hit Taiwan on 31 July,1996. During the Chi-Chi earthquake in 1999, he also went to the disaster region to supervise rehabilitation of damaged bridges and roads.

1. INTRODUCTION

Yen-Fon bridge, located at Nan-Tun Town of Nan-Tao county and crossing Wu-Si river, is the main bridge connecting Tsao-Tun town and Pu-Li town on Taiwan Provincial Highway No. 14. The bridge is at the east of Cher-Lung-Pu fault and located between Cher-Lung-Pu fault and Shuang-Dung fault. Built in 1984, the bridge has a length and width of 455 meters (13@35m) and 17 meters, respectively. The superstructure of the bridge is composed of six prestressed I girders at each span. The substructure is of two-column frame type on a foundation of combined footing found on rock (Fig. 1). The height of the pier is 11 meters.

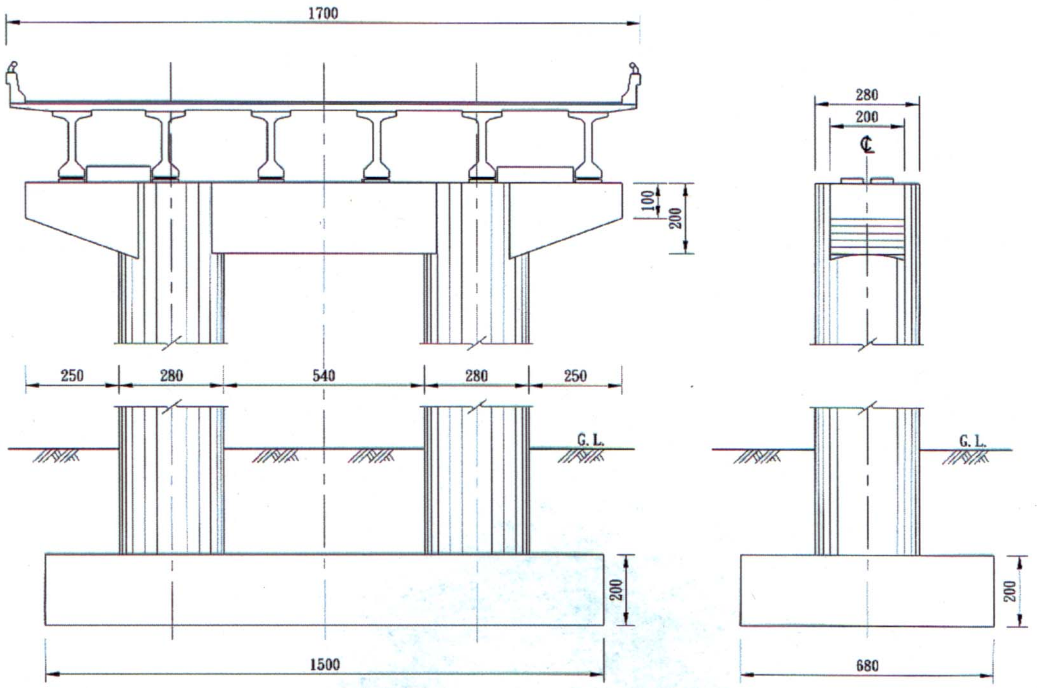
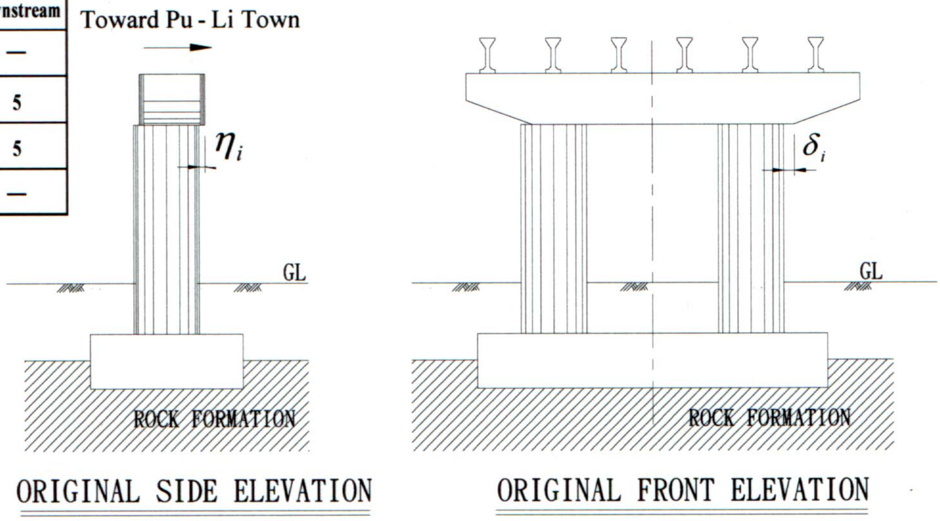


