SEISMIC ASSESSMENT AND RETROFIT STRATEGY OF TAIWAN ROADWAY BRIDGES

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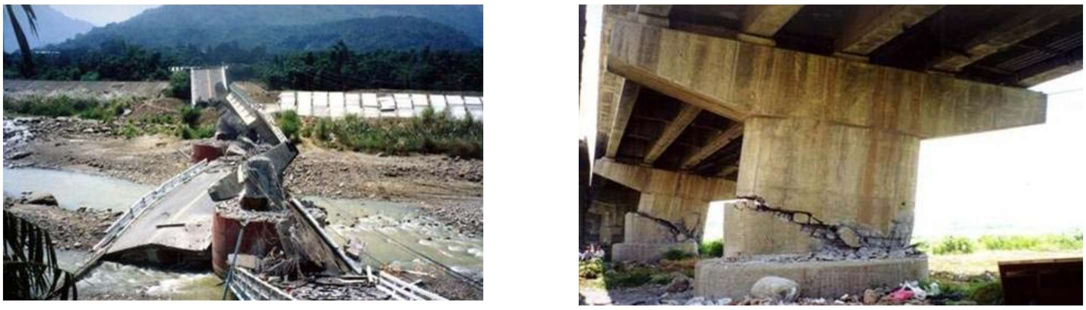
ABSTRACT :

Since Taiwan is located in a seismic hazard region, the seismic assessment and retrofit of older bridges is very important. In order to ensure the safety of traffic network, a project has been carried out to assess the seismic resistant capacity over 2,200 bridges on the Taiwan Roadway System. The assessment process is divided into two stages. The first stage is the preliminary assessment which all the bridges will be evaluated using simple seismic review sheets to determine the evaluation points. Further investigation will be carried out if the evaluation point is greater than 60 points. On the second stage, 5% of total bridges will be selected to perform the detail analysis. The state-of-the-art nonlinear static analysis (pushover analysis) is adopted to calculate the seismic capacity of bridge. Based on the assessment results, the retrofit strategy will be established. This paper will illustrate the assessment process and introduce the preliminary results.

KEYWORDS: Seismic Assessment, Ductility, Pushover Analysis, Retrofit

1. INTRODUCTION

Taiwan is located in the high seismic hazard zone and has been experienced a lot of earthquakes. Since the Chi-Chi earthquake, the seismic assessment for the existing bridges has become a major issue for the bridge engineering. In the past few years, all the bridge management authorities have focused on the retrofitting of those vulnerable bridges to avoid bridge collapses if there is another big earthquake shakes Taiwan. In the Chi-Chi earthquake, most of the damaged bridges (Picture 1.1) were located near the fault and were under the supervision of Directorate General of Highways, MOTC. Therefore, a project of seismic retrofitting feasibility study for Taiwan Provincial Highway bridges was issued by Directorate General of Highways, MOTC, and CECI Engineering Consultants, Inc., Taiwan is responsible to carry out the project. Totally 2,213 bridges have been evaluated in the project. In order to perform the seismic assessment effectively, it is important to establish a quick and accurate assessment procedure. The seismic assessment procedure is divided into two stages, a preliminary evaluation and detail analysis. At the first stage, simple seismic review sheets, one for bridge falling evaluation, one for ductility/strength evaluation are used to assess all the bridges. Then the second stage approximate 5% of the bridges, 132 bridges are selected to conduct the detail pushover analysis. Based on the evaluation results, adequate retrofitting schemes will be proposed and the approximate retrofitting cost will be estimated. With all these information suggested, a construction plan will be submitted to the Client for the annual budget planning of the Taiwan Highway Bridges seismic retrofitting.