Fig 1: Original Elevation

On September 21th 1999, the Chi-Chi earthquake strike central Taiwan and affect almost the whole island. This is the largest earthquake in a century in Taiwan. The Chi-Chi earthquake caused damage to Yen-Fon bridge in the following manner: (i) superstructures of span No. 4~No. 6 and span No. 12 were displaced transversely; and, (ii) except pier No. 6, all pier caps dislocated transversely to some extent and part of their main reinforcing bars were exposed or completely cut (Fig. 2~4). The damage is not catastrophic, however, two out of four lanes remained open to traffic in order to maintain the access to the area where emergency assistance is needed (Fig. 3).

pier#	δ_i (cm)	η_i (cm)	
		upstream	downstream
8	10	—	—
9	30	5	5
10	35	1	5
11	25	—	—



notes:

δ_i :Transverse Displacement of Cap Beam at pier #i

η_i :Longitudinal Displacement of Cap Beam at pier #i

Fig 2: Dislocation of Cap Beam

Fig 3: Conditions of Slab Displacement and Opening to Traffic

Fig 4: Conditions of Dislocation and Concrete Spalling at Bottom of Cap Beam

In considering of shortening the construction time and reducing the construction cost, Moh and Associates, Inc. and Highway Bureau decided to retrofit the bridge instead of building a new one. By considering the damaged pattern, the following design principles are adopted:

(i) increase design horizontal acceleration coefficient to 0.33; and,

(ii) increase ductility and shear capacity of piers. In addition, in order to accommodate the growing traffic in the future, the bridge width is increased to 21 meters. The design changes the pier type from two-column bents to four-column bents. The original two columns are used only to support part of vertical loading in the design and the new added two columns are designed to resist horizontal seismic forces and to resist the rest part of the loading. .

In the following sections, the cause of the earthquake and the reasons why the bridge was damaged are first explained, details of retrofitting design of the bridge is then described.

2. CAUSE OF EARTHQUAKE

The island of Taiwan was formed during pliocene, due to the collision of Eurasian Plate and Phillipine Sea Plate (subdivision plate of Pacific Plate, Fig. 5 HO 1986). The latter is drifting from south-east at a rate of 7-8 cm/yr. And its Northern tip subducted underneath the Eurasian Plate along the east of Central Mountain Range of Taiwan. This thrust force crushed the Tertiary sedimetary rocks of 10 km in thickness to form numerous faults and folds generally in the N-S direction, roughly the same as the axis of the island, and turns toward N-E at northern part of the Taiwan. The release of strain energy stored during the tectonic movement resulting in numerous inevitable earthquakes in Taiwan .

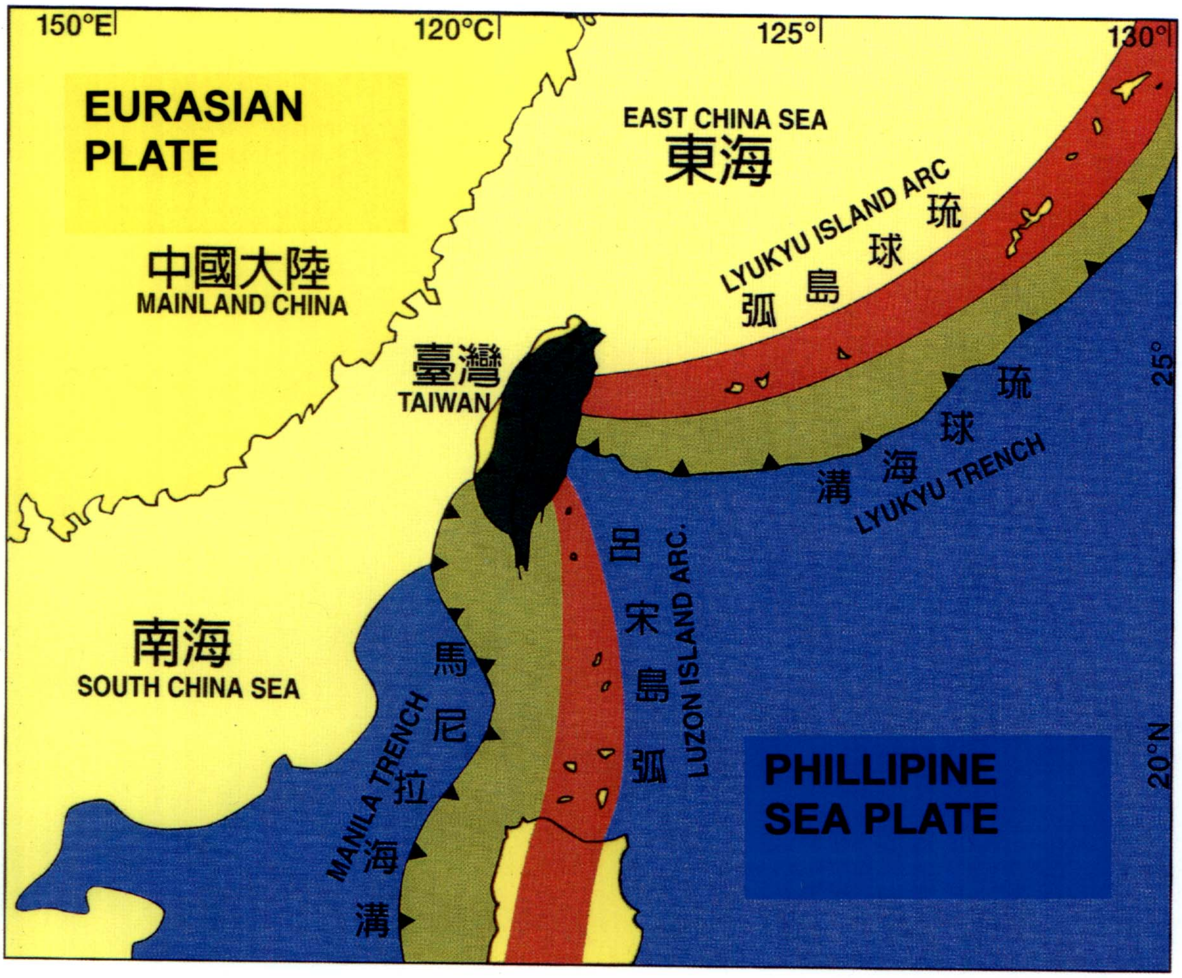


Fig 5: Tectonic Structure Around TAIWAN (After Ho.1986)

The Chi-Chi Earthquake was result of reactivation of Cher-Lung-Pu Fault with epicentre near town of Chi-Chi and at a depth of about 8 km. The Fault has been known as a thrust fault and to run in N-S direction, from Fung-Yan at north, toward Chu-Shan at south with a total length of 60km , dipping eastward at an angle of 30 degree or less.