Picture 1.1 Damaged bridges in Chi-Chi earthquake

2. PRELIMINARY SEISMIC EVALUATION

In the project, there are 2,213 bridges needed to be evaluated. Simple seismic review sheets have been developed for the preliminary seismic evaluation. There are two separate review sheets, one for the bridge falling assessment, and the other one for the ductility/strength capacity assessment. The bridges are evaluated according to different items and determined in different weighted points. For both review sheets, all the evaluation items are classified into three categories which are site condition, structural system and structural detail. For the ductility/strength capacity assessment, the category of site condition consists near fault condition, soil condition and liquefaction potential. Skew angle, pier size ratio, structural redundancy, pier height ratio and scouring depth are considered in the structural system category. And for the structural detail category, reinforcement details for pier are included. The strength/ductility evaluation seismic review sheet is shown in Figure 2.1. The review sheet for bridge falling assessment is similar to the strength/ductility evaluation review sheet. Except for the structural detail category, bearing seat length is taking into account instead of reinforcement detail. For those bridges graded over 60 points, detail analysis are necessary, in between 30 ~ 60 points further investigation might be needed. And for bridge graded under 30 indicates that the bridge is in good condition at the preliminary assessment stage. In order to verify the accuracy of the review sheet, the data of Chi-Chi earthquake were used to calibrate the weight in the review sheets to conform to the actual damages.

Figure 2.1 Strength/Ductility seismic review sheet

Seismic Review Sheet — Strength/Ductility Evaluation

Bridge Name： Bridge No.： STA： Unit： Evaluator： Date：

Build Year： □Before Year 1960 □Year 1960~1987 □Year 1987~1995 □Year 1995~2000 □After Year 2000

No.	Item			Weight	Evaluation Content	Grade	Point
G201	Site Condition	Near Fault		8	□Yes (1.0) □No(0)		
G202		Soil Type		6	□Taipei(1.0) □Type I(0.67) □Type II(0.33) □Type III(0) □ Design after 1987 (0)		
G203		Liquefaction Potential		6	□High(1.0) □Median(0.67) □Low(0.33) □None(0) □Design after 1995(0)		
G204	Structural System	Skew Angle, θ		4	$w = \theta/90° \le 1.0$		
G205		Pier Size Ratio, R		6	If $R \le 2.5, w = 1.0$; if $2.5 < R < 5$, $w = (5-R)/2.5$; if $R \ge 5$, $w = 0$		
G206		Pier Height Ratio, r		4	If $r \le 1.5$, $w = 1.0$; if $1.0 \le r < 1.5$, $w = -2 + 2r$		
G207		Redundancy		6	□None(1.0) □One Direction(0.5) □Both Directions(0)		
G208		Scouring Depth		24	Pile : $w = 2.0 - 2.0(h_{left}/h)$; Caisson : $w = 1.43 - 1.43(h_{left}/h)$		
G209	Structural Detail	Column Type	Pier Bottom Lapping	8	□With lapping(1.0) □Without lapping(0)		
G210			Plastic Hinge Detail	8	□Not Satisfy(1.0) □Partial Satisfy(0.5) □Satisfy(0)		
G211			Reinforcement Detail	4	□No Good(1.0) □In between(0.5) □Good(0)		
G212			Deterioration	8	□Sever (1.0) □Worse(0.67) □Bad (0.33) □OK(0)		
G209		Wall Type	Pier Bottom Lapping	6	□With lapping(1.0) □Without lapping(0)		
G210			Plastic Hinge Detail	8	□Not Satisfy(1.0) □Partial Satisfy(0.5) □Satisfy(0)		
G211			Reinforcement Detail	6	□No Good(1.0) □In between(0.5) □Good(0)		
G212			Deterioration	8	□Sever (1.0) □Worse(0.67) □Bad (0.33) □OK(0)		
G213		Bearing Condition or other Abnormal		8	Bearing Strength, Degree of Damage		
Total Points				100			

The bridge engineers go to the bridge site for each individual bridge to conduct the inspection, and fill out the review sheets for each bridge. A standard operation procedure (SOP) for site inspection and a guideline for filling the review sheet are also prepared to guide the engineers to fulfill the field tasks.

3. PUSHOVER ANALYSIS

In 1996, ATC-40 established a procedure to reveal the structural capacity based on the capacity spectrum method. The capacity spectrum can be determined from the pushover analysis. In addition, the demand spectrum obtained from elastic spectrum modified by a procedure of effective viscous damping, equivalent to the nonlinear response, was used to present the inelastic structure behavior under a specific ground motion. The intersection of capacity spectrum and inelastic spectrum, named as performance point, can be located through an iterative calculation.