GPS survey results indicated that an area east of the fault with a width of about 15km was displaced north-westward for a maximum horizontal displacement of 9.06m at Ta-Kung of Taichung, (10m horizontal displacement was measured on the ground at Fung-Shih Road of Fung-Yan City) and uplifted vertically about 9.8m at Shih-Kang Dam near the north tip of the fault line.

3. CAUSE OF BRIDGE DAMAGE

The upper part of formation near bridge is alluvium and the formation below is Pleistocene alternation. The formation displaced from east by south toward west by north during earthquake, which can be judged from dislocation and cracking pattern of damaged cap beams (pier No. 7~ No. 12). The ground acceleration measured at the nearest seismometer station is about 500 gal, which is much larger than the original design value. However, because the direction of formation displacement is perpendicular to the longitudinal direction of the bridge and two-column bent piers provides redundancy, the earthquake only caused minor damage such as dislocation of pier caps and spalling of concrete. Two lanes remains open to traffic after the earthquake.

4. STRUCTURAL ANALYSIS AND RETROFITTING DESIGN

The basic principle of the 1995 edition of Highway Bridge Seismic Design Code issused by the Ministry of Transportation and Communications is to allow structures to response only elastically in medium earthquake, and to allow formation of plastic hinges but without collapse when large earthquake strikes. Thus, the increase of shear capacity and ductility of pier is the main consideration in the retrofitting design.

4.1 Structural System

The original superstructure of the bridge is composed of six prestressed I girders of 2 meter height. The substructure is of two-column frame type on a foundation of combined footing founded on rock(Fig. 1). The diameter of pier column is 2.8 meters. All together there are 13 spans of which each span length is 35 meter long. All girders are simply supported. The bridge slab width is 17 meters. In order to accommodate the growing traffic in the future, the bridge width is increased to 21 meters in retrofitting work (widening 2 meters of bridge slab at both sides and adding one extra girder at both sides). Two new columns of 2.5m diameter are added to the outside of original two column bents to form four-column bent piers. Cap beams and foundations are enlarged at the same time (Fig. 6).

4.2 Design Code and Loading

4.2.1 Design Code and Live Load

The live load HS20-44 as per specification of AASHTO is adopted in the design (Ministy of Transportation and Communications, 1987) (AASHTO, 1996).

4.2.2 Design Seismic Load:

Earthquake force: $V=ZICW/1.2\alpha_y Fu$ (1)

(Ministy of Transportation and Communications, 1995)

Where

Z : design ground horizontal acceleration coefficient, 0.33 (Seismic zone 1A)

C: normalized acceleration response spectrum

W: total dead weight

α_y: the ratio of design ground acceleration to ground acceleration expected to initiate yielding in the structure, 1.65

I: importance factor, 1.2

Fu: seismic force reduction factor

4.2.3 Design Stress

Adopt ACI 318-95 design code (ACI, 1995),

Where

(a) concrete:

reinforced concrete	fc'=20 MPa
prestressed concrete	fc'=35 MPa

(b) reinforcement:

16mm and smaller size	fy=275 MPa
19mm and larger size	fy=415 MPa

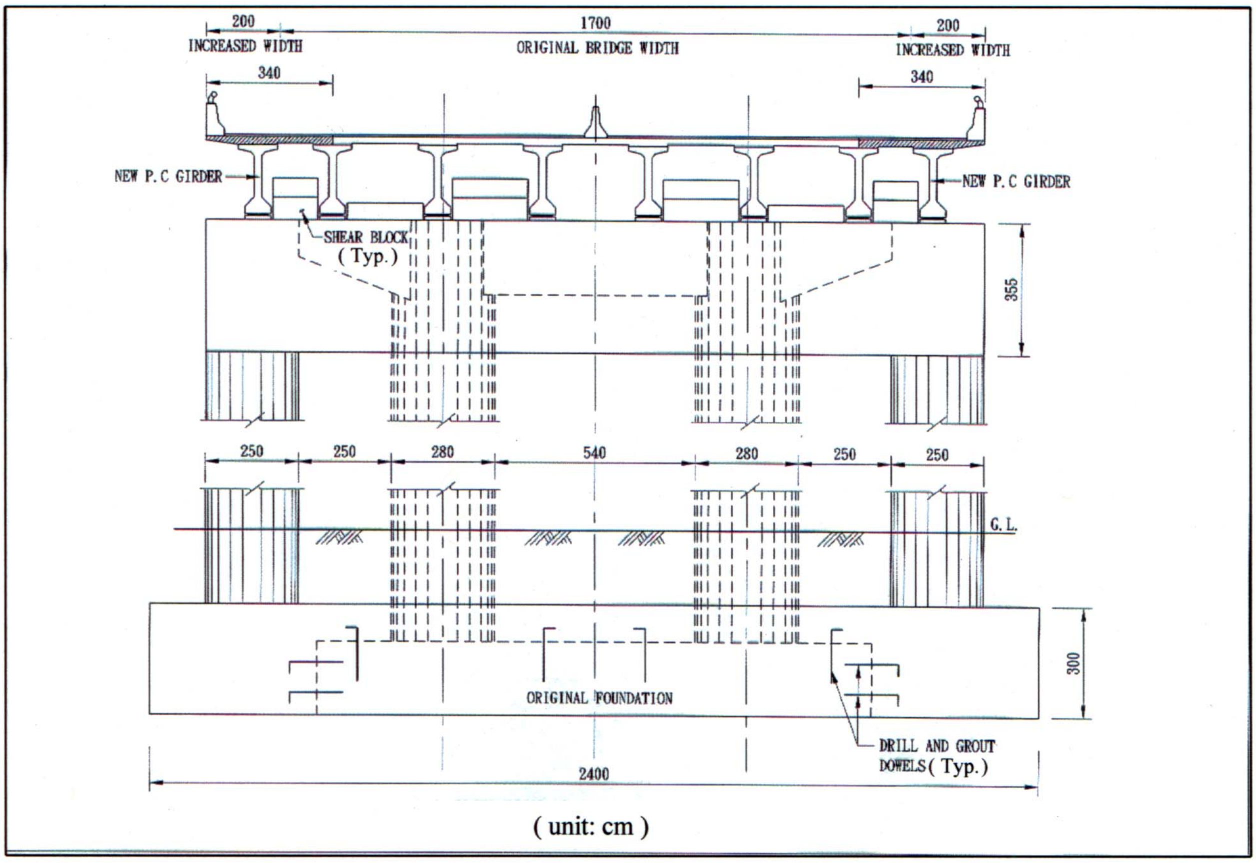


Fig 6: Front Elevation of the Retrofitted Bridge

4.3 Structural Analysis

SAP 90 is used for the analysis. Three-dimensional structural model is constructed using frame elements. Loading combinations consisted of dead load, live load, and earthquake force are applied to the structures. Dynamic analyses are performed to study the effect of earthquake force using response spectrum of TYPE I soil profile. The design ground horizontal acceleration coefficient is increased from 0.23 of seismic zone 2 to 0.33 of seismic zone 1A as per the local seismic design code.