A well-defined plastic hinge should be the key point to have an accurate pushover analysis result. The commercial software package SAP-2000 is used to perform the pushover analysis. Although SAP-2000 provided some convenient defaulted defining for the characteristic of plastic hinge of RC member, it was found that the analytical results sometimes are not quite matched with the time history analysis. Five points A~E are needed to be input to define the plastic hinge as shown in Figure 3.1. Where section AB represents the linear behavior and sections B to E are the nonlinear parts. In order to catch the actual behavior of RC columns, and get better simulation for the nonlinear behavior, a modification of the defaulted M3 model in SAP-2000 has been made. The corresponding three different failure modes, namely shear failure, bending to shear failure and bending failure are redefined, shown in Figure 3.2. The modified plastic hinge characteristic is used to replace the defaulted M3 model in SAP-2000. With this modification, it would help the pushover analysis for the bridge seismic evaluation with efficiency as well as accuracy. Pre-processor and post-processor are developed for the linking of pushover analysis. The pre-processor determines the modified plastic hinge properties, while as the post-processor could convert the capacity curve from the pushover analysis to a graphic output of the structural capacity spectrum.

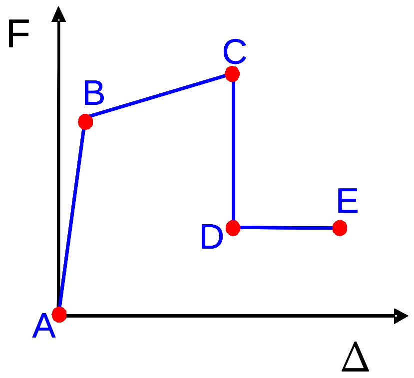
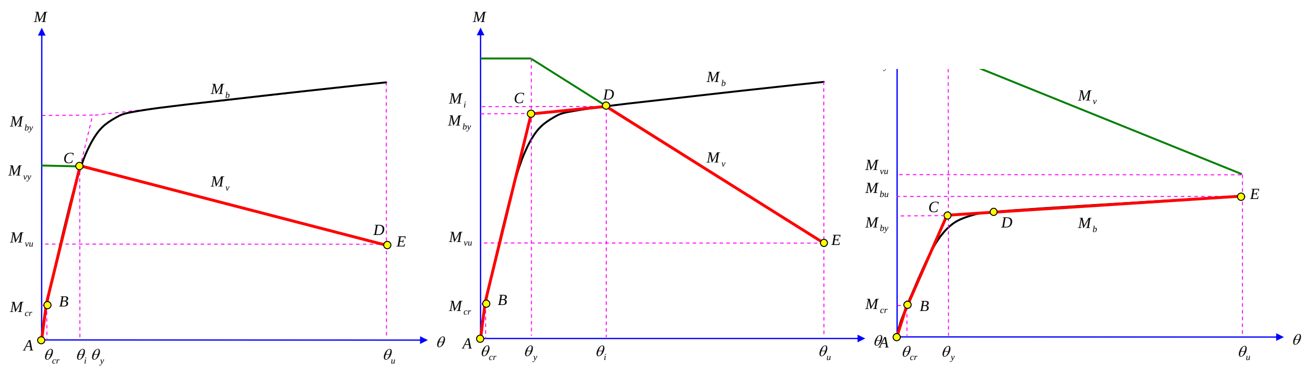


Figure 3.1 SPA2000 M3 plastic hinge



(a) shear failure (b) bending to shear failure (c) bending failure

Figure 3.2 Characteristic of plastic hinge for RC member

The basic objective of the ATC-40 is to evaluate the structural performance under a given seismic demand. General speaking, the ACT-40 scheme seems more suitable for the design task rather than the evaluation task. A new methodology has been proposed by Prof. Sung in 2003. Since the bridge does no fail, the structural performance point should be always locating right on the curve of the capacity spectrum. Every single performance point along the capacity curve can be determined as long as the pushover analysis has completed. Therefore, it can be used as "input" to calculate the corresponding seismic demand as "output", in such way that the complicated iterations can be eliminated. The performance point is located at the interaction of the capacity spectrum and the inelastic demand spectrum, as shown in Figure 3.3, and thus meets the mutual property of both spectrums. Such that spectral acceleration api and displacement dpi for the capacity spectrum would be the same as (S_a)inelastic and (S_d) inelastic for the inelastic demand spectrum. The effective damping β_{eff} includes the inherent damping β_{basic} in the structure and equivalent viscous damping β_o taking into account for the energy dissipation of the hysteretic loop.

According to ATC-40, β_{eff} is calculated as

$$\beta_{eff} = \beta_{basic} + \beta_o = \beta_{basic} + \frac{63.7\kappa(a_y d_{pi} - d_y a_{pi})}{a_{pi} d_{pi}} \quad (3.1)$$

Where κ is the damping modification factor to reflect the actual hysteretic behavior of the structure, and a_y and d_y is the spectral yield acceleration and displacement, respectively. The relationship between PGA and the spectral acceleration a_{pi} then can be expressed as

$$PGA = \frac{a_{pi}}{(S_a)_{inelastic} \times C_D} \quad \text{where} \quad C_D = \frac{(S_a)_{inelastic}}{(S_a)_{elastic}} = \frac{1.5}{40\beta_{eff} + 1} + 0.5 \quad (3.2)$$

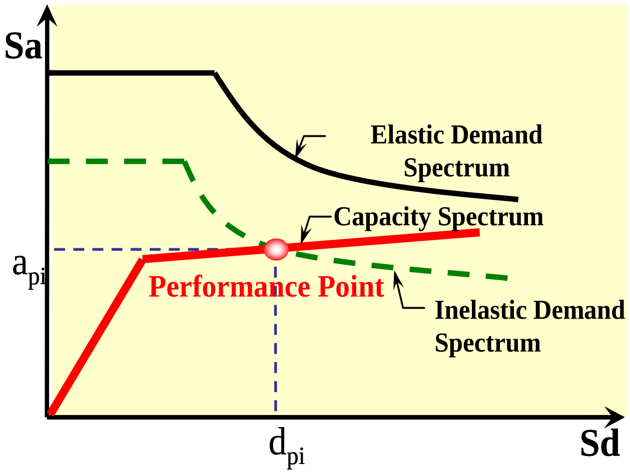


Figure 3.3 Capacity and the demand spectrum

4. DETAIL ANALYSIS

The bridge seismic detail analysis procedures are described as follows:

Step 1 : Set up the bridge analysis model.
Step 2 : Calculate the moment curvature of pier column, determine the failure mode, i.e. shear failure, bending to shear failure or bending failure. Define the plastic hinge for SAP2000.
Step 3 : Perform the pushover analysis, establish the capacity curve, convert the capacity curve to the capacity spectrum.
Step 4 : Calculate the pier column yielding ground acceleration S_{ay}
Step 5 : Calculate the effective damping β_{eff},, the damping correction factor C_D, then the performance point ground acceleration

$$Z = \frac{a_{pi}}{C(T) \times C_D(\beta_{eff})} \quad (4.1)$$

Step 6 : Output the envelope of pier top and bottom reaction forces from pushover analysis.
Step 7 : Check the bearing strength, foundation strength and stability.
Step 8 : Determine the ground acceleration of first damage case among bearing, pier column and foundation.

5. CASE STUDY

Li-Kun bridge located in Taiwan No.3 Provincial Highway is a P.C.I bridge with 43 units (Picture 5.1). The span arrangement is 3@35+16@40+(20+6@40+20)+15@40+25m, and the total length of the bridge is 1620m. Li-Kun bridge was widened in 1992. The old part of bridge was built in 1977, while the new part was built in 1992, so that the bridge was designed according to two different seismic design codes. The deck width of old bridge and new bridge is 8.1m and 17.9m, respectively. And now the total width of the deck is 26m. The pier for old bridge is column type with average height 8.5m and wall type pier for widened bridge is in average 10m high. The foundation of old bridge is 45 x 45cm RC piles, and the widen bridge is caisson foundation. The structure is simply supported with hinge on one pier and roller on the other pier.