4.4 Retrofitting Design

The original two columns are used only to support part of vertical loading in the design and the new added two columns are designed to resist horizontal seismic forces and to resist the rest part of the loading. Based on dynamic earthquake analyses, shear reinforcement is designed by the loading case which causes plastic hinges or by the earthquake force ZIg corresponding to a return period of 475 years. In addition, confining reinforcement at plastic zone is checked to meet ductility requirement described below:

$$\rho_S = 0.45\left[\frac{A_g}{A_c} - 1\right]\frac{f_c'}{f_{yh}}\left[0.5 + 1.25\frac{P_e}{f_c' A_g}\right] \qquad (2)$$

or

$$\rho_S = 0.12\frac{f_c'}{f_{yh}}\left[0.5 + 1.25\frac{P_e}{f_c' A_g}\right] \qquad (3)$$

whichever is greater , but is not less than:

$$\rho_S = 0.45\left[\frac{A_g}{A_c} - 1\right]\frac{f_c'}{f_{yh}} \qquad (4)$$

Where
Ac: core concrete area
Ag: gross concrete area
Pe: factorized axial force
fc': compressive strength of concrete
fyh: yielding strength of hoop or spiral reinforcement
ρ_S : volume ratio of hoop reinforcement to core concrete (calculating to the outside perimeter of spiral reinforcement).

The reactions at pier base transfered to foundation are used as foundation design forces.

The superstructures of span No. 4~6 and span No. 12 are dismantled and reconstructed. Earthquake stoppers are added and expansion joints are renewed.

The cap width is increased from 200 cm to 370 cm to provides enough space for stoppers, which also increases seating length at movement joints.

At the same time, the dimension of retrofitted foundations is increased from $15^M x 6.8^M x 2.0^M$ to $24^M x 14.8^M x 3.0^M$ (LxWxD) to provide appropriate bearing capacity.

4.5 Construction Procedure

By considering the safety during construction, the following retrofitting construction procedure is adopted:

1. Construct temporary supports for original superstructures.
2. Excavate soil and build temporary retaining structures for foundation construction.
3. Construct foundation slab and pier columns.
4. Backfill soil and construct pier caps.
5. Remove parapets on both sides and part of damaged slab; cut main reinforcement in original pier columns.
6. Remove temporary supports for superstructures.
7. Erect prestressed girders.
8. Construct bridge slabs.
9. Construct parapet, railing, and asphalt pavement.

5. CONCLUSIONS

Yen-Fon Bridge is located between two active faults in western Taiwan and is 4 kilometers to the east of the closer Shuang-Dung fault. The bridge construction was started on October 29th 1982 and completed on March 18th 1984. The original design used horizontal seismic coefficient Kh=0.15 and angle of repose of 30 degree. The ground acceleration near the bridge site in Chi-Chi earthquake is much higher than the original design value. Because of the redundancy provided by two-column bent piers, the bridge didn't suffer severe damage. In order to ensure the bridge response elastically in medium earthquake and allow formation of plastic hinges without collapse, the increase of ductility and shear capacity of pier is the main consideration in the retrofitted design.

6. ACKNOWLEDGMENTS

The authors wish to express their thanks to Mr. Chia-Tien Lin and Mr. Jui-Lung Wu of Highway Bureau and Dr. Jui-Tun Chou, Mr. His-Fu Pan and Mr. Hui-Yuan Chang of MAA for their assistance to the accomplishment of this paper.

7. REFERENCES:

ACI 1995, *Building Code Requirements for Structural Concrete*, ACI 318-95. American Concrete Institute P.O. Box 9094 Farmington Hills, MI 48333: 23-25 PP

AASHTO,1996 *Standard Specifications for Highway Bridges*, American Associates of State Highway and Transportation Officeals, Inc. Washington, D.C. U.S.: 20-21 PP

HO,C.S. 1986. *An Introduction of the Geology of Taiwan Explanatory Text of the Geologic Map of Taiwan (Second Edition)* Central Geological Survey ,Ministry of Economic Affairs ,Taipei ,Taiwan : 176 PP

Ministry of Transportation and Communications,1987. *Highway Bridge Design Code*, (in Chinese) Youth Cultural Enterprise Corporation Limit, Taipei, Taiwan. : 19-24 PP

Ministry of Transportation and Communications,1995. *Highway Bridge Seismic Design Code*. (in Chinese) Youth Cultural Enterprise Corporation Limit, Taipai, Taiwan.: 7-12 PP