Picture 5.1 Li-Kun Bridge

The analysis model for the evaluation unit is shown in Figure 5.1 with a typical span length of 40m. The model includes 10 P.C.I. girders, deck slabs, intermediate diaphragms and piers. The foundation is simulated as fixed condition. Figure 5.2 shows the SAP-2000 M3 plastic hinge input data box. The pre-determined the pier column plastic hinge is shown in Figure 5.3. The capacity curve from pushover analysis is shown in Figure 5.4. And the Figure 5.5 is the converted capacity spectrum from capacity curve. The widened bridge has higher capacity than the old bridge. The base shear capacity is 415 T and 224T for new bridge and old bridge, respectively. The top curve represents the capacity of entire bridge, which is 639 T equal to the sum of widen bridge and old bridge. The capacity spectrum of the bridge is shown in Figure 5.6 with three different κ values. The yielding PGA a_y is 138g from the analysis and taking κ=1/3 max., PGA a_u is 0.354g. Since there are lots of uncertainties for the pier reinforcement detail, the plastic hinge of pier might not be fully developed. The seismic resistant capacity of the bridge is conservatively chosen to be equal to a_y which is 0.138g.

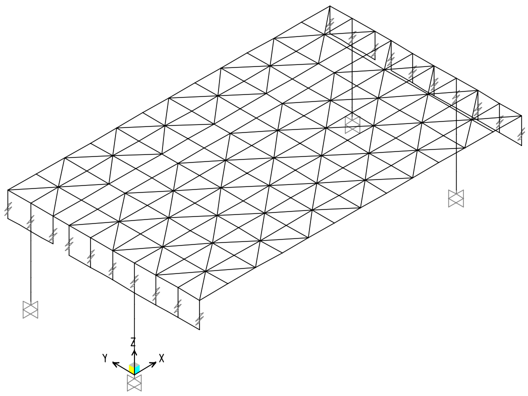


Figure 5.1 SAP-2000 analysis model

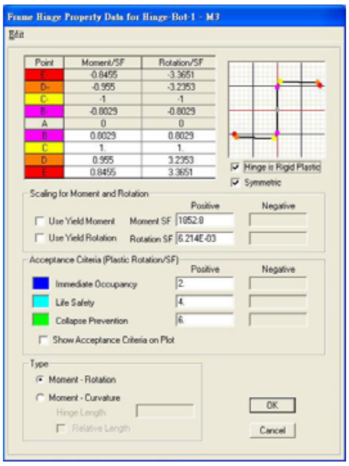


Figure 5.2 SPA-2000 M3 plastic hinge input data box

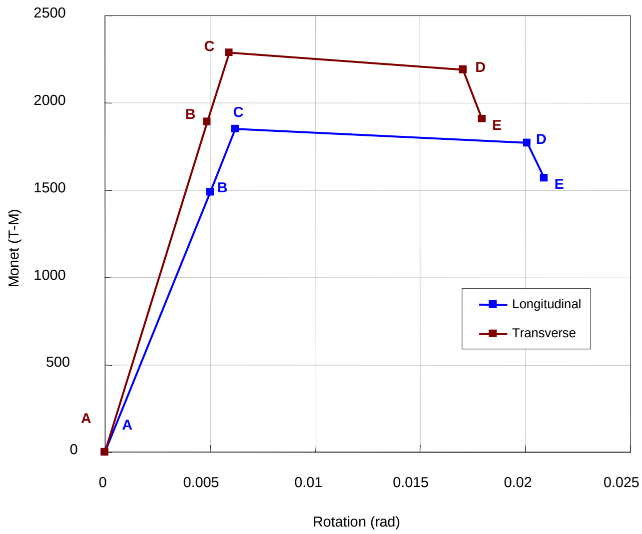


Figure 5.3 Modified pier column plastic hinge

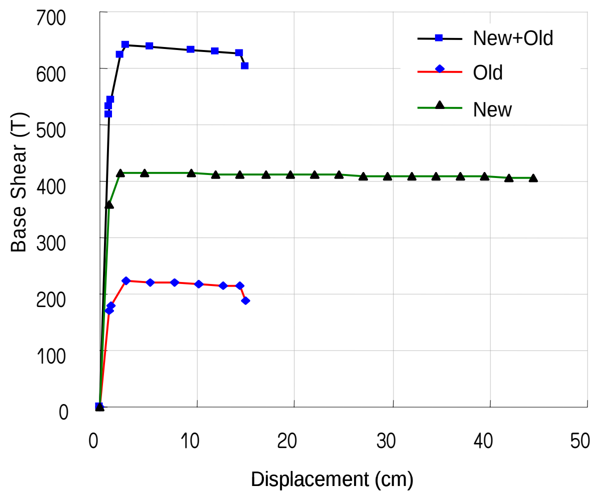


Figure 5.4 Capacity curve of Li-Kun Bridge

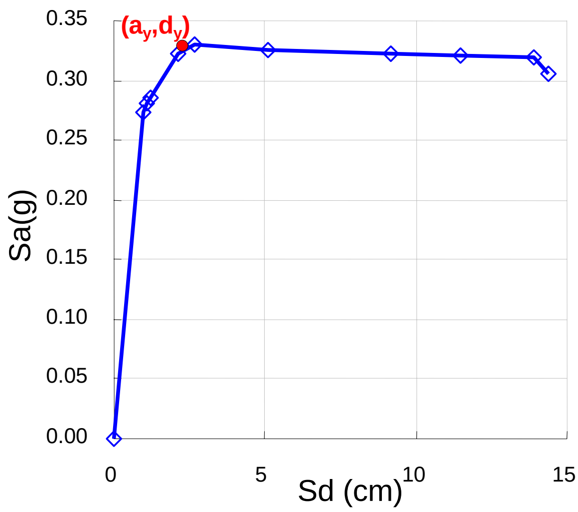


Figure 5.5 Capacity spectrum of Li-Kun Bridge

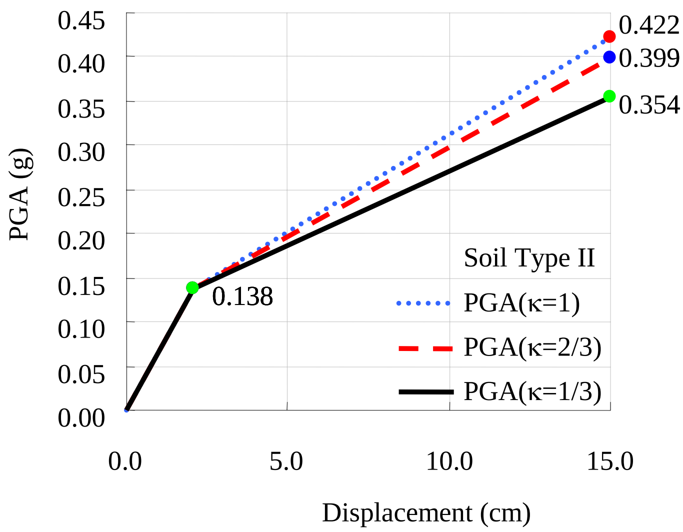


Figure 5.6 PGA vs. Displacement curve

6. RETROFIT STRATEGY

Before retrofit strategy is set up, there are two evaluation processes should be taken, one is screening and prioritization, the other is detailed evaluation. The appropriate retrofit plan should base on the results of detailed seismic evaluation. In general, the bridge damage patterns caused by earthquake can be classified, include riverbed corrosion, soil liquefaction, lack of falling prevention device, bearing functions vanish, structure system failure, member strength insufficient …etc. Each damage pattern should match their own unique retrofit method. For those members without enough strength cases, proper retrofit will usually be capbeam, column and foundation strengthening. In general, traditional column retrofits include RC jacketing, steel jacketing, mortar jacketing and FRP jacketing. No matter which retrofit is used, when member strength is insufficient, then foundation enhancing is usually needed in addition to column and capbeam retrofit. Therefore, the total retrofit cost will be quite high while dealing with foundation retrofit.

Different from traditional methods, a new retrofit strategy which is a cheaper way, an easy-repaired damage mechanism and can skip foundation retrofit problem is proposed here. It is an economical method, unlike traditional retrofit whose focus is on safety assurance and member ductile, this new strategy is not only on safety but also on performance and repair considerations. The new retrofit concept will be called “functional bearing mechanism”.

The concept of functional bearing system is based on the observation of bridge damages in Taiwan after Chi-Chi earthquake. Looking back at the statistic of bridge damages, investigations of 1,094 bridges revealed that most bridge columns suffered none-to-minor damages while few were severe damaged due to large surface rupture passed through. One of the reasons for this unexpected performance is the construction method of rubber bearing – an unbolted design on the simply-supported bridge structure. It is found that friction-sliding mechanism of rubber bearing reduced the seismic load passing to column and foundation. So column damages were surprising small and retrofits can be simplified. It is observed that more severe the bearing destroyed, the less column damaged. And it’s found that if the major bridge damage is on bearing, then the retrofit work will be easier and the transportation can still be provided simultaneously while bearing repair work is executing.

Current seismic design concept is that no bearing damage takes place until plastic hinge occurs in column, so called a “strong bearing system” concept. But for those none seismic bridges in Taiwan, Chi-Chi earthquake experiences show that bearing damage will occur first and then seismic force of column will be reduced, so called “soft bearing system” concept. The new retrofit idea bases on Chi-Chi experience is that much more bearing damages and exceeding displacement happened, then less in column damage or plastic-hinge occurred. “Functional bearing” concept is just like safety fuse. It can reduce retrofit work and avoid too much cost on foundation retrofit issue. According to Chi-Chi experience, a good functional bearing system should not only have an energy absorbing bearing, but also equip displacement limit devices, falling prevention devices and enough seating length. The bearing can be high damping rubber bearing, lead rubber bearing or elastomeric bearing, which can extend the original bridge period, reduce earthquake force and inactivate the inertial force of superstructure. Therefore, the ideal damage mechanism sequence should be that bearing reaches its ultimatecapacity, then partial plastic-hinge occurred in column, and falling prevention device can still function well at the final stage. The most important thing is that no matter what sequence is, the bridge won’t be allowed to collapse.

Utilizing the functional bearing system concept, the structure system can be improved in many ways, such as bearing replacement, adding damper device to abutment, enhancing horizontal resistance of backfill soil on abutment, adding displacement limit device...etc. Also, all previous measures can be combined to adopt.

So, the basic five functions of functional bearing system should at least provide are as below,

1. Displacement control – keep superstructure from sliding while resists vehicle driving force
2. Sliding-friction energy dissipation – rubber bearing slide-friction
3. Adequate shear keys – only for transverse falling-prevention
4. Enough sliding-friction displacement – provide friction energy dissipation mechanism
5. Enough seating length – no collapse

7. CONCLUSION

A simple and accurate seismic assessment procedure has been introduced. By using a simple seismic review sheet for quick seismic preliminary evaluation, one can screen out the potential candidate bridges for the detail analysis. A state-of-the-art pushover analysis method is adopted to calculate the seismic resistant capacity of the bridge. Few modifications have been made for pushover analysis to get more accurate results. Using functional bearing as an alternative retrofit method is introduced. This new retrofit strategy can avoid the foundation retrofit and reduce the cost of retrofitting. At the end of this project, a construction plan which includes retrofitting cost estimation and economics benefit evaluation will be proposed based on the seismic assessment results in the project.

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REFERENCES

921 Chi-Chi Earthquake Special Report, China Engineering Consultants, Inc. 2000.

Chang, D.W. “921 Chi-Chi Earthquake Bridge Damage Briefing”, 921 Chi-Chi Earthquake Structure Damage Investigation Seminar, Chinese Society of Structural Engineering, 1999.

Sung, Y.C., “Performance-Based Seismic Evaluation and Design of Bridges”, PhD Dissertation, Taiwan University, 2003. (in Chinese)

ATC-40, Seismic Evaluation and Retrofit of Concrete Building, Applied Technology Council, 1996.

Sung, Y.C., ”Seismic Evaluation of Existing Bridges: Theory and Application”, International Training Program for Disaster Prevention and Seismic Design of Structures, Oct. 25-29, 2004, Taipei, Taiwan.

Wu, H.M., Technical Report - Feasibility Study of Highway Bridges Seismic Assessment and Retrofitting, China Engineering Consultants, Inc. 2006.